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ACTIVITY REPORT 2010

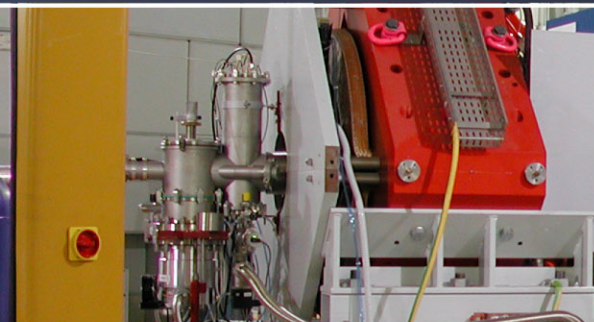
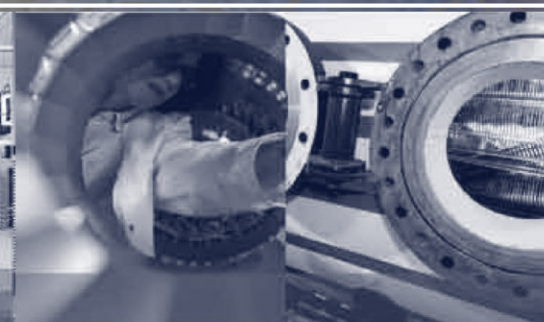


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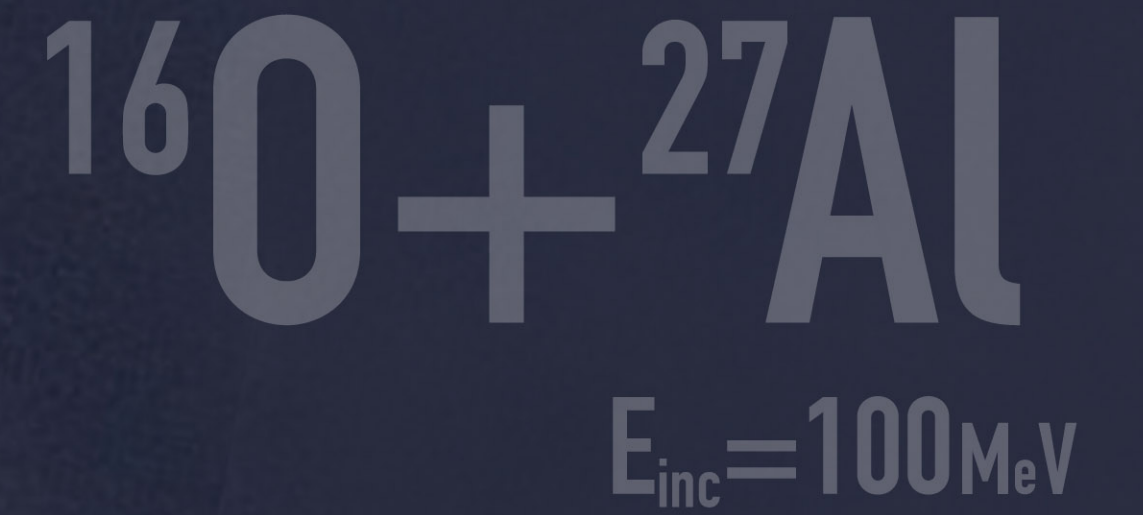
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Cover figure

The challenging measurement of the $^{16}\text{O} + ^{27}\text{Al}$ elastic and inelastic angular cross sections down to hundreds nb/sr and up to large scattering angles has been performed at 100 MeV, using the ray-tracing large acceptance magnetic spectrometer MAGNEX.

The elastic angular distribution shows a Nuclear Rainbow pattern, predicted by microscopic quantum-mechanical calculations based on the Sao Paulo Potential with couplings to target excited states, but unexpected by optical model calculations.

This discovery opens new perspectives in the understanding of the collisions between heavy ions (HI) at energies far from the Coulomb barrier. Moreover, complementary information in this field will be gained by the exploration of the neutron decay from the neutron rich nuclei resonances populated via HI multi-neutron transfers.

This will be accessed using MAGNEX to identify these resonances and the EDEN detector array to measure the associated neutron correlations.



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Foreword

In this Report the reader will find information on the research activities performed at LNS in 2010, ranging from basic nuclear physics and astrophysics to astroparticle physics, from the technological developments of accelerators and ion sources to the exploitation of physics methodologies and facilities in interdisciplinary fields like, for instance, medical physics and characterization of cultural assets.

Thus I will skip the long list of these themes and of the excellent results obtained so far, that are fully presented in the following. Rather I want to turn the attention of the reader to a couple of recent achievements that are equally important for the life of the laboratory, in so far as they refer to activities of primary interest for LNS.

First news is the realization of the announced upgrade of the cyclotron extraction line, aimed at improving the transport efficiency of the fragmentation products of the FRIBS@LNS facility. A promising increase of the intensities by a factor close to ten has been achieved indeed, also thanks to a new diagnostics system implemented on the line. A further gain by a factor three is expected after the simple substitution of some actuators placed along the line, that presently reduce the beam acceptance. After this last operation LNS will be much more competitive in the matter of production of in-flight radioactive beams at intermediate energies.

As a second relevant achievement, a tower, 600 meters high, has been deployed and anchored on the sea floor off the coast of Sicily at a depth of 2000 m, a crucial step towards the construction of an underwater telescope for neutrinos, the most useful messengers of the violent phenomena occurring in the remote regions of the Cosmos. This operation marked the conclusion of Phase 2 of the INFN Nemo Project and represented an important verification of the mechanical design of the Nemo tower that the international community has also adopted as base module of the European KM3 telescope to be installed in the Mediterranean Sea.

I have mentioned two gratifying results achieved in the frame of two different areas of the LNS activity. They remind us that the future of LNS relies on a balanced development of the many fields covered by our researches and on the awareness that a success achieved in any of them is a success for the whole Laboratory and its staff.

Marcello Lattuada
INFN-LNS Director

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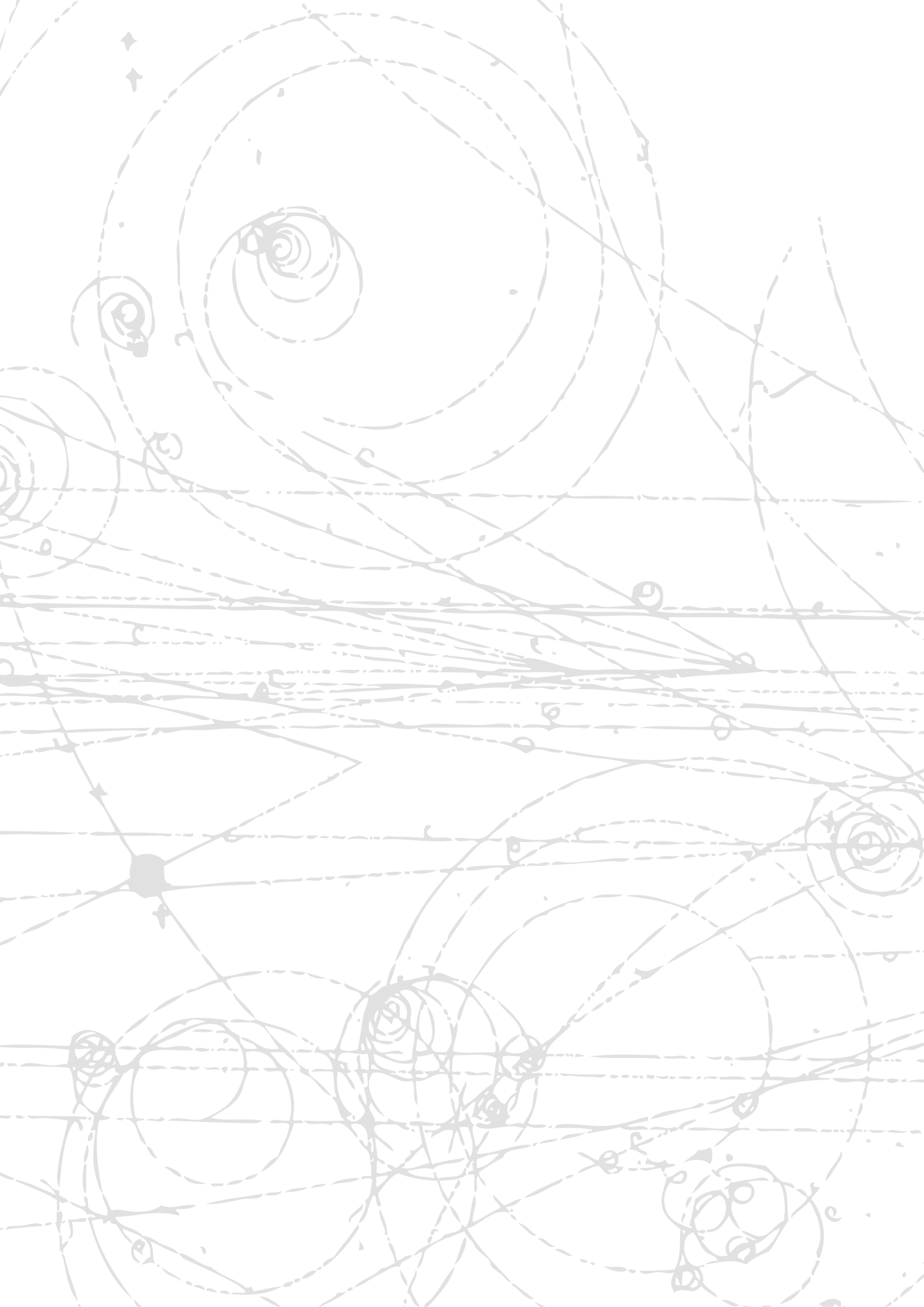
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LABORATORI NAZIONALI DEL SUD
ACTIVITY REPORT 2010

**EXPERIMENTAL
NUCLEAR PHYSICS
AND ASTROPHYSICS**



Challenging measurement of the $^{16}\text{O} + ^{27}\text{Al}$ elastic and inelastic angular distributions up to large angles

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Abstract - The $^{16}\text{O} + ^{27}\text{Al}$ elastic and inelastic angular distributions have been measured in a broad angular range ($13^\circ < \theta_{\text{lab}} < 52^\circ$) at about 100 MeV incident energy. The use of the MAGNEX large acceptance magnetic spectrometer and of the ray-reconstruction analysis technique has been crucial in order to provide, in the same experiment, high-resolution energy spectra and cross section measurements distributed over more than seven orders of magnitude down to hundreds of nb/sr.

INTRODUCTION

Recently [1] rainbow-like structures have been theoretically predicted in the elastic channel for heavy ions systems such as $^{16}\text{O} + ^{27}\text{Al}$ and $^{16}\text{O} + ^{58}\text{Ni}$ by a new generation of parameter free coupled channel calculations using the São Paulo potential [2] and the Glauber model [3]. These results, obtained at energies several times the Coulomb barrier, are unexpected due to the high absorption that should be present in such heavy system collisions.

The rainbow pattern has been experimentally well established for lighter systems like $\alpha + \text{nucleus}$, $^{12}\text{C} + ^{12}\text{C}$, $^{16}\text{O} + ^{12}\text{C}$ and $^{16}\text{O} + ^{16}\text{O}$, the heaviest system that so far has shown a prominent refractive structure in the elastic channel. An excellent topical review including a complete bibliography on this subject has been recently published by D. T. Khoa et al. [4]. It is important to point out that tremendous efforts have been done in order to reveal the rainbow structures, since at large scattering angles the elastic cross sections become extremely small ($d\sigma/d\omega \sim 100$ nb/sr and less). In such conditions, guaranteeing a reasonable signal to noise ratio in the measured spectra could represent a major problem. Moreover, supplementary difficulties arise for heavy systems scattering, resulting in stringent requirements as listed below:

1. The overlap between events from elastic and from other reaction channels must be avoided, which means that satisfactory ion identification is demanded.
2. The typically small excitation energy of the first excited states in heavy targets makes the separation between the elastic and inelastic channels much more challenging compared to lighter systems. In this case, a high energy resolution is required.
3. The discrimination between the scattering events of interest and those from the target contaminants could be rather difficult especially at backward angles, where the inelastic scattering on the contaminants can be dominant.
4. High angular resolution is required to characterize the rainbow structures and distinguish between the refractive and the diffractive nature of the oscillation patterns. The heavier is the system the more rapid are the oscillations and consequently the higher is the necessary resolution.
5. A higher angular accuracy is necessary for heavier systems, since the exact location of the minima in the angular distributions is fundamental to test different theoretical approaches against the experimental data.
6. The typical count rates in heavy ions experiments are smaller than light ones, due to more severe constraints in the target thickness and in the availability of intense beams. In this context, a large angular acceptance is needed to allow for statistically significant data especially at large angles.

All of these complications are expected in the experimental study of the $^{16}\text{O} + ^{27}\text{Al}$ elastic scattering and this explains the lack of experimental data for this process at sufficient backward angles. In a recent paper [5] we have illustrated the experimental technique and the data analysis method used to perform such an experiment and to extract energy spectra and angular distributions. It is based on the use of the MAGNEX large acceptance spectrometer for the detection of the ^{16}O ejectiles at the focal plane, and on the implementation of a high-performing algebraic ray-reconstruction technique. In the present report a brief review of the main results is

presented. It has been demonstrated that the above listed experimental requirements are fulfilled by MAGNEX which proves to be well suitable for this challenging experiment.

THE EXPERIMENT

The $^{16}\text{O}^{8+}$ beam, delivered by the Tandem Van der Graaff accelerator at 99.2 MeV total incident energy, was focused on a ^{27}Al self-supporting target located in the MAGNEX scattering chamber. The elastically and inelastically scattered ^{16}O ions have been momentum analyzed by the spectrometer and detected by its Focal Plane Detector (FPD) [6,7,8].

A system of diaphragms was used in order to limit the beam spot size and the angular divergence at the target to $1.2\text{ mm} \times 0.8\text{ mm}$ in the horizontal direction and $2.3\text{ mm} \times 3\text{ mm}$ in the vertical one. In such conditions, the contribution of the beam divergence to the overall energy spreading is less than 50 keV at backward angles. A particular care has been taken in aligning the diaphragm system to guarantee that the beam intercepts the target along the spectrometer optical axis, thus getting the best resolution.

The choice of the target thickness was the result of a careful compromise between energy resolution and reaction yield constraints. In fact the experiment should provide a complete separation of the elastic channel from the first inelastic excitation of the ^{27}Al at 844 keV, still getting a reasonable count rate at backward angles, where the predicted cross sections fall down. For this reason two different aluminum target foils have been mounted for the runs at different scattering angles, (i) a $100\text{ }\mu\text{g}/\text{cm}^2$ target for the runs at forward angles ($13^\circ < \theta_{\text{lab}} < 36^\circ$) and (ii) a $137\text{ }\mu\text{g}/\text{cm}^2$ one for the runs at backward angles ($31^\circ < \theta_{\text{lab}} < 52^\circ$). The uncertainty on the target thickness is about 10%.

The sources of energy spreading must be considered carefully to achieve the best energy resolution in the energy spectra. The use of the Tandem Van der Graaff accelerator guarantees a good monochromatic beam ($\approx 10\text{ keV}$). In this condition, the leading contribution to the overall energy widening comes from the kinematic broadening and from the energy straggling in the target. The former is particularly important for large scattering angles θ_{lab} . As an example, it produces an energy broadening of about 250 keV for the $^{27}\text{Al}(^{16}\text{O}, ^{16}\text{O})^{27}\text{Al}$ reaction at 100 MeV incident energy, considering an angular resolution of 0.2° at $\theta_{\text{lab}} = 50^\circ$.

In the different experimental runs, the optical axis of the spectrometer was centered at the laboratory angles $\theta_{\text{opt}} = 18^\circ, 24^\circ, 29^\circ, 35^\circ, 41^\circ$ and 46° . In all the runs the ejectiles trajectory were accepted between -5.2° and $+6.3^\circ$ in the horizontal direction and $\pm 7.0^\circ$ in the vertical, with respect to the optical axis. In such a way an angular overlap of about 6° between two contiguous sets of measurements was available.

Simulations were also performed considering different rotation angles of the target ladder θ_{target} . The energy

straggling was calculated as a function of θ_{target} for different scattering angles. According to the results of the simulations, it was decided to rotate the target ladder of $\theta_{\text{target}} = 20^\circ$ in all the runs at different scattering angles. This allowed to minimize the spreading due to the sensibly different energy loss between the incident ^{16}O ions and those emitted at lower kinetic energy in the reaction.

The beam intensity was about 10 pA for the runs at backward angles, being reduced down to 0.6 pA at $\theta_{\text{opt}} = 18^\circ$ to avoid distortions in the FPD response due to the high rate. A graphite Faraday cup (4 cm deep) having a circular aperture (8 mm diameter) and an electron suppression ring was used to stop the beam. A low noise circuit including a digital integrator was used to determine the collected charge with an intrinsic accuracy better than 0.5%.

The magnetic fields of the MAGNEX quadrupole and dipole were tuned in order to transmit the scattered $^{16}\text{O}^{8+}$. The different reaction ejectiles within the spectrometer acceptance were momentum analyzed and focused on the FPD. For each angular setting the vertical focus was optimized for the momenta corresponding to the elastic channel.

The MAGNEX FPD is a hybrid gas detector with an array of 54 silicon pad detectors ($70 \times 50\text{ mm}^2$ area, $500\text{ }\mu\text{m}$ thickness) at the back [6, 7, 8]. The FPD was filled with 99.95% pure isobutane at 7 mbar pressure. A voltage of -1100 V was applied to the cathode resulting in a reduced electric field of about $7.8\text{ V cm}^{-1}\text{mbar}^{-1}$ for the drift region. The multiplication wires were supplied with +750 V in order to maintain a proportional regime with a gain factor of about 200. The silicon detectors were biased with +50 V to get a full depletion of their active volume. In such working conditions the FPD allows to cleanly identify the detected ions in atomic (Z) and mass (A) number and electric charge (q), and to precisely measure the horizontal and vertical impact position (x_f, y_f) and direction (θ_f, ϕ_f) of the ions trajectory in the focal plane. Precise alignments were done in order to relate the parameters measured by the FPD to the spectrometer absolute reference frame, where the transport operators are defined. The sensitive elements of the detector (anodic strips, cathode, Frisch grid, field shaping wires) have been simultaneously sighted with specially designed pin-pot of the magnets by means of bubble levels and theodolites. An overall accuracy better than 0.1 mm has been achieved in both the horizontal and vertical positioning of the FPD.

The use of a latching scaler module allowed the measurement of the ratio between the number of triggers and the number of the events treated by the acquisition system, thus providing a coefficient which accounts for the actual acquisition dead-time.

DATA REDUCTION AND ANALYSIS

The first step of the MAGNEX data reduction procedure is to generate a transport map that describes the evolution of the phase-space parameters from the target point to the

focal plane. The ray-reconstruction algorithms [9] have been used to build it to 10th order. In the input, the geometry of the spectrometer (distances between the magnetic elements, length of the drift spaces, slits defining the solid angle) and the size and location of the FPD are set as the experimental ones. The dipole and quadrupole magnetic strengths have been measured by probes with an overall uncertainty of about $\pm 0.1\%$. Using the reconstructed momentum and the measured total kinetic energy of the ions, the particle identification is possible with a mass resolution as high as $\Delta A/A = 1/160$ as shown in detail in Ref. [10].

Fig. 1 shows an example of some of the reconstructed parameters for the $^{16}\text{O}^{8+}$ reaction ejectiles. In particular the scattering angle θ_{lab} is shown against the ^{27}Al apparent excitation energy E^* , which is defined as the excitation energy of the ^{27}Al reaction products, assuming a binary process. The ^{27}Al ground and several excited states are well visible as vertical and straight loci, as expected since the E^* parameter is not depending on the scattering angle for transitions to the ^{27}Al states. The tilted loci represent the events relative to the presence of ^{16}O and ^{12}C contaminants in the target that induce the population of the ^{16}O and ^{12}C ground and ^{12}C excited state at 4.439 MeV. The distinct curvatures are due to the different kinematics of ^{16}O scattering on the ^{16}O and ^{12}C target nuclei. This helps the identification and discrimination of such events, which is one of the qualifying features of the ray-reconstruction technique implemented in MAGNEX, meeting one of the key requirements listed in the introduction of the present report.

An average resolution of about 200 keV is obtained in the explored phase space, allowing a clean separation of the elastic from the inelastic channels. One can also notice the different counts distributions due to the different shapes of the angular distribution between the elastic and the inelastic transitions. In particular, those relative to the states at 0.844, 1.014, 2.212, 2.735 and 2.982 MeV show a very similar oscillating pattern, with a well defined minimum at around $\theta_{lab} = 17^\circ$. It is the expected behavior since all of those belong to the same $L = 2$ multiplet $^{28}\text{Si}(2^+) \otimes \nu(1d_{5/2})^{-1}$ [25, 26]. The analysis of the kinematic lines shown in Fig. 1 does allow a further check of the accuracy in the reconstruction of the experimental laboratory angle θ_{lab} . As an example, the crossing point of the ^{27}Al (^{16}O , ^{16}O) $^{27}\text{Al}_{2.212}$ inelastic locus with the $^{16}\text{O} + ^{16}\text{O}$ elastic one depends only on the laboratory angle, once the beam energy is known. The discrepancy between the kinematic predictions and the experimental data is within 0.1° . This is in agreement with the recently published results with the MAGNEX spectrometer in similar experimental conditions [10].

The angular distributions of the absolute cross section have been deduced for the transition to the ^{27}Al ground and unresolved excited states at 0.844 and 1.014 MeV. The results for the experimental runs at $\theta_{opt} = 18^\circ$, $\theta_{opt} = 24^\circ$ and $\theta_{opt} = 46^\circ$ are shown in Fig. 2. The differential solid angle for the full spectrometer acceptance has been carefully determined taking into account the overall

transport efficiency as described in Ref. [11]. A dead-time coefficient of about 15% has been measured. An angular bin of 0.3° has been chosen for the data-set at $\theta_{opt} = 18^\circ$ and $\theta_{opt} = 24^\circ$ and of 1° at $\theta_{opt} = 46^\circ$ in order to achieve a good compromise between the statistical uncertainties in the number of counts for each bin and the angular resolution. The error bars include both a statistical contribution (between about 1% at forward angles and 50% at the backward ones) and a component due to the uncertainty in the solid angle determination (about 3%). An overall systematic error of about 10% is estimated, mainly due to the uncertainties on the target thickness. A more detailed analysis of the errors in the differential cross-section has been done in Ref. [11].

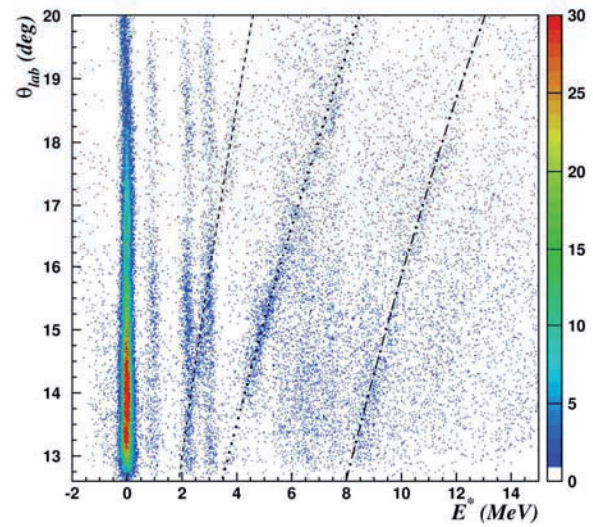


Figure 1: Two-dimensional plot of the reconstructed θ_{lab} against the ^{27}Al apparent excitation energy E^* for the $^{27}\text{Al}(^{16}\text{O}, ^{16}\text{O})^{27}\text{Al}$ reaction at 99.2 MeV and $\theta_{opt} = 18^\circ$. The lines represent the calculated kinematics for the population of the ^{16}O (dashed) and ^{12}C ground (dotted) and the ^{12}C excited state at 4.439 MeV (dot-dashed).

Thanks to the large angular acceptance of the spectrometer, significant overlaps between the two measurements at adjacent angles $\theta_{opt} = 18^\circ$ and $\theta_{opt} = 24^\circ$ are available, thus allowing a supplementary check of the quality of the absolute measurement of the cross section. The observed agreement in the overlap region is excellent both in the elastic and inelastic channels. In addition, the achieved angular resolution is estimated to be within 0.3° at $\theta_{opt} = 18^\circ$, with slightly poorer results in the run at $\theta_{opt} = 24^\circ$ and $\theta_{opt} = 46^\circ$ likely due to worse experimental conditions. The systematic error on θ_{lab} has been evaluated to be 0.3° based on the cross-points of kinematic lines referring to different reactions, as for example those shown in Fig.1. This is in agreement to what found for the spectrometer in similar conditions [9] and it is good enough to safely determine the minima of the angular distribution oscillation. All of this confirms the reliability of the instrument for this kind of studies.

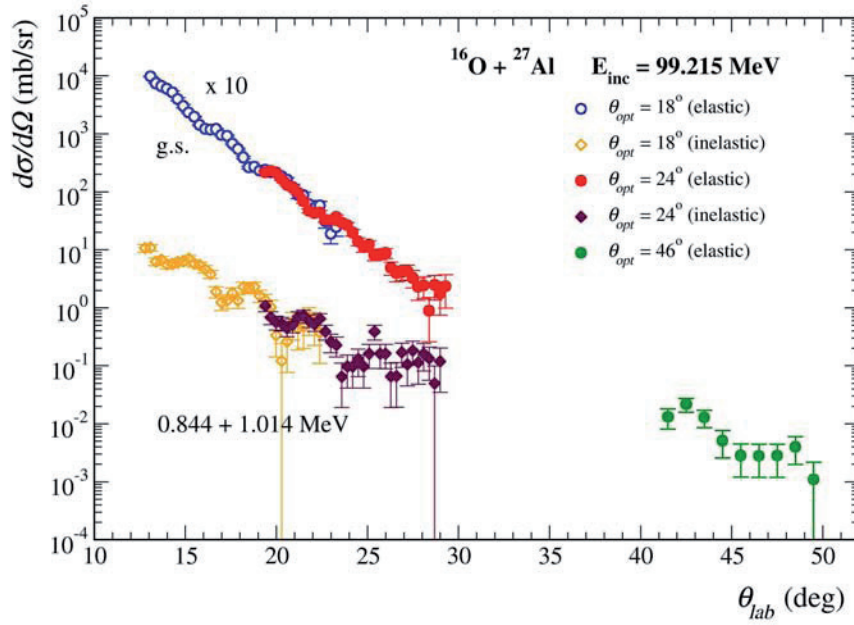


Figure 2: Angular distributions of the differential cross-section in the laboratory reference frame for the $^{16}\text{O} + ^{27}\text{Al}$ elastic and sum of the first two target excitation at 0.844 and 1.014 MeV and $\theta_{opt} = 18^\circ$ and $\theta_{opt} = 24^\circ$ and for the elastic at $\theta_{opt} = 46^\circ$.

CONCLUSIONS

The $^{16}\text{O} + ^{27}\text{Al}$ elastic and inelastic scattering has been successfully measured at 99.2 MeV incident energy using the MAGNEX spectrometer. The reaction ejectiles have been detected at forward and at backward angles up to $\theta_{lab} = 52^\circ$, corresponding to $\theta_{CM} = 80^\circ$ in the center of mass reference frame. All the challenging requirements of the experiment have been satisfied, allowing to clearly identify the ^{16}O ions, to separate the ground from the first excited states of ^{27}Al at 844 keV and to measure accurate absolute cross sections and angular distributions even at backward angles.

We emphasize that the cross-section decreases of about 7 order of magnitude in the explored angular region, down to about 100 nb/sr. A detailed analysis of the physical implications and of the motivations supporting this study is not the goal of the present work and will be discussed in a forthcoming publication. Nevertheless, the accomplishment of such results is an encouraging issue opening new perspectives in particular in the understanding of the fascinating research of nuclear rainbow with heavy ions [4] and more generally in the study of heavy-ion processes [12,13,14,15].

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Spectroscopy of the ^{66}Ni via the $^{64}\text{Ni}(^{18}\text{O},^{16}\text{O})^{66}\text{Ni}$ at 84 MeV

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Abstract - The study of the reaction $^{64}\text{Ni}(^{18}\text{O},^{16}\text{O})^{66}\text{Ni}$ at 84 MeV with the magnetic spectrometer MAGNEX is presented. The ^{16}O outgoing ejectiles, produced in this reaction, were successfully identified. The energy spectrum of the ^{66}Ni has been obtained applying the ray-reconstruction method. Many excited states of the ^{66}Ni has been populated. A large bump in the energy spectrum of the ^{66}Ni may be associated to the competition between the two-neutron transfer mechanism and more dissipative collisions.

INTRODUCTION

The study of the $^{64}\text{Ni}(^{18}\text{O},^{16}\text{O})^{66}\text{Ni}$ reaction belongs to a group of experiments concerning a systematic survey of the two-neutron transfer by the $(^{18}\text{O},^{16}\text{O})$ reaction at 84 MeV on light and heavy-medium targets (^9Be , ^{11}B , ^{12}C , ^{13}C , ^{28}Si , ^{58}Ni , ^{64}Ni , ^{120}Sn , ^{208}Pb). The importance of the $(^{18}\text{O},^{16}\text{O})$ reaction is twofold, first to study the features of the reaction mechanism of two-neutron transfer, second to highlight the behavior of the pairing interaction. Indeed, from the ^{18}O nucleus preferentially two neutrons of the $2s_{1/2}$ or $1d_{5/2}$ shell, coupled with angular momentum equal to zero and positive parity, will be transferred. Furthermore the reaction $^{64}\text{Ni}(^{18}\text{O},^{16}\text{O})^{66}\text{Ni}$ permits to study dissipative phenomena, that are much probable for reactions on heavier targets.

THE EXPERIMENT

A beam of $^{18}\text{O}^{6+}$, delivered by the INFN-LNS Tandem Van der Graaff accelerator of the LNS laboratory in Catania, bombarded a $113 \mu\text{g}/\text{cm}^2$ self supporting ^{64}Ni target at 84 MeV incident energy. A system of collimators was used in order to limit the beam spot size and the angular divergence to $1.2 \text{ mm} \times 0.8 \text{ mrad}$ in the horizontal direction and $2.3 \text{ mm} \times 3 \text{ mrad}$ in the vertical one. In addition, we have performed supplementary runs bombarding a $49 \mu\text{g}/\text{cm}^2$ self supporting ^{12}C target with the same beam at the same incident energy to evaluate the background in the spectra due to Carbon impurities in the target. The outgoing ejectiles, produced in the different reactions were momentum analyzed by the MAGNEX spectrometer (solid angle 50 msr) and detected by the focal plane detector FPD [1-2]. The optical axis was centered at $\theta_{\text{opt}} = 6^\circ, 12^\circ, 18^\circ, 24^\circ$ central laboratory

angles. Considering the large acceptance of the spectrometer, $-90 \text{ mrad} < \theta_i < +110 \text{ mrad}$ and $-125 \text{ mrad} < \Phi_i < 125 \text{ mrad}$, an overall angular interval of $3^\circ \div 30.3^\circ$ in the laboratory system spanned. The FPD is a large ($\sim 1600 \times 255 \times 500 \text{ mm}^3$) gas-filled hybrid detector with a wall of 54 large area Silicon pad detectors ($50 \times 70 \times 0.5 \text{ mm}^3$) at the back. The FPD measures the horizontal and vertical coordinates (x_f, y_f) of each incident particle at four sequential planes crossed by the ion trajectory, thus determining the respective angles (θ_f, Φ_f). It also measures the energy loss in the gas and the residual energy released in the Silicon detectors wall. The magnetic field was set in order to transport the ^{16}O ejectiles, corresponding to the population of the ground state of the ^{66}Ni in the $^{64}\text{Ni}(^{18}\text{O},^{16}\text{O})^{66}\text{Ni}$ reaction, 7% above the reference momentum, thus exploring the excited states of the ^{66}Ni up to about 30 MeV excitation energy (thanks to the large momentum acceptance $E_{\text{MAX}}/E_{\text{MIN}} \sim 1.5$ of the spectrometer).

DATA REDUCTION AND RESULTS

In a first stage, the experimental data reduction consists in the identification and selection of the events attributable to the two-neutron transfer reaction $(^{18}\text{O},^{16}\text{O})$ [3]. The atomic number (z) identification is obtained by the traditional technique ΔE - E . The different ions produced in the experimental conditions mentioned above, are disposed on different hyperbole, as shown in Fig.1, depending of the charge z and mass m of the ions. This method permits the discrimination of the different ion species. In Fig.1 E_{resid} parameter represents the residual energy of the ions measured at the end of the track by the Silicon detectors, while ΔE_{corr} is the energy loss of the ions along the focal plane detector. This latter is measured by the proportional wires and corrected for the horizontal angle of the ions at the focal plane. This correction accounts for the different track lengths of trajectories that cross the active volume of the detector with different inclination. Since the FPD is rotated of $\theta_{\text{tilt}} = 59.2^\circ$ respect to the plane normal to the axis of the spectrometer, it is necessary to use the relation:

$$\Delta E_{\text{corr}} = \Delta E \frac{\cos \theta_{\text{tilt}}}{\cos \theta_{\text{foc}}} \quad (1)$$

to obtain the correct energy loss.

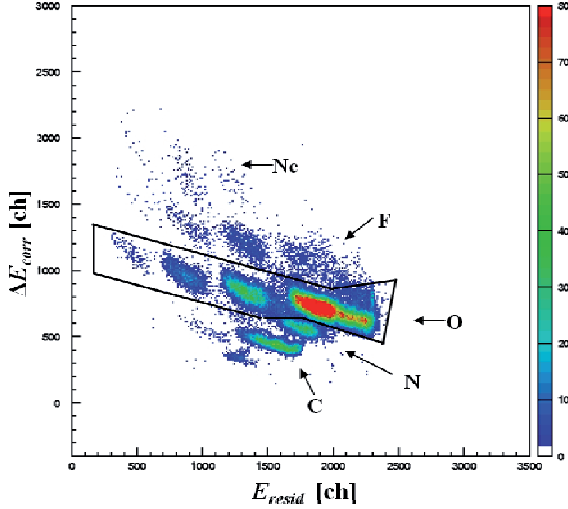


Fig.1: Typical two-dimensional spectrum $\Delta E_{corr} - E_{resid}$ measured in the $^{18}\text{O} + ^{64}\text{Ni}$ reaction at 84 MeV for unselected events. The contour line represents the graphical selection on the Oxygen ions.

Although the ΔE - E technique allows an effective z discrimination, the separation of the different isotopes of the various species is more difficult. In order to achieve a good mass identification the relation between the position in the focal plane X_{foc} and the kinetic energy of the particles has been considered. For a particle with momentum p , mass m and charge q , that crosses a region with a magnetic field B , its magnetic rigidity is:

$$B\rho = \frac{p}{q} \quad (2)$$

For non-relativistic energy of the incident particle and considering that the curvature ρ of a particle is related to its horizontal position on the focal plane X_{foc} , one obtains:

$$X_{foc} \propto \frac{\sqrt{m}}{q} \sqrt{E_{tot}} \quad (3)$$

Thus, as shown in Fig.2, in a two-dimensional spectrum $X_{foc} - E_{resid}$ the different ions come to dispose on different curves depending of the ratio $m^{1/2}/q$.

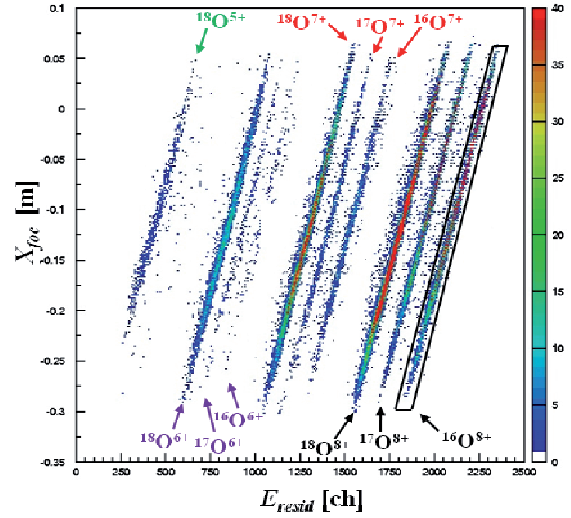


Fig.2: Typical two-dimensional spectrum $X_{foc} - E_{resid}$ measured in the $^{18}\text{O} + ^{64}\text{Ni}$ reaction at 84 MeV for the Oxygen ions selected as shown in Fig.1.

The contour line represents the graphical selection on the $^{16}\text{O}^{8+}$.

This technique allows the mass identification of the detected ions with a resolution of $\sim 1/160$ in the mass of the Oxygen isotopes [3]. After the particles identification is completed, it is possible to analyze the final phase space parameters ($x_f, \theta_f, y_f, \Phi_f$). This analysis shows that the residual aberrations are important and it is necessary to apply the ray-reconstruction method [4]. This consists in creating the high order direct transport matrix M with the COSY INFINITY code. Applying this matrix to the initial phase space vector $\mathbf{X}_i = (\theta_i, y_i, \Phi_i, \delta_i)$, the final phase space vector $\mathbf{X}_f = (x_f, \theta_f, y_f, \Phi_f)$ is generated, with the transformation: $\mathbf{X}_f = M\mathbf{X}_i$.

Thus, we compared the simulated final parameters obtained with this method to the final parameters measured at the focal plane. Once tested the accuracy of the direct matrix M , using again the COSY INFINITY code, the inverse matrix M^{-1} will be generated. Applying the inverse matrix M^{-1} to the measured final phase space vector $\mathbf{X}_f$, the initial phase space vector $\mathbf{X}_i$ was obtained. The knowledge of these initial parameters is essential for the reconstruction of both the scattering angle in the laboratory system and the excitation energy of the residual nucleus. In Fig.3 the two-dimensional spectrum $\theta_{lab} - E$ is shown: it is obtained applying the ray-reconstruction technique on the experimental data detected for $\theta_{opt} = 18^\circ$.

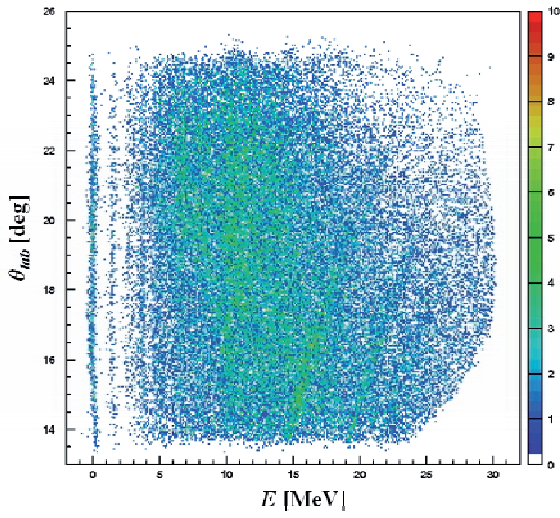


Fig.3: Reconstructed two-dimensional spectrum $\theta_{lab} - E$ for $^{18}\text{O} + ^{64}\text{Ni}$ reaction at 84 MeV and $\theta_{opt}=18^\circ$.

In Fig.3 the variable θ_{lab} represents the scattering angle in the laboratory system of the ^{16}O ejectiles, while the variable E represents the apparent excitation energy of the ^{66}Ni , that is the excitation energy of ^{66}Ni supposing that the ^{16}O detected is the ejectile of the binary reaction $^{64}\text{Ni}(^{18}\text{O}, ^{16}\text{O})^{66}\text{Ni}$. On the left in Fig.3 the loci corresponding to the population of the ground state and the low lying excited states of the ^{66}Ni are clearly visible. These loci are located almost vertically in the plot, while in the $15 \text{ MeV} < E < 25 \text{ MeV}$ region one can see some curved loci that represent the excited states of the ^{14}C , due to the $^{12}\text{C}(^{18}\text{O}, ^{16}\text{O})^{14}\text{C}$ reaction. Projecting the two-dimensional spectrum $\theta_{lab} - E$ shown in Fig.3 on the E variable one obtains energy spectrum of the ^{66}Ni , as shown in Fig.4.

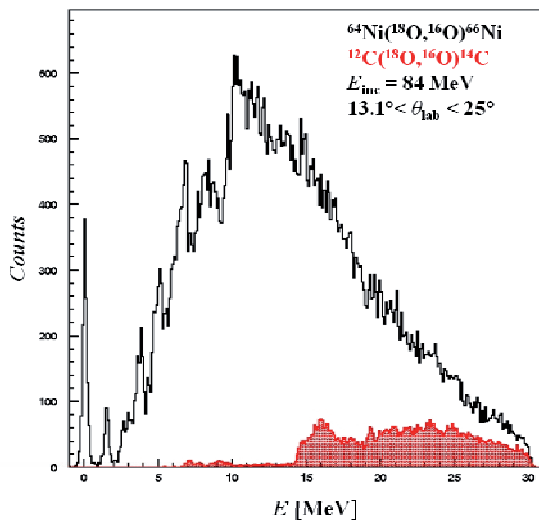


Fig.4: Apparent excitation energy spectrum of the ^{66}Ni $^{18}\text{O} + ^{64}\text{Ni}$ reaction at 84 MeV and $\theta_{opt}=18^\circ$.

The red histogram represents the energy spectrum of ^{14}C expressed as function of the excitation energy of the ^{66}Ni . It is necessary to subtract this contribute to obtain the energy spectrum of the ^{66}Ni , that is the black histogram shown in Fig.4. In this spectrum the ground state and many excited states of ^{66}Ni are visible. The resolution obtained in this experiment, estimate from Gaussian fit of the ground state peak (FWHM), is about 220 keV ($\sim 1/420$), principally limited by the energy straggling of the ^{16}O in the different crossed materials (^{64}Ni target, Mylar window entrance, etc). The particular shape of this spectrum can be explained considering the high level density of the ^{66}Ni [5]. The large bump in this spectrum may be associated at the competition between the two-neutron transfer mechanism and dissipative phenomena.

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Transport efficiency in the MAGNEX large acceptance spectrometer

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Abstract - A general technique to study the transmission efficiency of charged particles through a large acceptance magnetic device has been developed. This basically consists in the measurement of the impact positions and angles of the particles in any plane normal to the optical axis and in the use of a powerful algorithm for the reconstruction of the trajectories. This latter performs the calculations of highly non-linear transport functions and is essential when high-order aberrations are not negligible. The technique is applied to study the transport efficiency of the ions produced in different nuclear reactions and analyzed by the MAGNEX large acceptance spectrometer. Both the angular integral and differential efficiency have been deduced with overall accuracy of about $\pm 1.5\%$ and $\pm 5\%$ respectively.

INTRODUCTION

In modern experimental nuclear physics, the use of large acceptance devices plays a crucial role especially when the measurement conditions are characterized by low detection yields. This is a typical situation when dealing with low intensity radioactive ion beams or with investigations of suppressed reaction channels. Under these conditions, a large detection solid angle is essential to get a reasonable amount of data, thus improving the signal to noise ratio and preserving the statistical quality of the experimental observations.

In these cases, getting a precise estimation of the overall efficiency is mandatory, especially when measurements of absolute cross section are of interest. In particular, the accurate and high resolution measurement of angular distributions requires a precise description of the differential efficiency and solid angle at each angular bin. From a practical point of view, this corresponds to the need of a detailed study of the efficiency losses over the accepted phase space.

The transmission of the reaction products through the spectrometer is expected to depend on the interplay between the ion optics itself and the mechanical constraints of the system. This case is much more complicate than the small acceptance ones (beam lines, traditional magnetic spectrometers, etc.), where the size of the mechanical elements is safely larger than the beam envelopes. On the other hand, when extended beam

envelopes have to be transmitted the magnetic elements rapidly become encumbering and very demanding in terms of power consumption. Consequently, great efforts are typically made in order to design the vacuum chambers and pipes as close as possible to the expected beam envelopes. In such cases, efficiency losses could be easily generated by a not ideal set of the magnetic fields or by even small mechanical misalignments. The limited size of the focal plane detectors and their location along the optical axis can also generate losses of acceptance.

The MAGNEX spectrometer [1, 2] installed at the INFN - Laboratori Nazionali del Sud is an example of such a device, since it is characterized by a large angular (about 50 msr) and momentum (-14.3% , $+10.3\%$) acceptances. It basically consists of a large aperture quadrupole (20 cm bore radius) [3] and a dipole (20 cm poles gap) [4] magnet and of a focal plane detector (FPD) [5, 6] for the detection of the transmitted ions. The problem of the aberrations is faced by an accurate design of the spectrometer layout which minimizes the aberrations content [1] and a sophisticated technique of ray-reconstruction [7,8] based on the differential algebraic methods of COSY INFINITY [9]. This latter has been successfully applied to the precise reconstruction of the momentum vector [7] and to the identification of the ion mass [10].

THE TRANSPORT TECHNIQUE

In the phase space representation used in standard ion optics [11], the motion of a beam of charged particles, influenced by magnetic fields, can be represented as the dynamical evolution of the representative hyper-volume. For dispersive magnetic spectrometers where no degrading materials are introduced [12], the initial phase space vector $Q_i \equiv (\theta_i, Y_i, \varphi_i, \delta)$ defined at the target point is connected to the final one $Q_f \equiv (X_f, \theta_f, Y_f, \varphi_f)$, typically at the focus, by a general relation as follows:

$$G: Q_i \rightarrow Q_f \quad (1)$$

Here θ_i and φ_i are the horizontal and vertical angles, Y_i the vertical coordinate and $\delta = (p - p_0)/p_0$ is the fractional momentum deviation, being p the ion momentum and p_0 the reference one.

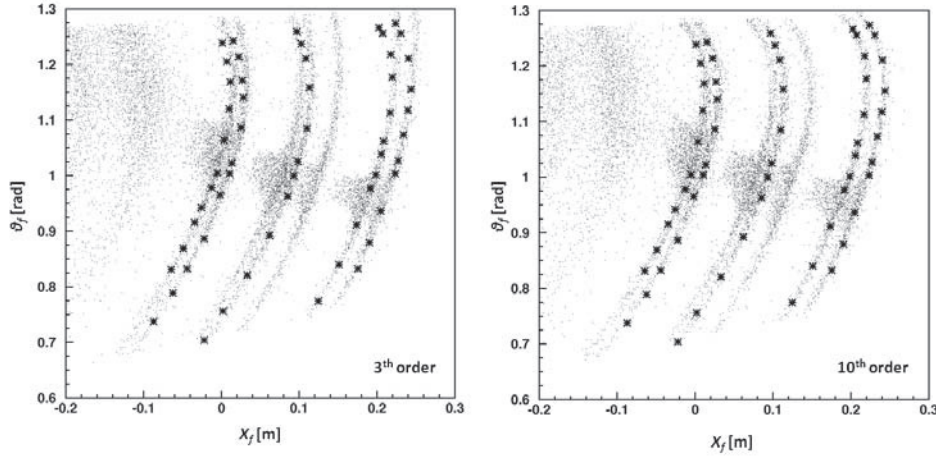


Figure 1: (X_f, θ_f) scatter-plot for the simulation of the $^{13}\text{C}(^{18}\text{O}, ^{16}\text{O})^{15}\text{C}$ at 84 MeV obtained by a ray-reconstruction to the 3th order (a) and to the 10th order (b). The asterisks are printed at the coordinates of the experimental data.

The final parameters $X_f, Y_f, \theta_f, \varphi_f$ are the horizontal and vertical coordinates and angles of the ions in a plane normal to the reference trajectory.

Eq. (1) describes a general non-linear transport map, where the application G is characteristic of the particular optical system. It can be inverted in order to get the initial momentum vector at the target point.

A reliable technique to solve eq. (1) is implemented in the COSY INFINITY program [9]. It is based on the formalism of differential algebra [13,14] and allows to calculate high order transport matrices avoiding lengthy ray-tracing procedures. The use of this technique in a real application does require a detailed description of the magnetic fields crossed by the ions trajectory, the exact knowledge of the geometry of the spectrometer and the accurate measurement of the phase space vector at the focal plane $(X_f, \theta_f, Y_f, \varphi_f)$ as discussed in [7].

Such a technique represents a great advantage in order to study the transport efficiency of the whole spectrometer since it allows to deduce the efficiency at different locations along the spectrometer up to the focal plane. Such a procedure would present remarkable difficulties if one operates in an experimental way, since the installation of detectors along the trajectory results hard and sometimes unfeasible.

COMPARISON WITH EXPERIMENTAL DATA

The technique described in the previous Section has been tested and the results have been compared with the experimental data. These have been collected during the experiment performed at the INFN – Laboratori Nazionali del Sud for the study the $^{13}\text{C}(^{18}\text{O}, ^{16}\text{O})^{15}\text{C}$ transfer reaction [15]. A beam of $^{18}\text{O}^{7+}$ ions was delivered by the Tandem accelerator at 84 MeV total incident energy. A 99% enriched and 50 $\mu\text{g}/\text{cm}^2$ thick ^{13}C target built at the LNS target laboratory was used. The reaction ejectiles were momentum analyzed by the MAGNEX spectrometer and detected by the FPD. The optical axis of the spectrometer was centered at an angle $\theta_{opt} = 12^\circ$ in the laboratory. Thanks to the large angular acceptance, an angular range between about 7° and 19° has been explored in an unique

setting of the spectrometer. The quadrupole and dipole fields were set in order to accept the $^{16}\text{O}^{8+}$ ejectiles corresponding to the transition to the ^{15}C excited states. The Oxygen isotopes have been identified using the simultaneous measurement of their positions at the focal plane and their residual energies by the FPD hodoscope of silicon detectors. Recently it has been shown that this technique allows to obtain a clear identification of the different detected ions with a mass resolution as high as 1/160 [10]. Once the $^{16}\text{O}^{8+}$ ejectiles are selected, the measured horizontal and vertical positions and angles at the focal plane are analyzed [5,6].

In Fig. 1 the results obtained by a ray-reconstruction ended up to the 3rd order and to the 10th order with the same technique is shown. The comparison demonstrates the necessity to treat the problem to 10th order to properly describe the highly non-linear shapes, especially at large θ_f .

EFFICIENCY LOSSES THROUGH THE SPECTROMETER

According to the ion optics calculations performed for the design of the spectrometer [2,10], three points are expected to be critical for the transport efficiency:

- The limited acceptance of the FPD [16];
- The size of the gate valve between the dipole and the FPD vessels;
- The vacuum vessels in the region between the quadrupole and the dipole, where the horizontal divergence of the beam envelope is quite large.

Specific calculations accounting for the role of these geometrical constraints have been recently published in Ref. [17].

A set of simulations has been performed in order to study the efficiency losses due to the different geometrical cut-off. For this purpose, the inelastic scattering of protons at 15 MeV incident energy on a ^{238}U target has been studied between 0° and 12° in the laboratory frame. In such a reaction, the kinematic dependence of the ejectiles momentum on the scattering angle is negligible, so that each simulated inelastic

channel is characterized by an almost unique value of relative momentum δ .

The dependence of the cut-off on the ejectiles momentum has been studied by generating particles with six values of δ spanning almost the whole accepted phase space. Practically, the efficiency $\varepsilon = N^*/N$ is deduced as the ratio of the N^* trajectories that reach the active region of the FPD over the N initially generated.

The transmitted trajectories selected by the focal plane have been studied at the initial point (the target point) by analysing the corresponding (θ_i, φ_i) loci. As an example, the (θ_i, φ_i) scatter-plots for the different values of δ constrained with the geometrical constraints on the FPD size only are shown in Figs. 2(a) - (f).

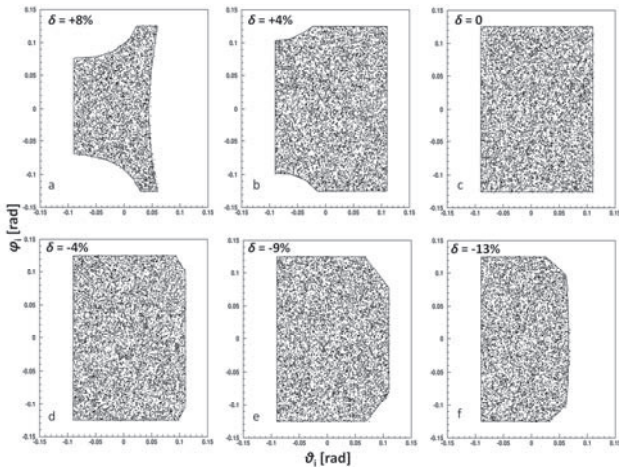


Figure 2: Plots of the (θ_i, φ_i) distributions simulated taking into account the geometrical constraints on the FPD size. The solid lines are the contours of the distributions. Particles with different values of relative momentum (a) $\delta = +8\%$, (b) $\delta = +4\%$, (c) $\delta = 0\%$, (d) $\delta = -4\%$, (e) $\delta = -9\%$, (f) $\delta = -13\%$ are simulated.

MEASUREMENT OF ABSOLUTE CROSS-SECTIONS

The reliability and the precision of such a procedure have been investigated through the measurement of the absolute cross section of the Rutherford scattering in the full solid angle accepted by the MAGNEX spectrometer.

In the experiment performed at LNS the elastic scattering of a $^{16}\text{O}^{8+}$ beam at 100 MeV incident energy on a ^{197}Au target (thickness $181 \pm 5 \mu\text{g}/\text{cm}^2$) has been explored. The spectrometer axis has been positioned at $\theta_{opt} = 18^\circ$ and the aperture diaphragms have been set within $-90 \text{ mr} < \theta_i < 110 \text{ mr}$ and $-100 \text{ mr} < \varphi_i < 100 \text{ mr}$ in the spectrometer reference frame. This corresponds to accept the ejectile trajectories between 12.8° and 24.9° in the laboratory. A graphite Faraday cup (4 cm deep) having a circular aperture (8 mm diameter) and an electron suppression ring was used to stop the beam. A low noise circuit including a digital integrator was used to determine the collected charge with an intrinsic accuracy

better than 0.5%. The overall number of recorded events was corrected for the data acquisition dead time. A factor of 0.79 has been measured as the ratio of the number of acquired events over the total event triggers [5]. Finally the detection efficiency of the FPD was assumed to be 95% uniformly distributed along the phase space.

In order to obtain the effective differential solid angle, simulations using the described transport technique have been performed. A systematic error between -0.6 and 0.8 mr in θ_i and between -4.2 and +5.8 mr in φ_i depending on θ_i and φ_i has been estimated (see Ref. [7] for details). A remarkable overall agreement is found indicating that the simulation describes also the details of the transmission losses. The obtained (θ_i, φ_i) contours have been used to deduce the differential solid angle. A step size of $\Delta\theta_{lab} = 0.625^\circ$ has been chosen in order to maintain the statistical uncertainties in the number of counts in each bin below 6%. The differential cross section $d\sigma/d\Omega(\theta_{lab})$ has been consequently derived at each angular bin.

Theoretical calculations in the DWBA formalism have been also performed for this reaction using the microscopic Sao Paulo Potential (SPP) [18]. This is known to be rather successful to describe the elastic and inelastic scattering of ^{16}O on many heavy targets in a broad range of incident energies. The DWBA calculations indicate that in the explored angular range the Rutherford mechanism is safely dominant, thus simplifying the comparison with the experimental data.

The experimental $\sigma_{exp}/\sigma_{Ruth}$ corrected for the efficiency losses with error bars is superimposed in the plot in Fig. 3. The error includes both a statistical part (about $\pm 3.8\%$) and a component due to the solid angle determination (about $\pm 2.5\%$ in the central bins). This latter becomes important mainly in the first and last bins where the systematic error on the measurement of the horizontal and vertical angles and the uncertainties on the spectrometer geometry give a major contribution.

A very good agreement is found all over the angular acceptance. The average value of the measured ratio, weighted according to the error in each experimental bin,

results $\frac{\sigma_{exp}}{\sigma_{Ruth}} = 0.996 \pm 0.015$. An average uncertainty of about $\pm 5\%$ is found in each angular bin. A $\pm 3\%$ uncertainty in the cross section scale, mainly due to the contribution of the target thickness, has been estimated. The measured $\sigma_{exp}/\sigma_{Ruth}$ without the correction for the efficiency losses is also shown. The accurate simulation of the spectrometer response and the consequent estimation of the effective differential solid angle allows to sensibly correct the experimental angular distribution at the borders of the accepted phase space. In this way the possibility to use the full acceptance of the spectrometer for accurate measurements of reaction cross sections is demonstrated.

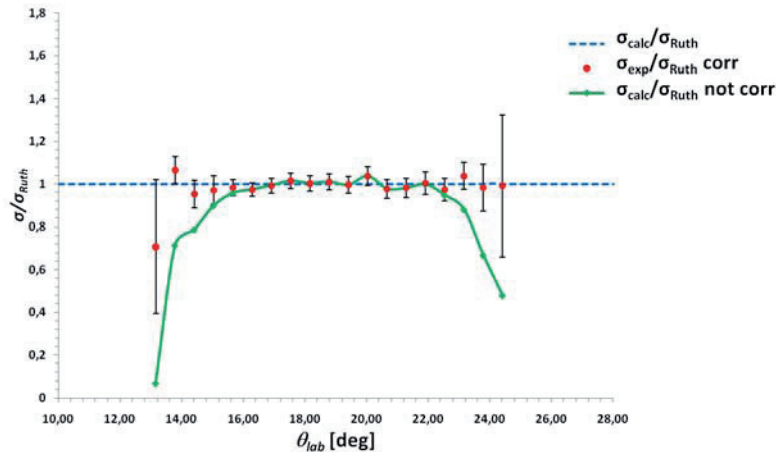


Figure 2: . Ratio of the cross section over the Rutherford one $\sigma/\sigma_{\text{Ruth}}$ obtained for the DWBA calculations described in the text (dashed blue line), for the measured data without the solid angle correction (green diamonds), and for the measured data with the solid angle correction (red circles).

CONCLUSIONS

A technique to estimate the transmission efficiency of the ions through a large acceptance spectrometer has been developed. It is based on the solution of high order transport equations for each particle reaching the focal plane or any intermediate plane along the optical axis. The deduced phase space parameters are then compared with the geometrical constraints of the spectrometer pipes and chambers.

In the case of the MAGNEX spectrometer, different sources of efficiency losses have been found especially due to the size and geometry of the FPD and of the vacuum vessels between the quadrupole and the dipole magnets. Such losses generate a reduction of the differential solid angle that has been studied as a function of the focus conditions and of the momentum of the transported particles. Thanks to the accuracy of the ray-tracing and reconstruction of the trajectories, it has been found that the response of the spectrometer can be simulated even in the fine details.

The reliability of the technique has been tested by studying the elastic scattering of a ^{16}O beam at 100 MeV on a ^{197}Au target at forward angles where the process is totally determined by the Coulomb field. The differential solid angle in the accepted angular range has been estimated by taking into account all the geometrical constraints of the spectrometer, and the angular distribution has been extracted. The comparison of the measured ratio $\sigma_{\text{exp}}/\sigma_{\text{Ruth}}$ with the $\sigma_{\text{calc}}/\sigma_{\text{Ruth}}$ derived by DWBA calculations allows to conclude that the reduction of the transmission efficiency observed at the borders of the accepted solid angle can be properly compensated for. The technique is crucial to allow accurate measurements of cross sections in large acceptance spectrometers.

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Measuring the ions momentum vector with a large acceptance magnetic spectrometer

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Abstract - A technique to measure the momentum vector of the ions produced in a nuclear reaction and analyzed by a magnetic spectrometer is presented. It consists of a powerful procedure for the reconstruction of the ions trajectory based on the use of a focal plane detector, accurate three-dimensional models of the magnetic fields and efficient algorithms to solve the highly non linear transport equations. The technique is quite general and reliable even with large acceptance optical devices. Experimental results obtained with the MAGNEX spectrometer show a remarkable resolution of about 0.2° in the horizontal direction, 0.7° in the vertical one and $1/1800$ in the momentum modulus.

INTRODUCTION

Modern magnetic spectrometers used in nuclear reaction experiments are typically conceived in order to detect the charged ejectiles with large acceptance both in solid angle and momentum [1-4]. This raises the problem to determine accurately not only the linear momentum modulus p but also the scattering angle θ_{lab} of the detected ions. However this goal is severely limited by the unavoidable large geometrical and chromatic aberrations and no suitable solution was available in the past. Recently new mathematical approaches have been developed, such as the Differential Algebra (DA), which permit to determine the ions trajectory with high precision [5-7]. In particular there is the possibility to transform the complicated differential equations of motion of charged particles in a magnetic spectrometer in a simpler algebraic problem.

As a consequence a renewed interest is recently raising for the magnetic spectrometry, stimulating the construction of several large acceptance devices all over the world. Among these an example is MAGNEX, installed at the INFN-LNS laboratory in Catania, which is a Quadrupole – Dipole (QD) spectrometer, with several innovative construction details implemented on the basis of sophisticated ion optics calculations [1-2].

In this paper a technique based on the use of the DA implemented in the Cosy Infinity code [8] is applied to analyse the experimental data taken with MAGNEX.

TECHNIQUE

The motion of a charged particle beam under the action of a magnetic force can be represented as a general phase space mapping [9,10]

$$F: P_i \rightarrow P_f, \quad (1)$$

which connects the final position $P_f \equiv (x_f, \theta_f, y_f, \phi_f, l_f, \delta_f)$ to the initial one $P_i \equiv (x_i, \theta_i, y_i, \phi_i, l_i, \delta_i)$. In eq. (1) x, θ, y, ϕ are the horizontal and vertical coordinates and angles at the impact point of the ions trajectory with a plane normal to the central trajectory, l is the trajectory length and $\delta = (p - p_0)/p_0$, is the final fractional momentum, where p_0 is the reference momentum and p is the actual one.

Equation (1) describes a general non-linear transport relation, where the mapping F depends on the general three-dimensional spatial distribution of the magnetic fields of the actual optical system.

As it was discussed in details in ref. [5,11], non-linear terms (aberrations) can severely limit the momentum and angular resolution achieved at the focal plane.

In order to get the momentum vector at the target position, it is necessary to invert eq. (1) with respect to the initial set of parameters, which formally gives

$$F^{-1}: P_f \rightarrow P_i. \quad (2)$$

The problem can be formulated in terms of the measured parameters. For example, in the case of MAGNEX the chosen set of measured quantities is $Q_f \equiv (x_f, \theta_f, y_f, \phi_f)$, while the reconstructed vector is $Q_i \equiv (\theta_i, y_i, \phi_i, \delta)$.

The achievement of a stable and accurate solution of the eq. (2) strongly depends on the device acceptance. Far from the optical axis and from the reference magnetic rigidity, high order terms in the Taylor expansions are required.

A method to relate the initial coordinates to the final ones was developed in the MOTER code [12], which, once the magnetic elements of the spectrometer are specified, performs the ray-tracing of a large number of trajectories spanning the whole phase space. The parameters of the F functions are obtained by polynomial fits.

A reliable technique to solve eq. (2) was developed at the Michigan State University for the S800 spectrometer [5]. This is based on the DA formalism [13] and allows the calculation of high order transport matrices avoiding lengthy ray-tracing procedures.

The COSY INFINITY program contains such an algorithm allowing at the same time the inclusion of externally determined magnetic fields.

To summarize the use of these advanced techniques in a real application does require the detailed description of the magnetic fields crossed by the ions trajectory, the exact knowledge of the geometry of the spectrometer and the accurate measurement of the phase space vector at the focal plane (x_f , θ_f , y_f , ϕ_f).

EXPERIMENTS AND DATA ANALYSIS

Experiments

The technique discussed in the previous section was applied to the analysis of several experimental data obtained using the Tandem Van der Graaff beams and the MAGNEX spectrometer at the INFN-LNS laboratory. In the following one of these is presented.

A beam of $^{16}\text{O}^{7+}$ at 100 MeV total incident energy, was focused on a $181 \mu\text{g}/\text{cm}^2$ thick ^{197}Au target placed in the scattering chamber of the spectrometer, whose optical axis was centered at 18° . A system of collimators was used in order to limit the beam spot size and the angular divergence to $1.2 \text{ mm} \times 0.8 \text{ mr}$ in the horizontal direction and $2.3 \text{ mm} \times 1.8 \text{ mr}$ in the vertical one. A pepper-pot shaped diaphragm, shown in Fig.1, was positioned between the target and the spectrometer, thus only ions having a few well defined trajectories were transmitted. The magnetic field of the quadrupole and dipole elements were set in order to transmit the elastically scattered $^{16}\text{O}^{8+}$ ions along the optical axis. The ejectiles produced in the reactions and emitted within the spectrometer acceptance were momentum analyzed and focused on the FPD [14]. This latter allows the identification of the ions [15] and the measurement of their impact point (x_f , y_f) and direction (θ_f , ϕ_f) in the focal plane both in the horizontal and vertical direction.

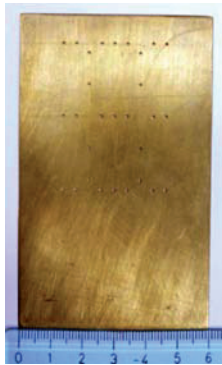


Figure 1: Pepper-pot diaphragm.

Data reduction

A set of simulations was developed for representing the above experimental conditions. The transport matrices have been calculated to the 10th order, if not explicitly indicated.

An example of the measured bi-dimensional (x_f , θ_f) plot is compared with the relative simulation in Fig. 2a. Since the elastic scattering dominates over other inelastic processes only one locus, corresponding to the $^{16}\text{O}^{8+}$ ejectiles, is clearly visible in the selected data. The effect of the pepper-pot diaphragm is to fragment this latter in seven loci corresponding to the pepper-pot holes.

Due to the not ideal focus and the strong effect of the aberrations, the observed locus deviate from the expected vertical behavior in a non-linear way, especially at the borders. However it is important to notice the rather faithful representation of the experimental data given by the simulations. The average deviation between the measured position of the spots in the (x_f , θ_f) plane and the simulated ones is estimated about $-0.5 \pm 0.9 \text{ mm}$ and $3 \pm 5 \text{ mr}$.

The different horizontal angles selected by the pepper-pot diaphragm are well separated, as shown in Fig. 2a and in the one-dimensional projection of the data on the θ_f axis in Fig. 2b. A FWHM ranging from about 12 mr at the larger θ_f to about 15 mr at the smaller θ_f is extracted. In Figs.2c-d a similar comparison between the experimental data and the simulation is shown for the (x_f , y_f) phase space scatter plot. In this representation the way the aberrations distribute the data along the x_f is dramatically clear. The loci cannot be represented by any kind of function, since multiple values of x_f are observed for a fixed y_f .

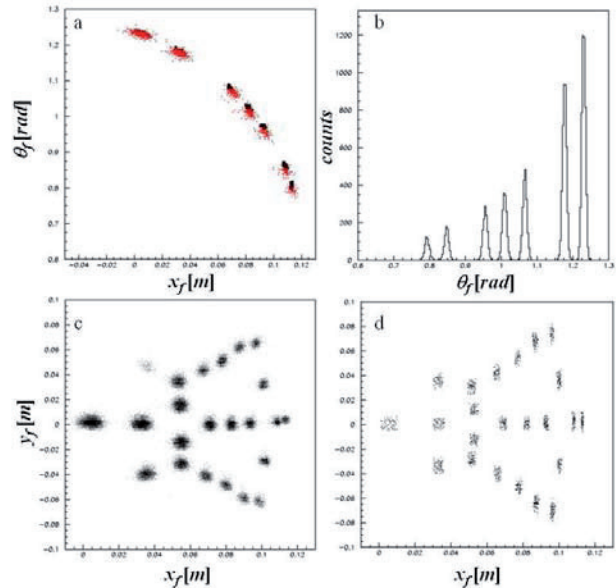


Figure 2: Comparison of the measured (red dots) and simulated (black dots) two-dimensional plot of the horizontal phase space at the MAGNEX focal plane (panel a). Projection of Fig.2a over the θ_f axis (panel b). Experimental (panel c) and simulated (panel d) (x_f , y_f) image of the pepper-pot diaphragm at the focal plane.

Angle reconstruction

An example of the reconstructed (θ_i, ϕ_i) scatter-plot is shown in Fig. 3 and compared with that generated by the pepper-pot diaphragm. This latter has been obtained by simulating a uniformly distributed ensemble of ion trajectories spanning the full solid angle and imposing the geometrical conditions of the pepper-pot hole positions.

A clear correspondence between the reconstructed loci and the expected ones is observed. An estimation of the overall geometrical deviation gives an average value of about -0.2 ± 0.7 mr ($-0.01^\circ \pm 0.04^\circ$) in horizontal and -0.8 ± 5 mr ($-0.05^\circ \pm 0.30^\circ$) in vertical. Thus the present analysis turns out to be an effective tool to evaluate in a local way the systematic errors in the determination of the scattering angle and therefore to correct them.

An angular resolution between 0.16° and 0.24° is extracted for the θ_i parameter, which is a quite remarkable result, not achieved even by several low acceptance spectrometers.

A slightly worse result is obtained for the reconstruction of the initial vertical angle ϕ_i , for which a FWHM ranging from 3 mr (0.2°) to 20 mr (1.2°) is measured. In fact the vertical motion is squeezed by the quadrupole lens to an almost point to parallel condition.

In the reconstruction of the scattering angle in the laboratory frame θ_{lab} both the horizontal and the vertical angles contribute according to basic geometrical relations. The reconstruction of the vertical angle is of minor importance unless one measures at very forward angles.

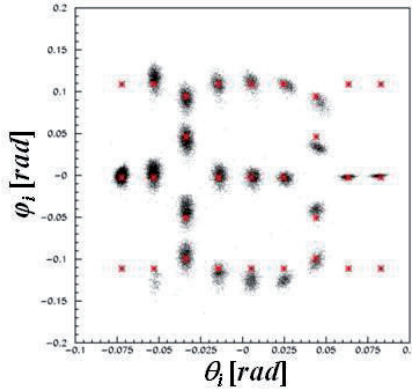


Figure 3: Reconstructed bi-dimensional (θ_i, ϕ_i) angular spectrum. The red asterisks indicate the expected positions of the loci as deduced by the geometry

Reconstruction of the momentum modulus

The reconstructed momentum modulus p is shown in Fig. 4 correlated with the reconstructed θ_{lab} . The different loci refer to the different holes in the diaphragm, which select different values of the momentum according to the kinematics.

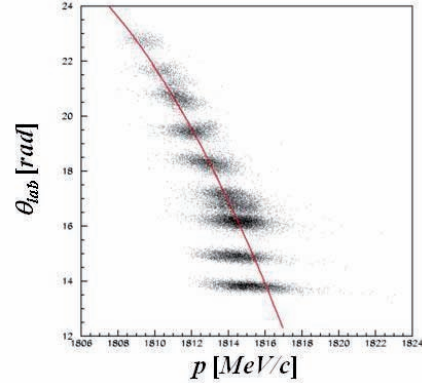


Figure 4: (p, θ_{lab}) scatter plot in the same conditions of Fig. 2. The red line represents the expected correlation curve from relativistic kinematics.

The comparison with the expected behavior, shown in Fig. 4 as a red line, demonstrates a striking correspondence with a maximum discrepancy of about $1/2000$. A slight deviation is systematically observed at the most forward angles, as result of a less precise reconstruction due to the not ideal focusing obtained there in this experiment (see Fig. 2 for the largest θ_j). For the same reason also the observed widths of the loci become larger at forward angles. At backward angles a projection of the upper part ($\theta_{lab} > 22^\circ$) over p axis generates a peaked structure characterized by a FWHM of $1/1850$. Slightly worse resolutions are obtained when projecting larger angular ranges.

Order of reconstruction

The effect of the finite order of the algorithm on the obtained results has been studied for the reconstruction of both the direction and the modulus of the momentum vector. As a general result the predicted higher sensitivity of the modulus to the non linear terms has been found [10], being the reconstruction of the angles quite good already at the 1st order.

A specific calculation of the effect of the non linear terms has been done in order to analyze the reconstruction of the momentum direction. It has been found that the effect of the aberrations in the reconstruction of the horizontal angle does not exceed 2 mr. Larger values are obtained for the vertical angle, where one can get a contribution of about ± 10 mr for the extreme rows of the diaphragm. These effects can be almost fully compensated by the inclusion of 3rd order terms in the transport matrices.

For the reconstruction of the momentum, a set of calculations at different orders has been performed for the same data discussed above and the results have been compared with the expected kinematics. The results are shown in Fig. 5 and demonstrate that large deviations are obtained even with a 3rd order calculation. The convergence is obtained starting from the 7th order, thus proving the essential role of the algorithm for the achievement of the overall performances of the spectrometer.

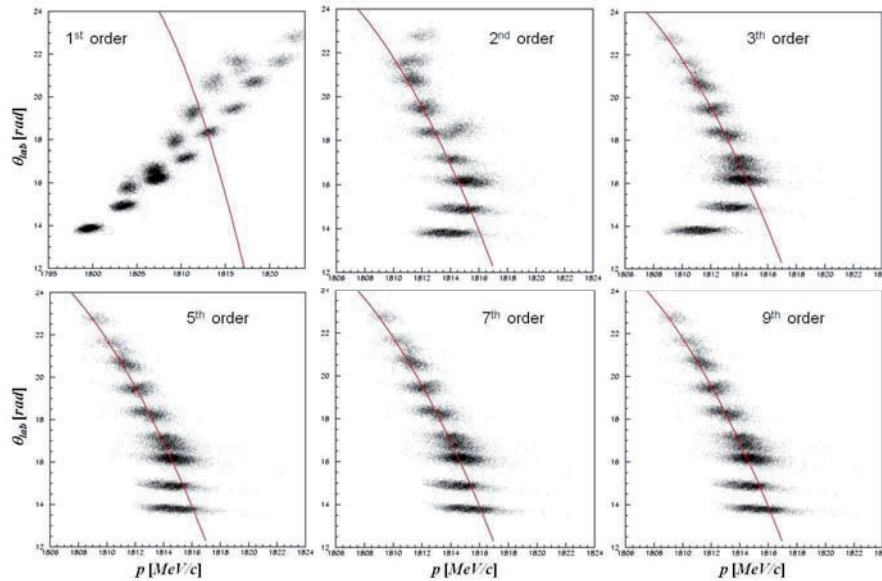


Figure 5: Reconstructed (p, θ_{lab}) scatter plots in the same experimental condition of Fig. 2. In the different panels the order of the reconstruction algorithm has been varied. The red line represents the expectation of the kinematics in such conditions.

CONCLUSIONS

The presented innovative technique to determine the momentum vector of the ions detected by a large acceptance spectrometer, has proven to be accurate and precise enough to be applied to refined data analyses.

The data measured at the focal plane have shown the strong effect of the high order aberrations, which limit the use of standard techniques of magnetic spectrometry for large acceptance devices. The comparison of the experimental data with the simulations based on the Cosy-Infinity approaches indicates the high level of accuracy and reliability of these latter. As a consequence the inverse high order transport matrices built by such mathematical methods are accurate enough to be applied to the data analyses.

The reconstructed horizontal and vertical angles do not differ significantly from the values expected on the basis of simple geometric considerations about the pepper-pot diaphragm and target distance. The very small systematic error obtained in the horizontal ($-0.01^\circ \pm 0.04^\circ$) and vertical ($-0.05^\circ \pm 0.30^\circ$) is a major achievement of the reconstruction technique presented in this paper. In addition a high resolution has been obtained in the horizontal (0.2°) and vertical angle (0.7°). This in turn guarantees, especially at backward angles in the laboratory, a high precision in the reconstruction of the scattering angle in the full solid angle.

Another relevant result is the resolution of $1/1800$ obtained for the reconstructed momentum modulus.

A detailed study of the effect of the non linear terms to the transport equations have demonstrated that the momentum modulus is more sensitive to the aberrations. Although a third order approach could be enough to precisely and accurately reconstruct the direction of the detected ions, it would be very unsatisfactory for the

modulus where the treatment of the higher order terms is essential.

We believe that this general and powerful technique can be considered a basic tool for operation with modern and future magnetic spectrometers.

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N/Z effects on evaporation residue emission in nuclear collisions $^{40,48}\text{Ca}+^{40,48}\text{Ca}$ at 25 MeV/nucleon studied with the Chimera detector

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Abstract - We will discuss results concerning the fate of hot nuclear systems populated in $^{40,48}\text{Ca}+^{40,48}\text{Ca}$ reactions at 25 MeV/nucleon. We found that the partition between the persistence of binary-like residues and evaporation residues emissions in semi-central collisions is sensitive to the N/Z of the entrance channels. By comparing data with CoMD-II model calculations, we can extract information about the density depend part of Symmetry Potential in the Nuclear Equation of State at near-saturation densities.

INTRODUCTION

The fate of hot nuclear systems populated in heavy ion collisions at bombarding energies near 20 MeV/nucleon represents an interesting topic in nuclear physics. In this energy regime, the reaction cross section for semi-central and central collisions is distributed between evaporation residues emission (produced mainly by means of incomplete fusion mechanisms) and other more complex phenomena (such as damped binary-like emission or multi-fragment emission) [1-3]. In this energy regime, moreover, the density dependent part of symmetry energy could play a non negligible role in the evolution of reaction dynamics, especially for nuclear collision involving strong rearrangement of surface degrees of freedom [4]. Actually, for semi-central collisions, many dynamical models predict that the balance between

evaporation residue emission and binary-like emission in this type of collisions can be an useful probe to determine the behaviour of the density dependent part of the symmetry energy in the Nuclear Equation of State [5-7].

In this respect, we performed the collisions $^{40,48}\text{Ca}+^{40,48}\text{Ca}$ at 25 MeV/nucleon. In this way, we populated various nuclear systems differing for the neutron to proton ratio (N/Z) in the entrance channel, and we had the possibility to investigate on effects due to the neutron excess in the evolution of nuclear dynamics. Comparisons of experimental data with CoMD-II calculations confirm that a moderately stiff behaviour of symmetry potential have to be used to reproduce data.

EXPERIMENTAL DETAILS

The experiment was performed at INFN-Laboratori Nazionali del Sud Superconducting Cyclotron facility. In the framework of ISOSPIN campaign (2003), ^{40}Ca beams were accelerated at 25 MeV/nucleon and impinged on self-supporting targets of ^{40}Ca (1.24 mg/cm² thick) and ^{48}Ca (2.7 mg/cm² thick) (*limiting* experiment). We enlarged these reaction systems by performing, on June 2009, the *isospin-1* experiment (EXOCHIM campaign). We accelerated ^{48}Ca nuclei at 25 MeV/nucleon bombarding energy, and they impinged on $^{40,48}\text{Ca}$ targets of the same thickness as in the previous experiment.

In both experiments, reaction products were detected by using the 4π multi-detector Chimera [8]. It is constituted by 1192 Si-CsI(Tl) telescopes, covering about 94% of the whole solid angle. Si detectors are 300 μm thick, while CsI(Tl) thicknesses vary as a function of the polar angle.

An example of ΔE -E identification plot for ions punching through the Si stage [9] is shown in Figure 1; it is referred to a well performing Si-CsI(Tl) telescope placed at $\theta=10.8^\circ$ for the system $^{48}\text{Ca}+^{48}\text{Ca}$.

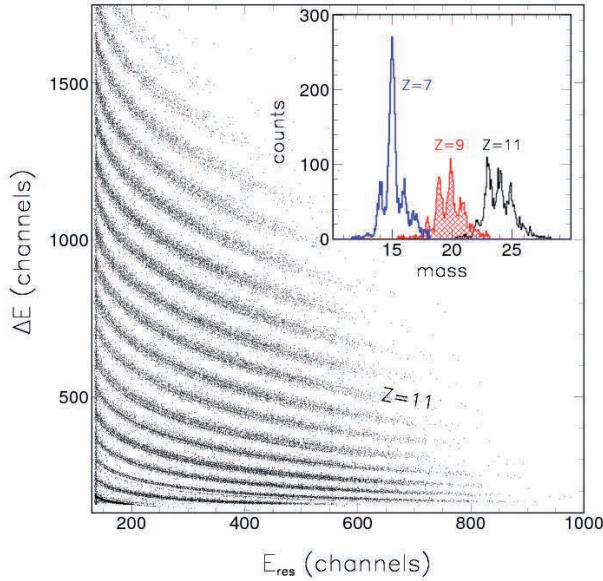


Figure 1. mass-velocity correlations for the largest fragment emitted in semi-central events of $^{48}\text{Ca}+^{48}\text{Ca}$ ($N/Z=1.4$), $^{40}\text{Ca}+^{40}\text{Ca}$ ($N/Z=1.2$) and $^{40}\text{Ca}+^{40}\text{Ca}$ ($N/Z=1.0$) reactions.

More details about the array and its detection and identification capabilities are described in Refs. [8,9,10]. The obtained mass resolution by means of time of flight method is around 5% for nuclei having masses $A\approx 50$, that are typical of evaporation residues detected in this type of reactions. In order to analyze only well reconstructed events, we imposed a constraint on the total detected charge (between 80% and 100% of the total charge), and on the total parallel momentum (larger than 70% of the entrance momentum). Quasi-elastic reactions were strongly reduced during the experiment by the chosen electronics trigger condition, requiring the detection of at least three charged particles.

EVAPORATION RESIDUE EMISSION

Following the suggestion of Ref. [11], we measure the centrality of the collisions by means of a constraint on charged particle multiplicity. Much attention was put in recognising in the event the presence of a fast quasi-projectile nucleus (massive transfer phenomena) [12]. To select the presence of the fast quasi-projectile we require that the second or the third largest fragment emitted had a velocity larger than 1.3 times the centre of mass velocity ($v_{\text{cm}}\approx 0.11c$) [12,13,14].

Mass spectra of the largest fragment emitted can be useful to extract the yield ratios of evaporation residue emission versus other mechanisms. To avoid further contaminations due to quasi-projectile and quasi-target-emission, we selected only heavy fragments emitted in a range of velocity $0.04c < v < 0.15c$, i.e. centred on the v_{cm} velocity [12,14]. The mass spectra so obtained seem to be a superimposition of two Gaussian-like contributions (see figure 2). The first one, peaked near 50-55 amu, can be related to evaporation residue emission, while the second one, peaked at lower values, can be attributed to binary-like or, alternatively, to more dissipative multi-fragmentation mechanisms. In order to obtain quantitative evaluations, we fitted these mass distributions by means of two Gaussian curves, and we were able to extract, from the fit procedure, the relative emission yield of evaporation residues, normalized to the whole number of semi-central events selected as described previously in the text. In this way, a correlation between the N/Z of the entrance channel and the emission yield of evaporation residues can be traced, as shown in figure 2 panel (e). In details, it seems that by increasing the N/Z of the entrance channel, the relative emission of evaporation residues (produced by means of incomplete fusion mechanisms) increases.

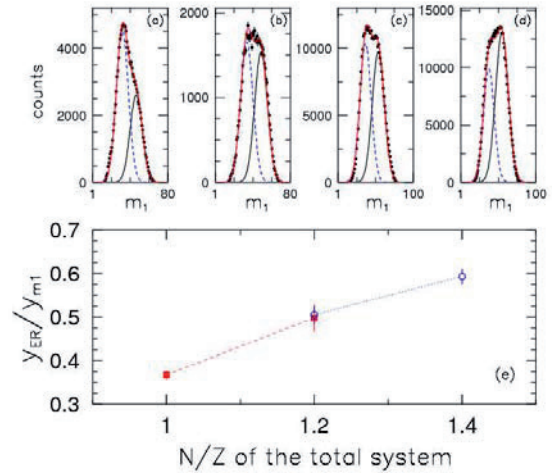


Figure 2: yields of evaporation residues emitted in semi-central events of reactions, selected as described in the text. The emission yields have been extracted by means of a two Gaussian fit on the mass spectra of the largest fragment emitted.

COMPARISON WITH COMD-II MODEL CALCULATIONS

We had also compared our experimental mass distributions for the selected semi-central collisions with calculations performed by using the dynamical model CoMD-II [15]. In particular, we compared the $\Delta M_{\text{nor}}=(m_1-m_2)/m_{\text{tot}}$ quantity, defined as the difference of the two largest fragments masses (that we called m_1 and m_2), normalized to the total mass of the entrance channel

(m_{tot}). The ΔM_{nor} observable can be useful to give a compact schematization of the two main classes of reaction mechanisms contributing to our selected semi-central events: $\Delta M_{\text{nor}} > 0.4$ roughly select the emission of an evaporation residue, while events with a low ΔM_{nor} value are mainly associated to binary-like, fusion-fission and multi-fragment emission. In our previous letter [12], where we compared the results of the *limiting* experiment with calculations, we found that the shape of the ΔM_{nor} distribution is sensitive to the various options adopted to describe the behaviour of the density dependent part of symmetry energy in the Nuclear Equation of State. In particular, the best agreement between experimental data and CoMD-II model calculations (filtered by GEMINI code to take into account the statistical decay of excited fragments) was obtained by choosing a Stiff2 option [16,17] for the symmetry potential.

Now we have the possibility to compare the recent experimental data of the very neutron rich $^{48}\text{Ca}+^{48}\text{Ca}$ system with CoMD-II model calculations. The experimental ΔM_{nor} and m_1 distributions for semi-central collisions (selected as described in the previous sections) are shown as blue dots in Figure 3. Calculations performed with CoMD-II model are superimposed as filled histograms. Three more representative options [16,17] were chosen to parameterize the behaviour of the symmetry potential: Stiff1, Stiff2 and Soft. In a commonly used way, these options can be expressed as a power of the reduced density: $(\rho/\rho_0)^\gamma$. In this way, Stiff1, Stiff2 and Soft parameterizations correspond to $\gamma=1.5$, $\gamma=1.0$ and $\gamma=0.5$ respectively [18]. As seen in Figure 3, a quite good agreement between experimental data and calculations is obtained for the Stiff2 options, i.e. for a moderately stiff behaviour of the symmetry potential.

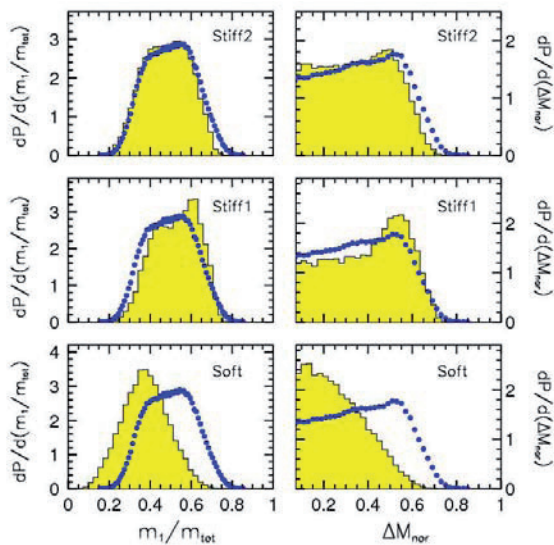


Figure 3: comparison of experimental ΔM_{nor} spectra (blue dots) with CoMD-II model (GEMINI filtered) calculations (filled histograms) for the $^{48}\text{Ca}+^{48}\text{Ca}$

reaction. Stiff1, Stiff2 and Soft options are used to parameterize the behaviour of the symmetry potential.

CONCLUSIONS AND PERSPECTIVES

We presented results concerning the emission of evaporation residues in nuclear collisions involving medium mass systems $^{40}\text{Ca}+^{40}\text{Ca}$, $^{40}\text{Ca}+^{48}\text{Ca}$ and $^{48}\text{Ca}+^{48}\text{Ca}$ at 25 MeV/nucleon bombarding energy. By selecting semi-central collisions, we observed that by increasing the N/Z of the total system, the probability of emitting an evaporation residue in incomplete fusion mechanisms is enhanced. By comparing our experimental mass distribution with CoMD-II dynamical model calculations, we observed that the behaviour of the symmetry potential in the nuclear equation of state plays a role on the interplay between the different reaction mechanisms observed.

Similar studies, in the region of medium mass heavy ion collisions, have been recently performed with the Chimera detector [19]. All these findings open the way for further investigations to be performed with radioactive beams having masses in the calcium region, but with exotic N/Z values (such as, for example, ^{34}Ar or ^{52}Ca). In this way, further details on the N/Z dependence of evaporation residue emission at the fragmentation threshold could be deeper investigated.

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The improved fragmentation beam at LNS

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Abstract – The production yields of fragmentation beams was measured after the rearrangement of the beam production line. Also due to the good performances of the new diagnostic system for the transport of EXCYT beam an increase of the beam intensity of a factor around 8 was measured in the CHIMERA scattering chamber. Beams from ^8He to ^{34}Ar were produced.

INTRODUCTION

Since many years the production of radioactive beams with the in flight fragmentation method is done at LNS using as fragment separator a sector of the standard beam transport line of the Cyclotron [1]. Very good results were achieved using such beams [2] and various experiments were started [3]. The CHIMERA detector [4] was moved in its new hall in order to use the better transmission guaranteed by the new beam lines. At the end of 2009 it was approved and financed by INFN the plan to further improve the beam production rate, by installing new magnetic elements and redesigning the whole transport beam line in the Cyclotron and High energy halls [5]. We have compared the production yields after this upgrading, using the same setting of a 2009 measurement for the production of ^{11}Be with a ^{18}O 55 MeV/A primary beam. During the same experimental campaign, the production of proton rich Ar beams was also checked, together with the production and transport of ^8He and ^{11}Li and ^{12}Be beams.

THE ^{11}Be SETTING

In order to produce ^{11}Be and others neutron rich nuclei for the UNSTABLE experiment, we used ^{18}O 55 MeV/A

primary beam impinging on a 1.5 mm ^9Be target. The use of the same magnetic setting of the 2009 runs was guaranteed by the use of the primary $^{18}\text{O}^{7+}$ beam as pilot beam. Such beam has in fact the same magnetic rigidity of ^{11}Be .

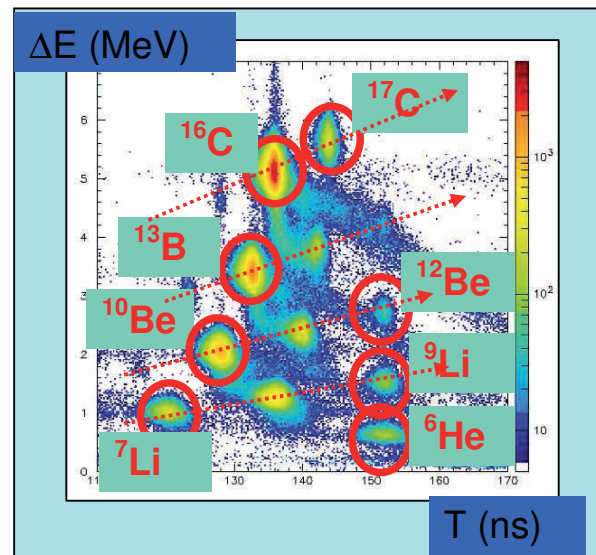


Figure 1: Identification scatter plot of the beams obtained with the ^{11}Be magnetic setting

After this preliminary setting we inserted the ^9Be target obtaining the fragmentation beam. We have monitored the transport of this beam by using the new diagnostic system

for the transport of EXCYT beams [6]. The various diagnostic points of this system are all equipped with a plastic scintillator and a position sensitive silicon detector. So in each point we can monitor the absolute yield of the beam and its shape. Using this system operators are able to set all the magnetic elements of the beam line for the best beam transport.

In fig.1 we show the identification scatter plot of the beam transported in the scattering chamber with this setting.

The identification was obtained using the CHIMERA tagging system. With this system we measure the beam energy loss in a double sided silicon strip detector 62 μm thick. The time reported in the abscissa of fig.1, it is the time of flight (TOF) from a microchannel plate (MCP) to the strip detector. The MCP was placed, along the beam line around 13 m away from the strip detector [7]. The most intense beam transported was ^{16}C (about 60kHz with 100W of primary beam). The observed yields show a gain of a factor around 8 respect the production rates observed during the 2009 experiment. This enhancement is due to the new beam line design, but also to the new beam diagnostic system allowing an accurate beam transport. During the beam transport we have also observed that an important fraction of the beam is lost in some collimators placed, along the beam line, in correspondence of each radioprotection faraday cup. These collimators must ensure the complete stop of the beam in order to allow the access into controlled areas.

The replacement of such collimators is going and this will allow a gain of at least a factor 2 on the production yields.

OTHER BEAMS

^8He and ^{11}Li

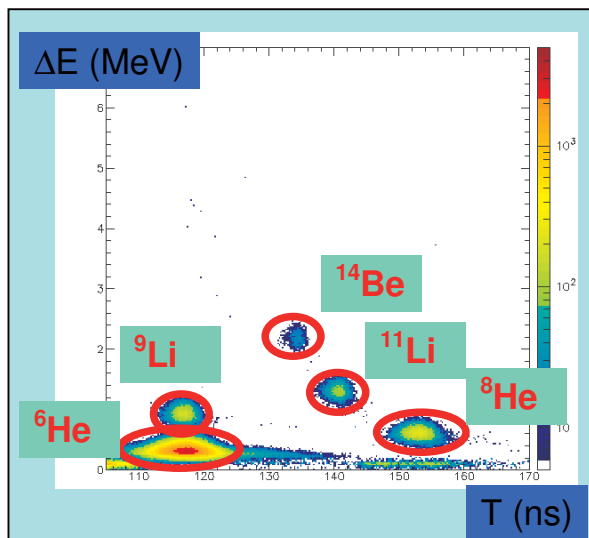


Figure 2: Identification scatter plot of the beams obtained with the ^8He magnetic setting

Using the same ^{18}O primary beam we have also checked the production of ^{11}Li and ^8He . The beam diagnostic system was needed in this case because it is not simple to produce a pilot beam for ^8He as for practically all neutron rich beams. ^{18}O beam is not the best beam suited for ^8He production, so a rate of the order of only 80 Hz was measured. In fig. 2 we plot the identification scatter plot obtained with such setting.

The most intense beam produced is ^6He with a production rate of the order of 1 kHz. ^{11}Li is also present however the production yield is rather low of the order of 20 Hz. The replacement of radioprotection collimators will surely improve such yields. New tests also using other primary beams are necessary to try to obtain more intense yields.

^{12}Be

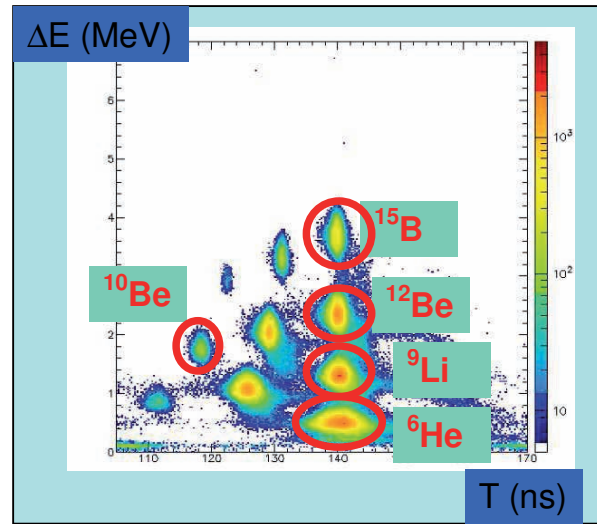


Figure 3: Identification scatter plot of the beams obtained with the ^{12}Be magnetic setting.

Another useful attempt was done to observe the production of ^{12}Be and in general of $N=2Z$ nuclei as ^6He , ^9Li , ^{12}Be , ^{15}B . In fig.3 we show the identification scatter plot obtained for such setting. We note that nuclei with the same ratio N/Z are detected with the same TOF because they have practically the same magnetic rigidity. Again the beam diagnostic system was crucial to transport this beam. The most intense yield, normalized to 100 watt primary beam intensity was obtained for ^6He , with about 4kHz, ^{12}Be was produced with a rate of about 1.5kHz.

^{34}Ar beam

Another production test was performed using a primary beam of ^{36}Ar at 42 MeV/A. The idea was to produce ^{34}Ar beam around 25 MeV/A. In this case, due to various problems, we could not use the beam diagnostic system.

The beam transport was done simply using the pilot beam technique. As in general true for proton rich beams, the pilot beam can be simply produced inserting a thick degrader to reduce the energy of the primary beam. More in detail, the magnetic rigidity required by LISE++ calculation [8] for the transport of ^{34}Ar was 1.53 Tm. This is the same rigidity of a ^{36}Ar beam at 27.8 MeV/A, and to get such a beam it is enough to insert an Al degrader of about 500 μm . By using such a thick degrader, we have another advantage, we obtain a pilot beam with an emittance rather similar to the one of the radioactive beams to be simulated. For this reason we estimate that using the beam diagnostic system in future experiments we could obtain a further gain in beam intensity not larger than 10-20%.

In fig. 4 we plot the identification scatter plot obtained in this case. The most intense beam produced was ^{37}K with intensity, scaled to 100 W primary beam, of about 50 kHz. This is a beam obtained by proton pick-up on the ^9Be target. We have verified with various primary beams that this is a rather common production mechanism for primary beams with energy around 30-50 MeV/A. This behaviour is not well predicted by LISE++, (we have seen for instance a rather strong ^{21}Na production with ^{20}Ne , and ^{17}F production with ^{16}O [2,3]).

The ^{34}Ar production yield was smaller than LISE++ predictions, we get a yield, normalized to 100 Watt of primary beam intensity, of around 7 kHz against predictions more than 10 times larger, again the replacement of collimators near the radioprotection faraday cups could allow a larger yield.

In conclusion we can say that the upgrading of the fragmentation beam is going to respect the objective to get an increase of a factor at least 20 in the beam intensity measured on the secondary target. This increase in yield will allow to explore nuclei rather far from the stability line.

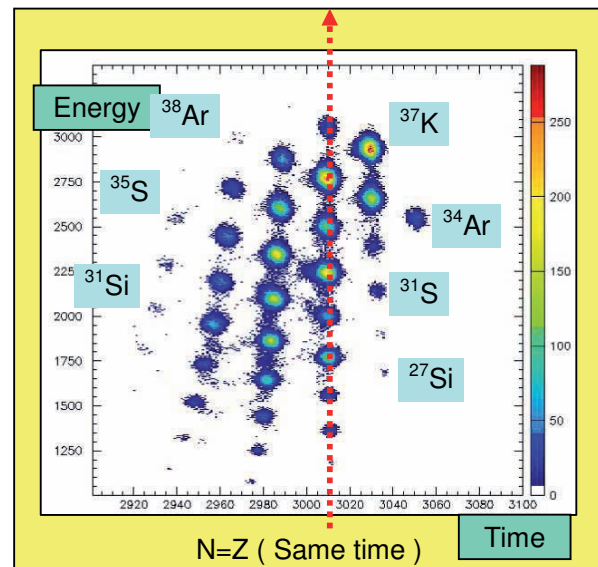


Figure 4: Identification scatter plot of the beams obtained with the ^{34}Ar magnetic setting

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Isospin dependence of nucleon exchange in the peripheral nuclear reactions

$^{78,86}\text{Kr} + ^{40,48}\text{Ca}$ at 10 MeV/A

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Abstract - Preliminary results are presented of theoretical simulation calculations as well as experimental data obtained in the ISODEC experiment performed in January 2010 with the LNS-CHIMERA multi-detector array. One of the main objective of this experiment is to explore and characterize the isospin dependence of the flow of energy and mass in damped nuclear reactions. With a bombarding energy of $E/A = 10$ MeV the system approaches the limits to an adiabatic response of the nucleus associated with a separation of time scales of macroscopic and microscopic degrees of freedom. However, non-equilibrium effects are expected to be still relatively weak such that nuclear disintegration processes should be of dominantly statistical nature [1].

INTRODUCTION

Heavy-ion reactions at a few MeV per nucleon are characterized by a host of transport phenomena which are summarized by the classification “dissipative nuclear reactions.” Although the reactions have been studied for more than 20 years, important features

related to the correlation between neutron and proton exchanges between projectile and target remain poorly understood. The present work is motivated to provide a new set of data that will serve to tests models of nucleon transfer and energy dissipation.

At energies close to the interaction barrier, many nuclear transport phenomena can be understood in terms of the exchange of independent nucleons between projectile and target nuclei [1]. Earlier studies of the process have demonstrated the validity of the one-body Nucleon Exchange Model (NEM) developed by Randrup [2] and realized in the Rochester computer code CLAT (Classical Transport Model) [3]. This classical approach considers the effect of dynamical forces driving nucleon exchange and all related transport processes. At bombarding energies of interest here, the static components of the driving forces represented by the chemical potential or the potential energy surface (PES) should have predictive power for the mean flow of mass, charge and energy between the reaction partners. The following section will briefly relate experimental observables to the PES topology.

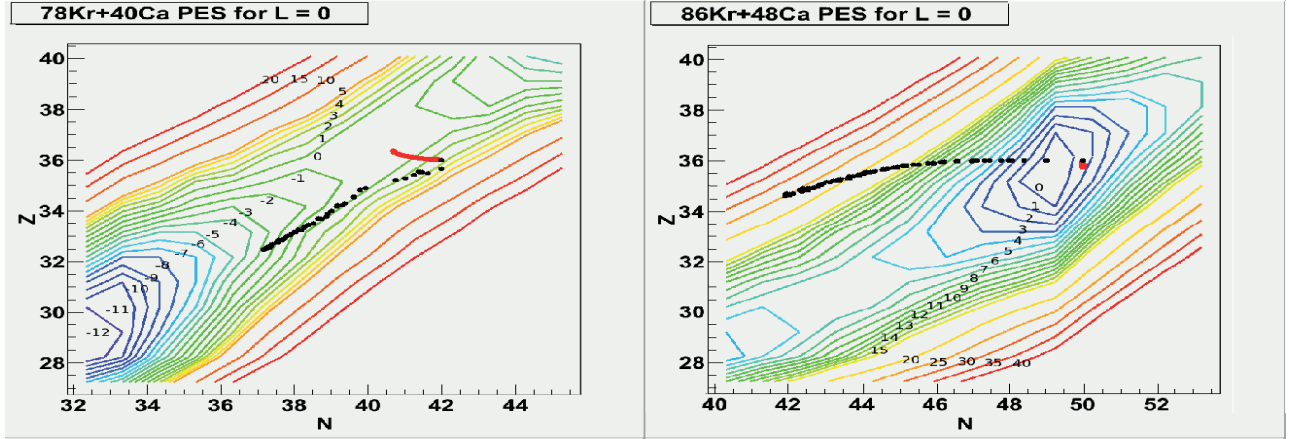


Figure 1: Equipotential contour maps of the liquid-drop model potential-energy surface with shell corrections for dinuclear fragmentation specified by Z and N of the PLF reaction fragments for the system $^{78}\text{Kr} + ^{40}\text{Ca}$ (left) and $^{86}\text{Kr} + ^{48}\text{Ca}$ (right). The red points mark the trajectories on the PES predicted by theory (CLAT) for the primary PLF for initial orbital angular momenta varying from grazing to critical l value for fusion. The black points represent the corresponding trajectory when account is taken of the statistical PLF decay. The decay is simulated using the statistical model code GEMINI++.

SIMULATIONS CALCULATIONS

The NEM (CLAT) describes the time evolution of primary macroscopic reaction variables such as nuclear excitations and spins, as well as mass and charge asymmetries between projectile (PLF) and target-like (TLF) reaction products. Numerical integration of the equations of motion with a consistent set of conservative and dissipative nuclear proximity forces allows one to estimate the interaction time of the system. From the equations of motion dissipation and nucleon exchange rates can be approximated for nuclei in a dinuclear state. Utilizing this information one can predict the probability distributions for mass and charge asymmetries. This results in limited transfer and associated heating of the projectile- and target-like fragments. This dynamical simulation of the reaction system takes into account the Fermi nature of the nucleons obeying the Pauli Exclusion Principle.

The theoretical joint probability distributions $P(N, Z)$ for neutron and proton numbers of PLF (or TLF) are represented by the correlated bivariate Gaussian distribution

$$P(N, Z) = \frac{1}{2\pi\sigma_N\sigma_Z\sqrt{1-\rho^2}} \exp\left[\frac{-z}{2(1-\rho^2)}\right] \quad (1)$$

$$z = \frac{(N-\bar{N})^2}{\sigma_N^2} - \frac{2\rho(N-\bar{N})(Z-\bar{Z})}{\sigma_N\sigma_Z} + \frac{(Z-\bar{Z})^2}{\sigma_Z^2}$$

$$\rho = \text{cor}(N, Z) = \frac{\sigma_{NZ}}{\sigma_N\sigma_Z}$$

Here the quantities $\bar{N}$, $\bar{Z}$, σ_N^2 , and σ_Z^2 represent the first and second moments, respectively, of the joint distribution $P(N, Z)$. They are related to the number of exchanges of neutrons and protons, respectively, between projectile and target. The covariance σ_{NZ} is a

measure of the correlation between neutron and proton exchanges between projectile and target nuclei.

In the governing nucleon exchange, the chemical potential or the PES play important roles. In the present simulations, the potential energy surface is derived from the phenomenological liquid drop binding energies with shell corrections for a range of fragmentations of the total mass and charge of the system [1]. The effective potential energy is given by

$$V(1, 2) = V_{\text{Coul}} + V_N + V_1 + V_2 \quad (2)$$

where V_{Coul} is the Coulomb potential approximated by two homogeneous spheres, V_N is the nuclear interaction potential and V_1 and V_2 represent the binding energies of the two reaction fragments. The quantities

$$\Delta V(1, 2) = V(\text{Projectile, Target}) - V(1, 2) \quad (3)$$

represent the static part of the driving force for the exchange process leading to a fragmentation ($1, 2$) = (PLF, TLF) for the Kr + Ca systems.

MODEL PREDICTIONS

The two systems studied are the proton rich system $^{78}\text{Kr} + ^{40}\text{Ca}$ and the neutron rich system $^{86}\text{Kr} + ^{48}\text{Ca}$. The exchange of nucleons is expected to have a strong dependence on the initial asymmetries of the system. Neutrons have a higher mobility than protons due to the Coulomb barrier that protons have to overcome.

The computer code CLAT was utilized in this work to simulate the dynamics of each reaction for a range of initial angular momenta from the system's grazing angular momentum to the critical angular momentum for fusion. The simulation predicts the final average N and Z values for the PLF and TLF, as well as the

associated covariance tensor (σ_N^2 , σ_Z^2 , σ_{NZ}), as functions of the angular momentum or dissipated energy.

Since the reaction model simulations generate only the often highly excited and unstable primary fragments, which are not easily accessible to experiment, the subsequent disintegration of these primaries has to be simulated separately and in addition. For this latter task, the statistical decay code GEMINI++[4] was used.

Figure 1 displays, for each system, the predicted average trajectories plotted vs. PLF N and Z values. These trajectories are superimposed on the PES for zero angular momentum. According to the calculations, with decreasing impact parameter the projectile of the proton rich system experiences a drift of probability in mean N and Z, essentially increasing the proton richness of the PLF with respect to the projectile, while that of the TLF decreases. The larger decrease in the average N as compared to the increase in average Z is due to the fact that the neutrons have a greater mobility than protons.

Inspection of the PES makes such outcome plausible. For the proton rich system the injection point on the PES (initial projectile-target system) is located on the steep slope in the potential such that the system experiences strong driving towards smaller PLF/TLF charge and larger mass asymmetries.

In contrast to the evolution of the proton rich system, the neutron rich system is predicted to experience little to no change in the average N or Z of the PLF, retaining the initial charge and mass asymmetries for the primary fragments. However, in this system there is an excess of neutrons that are transferred back and forth between PLF and TLF reaction partners in a diffusion-like process. This type of neutron exchange does not result in an average net change of N or Z for the projectile. It appears from the PES that the neutron rich projectile-target system is injected and permanently trapped in a local PES minimum preventing any net drift of the mean N and Z distributions.

Depending on the excitation energy acquired by the reaction primaries, their sequential decay will show

sensitivity to the primary N/Z asymmetry of the decaying primary fragment and that of the reaction system. Obviously, because of their higher excitations, it is more difficult to reconstruct the reaction primaries emerging from more central collisions than from peripheral interactions.

As seen from the black points in Fig. 1, simulation calculations for the sequential decay of the neutron-rich primary PLF predict a larger change in its mean fragment N than in its mean Z value. The ejectiles from such decay are mainly neutrons and relatively few but highly neutron rich light charged particles and clusters. This results in a relatively good preservation of the charge of the PLF for peripheral and semi-peripheral collisions. With decreasing impact parameter, the ejectiles should become less neutron rich.

In contrast, the PLF generated in the proton rich reaction system should emit numerous light charged particles with relatively small neutron excess. Therefore, the different iso-asymmetries of the reaction system are predicted to be visible in the multiplicities and neutron richness of the associated charged particles and clusters.

PROGRESS IN DETECTOR CALIBRATION

An important task for analysis of the experimental data is to reconstruct the pre-evaporative PLF. This requires calibration of the CHIMERA detectors with respect to energy, mass, charge and time-of-flight (TOF). To date, $\Delta E/E$ identification technique, the Si detector response with respect to energy and the calibration of the TDC have been performed.

PRELIMINARY RESULTS

In the preliminary results presented below, data are compared for the two different Kr+Ca systems studied here. Particles passing through Si transmission detectors but are stopped in the corresponding CsI detectors are identified with the $\Delta E/E$ technique both in Z and A. For light charged particles and intermediate-mass clusters the $\Delta E/E$ technique provides mass

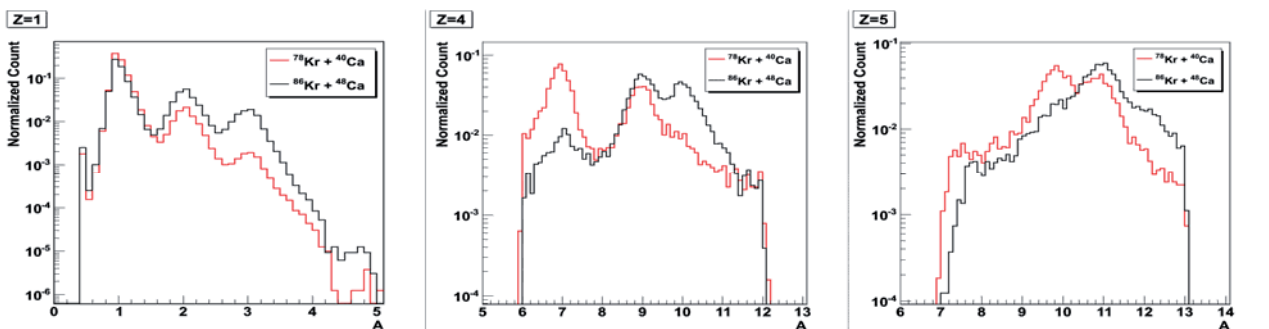


Figure 2: Isotopic distributions for Z=1, 4 and 5. The counts have been normalized for comparison.

identification, allowing investigations of the particle isotopic composition. Figure 2 presents the measured mass distributions for $Z=1, 4$ and 5 . As expected from the simulations discussed above, the isotopic distributions for the neutron rich system exhibit increased yields of the heavier isotopes at the expense of lighter ones, opposite for the proton rich system.

This behavior is strongly evident in the case of Be ($Z=4$) for which the production of the light ^7Be isotope is by approximately one order of magnitude less intense than for the proton rich system. As expected from the theoretical PLF trajectories depicted in Fig. 1, the post-evaporation PLF from the proton rich system moves close and parallel to the attractor line ($N=Z$ line) experiencing approximately equal changes in mean N and Z values. The trajectory of the post-evaporation PLF from the neutron rich system shows different behavior, moving toward the $N=Z$ line with decreasing impact parameter. This difference is reflected in a large intensity of neutrons evaporated from the PLF produced by the neutron rich system, as well as in an enhancement of the yields of heavier isotopes produced. Tentatively, the above preliminary data are consistent with the simulation calculations and the underlying assumptions.

For particles stopped in the Si detector the masses are identified utilizing measured energies and TOF times.

Figure 3 depicts a comparison of the mass

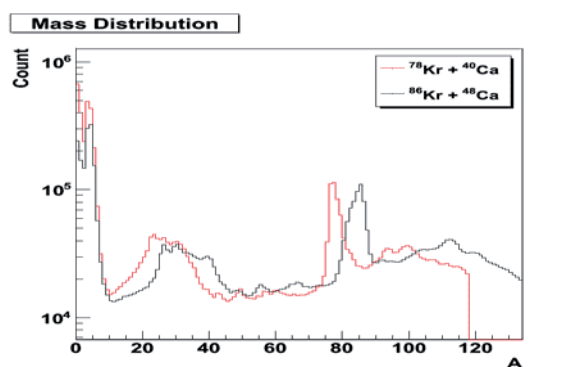


Figure 3: Comparison of the integrated mass distribution for the two systems. The limit at $A=120$ in the $^{78}\text{Kr}+^{48}\text{Ca}$ mass distribution is due to an instrumental cutoff.

distributions of all identified charged products measured in the forward angular range. There are obviously similarities and striking differences in the two mass distributions extending from the light charged particles to the domain of fusion evaporation residues. Furthermore, each of the two mass distributions exhibits a prominent peak in intensity, most likely associated with corresponding PLFs. Each peak is located in mass close to that of the corresponding projectile, i.e., at $A=78$ and $A=86$, respectively. To interpret the interesting difference in width and shape of these PLF mass peaks requires

more extensive simulations. Likewise, broader features appear in the mass region of Ca-like, target related recoil products (TLFs) need to be investigated in more detail.

SUMMARY

Theoretical model simulations and data presented in this report are to be regarded as preliminary. Significant progress has been made towards calibrating the CHIMERA detector telescopes. The various comparison of data for the two systems suggest interesting isotopic differences in the reaction dynamics revealed by the measurements of light charged particles, intermediate mass clusters and the more massive reaction products. Continued work will be devoted both to a search for characteristic correlations between different classes of data and to more detailed theoretical modeling of the phases of primary reaction and subsequent decay.

ACKNOWLEDGEMENT

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ISODEC experiment : study of the decay mode in the reactions $^{78}\text{Kr}+^{40}\text{Ca}$ and $^{86}\text{Kr}+^{48}\text{Ca}$ at 10 AMeV with CHIMERA detector at LNS

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Abstract - We present the preliminary results of the ISODEC experiment, performed at the INFN-LNS with the CHIMERA device in January 2010, in order to study the competition between the various disintegration modes of $^{118,134}\text{Ba}$ compound nuclei produced by bombarding $^{40,48}\text{Ca}$ targets with beams of $^{78,86}\text{Kr}$ at 10 AMeV. This work aims to explore the isospin dependence of the decay modes of medium mass compound nuclei formed by fusion processes.

INTRODUCTION

The ISODEC experiment was performed at the INFN-Laboratori Nazionali del Sud (LNS) by using the 4 π CHIMERA detector, in order to study the competition between the various disintegration modes of $^{118,134}\text{Ba}$ compound nuclei produced in the reactions $^{78}\text{Kr}+^{40}\text{Ca}$ and $^{86}\text{Kr}+^{48}\text{Ca}$ at 10 AMeV.

The experiment complements data already obtained at 5.5 MeV/A for $^{78,82}\text{Kr}+^{40}\text{Ca}$ reactions[1], previously

realized with beams delivered by GANIL facility and by using the INDRA detector. Besides, this experiment is part of a project that aims to explore the isospin (N/Z) dependence of medium mass compound nuclei decay formed by fusion process.

The neutron enrichment of the compound nuclei in fact is expected to play an important role on the various emission mechanisms, providing crucial information on fundamental nuclear quantities as level density, fission barrier or viscosity. Thus the chemical composition influence the fission dynamics and a program of systematic measurements of fission cross-section for a large isotopic chain of compound nuclei, from neutron-rich to neutron-poor, provides careful information.

The investigated systems allow to produce compound nuclei with different (N/Z)_{CN} with similar both spin distribution and excitation energy. Such a set of data also will provide new constraint on sophisticated models attempting to describe statistical and/or dynamical properties [2] of excited nuclei.

EXPERIMENTAL SET UP AND METHODS

The key observables for such a program are the cross-sections, multiplicities, angular and kinetic energy distributions of the reaction products (Intermediate Mass Fragments, IMFs, Light Charge Particles, LCPs, and Fission Fragments, FF). The measurement of these observables, requires a good isotopic resolution, a low energy thresholds for LCPs and IMFs, a high granularity and a broad angular acceptance. The presence at LNS of a second generation 4π multi detector CHIMERA [3], and the very good beam facility strongly suggested to perform the experiment in Catania. Briefly, CHIMERA consists of 1192 detector telescopes, arranged on 9 rings, in the forward part, and 17 rings, in spherical configuration, in the backward part; the covered polar angle goes from 1° to 176° , and the efficiency is the 94% of the total solid angle.

In figure 1, a picture of the detector in the devoted experimental scattering chamber at LNS is reported.

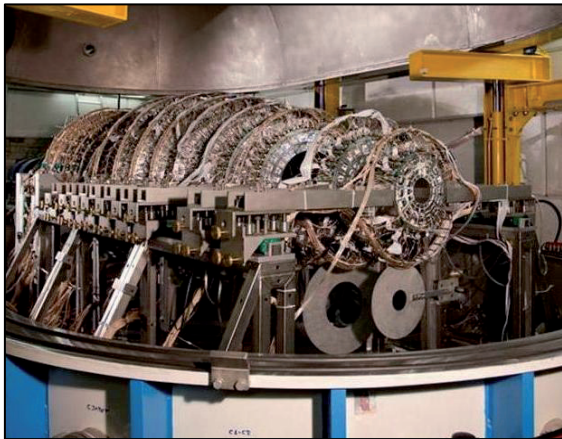


Fig. 1. The CHIMERA detector at LNS

The single detection cell consists of a silicon detector (Si, thickness about $300\ \mu\text{m}$) followed by a Caesium Iodine, Thallium doped crystal, (CsI(Tl), thickness from 3 cm to 12 cm), coupled to a photodiode.

The identification methods employed are :

ΔE -E, for charge identification of the particles punching through the Si detector and stopped in the CsI(Tl) with also mass identification for particles with $Z \leq 9$;

E-TOF (Time of Flight), for mass identification, velocity and energy measurement of the particles stopped in it;

PSD (Pulse Shape Discrimination) in CsI(Tl), for isotopic identification of light charge particles;

PSD (Pulse Shape Discrimination) in Si detector, for charge identification of the particles stopped in the Silicon detector.

This last method [4,5] was recently implemented in CHIMERA, allowing to work for the first time with this device in a low energy domain.

In figure 2 is reported as an example, the Energy (E_{Si}) vs Rise Time (RT_{Si}) plot obtained by the PSD methods in silicon detector, for the n-poor system $^{78}\text{Kr}+^{40}\text{Ca}$ at 10 AMeV at $\theta = 34^\circ$.

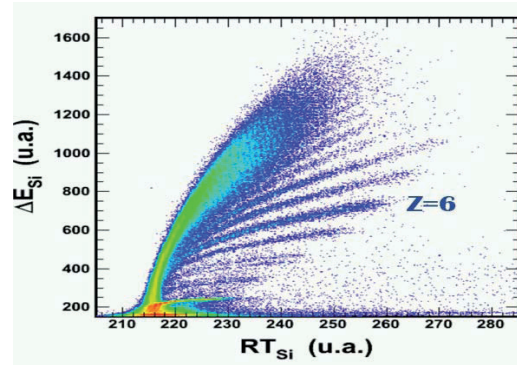


Fig. 2. Energy - Rise Time plot for $^{78}\text{Kr}+^{40}\text{Ca}$, at $\theta = 34^\circ$.

Besides, the CHIMERA multidetector is characterized by a low energetic detection threshold, that is less of 0,5 MeV/A for heavy ions and 1 MeV/A for light particles.

These characteristics allowed the complete identification of LCP in a wide energy range, the complete identification in charge and mass of the IMF ($3 < Z < 12$) products, the charge identification up to $Z = 14-16$ for products stopped in the Silicon, and up to about $Z = 30$ for the most energetic particles stopped in CsI.

In the experiment, self-supporting $1\ \text{mg}/\text{cm}^2$ thick ^{40}Ca and ^{48}Ca targets were prepared in collaboration between INFN-LNL and INFN-LNS Target Laboratories, were bombarded by $^{78,86}\text{Kr}$ beams at 10 AMeV, delivered by the LNS Superconductive Cyclotron, with typical request of beam intensity of 800 - 1000 pA. Under this experimental conditions, the expected particles rate at forward angles was evaluated to be very high, so, in order to avoid pile-up, preserving good energy resolution, and monitoring elastic scattering cross section in this angular range, the ring 1 and the ring 2 were carefully shielded by thick frames with holes of 1 cm diameter. In this way, also the dead time was taken at a low level and good statistics was collected for normalization purpose.

The beam was delivered with a timing resolution about 800 ps- 1 ns. This time resolution was a mandatory request to obtain the needed mass resolution.

Inclusive and coincidence measurements were realized. Energy and time calibration measurements were performed by using ^{12}C , ^{16}O and proton beams, delivered by the TANDEM SPM of the LNS, at incident energy ranging from 10 to 100 MeV.

EXPERIMENTAL RESULTS

The first results [6] compare the inclusive data at $\theta = 12^\circ$, for the two studied systems $^{78}\text{Kr}+^{40}\text{Ca}$, and $^{86}\text{Kr}+^{48}\text{Ca}$, at 10 AMeV.

In figure 3 are reported the charge distributions for the two systems, obtained by using ΔE -E and PSD in Si, identification methods: in this way, we identified all LCP and IMF detected at 12° and reaction products stopped in the Silicon up to $Z = 14$. The next development of the data analysis will complement these preliminary results.

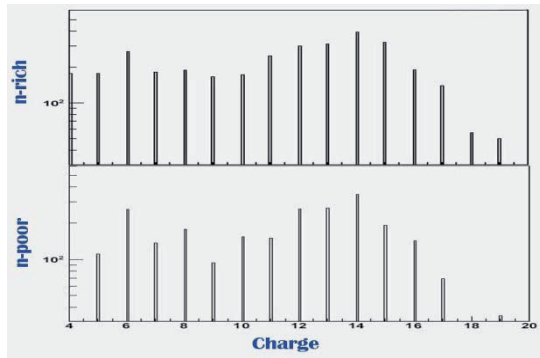


Fig. 3. Charge distributions for the two studied systems.

In the figure, we can see a strong odd-even staggering of the Z yield for $Z < 10$ detected fragments, and this effect persists for higher Z with a smaller amplitude.

Besides, when we compare the two systems with different isospin, the yields of the Intermediate Mass Fragments (IMF, $3 < Z < 12$) exhibited an even-odd staggering that is more pronounced for the neutron-poor system. It seems also that the neutron excess affects the yields of the light fragments, but we have to wait the extraction of the absolute cross section of the reaction products to confirm this result. The analysis is in progress.

In figure 4 are reported the mass distributions for the IMF with $Z = 4, 5, 6$, and for the two systems.

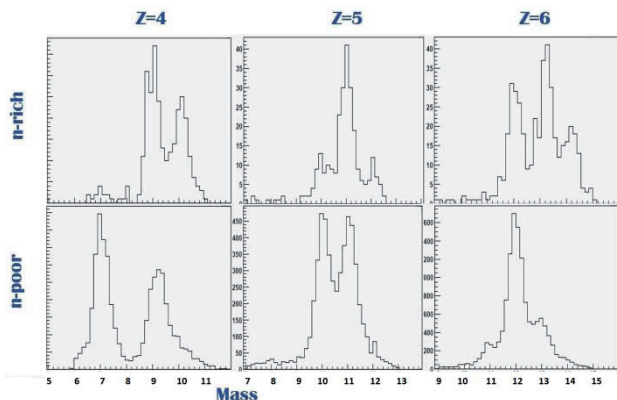


Fig. 4. Mass distributions for $Z = 4, 5, 6$ and for the two studied systems

We can see the different isotopic composition and relative enrichment in correspondence of the same Z , for the compared systems. In particular this effect is evident for the Be element, in which the isotopic composition goes from $A=7,9$, in the n-poor system, to $A=9,10$, in the n-rich one.

CONCLUSION

Experimental methods and first result of the ISODEC experiment were illustrated. The experiment aims the study of the $^{78,86}\text{Kr} + ^{40,48}\text{Ca}$ reactions at 10 A MeV incident energy. This experiment is complementary to the $^{78,82}\text{Kr} + ^{40}\text{Ca}$ reactions [1] at 5.5 MeV/A, realized with beams delivered by GANIL facility and by using the INDRA detector.

First results on the experimental features of the produced fragments were shown, in particular charge and mass distributions at $\theta=12^\circ$ were reported and compared for the two systems with different third component of the isospin. Staggering effects are evident in the Z distributions, as well as different isotopic composition and enrichment for the reaction products in the two systems.

The observed effects are probably due to the role of the N/Z degree of freedom on the decay channels.

Absolute cross sections calculations of the reaction products are in progress, and these could provide important indication on the isospin influence on the reaction mechanism and fragments production.

Comparisons with theoretical models are in progress; and by comparing calculation with the new set of experimental data we could able to estimate the influence of structural effects during the separation phase in asymmetric fission.

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Halo effects on fusion cross section in ${}^4\text{He}+{}^{64}\text{Zn}$ collision around and below the Coulomb barrier

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Abstract – By using an activation technique, a new measurement of the fusion cross section for the system ${}^4\text{He}+{}^{64}\text{Zn}$ was performed at sub-barrier energies. Comparing the fusion cross section with the ones previously measured for the system ${}^6\text{He}+{}^{64}\text{Zn}$, in the same energy region, it has observed an enhancement of the fusion cross section for the reaction induced by the ${}^6\text{He}$ halo-nucleus with respect to the one induced by the ${}^4\text{He}$.

INTRODUCTION

In recent years, a lot of experimental and theoretical works have been performed in order to understand the role of the halo structure in the reaction induced by these nuclei at energies around and below the Coulomb barrier.

Most of the authors are in agreement that direct processes are favoured due to the low binding energy of the valence nucleons. Instead an intense debate arose about the role played by the halo structure in fusion reactions. If from one hand the presence of the diffuse halo affects the shape of projectile-target potential reducing the Coulomb barrier and enhancing the fusion cross section, from the other it is necessary to take into account dynamic effects whose role it is not yet clear.

They are due to the coupling of the relative motion of projectile and target to their intrinsic excitations or to the other reactions channels, in particular with break-up channel.

According to the Continuum-Discretised Coupled-Channel (CDCC) calculations [1,2] these dynamic effects should cause an enhancement of the sub-barrier total fusion cross-section with respect to the nocoupling case; on the other hand the high probability of the break-up process should generate a suppression of the total fusion cross-section at energies above the barrier. But not all theoretical model are in agreement with this prediction.

For example opposite results have been obtained using an approach [3] based on a time dependent wave-packet formalism the cross-section in the neutron halo case is slightly suppressed compared to the non-halo case.

The experimental investigation is quite difficult owing to the very low intensity of the available radioactive beams coupled to the difficulty of measuring fusion cross-

section at low energy for reactions induced by light projectiles. Fusion reactions induced by the 2n halo ${}^6\text{He}$ nucleus in the energy region around the Coulomb barrier are the most studied of any involving light radioactive beams [4-9], because ${}^6\text{He}$ beams are available in several radioactive beam facilities with good intensities (up to 10^7 pps). Despite of these, so far, all the authors did not reach similar conclusion about the enhancement or suppression effect on the fusion cross section due to ${}^6\text{He}$ structure. It should be noticed that the most of the existing data do not really explore the region below the barrier with reasonable errors and moreover is not always clearly discussed which is the role played in the observed final result by different static and dynamic effects.

We have performed the ${}^4\text{He}+{}^{64}\text{Zn}$ fusion reactions at the Centre of Research of Cyclotron in Louvain la Neuve (Belgium) [10-11]. From this measurement it has been concluded that no evident effects were observed for ${}^6\text{He}+{}^{64}\text{Zn}$ fusion with respect to ${}^4\text{He}+{}^{64}\text{Zn}$ within the explored energies, but we need to underline that ${}^6\text{He}$ data extend to lower energies than the ${}^4\text{He}$ ones. For this reason we decided to perform a new measurement with ${}^4\text{He}$ beam in order to extend the fusion excitation function to lower energies, to cover the same energy region of the ${}^6\text{He}$ data.

NEW ${}^4\text{He}+{}^{64}\text{Zn}$ EXPERIMENT

Experimental Technique

The new ${}^4\text{He}+{}^{64}\text{Zn}$ experiment was performed at Ruder Boskovic Institute, in Zagreb, with an average ${}^4\text{He}$ beam current of about 10^{11} pps. The reaction was measured at $E_{\text{lab}}=8.1$ MeV, 9.2 MeV and 10.1 MeV. As in our previous measurement [10-11] the fusion excitation function was performed using an activation technique. At these low energies the most part of the evaporation residues (E.R.) do not have enough kinetic energy to leave the target but by choosing a suitable target almost all of them will decay by electron capture (E.C.). It is possible to “detect” the E.R. by looking at X-ray emitted in their E.C. decay. During the irradiation time a ${}^{93}\text{Nb}$ catcher ($1000\mu\text{g}/\text{cm}^2$) is placed behind the Zn target

(550 $\mu\text{g}/\text{cm}^2$) to stop the small fraction of residues which emerges from the target.

Possible reactions induced by the beam on the ^{93}Nb catchers do not represent a problem since the X-ray energies are different to the ones corresponding to reactions on ^{64}Zn . After being irradiated the target and catcher are placed very close to the Si(Li) detector to measure the residues activity. The activated target were measured at Laboratori Nazionali del Sud for about twenty days.

Experimental Results

From the X-ray spectrum it is possible to identify different elements produced in the fusion-evaporation reaction. In figure 1 a typical X-ray spectrum for the $^4\text{He}+^{64}\text{Zn}$ reaction is shown. The two peaks correspond to the K_α and K_β X-ray emission of Zn. It is possible to discriminate the different isotope contributions by their half- lives, following the X-ray activity as a function of time.

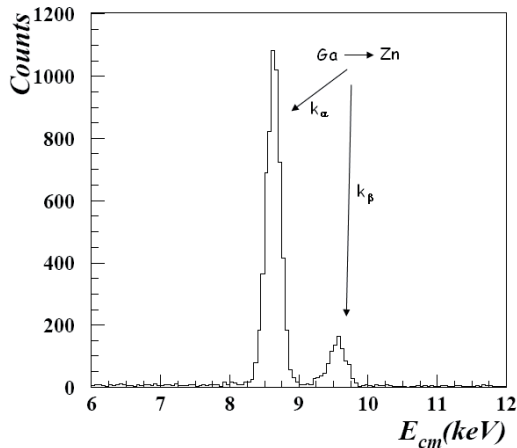


Figure 1. Typical X-ray spectra measured off-line for the reaction $^4\text{He}+^{64}\text{Zn}$. It is possible to distinguish two peaks which correspond to the K_α and K_β X-ray emission of Zn

In figure 2 the activity curve for the Ga isotope is shown. As one can see from the slope of the activity curve only the contribution of ^{67}Ga isotope is present.

By using statistical model calculation we had estimated that not only ^{67}Ga but also and ^{67}Ge should be produced in this reaction. We detected only the first one since ^{67}Ge is a shortlived nucleus ($t_{1/2}=18$ minutes) and it decays by E.C. 100% into ^{67}Ga . Therefore, after one day, time at which the off-line measurement started, we observed only the ^{67}Ga contribution which, however, is the sum of both ^{67}Ge and ^{67}Ga .

The total fusion cross section corresponds to the longer lived ^{67}Ga ($T_{1/2}=3.26$ d) cross section.

In figure 3 the preliminary data of $^4\text{He}+^{64}\text{Zn}$ (inverted triangles) are plotted together the previous data of $^4\text{He}+^{64}\text{Zn}$ [10]. The consistency of the two data sets is guaranteed by the good agreement of the points around 9.5 MeV.

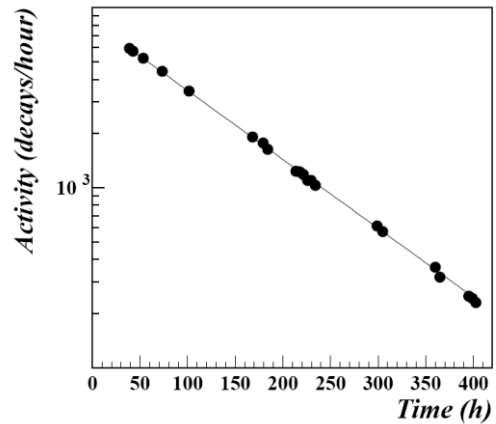


Figure 2. Activity curve for the ^{67}Ga isotope extracted in the activation run.

An enhancement of the fusion excitation functions at energies below the Coulomb barrier in the case of ^6He with respect the ^4He one is observed. The enhancement is attributed to the halo structure of ^6He , but from this it is not possible to disentangle between static and dynamic effects.

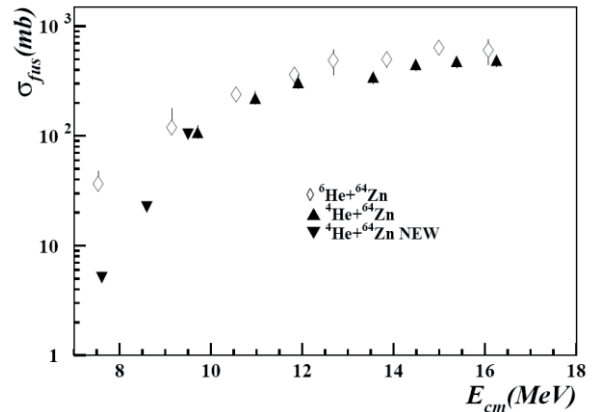


Figure 3 $^6\text{He}+^{64}\text{Zn}$ (diamonds) and $^4\text{He}+^{64}\text{Zn}$ (triangles) fusion excitation function. The ^6He and ^4He at upper energies (inverted triangles) are the data of the previous experiment [10,11]. With the closed stars are plotted the new preliminary ^4He data

CONCLUSION

Despite of a lot experiments have been performed to study the fusion mechanisms in collisions induced by halo nuclei a clear systematic behavior for all systems is not yet observed. Concerning our measurement it has been observed an enhancement of the $^6\text{He}+^{64}\text{Zn}$ fusion cross section with respect to $^4\text{He}+^{64}\text{Zn}$ at energies around and below the Coulomb barrier. This behavior it is surely linked to the halo structure of the ^6He and it seems to be correlated to static effects.

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$^{12}\text{C}+^{12}\text{C}$ fragmentation study at 62 AMeV

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Abstract – The study of fragmentation processes is relevant in different fields of physics concerning both basic research and applications. Nuclear fragmentation complicates both treatment planning for radiotherapy and spacecraft shielding design.

Hadrontherapy treatments require very high precision on dose deposition ($\pm 2.5\%$ and $\pm 1.1\text{ mm}$) to keep benefit of the ion's ballistic. The largest uncertainty on the physical dose deposition is due to ion's nuclear interaction through the traversed material. The nuclear interactions of the incident ions must also be taken into account in understanding and addressing the effects of galactic cosmic rays ions on humans and sensitive components in space. Today the simulation codes are not able to reproduce the fragmentation process with the required precision. In order to constraint the model within the codes and complete fragmentation cross section databases, experimental campaign has started since few years at LNS to study the fragmentation of ^{12}C on various target at intermediate energies. Measurements of energy and angular distributions of charged fragments, and double differential cross sections will be addressed. Preliminary results and future perspectives are reported.

INTRODUCTION

Protons and ion beams, mainly ^{12}C , at intermediate and relativistic energies are widely used nowadays for cancer treatments. Compared to conventional radiotherapy, they present two main advantages: a maximum of dose deposition at the end of their range (the so called Bragg peak) and, for ions heavier than protons, an enhanced biological effectiveness in the Bragg peak region. However along the penetration path in the patient tissue, the incident ions undergo nuclear interactions that, while reducing the number of incident ions, produce a wide

spectrum of fragments ranging from the lighter ones up to the mass of the projectile. As a consequence a non-negligible part of the dose is released in the surrounding tissues and a dose decrease into the tumor is seen, as shown in Fig.1. Normally less than 50% of the carbon projectiles actually reach the tumor in therapy, and this make very clear that a precise knowledge of the nuclear reaction effects is necessary for treatment planning [1].

Nuclear interaction in the medium substantially modifies also the radiation fields inside the spacecraft and must be carefully taken into account in design of the spatial vehicles [2, 3]. Shielding is today considered the

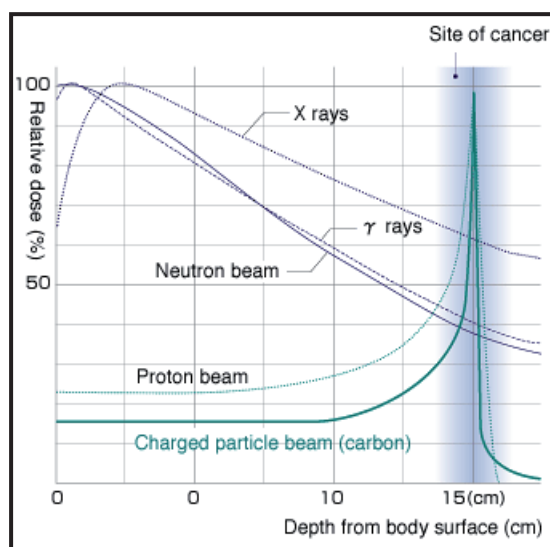


Figure 1. The relative dose produced by a carbon beam in passing through tissue compared to the dose curve of a proton beam. The absorption of beams of energetic photons (X and γ rays) and neutrons which is also shown.

only practical and effective solution to protect humans and sensitive components from some of the hazards of space radiations, the major risk for crews in interplanetary mission. Spacecraft shielding design is extremely complicated by the production of secondary fragments, including neutrons and bremsstrahlung radiations, generated in the nuclear interaction of the space radiation with the shielding material. In particular, the cascade of secondary particles can become very significant for heavy structure such as the Space Shuttle, the International Space Station, and the large observatories.

Measurements at particle accelerators can be used to evaluate fragmentation effects with well-defined beams and target with high statistics. Until few years ago, most nuclear fragmentation studies and transport models in matter were driven by the interests of the nuclear physics and later, of the hadrontherapy communities. However the experimental and theoretical methods developed for heavy ion nuclear physics are directly applicable to radiotherapy and space radiation studies. While these measurements cannot simulate the complex radiation fields found in space, they can be used to test fragmentation and radiation model performance for selected critical parameter sets.

Radiation transport computer codes, which simulate in detail the physical interactions of particles as they pass through matter, have been available for decades both in hadrontherapy and space radiation protection [4]. Such codes include deterministic codes: TRiP used by SIEMENS for hadrontherapy in Europe, HIBRAC used for carbon therapy in Japan and, HZETRN used by NASA for spacecraft shielding design; as well as Monte Carlo codes: FLUKA, GEANT4, SHIELD-HIT, and PHITS.

However the accuracy of these code is not sufficient to obtain the precision (about 2.5%) on the deposited dose required by medical and space applications; the largest uncertainty coming from the physical models and the lack in the fragment production cross sections [5].

To guarantee the reliability and predictiveness of these codes in all domain of application, check and validation on precise experimental data (energy and angular distributions and production cross-sections for all the produced fragments) of the physical models, included in the transport codes, is therefore mandatory. In this context it becomes extremely important to perform extensive measurements of ^{12}C and heavy ions fragmentation reaction especially in the energy domain where lack of data exists or where the existing data do not have the required precision.

To improve the knowledge of ^{12}C fragmentation at intermediate energies we have started an experimental campaign at LNS devoted to the measurements of production cross sections, energy spectra and angular distributions of fragments produced in ^{12}C fragmentation on thin ^{12}C , ^{197}Au and CH_2 targets. In this paper we report results on $^{12}\text{C}+^{12}\text{C}$ at 62 AMeV.

CROSS SECTIONS MEASUREMENTS OF $^{12}\text{C}+^{12}\text{C}$ REACTION AT 62 AMeV

The experiment

The aim of the experiment performed at LNS was the measurement of production cross sections, energy spectra and angular distribution of light fragments produced in the collision of ^{12}C beam on thin ^{12}C target and to compare the results with Monte Carlo simulations. The ^{12}C beam was delivered by the LNS Superconducting Cyclotron at incident energy of 62 AMeV. The detection system consisted on two Si-CsI hodoscopes with different granularity:

- 81 two-fold $1\times 1\text{ cm}^2$ of active area telescopes: 300 μm Si detectors followed by a 10 cm long CsI(Tl),
- 88 three-fold $3\times 3\text{ cm}^2$ of active area telescopes: 50 μm +300 μm Si detectors followed by a 6 cm long CsI(Tl).

Its high granularity is suitable for accurate measurements of angular distributions [6]. A typical inclusive ΔE -E plot from one of the telescopes is shown in Fig. 2. It's possible to note the excellent isotopic resolution for fragments with $Z\leq 4$.

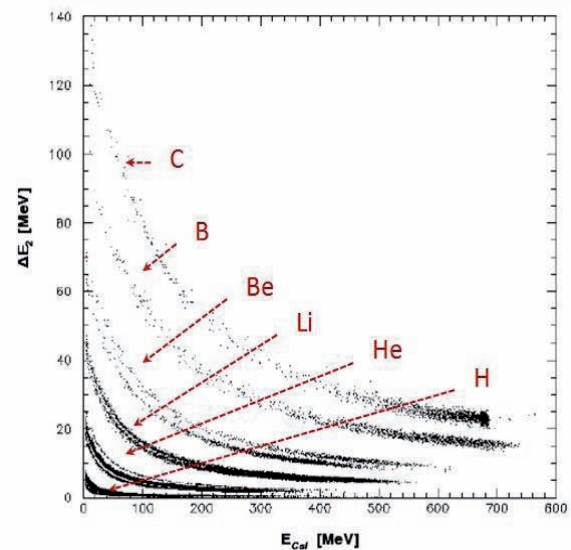


Figure 2. ΔE -E identification plot from one of telescopes.

Data analysis

Typical inclusive energy spectra for fragments detected at $\theta=2.75^\circ$ is shown in Fig.3. The data display the well-known behavior of a bump centered at the projectile's velocity which is the typical feature of pure fragmentation reactions [7, 8]. The distributions however are not completely Gaussian but show a tail towards smaller energies. The contribution of the tail appears almost

negligible at the smaller angle, but becomes larger for larger scattering angle clearly showing an increased fragment emission from nuclear sources (mid-rapidity or target-like sources) other than the projectile. As expected in the intermediate energy regime, various reaction mechanism (break-up, fusion, stripping in the continuum, deep-inelastic, etc ...) are superimposed in the energy spectra with relative contributions depending on the incident energy and target.

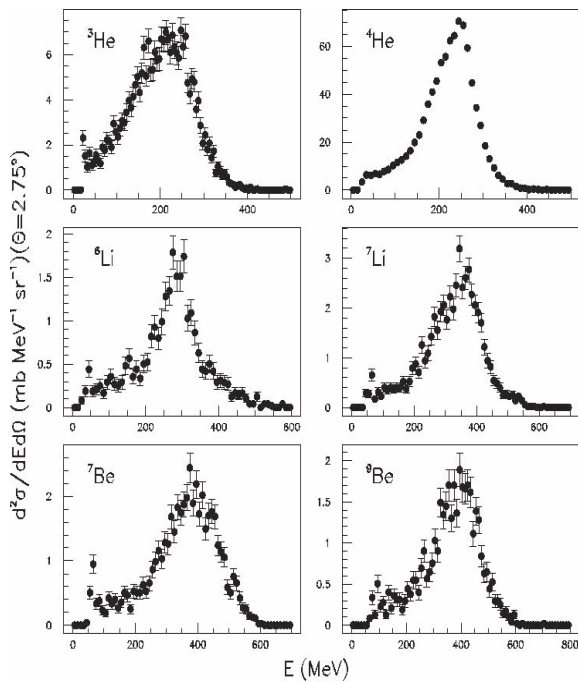


Figure 3. Double differential cross sections of fragments detected at $\theta=2.75^\circ$ with $2 \leq Z \leq 4$.

In order to gain qualitative insight and to provide reasonable extrapolation to unmeasured particle energies, the data were fitted with simple analytic functions.

Fragment kinetic energy spectra in the laboratory frame for $3 \leq Z \leq 6$ can be rather well described by the superimposition of two independent Gaussian distributions [9, 10]. The first Gaussian well reproduces the emission of a quasi-projectile source. The second Gaussian is introduced in order to obtain a satisfactory description of the energy spectra at low energy but its contribution is negligible confirming previous hypothesis.

It is not the purpose of the present investigation to provide a unique interpretation of the single-particle reaction cross sections. Nevertheless, the calculations indicate possible contributions from a number of different sources, i.e. the superimposition of different reaction mechanisms, which cannot be disentangled without ambiguity in our frame.

The angular distributions of detected fragments are shown in Fig. 4.

From the plot we can clearly see how increasing the detection angle the distributions decrease exponentially; the fragments are emitted mainly forward, in a rather small cone around the direction of the incident beam; increasing the fragments mass the distributions slope increases.

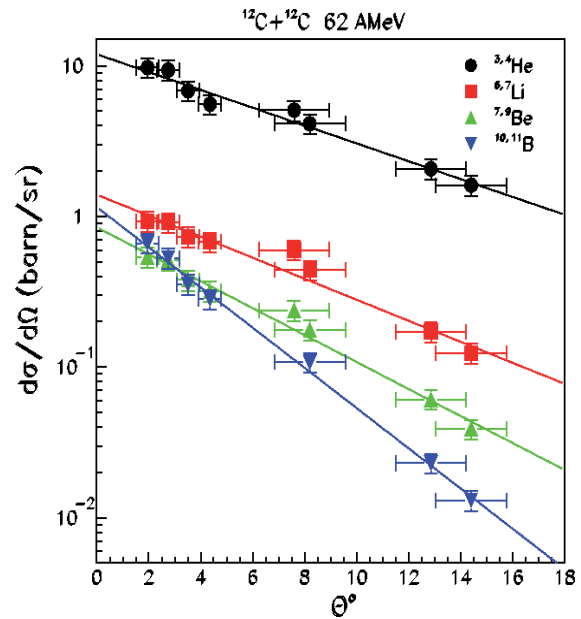


Figure 4. Differential cross sections of fragments detected between 1.45° and 14.41° in the laboratory frame.

Carlo toolkit Geant4 [11] and preliminary results are showed in Fig. 5. They have been obtained using the Geant4.9.4 version and implementing two different physics lists that use Binary Light Ion Cascade (BLI) [12] and Quantum Molecular Dynamic (QMD) [13] models for hadronic physics in the energy range of the experiment.

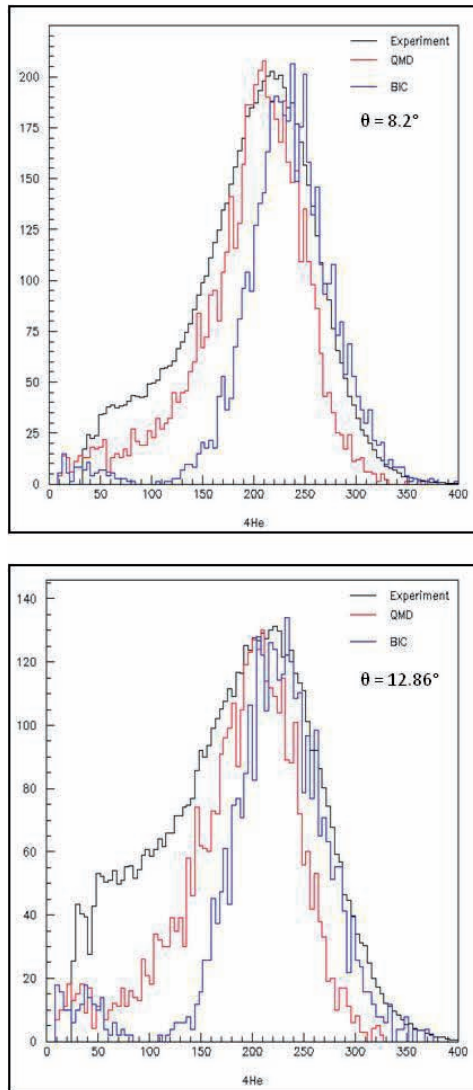


Figure 5. Energy spectra of secondary alpha produced at the polar angles 8.2° and 12.86° . The black lines are the experimental data while the red and blue lines are the simulation with QMD and BIC models, respectively.

CONCLUSIONS

A first experiment has been performed at LNS with a ^{12}C beam on thin ^{12}C , ^{197}Au and CH_2 target at incident energy of 62 AMeV and a preliminary comparison with simulations have been achieved. The energy spectra show the superimposition of different reaction mechanisms which cannot be easily disentangled.

Extensive comparisons with GEANT4 simulations will be achieved in order to evaluate the accuracy of the different hadronic models implemented in the code in the description of this intermediate energy regime. These results will allow to complete the set of fragmentation production cross-sections required at energy lower than 100 AMeV.

In order to extend the measurements to relativistic energies, our collaboration has proposed a new experiment at GSI in Darmstadt using ^{12}C beams and heavy beams in the energy range 200-1000 AMeV. This experiment, FIRST (Fragmentation of Ions Relevant for Space and Therapy), in which are involved international institution like INFN, CEA, GSI and ESA was approved by the G-PAC and scheduled for next summer.

The apparatus is a complex setup consisting on a new version of the ALADiN, MUSIC-IV, ToF, LAND devices upgraded for our specific purposes.

This multidetector device will allow to detect charge and neutral fragments coming from the projectile fragmentation. Moreover, by using the ALADiN magnet, measurements of fragment emission at zero degree scattering angle will be achieved.

The full experimental program consists on measurements of ^{12}C fragmentation at 200, 400, and 1000 AMeV, on C and Au target, ^{16}O fragmentation at 200, 400 on C target, and ^{28}Si at 500 and 1000 AMeV on C and Si targets.

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Extension and limitations of the High-Velocity Transient-Field (HVTF) technique for the measurement of magnetic moments

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Abstract - We studied the strength and the velocity dependence of the transient field (TF) at high velocities ($\sim Zv_0$). In several experiments at MSU (USA) and at GANIL (France) it has been shown that this technique can be used for g-factor measurements of short-lived states of radioactive nuclei. One advantage of the High-Velocity Transient-Field (HVTF) with respect to the standard TF technique is brought by the potential for much higher magnetic field strengths at higher velocities. Higher fields significantly increase the sensitivity, enabling the application of the method to less intense radioactive beams. However, the lack of experimental data for the characterization of the TF strength at high-velocity imposes limitations. Therefore, we carried out a study of the velocity and Z dependence of the TF strength up to $Z=36$. It was found that the behaviour of the HVTF for heavy ions does not continue the trends found for light ions with $Z < 20$. For $Z > 20$ we find a decrease of the TF strength with increasing Z at high velocity. Despite this limitation, the technique can be used for measurements of magnetic moments of states produced in intermediate-energy projectile-fragmentation reactions up to $Z \sim 36$.

INTRODUCTION

One of the most widely used methods to study gyromagnetic factors in short-lived (picoseconds) states is the transient field technique. The states of interest, usually populated via Coulomb excitation, either in conventional [1,2,3] or inverse kinematics [4,5] reactions, subsequently traverse a polarized ferromagnetic layer, in which they experience a strong magnetic field of the order of thousands of Tesla.

The strength of the transient field cannot be calculated from first principles, so several parameterizations have been proposed. Each parameterization needs to be tuned to experimental data. Most of the TF measurements up to now have been carried out under conditions where the nuclei of interest move in the ferromagnetic layer at

velocities well below the velocity of the electrons in the K-shell ($v_K = Z \cdot v_0 = Z \cdot c/137$).

The polarized electron capture model (e.g. [4,6]) proposes a parameterization based on a semiquantitative microscopic understanding of the mechanism that gives rise to the transient field. The parameterization is described by the formula

$$B_{TF} = p_{1s}(Z, host) \cdot q_{1s}(v, Z, host) \cdot B_{1s}(Z),$$

where q_{1s} is the fraction of ions carrying a single electron in the $1s$ orbital, p_{1s} is the degree of polarization of these vacancies, and $B_{1s} \sim 16.7 \cdot Z^3$ is the Fermi contact field in Tesla. B_{TF} is a function of the Z and the velocity of the moving ion, and the nature of the ferromagnetic host.

There are several compilations of transient-field strength measurements, mainly limited to velocities well below v_K . Measurements at, and above, v_K have been reported for carbon [7-9], neon [10] magnesium [11], and sulphur [12]. Apart from a measurement on Cr ions [13], for ions with $Z > 16$ there are no available measurements at high velocities. In a recent experiment performed in GANIL to measure the magnetic moment of the first 2^+ state of ^{72}Zn ($Z=30$) using HVTF [14], it has been shown that the magnitude of the measured transient field strength is ~ 10 times smaller than expected based on a naive extrapolation of the low-Z parameterizations [11]. The results from [14] show that at high velocities the TF is essentially unknown for higher Z values. Despite that, it was possible to obtain an experimental g-factor of ^{72}Zn , demonstrating that the technique remains suitable for high-velocity heavy ions up to $Z \sim 32$.

The interest in application of the TF technique to high velocities lies in the potential for higher magnetic fields than those obtained in the standard velocity regime. In particular, some radioactive species can be produced only in intermediate-energy fragmentation reactions, with the fragments moving with velocities in the high velocity regime. Higher energy projectiles also allow for the use of thicker targets and ferromagnetic layers, resulting in

enhanced excitation rates, and longer interaction intervals, which increase the sensitivity of a g-factor measurement.

EXPERIMENTAL SET-UP

The experiment consisted of two runs. The first one, (run I) carried out with a ^{78}Kr beam, used seven HPGe detectors and a circular particle detector; in the second one (run II), with a ^{74}Ge beam, eight HPGe detectors and a segmented particle detector were used. The energy of the beam was 40 MeV/nucleon for both runs, corresponding to velocities $v \sim v_K$.

The geometry of the two experiments was very similar, see Fig.1. The accelerated beam, provided by the Superconducting Cyclotron (CS) at LNS, was impinging on the gadolinium target, used both for the Coulomb excitation and as ferromagnet. In both runs, two different target thicknesses were used: a thick (197 mg/cm^2) target and a thin (79 mg/cm^2) one. In all cases the targets were cooled well below the Curie temperature. In addition, a lead/iron target ($94+91 \text{ mg/cm}^2$) was used with ^{78}Kr . For this last target, in an HVTF experiment with ^{76}Ge [14] no effect was observed, so we decided to cross-check the result. The target was polarized with an electromagnet providing a field of 1000 G. The direction of the field was reversed every 10 minutes, approximately.

The γ -radiation was detected by HPGe detectors placed in the plane defined by the beam direction and perpendicular to the magnetic field. The detectors were pointing at the target and positioned at a distance of 24 cm (20 cm during run II).

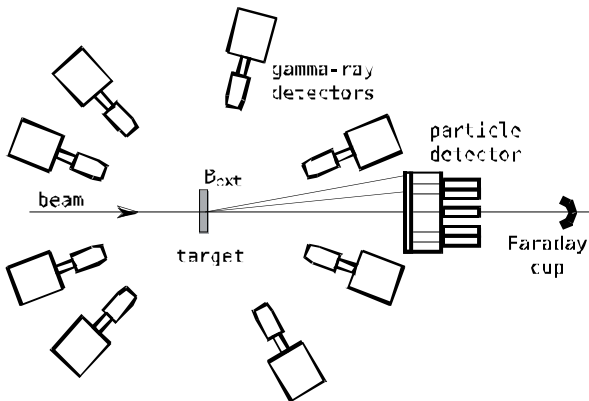


Figure 1: Experimental set-up.

The total photo-peak efficiency of the set-up was estimated with GEANT simulations to be $\epsilon_\gamma \sim 1.0\%$. In run I, six out of seven detectors were arranged in three pairs positioned symmetrically with respect to the beam direction, two at backward angles and one at forward angles, and the last detector was positioned at 60° for a better determination of the particle- γ angular correlation. During run II, the detector arrangement was kept the same and an eighth detector was added at 75° . The detector pairs were used to measure the precession effect and positioned so as to have the best compromise between the slope and the intensity of the angular correlation of the emitted decay radiation, $W(\theta)$, while the uncoupled

detectors were positioned at angles near the maximum of the angular correlation.

Downstream, an annular plastic scintillator counter was used to detect the particles scattered within the interval 4° - 6° . The selection on the particle scattering angle θ_p was performed to ensure “safe” Coulomb excitation reactions, avoiding impact parameters for which nuclear interactions between the beam and the target can occur. Consequently, the unperturbed angular correlation of the emitted radiation can be precisely determined from Coulomb excitation theory [15,16]. The main difference between the set-ups of the two runs was the particle detector. In run I, a 140-mm circular detector was used. An aluminum H-shaped mask, as shown in Fig. 2, was placed in front to protect it from direct, unscattered beam.

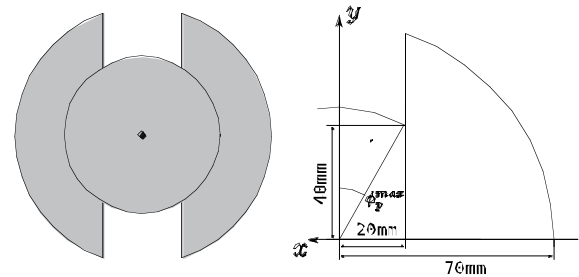


Figure 2: Particle detector mask, run I.

The mask was also used to perform a selection on the azimuthal ϕ_p angle. For run II we used an eight-fold segmented plastic detector, see Fig. 3. The segmented detector increases the count rate capability of the experiment and allows us to evaluate the extent to which measuring azimuthal angular correlations can increase the sensitivity of the HVTF method. A mask in front reduced the angular coverage of each segment from 45° to 30° , to enhance the effect of the segmentation. The annular shape allowed the beam to pass through the detector and to stop in a Faraday cup positioned downstream, far from the HPGe detectors, in order to decrease the background radiation.

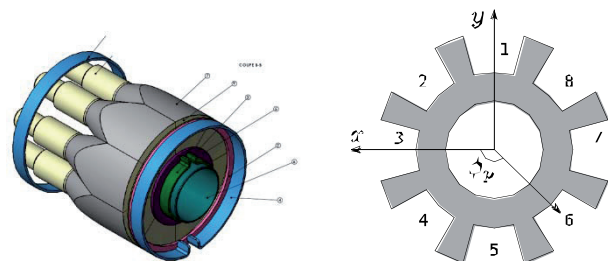


Figure 3: Segmented particle detector (left) and mask (right), run II.

A fully digital acquisition system was used, composed of five TNT2D cards. These cards were designed to work directly with the signals from the preamplifiers of the Ge detectors, sampling the input signals with a frequency of 100 MHz, corresponding to a sample each 10 ns. The

signal of the plastic detector, only a few ns wide, was shaped with a timing filter amplifier (TFA) to make it long enough to be accepted by the cards. The data acquisition was triggered by particle- γ coincidences.

The coincidence trigger ensured pure Coulomb excitation and contributed to clean the energy spectra from the random background. The time difference between the detection of the γ -ray and of the particle was calculated for each event in coincidence. Building the matrix time-difference versus Ge energy it was possible to estimate precisely the prompt conditions and to reduce the random coincidences recorded in the coincidence window. The same method was used to gate the energy of the particle detector. Multiplicity-one filter and random events subtraction following time gating was also performed. Efficiency calibration, necessary to obtain a reliable angular distribution, was performed before and after the experiment with a ^{152}Eu source positioned in the reaction chamber at the target position. The activity of the source was such that the average counting rate in the germanium detectors was ~ 1000 counts per second.

RESULTS

A thorough theoretical analysis based on the work of Alder *et al.* [15] was performed in order to predict the angular distribution of the emitted radiation $W(\theta)$ when a selection on the azimuthal angle of the emitted particle was performed. It appeared clear that under some condition the angular distribution's amplitude, and hence the sensitivity of the technique, is increased. In Fig. 4 a comparison between angular distributions with different azimuthal angles of selection is presented, together with the case where the particles are detected without selection on the azimuthal angle (i.e. the typical case of an annular particle detector).

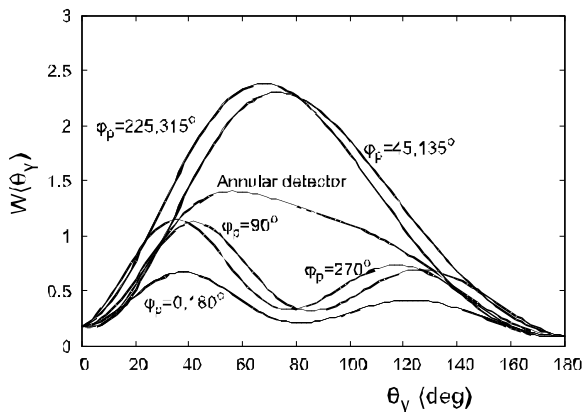


Figure 4: Theoretical angular distribution $W(\theta)$ as function of the projectile's azimuthal scattering angle (solid line). The case of no selection (dashed line) is given as comparison.

The experimental angular distribution of the emitted γ -rays is affected by recoil in vacuum (RIV) attenuations, which must be evaluated by comparison with the

theoretically calculated unperturbed angular correlation. An example is shown in Fig. 5 (^{78}Kr on 197 mg/cm 2 Gd target). A deeper analysis showed that the effect of the recoil in vacuum is much greater on the ϕ_p dependence of the angular correlation than on the familiar θ dependence.

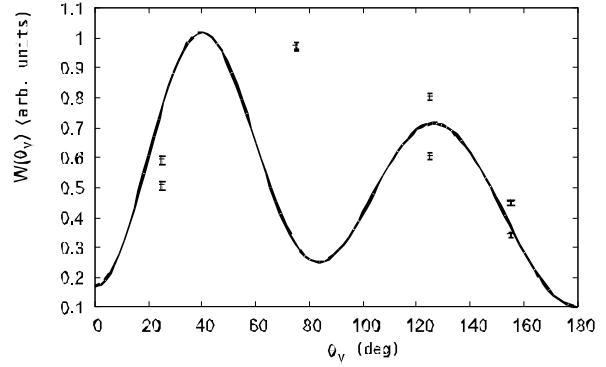


Figure 5: Angular distribution for ^{78}Kr , without RIV, theory (solid line) versus experiment (points).

A simple intuitive model can explain this effect. Coulomb excitation, under the conditions of this experiment, produces a well-oriented prolate spin distribution [17]. The angular momentum of the nuclear state is $I = 2$, while the electrons in their ground states typically have $J = 1/2$. Assuming the nuclear spins are all directed along the z -axis and that the electron spins are isotropically distributed, the resulting total angular momentum F will be directed in a solid angle with an aperture of 14° with respect to the beam axis, as illustrated in Fig. 6.

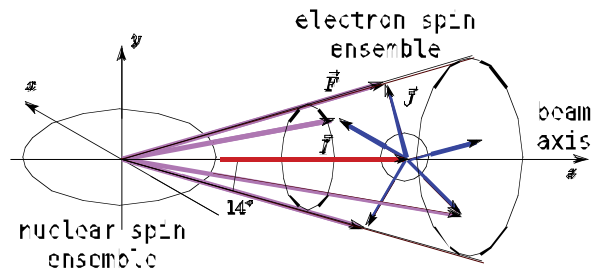


Figure 6: Recoil-in-vacuum (RIV) effect on θ and ϕ .

This angle is small enough to allow us to consider that, as a first approximation, the precession due to the RIV hyperfine fields is around the z -axis. According to this assumption, each ion exiting from the target will be rotated about the z -axis at a random angle ϑ . If we assume that an angle $\vartheta = \pi$ rad is enough to wash out completely the sensitivity of the angular distribution to the angle ϕ , we infer that fields of ~ 10 kT will wash out the ϕ dependence for states that live about 20 ps. For a nucleus with $Z = 36$ the hyperfine fields for ns electrons up to $n = 5$ are strong enough to have a destructive effect on the ϕ dependence of the angular correlation (see Table 1).

Table 1: Hyperfine fields at the nucleus, in kT

n	1	2	3	4	5	6
B_{ns}	780	97	29	12	6	4

Despite its crudeness, this model gives a physical motivation to assume the dependence on the azimuthal ϕ angle is completely lost. In terms of a more conventional analysis in terms of the vacuum attenuation coefficients G_2 and G_4 , the ϕ dependence is lost because it is much more sensitive to the G_4 term in the angular correlation than the G_2 term, and the hard core values of G_4 are always much smaller than G_2 . In contrast, the usual θ correlation is insensitive to G_4 and determined predominantly by G_2 .

We thus explain the disagreement between the theoretical angular distribution and the experimental results shown in Fig. 5. The angular distribution shown in Fig. 7 was calculated averaging on the ϕ angle, i.e. like in the case of an annular particle detector. The so obtained theoretical curve is in good agreement with the experimental points.

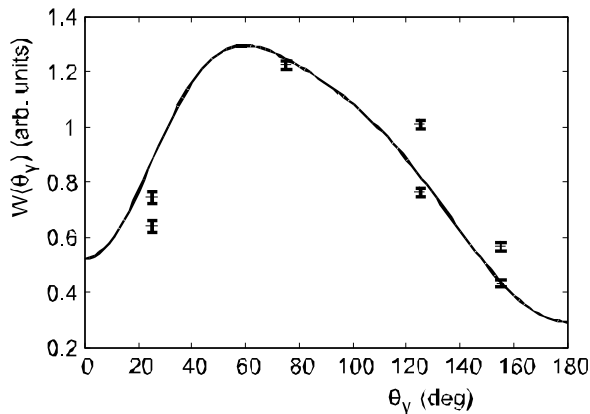


Figure 7: Angular distribution for ^{78}Kr , theory (solid line) versus experiment (points), with effects RIV included.

We can place a limit on the transient field strength for the krypton in gadolinium. From the analysis of the results obtained using germanium and zinc as probes [14] a new parameterization of the polarization p_{1s} is suggested. There is a strong indication that the polarization drops very fast as the Z of the projectile increases. From this new insight the estimated precession angle for ^{78}Kr with the thick Gd target is ~ 10 mrad, which is at the observation limit with the available statistics.

The TF strength for ^{78}Kr using iron as ferromagnetic material was measured to be 0 ± 220 T, in line with the result in [14]. This result is important for the use of the TF technique for heavy ions at high velocities: iron is not a suitable ferromagnetic host for heavy ions at high velocities.

CONCLUSIONS

We have demonstrated the validity and the limits of the high velocity transient field technique for measuring magnetic moments in radioactive nuclei up to the $Z = 30$

region. The importance of the recoil-in-vacuum effect on azimuthal angular correlations has been evaluated. Nevertheless, in some situations the RIV effect is absent, e.g. when the probe is decaying inside the target. This is the case for probes with very short life times and/or thick targets. Such is the case for the 2^+_{11} states of the stable even Ni isotopes, which were already measured, or the 2^+_{11} state of the supposedly doubly magic ^{68}Ni . When such radioactive isotopes become available with sufficiently high intensities, the HVTF technique could take advantage of considerably enhanced sensitivity from the measurement of azimuthal angular correlations.

The null result for the iron ferromagnetic target, already observed in another HVTF experiment with heavy ions [14], was confirmed. The reason for such behavior is still to be investigated, but it must stem from the polarization transfer mechanism [19], and may have the same origin as the lower than expected fields observed in the gadolinium target.

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Measurement of neutron production yield by absorption of protons on a thick Beryllium target

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Abstract - In the framework of research on generation IV reactors, it is very important to have the opportunity of using infrastructures specifically dedicated to the study of fundamental parameters in dynamics and kinetics of future, fast-neutron based, reactors. A low power prototype neutron amplifier that could be used within a research facility was recently proposed by INFN. It is based on a proton beam impinging on a thick Beryllium converter that produces a fast neutron spectrum. The amount of data about neutron production yield from thick Beryllium targets is rather scarce in the range 4.5-113 MeV proton energy, with only a few distributions measured. Therefore, it is important to measure the neutron yield from Beryllium at energies as close as possible to the 70 MeV foreseen for the neutron amplifier project. In this report we briefly describe a feasibility test performed in 2010 at the E x-Neutroni (MEDEA experimental area) beamline of the LNS.

SCIENTIFIC GOALS

Since long time, new systems for producing energy via nuclear reactions have been proposed, the so-called Accelerator Driven Systems (ADS), where a subcritical fission reactor core is coupled to an external neutron source, such as the one obtained by impinging a proton, deuteron, or ion beam on a thick target where the projectile is fully absorbed. Since neutrons emerging from the target have a fast spectrum with typical kinetic energies covering sub-MeV until hundreds of MeV, depending on the beam energy, it is natural to couple the neutron source to a fast reactor core. Such a system presents several advantages, among which one can mention the intrinsic safety due to the fact that the reactor core power will automatically vanish by just switching off the neutron source, i.e. the beam. Moreover, the fast neutron spectrum allows to study kinetics and dynamics of a low power fast reactor core as well as radioactive waste burn-up by fission and transmutation by neutron capture.

Based on this perspective, a subcritical fast reactor core based on Uranium Oxide rods enriched with 20 % ²³⁵U, with solid lead as diffusing medium and helium gas as a coolant, coupled to a 70 MeV proton beam at a current of about 1 mA produced by a commercial cyclotron, has been proposed within INFN in cooperation with the Ansaldo Nucleare company [1]. For this project, a Beryllium target has been proposed as the proton-to-neutron converter. Preliminary simulations performed with the MCNPX simulation codes resulted, for 1 mA continuous beam current at 70 MeV proton energy, in a thermal power of about 200 kW. The proton energy and current were chosen based on the ongoing procurement of a commercial cyclotron of 70 MeV energy and about 1 mA current, that will be installed at the INFN Legnaro laboratory. The cyclotron will be used as driver of SPES, a research facility for the production of radioactive ions already foreseen in the INFN scientific plan. The cyclotron is foreseen with two extraction points and therefore it may be also used simultaneously as driver of the above mentioned neutron amplifier. In order to validate calculations of the primary neutron flux and energy and therefore of the system power by codes like MCNPX [2], accurate data on the neutron yield from a thick Beryllium target are needed. In the region 4.5-113 MeV, the available data are limited to [3-8] and therefore the scarcity of points for many angles and energies calls for a dedicated measurement.

TEST RUN

During 2009 -2010, this collaboration decided to perform a test run to explore the feasibility of such measurements at LNS. The purpose of the test run was to study backgrounds in the experimental room, test the feasibility of the Time-of-Flight technique, and choose the best suited detector between simple plastic scintillator (with no neutron-gamma PSD) and liquid

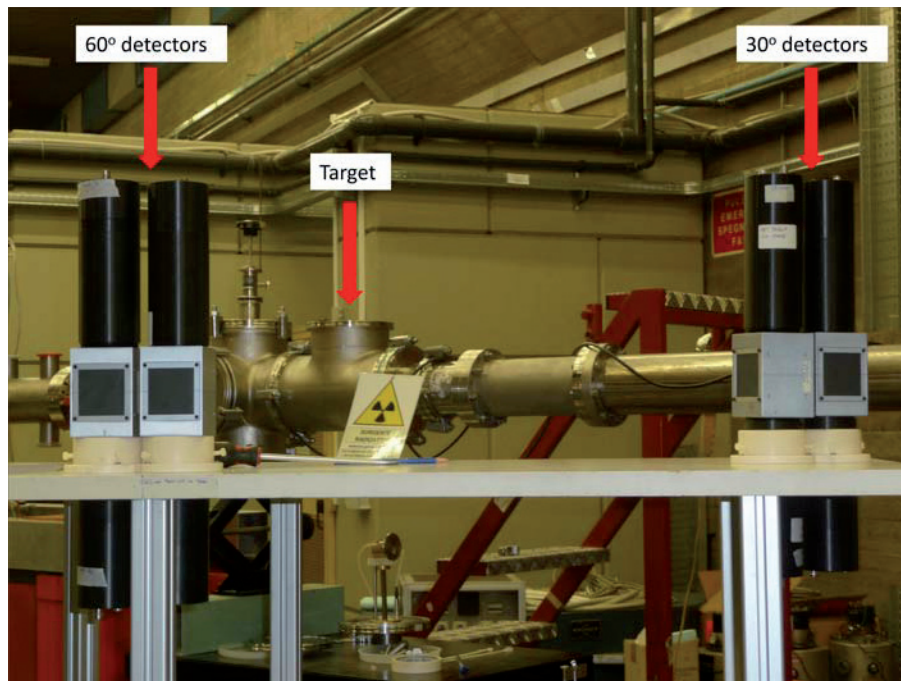
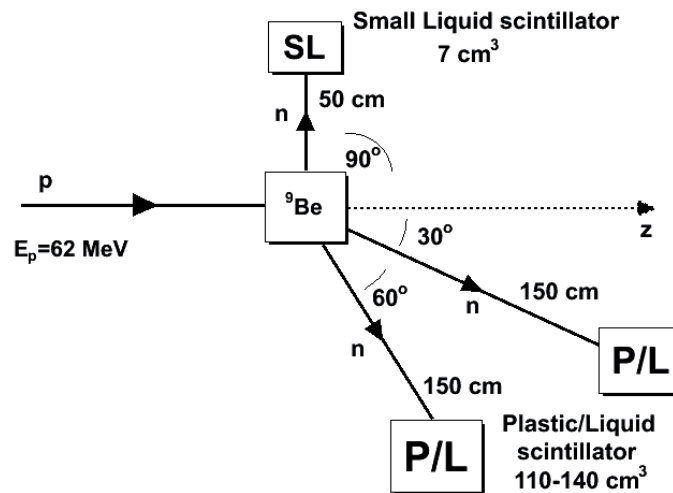


Figure 1: A graphical view (top) and a photograph (bottom) of the test run setup

scintillator (with PSD). As target, we used a Beryllium cylinder with 30 mm thickness and 35 mm diameter. The beam current was read out from the target itself via a direct electrical connection to a current integrator and found in agreement with the current measured by an upstream movable Faraday Cup.

The test was conducted between July 19 and 22, 2010. Fig. 1 is illustrating the experimental setup used in the test. The SC delivered 62 MeV protons at a current ranging between 50 and 100 pA. Four bunches every five were suppressed to obtain a beam period of 125 ns instead of the intrinsic 25 ns. As a compromise between minimizing the minimum kinetic energy for which the TOF is correctly measured and keeping the DAQ dead

time within 10-20 %, a distance of 150 cm from the target was chosen, leading to a minimum kinetic energy (corresponding to the maximum measurable TOF) of 0.75 MeV. At this distance, the TOF of the fastest neutrons is 14 ns, while the photon TOF is equal to 5 ns. Two plastic/liquid scintillator pairs were initially installed at this distance and at 30° and 60° with respect to the beam direction, then one of the pairs was moved to 90° to measure spectra at that angle as well. A smaller liquid scintillator cell was instead placed at 50 cm distance and at 90°, leading to a minimum kinetic energy of 85 keV. At this distance, the TOF of the fastest neutrons is 5 ns, while the photon TOF is equal to 2 ns. Therefore, with a typical expected TOF resolution of less than 2 ns FWHM,

prompt gammas directly produced in the target are very well separated from the fastest neutrons at 150 cm distance and still rather well separated at 50 cm distance. On the other hand, the prompt gamma peak can be used to precisely establish the absolute time scale in the system. On average approximately, we ran at a single detector rate of 1.5 to 1.8 kHz and a total rate for five detectors of 8 kHz with a global dead time of 18 %. We later found out and eliminated one source of overhead in the DAQ so that at the same total rate the dead time in future measurements will be about 11 %. In summary, we accumulated 4-5 million events per detector in less than an hour, resulting in percent statistical errors in the less populated high energy bins.

Results from the test run

The test run was very successful as we were able to measure the neutron yield as a function of the kinetic energy at all three above mentioned angles. Moreover, several important points were investigated and clarified[9]. They are summarized here and further discussed below

- first of all, the feasibility of the measurement using a simple apparatus based on organic scintillators to measure both the TOF and the deposited energy has been shown
- the experimental backgrounds were measured by means of a "shadow bars" and were shown to be dominated by out-of-time photons produced by neutron interaction with the surrounding materials, most notably the beamline
- the advantage of using liquid scintillators that permit a further reduction of the background by means of the neutron/gamma PSD
- the feasibility of the current measurement from the target by means of a good electrical insulation and an appropriate current integrator

Experimental backgrounds

Backgrounds in the experimental room were measured by means of a "shadow bar". The shadow bar assembly comprised a paraffin-boron bar followed by lead blocks. The bar was a parallelepiped with a square 7x7 cm² base and 50 cm height, and featured alternate paraffin and boron layers, with an overall 10 % Boron in weight. The bar was placed horizontally, so that neutrons and photons were crossing 50 cm of the material. Following the bar, we placed 10 cm lead in form of blocks. Simulations indicated that this assembly could reduce both direct neutrons and photons from the target to the percent level (including in the surviving particles also secondaries produced in the shadow bar itself), thereby allowing to measure amounts of background above the percent level.

Backgrounds in the experimental room were measured to be at the level of about 20 to 30 %. In the analysis of the test run, such background was simply subtracted from the data.

Neutron/gamma separation

In the case of liquid scintillators, we performed the analysis of "fast" and "total" signal to achieve some degree of neutron/gamma separation through PSD. Fig. 2 reports two typical PSD plots, where again the vertical axis represents the area obtained from integrating the detector pulse in the ADC from the leading edge up to approximately its maximum, while the horizontal axis represents the total area of the signal. The two bands corresponding to neutrons and photons are clearly distinguished. For the bigger cell a third band below the neutron one shows up, presumably being due to α particles being produced by energetic neutrons interacting with carbon nuclei in the scintillator. The latter were therefore included in the neutron sample.

By closer inspection, we estimated that neutrons and gammas are separated at $\geq 3-4 \sigma$ level down to about 800 keVee for the big liquid scintillators, and 300 keVee for the small liquid scintillator. This means that we could

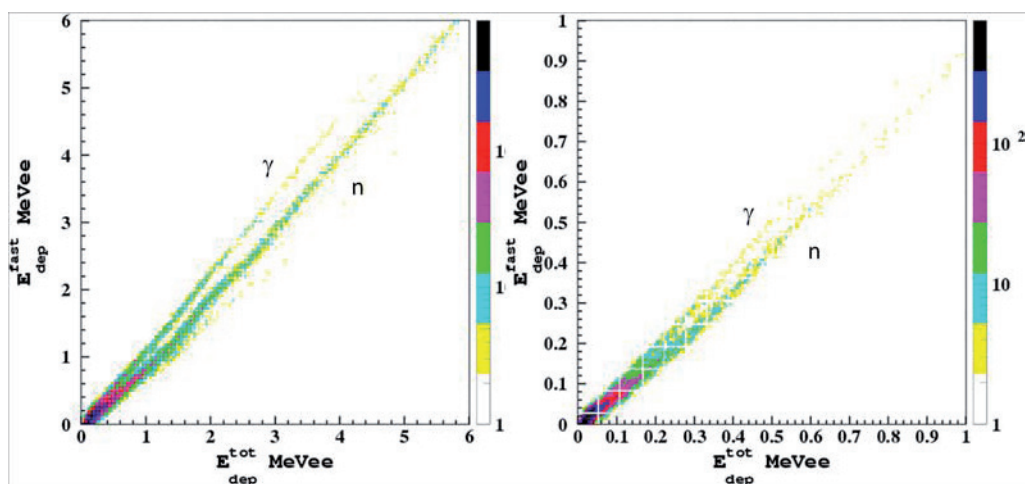


Fig. 2. “Fast” versus “total” pulse components converted to MeVee for the big liquid scintillator at 60° (left) and the small one at 90° (right). The neutron and gamma loci are indicated. In the left plot, there seems to be a third locus presumably corresponding to α particles.

safely clean up the neutron sample from the gammas down to about 4 MeV kinetic energy for the big scintillators and down to about 2.5 MeV for the small one.

The separation depends critically on the amount of collected light, the signal to noise level in the transmission of the pulse from the detector to the front-end electronics and the ADC relative resolution. Therefore, for future measurements the separation at low energies could be improved by using one more detector

setup at a smaller distance, by increasing the PMT gains and possibly by using current amplifiers to boost the signals and reduce the noise even further.

One final important point is that the PSD analysis allowed to conclude that 80-90% of the physical background as measured by means of the shadow bars is given by gammas. Monte Carlo studies indicated that this can be attributed to the neutron interactions with the steel

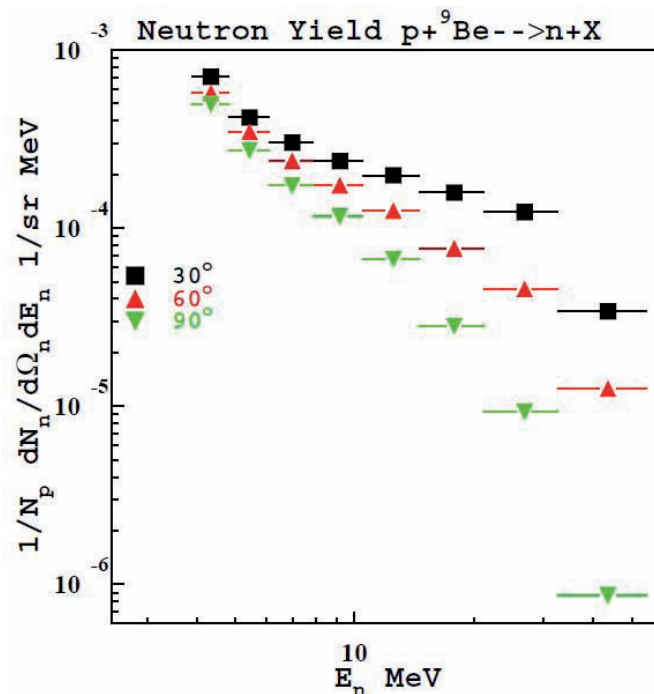


Fig. 3. Final neutron yield per solid angle and per kinetic energy bin as obtained from the analysis of the liquid scintillator data in the test run.

beamline. It was seen that background gammas are also present underneath the neutron spectrum, which is presumably due to neutrons hitting the support table and the floor, surfaces that are closest to the detector, in which case the TOF will resemble that of a true neutron event. Further reduction of the material budget in the support structure is therefore one additional improvement indicated by our test run.

Final results

We report in Fig. 3 our final results for the neutron yield per solid angle and per kinetic energy bin, normalized to the number of incident protons, obtained from the liquid scintillator analysis and after background subtraction. A similar analysis on the plastic scintillator provided data compatible within the systematic errors

with those from the liquids. However, the liquids clearly have the advantage of the neutron/gamma separation, thereby reducing the amount of background to subtract. As one can see, the data show the expected trend in that the endpoint is decreasing with the angle and the data at different angles converge to similar values in the MeV region. We estimated systematic errors in the test run data to be in the order of 20-30%.

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Competition between fusion-evaporation and multifragmentation in central collision in $^{58}\text{Ni}+^{48}\text{Ca}$ reaction at 25 AMeV

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Abstract – The main features of the reaction products in $^{58}\text{Ni}+^{48}\text{Ca}$ central collisions at $E_{\text{lab}}(\text{Ni})=25$ AMeV have been analyzed in order to investigate the competition of different reaction mechanisms. In particular, some global observables and their correlations, able to characterise the pattern of central collisions, have been constructed, in event-by-event mode, in order to disentangle about the competition between residues of fusion-evaporation processes and clusters produced by the decay of a well defined (if any) transient nuclear system undergoing multifragmentation. The description of the method adopted to select central collisions and some new results are presented. The data were collected by using the CHIMERA 4 π device.

INTRODUCTION

Heavy Ion collisions in the Fermi energy domain are characterised by the coexistence of the one-body (mean field) and the two-body (nucleon-nucleon) dissipation. In particular, in this paper we explore central collisions where the formation of single highly excited sources are expected. The region of small impact parameter at

intermediate energies is of great interest, because it allows to investigate the competition between fusion-evaporation processes, in which an heavy residue is observed in the exit channel as a result of statistical sequential decay process of a compound nucleus, and the so-called multifragmentation prompt decay in several fragments of intermediate masses by a transient unstable system at sub-saturation nuclear density [1].

EXPERIMENT

The experiment was performed at the INFN-Laboratori Nazionali del Sud, with ion beams of ^{58}Ni accelerated at 25 AMeV by the LNS Superconducting Cyclotron against self-supporting ^{48}Ca target, embedded between two carbon foils in order to reduce their oxydation. The emitted fragments were detected by the CHIMERA 4 π multidetector [2], consisting of 1192 Silicon-CsI(Tl) telescopes arranged in 26 rings covering 95% of the total solid angle. Events were registered when the Silicon detectors of at least two telescopes were fired. In order to reject incomplete or incorrectly reconstructed events we have chosen to analyze only those events where the total detected charge ranged between the 70% and 105% of the total incoming charge; the same condition was imposed to

the total longitudinal momentum (i.e. projection of the total momentum along the beam axis) respect to the linear momentum of the projectile.

EVENT SELECTION METHOD

Since we are interested to central collisions, the first part of the analysis was devoted to the choice of the selection method. A crude selection on the particle multiplicity of charged particles is not able to fully disentangle central collisions from more semi-peripheral ones; a much better

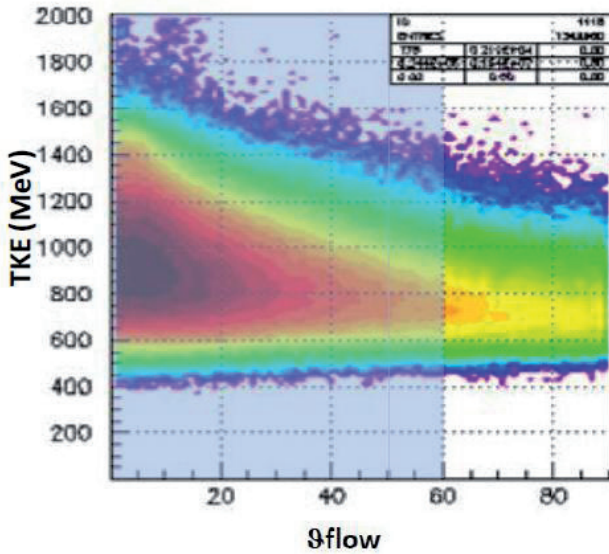


Fig.1 Correlation between 9-flow angle and total kinetic energy for all complete events. The obscured zone reflects events that we discard in our analysis.

observable to select central collision is obtained by means of cuts on Total Kinetic Energy (TKE) and 9-flow angle correlation [3,4]. Fig.1 shows such a correlation between 9-flow angle and the TKE for all the selected events. 9-flow gives the orientation of the principal axis of the ellipsoid momentum-tensor with respect to the beam direction. In fig.1 the TKE is calculated as sum of the kinetic energies of all detected particles. The less dissipative collisions are cut-off from our selection of centrality by selecting events having 9-flow > 60°.

FUSION-EVAPORATION AND MULTIFRAGMENTATION EVENTS

To better characterize these central events we performed a correlation between the longitudinal component (i.e. along the beam axis) of velocity, v_{par} , and the mass for both fragments, which we denote as IMFs (fragments with $Z \geq 3$), and light particles emitted. This correlation is shown in fig.2 for the reaction in study.

In this figure we can clearly see an abundant presence of heavy fragments with mass around 60-70 amu and longitudinal velocity close to centre of mass velocity ($v_{cm} = 3.8$ cm/ns). This fragments are good candidates for representing evaporation residues.

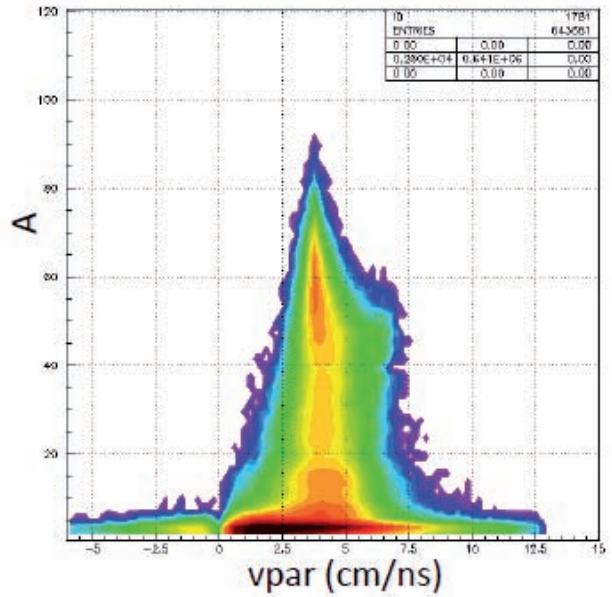


Fig.2 Correlation between the longitudinal component of velocity and mass for charged particles detected in selected central events.

In order to isolate and to elucidate better this contribution to the emission of fragments and to understand the origin of the events characterized by presence of this heavy fragment, in fig.3 the same correlation of fig.2 is shown for the largest fragment present in each event.

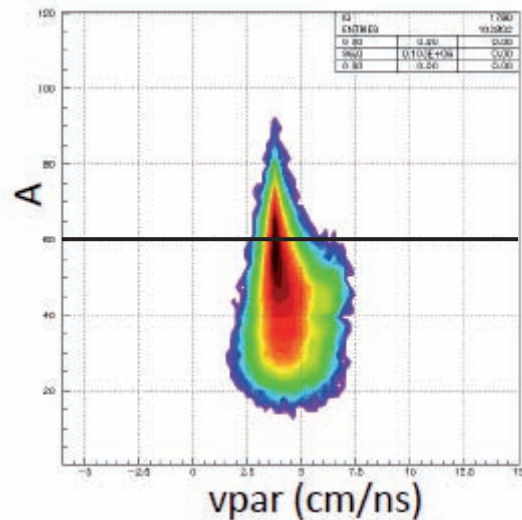


Fig.3 Longitudinal velocity-mass correlation for the biggest fragment emitted in central collisions.

Our analysis shows that the biggest fragment with mass 60 uma or larger is preferentially emitted together with light particles (3-4) and a few lighter fragments. This behaviour can be deduced through the fig.4a-b, where the IMF and light particle multiplicities, M_{IMF} and M_{LP} respectively, are shown for events in the upper part of fig.3, and confirmed in fig.4c, where the mass

distributions of the three biggest fragments for the same events are reported.

Therefore, we interpret events with such a big residue as formation of an equilibrated compound system of primary mass evaluated around 75-80 amu, which sequentially evaporates light particles.

These events constitute an important contribution of the total selected events, classified as “central collision events”. Quantitative evaluations to quote the associated cross sections are in progress.

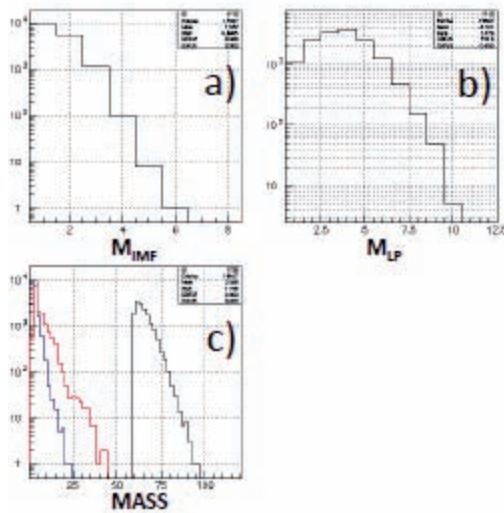


Fig.4: IMF (a) and light particle (b) multiplicity for central events where the biggest fragment has mass larger than 60 amu. c) Mass distributions of the three heaviest fragments emitted in the same events.

Among the events in the lower part of fig.3 (i.e. events where the biggest mass is less than 60 amu), there are candidates for multifragmentation-like phenomena of an highly excited source formed in central collisions. We made a further selection of these events by imposing cuts on high values of fragment multiplicity M_{IMF} .

We notice that, in such events, the probability for the presence of massive fragments is still not vanishing. However, as the multiplicity M_{IMF} is increased, the mass distributions of the three biggest fragments in each event show the characteristic features of typical multifragmentation events with the tendency towards the splitting of the system in fragments with equal masses.

In fig.5 the mass-distributions of these three biggest fragments are reported, for $M_{IMF} > 4$. However, further studies are required to sign unambiguously the origin of these fragments. The analysis is in progress.

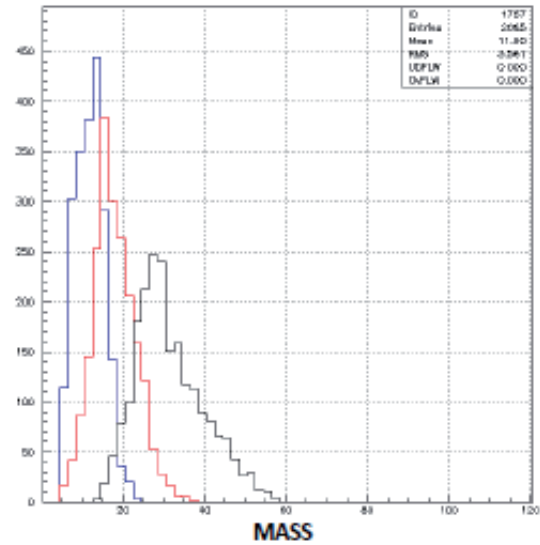


Fig.5: Mass distributions of the three heavier fragments emitted for $M_{IMF} > 4$ (see text).

CONCLUSIONS

We report preliminary results about experimental features of fragments produced in central $^{58}\text{Ni}+^{48}\text{Ca}$ collisions at 25 AMeV, performed at LNS by using 4π CHIMERA multidetector.

The adopted selection method for central collisions is discussed, and different observables and correlations have been analyzed in order to study the competition among different reaction processes. In particular mass and velocity distributions of the emitted fragments and some global variables like multiplicity of IMFs and light particles, theta flow angle, kinetic energy loss, have been analysed in order to characterize the selected events.

Our analysis, still in progress, is mainly devoted to disentangle fusion-evaporation from multifragmentation of sources formed in central collisions.

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Evidences of quasi-free mechanism in the ${}^9\text{Be}(d,d^8\text{Be})n$

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Abstract - The simultaneous study of light elements abundances lithium, beryllium and boron (LiBeB) in the stellar atmospheres could give several information about some not yet well understood “mixing mechanism” of stellar plasma in such environments. Due to these process, LiBeB can be transported to the region where (p,α) reactions represent the main channel for their destruction and therefore precise measurements of their burning cross-sections are needed. The ${}^9\text{Be}(p,\alpha){}^6\text{Li}$ and ${}^9\text{Be}(p,d){}^8\text{Be}$ reactions were studied through the THM by selecting the quasi-free contribution of the p-induced reactions on ${}^9\text{Be}$. The preliminary results are here presented.

INTRODUCTION

The understanding of stellar internal structure and mixing mechanism via light-element depletion is enhanced by abundance determinations of more than one of the trio Li, Be and B. These isotopes are destroyed by nuclear fusion reactions at different depths inside stars corresponding to temperatures near $2.5 \cdot 10^6$ K for Li, $3.5 \cdot 10^6$ K for Be and $5 \cdot 10^6$ K for B. Thus the surface zone in which each element is preserved have different dimension; the amount of each element remaining on the stellar surface indicates the nature of the mixing and how deep the mixing has been [1,2]. Due to these process, LiBeB are then transported into the regions where they are mainly destroyed via the (p,α) channel, with a Gamow energy E_G of few keV's. These energies are low if compared with the Coulomb barrier E_C , usually of the order of MeV's, thus implying the reactions take place via tunnel effect with an exponential decrease of the cross section,

$$\sigma(E) \propto \exp(-2\pi\eta)$$

(where η is the Sommerfeld parameter). Due to the exponential suppression, the behavior of the direct cross sections at astrophysical energies are usually extrapolated from that at higher energies by using the definition of the astrophysical factor

$$S(E) = E\sigma(E)\exp(2\pi\eta) \quad (1)$$

which, for non resonant reactions, varies smoothly with energies. Nevertheless this extrapolation procedure can introduce some uncertainties due, for example, to the presence of unexpected sub-threshold resonances or electron-screening effects [3].

However, in recent years, many indirect methods have been developed in order to extract the $S(E)$ -factor without extrapolations. In particular the THM [4-6] is a powerful tool which selects, under appropriate kinematical conditions, the quasi-free (QF) contribution of a suitable three-body reaction performed at energies well above the Coulomb barrier to extract a charged particle two-body cross section at astrophysical energies, free of Coulomb suppression.

The study of the ${}^9\text{Be}+p \rightarrow {}^8\text{Be}+d$ reaction (the major Be-burning channel in astrophysical environments together with ${}^9\text{Be}(p,\alpha){}^6\text{Li}$, already studied via THM in [7]) requires as a primary step the study of the presence and possible discrimination of the quasi process in the $d({}^9\text{Be},d^8\text{Be})n$ three body reaction.

THE EXPERIMENT

Trojan Horse Method (THM) was successfully applied to study several astrophysically relevant two-body reactions by using appropriate three-body break-up reactions. The method has proven to be particularly suited for acquiring information on charged-particle induced reaction cross-sections at astrophysical energies, since it allows to overcome the Coulomb-barrier of the two-body entrance channel. One can briefly describe the method as follows (more details can be found in refs. [4-6]). A projectile a strikes a target nucleus A , whose wave function has a large amplitude for a s - b cluster configuration. Under proper kinematical conditions, the particle a interacts only with the part b (participant) of the target nucleus A , while the other part s behaves as a spectator to the process $a+b(+s) \rightarrow c+d(+s)$ (quasi-free

mechanism). In order to completely determine the kinematical properties of the spectator s , the other two particles have to be detected and identified and their energies and angles of emission measured. Since the bombarding energy is chosen in order to overcome the Coulomb barrier in the entrance channel for the $a+A \rightarrow c+d+s$, the particle b can be brought into the nuclear field and to induce the $a+b \rightarrow c+d$ reaction. Moreover, assuming that the beam energy can be compensated for by the $b+s$ binding energy, the two-body reaction can take place at very low $a-b$ relative energy, e.g. in the region of astrophysical relevance.

In the plane wave impulse approximation the three body cross section can be expressed as:

$$d\sigma/dE_c d\Omega_c d\Omega_d \propto (KF) |\Phi(p_s)|^2 d\sigma^N/d\Omega$$

where KF is a kinematical factor containing the final state phase space factor, $|\Phi(p_s)|^2$ is the momentum distribution of the spectator s inside A , and $d\sigma^N/d\Omega$ is the differential nuclear cross section for the two body reaction $a+b \rightarrow c+d$.

The study of this reaction continues a long and fruitful sequence of measurements which started for the ${}^9\text{Be}(p,\alpha){}^6\text{Li}$ at LNS in 2003 and ended in 2008 at LNS with an additional experiment in CIAE Beijing in 2007 [7]). In order to have a complete knowledge of the two channels which dominate the ${}^9\text{Be}$ burning in stellar environments the study of the ${}^9\text{Be}(p,d){}^8\text{Be}$ reaction is required.

Data for ${}^9\text{Be}(p,\alpha){}^6\text{Li}$ clearly show that direct data are reproduced at higher energies and that in the low energy range the electron screening effect is present. THM data allowed us to measure the electron screening potential $U_e = 676 \pm 86$ eV much larger than the adiabatic limit. The results are shown in picture 1.

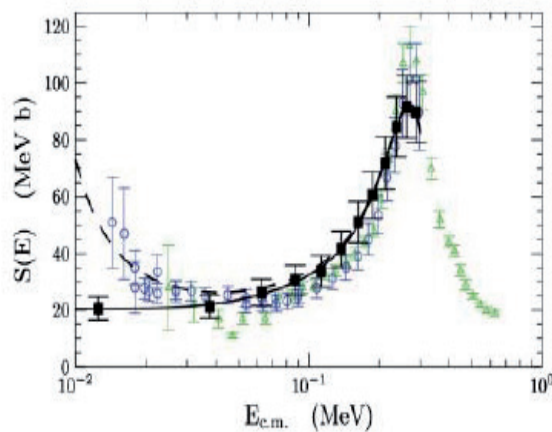


Figure 1: ${}^9\text{Be}(p,\alpha){}^6\text{Li}$ studied via the THM applied to the ${}^2\text{H}({}^9\text{Be}, {}^4\text{He}{}^6\text{Li})n$ [11]. THM data (full squares) are compared with the direct ones

The experiment $d({}^9\text{Be}, d){}^8\text{Be}n$ was performed at the LNS INFN in Catania. The Tandem Van de Graaf

accelerator provided a 22 MeV ${}^9\text{Be}$ beam with a spot size on target of about 1 mm and intensities up to 1 nA. A deuterated polyethylene target (CD_2) of about $150 \mu\text{g}/\text{cm}^2$ was placed at 90° with respect to the beam axis direction. The detection setup consisted of two $1000 \mu\text{m}$ PSD1 and PSD2 aimed to detect the deuterons and a Dual Position sensitive detector (DPSD) system suited for ${}^8\text{Be}$ detection. The PSD1 and PSD2 was placed at a distance $d_1=250$ mm from the target, covering the angular range 5° - 16° and 20° - 31° . The DPSD, devoted to ${}^8\text{Be}$ detection, was placed in opposite side with respect to the beam direction at a distance $d_2=246$ mm from the target, covering the angular ranges 5° - 17° . The displacement of the experimental setup (sketched in fig.2) was chosen in order to cover the whole QF-angular range, known “a priori” from a Monte Carlo simulation. The trigger for the event acquisition was given by the coincidence between PSD1 or PSD2 and the DPSD. Energy and position signals for the detected particles were processed by standard electronics and sent to the acquisition system for on-line monitoring.

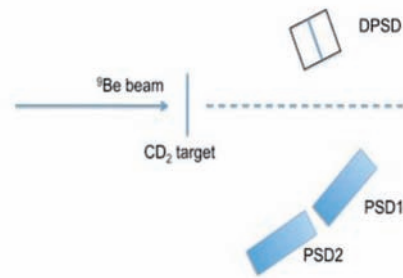


Figure 2: Sketch of the experimental set-up described in the text.

DATA ANALYSIS

The position and energy calibration of the detector involved were performed by using the data from different reactions and ${}^{197}\text{Au}({}^6\text{Li}, {}^6\text{Li}){}^{197}\text{Au}$ reactions induced at a beam energy of 10 MeV and 16 MeV. A standard alpha-source of 5.48 MeV was further used for the calibration of the low-energy region in the detectors.

The ${}^8\text{Be}$ particles were selected on DPSD system while no identification was needed for the alpha particles on PSD1 and PSD2. The relative energy of the two alphas detected on DPSD (arising from the ${}^8\text{Be}$ decay) was reconstructed using standard kinematics. A peak around -90 keV shows up and it is due to that decay (fig. 3). For the further analysis only the ${}^8\text{Be}$ particles, thus identified, were used.

After such ${}^8\text{Be}$ selection the kinematic locus of ${}^8\text{Be}$ vs. proton energy is studied and plotted in figure 4.

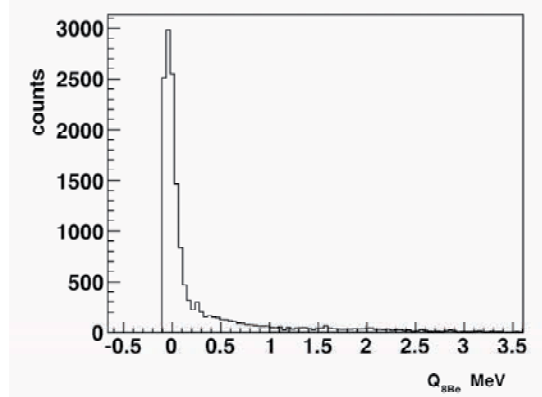


Figure 3: Relative energy spectra of the two alpha's in DPSP arising from ^8Be decay.

After particle identification and with the assumption of mass number 1 for the undetected third particle, the kinematical locus of events (fig.4) was reconstructed in very good agreement with the simulation. Moreover the experimental Q-value spectrum for the three-body reaction is centered at about $Q_{\text{expe}} = -1.8$ MeV, according to the expected theoretical value ($Q_{\text{theor}} = -1.7$ MeV). Events below this peak were then selected as coming from the $^2\text{H}(^9\text{Be}, p^8\text{Be})n$ and used for the further analysis.

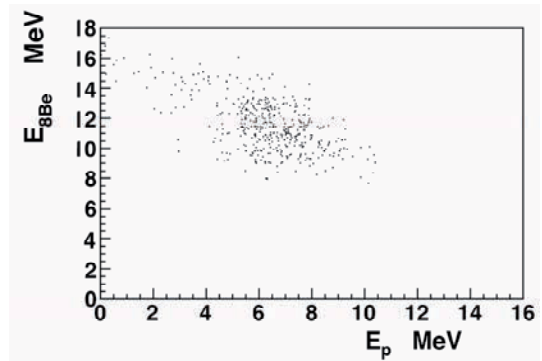


Figure 4: Kinematic locus of the ^8Be energy versus the d energy.

It can be pointed out that the number of events within the kinematic cut is rather small. Nevertheless it will be investigated whether is present a quasi-free mechanism as required from the THM prescriptions.

In order to do this according to the prescriptions in [7,8] the momentum distribution of the third and undetected particle will be examined. This will give a major constraint for the presence of the quasi-free mechanism and the possible application of the THM.

In figure 5 the momentum distribution of the third particle (a neutron) is plotted. It was obtained as reported

in [8] and it is compared with the theoretical distribution calculated from the Hulthen function. It is then clear how within the experimental errors the theoretical curve reproduces experimental data, thus confirming the hypothesis that the neutron is acting as a spectator and that the process under investigation is quasi-free.

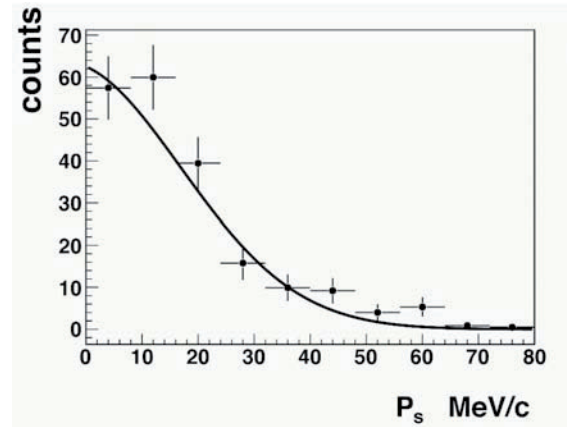


Figure 5: Momentum distribution for the neutron (spectator to the quasi-free process). The solid line represents the momentum distribution resulting from the Hulthen function.

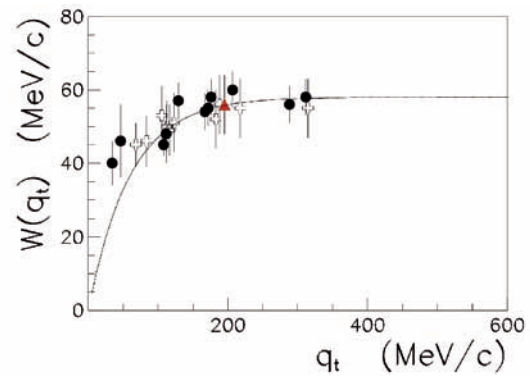


Figure 6: Momentum distribution width as a function of the transferred momentum defined in [8]. The red triangle represents the value arising from present data.

The spectator momentum full width at half maximum, measured from figure 5 is then reported in figure 6 (red triangle) as a function of the transferred momentum q_t . Also in this case the trend seen in [8] is confirmed.

The present result, although the lack of statistics clearly shows that the QF mechanism is present and is separable from the others present in the target. Then further experimental runs are necessary to extract the

astrophysical S(E)-factor with the desired accuracy. This will be done in the next future.

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First results of the measurement of the $^{19}\text{F}(\text{p},\alpha)^{16}\text{O}$ S(E)-factor at energies of astrophysical interest

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Abstract - The $^{19}\text{F}(\text{p},\alpha)^{16}\text{O}$ reaction is the main destruction channel of fluorine in AGB stars. Because of the Coulomb barrier, measurements in the literature do not have access to the energy region of astrophysical interest, which is the Gamow peak ($E_{\text{cm}} \sim 38$ keV). The cross section at this energy was then measured by using the indirect method of the Trojan Horse, extracting the quasi-free contribution to the $^2\text{H}(^{19}\text{F},\alpha^{16}\text{O})\text{n } 2 \rightarrow 3$ reaction at $E_{\text{Beam}} = 50$ MeV. The indirect measurement of the α_0 channel shows the presence of resonant structures that could cause a significant increase in the reaction rate at astrophysical temperatures, with important consequences for stellar nucleosynthesis.

INTRODUCTION

The importance of ^{19}F in the study of AGB stars is two-fold: on one hand, the understanding of fluorine nucleosynthesis in AGB stars is crucial to reproduce observed fluorine abundances, such stars being one of the main sources of galactic fluorine. On the other hand, fluorine abundance observed in giants can constrain AGB star models since it is strictly connected to the mixing processes (standard and extra-mixing) taking place inside AGB stars [1]. Anyway, the highest values of the observed ^{19}F enhancements in the stellar atmosphere are not matched by the models, thus further investigations focusing on fluorine production in AGB stars are highly required. Primary sources of uncertainty in predicting fluorine abundances in AGB stars are both the treatment of the mixing phenomena and the associated nucleosynthesis at the bottom of the convective envelope and the adopted reaction rates [1,2].

In particular, in this report we will focus on the $^{19}\text{F}(\text{p},\alpha)^{16}\text{O}$ reaction that represents a major fluorine destruction channel in this low-temperature ($T \sim 10^7$ K), proton-rich environment.

Its reaction rate is determined by the contribution of several resonances and by a non-resonant term. Direct measurements of the cross section stop at about 460 keV [3], well above the Gamow energy, $E_G \sim 30$ keV. Only unpublished data are available below 460 keV [4], providing the $^{19}\text{F}(\text{p},\alpha)^{16}\text{O}$ differential cross section down to about 120 keV. According to these data, for the α_0 channel the low-energy region should be dominated by direct proton capture with no formation of compound ^{20}Ne nucleus and feeding of resonance states. The accuracy of these data is questioned in [3], as far as the absolute normalization is concerned. Further investigations are therefore required to make clear whether any resonance may occur in the energy region of astrophysical interest, with possible dramatic effects on the $^{19}\text{F}(\text{p},\alpha)^{16}\text{O}$ reaction rate, as in the case of the $^{18}\text{O}(\text{p},\alpha)^{15}\text{N}$ reaction [5,6].

Since the cross section of the $^{19}\text{F}(\text{p},\alpha)^{16}\text{O}$ at $E_{\text{cm}} \sim 30$ keV is predicted to be about 10^{10} times smaller than what measured at the lowest energy available [4], only indirect measurements can provide a way to explore the energy region of astrophysical interest.

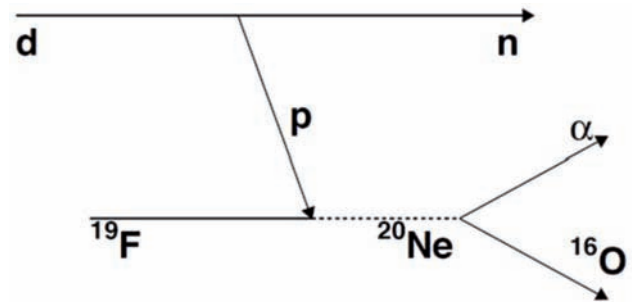


Figure 1: Sketch of the QF reaction.

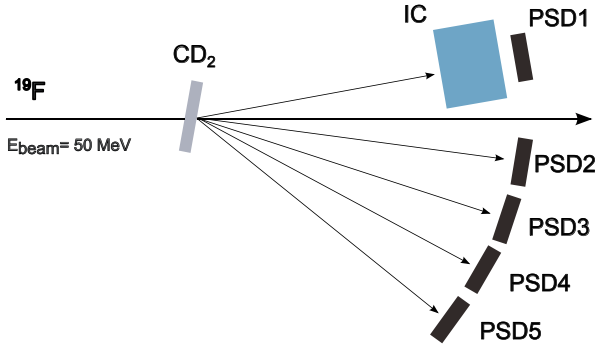


Figure 2: Sketch of the experimental setup.

THE EXPERIMENT

The $^{19}\text{F}(p, \alpha_0)^{16}\text{O}$ reaction has been measured at the Laboratori Nazionali del Sud (Catania) by means of the Trojan Horse Method (THM) [7,8], selecting the quasi-free (QF) contribution from the $^2\text{H}(^{19}\text{F}, \alpha^{16}\text{O})n \rightarrow 3$ reaction at $E_{\text{Beam}} = 50$ MeV. A sketch of the QF process through which the cross section of the binary reaction is demonstrated in Fig. 1, while a drawing of the experimental setup is given in Fig. 2. It consisted of a telescope devoted to oxygen detection, made up of an ionization chamber (IC) and a silicon position sensitive detector (PSD 1) on one side with respect to the beam direction. The ionization chamber was used to discriminate oxygen nuclei by means of the standard $\Delta E - E$ technique. The IC was filled with 50 mbar butane gas that provided an energy resolution of about 10%, which was enough to discriminate the impinging particles according to their nuclear charge but not their mass. No threshold was introduced in the ^{16}O detection by the ionization chamber. Four additional silicon PSDs (2-5) were placed on the opposite side with respect to the beam direction.

Angular conditions were selected in order to maximize the expected QF contribution. Indeed, they were chosen to cover momentum values of the undetected neutron ranging from 0 to 150 MeV/c. Thus, the bulk of the QF contribution for deuteron breakup fell inside the investigated region because the momentum distribution for the $n - p$ system has a maximum at $p_s = 0$ MeV/c.

Data corresponding to coincidence events in PSD1 and one out of PSD2-5 were selected by means of a time-to-amplitude converter (TAC) and stored for later analysis.

SELECTION OF THE REACTION CHANNEL

To disentangle the events corresponding to the $^2\text{H}(^{19}\text{F}, \alpha^{16}\text{O})n$ reaction, a channel selection is performed by gating on the coincidence peak in the TAC spectrum for each coincidence couple and by carrying out a careful investigation of the reaction kinematics. This is required

since only partial particle identification was permitted by the experimental setup, as pointed out in the previous section. By means of the standard $\Delta E - E$ approach no isotopic separation has been possible, as it is displayed in Fig. 3. This figure shows that the contribution from scattered ^{19}F beam particles is clearly separated from the oxygen locus. Gating on such locus, energy correlation spectra have been deduced and compared with the simulated ones to single out the kinematic locus for the $^2\text{H}(^{19}\text{F}, \alpha^{16}\text{O})n \rightarrow 3$ reaction.

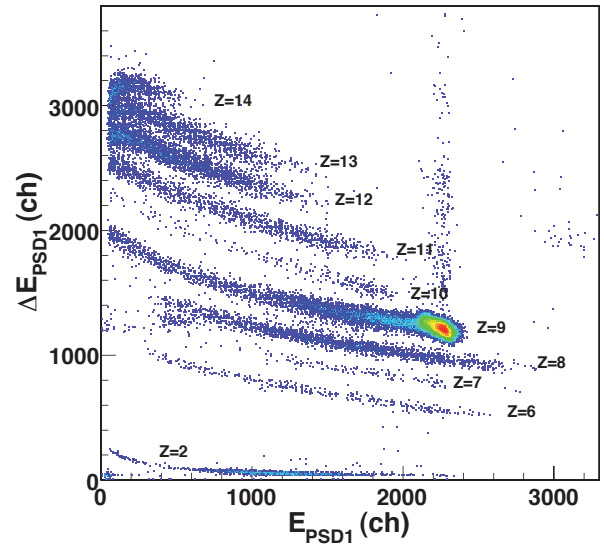
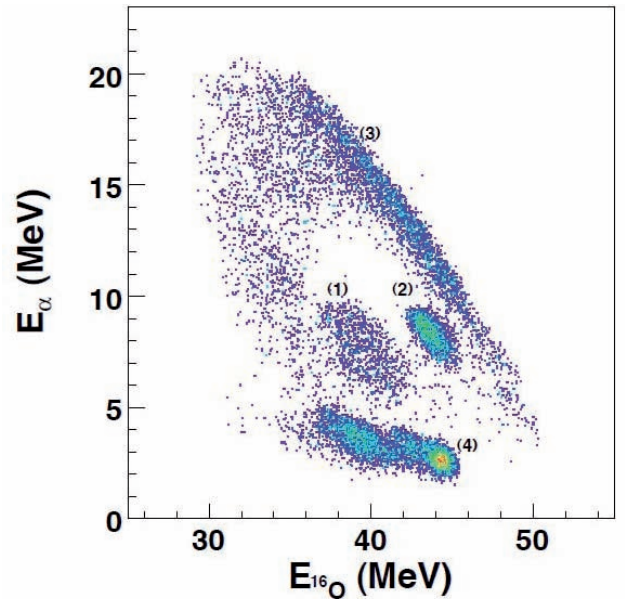
Figure 3: Particle ID with the standard $\Delta E - E$ technique.

Figure 4: Kinematic locus from the PSD1-5 coincidence.

From Fig. 4 it turns out that several reaction channels contribute in the explored phase space region. They can be easily disentangled as they are well separated in Fig. 4.

From its analysis (1) and (3) are recognized as the loci of the $^2\text{H}(^{19}\text{F},\alpha)^{16}\text{O}$ n and the $^2\text{H}(^{19}\text{F},\alpha)^{16}\text{O}$ n reactions while (2) and (4) are attributable to binary reactions, $^{19}\text{F}(\text{d},\alpha)^{17}\text{O}$ and $^{19}\text{F}(^{12}\text{C},^{15}\text{N})^{16}\text{O}$, respectively. By means of a graphical cut the events corresponding to the loci marked as (1), (2) and (4) have been excluded from the following analysis. To check for the presence of further background and to evaluate the accuracy of the performed calibrations, the experimental Q-value has been extracted and compared with the theoretical one. It is shown in Fig. 5 where the arrow indicates the Q-value for the $^2\text{H}(^{19}\text{F},\alpha)^{16}\text{O}$ n reaction. The presence of a single and symmetric peak, centred at the expected Q-value, rule out the occurrence of significant systematic errors.

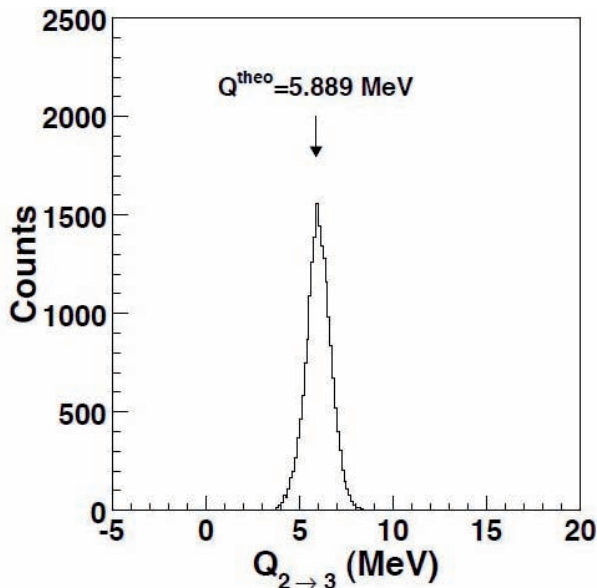


Figure 5: Q-value from the PSD1-5 coincidence, obtained by singling out the spurious contributions observed in Fig. 4.

We will focus on the PSD1-5 detector couple as from their coincidence yield the largest contribution from the $^2\text{H}(^{19}\text{F},\alpha)^{16}\text{O}$ n channel is obtained.

SELECTION OF THE QF REACTION MECHANISM

The same outgoing channel can be fed through different reaction mechanisms, for instance via the decay of different intermediate compound nuclei. The THM, however, requires for its application that the diagram in Fig. 1 can describe the process, namely that the neutron acts as a spectator to the ^{19}F -p interaction. Therefore the QF mechanism has to be identified and disentangled in the overall reaction yield. This is accomplished by a thorough study of the reaction dynamics to select those kinematical regions where QF is dominant.

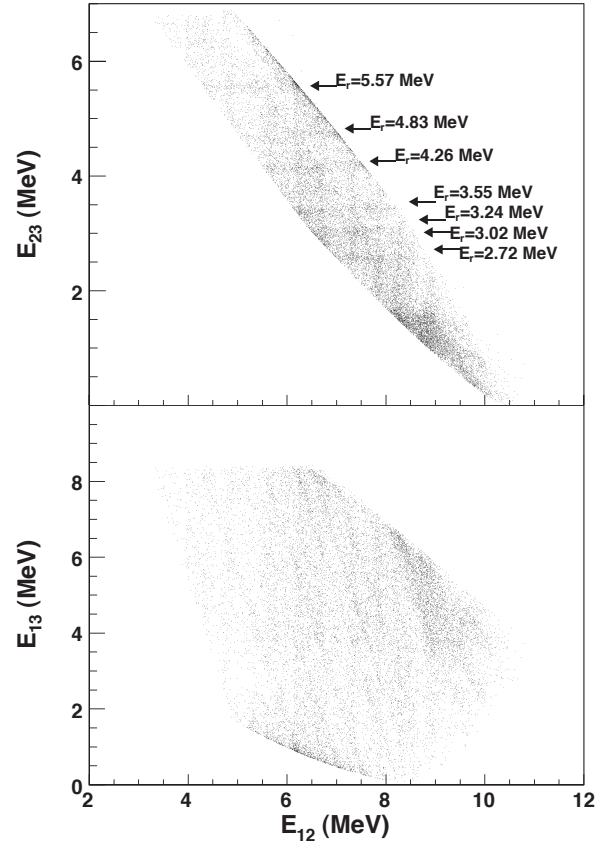


Figure 6: Relative energy spectra for the ^{16}O - α (E_{12}), α -n (E_{13}) and ^{16}O -n (E_{23}) systems.

Relative energy spectra for the ^{16}O - α (E_{12}), α -n (E_{13}) and ^{16}O -n (E_{23}) systems were evaluated to ascertain the population of ^{20}Ne , ^5He and ^{17}O excited states. Fig. 6 displays that the final $^{16}\text{O}+\alpha+n$ channel has been populated through the decay of ^{20}Ne and ^{17}O unbound levels as vertical and horizontal (upper panel of Fig. 6) loci show up, respectively. No horizontal loci appear in the lower panel, ruling out any contribution from ^5He sequential decay. While the ^{20}Ne levels are possible candidates for a population via a QF process (compare Fig. 1), ^{17}O states are formed only through sequential mechanism, namely in a two step process that can be described by the diagram in Fig. 7.

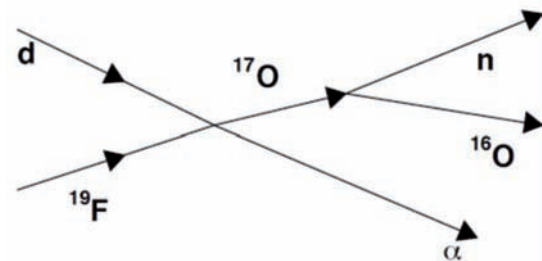


Figure 7: Sketch of the sequential process feeding ^{17}O states.

The ^{17}O states contributing to the coincidence yield are marked with an arrow in Fig. 6. These levels marginally contribute above $E_{12}=8$ MeV, that is the region of interest for the investigation of the $^{19}\text{F}(p,\alpha)^{16}\text{O}$ reaction. Anyway, the states at $E_x=2.72$, 3.02 and 3.24 MeV represent a background to the QF process and their contribution have to be evaluated and subtracted.

Regarding ^{20}Ne levels, additional evidence is needed to make their QF nature clear. A way to discriminate between SD and QF events is through the study of the reaction yield as a function of the neutron momentum p_s [7,8]. Indeed, only if the deuteron breakup process is direct, the neutron momentum distribution keeps the same shape as inside deuteron. Thus, the agreement between the shape of the deuteron momentum distribution and the experimental one is a compelling evidence of the occurrence of the QF mechanism. The experimental neutron momentum distribution is compared with the theoretical one, namely the Hulthén function in momentum space in the plane-wave impulse approximation (PWIA), in Fig. 8.

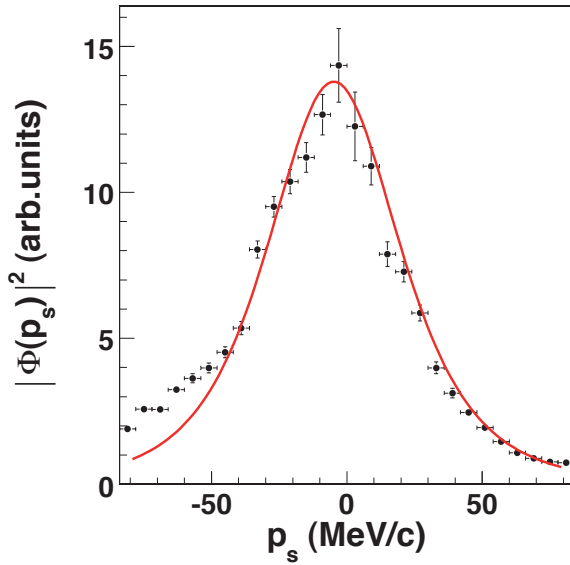


Figure 8: Experimental neutron momentum distribution (black dots) compared with the expected one.

Fig. 8 demonstrates a good agreement between the two for $p_s > 0$ MeV/c. Deviations show that in such phase space region processes other than QF take place, which have to be excluded in the subsequent analysis. To this reason the E_{12} vs. p_s 2D spectrum have been extracted (Fig. 9).

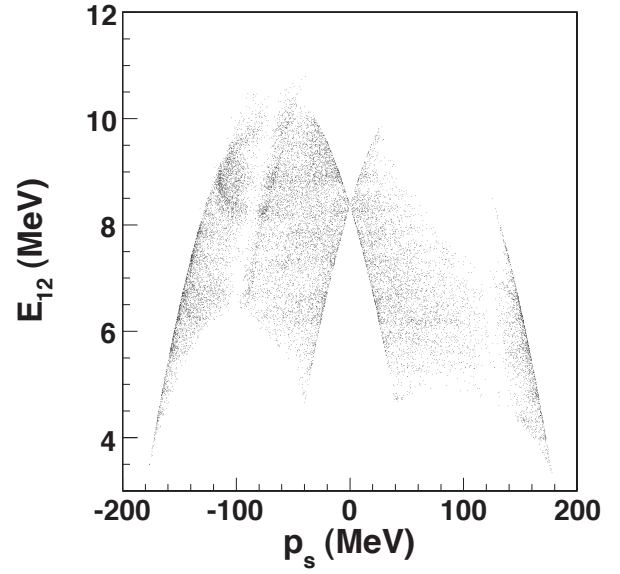


Figure 9: E_{12} vs. p_s 2D spectrum.

This figure demonstrates that background events from sequential decays mostly appear in the region $p_s < 0$ MeV/c at $E_{12} > 8$ MeV. Indeed, only horizontal loci of decreasing intensity as p_s increases can be described as product of a QF process. This is absolutely coherent with what is observed in Fig. 8, where deviations from the theoretical distribution are found for $p_s < 0$ MeV/c. As a consequence, only events with $p_s > 0$ MeV/c will be considered in the extraction of the QF cross section for THM application. An additional cut $p_s < 40$ MeV/c has to be introduced the THM equations to be valid [9].

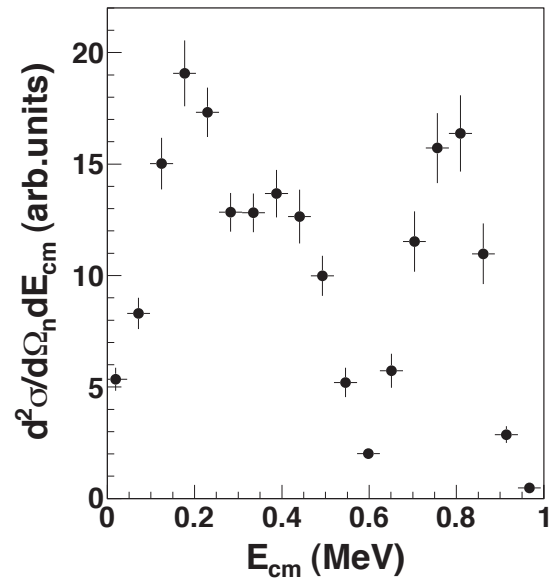


Figure 10: $d^2\sigma/d\Omega_n dE_{cm}$ cross section.

The $2 \rightarrow 3$ cross section is then obtained by evaluating the E_{cm} spectrum, where $E_{\text{cm}} = E_{12} - Q_{2 \rightarrow 3}$, and dividing out the expected modulation by the phase-space population factor and by the neutron momentum distribution. By integrating over the angular distributions of the $^{19}\text{F}(p,\alpha)^{16}\text{O}$ sub-reaction, the $d^2\sigma/d\Omega_n dE_{\text{cm}}$ cross section is deduced in arbitrary units, as shown in Fig. 10. This cross section clearly shows a resonance behaviour, in particular the peak centred at about 800 keV can be attributed to the overlap of the 13.573, 13.586 and 13.642 MeV ^{20}Ne levels. The two peak at lower energies can be due to the population of the 13.222, 13.224 and 13.226 MeV states, leading to a enhancement of the $d^2\sigma/d\Omega_n dE_{\text{cm}}$ cross section around 0.4 MeV, while the peak sitting at ~ 150 keV might be traced back to the decay from the 13.048 and 12.957 MeV levels in ^{20}Ne . It is worth noting that the $2 \rightarrow 3$ cross section cannot be directly related to the $^{19}\text{F}(p,\alpha)^{16}\text{O}$ cross section, the former describing a half-off-energy-shell process (the transferred proton being a virtual particle), the latter an on-shell reaction. Therefore, the modified R-matrix approach [10] has to be applied to

be applied to extract information on the resonance parameters and to calculate, as a consequence, the reaction rate that is the input quantity for astrophysical nucleosynthesis codes.

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The ${}^8\text{Li}(\alpha, n){}^{11}\text{B}$ reaction rate at astrophysical temperatures

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Abstract - At temperatures $(0.5-1.2) \cdot 10^9$ K, the ${}^8\text{Li}+{}^4\text{He} \rightarrow {}^{11}\text{B}+n$ reaction can allow ${}^{12}\text{C}$ and heavier element production in the framework of the inhomogeneous Big Bang nucleosynthesis. At temperatures $(2.5-5) \cdot 10^9$ K, it can influence the production of seed nuclei, later burnt to heavier elements by means of rapid neutron capture reactions, during Type II SNe explosions. Anyway, previous determinations of the reaction rate show an untenable disagreement. In this work, an updated critical analysis as of the conflicting cross section data sets used for the existing reaction rate calculations as well as of the following recent measurements is performed. A new reaction rate calculation is proposed for the intervals of astrophysical interest. This new recommendation turns out to be up to a factor of five larger than the most recent rate in the literature, thus enforcing the role of the ${}^8\text{Li}+{}^4\text{He} \rightarrow {}^{11}\text{B}+n$ as a candidate astrophysical key reaction. The analytic expression of the present-work recommended reaction rate is given.

ASTROPHYSICAL BACKGROUND

Experimental studies of the ${}^8\text{Li} + {}^4\text{He} \rightarrow {}^{11}\text{B}+n$ reaction have been motivated by the investigation of the Big Bang nucleosynthesis (BBN) and of the heavy element production through the r-process. During the early stages of evolution of the universe, it might have represented a viable process to overcome the $A=8$ mass gap, possibly leading to the production of heavy elements during the big bang (Kajino & Boyd 1990; Lara et al. 2006; Malaney & Fowler 1988; Rauscher et al. 2007). According to present-day models, primordial nucleosynthesis began at $t \sim 100$ s, at a temperature of about $1.2 \cdot 10^9$ K, when deuteron photodissociation rate became low enough to form a significant amount of such an isotope (Malaney & Fowler 1988). When the temperature got below about $0.5 \cdot 10^9$ K (Cyburt 2004), the reaction rate had diminished so much to substantially halt further nucleosynthesis. If neutron-rich high baryon-density regions formed before the onset of nucleosynthesis (inhomogeneous model (Kajino & Boyd 1990; Lara et al. 2006; Malaney & Fowler 1988; Rauscher et al. 2007)), the reaction chain ${}^7\text{Li}(n, \gamma){}^8\text{Li}({}^4\text{He}, n){}^{11}\text{B}(n, \gamma){}^{12}\text{B}(\beta^-){}^{12}\text{C} \dots$ would have been active and the evidence of a non-negligible abundance of heavy nuclides in high-redshift very primitive astrophysical objects (Matsuura et al. 2005) could find a possible explanation.

The most popular scenario for the r-process is neutrino-driven winds from Type II SNe. Conditions suitable for the r-process could also be realized in different scenarios,

namely neutron star mergers or gamma-ray bursts, where high neutron fluxes can be produced. Seed nuclei (in the mass range $70 < A < 120$, like e.g. the doubly magic ${}^{78}\text{Ni}$), which are eventually burnt to heavier elements in the fast neutron capture reactions, could be obtained through the so-called α -process (Woosley & Hoffman 1992), namely through α -capture reactions beginning from the two chains (Sasaqui et al. 2006; Woosley & Hoffman 1992; Hoffman et al. 1997; Terasawa et al. 2001): (a) ${}^4\text{He}(\alpha, n){}^9\text{Be}(\alpha, n){}^{12}\text{C}$ and (b) ${}^4\text{He}(t, \gamma){}^7\text{Li}(n, \gamma){}^8\text{Li}(\alpha, n){}^{11}\text{B}$, taking place at temperatures $(2.5-5) \cdot 10^9$ K. The ${}^8\text{Li}+{}^4\text{He} \rightarrow {}^{11}\text{B}+n$ reaction is then important to constrain the parameter space for the r-process possible environments (Sasaqui et al. 2006). The experimental determination of the reaction rate R (in $\text{cm}^3 \text{mol}^{-1} \text{s}^{-1}$) as a function of the temperature T_9 (in units of 10^9 K) is obtained through the standard formula for the interaction between particle 1 and 2 having relative velocity v and reduced mass μ_{12} (a.m.u.) as

$$R(T_9) = N_A \langle \sigma v \rangle_{12} = \frac{3.73 \cdot 10^{10}}{\sqrt{\mu_{12} T_9^3}} \int_0^\infty E_{\text{cm}} \cdot \sigma(E_{\text{cm}}) \cdot e^{-11.605 \frac{E_{\text{cm}}}{T_9}} dE_{\text{cm}} \quad (1)$$

where N_A is the Avogadro number, E_{cm} is the total kinetic energy available in the center-of-mass. The function $\sigma(E_{\text{cm}})$ is the cross section of the ${}^8\text{Li} + {}^4\text{He} \rightarrow {}^{11}\text{B} + n$ reaction summed over all ${}^{11}\text{B}$ final states. The production of ${}^8\text{Li}$ radioactive projectiles is the first fundamental step of the experimental cross section determination (see e.g. Agodi et al. (2006)). In recent years, various measurements have been attempted using different detection techniques. An exhaustive review can be found in La Cognata et al. (2008, 2009, 2010), thus in the following we will focus on the connection between the different data sets and the calculation of the reaction rate according to Eq. 1.

The ranges of center-of-mass energy where the bulk of the reaction rate in each relevant T_9 interval originates from can be singled out from Eq. 1 in terms of the link between the Gamow energy and the temperature (Rolfs & Rodney 1988; Iliadis 2007)

$$E_G = 0.122 \cdot (Z_1^2 Z_2^2 \mu_{12} T_9^2)^{\frac{1}{3}}, \quad (2)$$

where Z_1 and Z_2 are the atomic numbers of the two interacting nuclei. Considering the typical temperatures involved, this procedure candidates the center-of-mass energy ranges 0.35 - 0.63 MeV, for BBN ($T_9 = 0.5 - 1.2$), and 1.03 - 1.63 MeV, for the α -process preceding the r-process nucleosynthesis in Type II SNe ($T_9 = 2.5 - 5$).

Two previous experimental estimates of the ${}^8\text{Li} + {}^4\text{He} \rightarrow {}^{11}\text{B} + n$ reaction rate are reported in the literature. In both cases the necessary cross section data inside these relevant astrophysical ranges could not be measured. To circumvent this problem, both estimates adopted a procedure which gets benefit from the experimental knowledge of the cross section σ_0 of the reaction branch ${}^8\text{Li} + {}^4\text{He} \rightarrow {}^{11}\text{B} + n_0$ populating the ${}^{11}\text{B}$ ground state in the $E_{\text{cm}} = 0.373 - 5$ MeV range (Paradellis et al. 1990). Then the extrapolation of the cross section to small center of mass energies is performed by postulating constant branching ratio σ_0/σ .

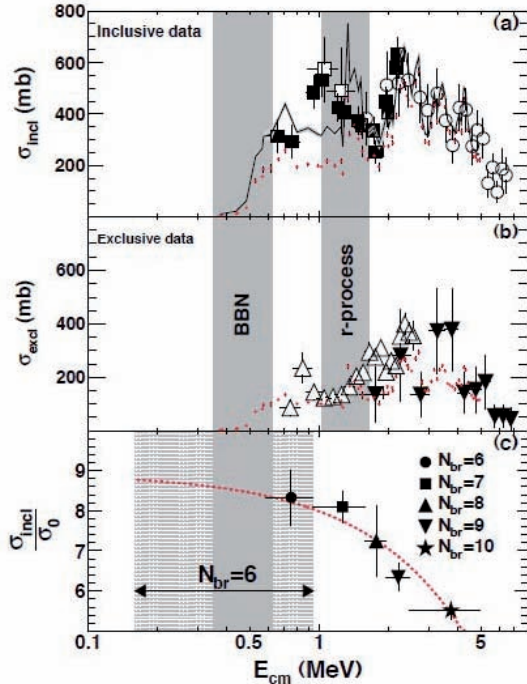


Figure 1: (a) Inclusive ${}^8\text{Li} + {}^4\text{He} \rightarrow {}^{11}\text{B} + n$ reaction cross section data versus E_{cm} : ${}^{11}\text{B}$ measurements from Boyd et al. (1992) (open circles) and Gu et al. (1995) (filled squares) and neutron measurements from Cherubini et al. (2004); La Cognata et al. (2008) (open squares). The experimental cross section σ_0 from (Paradellis et al. 1990) multiplied by the factor 5 used in (Gu et al. 1995) is shown (dots). The broken solid lines depict the (Jo data from (Paradellis et al. 1990) modulated by the factors in panel (c) as described in Section 3; (b) exclusive cross section data versus E_{cm} from Mizoi et al. (2000) (filled triangles) and Ishiyama et al. (2006) (open triangles). The cross section σ_0 from (Paradellis et al. 1990) multiplied by the factor 2.6 used in Mizoi et al. (2000) is shown (dots). The shaded grey bands schematically mark the energy ranges of interest for the BBN ($0.35 < E_{\text{cm}} < 0.63$) MeV and α -process ($1.03 < E_{\text{cm}} < 1.63$) MeV as described in Section 1. (c) $\langle \sigma_{\text{incl}} \rangle / \langle \sigma_0 \rangle$ as a function of E_{cm} (symbols). The horizontal bars set the energy averaging intervals, corresponding to the indicated number of open branches N_{br} . The short dashed line is the linear fit to the data.

PREVIOUS REACTION RATE ESTIMATES

The first rate estimate was deduced in Gu et al. (1995) from two sets of inclusive measurements, where the outgoing ${}^{11}\text{B}$ recoil was detected (Boyd et al. 1992; Gu et al. 1995). These two partially overlapping sets of cross section data are shown in Fig. 1a as open circles (Boyd et al. 1992) and filled squares (Gu et al. 1995). This inclusive data does not cover the range of interest for BBN. The extrapolation below the lowest energy (0.6 MeV) explored in Gu et al. (1995) was performed by matching the inclusive experimental σ data (Boyd et al. 1992; Gu et al. 1995) with the scaled σ_0 in Paradellis et al. (1990) above 0.6 MeV. The value of the scaling factor σ/σ_0 equal to 5 is quoted in (Gu et al. 1995).

In Fig. 1a, the cross section σ_0 from Paradellis et al. (1990) multiplied by 5 is shown as small red dots. Its trend below $E_{\text{cm}} = 0.6$ MeV was assumed by Gu et al. (1995) to depict the dependence of the cross section σ summed over all ${}^{11}\text{B}$ final states. Finally, the joined (measured + extrapolated) σ data set was inserted into Eq. 1 to obtain the reaction rate denoted as R_{Gu} in Fig. 2a (short dashed line). The analytical expression of R_{Gu} as a function of T_9 is given in Gu et al. (1995).

The other reaction rate estimate was deduced from an exclusive coincidence measurement of both ${}^{11}\text{B}$ and The neutron (Mizoi et al. 2000) in the reaction exit channel. This data set is shown in Fig. 1b by filled triangles.

By averaging out both σ_0 from Paradellis et al. (1990) and their exclusive σ data in the $E_{\text{cm}} = 1.5 - 2$ MeV window, Mizoi et al. (2000) recommended the σ/σ_0 scaling factor value of 2.6 to extrapolate the cross section σ at lower E_{cm} energies.

The resulting reaction rate, denoted here as R_{Mizoi} , is shown in Fig. 2a as a solid line. The analytical expression of R_{Mizoi} as a function of T_9 is given in Mizoi et al. (2000). Again, by considering the shaded grey bands in Fig. 1 we conclude that the experimental key information on the whole region of astrophysical interest almost exclusively relies on the type of extrapolation adopted in Mizoi et al. (2000). For a detailed comparison, Fig. 2b shows the R_{Gu} to R_{Mizoi} ratio as a function of the temperature (short dashed line). At the temperatures of interest for the BBN, $0.5 < T_9 < 1.2$, the difference (about a factor of 2) between the Gu et al. (1995) and Mizoi et al. (2000) rate can be mostly attributed to the different scaling factors, 5 in (Gu et al. 1995) and 2.6 in (Mizoi et al. 2000), used in the extrapolation. Instead, at temperatures $2.5 < T_9 < 5$, corresponding to the interval where the α -process is supposed to be most effective, the difference is not clear. Indeed, the inclusive cross section from Gu et al. (1995) (filled squares in Fig. 1a) is generally larger than the exclusive one in (Mizoi et al. 2000) (filled triangles in Fig. 1b). Combining this fact with the different scaling factors used in the extrapolation should have resulted in a ratio $R_{\text{Gu}}/R_{\text{Mizoi}}$ significantly larger than one inside the whole shaded grey band, at variance with the curve in Fig. 2b. This point will be reconsidered later on in this text.

In Fig. 1 the current experimental state of the art is updated. Fig. 1b includes the recent exclusive ${}^8\text{Li} + {}^4\text{He} \rightarrow {}^{11}\text{B} + n$ cross section measurements by Ishiyama et al. (2006) in the $0.75 < E_{cm} < 2.55$ MeV (open triangles), in partial overlap with the data set by Mizoi et al. (2000). No calculation of the reaction rate is reported in Ishiyama et al. (2006). The comparison with the inclusive data in Fig. 1a shows that a large discrepancy between inclusive and exclusive ${}^{11}\text{B}$ measurements exists: at $E_{cm} \sim 1$ MeV the exclusive cross section is of the order of 100 mb whereas the inclusive one equals approximately 500 mb.

The reason for the inclusive and exclusive cross section data in Fig. 1a,b to appear so much different has been identified in La Cognata et al. (2009). In the exclusive measurements by Mizoi et al. (2000); Ishiyama et al. (2006) the neutrons were detected using plastic scintillators which, in the best case, exhibit a threshold of the order of 0.5 MeV on the neutron energy. In La Cognata et al. (2009) it is shown that, due to this instrumental threshold, at center-of-mass energies right above the onset of a ${}^{11}\text{B}$ excited level the detection of the associated reaction branch is completely missed. Consequently, the exclusive experiments (Mizoi et al. 2000; Ishiyama et al. 2006) could not measure the reaction cross section summed over all ${}^{11}\text{B}$ final levels. Instead, the inclusive ${}^{11}\text{B}$ measurements (Boyd et al. 1992; Gu et al. 1995) obviously set no threshold on the neutron detection and, therefore, these could determine the required reaction cross section summed over all ${}^{11}\text{B}$ final levels. Therefore, even considering the recent data Ishiyama et al. (2006) the exclusive cross section σ_{excl} in Fig. 1 b would definitely lead to a reaction rate estimate which cannot be recommended both at BBN temperatures, where the cross section data indicates the seemingly small scaling factor $\sigma/\sigma_0=2.6$ (Mizoi et al. 2000), and at α -process temperatures, where the untenable experimental cross section discrepancy right occurs.

On the other hand, the close agreement in Fig. 1a with the recent complementary neutron measurements by Cherubini et al. (2004); La Cognata et al. (2008) (open squares) strongly supports the magnitude of the inclusive cross section σ_{incl} by Boyd et al. (1992); Gu et al. (1995). Moreover, in La Cognata et al. (2009) it is shown that the amount of the deviation of the exclusive cross section from the inclusive one is of true physical origin as it directly reflects the reaction branch non uniformity in the population of the ${}^{11}\text{B}$ final levels. Therefore, calculating the reaction rate through the inclusive cross section data continues to constitute the only presently practicable approach. However, the extrapolation to low energy, qualitatively leading to the scaling factor $\sigma/\sigma_0=5$ in Gu et al. (1995), has to be appropriately addressed.

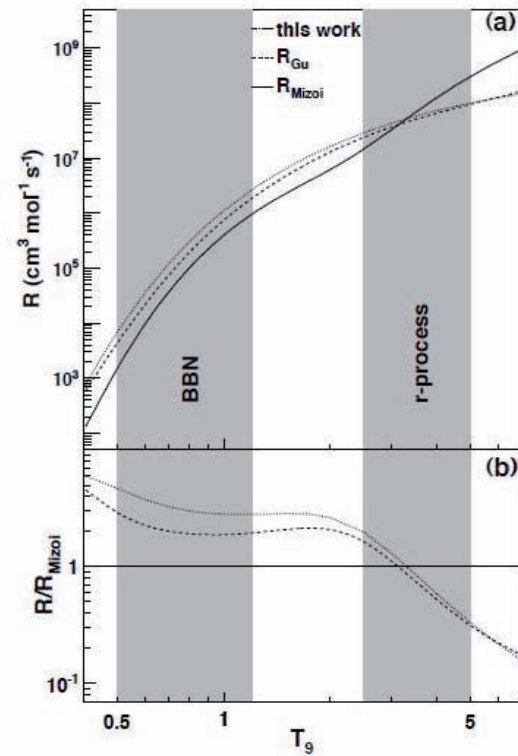


Figure 2: (a) Summary of the reaction rates of the ${}^8\text{Li}+{}^4\text{He} \rightarrow {}^{11}\text{B}+n$ available in the literature, short dashed (Gu et al. 1995) and full lines (Mizoi et al. 2000). The dotted line is instead the result of the present-work reaction rate calculation. The shaded grey bands schematically mark the temperature ranges of interest for the primordial nucleosynthesis ($0.5 < T_9 < 1.2$) and α -process ($2.5 < T_9 < 5$). (b) Ratios of the rates shown in (a) to the one from Mizoi et al. (2000). The line styles are the same as in (a)

NEW RECOMMENDED ${}^8\text{Li}+{}^4\text{He} \rightarrow {}^{11}\text{B}+n$ REACTION RATE

In this section, a new and improved extrapolation procedure of the inclusive cross section data (Boyd et al. 1992; Gu et al. 1995), again based on σ_0 by Paradellis et al. (1990), is proposed.

We have preliminarily considered that each data point of the cross section σ_{incl} (Boyd et al. 1992; Gu et al. 1995) shown in Fig. 1a includes the feeding of the 11 B states which not only are energetically accessible at the corresponding E_{cm} but are also accessible to the experimental observation. Thus, as the tenth and higher ${}^{11}\text{B}$ excited states decay almost entirely by α emission (Hardie et al. 1984), these are hardly observed in the measurements which are based on the (inclusive or exclusive) detection of ${}^{11}\text{B}$. Accordingly, depending on E_{cm} , and considering also the ${}^{11}\text{B}$ ground state, it is reasonable to conclude that at most 10 reaction branches are involved in the reaction events observed by Boyd et al. (1992); Gu et al. (1995).

In the following step, the number of reaction branches N_{br} has been assumed to be the order parameter. The ordering center-of-mass energy intervals corresponding to each N_{br} -value have been deduced from La Cognata et al. (2009). Then, having in mind that

$$\frac{\langle \sigma \rangle}{\langle \sigma_0 \rangle} = \frac{\sum_{i=0}^{N_{br}-1} \langle \sigma_i \rangle}{\langle \sigma_0 \rangle}, \quad (3)$$

we have determined the experimental ratio as a function of N_{br} , each average being performed over the corresponding ordering E_{cm} interval. Fig. 1c shows $\langle \sigma_{incl} \rangle / \langle \sigma_0 \rangle$ as a function of the central value of each of these E_{cm} -intervals. The horizontal bars mark the width of each ordering energy bin. Noteworthy, this figure shows that the BBN shaded grey band, where the extrapolation of the cross section data is mostly required, is entirely located inside the energy region characterized by $N_{br} = 6$ (light-grey region). Furthermore, inside the subinterval $E_{cm} = 0.59 - 0.9$ MeV, covering as much as approximately the upper half of the $N_{br} = 6$ energy range the experimental value of $\langle \sigma_{incl} \rangle / \langle \sigma_0 \rangle$ is available (filled circle). Moreover, such a sub-interval is located only 0.1 MeV above the the BBN grey band central value (at about 0.5 MeV). Finally, the trend of $\langle \sigma_{incl} \rangle / \langle \sigma_0 \rangle$ is close enough to a straight line (linear correlation factor $r^2 = 0.93$). By extrapolating accordingly, we have determined the value of $\langle \sigma \rangle / \langle \sigma_0 \rangle = 8.45 \pm 0.36$ (including correlations) at the grey-band central value $E_{cm} = 0.5$ MeV. This has been assumed to be the scaling factor of the σ_0 dependence on E_{cm} which better provides the requested extrapolation of the reaction cross section σ_{incl} below 0.6 MeV. The extrapolated curve is shown in Fig. 1a as a broken solid line. The narrow light-grey band around it denotes the statistical uncertainty affecting the extrapolated cross section.

We have also scaled the excitation function σ_0 inside each $N_{br}=7-10$ energy interval by the value of the corresponding $\langle \sigma_{incl} \rangle / \langle \sigma_0 \rangle$ factor in Fig. 1c. The resulting re-scaled σ_0 (broken solid line) is compared with the cross section data σ_{incl} (Boyd et al. 1992; Gu et al. 1995) in Fig. 1a. The good agreement in the whole energy range further corroborates the reliability of the adopted procedure.

With this new σ_{incl} (data+extrapolation) into Eq.1, the resulting reaction rate is given in Fig.2a as a dotted line, while in Fig.2b the ratio of the present result to the Mizoi et al. (2000) is displayed as a dotted line as well.

Inside the BBN temperature range the reaction rate here obtained is up to five times larger than R_{Mizoi} (Mizoi et al. 2000) and about 70% larger than R_{Gu} (Gu et al. 1995).

At higher temperatures, where the r-process is supposed to take place, a fair agreement between our and the R_{Gu} (Gu et al. 1995) rate is apparent, due to the scarce influence in this region of the extrapolated cross section below 0.6 MeV. Instead, both are in total disagreement with R_{Mizoi} . This fact suggests that the analytical expression of R_{Mizoi} recommended by Mizoi et al. (2000) fails right in the range of T_9 which is closer to their exclusive data (filled triangles in Fig. 1b).

SUMMARY AND CONCLUSION

The reliability of the inclusive cross section data (Boyd et al. 1992; Gu et al. 1995) is supported by the recent inclusive neutron measurements in (Cherubini et al. 2004; La Cognata et al. 2008). Although these inclusive measurements cover the broad centre-of-mass energy range 0.6-7 MeV, nevertheless they miss the experimental key information on BBN, namely at $E_{cm}=0.35-0.63$ MeV. Consequently, in the previous estimate (R_{Gu}) using these data (Gu et al. 1995) the rate in such a relevant energy region is exclusively determined by the type of extrapolation adopted.

In the present work we propose a new improved rate calculation of the ${}^8\text{Li} + {}^4\text{He} \rightarrow {}^{11}\text{B} + n$ reaction. Again it is based on the inclusive cross section data (σ) (Boyd et al. 1992; Gu et al. 1995) and on the contribution (σ_0) of the ${}^8\text{Li}+{}^4\text{He} \rightarrow {}^{11}\text{B}+n_0$ branch leading to the ${}^{11}\text{B}$ ground state. To this aim, we have devised a powerful sorting procedure of the $\langle \sigma \rangle / \langle \sigma_0 \rangle$ data ratio according to the number of reaction branches observable in the inclusive measurements (Boyd et al. 1992; Gu et al. 1995). It results (Fig. 1c) that only approaching the highest explored energy the trend of $\langle \sigma_{incl} \rangle / \langle \sigma_0 \rangle$ actually tends to the value of $\sigma / \sigma_0 = 5$ used in Gu et al. (1995) to determine the reaction rate R_{Gu} , namely, rather far from the unexplored BBN energy region. Moreover $\langle \sigma_{incl} \rangle / \langle \sigma_0 \rangle$ significantly increases with decreasing the experimentally explored energy. Its close to linear dependence down to energies right at the border of the BBN bin attributes a high confidence level to the extrapolation performed accordingly.

For future applications, the present-work recommended reaction rate, resulting from numerical integration according to Eq.1, has been fitted by the standard analytic expression:

$$R(T_9) = \exp \left(a_1 + \frac{a_2}{T_9} + \frac{a_3}{T_9^{1/3}} + a_4 T_9^{1/3} + a_5 T_9 + a_6 T_9^{5/3} + a_7 \log T_9 \right). \quad (4)$$

The best fit procedure has provided the following parameters (the resulting rate is expressed in $\text{cm}^3/\text{mol s}$):

$$\begin{aligned} a_1 &= 0.3563 \cdot 10^2 \\ a_2 &= -0.2510 \cdot 10^1 \\ a_3 &= -0.3233 \cdot 10^2 \\ a_4 &= 0.1317 \cdot 10^2 \\ a_5 &= -0.1816 \cdot 10^{-1} \\ a_6 &= -0.2032 \cdot 10^{-1} \\ a_7 &= -0.1238 \cdot 10^2, \end{aligned}$$

yielding a maximum per cent difference between fit and data points of 2.3%.

As an important consequence of this work for astrophysics at $T_9=2.5-5$, the contribution to nucleosynthesis of the path passing through the ${}^8\text{Li}(\alpha, n){}^{11}\text{B}$ can much more reliably be established by the reaction rate R_{cu} in (Gu et al. 1995) than by R_{Mizoi} (Mizoi et al. 2000). For instance, present work strongly supports the prediction in Sasaqui et al. (2006), where,

using R_{Gu} , the contribution to r-process from the path ${}^4\text{He}(t,\gamma){}^7\text{Li}(n,\gamma){}^8\text{Li}(\alpha,n){}^{11}\text{B}$ is evaluated to double the entropy of the astrophysical environment, compared with calculations assuming the ${}^4\text{He}(t,\gamma){}^7\text{Li}(n,\gamma){}^8\text{Li}(\alpha,n){}^{11}\text{B}$ reaction path only.

As a further important consequence, from this new calculation it turns out that a larger rate than what is given in the literature has to be considered at the temperatures of interest for the BBN ($T_9 = 0.5 - 1.2$), where it is up to

five times larger than the most recent determination (Mizoi et al. 2000).

It is worth to remark once again that this new reaction rate determination is still based on the extrapolation of the cross section trend below 0.6 MeV. Though it calls for new astrophysical calculations, on the other hand it makes clear the importance of new and improved measurements, aiming to cover of the low-energy region of the reaction cross section.

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Study of the reaction $^{17}\text{O}(n,\alpha)^{14}\text{C}$: extension of the Trojan Horse Method to the neutrons induced reactions

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Abstract- The experimental study of the $^{17}\text{O}(n,\alpha)^{14}\text{C}$ reaction has been performed in the energy range 0-350 keV. This reaction could play an important role in explaining heavy elements (s-process) nucleosynthesis in various astrophysical scenario. To overcome the practical problems arising from the neutrons production, a new application of the Trojan Horse Method has been recently suggested. In more details, the preliminary study of the $^{17}\text{O}(n,\alpha)^{14}\text{C}$ neutron induced reaction via the deuteron quasi-free break-up in the $^2\text{H}(^{17}\text{O},\alpha^{14}\text{C})\text{p}$ reaction at 43.5 MeV shows again the possibility of using the deuteron as source of virtual neutrons.

INTRODUCTION

The importance of the $^{17}\text{O}(n,\alpha)^{14}\text{C}$ reaction is twofold, first in nuclear reactors and second in many astrophysical scenario. However, only few direct measurements are reported in literature, showing discordances at neutron thermal energy range [1-4].

The knowledge of the $^{17}\text{O}(n,\alpha)^{14}\text{C}$ is important for nuclear reactors where the neutron induced reaction on ^{14}N or ^{17}O are the dominant sources of the radioactive isotope ^{14}C ($T_{1/2}=5730\text{yr}$). Depending on the reactor, these materials are present as normal or impurity components of fuel element, cooling water or structural materials. The ^{14}C pollution in nuclear reactor is one of the most serious. Indeed, it is released to the environment as carbon dioxide and, because carbon is one of the principal constituent of the living matter, it is easily absorbed by the living organisms [5].

In nuclear astrophysics, the reaction plays a role in the inhomogeneous Big-Bang model, in which the ^{14}C may act as a bottleneck in the production of elements heavier than $A=17$ [6,7], or in asymptotic giant branch stars and in circumstellar Al_2O_3 meteorite grains, where could help to explain anomalies in $^{18}\text{O}/^{16}\text{O}$ and $^{17}\text{O}/^{16}\text{O}$ ratios [8], or even in the nucleosynthesis of the s- or r-process elements, since the ^{17}O produced by the preceding CNO cycle can be a neutron poison [9].

For all these reasons, a detailed measurement of the cross section in the energy range from 0 up to a few hundred keV is needed. In these energy region, several states of

the compound ^{18}O nucleus contribute to the total cross section, thus meaning that a careful evaluation of their strength is needed. However, the measurement of the cross section in the reactions involving the neutrons present two principal problems: the production of the neutron beam or alternatively, using the inverse reactions, the detection of the neutrons.

The aim of this work is to show how the application of the indirect method of the Trojan Horse Method (THM) [10,11] allows to use the deuteron quasi-free (QF) break-up as a source of virtual neutrons. This approach was applied recently for the reactions $^6\text{Li}(n,\alpha)^3\text{H}$, $^{10}\text{B}(n,\alpha)^7\text{Li}$ and in the previous run of the same $^{17}\text{O}(n,\alpha)^{14}\text{C}$ reaction studied at Laboratori Nazionali del Sud of Catania via the $^2\text{H}(^{17}\text{O},\alpha^{14}\text{C})\text{p}$ experiment performed at 41 MeV [12-14]. Basically, the QF break-up mechanisms are direct processes in which the interaction between an impinging nucleus and the target can cause the break-up of the target (TBU) or, that is the same, of the projectile (PBU) [15]. In particular, the so-called QF are processes having three particles in the exit channel one of which can be thought as "spectator", maintaining in the exit channel the same momentum distribution it had before the occurrence of the break-up.

The analysis of the QF reactions is usually performed in the framework of the Plane Wave Impulse Approximation (PWIA) [16], for which, by assuming the cluster $A = x \oplus s$ configuration, the QF $A+a \rightarrow c+C+s$ cross section can be factorize as [17]

$$\frac{d^3\sigma}{dE_c d\Omega_c d\Omega_C} \propto KF |\Phi(p_S)|^2 \left(\frac{d\sigma}{d\Omega} \right)^N \quad (1)$$

where KF is a kinematical factor containing the final state phase-space factor and it is a function of the masses, momenta and angles of the outgoing particles, $\Phi(p_S)$ is the Fourier transform of the radial wave function for the x-s inter-cluster motion inside A and $(d\sigma/d\Omega)^N$ is related to the a-x process cross section.

In the last decades, the indirect method of the Trojan Horse has been recognized as a powerful method for studying charged particles induced reactions at very low energies ($\sim \text{keV}$). The method allows one to measure the

cross section of a two-body reaction overcoming both Coulomb suppression and the electron screening effects [10,11,18]. Recently, an extension of the method itself has been proposed, i.e. the possibility of studying neutron induced reactions overcoming the effect due to the centrifugal barrier [12,19]. Here the preliminary results of the $^{17}\text{O}(n,\alpha)^{14}\text{C}$ reaction by means of the THM applied to the quasi-free $^2\text{H}(^{17}\text{O},\alpha^{14}\text{C})\text{p}$ reaction at 43.5 MeV will be discussed.

THE EXPERIMENT

The experiment has been performed at the Institute for Structure and Nuclear Astrophysics (ISNAP) at the University of Notre Dame, South Bend (Indiana, USA). The JN Tandem Van der Graaff provided a 43.5 MeV ^{17}O beam impinging on a deuterated polyethylene target (CD₂) of about 150 $\mu\text{g}/\text{cm}^2$ placed at 90° with respect to the beam direction. A schematical view of the used detection setup is shown in Figure 1.

The positioning of the setup was chosen in order to cover the phase-space region where a strong contribution of the QF reaction mechanism is expected from a previous Monte Carlo simulation.

It consists of four Position Sensitive Detectors, PSD, (called PSD2, PSD3, PSD5 and PSD6) of 500 μm thickness and two telescopes made up of a ionization chamber (IC) as ΔE and a 1000 μm PSD (PSD1 and PSD4) as E detector. A symmetric displacement of the setup with respect to the beam axis was chosen due to increase the statistic.

PSD2 and PSD5 are placed at a distance $d_2=476$ mm and $d_5=494$ mm from the target, covering the angular ranges $17.5^\circ \pm 2.5^\circ$ while PSD3 and PSD6 were placed at $d_3=381$ mm and $d_6=405$ mm from the target covering the angular range $27.3^\circ \pm 3.5^\circ$. Finally, the two telescopes are placed at a distance $d_1=464$ mm and $d_4=495$ mm from the target, and they cover the angular range $7.5^\circ \pm 2.5^\circ$.

The ICs were filled with 48.7 mbar isobutane gas that provided an energy resolution of $\sim 10\%$, which was enough to discriminate the particles by their charge but not their mass. Two thin mylar foils respectively of 0.9 μm and 1.5 μm were used as entrance and exit window of IC. Their thickness was chosen to minimize the angular straggling.

The telescopes were devoted to ^{14}C detection while the other PSDs were used as alpha particle detectors. Energy and position signals for the detected particles were processed by standard electronics and sent to the acquisition system, allowing the on-line monitoring of the experiment and the data storage for the off-line analysis. The logic AND between one of the two telescopes and the logic OR of the other PSDs has been used as trigger for the ACQ system.

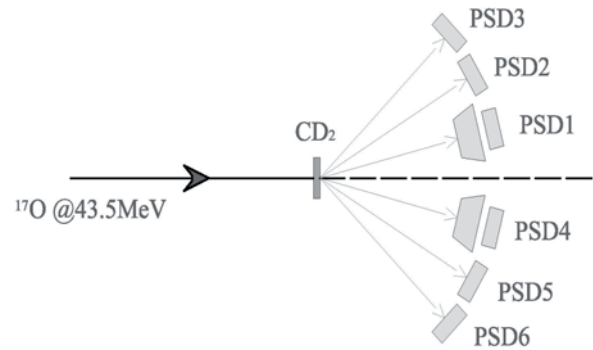


Figure 1: Schematic view of the experimental setup used in the $^2\text{H}(^{17}\text{O},\alpha^{14}\text{C})\text{p}$ experiment, discussed in the text.

DATA ANALYSIS AND RESULTS

The first stage of the experiment was the calibration of the involved detectors to assure a good angular as well as energy calibration. To fix the angular range covered, an equally spaced grid was mounted in front of each PSD and the angular position of each grid determined by using a theodolite. The position and energy calibrations were then performed using two kind of beams: ^4He and ^{12}C on a target of ^{197}Au of 93 $\mu\text{g}/\text{cm}^2$ of thickness at energies from 5 up to 50 MeV in order to measure the elastic scattering peaks at various energies.

After the calibration of the involved detectors, the first step of a typical “TH-analysis” is to discriminate the channel of the three-body reaction of interest from the ones induced, in this case, by the interaction of ^{17}O on CD₂.

In order to identify the channel of interest the C isotopes were selected in the ΔE -E two-dimensional plot and the coincidence with the detectors placed on the opposite side with respect to the beam axis was considered.

Figure 2 shows a typical ΔE -E plot and the C selection used for the further analysis.

The identification of the $^{14}\text{C}+\alpha+\text{p}$ exit channel of interest was done by selecting the correspondent kinematical locus on the correlation spectra of the energies measured, under the hypothesis that the third *undetected particle* had mass number 1, by following the standard procedure described in [11].

By means of the energy conservation law, the experimental Q-value spectrum for the selected events was also reconstructed (Figure 3). A good agreement with the expected value $Q_{\text{theo}}=-0.407$ MeV is obtained. This, within the experimental uncertainties, is a signature of our good calibration and a precise selection of the $^2\text{H}(^{17}\text{O},\alpha^{14}\text{C})\text{p}$ reaction.

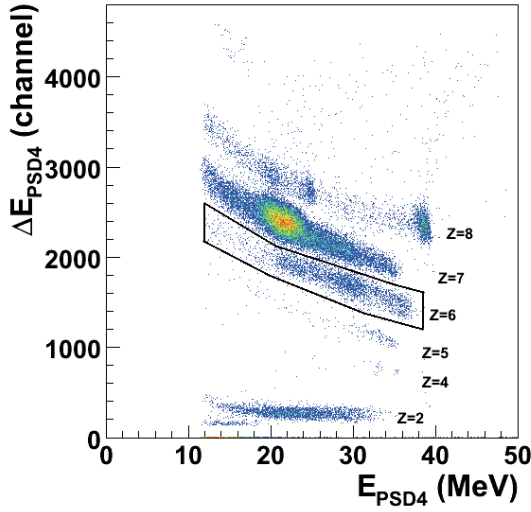


Figure 2: Typical ΔE -E plot used for carbon identification.

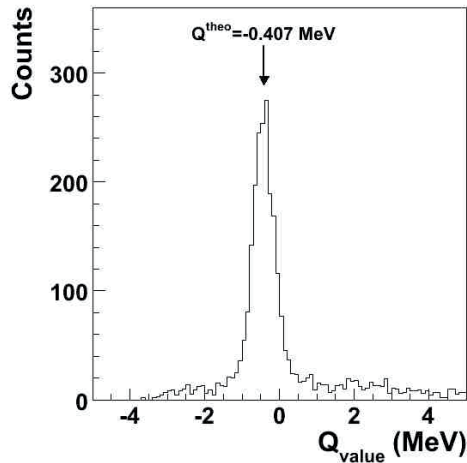


Figure 3: Experimental Q_{value} in agreement with the theoretical prediction of -0.407 MeV for the ${}^2\text{H}({}^{17}\text{O}, \alpha {}^{14}\text{C})\text{p}$ reaction.

For the following analysis only the events falling inside the Q -value experimental peak will be taken in account. After the identification of the 3-body channel of interest, it is necessary to discriminate the QF reaction mechanism among the other reaction mechanisms, as sequential decay and direct break-up, feeding the same particles in the final states. In order to study the nature of the events belonging to the kinematical locus of ${}^2\text{H}({}^{17}\text{O}, \alpha {}^{14}\text{C})\text{p}$, the relative energy correlations for any two of the three outgoing particles was studied. These plots (Figure 4) show very clear vertical loci due to the excitation of the compound nucleus ${}^{18}\text{O}$ on the variable $E_{\text{c.m.}} = E_{\alpha 14\text{C}} - Q_2$, where $E_{\alpha 14\text{C}}$ is the relative energy

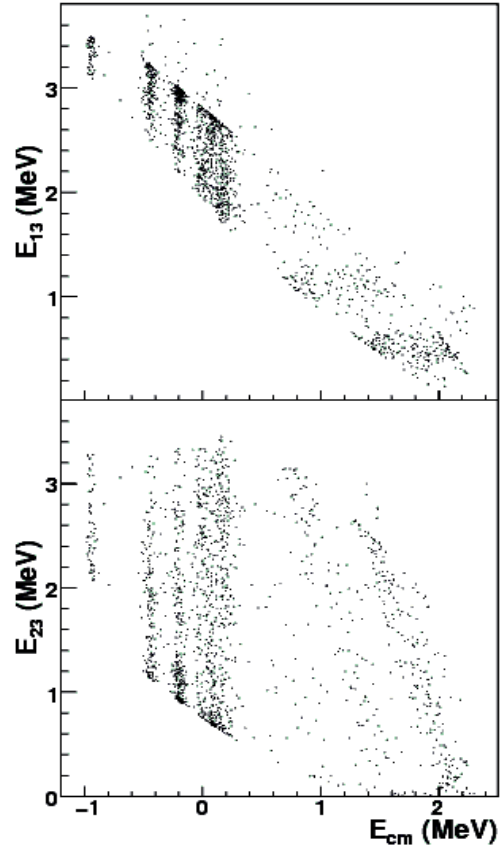


Figure 4: Correlation spectra between the relative energy $E_{23} - E_{\text{cm}}$ and $E_{13} - E_{\text{cm}}$.

between the detected α and C particles and $Q_2 = 1.817$ MeV is the Q -value of the ${}^{17}\text{O}(\text{n}, \alpha){}^{14}\text{C}$ reaction. On the contrary no evidence of the population of ${}^{15}\text{N}$ and ${}^5\text{Li}$ levels was detected.

After this study, we can proceed with the further steps of the analysis and, in particular, with the selection of the events coming from the QF-mechanism.

The QF-mechanism is connected with the behaviour of the undetected third particle in the exit channel. An observable sensitive to the reaction mechanism is the momentum distribution for the relative p - n motion in the deuteron. For such reason, the experimental momentum distribution has been determined following the standard procedure described in [12]. Selecting then a small energy region where the two-body cross section can be assumed almost constant, the three-body coincidence yield corrected for the phase-space factor will be proportional to the momentum distribution. The experimental result is shown in Figure 5, where the coincidence yield for the events in the energy window $E_{\text{cm}} = 166 \pm 40$ keV corrected for the phase-space factor is reported. The good agreement, with $|p_s| < 40$ MeV/c, between the experimental data and the theoretical Hulthén function for the n - p motion inside the deuteron. Moreover, because of the high transferred momentum for the proton in the exit channel ($q \sim 225$ MeV/c), an agreement between the experimental value of the FWHM of the momentum distribution and the theoretical one is also expected [20].

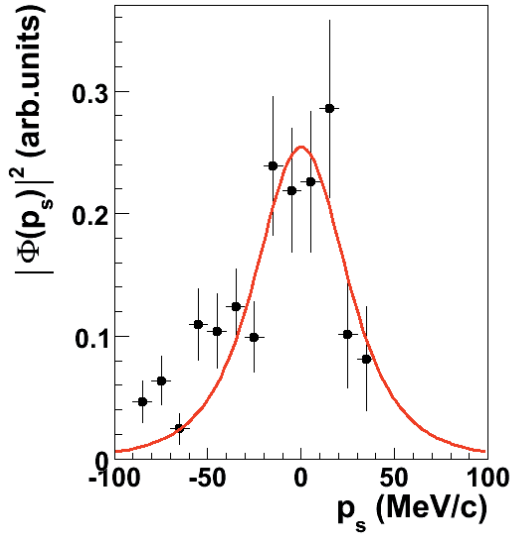


Figure 5: The experimental momentum distribution (black points) compared with the theoretical one given in terms of the Hulthén function (red line).

The results in Figure 5 is the experimental evidence that the proton acted as “spectator” during the break-up occurred in the $^2\text{H}(^{17}\text{O}, \alpha^{14}\text{C})\text{p}$ reaction.

After the QF selection, the experimental coincidence yield (Figure 6) has been studied. It shows up the contribution of several ^{18}O excited levels, mainly in the energy range of our interest, 0-350 keV. Table 1 reports a schematic overview of the levels of the ^{18}O populated through the reaction in study, the related J^π and the orbital angular momentum (l_{in}) that characterized the ingoing state [21]. The levels marked as *A* and *B* are *subthreshold* while the level *C* is inhibited in direct data [1-4] because of the centrifugal barrier, that can be described through the formula

$$P_l(kr) = \frac{1}{kr[J_l^2(kr) + n_l^2(kr)]} \quad (2)$$

In (2), l is the initial state, $J_l(kr)$ and $n_l(kr)$ are respectively the spherical Bessel and Neumann functions, k is the ^{17}O -n relative momentum and r is the channel radius (it was used for the ^{17}O a value of 3.08 fm) [22].

In order to increase the statistic, in Figure 6 is shown the preliminary result of the off energy shell cross section of the sum of the events of the symmetric couples PSD1-PSD5 and PSD4-PSD2. The full dots are the experimental data, the horizontal error bars represent the integration energy bin, the vertical bars take into account the statistical error, the black line is the result of a fit using five Gaussian that are shown as red dashed line.

The future aim of this work is focused on extracting the resonance strength of the subthreshold level and in determining its contribution on the total reaction rate.

Moreover, the presence of the 8.125 MeV ^{18}O level is a strong signature of centrifugal barrier suppression effect in THM with respect direct measurements.

Table 1 –Excitation levels of the ^{18}O shown in Figure 6

	E^* (MeV)	J^π	$E_{\text{c.m.}}$ (MeV)	l_{in}
A	7.864	5^-	-0.183	3
B	8.039	1^-	-0.007	1 ; 3
C	8.125	5^-	0.075	3
D	8.213	2^+	0.166	0 ; 2
E	8.282	3^-	0.236	1

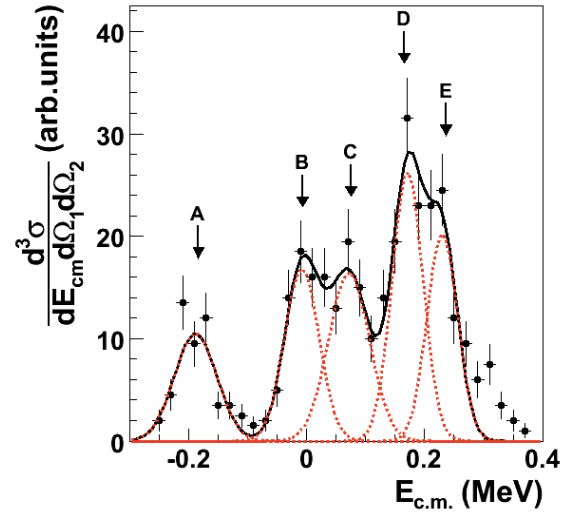


Figure 6: Excitation function (black points) of the $^{17}\text{O}(n, \alpha)^{14}\text{C}$ reaction with its empirical fit (solid black line) given as the sum of with five Gaussian (red dashed line). The arrows indicate the levels listed in Table 1.

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“Didattica” : An introductory experiment to heavy-ions nuclear reaction measurements

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Abstract - We report briefly on results obtained by the Nuclear Physics “Didattica experiment” at LNS-Tandem accelerator performed in May 2010 in the framework of “Nuclear Physics Laboratory” Course for master Degree in Physics of Catania University. It seems that this experience represents a good opportunity to introduce students into the experimental Nuclear Physics world.

INTRODUCTION

Teaching Physics by means of experiments is probably the best way to form young pupils. In particular, for graduate students attending to Nuclear Physics Master Degree, it is extremely important to deal with electronics, detectors and acquisition systems in conditions directly related to typical and dynamical problems of experiments. Since 2007 the possibility to use the LNS Tandem-accelerator facilities has been open for teaching purposes so that, at university of Catania, we had the unique opportunity to profit of a well qualified structure, equipped with many beam lines and measure points. In this light, an experiment conclusive of the Nuclear Physics Laboratory Course, has been performed together with the related students, each year. In past year 2009-2010 the experiment has been devoted to study some reactions at low energies [1,2]. In particular, students were requested to study the three nuclear reactions: $^{16}\text{O}+^{12}\text{C}$, $^{16}\text{O}+^{27}\text{Al}$ and $^{16}\text{O}+^{197}\text{Au}$ at 84 MeV bombarding energies. After the mounting phase and assembling the detection systems inside the LNS-2000 scattering chamber, students participated to the tuning of electronics, and to data-taking phase, and finally they were strongly involved in the data reduction and analysis. [1,2].

Elastic scattering angular distributions have been obtained and compared with Rutherford prediction and previous measurements reported in literature. For the system $^{16}\text{O}+^{27}\text{Al}$, a tentative Optical Model Fit was performed by using the FRESKO code [3]. For the same system, an analysis of evaporation residues emitted in fusion-evaporation events has been done. Comparisons of evaporation residue spectra with PACE IV statistical model [4] were also performed.

MOUNTING THE EXPERIMENTAL APPARATUS

The experiment was performed at INFN-Laboratori Nazionali del Sud, Catania. A beam of ^{16}O (with an intensity up to 70 nA) at 84 MeV bombarding energy was delivered by the Tandem accelerator. It impinged alternatively on two different targets of ^{12}C ($100\text{ }\mu\text{g}/\text{cm}^2$), ^{27}Al ($77\text{ }\mu\text{g}/\text{cm}^2$). Similar targets had a thin evaporated film of and ^{197}Au ($3\text{ }\mu\text{g}/\text{cm}^2$) for normalization purposes. Targets and detectors were mounted on the LNS-2000 chamber, that is furnished of two movable arms, where the detectors were installed.

The detectors used in this experiment were:

1) a Time of Flight (ToF) arm, constituted by a Microchannel Plate detector working in transmission [5] (start detector), followed (65 cm far) by a surface barrier silicon detectors (stop detector) 150 μm thick [6]. Alignment of the ToF arm was checked by means of a theodolite. This system was mounted on the first movable arm of LNS-2000 chamber.

2) a ΔE -E telescope, constituted by two surface barrier silicon detectors; the first one was 10 μm thick, the second one 350 μm . It was mounted on the second movable arm of LNS-2000 chamber

3) a Monitor detector, fixed at a laboratory angle $\theta=15^\circ$, useful for normalization check of elastic scattering angular distributions. A sketch of the experimental configuration is shown in figure 1.

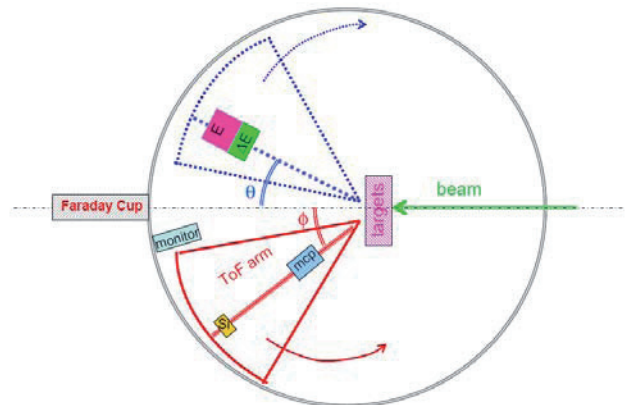


Figure 1. Geometrical sketch (not in scale) of the detection systems mounted inside the LNS-2000 Chamber during the Didattica experiment.

The electronic chain used was a standard, NIM based, modular electronics [6], constituted by charge and current pre-amplifiers (sited in the experimental hall) Ortec mod. 142A and 110VT, spectroscopy amplifiers Ortec mod. 572 and 672, constant fraction discriminators (CFD Ortec mod. 935), Time Filter Amplifiers Ortec mod. 474, a Time to Amplitude Converter Ortec, an Octal Gate Generator Ortec mod. 8800, an ECL-NIM-ECL converter by Lecroy and a delay unit made by LNS-electronic service. Silena ADC 4418/A allowed the conversion of analogical signals obtained from Spectroscopy Amplifier and Time-to-Amplitude Converter in digital information. A sketch of the electronic chain is given in Figure 2. The data acquisition systems used was CAMDA, an easy-to-use packet that allowed to perform data storage (as ASCII files) and on-line visualization of 1-and 2-dimensional spectra [7]. Off line analysis was performed mainly by using the PAW environment [8], a widely used modern tool to perform data analysis especially in Nuclear and Sub-nuclear physics communities.

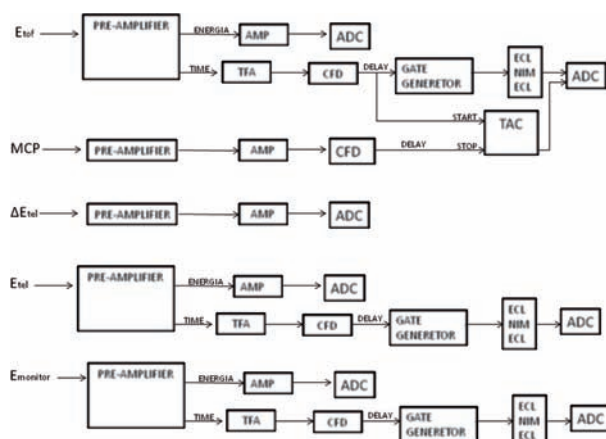


Figure 2. Block scheme of the electronic chain used to process energy, ΔE and Time of Flight signals coming from the used detectors.

ENERGY AND TIME CALIBRATIONS

Energy calibrations of used Si detectors were performed by correlating the central value (in channel) of the elastic peak with the predicted elastic peak energy (in MeV) for O+Al, Au elastic scatterings at various laboratory angles at 84 MeV bombarding energy. Energy calibration was done by performing also some short runs at 72 and 96 MeV bombarding energy. The obtained correlation (channel-energy) is linear for Si detectors used, at least in the energy interval considered. For this reason, a linear relationship to calibrate in energy Si detectors was used.

TAC was calibrated in nanoseconds by adding various known delays before the stop signal. The absolute time offset, t_0 , was obtained by calculating the theoretical time of flight predicted for elastically scattered Oxygen ions

and the observed centre of the time peak in channels. A linear time calibration was used.

ELASTIC SCATTERING ANGULAR DISTRIBUTIONS

We suggested to the students to extract angular distributions of elastic scattering on ^{197}Au , ^{27}Al and ^{12}C targets. To find the elastic scattering angular distribution, elastic peak counts have been normalized to the integrated total charge of the beam (detected by the Faraday Cup and read by a NIM-scaler) for each angle measured in laboratory frame. We used both telescope and ToF silicon detectors to extract elastic scattering angular distributions. Geometrical efficiency was estimated carefully for both silicon detectors. A check of the performed normalizations was done by using the monitor Si detector.

Angular distributions were transformed from the laboratory frame to the centre of mass frame by means of standard kinematics relationship [9]. Kinematical and energy loss calculations have been performed by using the LISE++ program [10].

Angular distributions have been normalized to the Rutherford estimates, in order to obtain $\sigma/\sigma_{\text{Ruth}}(\theta_{\text{CM}})$ distributions [1,2,11]. Just as an example, we show in Figure 3 the case of $^{16}\text{O}+^{27}\text{Al}$ reaction. Experimental data are shown as red dots, while blue line is the results of a simple Optical Model fit performed by using the FRESKO code [3] and assuming only real and imaginary parts for the optical potential. The obtained fit parameters are in agreement with previous estimates reported in literature [12].

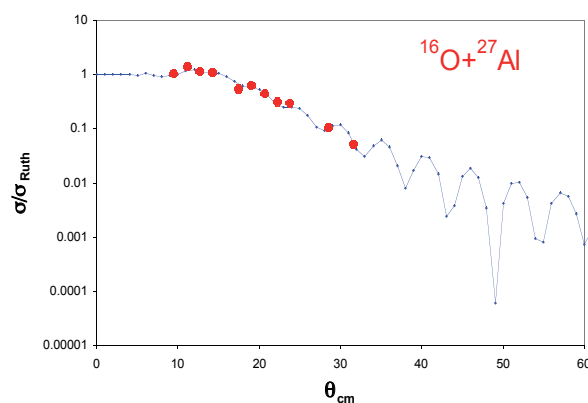


Figure 3. Elastic scattering angular distribution (normalized to Rutherford) for $^{16}\text{O}+^{27}\text{Al}$ at 84 MeV (red dots). The blue line represents the results of an optical model fit.

COMPLETE FUSION EVENTS

Even if, during the data taking, we had some troubles with the functioning of MicroChannel Plate, caused by the break-up of the thin carbon foil used for the emission of secondary electrons [5,12], students had the possibility to collect a quite good statistics for the $^{16}\text{O}+^{27}\text{Al}$ system. The Energy-Time of Flight correlation obtained from MicroChannel Plate and Si detectors in the ToF arm at

forward angle ($\theta_{\text{LAB}}=13^\circ$) is shown in Figure 4. The plot is given in MeV vs ns. Alpha-particles punching through the silicon detector (150 μm thick) are clearly visible. The experimentally observed punch-through energy (~ 16 MeV) is in agreement with energy loss estimates [10].

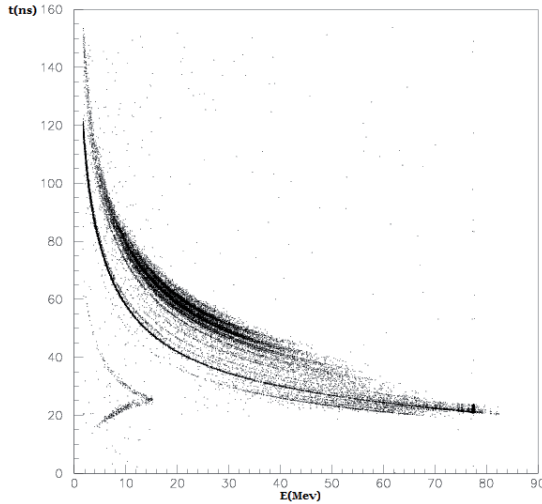


Figure 4. Energy-Time of Flight correlation for $^{16}\text{O}+^{27}\text{Al}$ at 84 MeV. Data were taken at $\theta_{\text{LAB}}=13^\circ$.

Students transformed the Energy-Tof scatter plot in an Energy-mass scatter plot; they did it easily by means of kinematical relationship and by knowing with precision the base of flight length. Energy-mass correlation is shown in Figure 5.

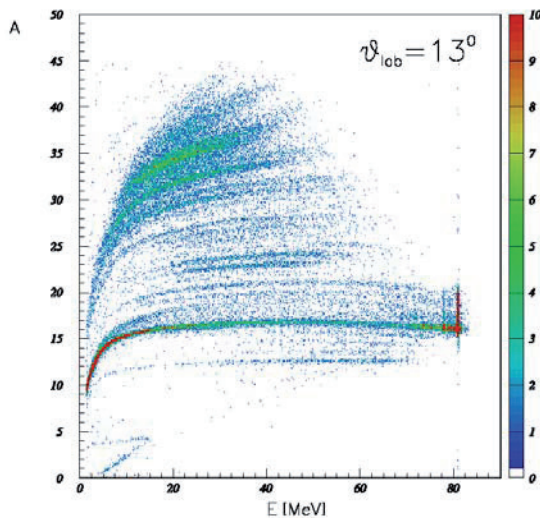


Figure 5. Energy-Mass correlation for $^{16}\text{O}+^{27}\text{Al}$ at 84 MeV. Data were taken at $\theta_{\text{LAB}}=13^\circ$.

Various lines are clearly distinguishable, due to the quite good timing performances of the Time of Flight arm. The drop of lines at low energies can be attributed to plasma delay and pulse height defect phenomena in surface barrier Si detectors [1,6]. Oxygen line, with elastic peak near 80 MeV is clearly seen. At the same time, various lines at higher estimated mass value can be

distinguished: they can be identified as evaporation residues emitted in the de-excitation phase of a complete fusion process: $^{16}\text{O}+^{27}\text{Al} \rightarrow ^{43}\text{Sc}^* \rightarrow \text{ER} + \text{light particles and gamma rays}$. The compound nucleus, ^{43}Sc , is expected to have an excitation energy around 31.3 MeV; it is quite high to cause a de-excitation process involving the emission of one or more light particles such as alphas, neutrons, protons [1,2,12].

We suggested to the students to extract the energy spectra of evaporation residues of a given observed mass by means of graphical cuts on the scatter plot of Figure 5. These energy spectra are shown in Figure 6, together with the prediction (red line) of the recoil velocity of the evaporation residue in a simplified complete fusion scheme: $E = (m_{\text{ER}} \cdot E_{\text{CN}} \cdot \cos^2 \theta_{\text{LAB}}) / m_{\text{CN}}$ (CN here stays for “compound nucleus”, E_{CN} is the compound nucleus recoil energy) [1,12,13]. ER having masses larger than 37 amu are peaked at energy values similar to those predicted by this simple formula, validating the hypothesis that they are emitted in complete fusion events. The spectra have been also compared with prediction of the statistical code PACE IV [4]; the shape of experimental energy spectra and calculated ones are in quite good agreement.

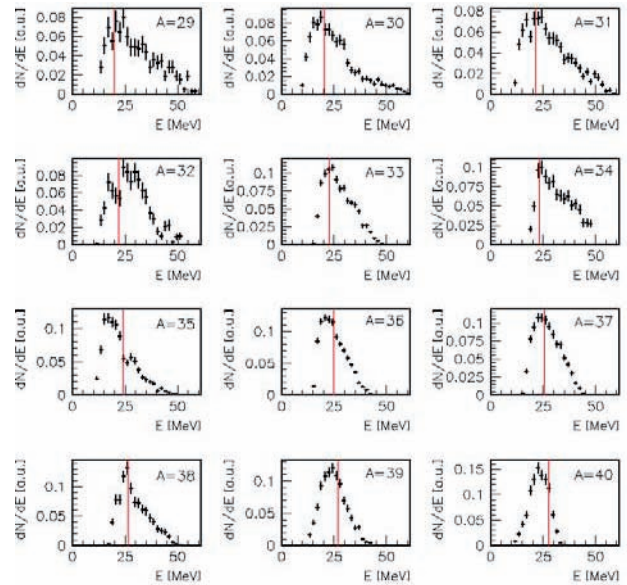


Figure 6. Energy spectra of evaporation residues emitted in $^{16}\text{O}+^{27}\text{Al}$ reaction at 84 MeV. Data were taken at $\theta_{\text{LAB}}=13^\circ$. The red line is the prediction of ER recoil energy in a complete fusion scheme.

It was interesting also to observe that, by selecting with a graphical cut the ^{16}O line in figure 5 and projecting the energy spectrum of ^{16}O nuclei, beyond the elastic scattering peak some less pronounced peaks appear. Centroids of these peaks correspond to the excited state of ^{27}Al nucleus; it seems therefore that these peaks can be associated to inelastic scattering of ^{16}O on ^{27}Al , leaving the target nucleus into an excited state.

CONCLUSIONS

The main aims of the “Didattica” experiments were:

- To introduce students of Nuclear Laboratory course students in the experimental nuclear reaction world: they participated and executed a real experiment, starting from the mounting of the detection system up to the data-analysis phase.
- To make students familiar with data analysis: they were strongly encouraged “to play with experimental data” and, to do this, they employed the PAW environment, i.e. a modern and widely used tool to make data reduction and data analysis in Nuclear and Sub-Nuclear fields.
- To introduce students to the use of programs and codes useful both for data reduction and data analysis (LISE++, PACE IV, FRESCO); the importance of studying previous results reported in literature on the investigated topics has been also strongly underlined.

At the end of this experience, considering the results obtained and enthusiastic participation of students we believe that main aims have been reached successfully; we hope that this opportunity could increase their interests in the experimental nuclear physics field.

ACKNOWLEDGEMENTS

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Calibration of the experimental data for $^{197}\text{Au} + ^{197}\text{Au}$ collisions at 23 AMeV

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Abstract – We present the current status of nuclear dynamics studies performed by the BREAKUP group with the 4π CHIMERA array, for the system Au+Au at 23 AMeV.

The experiment performed for the Au + Au reaction at 23 AMeV has two goals:

- a search for toroidal freeze out configurations predicted to be formed for this heavy system [1];
- an extension of an earlier study carried out at a lower energy of 15 AMeV, in which a new reaction mechanism of violent collinear breakup of non-fusing colliding systems into 3 and/or four massive fragments was discovered [2].

The experiment for the Au + Au reaction was performed in March 2010 using the CHIMERA detector [3]. Total number of collected events is of the order of 10^8 .

During the experiment two gold targets were used: 164 and 396 $\mu\text{g}/\text{cm}^2$. The thinner target was used in calibration measurements and the thicker one in the production runs.

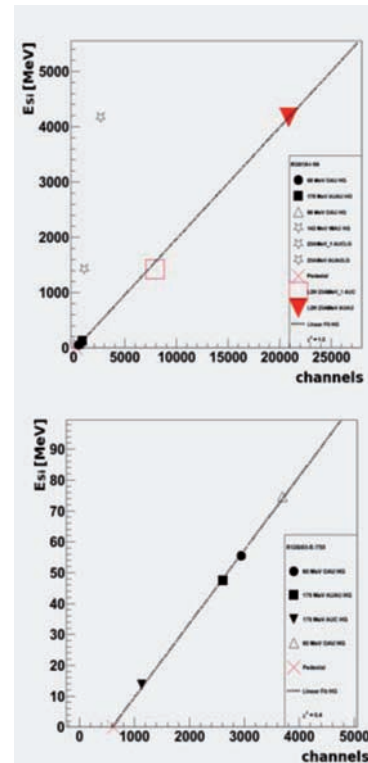


Figure 1: Energy calibration fits for detectors R3SI18 (top) and R12SI0-S (bottom), respectively.

The collected data are calibrated using a set of dedicated programs developed at LNS-INFN. Our present calibration procedure include: (i) energy calibration of Si detectors, (ii) charge identification of fragments, and (iii) mass identification of fragments. Next steps of calibration procedure will include: (i) energy calibration of CsI detectors and (ii) identification of light ejectiles.

Energy calibration of Si detectors was performed using ion beams, delivered both by the tandem and the cyclotron.

Data for the following systems were used: (i) the elastic scattering data for $^{16}\text{O} + \text{Au}$ at 60 and 80 MeV, $^{58}\text{Ni} + \text{Au}$ at 142 MeV, $\text{Au} + \text{Au}$ at 170 MeV and 23 AMeV; (ii) recoil peak for $\text{Au} + ^{12}\text{C}$ at 170 MeV; and (iii) fission fragments from $\text{Au} + ^{12}\text{C}$ reaction at 23 AMeV.

This calibration procedure was done in three steps: (i) pulser calibration of the High Gain and Low Gain electronic channels for each Si detector (ii) determination of the pedestal threshold (iii) energy calibration using elastic scattering peak observed both in Low Gain and High Gain raw spectra.

In our energy calibration of silicon detectors a pulse high defect was taken into account [4] by using the formula

$$PHD = 10^{b(Z)} E^{a(Z)},$$

where $a(Z) = 0.0223(Z^2/10^3) + 0.5682$ and $b(Z) = p_2(10^2/Z) + p_1$.

Following [4] we assumed $p_1=0.0825$ and $p_2=-0.1425$.

In Fig. 1 results of the calibration procedure are shown for detectors R3SI18-I and R12SI03-S located at 5.2 and 50 degrees.

The identification of particles observed in our reaction is in progress. Currently, we perform charge and mass identification of fragments.

For particles punching through the silicon detector we employ the ΔE -E technique.

In Fig. 2 an example of ΔE -E matrix is shown for a detector belonging to the R7E ring, at a polar angle $\theta_{\text{lab}} = 19^\circ$.

The corresponding Z spectrum is presented in Fig. 3. Up to now the identification procedure was performed for 40% of CHIMERA detectors.

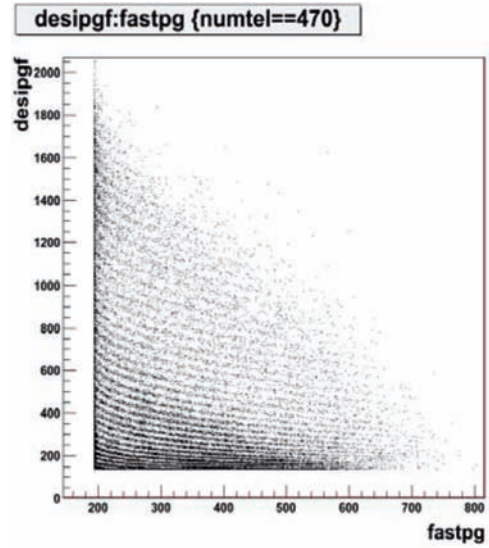


Figure 2: E- ΔE plot for fragments detected in a selected telescope placed at $\theta_{\text{lab}}=19^\circ$ for $^{197}\text{Au} + ^{197}\text{Au}$ reaction at 23 AMeV.

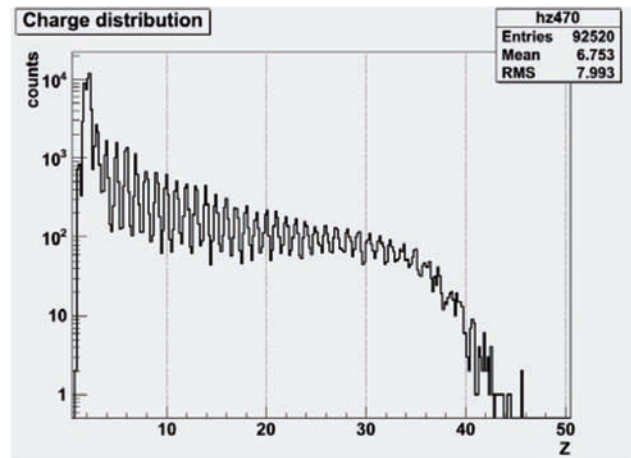


Figure 3: Z spectrum of fragments observed in a telescope placed at $\theta_{\text{lab}}= 19^\circ$ for $^{197}\text{Au} + ^{197}\text{Au}$ reaction at 23 AMeV.

For fragments that were stopped in the silicon detector, the TOF technique was applied. The dependence of the time offset parameter t_0 on the fragment's energy and Z is under investigation.

In Fig. 4 the observed dependence of t_0 on kinetic energy of the fission fragments originating from the $\text{Au} + ^{12}\text{C}$ reaction at 23 AMeV is presented for the detector located at 9.3 degrees. The data points are fitted by red line.

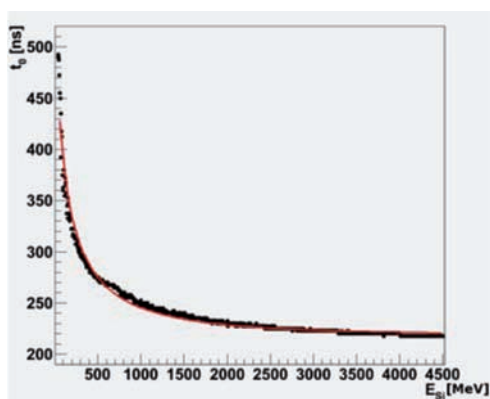


Figure 4: The t_0 parameter vs fission fragment kinetic energy detected in the detector R4SI35-E.

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Characterization of DSSSD detectors

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Abstract -The efficiency for full energy reconstruction in Double Sided Silicon Strip Detectors (DSSSD) is affected by anomalous charge collection effects for ions entering the interstrip region. It is found that for these detectors the effective interstrip region is larger than the geometrical one, moreover inverse polarity pulses are also observed. A systematic study of efficiency and charge collection effects for ions entering the interstrip region of DSSSD detectors is described.

INTRODUCTION

Highly segmented detectors are often used in nuclear physics. Detector segmentation is very useful to obtain accurate measurements of angular distributions or to study reactions where the coincidences between two or more particles are requested to fully characterize the final state. Aim of the present experiment is to characterize Double Sided Silicon Strip Detectors (DSSSD) in order to obtain precise information on the efficiency for full energy reconstruction. The solid state detectors that we had studied are DSSSD manufactured by Micron Semiconductor with active surface of 50x50 mm² and thickness of about 1000 µm. Each face of the detector is divided into 16 vertical strips for the front side (junction side) and into 16 horizontal strips for the back side (ohmic side). The overlapping regions between each front strip with each back strip determine 256 3x3 mm² pixels.

The presence of an insulating layer between adjacent strips (100 µm wide layer of SiO₂) deeply affects the charge collection on each strip for particles reaching the interstrip region, thus decreasing the efficiency for full energy reconstruction.

As shown in ref [2,3] the pulse of a particle that hits a back interstrip is split between the two strips. In this case in order to recover the interstrip events, it is enough to sum the pulses of the two adjacent strips.

The charge sharing of particles hitting the front interstrips is very different. Particles entering the detector through the front interstrip can generate pulses in both or just in one of the adjacent strips, but the sum of the pulses is smaller than the pulse produced by a particle having

same energy but entering the detector through the central region of a strip [1]. Moreover, as shown in ref. [1,2], inverted polarity pulses can be generated as well. A possible model to explain these effects is described in ref. [1]. The flowing charge coming from the leakage current and ionization build up on the insulating layer of SiO₂ modifying the field between the strips. The modified field and the induction process influence the charge collection on adjacent strips and can generate inverted polarity pulses, making the effective interstrip region larger than geometrical interstrip. Pulse height defect and modified polarity pulses are basically due to the charge produced by the ionizing particles in the region of the modified field. The higher is the charge produced in the modified field region the higher is the pulse height defect and the higher is the probability to get inverted polarity pulse. Then the efficiency for full energy reconstruction depends upon energy, mass and Z of the incident particle.

The main aim of this test is to perform a systematic measurement of the efficiency for the reconstructed energy of the DSSSD by scanning different implantation depth using ⁶Li and ¹⁶O ions at energies that range between 11 and 30 MeV for the first and from 10 to 52 MeV for the second. In addition we want to study the behavior of front interstrip and investigate on the feasibility to recover the energy of the particle impinging on the front interstrip by measuring at the same time negative and positive pulses.

EXPERIMENTAL SET-UP

The experimental set-up conceived is very simple. A DSSSD is placed in the LNS CT2000 chamber at 0°. The beam of very low intensity is directly sent to the detector. A MCP with high efficiency [5] was placed along the beam line to measure the beam particle rate. From the number of particles counted by MCP and the number of particle that generate in the DSSSD a pulse of correct energy we can easily determine the efficiency of the DSSSD. One of the main drawbacks is that, since the beam profile is not uniform, the detector is not uniformly

illuminated. Three different DSSSD were used to check possible differences between detectors of the same type.

Moreover one of them was reversed, that is the back side (ohmic side) was facing the beam to observe if the interstrip effects can be entirely imputed to the differences in the manufacturing of the front side (junction side).

The acquisition system was set in such away that both positive and negative signal are acquired at the same time.

From the output of the preamplifiers the signals were split and sent to the amplifiers.

PRELIMINARY RESULTS

An example of energy spectrum from the front face of the DSSSD is shown in fig 1. The full energy peak corresponds to particles entering the detector through the considered strip. The FWHM (that is the resolution) is about 120 KeV. The pedestal is due to particles crossing the MCP that trigger the acquisition and that do not enter the detector or that enter the detector in another strip, so they do not produce any signal. Moreover negative signals are observed as reported in reference [1,2]

It is possible to observe a continuous background of events with energy smaller than the full energy [1,2].

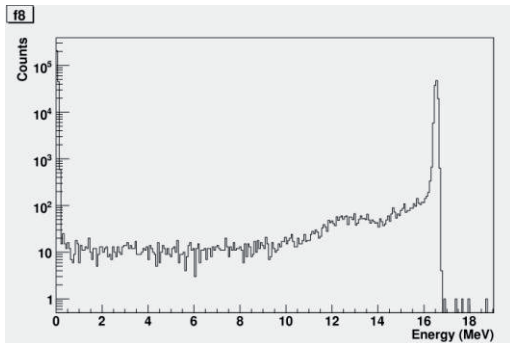


Figure 1: Energy spectrum from a front face strip for a ^7Li beam at 17 MeV.

The ratio between the counts in the background and the counts inside the full energy peak is 6-9%. We observe that the ratio depends on the energy and on the ion specie.

In fig. 2 is shown an example of energy spectrum for the back face of the DSSSD. In this case we do not observe any inversed polarity signal. In this case the ratio between counts in the background and the full energy peak is larger and ranges between 19% and 34% in this case a strong dependence on the energy and on the ion species is observed.

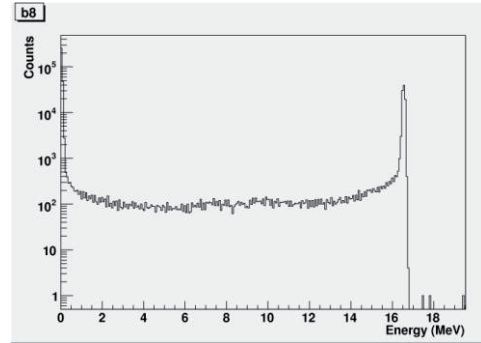


Figure 2: Energy spectrum from a back face strip for a ^7Li beam at 17 MeV.

The background events are due to particles entering the detector through the interstrip region. This can be fully understood looking to the correlations between two adjacent strips.

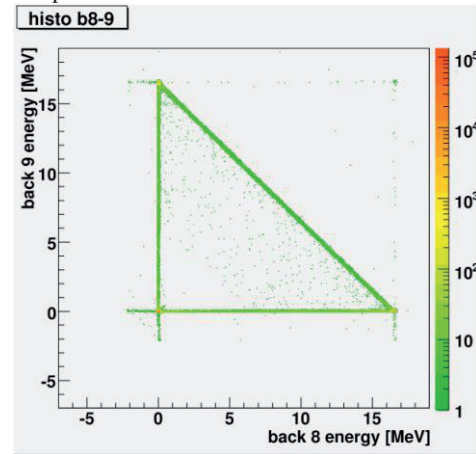


Figure 3: correlations between energy measured from two adjacent back strips.

In fig. 3 is shown the correlation between two adjacent back face strips (strips 8 and 9). For particle entering the detector near a back interstrip the charge produced is divided between the two adjacent strips.

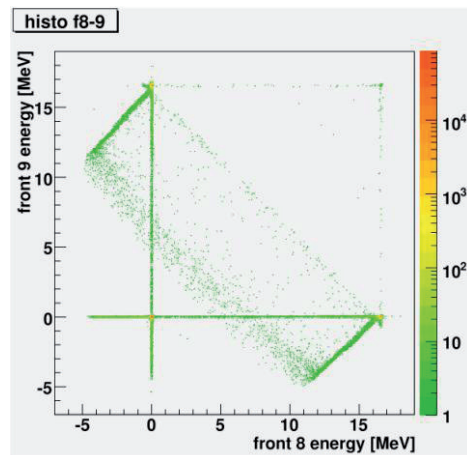


Figure 4: correlations between energy measured from two adjacent front strips.

A more complicated situation appears for the front face adjacent strip correlations displayed in figure 4. The regions labelled with A are the full energy peaks for the two strips. In the region B are present two signals in coincidence where one of that is negative, their sum in absolute value still giving a full energy signal. C labels the region of interstrip with the two other neighbour strips. Region D is made by events where positive-negative or positive-positive coincidences are present, but in this case the sum (in absolute value) does not give a full energy signal.

The same phenomena was already observed in ref. [1,2]. It was explained in by the presence of the SiO₂ layer separating the strips. The positive charges that accumulate on this insulating layer can locally generate an electric field which direction is opposite to the electric field generated by the bias of the detector. This reversed field modify the charge collection for particle entering the detector through the interstrip region.

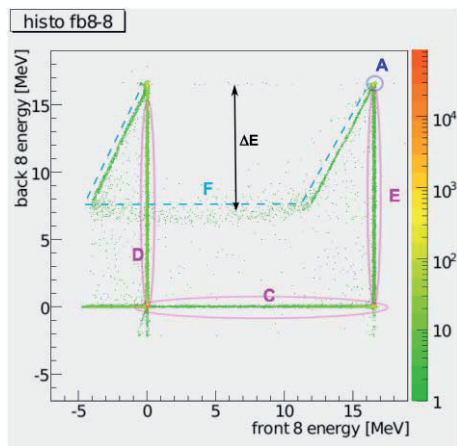


Figure 5: Coincidences between a front strip and a back strip for ⁷Li at 17 MeV and Bias 1 FDV. More details are given in the text.

Dependence on the energy

In figure 5 are shown the coincidences between front strip 8 and all the back strip 8 for a ⁷Li beam at 17 MeV and a bias of 200 V (corresponding to the full depletion voltage (FDV)). Region A corresponds to particles that hit the detector in front strip 8 and back strip 8. Region C (D) to particles that impinge on the detector through strip front (back) 8 and a strip back (front) that is not 8. Region E corresponds to particles entering the front strip 8 and are interstrip event for the back because the front strip give a signal of full energy while the back strip give a lower amplitude signal. Region F correspond to front interstrip events. In this case is evident that the front interstrip events give also a lower amplitude signal for the back. The difference ΔE between the full energy and the reduced energy is shown pictorially in figure 5. In figure 6 it is shown the same plot of figure 5 for a ⁷Li beam of 24 MeV for the same bias of the detector. It is important

to observe that ΔE depends on the energy of the incident particle. Moreover ΔE depends also on the bias applied to the detector. This is shown in figure 7 that refers to Li beam at 17 MeV but with bias of 280 V (1.4 FDV).

Next step will be the determination of the efficiency for full energy reconstruction as a function of the incident energy for the two different ions and for the two different detector biases.

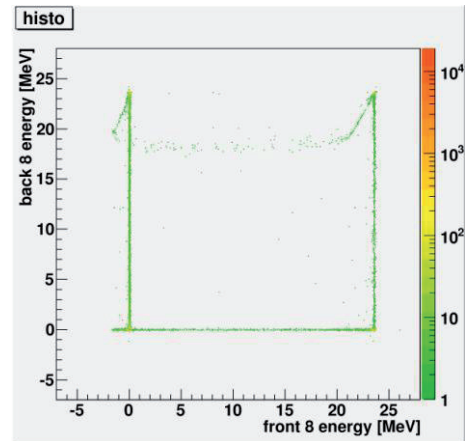


Figure 6: Coincidences between a front strip and a back strip for ⁷Li at 24 MeV and Bias 1 FDV. More details are given in the text.

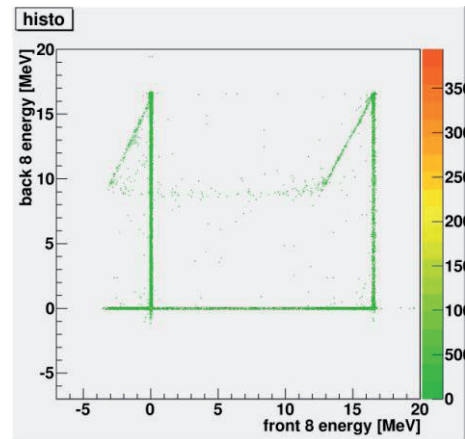


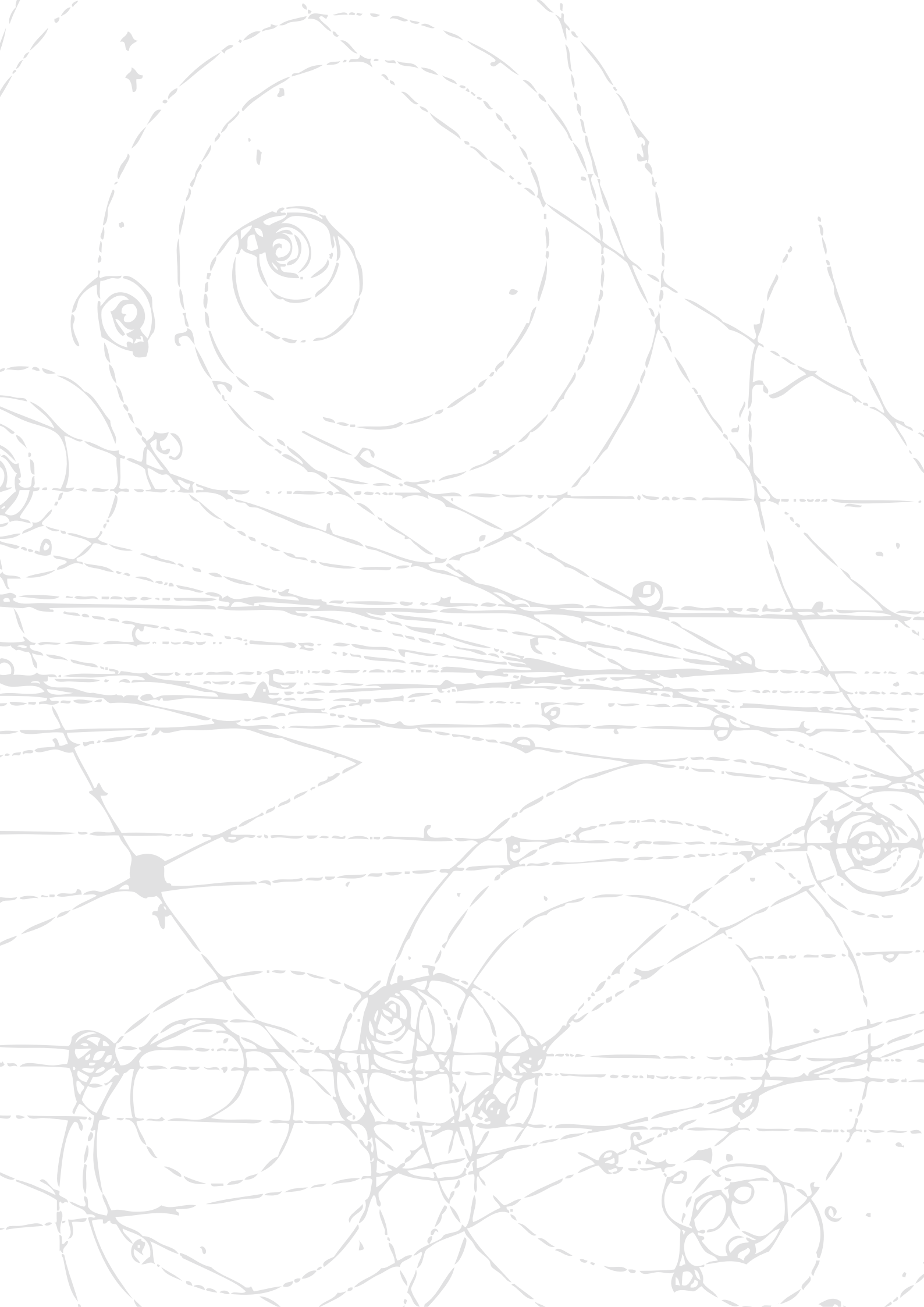
Figure 7: Coincidences between a front strip and a back strip for ⁷Li at 17 MeV and Bias 1.4 FDV. More details are given in the text.

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ISTITUTO NAZIONALE DI FISICA NUCLEARE
LABORATORI NAZIONALI DEL SUD
ACTIVITY REPORT 2010

**THEORETICAL
NUCLEAR
PHYSICS**



Ion acceleration by high-intensity lasers for medical isotope production

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Abstract - We have investigated the feasibility of using laser accelerated protons/deuterons for positron emission tomography (PET) isotope production. Especially the yield of the isotopes ^{11}C and ^{18}F are estimated by means of the nuclear reactions $^{11}\text{B}(\text{p},\text{n})^{11}\text{C}$, $^{10}\text{B}(\text{d},\text{n})^{11}\text{C}$, $^{18}\text{O}(\text{p},\text{n})^{18}\text{F}$ and $^{20}\text{Ne}(\text{d},\alpha)^{18}\text{F}$. The deuteron-induced reactions have positive Q-values and no energy threshold. One can, therefore, make use of the lower energy part of the laser-generated deuterons, which includes the majority of the accelerated deuterons. By assuming that the deuteron spectra are similar to the proton spectra, a high-repetition table top laser irradiation is estimated to generate 3.5×10^7 ^{11}C per shot from the reaction $^{10}\text{B}(\text{d},\text{n})^{11}\text{C}$. In terms of the ^{11}C activity, it is about 2×10^4 Bq per shot. If this laser delivers kHz, the activity is integrated to 1 GBq after 3 minutes. The number is sufficient for the practical application in medical imaging for PET. While the ^{18}F production requires higher-energy protons/deuterons, i.e., a high-power laser to accelerate the ions, in order to obtain a sufficient yield for the application.

INTRODUCTION

Laser accelerated proton beams have been applied to produce positron emitting isotopes by several groups [1–4]. Those groups investigate the feasibility of ^{11}C and ^{18}F isotope production rates by the laser-induced reactions $^{11}\text{B}(\text{p},\text{n})^{11}\text{C}$ and $^{18}\text{O}(\text{p},\text{n})^{18}\text{F}$. The reactions have negative Q-values of 2.765 MeV and 2.44 MeV, respectively, and, therefore, require large-scale lasers like the VULCAN laser facility at the Rutherford Appleton Laboratory (RAL). Such large scale lasers are single shot. At current technology table-top lasers, which generate low temperature plasma but operate at high repetition rate, cannot lead to the reaction. In Ref. [1] from the reaction $^{11}\text{B}(\text{p},\text{n})^{11}\text{C}$ induced by the laser-generated protons and the secondary boron target, the activities of 2×10^5 Bq of the isotope ^{11}C have been measured. They have carried out the experiments using the VULCAN laser, which delivers pulses of energies up to 120 J, duration 0.9 – 1.2 ps and a wave length of 1053 nm. This laser pulse focused on a thin Al foil generates protons of energies as high as 37 MeV, from the contaminants on the foil target. Lately, the experiment is repeated at the same VULCAN laser at a pulse energy of 300 J with a pulse duration of 750 fs [3], ^{11}C and ^{18}F activities of 6×10^6 Bq and 2×10^5 Bq, respectively, have been reported. On the other hand the activity required for PET is at least 200 MBq and ideally it is 800 MBq [1]. In this paper we investigate the feasibility of this application but using the reaction $^{10}\text{B}(\text{d},\text{n})^{11}\text{C}$ and $^{20}\text{Ne}(\text{d},\alpha)^{18}\text{F}$, instead. These reactions have positive Q-values. There is, therefore, no energy-threshold for the reactions [5,6]. This means that smaller size lasers with higher-repetition rates can be used in contrast to the large-scale lasers, though such lasers generate proton beams at lower energies. Laser-generated deuterons from deuterated plastic layer on an Al foil target has been investigated only recently [7–10]. A numerical investigation suggests that by eliminating surface contaminants, which contain protons, deuterons can be accelerated successfully, even though the laser pulse energy is relatively low. Specially regarding the production of the isotope ^{18}F , the proton induced reaction uses ^{18}O . The natural isotope abundance of ^{18}O is very small and it is 0.2 %. While ^{20}Ne , which is used for the deuteron induced reaction, is the most abundant isotope of neon. The deuteron-induced reaction has a positive Q-value of 2.8 MeV.

We compare estimates of ^{11}C and ^{18}F yields for the proton- and deuteron-induced reactions irradiated by a table-top laser, ASTRA Ti:sapphire laser facility [10] at RAL. This laser delivers a pulse energy of 200 mJ, a pulse length of 60 fs and a wave length of 790 nm, with a repetition rate of 2 Hz.

ION ACCELERATION BY LASERS

Several mechanisms are proposed to be responsible for the ion acceleration by interaction of high-intensity laser pulses with thin foil targets. The target normal sheath acceleration (TNSA) is one of those mechanisms and is thought to be the dominant mechanism at laser intensities from 10^{18} to 10^{21} W/cm². We assume the TNSA mechanism as the mechanism of the proton and deuteron acceleration. In the electric field of a laser, electrons on the front surface of the target quiver. The oscillating motion of the electrons causes a force, which drives the electrons into the target normal direction, due to the oscillational magnetic field perpendicular to the electrons' motion. The accelerated electrons penetrate through the target, ionizing the surface contaminants on the back, and form a dense sheath on the back. The charge separation between the escaping electrons and the ions left behind causes an electrostatic field which accelerates the protons in the hydrocarbon contaminant on the back surface. Under the TNSA mechanism, the protons and deuterons are expected to be accelerated by the same force eE , where e and E are the electron charge magnitude and the electric field due to the charge separation, respectively. The energy of the deuterons accelerated by the electro

static field is determined by the charge of the deuteron which is the same of protons. Consequently the energy of the deuterons should be the same as the energy of the protons accelerated by the same field, while their velocities are different. On this account we expect that the deuteron energy spectra is similar to that of the protons. However, recently published experimental data [7–9] show a controversial result. Experiments on the deuteron acceleration have been performed using T-cubed laser at the university of Michigan. This laser delivers a pulse energy up to 6 J in a 400 fs. The target was a 6 mm thick Al or 13 mm thick Mylar, coated with a layer of deuterated polystyrene either on the back or on the front or both side of the target.

For the detection of accelerated ions, a Thomson parabola spectrometer has been used with a micro channel plate with a phosphor screen. The experimental observation that protons are accelerated preferentially to deuterons [7,9] is because the protons in the surface contaminants are on the top of the deuterated plastic layer. The protons, which are facing directly to the charge-separation electric field, see the maximum field strength, while the deuterons underneath the surface contaminant see the reduced electric field shielded by the protons. If the electrostatic field formed on the back surface is large enough, the layer of protons are ablated totally by the field. Then the ions of the target become exposed to the field and are accelerated by the remaining electrostatic field energy.

Another reason could be that if you have a mixture of different particles, the ones with lower mass leave the target first because of the higher velocity. Thus once they leave the target the electric field is reduced and the heavier ones see a lower field. Thus it is important to have pure targets to maximize the deuteron flux. The surface contaminants layer can be removed either by thermal heating [10] or using a secondary laser to ablate the surface. The use of high-repetition lasers has an advantage from this view point, since the contaminants of lower mass (protons) will be removed in the repetitional pulses. The removal of the contaminant allows acceleration of the target material (deuterons) efficiently [7,9]. The reductions both in the maximum deuteron energy and in the number of accelerated deuterons compared to the case of protons is observed to be approximately 1:10 [9] at the given experimental condition, i.e., the thicknesses of the target and of the contaminant layer, and the specific laser parameters.

Further experimental investigations are needed to understand difference between the proton- and deuteron-spectra, generated at different laser parameters and experimental conditions. For the purpose of the yield estimate of positron emitting nuclei, we use the same energy spectra as protons for deuterons at a set of given laser parameters. We stress that this alternative reaction to produce radioisotopes using deuterons is in any case interesting, considering the possibilities that with advancing technologies, higher repetition lasers of relatively low energy and short pulse might be feasible.

YIELD EVALUATIONS

The yield (N_f) at a given incident energy E is evaluated by [5,6]

$$N_f = N_i \sigma(E) n_T d \quad (1)$$

where N_i , $\sigma(E)$, n_T and d are the number of accelerated ions, the cross section of the reaction, the density of the target and the effective thickness of the target, respectively. In a simple approximation the effective thickness of the target is replaced by the projected range of the protons in the target. That is the cross section is assumed to be a constant at the given incident energy, through the whole target. This assumption is correct, if the target is thin and the energy loss of the ions in the target is negligible; otherwise the yield from a thick target at an incident energy (E_{in}) is given by integrating the beam energy down to zero. This integral takes into account that the projectile ion loses its initial energy in the target. Since the incident protons have an energy spread characterized by a Maxwellian, Eq. (1) must be integrated over the incident energy, to obtain the total yield. We estimate the angular distribution of the reaction products, i.e., neutrons and alpha-particles for the reactions $^{11}\text{B}(p, n)^{11}\text{C}$, $^{10}\text{B}(d, n)^{11}\text{C}$, $^{18}\text{O}(p, n)^{18}\text{F}$ and $^{20}\text{Ne}(d, \alpha)^{18}\text{F}$ from the given proton/deuteron spectra.

Spencer et al. [10] studied proton spectra from plastic, aluminum and copper targets from a high-repetition-rate tabletop-laser irradiation. The laser parameters in the experiment are the laser energy of 200 mJ, the pulse length of 60 fs and the wave length of 790 nm. It is of interest that the plastic target irradiation, at such laser parameters, generates higher energy protons and that the proton spectra have characteristic shape which cannot be approximated by a simple Maxwellian. Thus we choose a proton spectra from Mylar target irradiation, which are shown in Fig. 2 in Spencer et al. [10]. The proton spectrum is reproduced in the top panel in Fig. 1. Assuming that the deuteron spectra in deuterated plastic target irradiation are similar to the proton spectra, we estimate the total yield for the reaction $^{10}\text{B}(d, n)^{11}\text{C}$. The angular distribution of the neutron yield with the secondary boron target is calculated. The neutron spectra at five selected emission angles are estimated and shown in Fig. 1. The neutron spectra range from 5.9 to 8.1 MeV at the forward angle and to 6.4 MeV at the backward angle. The evident two peaks in the neutron spectra are due to the two peaks in the proton spectra in the top panel. By integrating the neutron yield, the total yield of the reaction $^{10}\text{B}(d, n)^{11}\text{C}$ is estimated to be 3.5×10^7 per shot. While in the reaction $^{11}\text{B}(p, n)^{11}\text{C}$ there will be no ^{11}C yield at this table-top high-repetition laser irradiation.

The ^{18}F yield of the reaction $^{20}\text{Ne}(d, \alpha)^{18}\text{F}$ is estimated using the same deuteron spectra at the high-repetition laser and the stopping power of the hydrogen ions in a neon gas target. The estimated yield is 1.6×10^5 .

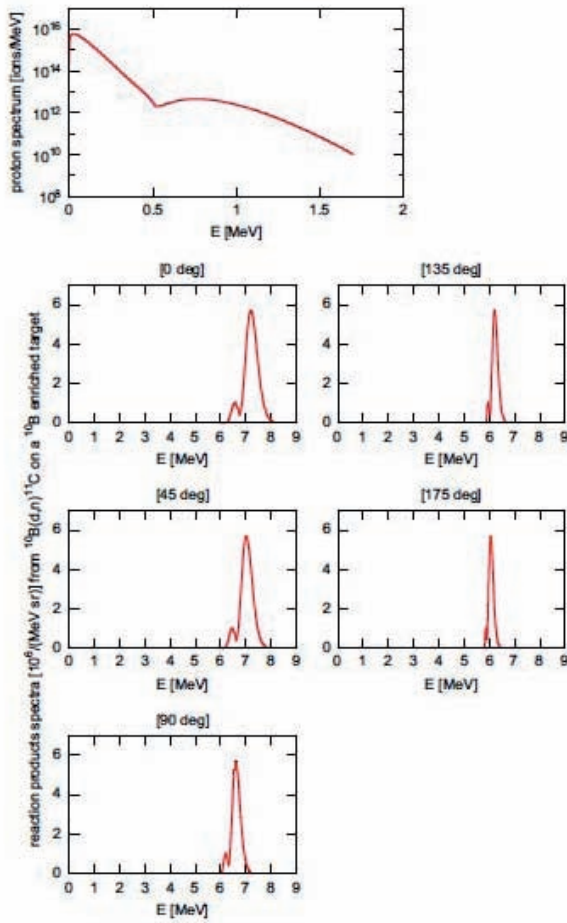


Figure 1: Proton spectrum at a table-top laser irradiation on a 36 mm-thick Mylar target (top panel). Expected neutron spectra from the reaction $^{10}\text{B}(\text{d},\text{n})^{11}\text{C}$ on a 3 mm-thick ^{10}B enriched target at five selected emission angles at a high-repetition-rate table-top laser irradiation.

DISCUSSIONS

Using the reaction $^{10}\text{B}(\text{d}, \text{n})^{11}\text{C}$ and the table-top, high-repetition laser, we have estimated ^{11}C production of 3.5×10^7 per shot. In terms of the ^{11}C activity it is 2×10^4 Bq per shot. Considering that ^{11}C decays with the half-life of 20.4 min and given 2 Hz repetition rate, after 30 min of irradiation the activity is integrated to be 22 MBq. If this laser delivers kHz, the activities are integrated to 1 GBq after 3 min and meet the required activity for the practical use of the PET isotope production.

The ^{18}F yield of the reaction $^{20}\text{Ne}(\text{d},\alpha)^{18}\text{F}$ is estimated to be 1.6×10^5 . In terms of the ^{18}F activity it is 16 Bq per shot. Given that 2 Hz repetition-rate, after 30 min of irradiation the activity is integrated to be 5.3×10^4 Bq. If the repetition rate can be increased to kHz, after 30 min of irradiation, the activity is integrated to be 2.6×10^7 Bq.

The estimated activity at a kHz repetition-rate laser after 30 min of irradiation is much lower than the required activity for the practical application. The ^{18}F activities estimated at the high-repetition rate laser and with deuterated cluster target irradiation are considerably lower compared with the required activity. This is because the cross section of the reaction $^{20}\text{Ne}(\text{d},\alpha)^{18}\text{F}$ is small at the incident energy less than 2 MeV. In order to take full advantage of the peak of the cross section of the reaction, the deuterons must be accelerated at least up to 5 MeV.

SUMMARY

We have studied the feasibility of ^{11}C isotope production by means of the nuclear reactions $^{11}\text{B}(\text{p},\text{n})^{11}\text{C}$, $^{10}\text{B}(\text{d},\text{n})^{11}\text{C}$, $^{18}\text{O}(\text{p},\text{n})^{18}\text{F}$ and $^{20}\text{Ne}(\text{d},\alpha)^{18}\text{F}$, induced by laser-accelerated protons/deuterons. The yield of ^{11}C at a table-top, high-repetition laser has been estimated to be 3.5×10^7 per shot for the deuteron induced reaction. In terms of the ^{11}C activity, it is about 2×10^4 Bq per shot. If this laser delivers kHz, the activity is integrated to 1 GBq after 3 min and meet the required activity for the practical use of the PET isotope production. With regard of the reactions $^{18}\text{O}(\text{p},\text{n})^{18}\text{F}$ and $^{20}\text{Ne}(\text{d},\alpha)^{18}\text{F}$, The ^{18}F activities estimated at the high-repetition rate laser and with deuterated cluster target irradiation are considerably lower compared with the required activity. However the former reaction requires the isotope ^{18}O which has a very small natural abundance, while the latter reaction has an advantage of using an abundant isotope ^{20}Ne .

The realization of this potential application requires further research to understand optimum parameters for deuteron acceleration by intense lasers. Our results have demonstrated a promising alternative way of using high-intensity laser for the application in the PET isotope production.

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How temperature dependence of the energy loss influences jet quenching observables

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Abstract - Jet quenching is one fundamental tool to study the QGP formed in ultra-relativistic heavy-ion collisions. We have analyzed, by a simple jet quenching modeling, the correlation between different observables like the nuclear modification factor $R_{AA}(p_T)$, the elliptic flow v_2 and the ratio of quark to gluon suppression $R_{AA}(quark)/R_{AA}(gluon)$. We show that the relation among these observables is strongly affected by the temperature dependence of the energy loss. We find that an energy loss that increase as $T \rightarrow T_c$, the $q \leftrightarrow g$ in-medium conversion and an expansion-cooling of the fireball according to a lattice QCD EoS improve the agreement between theoretical prediction and experimental data.

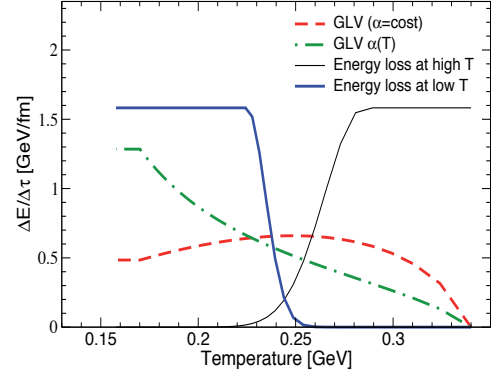


FIG. 1: Temperature dependence of the energy loss for a parton with transverse momentum p_T equal to 10 GeV.(see text for further details).

INTRODUCTION

In the first stages of the ultra relativistic heavy Ion collision are created high energy jets ($p_T \gg T, \Lambda_{QCD}$) that can be exploited to probe the Quark Gluon Plasma (QGP). This energy loss can be quantified by the suppression of observed hadron spectra at high transverse momenta p_T , namely $R_{AA}(p_T)$ [1]. Although the observation of the jet suppression cannot be questioned there are several fundamental issues that still remain open. To investigate them we have constructed a model that permit to study two observables beyond the $R_{AA}(p_T)$ i.e. the elliptic flow $v_2(p_T)$, and the ratio $R_{AA}(q)/R_{AA}(g)$. We suggest that the study of the correlation between these two observables carry information on the temperature dependence of the quenching and on the mechanism of parton flavor conversion.

MODELING THE JET QUENCHING

In the model the density profile of the bulk is given by the standard Glauber model while the hard parton distributions in momenta space are calculated in the next-to-leading- order (NLO) pQCD scheme. For the hadronization the Albino-Kramer-Kniehl (AKK) fragmentation functions have been employed. For further details see Ref. [2]. With regard to the jets energy loss we have employed various schemes, however to make a connection to other

works, we have used also the Gyulassy-Levai-Vitev (GLV) formula at first order in the opacity expansion [3].

$$\frac{\Delta E(\rho, \tau, \mu)}{\Delta \tau} = \frac{9\pi}{4} C_R \alpha_s^3 \rho(x, y, \tau) \tau \log \left(\frac{2E}{\mu^2 \tau} \right) \quad (1)$$

where C_R is the Casimir factor equal to 4/3 for quarks and 3 for gluons, α_s is the strong coupling, $\rho(x, y, z)$ is the local density, τ the proper time, E is the energy of the jet and $\mu = gT$ is the screening mass. In Fig.1 we show by dot-dashed and dashed lines the temperature dependence of the energy loss for the GLV with a dependence of the coupling (GLV- $\alpha_s(T)$) and with a constant coupling $\alpha_s = 0.27$ (GLVc). Furthermore we show two other opposite cases for $\Delta E/\Delta \tau$: the thick line that shifts the energy loss to lower temperature as suggested in [3,4] and the other (thin line) that gives a dominance of quenching at high T , considered here just for comparison respect to the opposite case.

We have applied our modelling of the jet quenching to Au+Au collisions at 200 AGeV and in Fig.2 we can see that the dependence on centrality is correctly predicted with a GLV formula for both constant and T-dependent α_s .

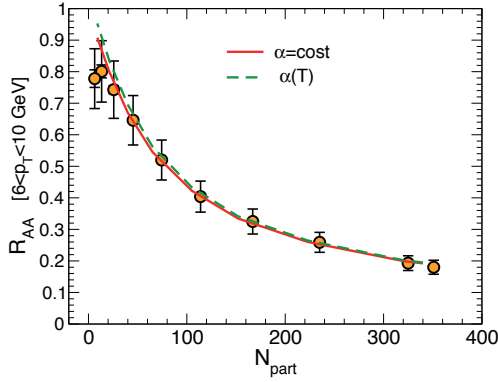


FIG. 2: Nuclear Modification Factor as a function of the number of participant in $Au + Au$ at 200 AGeV [6].

ANGULAR AND FLAVOR DEPENDENCE OF THE QUENCHING

Experimental data relative to v_2 are considerably larger than theoretical prediction moreover the flavor dependence of quenching is not clearly understood. We call this open issues the "azimuthal" and the "flavor" puzzle respectively. To analyze them we have explored the relation between the temperature dependence of quenching, the value of the elliptic flow and the value of the ratio $R_{AA}(q)/R_{AA}(g)$. In Fig.3 and in Fig. 4 we can see that even if the amount of total quenching has been fixed to the experimental value of $R_{AA}(p_T)$ the amount of elliptic flow and the ratio $R_{AA}(q)/R_{AA}(g)$ are strongly dependent on the temperature dependence of the E_{loss} . In particular an energy loss predominant at low T move v_2 toward observed data but move the ratio $R_{AA}(q)/R_{AA}(g)$ away from experimental indications. This is evident if one looks at the upper symbols of Fig.6 where $(R_{AA}(q)/R_{AA}(g))$ vs v_2 is shown. To understand this behavior see [2].

We have also performed some calculation for the LHC energies to study how the longer lifetime and higher temperatures reached at LHC can affect the observed correlations between temperature dependence of quenching v_2 and $R_{AA}(q)/R_{AA}(g)$. We have used less extreme temperature dependences of the energy loss with respect to those shown in Fig.1. The results for the ratio between the nuclear suppression factors are shown in Fig.6. The rises that we see between 5 and 15 GeV are independent from the typologies of energy loss and are due to the changes in the slope of the parton spectra, and in particular to the differences in such changes between the quark spectrum and the gluon spectrum.

To solve the "flavor puzzle" inelastic collisions that cause a change of the flavor has been invoked [8]. Such a process would at the end produce a net conversion of quarks into gluons. Hence a decrease of gluons suppression with respect to the original suppression and an increase of the quark one. We have

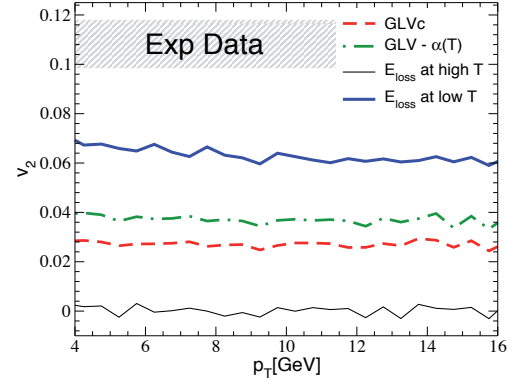


FIG. 3: Elliptic Flow for pions ($b=7.5$ fm) for the different T dependence of the energy loss. The shaded area shows the experimental data [6,7].

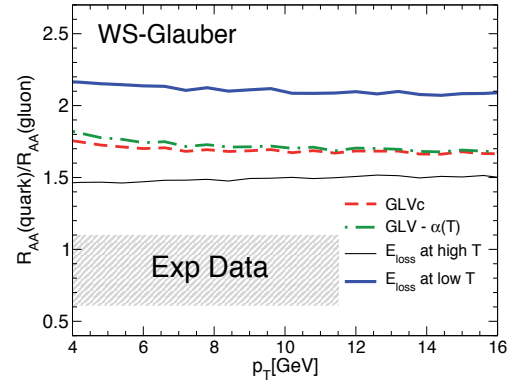


FIG. 4: Ratio of quark to gluon R_{AA} for the different T dependence of the energy loss. The shaded area approximatively shows the value expected for the ratio

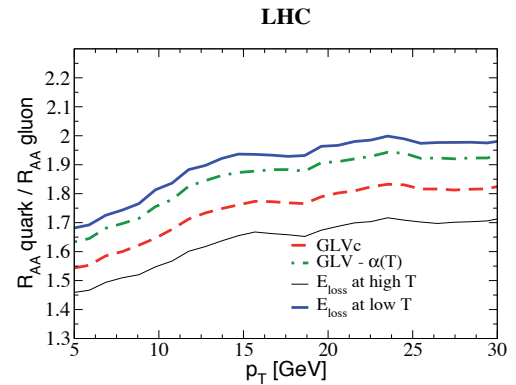


FIG. 5: Ratio of quark to gluon R_{AA} for the different T dependence of the energy loss for LHC.

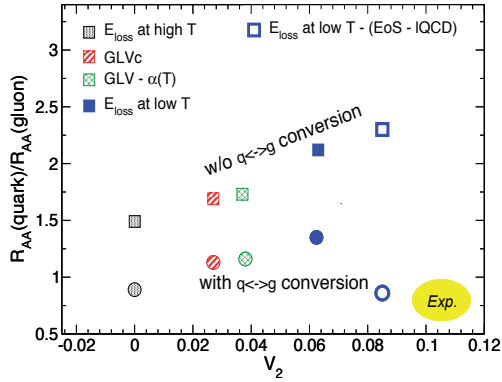


FIG. 6: Correlation between the $R_{AA}(q)/R_{AA}(g)$ and the elliptic flow of pions with transverse momentum in the range $6 < p_T(\text{GeV}) < 10$ (see Text).

included this mechanism in our model and the results are the lower symbols in Fig.6. We can observe that the $q \leftrightarrow g$ conversion does not affect the v_2 and allows to get closer to the experimental observed value i.e. a $v_2 \sim 0.1$ and an $R_{AA}(q)/R_{AA}(g) \leq 1$.

As a last point, we have observed that if the quenching is predominant near the phase transition the free gas approximation is no longer a reasonable approximation. We have made some explorative studies on the impact that a more correct equation of state (EoS) can have on the correlation between $R_{AA}(q)/R_{AA}(g)$ and $v_2(p_T)$. Making a fit to the lattice QCD data [9] we have obtained the following relation between density and temperature

$$\frac{T}{T_0} = \left(\frac{\rho}{\rho_0} \right)^{\beta(T)} \quad (2)$$

where $\beta(T) = 1/3 - a(T_c/T)^n$ with $T \geq T_c$, $a = 0.15$ and $n = 1.89$. In order to estimate the impact of this correction we have performed a simulation for the $\Delta E_{loss}(T)$ behavior represented by the thick solid line in Fig.1. The results are given by open symbols in Fig.6. Respect to the free gas expansion cooling the system spends more time at $T \sim T_c$ and this reflects in a further enhancement of both $v_2(p_T)$

and efficiency of the $q \leftrightarrow g$ conversion moving the two observables closer to experimental data (shaded area in Fig.6).

CONCLUSIONS

We have found that the elliptic flow and the ratio between the quark and gluon suppression are strongly related to the temperature dependence of the energy loss. In particular the large v_2 and the nearly equal $R_{AA}(p_T)$ of quarks and gluons can be accounted for only if the energy loss occurs mainly around the temperature T_c and the flavour conversion is significant. Moreover we have spotted the relevance that the EoS may have in case of E_{loss} dominant in the $T \sim T_c$ region. In any case our study, although already revealing several interesting indications, is mainly explorative and it can be considered as a benchmark. A more quantitative analysis should be performed with more sophisticated models that include the energy loss fluctuations, realistic gain and loss processes, elastic energy loss and a more accurate description of the bulk.

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Probing the hadron-quark mixed phase at finite temperature, baryon and isospin chemical potentials

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Abstract - The two-Equation of State (Two-EoS) model is critically adopted to describe the hadron-quark phase transition in dense matter formed in heavy-ion collisions. For the hadron sector we use Relativistic Mean Field (RMF) effective models, already tested on heavy ion collision (HIC) observables. For the quark phase we consider various effective models, the MIT-Bag static picture, the Nambu–Jona-Lasinio (NJL) approach with the chiral dynamics and finally the NJL coupled to the Polyakov-loop field (PNJL), which includes both chiral and (de)confinement dynamics. The idea is to extract mixed phase properties which appear robust with respect to the model differences. In particular the phase transitions of isospin asymmetric matter are focussed on, and some possible observation signals are suggested to probe in heavy-ion collision experiments at intermediate energies.

INTRODUCTION

The exploration of the phase diagram of strongly interacting matter and search for the signals of the phase transition from hadronic to quark-gluon phase are very important in both theory and experiment. As a fundamental tool, lattice QCD provides us a framework for investigation of non-perturbative phenomena such as confinement and quark-gluon plasma formation at finite temperature and vanishing (small) chemical potential [1–3]. However, lattice QCD suffers the sign problem of the fermion determinant with three color at finite μ . Although several approximation methods have been taken to try to evade this problem the validity of lattice simulations at finite chemical potential is still limited in the region $\mu_q/T < 1$. The results given with $\mu_q/T > 1$ should be taken with care [4].

On the other hand, many phenomenological models [5–8], as well as the more microscopic Dyson-Schwinger equations (DSEs) approach [9], have

been proposed to give a completed description of QCD phase diagram. Among these effective models, the Nambu–Jona-Lasinio model (NJL) is a predominant one, which offers a simple illustration of chiral symmetry breaking and restoration, a key feature of QCD [10–12]. One deficiency of the standard NJL model is that quarks are not confined. Recently, an improved version of the NJL model coupled to Polyakov loop (PNJL) has been proposed [13]. The PNJL model takes into both the chiral symmetry and (de)confinement effect, giving a good interpretation of lattice data at zero chemical potential and finite temperature, and make predictions in the region that cannot be reached in lattice calculation [14–16].

Most effective models, including the PNJL model, study the hadron-quark-gluon phase transition based on quark degrees of freedom. As a matter of fact, at low temperature and small chemical potential, the QCD dynamics is governed by hadrons. Therefore, it is natural to describe the strongly interacting matter with hadronic degrees of freedom at low T and small μ and quarks at high T and large μ . This picture can be realized in the two equation of state (Two-EoS) approach in which hadronic and quark phases are connected by Gibbs (Maxwell) criteria. This frame is widely used in describing the phase transition in the interior of compact star in weak equilibrium (e.g., [17–20]). Recently, it has also been taken to explore the phase diagram of hadron-quark transition at finite temperature and density concerned with heavy-ion collision [21–26]. Moreover, more attention was paid to asymmetric matter, and some observable effects have been already suggested in Ref. [22, 23].

We have studied the hadron-quark phase transition in the Two-EoS model by using the Relativistic Mean Field EoS for the hadron sector and various effective approaches for the quark phase, the static

MIT-Bag model [23, 26], the NJL model [27] with the chiral dynamics and finally the extension to the Polyakov-Loop coupling (PNJL) [28] to include also the (de)confinement dynamics.

We obtain the phase diagrams of hadron-quark-gluon phase transition in $T - \rho_B$ and $T - \mu_B$ planes. The calculations show that some interesting signatures of the transition are very robust, in the sense that they appear for all the different quark EoS:

- The transition is of the first order at finite temperatures and chemical potentials.
- For isospin asymmetric matter the onset density of the mixed phase is much smaller than the one of symmetric matter. This appears important for the possibility of observations in heavy ion collisions at intermediate energies.
- The Isospin Distillation Effect, i.e. the isospin enrichment of the quark component in the mixed phase in the case of asymmetric matter, is always present, in particular at lower temperatures.

All that leads to some confidence about the possibility of an experimental confirmation.

Besides, the results show that the phase-transition region is greatly modified when both the chiral dynamics and (de)confinement effect are considered. The phase-transition at high T is more close to the result given by lattice calculation at small chemical potential. A Critical-End-Point (CEP) is found at $T \simeq 170 \text{ MeV}$ and baryon chemical potential $\mu_B \simeq 600 \text{ MeV}$, i.e. at a quark chemical potential $\mu_q/T_c \simeq 1$, in a region that could be tested by extended lattice calculations.

HADRON MATTER, QUARK MATTER AND THE MIXED PHASE

In the Two-EoS model, the hadron matter at finite temperature and density/chemical potential is described by the non-linear Walecka model, the Relativistic Mean Field (RMF) effective theory which provides an excellent description of nuclear matter and finite nuclei as well as of compressed matter properties probed with heavy ion collisions at high energies [21, 22, 29, 30]. The exchanged mesons include the isoscalar-scalar meson σ and isoscalar-vector meson ω (NL force, for isospin symmetric matter), isovector-vector meson ρ and isovector-scalar meson δ , ($NL\rho$ and $NL\rho\delta$ forces, for isospin asymmetric matter).

The quark matter at the same conditions is described by the MIT-Bag [23, 26], NJL [27] and PNJL [28] models. For the mixed phase between the pure hadronic and quark phase, the two phases are connected each other with the Gibbs conditions

with the thermal, chemical and mechanical equilibriums.

Our aim is to compare mixed phase results obtained with different quark models but keeping the same hadron EoS. However we face a problem since while the microscopic NJL and PNJL approaches have no free parameters, in the MIT-Bag picture the Bag constant can be largely varied, in particular at high densities. Here we have chosen the Bag constant value in order to reproduce the same critical point at high chemical potential as in the NJL and PNJL cases (for isospin symmetric matter). From the systematic study reported in ref.[26] a good choice seems to be $B^{1/4} = 160 \text{ MeV}$.

Based on the conservations of baryon number and isospin during the strong interaction, the Gibbs conditions describing the phase transition can be expressed by

$$\begin{aligned}\mu_B^H(\rho_B, \rho_3, T) &= \mu_B^Q(\rho_B, \rho_3, T) \\ \mu_3^H(\rho_B, \rho_3, T) &= \mu_3^Q(\rho_B, \rho_3, T) \\ P^H(\rho_B, \rho_3, T) &= P^Q(\rho_B, \rho_3, T),\end{aligned}\quad (1)$$

where $\rho_B = (1 - \chi)\rho_B^H + \chi\rho_B^Q$ and $\rho_3 = (1 - \chi)\rho_3^H + \chi\rho_3^Q$ are the total baryon density, isospin density of the mixed phase, respectively, and χ is the fraction of quark matter, The global asymmetry parameter α for the mixed phase is

$$\alpha \equiv -\frac{\rho_3}{\rho_B} = \frac{(1 - \chi)\rho_3^H + \chi\rho_3^Q}{(1 - \chi)\rho_B^H + \chi\rho_B^Q} = \alpha^H|_{\chi=0} = \alpha^Q|_{\chi=1}, \quad (2)$$

which is determined by the heavy-ion source used in experiment.

Before showing detailed phase diagrams we can already predict the effects of chiral and (de)confinement dynamics on the quark pressure and then on the phase transition. The chiral symmetry restoration at finite temperature and low chemical potentials will largely increase the quark pressure leading to an End-Point for the pressure matching with the hadron part. When the confinement dynamics is added we will also get a reduction of the quark degrees of freedom and so in general the quark pressure will be reduced. This will imply the shift of the matching with the hadron pressure, and so also of the Critical-End-Point, to higher temperatures [28].

NUMERICAL RESULTS AND DISCUSSIONS

We present firstly the phase transition from hadronic to deconfined quark phase in $T - \rho_B$ plane for isospin symmetric matter in Figs. 1(solid lines), 2 and 3 using the same NL hadron interaction and the MIT-Bag, NJL, PNJL respectively for the quark sector. In the Figs. 1 (dot-dashed lines),

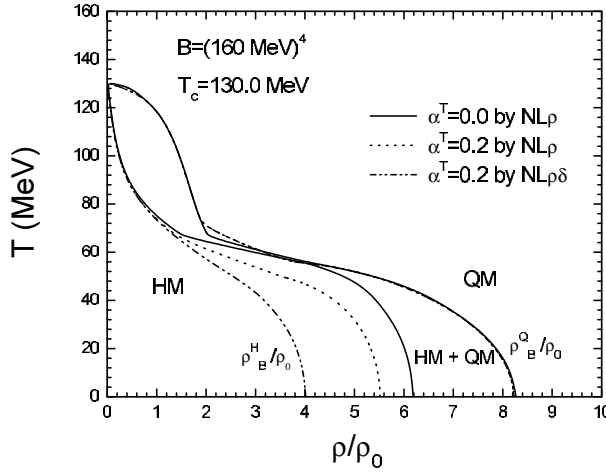


FIG. 1: Phase diagram in $T - \rho_B$ plane in the Two-EoS Hadron-MIT Bag model for isospin symmetric and asymmetric matter. $NL\rho$, $NL\rho\delta$ hadron interactions.

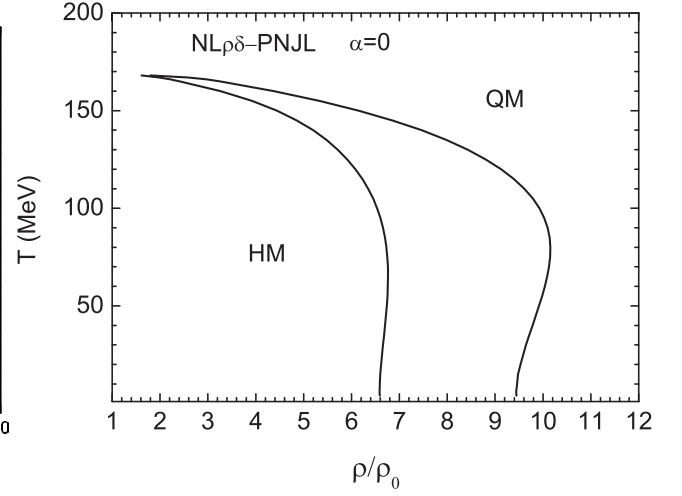


FIG. 3: Phase diagram in $T - \rho_B$ plane in the Two-EoS Hadron-PNJL model for symmetric matter. NL hadron interaction.

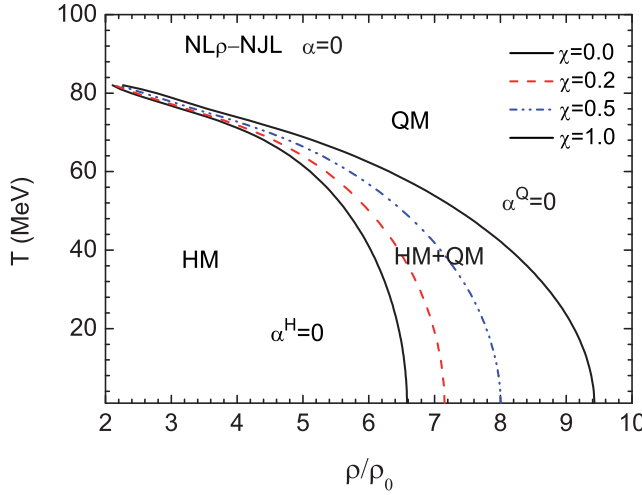


FIG. 2: Phase diagram in $T - \rho_B$ plane in the Two-EoS Hadron-NJL model for symmetric matter. NL hadron interaction. χ is the quark fraction in the mixed phase.

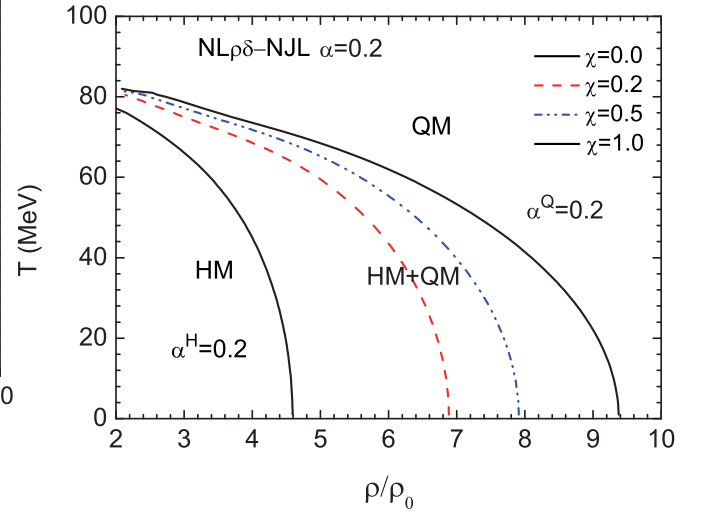


FIG. 4: Phase diagram in $T - \rho_B$ plane in the Two-EoS Hadron-NJL model for asymmetric matter with the global asymmetry parameter $\alpha = 0.2$. χ represents the fraction of quark matter. $NL\rho\delta$ hadron interaction.

4 and 5 the corresponding transition curves for isospin asymmetric matter with the global asymmetry parameter $\alpha = 0.2$. The same $NL\rho\delta$ interaction is used for the hadron matter.

For symmetric matter at a fixed T , the first order phase transition takes place with the same pressure and μ_B in both phases, but a jump in extensive variables, like density, energy density and entropy. In the mixed phase, the pressures of both phases keep unchanged and $\alpha = \alpha^H = \alpha^Q = 0$ for any quark fraction χ .

These features are quite different for the mixed phase in isospin asymmetric matter. For all the different quark EoS, MIT-Bag [22, 23, 26], NJL [27]

and PNJL [28] we see a clear Isospin Distillation effect, i.e. a strong enhancement of the isospin asymmetry in the quark component inside the mixed phase, as reported in Figs. 6 (dotted line), 7, 8, where the asymmetry parameters in the two components are plotted vs. the quark fraction χ . As a consequence the pressure in the mixed phase keeps rising with χ , more rapidly for quark concentrations below 50 %, see details in [23, 27].

From Figs. 7, 8 we remark that this isospin enrichment of the quark phase is rather robust vs. the increasing temperature. This is important since

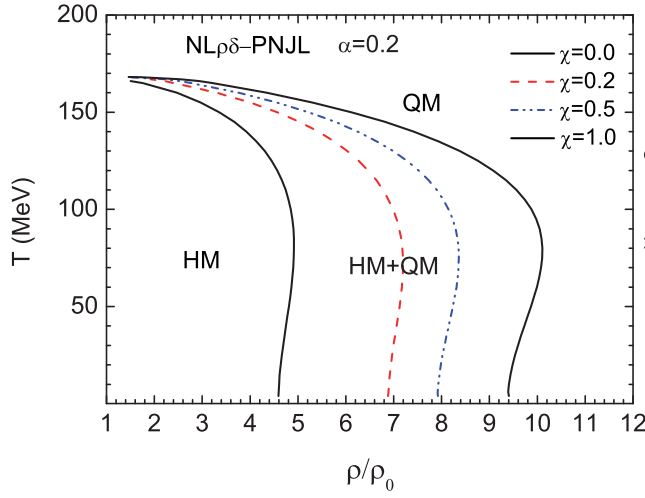


FIG. 5: Phase diagram in $T - \rho_B$ plane in the Two-EoS Hadron-PNJL model for asymmetric matter with the global asymmetry parameter $\alpha = 0.2$. χ represents the fraction of quark matter. $NL\rho\delta$ hadron interaction.

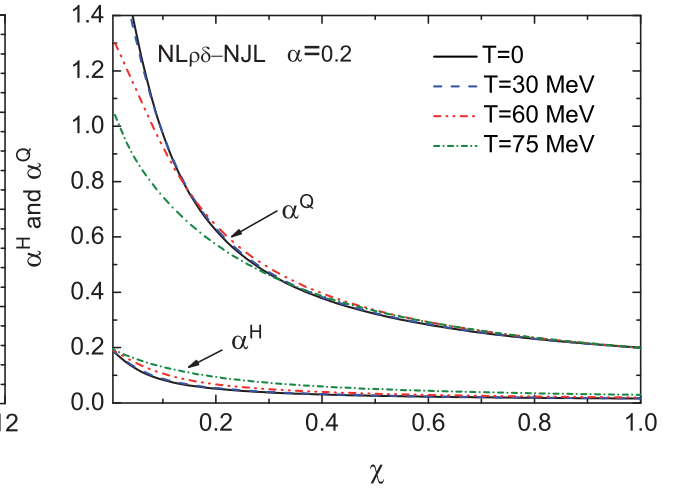


FIG. 7: The behaviors of local asymmetric parameters α^H and α^Q in the mixed phase with several values of temperature. Hadron-NJL picture with $NL\rho\delta$ hadron interaction.

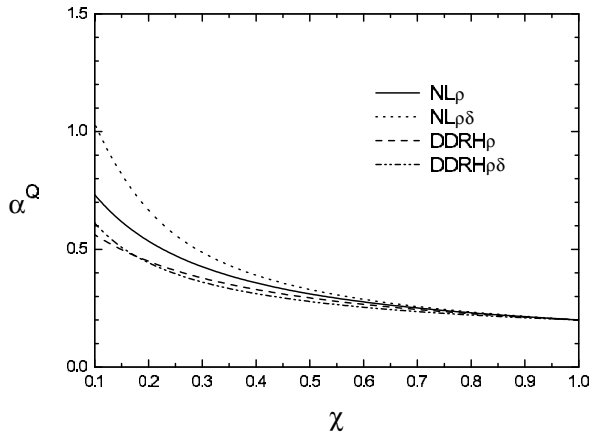


FIG. 6: The behavior of local asymmetric parameter α^Q in the mixed phase at zero temperature in the Hadron-MIT Bag model. Dotted line: $NL\rho\delta$ hadron interaction. Global asymmetry $\alpha = 0.2$.

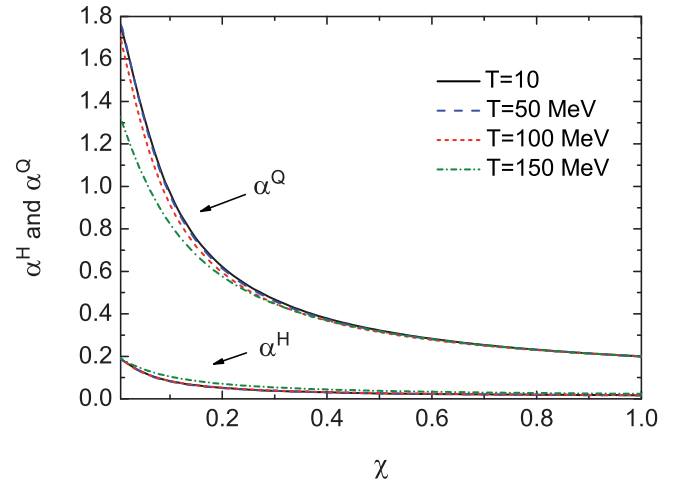


FIG. 8: The behaviors of local asymmetric parameters α^H and α^Q in the mixed phase with several values of temperature. Hadron-PNJL picture with $NL\rho\delta$ hadron interaction.

color pairing correlations at low temperatures will decrease all symmetry energy effects [25].

Such behavior of the local asymmetry parameters will possibly produce some observational signals in the following hadronization during the expansion, see last Section.

We plot the $T - \mu_B$ phase diagrams in Figs. 9 (MIT-Bag quark EoS) and 10 (upper: Hadron-PNJL; lower: Hadron-NJL) for symmetric matter with the NL hadron interaction. In the Figs. 11

(Hadron-MIT Bag) and 12 (upper: Hadron-PNJL; lower: Hadron-NJL) the corresponding for asymmetric matter are shown.

Figs. 9, 10 clearly show that there is only one phase-transition line, not dependent on the quark fraction χ , in the $T - \mu_B$ plane. At variance, for asymmetric matter, the phase transition curve varies for different quark fraction χ . The two lines in Figs. 11, 12 are obtained with $\chi = 0$ and 1, representing the beginning and the end of hadron-quark phase transition, respectively.

In Figs. 10, 12 we compare the phase transition curves with the same hadron EoS and the two

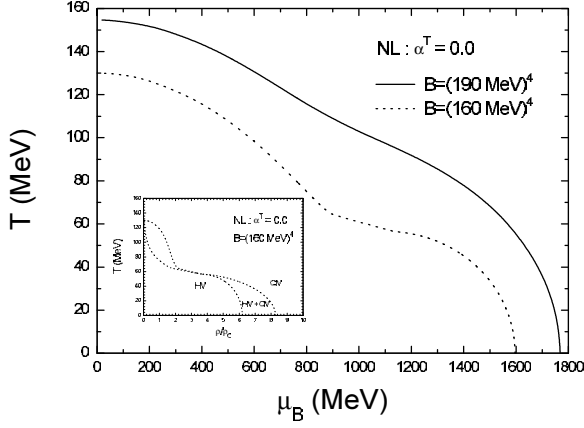


FIG. 9: Phase diagram in $T - \mu_B$ plane for symmetric matter. NL/Hadron-MIT-Bag picture.

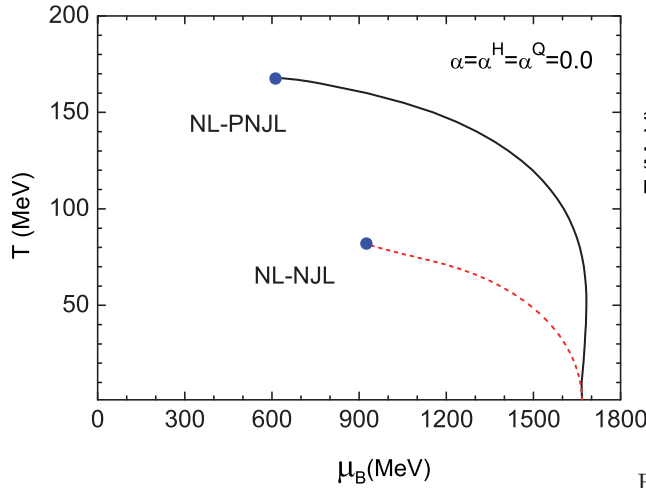


FIG. 10: Phase diagram in $T - \mu_B$ plane for symmetric matter. Upper: Hadron-PNJL. Lower: Hadron-NJL.

NJL/PNJL quark pictures. For the NJL model with only chiral dynamics, no physical solution exists when the temperature is higher than ~ 80 MeV. The corresponding temperature is enhanced to about ~ 166 MeV with the Hadron-PNJL model, which is closer to the phase transition temperature given by full lattice calculation at zero or small chemical potential [1–3].

Besides the critical end points given by the Hadron-PNJL model and Hadron-NJL model, the difference of the phase diagrams given by the two models is quite large, even at lower temperatures and chemical potentials. This can be qualitatively

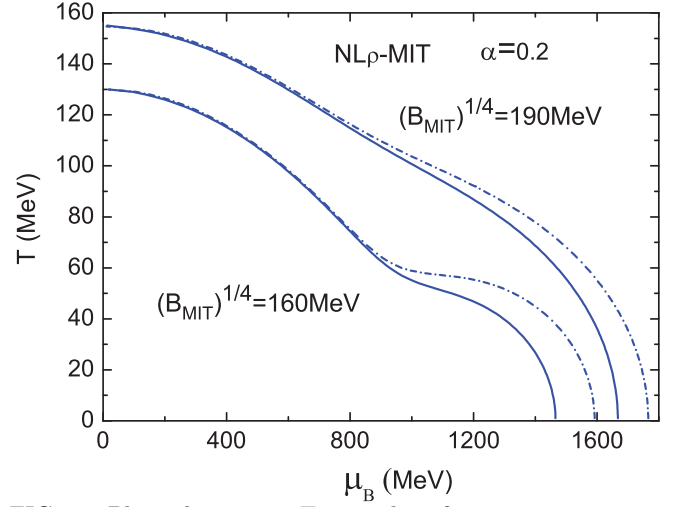


FIG. 11: Phase diagram in $T - \mu_B$ plane for asymmetric matter with the global asymmetry parameter $\alpha = 0.2$. NL $\rho\delta$ /Hadron-MIT-Bag picture.

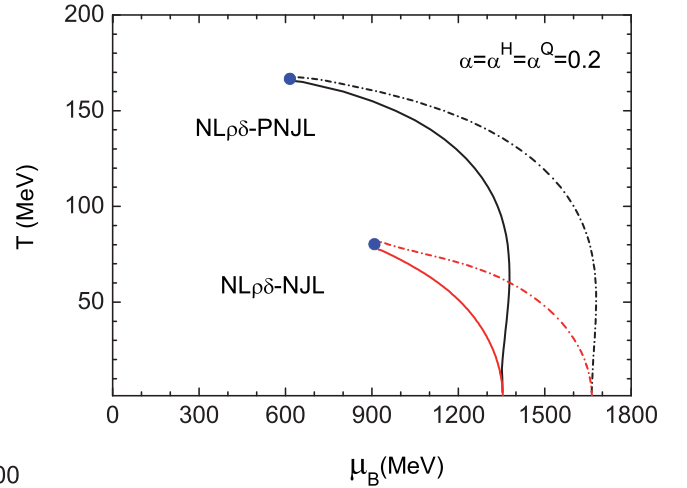


FIG. 12: Phase diagram in $T - \mu_B$ plane for asymmetric matter with the global asymmetry parameter $\alpha = 0.2$. Upper: Hadron-PNJL; Lower: Hadron-NJL. NL $\rho\delta$ hadron interaction.

understood from the analysis of the quark pressures discussed at the end of Section II.

Finally in Fig.13 we present together the phase diagrams obtained by the PNJL pure quark model and the two EoS Hadron-PNJL approach. We find that the deconfined phase transition curve in the PNJL model is close to the one obtained in the Hadron-PNJL scheme at high temperature and intermediate chemical potential. At larger chemical potential, the deconfinement phase transition curve in the PNJL model is still at rather high temperature. This is naturally leading to the formation of a *quarkyonic* phase (chirally restored but still de-

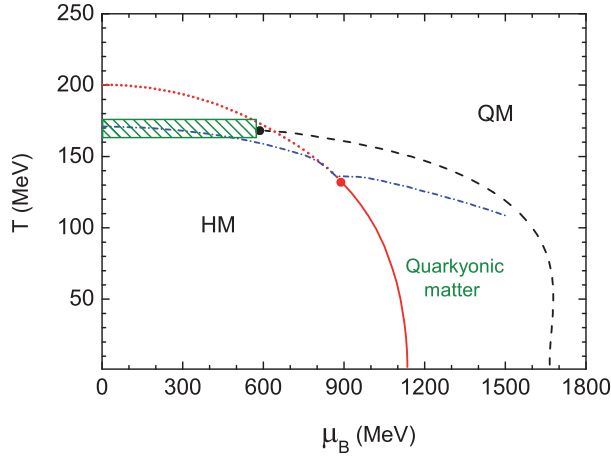


FIG. 13: Phase diagrams of the PNJL model and the Two-EoS model

confined) [31], although the interpretation of the Polyakov Loop Φ as order parameter at low temperatures and large chemical potentials is not clear. In any case this is also a strong indication that presently we must rely on the Two-EoS approach for predictions in the region of interest for heavy ion experiments at intermediate energies, i.e. at high ρ , μ_B and finite temperatures.

SUMMARY

In this study, the hadron-quark phase transition are investigated in the Two-EoS approach. We describe the hadron matter with nonlinear Walecka model and separately the quark matter with the MIT-Bag and the NJL(PNJL) models. We follow the Gibbs criteria to construct the mixed phase with baryon number and isospin conservations, likely reached during the hot and dense phase formed in heavy-ion collision at intermediate energies. The parameters in both models are fitted to give a good reproduction of the properties of nuclear matter, also at suprasaturation densities, and of lattice data at high temperature with zero/small chemical potential.

The phase diagrams for symmetric and asymmetric matter are explored in the $T - \rho_B$ and $T - \mu_B$ planes. In both Hadron-(P)NJL calculations we get a first order phase transition with a Critical-End-Point at finite temperature and chemical potential. In the PNJL case the *CEP* is shifted to larger temperatures and smaller chemical potential, to the (166,600) MeV point in the (T, μ_B) plane. This appears a nice indication of a decrease of the quark pressure when confinement is accounted for. Such result is particularly interesting since the *CEP* is now in the region of $\mu_q/T_c \simeq 1$ (where μ_q is the quark chemical potential) and so it could be reached

with some confidence by lattice-QCD complete calculations.

Isospin effects are almost negligible when we approach the *CEP*. At variance the calculation shows that the onset density of asymmetric matter is lower than that of symmetric matter. Moreover in the mixed phase of asymmetric matter, the decreasing of local asymmetry parameter α^H and α^Q with the increasing quark fraction χ may produce some observable signals. In particular we remark the noticeable isospin distillation mechanism (isospin enrichment of the quark phase) at the beginning of the mixed phase, i.e. for low quark fractions, that should show up in the hadronization stage during the expansion. We also see from Figs.6, 7 and 8 that this effect appears in all quark EoS models and it is still there even at relatively large temperatures, certainly present in the high density stage of heavy ion collisions at relativistic energies [22, 30].

EXPECTED OBSERVABLES

A first expectation of the Isospin Distillation will be a kind of *neutron trapping* in the quark phase, supported by statistical fluctuations [22] as well as by the symmetry energy difference in the two phases [23]. In fact while in the pure hadron matter (neutron-rich) at high density we have a large neutron potential repulsion (in both $NL\rho$, $NL\rho\delta$ cases), in the quark phase the d -quarks see a smaller symmetry repulsion essentially only due to the kinetic contribution from the Fermi gas. As a consequence while in a pure hadronic phase neutrons are quickly emitted or “transformed” in protons by inelastic collisions [32], when the mixed phase starts forming, neutrons are kept in the interacting system, in the quark phase, where they can even thermalize, up to the subsequent hadronization in the expansion stage. Observables related to such neutron “trapping” could be

- (i). An inversion in the trend of emission of fast neutron rich clusters with increasing beam energy, to be seen in the n/p , ${}^3H/{}^3He$ ratios at high kinetic energies;
- (ii). An enhancement of the production of isospin-rich nucleon resonances and subsequent decays, that can be evaluated via equilibrium statistical approaches [33];
- (iii). Related to the previous point, an increase of π^-/π^+ , K^0/K^+ yield ratios for mesons coming from high density regions, to be selected via large transverse momenta, corresponding to a large radial flow.

If such kinetic selection of particles from the mixed phase can really be successful also other potential signatures would become available. One is

related to the general softening of the matter, due to the contribution of more degrees of freedom, that should show up in the damping of collective flows [34].

The azimuthal distributions (elliptic flows) will be particularly affected since particles mostly retain their high transverse momenta escaping along directions orthogonal to the reaction plane without suffering much rescattering processes. Thus a further signature could be the observation, for the selected particles, of the onset of a quark-number scaling of the elliptic flow: a property of hadronization by quark coalescence that has been predicted and observed at RHIC energies, i.e. for the transition at $\mu_B = 0$ [35].

Finally, an evident feature of Figs. 1 (dot-dashed lines), 4, 5 is that the onset density of hadron-

quark phase transition for asymmetric matter is much lower than that of the symmetric one, and therefore it will be easier to probe in heavy-ion collision experiments at intermediate energies.

All that support the possibility of an experimental observation in the new planned facilities, for example, FAIR at GSI-Darmstadt and NICA at JINR-Dubna, with realistic isospin asymmetries for stable/unstable beams.

ACKNOWLEDGEMENTS

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Energy density functionals from Brueckner-Hartree-Fock theory

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Abstract - Skyrme-like energy density functionals are built upon *ab initio* calculations of nuclear matter which reproduce the empirical saturation properties performed in the

framework of the Brueckner-Hartree-Fock approximation with consistent two and three body forces [1]. The Skyrme parametrizations are obtained from a simultaneous fit of the spin-isospin components of the potential energy of symmetric nuclear matter and of the experimental energies and charge radii of a number of closed-shell

and closed-subshell nuclei. These parametrizations are tested on the energies and charge radii of the Sn isotopic chain and on the ²⁰⁸Pb giant resonances, showing a substantial improvement of the LNS functional obtained in a previous fit. The comparison with standard Skyrme forces can give some hints on how to reconcile nuclear matter and finite nuclei. energies.

FITTING PROCEDURE

We fit the spin-isospin components of the energy potential per particle V_{ST} calculated from the BHF theory in symmetric nuclear matter by means of a Skyrme-type functional:

$$\begin{aligned}
 V(\mathbf{r}_1, \mathbf{r}_2) = & t_0(1 + x_0 P_\sigma) \delta(\mathbf{r}) \\
 & + \frac{1}{2} t_1(1 + x_1 P_\sigma) [\mathbf{P}'^2 \delta(\mathbf{r}) + \delta(\mathbf{r}) \mathbf{P}^2] \\
 & + t_2(1 + x_2 P_\sigma) \mathbf{P}' \cdot \delta(\mathbf{r}) \mathbf{P} \\
 & + \frac{1}{6} t_3(1 + x_3 P_\sigma) [\rho(\mathbf{R})]^\sigma \delta(\mathbf{r}) \\
 & + i W_0 \sigma \cdot [\mathbf{P}' \times \delta(\mathbf{r}) \mathbf{P}] , \quad (1)
 \end{aligned}$$

The V_{ST} from BHF are shown in Fig.1 in comparison with the calculations based on phenomenological Skyrme forces.

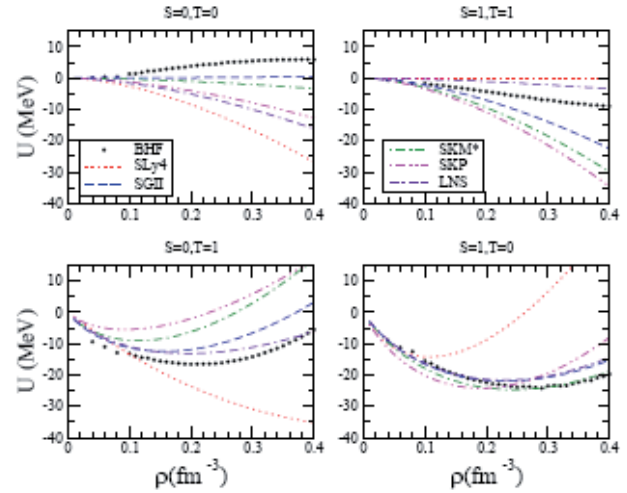


Fig.1 – The four (S,T) components of the energy potential in symmetric nuclear matter from *ab initio* BHF and phenomenological Skyrme calculations.

The fit is based on a mean-squares method involving both the BHF data for V_{ST} and the experimental binding energies and charge radii of a number of closed-shell and closed-subshell nuclei. In Table I two sets of Skyrme parameters are reported: LNS1 and LNS5 differ from a factor 1:5 weighting the experimental data in the fit. The corresponding binding energies and charge radii are shown in Table II. The two parametrizations have also been applied to the Sn isotopic chain and to the giant resonances. The results are in excellent agreement with the experimental data,

	LNS5	LNS1
t_0 (MeV fm ³)	-2194.776	-2215.322
t_1 (MeV fm ⁵)	482.518	532.536
t_2 (MeV fm ⁴)	138.137	67.761
t_3 (MeV fm ^{3(1+σ)})	10784.169	10931.718
x_0	0.134	0.463
x_1	-0.097	0.128
x_2	-1.399	-2.174
x_3	0.171	0.615
W_0 (MeV fm ⁵)	105.674	116.789
ρ_0 (fm ⁻³)	0.1599	0.1604
E/A (MeV)	-15.57	-15.86
K_∞ (MeV)	240.06	241.42
a_s (MeV)	29.21	29.63
$\frac{m^*}{m}$	0.603	0.615
χ^2 per point	1.76	0.38

TABLE I : The two sets of Skyrme parameters resulting from the fit of BHF energy functional

Therefore the BHF calculations using realistic meson exchange potentials and including three-body effects can provide a sound framework for determining EDF of the Skyrme type. The reason why the latter are not yet fully competitive with the purely phenomenological Skyrme forces is still an open problem. Nevertheless the parametrizations thus obtained can describe nuclear ground states at a reasonably good quantitative level. They might be used with more confidence than purely phenomenological parametrizations for exploring regions of the nuclear chart far from the stability valley. Finally, we can say that further improvements of microscopically based parametrizations of the Skyrme type must await for more accurate descriptions of the nuclear matter EoS in the density domain below $(0.4-0.5)\rho_0$. Indeed, this range of densities is important for finite nuclear systems but its treatment is generally difficult in microscopic calculations of nuclear matter

	Exp	LNS5	LNS1
¹⁶ O	-127.62 2.73	-137.27 2.758	-131.52 2.745
⁴⁰ Ca	-342.05 3.49	-354.55 3.551	-348.00 3.521
⁴⁸ Ca	-415.99 3.48	-427.13 3.485	-421.03 3.500
⁵⁶ Ni	-483.99 3.75	-484.97 3.768	-482.41 3.751
⁷⁶ Ni	-642.40	-653.81 3.961	-645.24 3.973
¹⁰⁰ Sn	-825.78	-823.69 4.446	-825.81 4.457
¹³² Sn	-1102.90	-1108.23 4.694	-1104.9 4.700
²⁰⁸ Pb	-1636.44 5.50	-1625.41 5.531	-1633.41 5.531

TABLE II: Energies (MeV) and charge radii (fm) for the two Skyrme-type parametrizations

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Pairing screening in asymmetric nuclear matter

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The influence of the medium polarization on the pairing interaction has been studied in finite nuclei and nuclear matter. Despite of displaying different mechanisms, surface vibrations in nuclei and spin-isospin vibrations in nuclear matter, it results in a significant variation of the pairing gap. In nuclear matter this effect comes from the interplay between attractive and repulsive components of the effective interaction, characterized by a strongly isospin dependence.

In fact, whereas in symmetric nuclear matter (SNM) the pairing interaction is reinforced by the medium polarization, in pure neutron matter (PNM) it is weakened [1]. Unfortunately, the isospin effect is highly non linear with respect to the asymmetry parameter, even with the only bare interaction [2], and thus the interpolation between the two extreme states, successfully adopted for other observables, fails down in the case of the pairing gap. Nuclei aside, the isospin effect is very important to study the superfluidity in neutron stars, where the neutron-to-proton asymmetry can be quite large owing to beta-equilibrium condition.

In the present investigation we extend the calculation of the induced interaction, performed in the two extreme situations of PNM and SNM, to the isospin-asymmetric nuclear matter. The pairing interaction is given by

$$V = V_0 + V_0 \Gamma V_0$$

where V_0 is the bare interaction and Γ is the particle-hole (ph) propagator. The second term, depicted in Fig.1, represents the medium-polarization effect on the pairing interaction. The bubble is the dressed ph propagator,

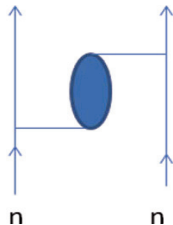


Fig.1 – Screening interaction in the neutron-neutron pairing.

which in compact form is written as

$$\Gamma = \Gamma_0 + \Gamma_0 V_{\text{ind}} \Gamma_0$$

where Γ_0 is the free ph propagator and V_{ind} is the induced interaction. Both Γ_0 and V_{ind} are isospin dependent in asymmetric nuclear matter. They are 2x2 matrices corresponding to the two isospin components, i.e. neutrons and protons.

The induced interaction is calculated in the RPA, by means of the Landau parameters, plotted in Fig.2 as a function of the asymmetry parameter β .

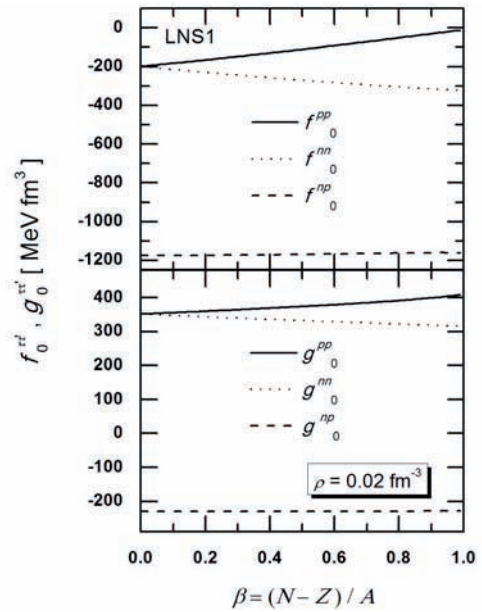


Fig.2 – Landau parameters in asymmetric nuclear matter, calculated from the LNS1 Skyrme force [3].

This is the first step in the calculation of the medium screening effect on the pairing in asymmetric matter, which presently is under way.

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Symmetry energy effect on fusion cross section

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Abstract - We investigate the reaction path followed by Heavy Ion Collisions (HIC) with exotic nuclear beams at low energies. We will focus on the interplay between reaction mechanisms, fusion vs. break-up (fast-fission, deep-inelastic), that in exotic systems is expected to be influenced by the symmetry energy term at densities around the normal value. The evolution of the system is described by a Stochastic Mean Field transport equation (SMF), where two parametrizations for the density dependence of symmetry energy (Asysoft and Asystiff) are implemented, allowing one to explore the sensitivity of the results to this ingredient of the nuclear interaction.

INTRODUCTION

Production of exotic nuclei has opened the way to explore, in laboratory conditions, new aspects of nuclear structure and dynamics up to extreme ratios of neutron (N) to proton numbers (Z). An important issue addressed is the density dependence of the symmetry energy term in the nuclear Equation of State (EOS), of interest also for the properties of astrophysical objects [1-3].

In this work we will focus the attention on the interplay of fusion vs. deep-inelastic mechanisms for dissipative HIC with exotic nuclear beams at low energies, just above the Coulomb Barrier (between 5 and 20 A MeV), where unstable ion beams with large asymmetry will be soon available. We will show that the competition between reaction mechanisms can be used to study properties of the symmetry energy term in a density range around the normal value. Within our approach, the reaction path is fully characterized by the fluctuations, at suitable time instants, of phase space quadrupole collective modes that lead the composite system either to fusion or to break-up.

Moreover, it is now well established that in the same energy range, for dissipative reactions between nuclei with different N/Z ratios, the charge equilibration process has a collective character resembling a large amplitude Giant Dipole Resonance (GDR), see for instance [4,5]. The gamma yield resulting from the decay of such pre-equilibrium isovector mode can also encode information about

the early stage of the reaction and the density dependence of the symmetry energy [6-8].

REACTION DYNAMICS

The reaction dynamics is described by a Stochastic Mean-Field (SMF) approach, extension of the microscopic Boltzmann-Nordheim-Vlasov transport equation [2]. It must be noted that, for low energy collisions, the simulations cannot be trusted on the time scale of a compound nucleus formation, mainly for the increasing numerical noise. However, the nice feature of the procedure described here to evaluate the fusion probability is that, on the basis of a shape analysis in phase space, we can separate fusion and break-up trajectories at rather early times, of the order of 200-300 fm/c, when the calculation can still be fully reliable. The nuclear mean field is built from Skyrme forces. For the density dependence of the symmetry energy, we have considered two different parametrizations [9]: In the Asysoft EOS choice the symmetry energy has a weak density dependence close to the saturation, being almost flat around ρ_0 . For the Asystiff case, the symmetry energy is quickly decreasing for densities below normal density. Aim of this work is to show that fusion probabilities, as well as properties of prompt collective modes, in collisions induced by neutron-rich exotic beams, are sensitive to the different slopes of the symmetry term around saturation.

FUSION DYNAMICS FOR ^{132}Sn INDUCED REACTIONS

In order to study isospin and symmetry energy effects on the competition between fusion and break-up (deep-inelastic) we consider the reactions $^{132}\text{Sn} + ^{64,58}\text{Ni}$ at 10 A MeV, having in mind that ^{132}Sn beams with good intensities in this energy range will be soon available in future Radioactive Ion Beam facilities. In particular, we have performed collision simulations for semi-peripheral impact parameters (from $b = 4.5$ fm to $b = 8.0$ fm, with $\Delta b = 0.5$ fm), to explore the region of the transition from fusion to break-up dominance. The transport equations clearly give fusion events at central impact parameters and break-up events for

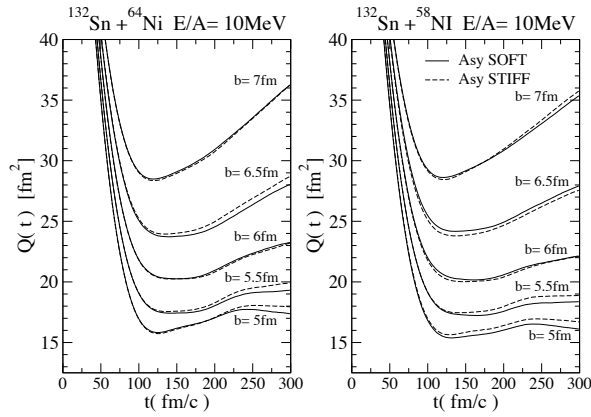


FIG. 1: Time evolution of the space quadrupole moments for different centralities and for the two systems. Solid line: Asysoft. Dashed line: Asystiff.

peripheral collisions, but there are some problems when we consider semi-peripheral impact parameters at such low energies, since the time scales for break-up are not compatible with the transport treatment, as already noted. Therefore we have tried to find a reliable criterion that can indicate when the reaction mechanism is changing, from fusion to deep-inelastic dominance. This will also allow to evaluate the corresponding absolute cross sections.

The new method is based on a phase space analysis of quadrupole collective modes. The information on the final reaction path is deduced investigating the fluctuations of the system at early times (200-300 fm/c), when the formation of composite elongated configurations is observed and phenomena associated with surface metastability and/or instability may take place. We start considering the time evolution, in each event, of the quadrupole moment in coordinate space which is given by:

$$Q(t) = \langle 2z^2(t) - x^2(t) - y^2(t) \rangle,$$

averaged over the space distribution in the composite system. At the same time-steps we construct also the quadrupole moment in momentum space:

$$QK(t) = \langle 2p_z^2(t) - p_x^2(t) - p_y^2(t) \rangle,$$

in a spatial region around the center of mass. The z-axis is along the rotating projectile-like/target-like direction, the x-axis is on the reaction plane.

We run 200 events for each set of macroscopic initial conditions and we take the average over this ensemble. In Fig.1 we present the time evolution of the mean space quadrupole moment at various centralities for the two reactions and for the two choices of the symmetry term. We notice the difference in $Q(t)$ between the behavior corresponding

to more peripheral impact parameters and that obtained for $b=5.5-6$ fm, where we have still a little oscillation in the time interval between 100 and 300 fm/c, good indication of a fusion contribution.

We can interpret these observations assuming that starting from about $b = 5$ fm, we have a transition from fusion to a break-up mechanism, like deep-inelastic. Positive values of the $Q(t)$ -slope should be associated with a quadrupole deformation velocity of the dinuclear system that is going to a break-up exit channel. We notice a slight systematic difference, especially in the most neutron-rich system, with a larger deformation velocity in the Asystiff case. Hence, just from this simple analysis of the average space quadrupole “trajectories” we can already appreciate that the Asysoft choice seems to lead to larger fusion cross sections, at least for less peripheral impact parameters, between $b=5.0$ fm and $b=6.5$ fm.

It is very instructive to look also at the time evolution of the quadrupole deformations in momentum space. For each event we perform the calculation in a spherical cell of radius 3 fm around the system center of mass. With increasing impact parameter the average quadrupole $QK(t)$ becomes more negative in the time interval between 100 and 300 fm/c: the components perpendicular to the symmetry axis, that is rotating in reaction plane, are clearly increasing. We can interpret this effect as due to the presence, in the considered region, of Coriolis forces that are enhanced when the angular momentum is larger. These forces help to break the deformed dinuclear system. Then the break-up probability will be larger if the quadrupole moment in p-space is more negative. One can see that there is a region of impact parameter ($b = 5-6.5$ fm) where the derivative of the quadrupole moment in coordinate space, Q' , and the quadrupole moment in momentum space, QK , are both rather close to zero. This is the region where we expect that fluctuations of these quantities should play an important role in determining the fate of the reaction and event-by-event analysis is essential to estimate fusion vs. break-up probabilities.

ANALYSIS OF FLUCTUATIONS AND FUSION PROBABILITIES

To define a quantitative procedure to fix the event by event fusion vs break-up probabilities, we undertake an analysis of the correlation between the two quadrupole moments introduced in the previous Section, in the time interval defined before (100-300 fm/c).

In order to get the fusion probability from the early evolution of the system we assume positive Q' and negative QK for break-up events. In other words, we suppose that, in the impact parameter range where the average value of the two quantities

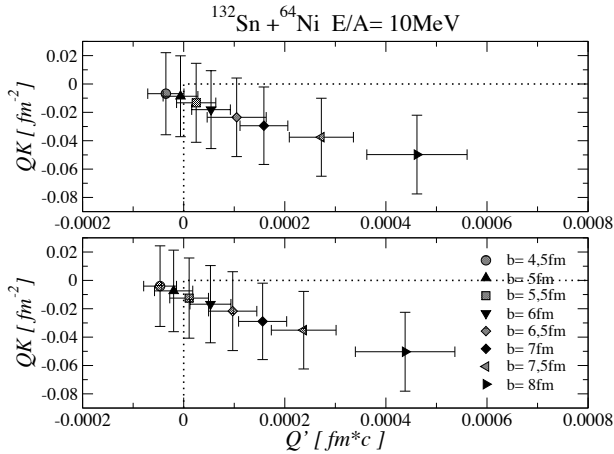


FIG. 2: $^{132}\text{Sn} + ^{64}\text{Ni}$ system. Mean value and variance of QK vs Q' , averaged over the 100-300 fm/c time interval, at various centralities in the transition region. The box limited by dotted lines represents the break-up region. Upper panel: Asystiff. Bottom Panel: Asysoft.

is close to zero, the system evolution is decided just by the amplitude of shape fluctuations, taken at the moment when the formation of a deformed composite system is observed along the SMF dynamics ($t = 200\text{-}300$ fm/c). Within our prescription, the fusion probability is automatically equal to one for central impact parameters, where the system goes back to the spherical shape and Q' is negative, while it is zero for peripheral reactions, where Q' is always positive and QK always negative.

The correlation plots for one of the systems studied and the two asy-EOS is represented in Figs.2. Through the quantities displayed in the Figures, mean value and variance of the two extracted properties of the phase space moment evolution, we can evaluate the relative areas, for each impact parameter, of the two types of events: break-up events will be located in the regions with both positive slope of $Q(t)$ and negative QK . In this way, for each impact parameter we can evaluate the fusion events by the difference between the total number of events and the number of break-up events. Finally the fusion cross section is obtained (in absolute value) by

$$\frac{d\sigma}{dl} = \frac{2\pi}{k^2} l \frac{N_f}{N_{tot}}, \quad (1)$$

where l is the angular momentum calculated in the semiclassical approximation, k is the relative momentum of the collision, N_f the number of fusion events and N_{tot} the total events in the angular momentum bin. In Fig.3 we present the fusion spin distribution plots for the two systems. We note that just in the centrality transition region there is a difference between the σ -fusion corresponding to the two different asy-EOS, with larger values for

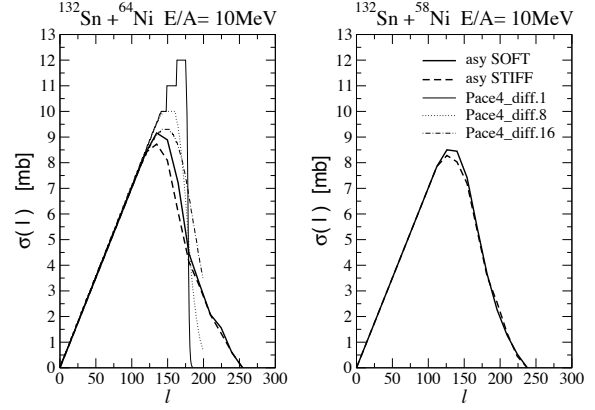


FIG. 3: Angular momentum distributions of the fusion cross sections (mb) for the two reactions and the two choices of the symmetry term. For the $^{132}\text{Sn} + ^{64}\text{Ni}$ system (left panel), the results of PACE4 calculations are also reported, for different l -diffuseness. The best agreement with our results is obtained for large diffuseness values, pointing to the importance of neutron skin effects.

Asysoft, especially in the n-richer case.

In fact, the total cross sections are very similar: the difference in the area is about 4-5 % in the neutron rich system, 1128 mb (Asysoft) vs. 1078 mb (Asystiff), and even smaller, 1020 mb vs. 1009 mb, for the ^{58}Ni target. However, through a selection in angular momentum, $130 \leq l \leq 180$ ($\hbar$), we find that the Asysoft curve is significantly above the Asystiff one, and so in this centrality bin the fusion cross section difference can reach a 10% in the case of the more neutron-rich system. Then it can be compared to experimental data as an evidence of sensitivity to the density dependence of the symmetry energy. Finally we like to note that for the neutron-rich case, $^{132}\text{Sn} + ^{64}\text{Ni}$, our absolute value of the total fusion cross section presents a good agreement with recent data, at lower energy (around 5 AMeV), taken at the ORNL [10].

THE PROMPT DIPOLE MODE IN FUSION AND BREAK-UP EVENTS

From the time evolution of the nucleon phase space occupation, it is possible to extract at each time step the isovector dipole moment of the composite system. This is given by $D(t) = \frac{NZ}{A} X(t)$, where $A = N + Z$, and $N = N_1 + N_2$, $Z = Z_1 + Z_2$, are the total number of participating nucleons, while $X(t)$ is the distance between the centers of mass of protons and neutrons. It has been clearly shown, in theory as well as in experiments, that at these beam energies the charge equilibration in fusion reactions proceeds through such prompt collective mode. In our study we have focused the attention on the system with larger initial charge

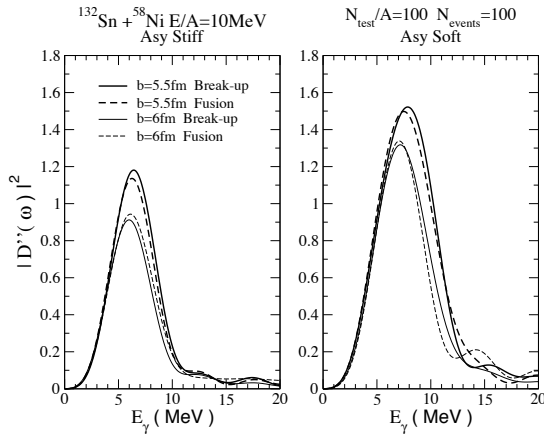


FIG. 4: Reaction $^{132}\text{Sn} + ^{58}\text{Ni}$ semiperipheral. Prompt Dipole strengths (in c^2 units), see text, for break-up (solid lines) and fusion (dashed lines) events. Left Panel: Asystiff. Right Panel: Asysoft.

asymmetry, the ^{132}Sn on ^{58}Ni case. We nicely see that in both classes of events, ending in fusion or deep-inelastic channels, the dipole mode is present almost with the same strength.

The corresponding emission rates can be evaluated, through a "bremsstrahlung" mechanism, in a consistent transport approach to the reaction dynamics, which can account for the whole contribution along the dissipative non-equilibrium path, in fusion or deep-inelastic processes [7].

In Fig.4 we report the prompt dipole strengths $|D''(\omega)|^2$ for fusion and break-up events.

The dipole strength distributions are very similar for the two classes of events and the strength is smaller in the less central collisions ($b=6.0\text{fm}$), with a centroid slightly shifted to lower values, corresponding to more deformed shapes of the dinuclear composite system.

In the Asysoft choice we have a systematic increase of the yields, roughly given by the area of the strength distribution, of about 40% more than in the Asystiff case, for both centralities and selections. Indeed the Asysoft choice corresponds to a larger symmetry energy below saturation. Since the symmetry term gives the restoring force of the dipole mode, our result is a good indication that the prompt dipole oscillation is taking place in a deformed dinuclear composite system, where low density surface contributions are important, as already observed in ref.[8].

CONCLUSIONS

We have undertaken an analysis of the reaction path followed in collisions involving exotic systems at beam energies around 10 AMeV. In this energy regime, the main reaction mechanisms range from fusion to dissipative binary processes, together with the excitation of collective modes of the nuclear shape. Moreover, in charge asymmetric systems, isovector dipole oscillations can be excited at the early dynamical stage. We have shown that, in neutron-rich systems, fusion vs. break-up probabilities are influenced by the neutron repulsion during the approaching phase, where densities just above the normal value are observed. Hence larger fusion cross sections are obtained in the case of the Asysoft parametrization of the symmetry energy, associated smaller values at supra-saturation densities. On the other hand, the isovector collective response, that takes place in the deformed dinuclear configuration with large surface contributions, is sensitive to the symmetry energy below saturation. Finally, we would like to stress that, according to our analysis, considerable isospin effects are revealed just selecting the impact parameter window corresponding to semi-peripheral reactions. Interesting perspectives are opening for new experiments on low energy collisions with exotic beams focused to the study of the symmetry term below and above saturation density.

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Collective Flows and Quark-Gluon plasma viscosity in a Transport Approach

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Abstract - We have developed a transport approach at fixed shear viscosity to entropy ratio to study the generation of collective flows in ultra-relativistic heavy-ion collisions. Transport theory supplies a covariant approach valid also at large and at intermediate transverse momentum p_T , where deviations from equilibrium is no longer negligible. Such an approach shows that at RHIC energies a temperature dependent enhances significantly the v_4/v_2^2 respect to the case of constant . Furthermore if NJL chiral dynamics is self-consistently implemented we show that it does not modify the relation between v_2 and .

INTRODUCTION

The RHIC program at BNL has shown that the azimuthal asymmetry in momentum space, namely the elliptic flow v_2 , is the largest ever seen in HIC suggesting that an almost perfect fluid with a very small shear viscosity to entropy density ratio, , has been created [1,2]. Nonetheless it has been found that dissipative effects cannot be neglected and even a small shear viscosity to entropy ratio produce sizeable effect increasing with the transverse momentum p_T of the particles [3]. This has triggered a lot of activity in developing a relativistic theory of viscous hydrodynamics. Viscous corrections to ideal hydrodynamics are indeed large and a simple relativistic extension of first order Navier Stokes equations is affected by causality and stability pathologies [5]. It is therefore necessary to go to second order gradient expansion, and in particular the Israel-Stewart theory has been implemented to simulate the RHIC collisions providing an upper bound for $\eta/s \leq 0.4$ [4]. Such an approach, apart from the limitation to 2+1D simulations, has the more fundamental problem of a limited range of validity in and in the transverse momentum p_T .

On the contrary a relativistic transport approach has the advantage to be a 3+1D approach not based on a gradient expansion in viscosity that is valid also for large and for out of equilibrium momentum distribution allowing a reliable description also of the intermediate p_T range where the important property of quark number scaling (QNS) of $v_2(p_T)$ has been observed [10]. In this p_T region viscous hy-

drodynamics breaks its validity because the relative deviation of the equilibrium distribution function $\delta f/f_{eq}$ increases with p_T^2 becoming large already at $p_T \geq 3T \sim 1\text{GeV}$ [5]. Furthermore Boltzmann-Vlasov transport theory distinguishes between the short range interaction associated to collisions and long range interaction associated to the field interaction, responsible for the change of the Equation of State (EoS) respect to that of a free gas. This last feature allows to unify two main ingredients that are relevant for the formation of collective flow. In ideal hydrodynamics the depends strongly on the EoS namely on the sound velocity $c_s^2 = dP/d\epsilon$ [8], while the mean free path λ is assumed to be vanishing. In the parton cascade approach the EoS is fixed to be the one of a free gas $c_s^2 = 1/3 = P/\epsilon$, on the other hand the mean free path $\lambda = 1/\rho\sigma$ is finite. In the first stage of RHIC the two different approaches were able to account for the large observed; in particular the parton cascade with large scattering cross section predicted the saturation of vs p_T [9]. Anyway once viscosity is finite both a finite λ and the EoS are important for the generation of the momentum anisotropies.

The basic equation of transport for the (anti-) quark phase-space distribution function $f^\pm$ under a scalar field interaction can be written as:

$$p^\mu \partial_\mu f^\pm(x, p) + M(x) \partial_\mu M(x) \partial_p^\mu f^\pm(x, p) = \mathcal{C}(x, p) \quad (1)$$

where the first term is related to the free streaming, the second term represents the effect of a scalar field modifying the $\epsilon = 3P$ relation (giving a finite interaction measure, see Fig.2 (left)) and the last term is the effect of the collisions directly associated to a finite λ and therefore to a finite .

In the following we will show two results obtained with such an approach: one related with the large v_4/v_2^2 ratio observed at RHIC and the other discussing the role of the NJL chiral dynamics on the relation between and . We will show calculations for $Au + Au$ at 200 AGeV; the density distribution in coordinate space is given by the standard Glauber model. The maximum initial temperature is $T = 340$ MeV and the initial time is $\tau_0 = 0.6$ fm/c as usually done also in hydrodynamical calculations.

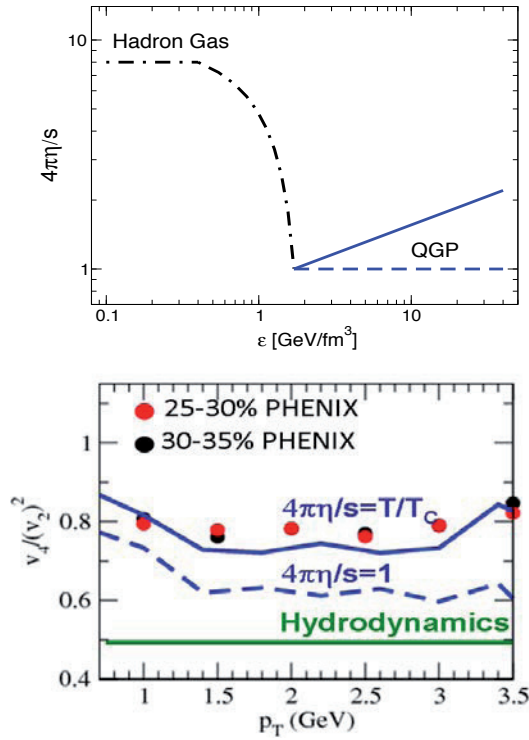


FIG. 1: Left: Dependence of $4\pi/s$ on the energy density ϵ implemented in the transport code. Right: v_4/v_2^2 for $Au + Au$ collisions in the mid-rapidity region $|y| < 1$ at $b = 8$ fm; dashed line is the result for a constant $4\pi = 1$, the solid line is the result for a temperature dependence of the $4\pi/s$ like shown by solid line on the left figure.

THE LARGE V_4/V_2^2 RATIO

We first consider the reduction of the transport approach to a cascade, i.e. neglect the field interaction, included in the next section. In such a case the mass $M(x) = 0$ in Eq.(1). It has been shown that a fluid at finite ϵ can be studied within a transport approach renormalizing locally the scattering cross section according to $\sigma_{tr} = \langle p \rangle / 15\rho$, for details see Ref.s [5,6,7]. The system of course expands and cools and when the energy density is below $\epsilon = 2 \text{ GeV/fm}^3$ it starts the cross-over region and then the hadronic stage. During this phase we increase the η/s of the medium according to Fig. 1 (left) in order to have finally in the hadronic phase an $\eta/s = 8/4\pi \sim 0.65$ in agreement with several calculation of η/s .

At RHIC it has been observed $v_4(p_T)/v_2^2(p_T)$ ratio of about 0.8-0.9 quite larger than first ideal hydrodynamical predictions of about 0.5. More realistic hydrodynamical calculations show that the ratio can be even lower than 0.5 and viscosity does not strongly affect such a ratio but can bring it up to about 0.6. Furthermore in Ref. [11] it has been shown that such a ratio is almost independent on the initial eccentricity, on the viscosity, on the

particle species. Therefore even if v_4 and v_2 can depend on several details such a ratio is a quite stable one and its large value should be considered as an opportunity to have some new information on the system not yet spot. In Ref. [7] we have shown that indeed the formation time of v_4 is larger than the v_2 one and therefore it is more affected by dynamics of the later stage of the reaction. Thanks to the difference in the formation time we argue that such a ratio is significantly affected by the temperature dependence of the $4\pi/s$. Therefore we have performed two calculations one with a constant $4\pi = 1$ in the QGP phase (dashed line) and the other, shown by solid line in Fig. 1 (left), with a T or ϵ energy density dependence $4\pi = T/T_0 = (\epsilon/\epsilon_0)^{1/4}$ where $\epsilon_0 = 1.7 \text{ GeV/fm}^3$ gives the beginning of the cross over region. We remind that an increase of $4\pi/s$ is expected moving away from the phase transition region on general considerations [12].

In Fig.1 (left) we show the results of the two calculations for $Au + Au$ at 200 AGeV. For a constant we find a value of about 0.6 while in the case of a temperature dependent $4\pi/s$, it increases getting very close to experimental data, $v_4/v_2^2 \sim 0.8$. The reason for the sensitivity of this ratio on the T dependence is that the elliptic flow v_2 mainly develops earlier respect to v_4 and therefore on the average at larger p_T (for the solid line case), while v_4 develops more when the $4\pi/s$ is smaller hence is less suppressed by dissipative effects.

IMPACT OF NJL DYNAMICS

To start the investigation of the role of the field interaction we have implemented the NJL dynamics that introduces the generation of a finite mass associated to chiral symmetry breaking. Therefore particles do not have a vanishing mass but a finite one according to the mass gap equation of the NJL model:

$$\frac{M(x) - m}{4g N_c} = M(x) \int \frac{d^3p}{(2\pi)^3} \frac{1 - f^-(x,p) - f^+(x,p)}{E_p(x)} \quad (2)$$

that determines the local mass $M(x)$ at the space-time point x in terms of the distribution functions $f^\pm(x,p)$. For a gas at finite mass $\epsilon - 3P$ is no longer vanishing as shown in Fig.2 (right) for several NJL parametrization.

Eqs.(1) and (2) form a closed system of equations constituting the Boltzmann-Vlasov equation associated to the NJL Lagrangian. The space-time dependence of the mass $M_\alpha(r,t) = m - 2g\langle\bar{\psi}\psi\rangle$ influences the momenta of the particles because the finite gradient of the condensate generates a force which changes the momentum of a particle proportionally to $\vec{\nabla}_r\langle\bar{\psi}\psi\rangle$. The last is negative because the phase transition occurs earlier in the surface of the expanding QGP fireball. Therefore the

phase transition which take place locally results in a negative contribution to the particle momenta that makes the system more sticky respect to a free massless gas. To study a fluid at finite and NJL field interaction one has to extend the simple relation $\sigma_{tr} \cdot \eta/s = \langle p \rangle / 15\rho$ valid for a massless gas to the general case of massive relativistic particles and this has been discussed in Ref. [13]. In Fig.2, we

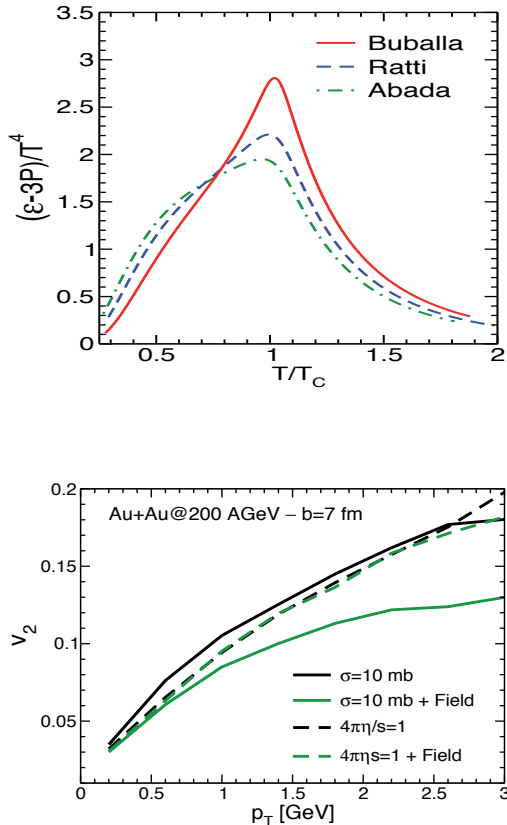


FIG. 2: Left: Interaction measure shown as a function of temperature T for three different NJL parameter sets. Right: Average elliptic flow as a function of time for $Au + Au$ collisions in the mid-rapidity region $|y| < 1$ at $b = 7$ fm; see text.

show the elliptic flow as a function of p_T . We find that the presence of an NJL-field that drives the chiral phase transition suppress the $v_2(p_T)$ by about 20% at $p_T > 1$ GeV. This would imply the need of a parton scattering cross section σ_{tr} even larger than that estimated with the cascade model which was already quite larger than the pQCD estimates [9] in order to describe the data. On the other hand the mean field modifies both the local entropy density, reduced by the mass generation, and the shear viscosity that increases respect to the massless case. Considering that one of the main goal is to deter-

mine the η/s of the QGP, we have investigated what is the action of the mean field once the η/s of the system is fixed to be the same with and without the NJL field. This of course implies different values of the cross section in the two cases.

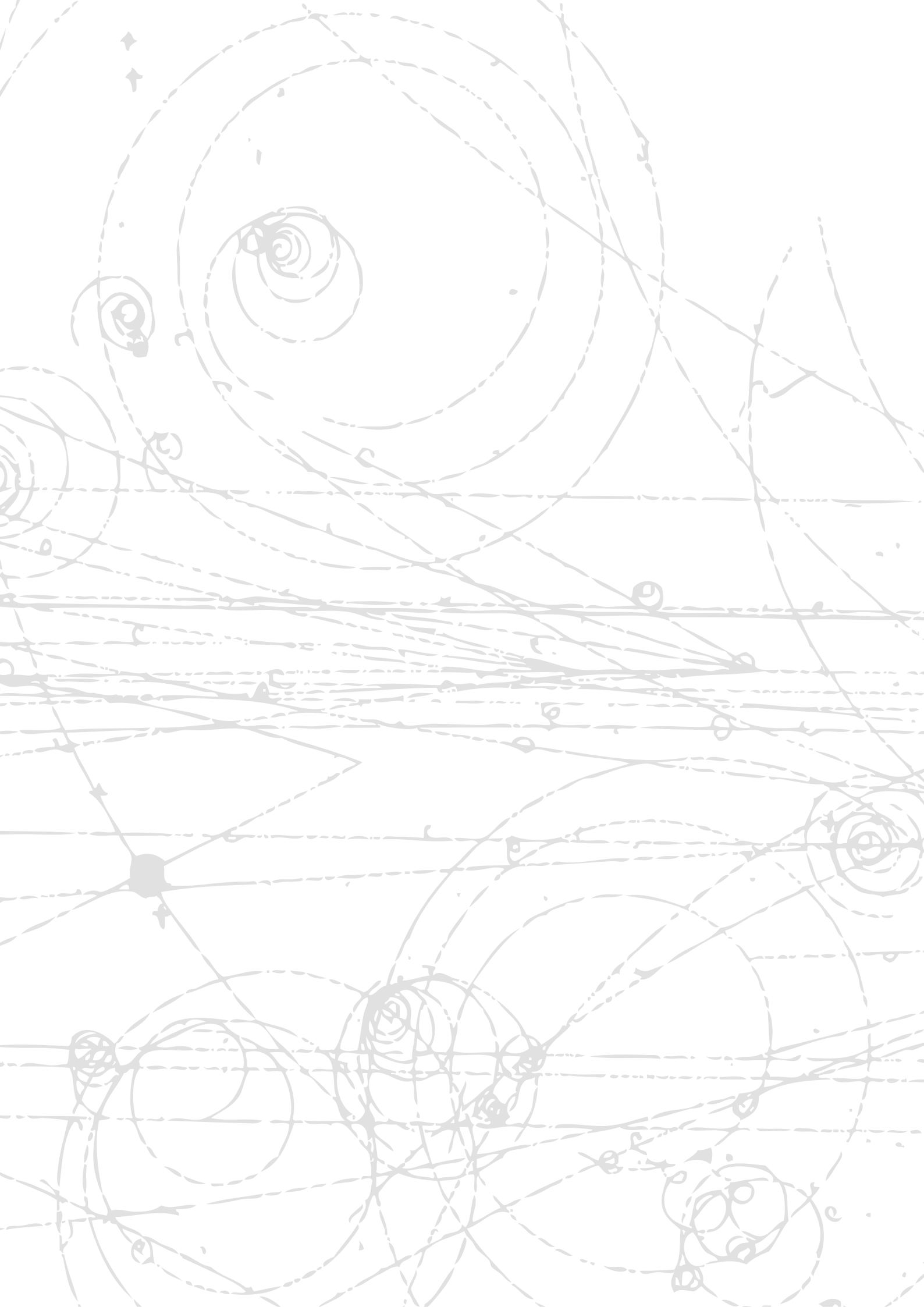
The results for $4\pi\eta/s = 1$ are shown by dashed lines in Fig. 2 (right), the (black) dashed line is the case with only the collision term (cascade) while the (green) dashed line is the case with the field. We can see that once the η/s is fixed there is essentially no difference in the calculations with and without a field dynamics included. This is a key result that shows that even in a microscopic approach that distinguishes between the mean field and the collisional dynamics the $v_2(p_T)$ is mainly driven by the η/s of the fluid. In other words we have found that in a microscopic approach the η/s is the pertinent parameter and the language of viscous hydrodynamics is appropriate. Of course this does not mean that $v_2(p_T)$ in the transport theory is the same as in viscous hydrodynamics (especially at $p_T > 1.5$ GeV), but that the direct relation between $v_2(p_T)$ and η/s is not modified by the NJL field dynamics. This confirms the validity of the studies pursued till now even if they miss an explicit mean field dynamics and/or the chiral phase transition.

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**ASTROPARTICLE
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Status of the NEMO Phase II and SMO experiments

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Abstract- Within the activities of the INFN NEMO Collaboration a new demonstrator for a deep-sea neutrino detector is going to be deployed at 3500 m water depth offshore Capo Passero. The detector, NEMO Phase II, is born from the technological and scientific experience of the NEMO Phase I experiment [1]. Major improvements with respect to Phase I concern mechanics, power distribution, data transmission, and installation of novel acoustic sensors aimed at a new positioning system fully integrated with the detector electronics. Data from acoustic sensors will be also used for multidisciplinary Earth and Sea science in the framework of the SMO project (Submarine Multidisciplinary Observatory, funded by the Italian MIUR). Thanks to recent refurbishment of the Capo Passero INFN-LNS infrastructure, NEMO Phase II will represent another fundamental step toward the construction of KM3NeT, being the first cabled detector deployed at 3500 m depth, fully connected via optical fibre to the GARR backbone.

THE CAPO PASSERO SITE AND INFRASTRUCTURE

In about 10 years of scientific activity, more than 30 sea campaigns were performed by the NEMO Collaboration aiming at seeking and characterization of a deep sea site for the installation of a km³-scale neutrino detector in the Mediterranean Sea. The Capo Passero site (CPS, shown in Figure 1-left, latitude 36°25.010' N, longitude 015°53.660' E, depth 3470 m) was found with optimal features to host the detector: low optical background (30 kHz on 10'' PMTs at 0.5 s.p.e. threshold), blue light absorption length of 70m (close to optically pure water), low currents (3 cm/s in average) and low sedimentation rate [2]. The site is located on a wide abyssal plateau, it has very stable environmental conditions and a flat seabed morphology over several hundreds km², allowing for possible extension of the telescope.

Based on this choice, INFN has built a dedicated infrastructure for the underwater KM3NeT detector. The infrastructure includes a shore laboratory located in the harbour area of Portopalo di Capo Passero (Figure 1, right), a 96 km-long electro-optical cable which links a shore station to the underwater infrastructure, consisting of a main Junction Box (JB) used to connect detector prototypes and structures.

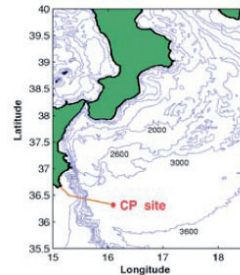


Figure 1: Left- Map and bathymetric chart of the Capo Passero Site (CPS). Right- the INFN-LNS shore lab of Capo Passero.

The underwater cable is an umbilical underwater e.o. cable containing 20 optical single-mode fibres (standard ITU-T G-655) and 1 electrical copper conductor with sea return, suitable for medium voltage DC power transmission (10 kVDC) up to 80 kW. The underwater cable is presently terminated with a Junction Box (JB) deployed at CPS. The JB (Figure 2) consists of a CTA (Cable Termination Assembly), an MVC (Medium Voltage Converter from 10 kVDC to 375 VDC), an hybrid electro-optical splitter and 3 ROV operable deep sea connectors ODI Rolling Seal hybrid connector 5 ways –NRH series. The JB mechanical frame dimensions are about 2x1x1(h) m. Connector output provides 375 VDC power supply and multi-fibre optical link. The cable and the JB are fed with 10kVDC from shore by a PFE (Power Feeding Equipment). The JB then distributes 375 VDC power supply to the underwater instrumentation. The available power supplied by the JB is 10 kW.



Figure 2: The Capo Passero deep-sea Junction Box, successfully deployed in November 2009. A detail showing the three ROV operable connectors is shown on the right.

To date, the Collaboration plans to attach three detectors to the JB: an ANTARES Mini-Line, the NEMO PhaseII/SMO detectors and the Pre Production Model of KM3NeT (see following sections). The maximum power that can be supplied by the PFE is 60 kW, suitable for about 100 detection units of the future KM3NeT detector. A fundamental upgrade of the infrastructure is foreseen at the end of this year with the installation of a dedicated optical fibre link between the Capo Passero shore lab and INFN-LNS. The link (Figure 3) will be deployed,

operated by the Italian Consortium for Research Network (GARR [3]), within the GARR-X project and it will be managed by INFN-LNS.



Figure 3: The complete GARR-X backbone. A dedicated optical-fibre link will connect the LNS to the Capo Passero shore lab.

INFN has also improved its capabilities to deploy and manage underwater experiments, owing a deep-sea light-class ROV with 2 manipulators (SeaEye Cougar, 4000-m operative depth, Figure 4). The ROV has been acquired and built in the frame of the PEGASO project, coordinated by INFN and INGV (Istituto Nazionale di Geofisica e Vulcanologia, Italy).

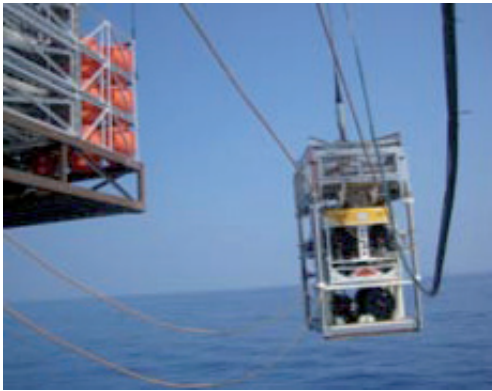


Figure 4: The PEGASO ROV in operation during the deployment of the NEMO tower mechanical demonstrator (February 2010).

THE NEMO PHASE II DETECTOR

The mechanical lay-out of the NEMO Phase II detector concept is based on semi-rigid vertical structures, *towers*, composed of a sequence of horizontal frames (named *stories*) made of marine grade aluminium. Each storey has two optical modules at either end, one looking vertically downwards and the other horizontally outwards and hosts instrumentation for positioning and environmental parameter monitoring. A tower, which consists of a sequence of stories interlinked by a system of ropes is anchored to the seabed and kept vertical by appropriate buoyancy on the top. The spacing between storeys is 40 m, while the distance between the anchor and the

lowermost storey is about 100 m. The structure design permits assembly and deployment in a compact configuration, and unfurling on the sea bottom under the pull provided by the buoy. Once unfurled each floor assumes an orthogonal orientation with respect to its vertical neighbours, obtaining a three-dimensional displacement of PMTs. Differently from the one-dimensional strings –e.g. ANTARES [4] or IceCube [5]– of PMTs, the tower allows disentangling of the muon azimuthal direction reconstruction even with data from only one structure.

With respect to the NEMO Phase I [1], the Phase II tower mechanics was designed and built aiming at simplifying the integration and at reducing construction costs.

The NEMO Phase II tower (Figure 5, left) will be equipped with 8 stories of 8 meters length, hosting 32 optical modules, 18 acoustic sensors, environmental probes (2 CTD-conductivity temperature-depth probes, 1 current metre, 1 light transmission meter), data acquisition and transmission electronics, power supply and distribution electronics, and an electro-optical cabling system. Optical modules (OMs) for Phase II (Figure 5, right) consist of a 13'' glass housing (17'' housing were used in Phase I), containing a 10'' Hamamatsu PMT R7081-SEL, its base and read-out electronics. Read-out samples the PMT signal at 200 MHz, with quasi-logarithmic 13 bit amplitude compression and sends the data to the floor control module (FCM) board through dedicated SPI link (144 Mb/s). A time-calibration board will be also installed in the OM. This board receives a trigger signal from the FCM –synchronous with the detector master clock– and emits a known light signal to calibrate the time and amplitude response of each PMT [6].

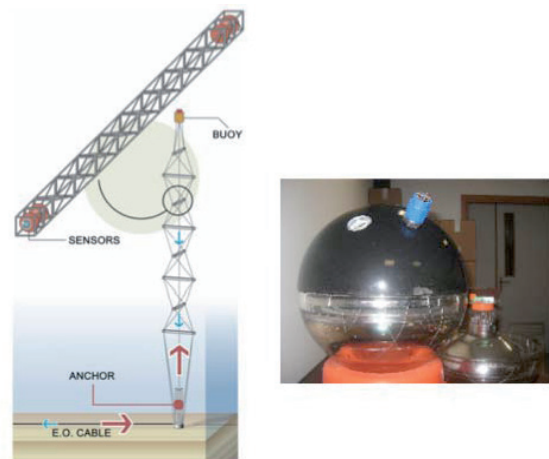


Figure 5: Left- Scheme of the NEMO Phase II detector. Right- The NEMO Phase II Optical Module.

PMT signals are acquired and serialised by the FCM, located inside a pressure resistant aluminium vessel located in middle of each storey. The FCM receives and serialises also data from: a Slow Control Interface (SCI) board, which monitors environmental probes (vessel temperature, humidity, sea parameters), and from an AcouBoard described in the next section.

Point-to-point communication between FCM and the shore is obtained through optical fibre network: a vertical electro-optical backbone cable (distributed along the tower) and a jumper cable, laid on the seabed, from the tower to the JB. Optical fibre connection is based on DWDM (Dense Wavelength Division Multiplexing) technology. Each FCM is characterised in the optical chain by two “colours”, one for the uplink (shore to sea, used for Master Clock and commands transmission), one for the downlink (sea to shore, used for detector data transmission). The optical chain for Phase II was designed to permit optical link over 100 km-long telecom cable without standard underwater amplifiers. An innovative technique based on optical signal amplification on-shore was developed and tested at INFN-LNS [7].

The detector power feeding system was designed to accomplish DC power supply over extreme distance. The 375 VDC power from the JB is sent to a main module installed on the tower base, controlled over optical fibre link from shore. This module permits –through RS-485 connection over the tower backbone cable– sequential switching-on of each tower storey, and control of power consumption and possible current and/or voltage overshoots at each storey. A dedicated board –hosted in each floor vessel– equipped with a DC/DC converter produces low voltage (4.2 VDC, 5 VDC and 12 VDC) for the storey electronics. Filters have been introduced to reduce the electronic noise over the power line.

Figure 6 shows the NEMO storey electronics and its integration inside the pressure vessel.

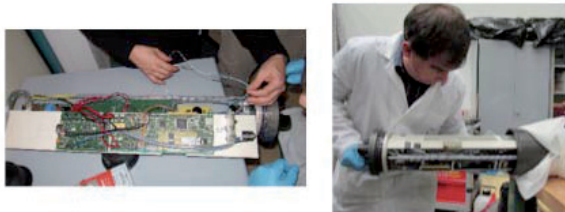


Figure 6: The storey electronics of NEMO Phase II is hosted in a rack and placed inside a pressure resistant aluminium vessel. Connections to OM, hydrophones and to the vertical backbone are obtained with dry-mate pressure resistant connectors and penetrators.

SMO ONBOARD NEMO PHASE II

An innovative array of 18 acoustic sensors will be also installed on-board the NEMO Phase II detector. The SMO (Submarine Multidisciplinary Observatory) array will be a high-sensitivity, broad-band acoustic antenna allowing real-time acoustic monitoring of sound sources in deep-sea. Hydrophones (submarine microphones) will be installed at the end-points of each storey and of the tower base and will form a 3D antenna of sensors. Data from all hydrophones will be continuously acquired, sampled and sent to shore. The typical hydrophone sensitivity response is -207 dB re 1V/ μ Pa, flat over a ultra-wide bandwidth (10 Hz- 70 kHz). Hydrophones' signals will be amplified with a gain of +38 dB by a preamplifier and read by an AcouBoard. This board, designed by INFN, has a stereo professional audio ADC

capable of 192 kHz/24 bit sampling [8]. Digital signals are converted in audio standard and sent to the FCM that adds a precise ($<1\mu$ s accuracy) underwater GPS time-stamp to acoustic data.

The main purpose of the array for NEMO's sake is to provide acoustic positioning of the tower, detecting acoustic signals produced by a long baseline (LBL) of five acoustic beacons anchored on the sea-floor. Beacons' positions will be accurately geo-referenced and displaced at about 500 m from the tower, to form a Cartesian reference system of orthogonal axes. Beacons will emit known sinusoidal packets of 32 kHz, 5 ms duration, 180 dB re 1 μ Pa at 1 m amplitude. Accurate TDoA (Time Difference of Arrival) measurement between beacon signal start-time and hydrophone signal reception stop-time, will permit hydrophone positions' calculation with an expected accuracy better than 10 cm (about $\frac{1}{2}$ of PMT diameter).

Data acquired by SMO will be analysed also in collaboration with the Earth and Sea science community, embracing three different scientific areas: geophysics, high energy physics and bio-physics. The straightforward goal of SMO, based on the experience of NEMO-OvDE [9,10] is devoted to the search and identification of marine mammals' sounds, with major interest on odontocetes (sperm whales, dolphins, Cuvier's beaked whales, ...). The 3D shape of the array will also permit tracking of animals and study on their social and feeding behaviour. Continuous monitoring of underwater noise variations in short- and long-term scales will also permit the study of noise variations due to the anthropogenic noise in the Mediterranean Sea: one of the most acoustically polluted seas over the World. Moreover it will be possible to study occurrence of correlated noise, using the acoustic data acquired at the Catania Site (see ref. [11]), at about 200 km from the Capo Passero site.

The physical application is devoted to preliminary studies on acoustic detection of high-energy astrophysical neutrinos. Following the interaction of an Ultra High Energy neutrino ($E > 10^{18}$ eV) neutrino in water, a large amount of the neutrino energy is deposited in a small pen-shaped volume of water. Instantaneous ionization of water produces heating, thus, a bipolar acoustic pulse. The expected pulse spectrum is centred at about 30 kHz with a spread of few tens kHz [12]. At these frequencies sound attenuation in seawater is small, and the expected pulse amplitude is some tens of mPa, for a 10^{20} eV neutrino, at 1 km distance from the neutrino interaction vertex. The expected number of such events is very small, order of few in 10 km^3 of water per year. Their detection can only be achieved using large detectors made of sparse and poorly dense arrays of hydrophones. SMO will permit to assess the technology of underwater acoustic arrays, and their possible use in correlation with underwater Cherenkov detectors.

The geophysical applications are mainly related to the study of low frequency acoustic signals as possible tsunami precursors. The goal of SMO is to test deep-sea systems able to use automatic analysis of hydro-acoustic measurements, to provide states of variable tsunami alert-level for coastal areas, also using appropriate numerical

models for generation and propagation of tsunami waves [13].

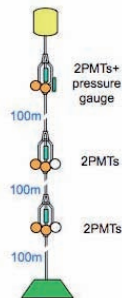
THE ANTARES MINI-LINE AND THE KM3NET PPM

The Capo Passero infrastructure will also host two other experiments: an ANTARES Mini-Line and the preproduction model of KM3NeT.

The ANTARES Mini-Line (Figure 7) hosts 3 storeys with 2 OMs each and standard ANTARES data acquisition and transmission system. The optical connections and power supply system have been modified by INFN to comply with DC power and optical link provided by the Capo Passero Junction Box. The Mini-Line was integrated at the INFN-LNS Test Site Laboratory of Catania. A tentative deployment was carried-out on December 2010, but it was stopped due to rough sea conditions; the deployment is now foreseen in summer 2011. The main scientific goal of the experiment is to monitor the environmental features of the site, with focus on optical background rate (mainly on bioluminescence mechanically stimulated by currents and detector movements). The mini-line will provide a direct comparison, unbiased by different mechanical behaviour of the detector, on bioluminescence rate at the Capo Passero and Toulon site.



Figure 7: Left- The ANTARES Mini-Line, during embark for tentative deployment in December 2010. Right- a sketch of the line.



Capo Passero will also host in 2012 the KM3NeT Pre-production Model (PPM). The PPM is a demonstrator of the KM3NeT Detection Unit (see KM3NeT TDR [14]): a vertical flexible structure composed of 20 storeys and a tower base. The storey is a bar of 6 m length; inter-distance among storeys is 40 m. Each bar hosts two DOMs (Digital Optical Modules) and acoustic sensors. The DOM is a “multi-PMT” array of 31 PMTs (3” size) with digital read-out based on time-over-threshold (Figure 8). The PPM will have only four active DOMs, located in the top-most storeys of the structure, but it will provide an ultimate benchmark for the technological choices of the KM3NeT Technical Design Report.



Figure 8: Sketch of the KM3NeT PPM; the Detection Unit, the storey (bar) and a photo of the DOM prototype.

ACKNOWLEDGMENTS

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First results of the ANTARES neutrino telescope

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Abstract - The ANTARES neutrino telescope was completed in May 2008 and its first results of the searches for point-like and diffuse neutrino fluxes are presented. The sensitivity reached for point-like searches for a live time of 295 days and for declination lower than -50° is of $7.5 \times 10^{-8} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$. For the search of diffuse flux the observed number of events is found to be compatible with the background expectation and a 90% C.L. upper limit of $5.3 \times 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ for a total live time of 334 days was set. The multi-messenger ANTARES program is also briefly described with particular emphasis on the neutrino alert system for the detection of transient source of neutrinos..

($42^\circ 48' \text{ N}$, $6^\circ 10' \text{ E}$) at a depth of 2475m. The ANTARES detector was completed in May 2008 but thanks to its modularity takes data since the deployment of its first line [2].

The ANTARES detector is the largest operating telescope looking at the Southern sky where the Galactic center and a large part of the Galactic plane are located. In this sky region high energy gamma detectors, like HESS, have disclosed a large number of TeV gamma sources that are very promising neutrino sources. The ANTARES detector is complementary to the AMANDA/IceCube [3] detectors located at the South Pole.

INTRODUCTION

ANTARES is the first operational neutrino detector in the Mediterranean Sea [1]. The main purpose of the detector is the observation of high energy neutrinos that are expected to be emitted by Galactic and Extragalactic sources where an high energy acceleration mechanism is present. The properties of neutrino makes it complementary to other probes as high energy gamma and charged particles. In fact, neutrinos can escape from dense matter surrounding the acceleration zone and, due to their neutral charge, they are not deflected by magnetic fields making possible to point back to the source with high precision. Moreover, the neutrino hadronic origin will allow to distinguish unambiguously between hadronic or leptonic mechanisms.

The neutrino detection principle is based on the observation of Cherenkov light produced in sea water from secondary charged leptons which originate in charged current interaction of neutrino with the water or rock near the instrumented volume. The long muon range makes muon neutrinos privileged with respect the other neutrino flavours that are detected with lower efficiency and poorer angular resolution. Measuring the photo-sensor positions and the photon arrival time it is possible to reconstruct the neutrino direction (the induced muon and the neutrino are almost collinear at the energy of interest of the telescope).

The ANTARES detector consists of 12 flexible lines, each one hosting 75 photomultipliers contained in glass spheres (Optical Modules OM). The lines are anchored to the sea bed at a distance of around 70m from each other and are kept vertically by a buoy. The OMs are located along the line and arranged in 25 storeys of three OMs. The distance between storeys is 14.5m. Each storey contains also the corresponding electronics. The detector is installed about 40 km off the Toulon coast (France)

SEARCHES FOR POINT-LIKE SOURCES AND DIFFUSE FLUX

First results of searches for point-like sources are based on data collected in 2007 and 2008 corresponding to an integrated live time of 295 days. In this period the detector was under deployment and it was in a configuration between 5 to 12 operational lines.

In the analysis the rejection of atmospheric muons, that are originated by the interaction of cosmic rays with the atmosphere, is based on a likelihood variable Λ deduced from the track reconstruction algorithm. The Λ variable is linked to the goodness of the fit and consequently to the reconstructed track precision. Putting cut on the Λ parameter and on the estimated fit error we can reject most of the atmospheric muons badly reconstructed as up-going. The number of data events selected as up-going was 2040 which is in good agreement with the MonteCarlo expectation.

Search of cosmic neutrinos from point-like sources was performed using an unbinned method following two different approaches. In the first approach, the full sky search, no assumption is made regarding the position in the sky of the neutrino sources and a search for event clusters is performed. No significant excess was found. The most significant cluster contains 8 events (only 3 background events are expected) that corresponds to a significance level of 2σ . In the second approach a list of 24 candidate sources was fixed and a search in order to find statistically significant excesses in that directions was carried on. For each source the observed flux limit is reported in Fig. 1 (full squares). The sensitivity (90% C.L.) is reported as a function of the source declination in Fig.1 (line): the value for the declinations with full visibility is $7.5 \times 10^{-8} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$. The flux limit

reached for point-like search is the best one that has been achieved for the Southern sky.

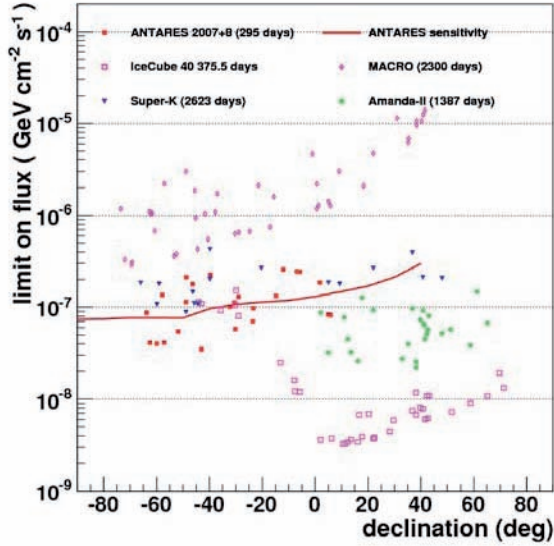


Figure 1: 90% C.L. flux limits as a function of the source declination. Published limits from other experiments are also shown.

SEARCH FOR A DIFFUSE FLUX

The search of flux of high energy ν produced by astrophysical sources without any particular assumption on the source direction is one of the main aims of a neutrino telescopes. The main existing predictions are based on the observed Cosmic Ray (Waxman-Bahcall) and Cosmic Ray and gamma-ray diffuse flux observations (Mannheim-Protheroe-Rachen) [4]. In the analysis the most challenging issue is the separation of atmospheric and astrophysical neutrinos. In ANTARES this goal has been reached with the implementation of an original energy estimator based on the average number of hit repetitions (R) in the OMs due to the different arrival times of direct (Cherenkov not scattered photons) and delayed photons (photons from secondary electromagnetic showers or scattered photons). High energy muons ($E_\mu > 1\text{TeV}$) are expected to produce more electromagnetic showers and the consequence is that the percentage of delayed photons with respect to the direct photons increases with the muon energy. The separation between the diffuse flux signal from the atmospheric neutrino background is performed by means of a cut on the R variable. The value of the cut on R has been estimated on Monte Carlo following the Feldmann and Cousins method [5] evaluating the best signal to noise ratio (Model Rejection Factor minimization). The obtained value is $R=1.31$. In Fig. 2 are reported MonteCarlo expectation for signal and background neutrino energy spectra as a

function of the true neutrino energy before and after the selection of the condition $R \geq 1.31$. It is highlighted the region where the 90% of the astrophysical neutrino signal is present. After data unblinding, 9 events have been found in data. From Monte Carlo the number of expected background neutrino events is 10.7 ± 2 . The corresponding upper limit is $E^2 \Phi_{90\%} = 5.3 \times 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ in the energy range between 20 TeV and 2.5 PeV. This limit has been obtained for 334 days of equivalent live time using at least 9 detection lines. In Fig. 3 this limit and, for comparison, limits from other experiments are reported [6].

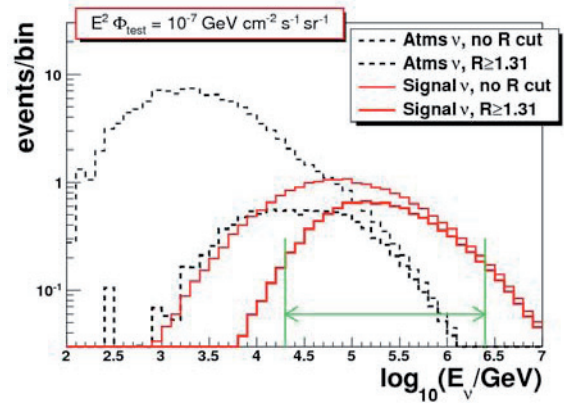


Figure 2: MonteCarlo expectation for signal and background neutrino energy spectra as a function of the true neutrino energy before and after the selection on the average number of hit repetitions R . The atmospheric neutrinos are the conventional Bartol+RQPM prompt and the signal is at level of $E^2 \Phi = 10^{-7} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$.

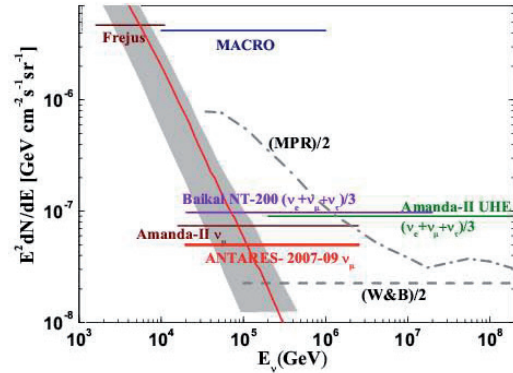


Figure 3: ANTARES upper limit (90% C.L.) for an E^{-2} diffuse high energy muon-neutrino flux compared with upper limits from other experiments. The prediction for transparent sources are also shown. The grey band represents the variation from vertical to the horizontal direction of the atmospheric ν_e flux, the central line the average flux.

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KM3NeT sensitivity and discovery potential to point-like sources

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Abstract - KM3NeT response to point-like sources as reported in the Technical Design Report published in 2010 by the collaboration is reported. A preliminary estimate of the sensitivity flux calculated with the unbinned method is also reported.

INTRODUCTION

Neutrino astronomy opens a unique new window for the observation of the Universe. The principal goal of KM3NeT is the observation of cosmic point-like sources of neutrinos, in particular in a region of the sky complementary to the field of view of IceCube [1] that, at the present time, is the most sensitive neutrino telescope in the world. IceCube is located at the South Pole and instruments a cubic kilometre of polar ice.

The KM3NeT consortium is formed by 40 European institutes with the aim to develop a research infrastructure in the Mediterranean Sea hosting a multi-cubic kilometre size detector. The primary objective is the construction and operation of a telescope for high energy neutrinos ($>100\text{GeV}$) in deep-sea. KM3NeT will provide innovative science opportunities on the Earth and Sea Science. This is possible through the synergy created by the use of a common infrastructure allowing for long term continuous operation of a neutrino telescope and marine instrumentation. In December 2009, the first phase of the project, the Design Study, funded by the European community (EU) FP6 framework, was concluded with the publishing of the Technical Design Report (TDR) [2]. In the TDR the chosen technologies and the expected physics performance of the future detector are detailed. An EU funded Preparatory Phase is already started which will lead to the start of the telescope construction.

In this report the main results, published in the TDR, regarding the detector performance to point-like sources will be reported. A first preliminary result regarding the calculation of the sensitivity flux with a different statistical method, the unbinned method, is also presented.

DETECTOR PERFORMANCE TO POINT-LIKE SOURCES

The expected performance of the KM3NeT neutrino telescope has been calculated by means of Monte Carlo simulations. The expected neutrino rates from the point sources (assuming a pure E^{-2} neutrino spectrum) have been computed and the sensitivity flux and discovery fluxes estimated.

The Monte Carlo software adopted for these simulations is the ANTARES software adapted to a km³-scale detector. In the simulations the neutrino interaction with

the medium surrounding the detector, the propagation of the resulting secondary particles, the light generation, the propagation in water, the optical background and the detector response are taken into account.

The final design, based on about 310 detection units (DU) made of flexible towers equipped with photo-sensors, has been defined at the end of 2010. The detector consists of two blocks of about 154 DU arranged in the sea bed with a roughly circular layout. The average distance between DU is about 180m. Each DU is a sequence of rigid bars, 6m long, placed orthogonally to each other with a vertical spacing of 40m. Each bar is equipped with two Optical Modules each one containing 31 photomultipliers with a diameter of 3 inches and a 30% of quantum efficiency.

The search for point-like sources is based on statistical techniques to detect a very small number of events from a cosmic source amongst large backgrounds. The two main methods developed to look for steady point-like sources are the binned and unbinned methods. In the binned method the sky is divided in bins of declination and right ascension and the fluctuations on the number of events detected are analyzed inside the bin. The search of an excess due to events from a source is performed assuming Poisson distribution of the events and optimizing the cone aperture. In the unbinned method the expected density distributions of signal and background are described by statistical functions and a likelihood is maximized. Moreover, in the unbinned method a criterion of significance is necessary to confirm or reject the existence of a point source.

The sensitivities calculated in the TDR have been obtained applying a binned method. This method does not imply an assumption on statistical functions that describe the background and signal distributions. The Model Rejection Factor (MRF) [3] and Model Discovery Potential (MDP) [4] have been applied to evaluate the sensitivities and the discovery fluxes respectively. The parameters that are optimised in order to minimise the MRF and MDP are the size of the search cone around the source, the cut on the reconstruction quality parameter and a cut on the number of neutrino hits that is related to the neutrino energy. The average number of events from a point-like source, at a given declination and with a spectral index α is estimated by means of Monte Carlo simulations, as well as the average number of background events inside the selected search cone centred around the source direction. The background is due to atmospheric neutrinos and atmospheric muons that are mis-reconstructed as up-going.

The sensitivity of the detector to neutrino point sources, based on one year of data, is shown in Figure 1 as a function of the source declination. The detector performance is presented as the flux that can be excluded at 90% CL (flux sensitivity) and the flux that can be detected at 5σ with 50% probability (discovery flux). This calculation assumes a E^{-2} neutrino energy spectrum. For comparison, the plot also shows the flux sensitivity of IceCube [5] (using an unbinned method and a likelihood that exploits the reconstructed energy information) and the IceCube discovery flux. The differences in shape of the sensitivity curves for KM3NeT and IceCube are caused by the different geographic location, the effect of neutrino absorption in the Earth and the different detector responses as a function of zenith angle. Recently an analysis based on the unbinned method has been exploited to evaluate the sensitivity (90% C.L.) and a $\sim 25\%$ improvement with respect to the binned value has been found (Fig. 1 green dashed-dotted line). This value can be further improved if a dependence of the likelihood on the reconstructed neutrino energy is included [6].

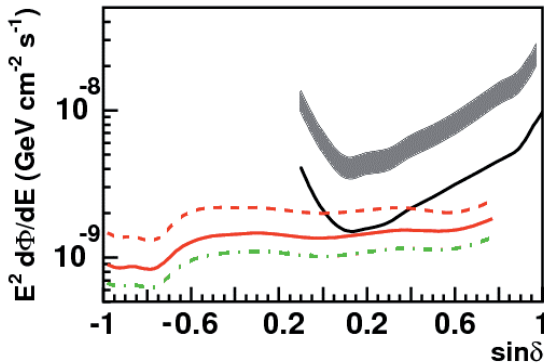


Figure 1: Sensitivity of the full KM3NeT detector to neutrino point sources with an E^{-2} spectrum for one year of observation, as a function of the source declination. The red lines indicate the flux sensitivity (90% CL; full line) and the discovery flux (5σ , 50% probability; dashed line). Both are estimated with the binned analysis method. The green dashed dotted line indicates the flux sensitivity estimated with the unbinned method. The black line is the IceCube flux sensitivity for one year, estimated with the unbinned method (full line). IceCube's discovery flux (5σ , 50% probability) is also indicated (grey band).

The estimated sensitivity of the detector to neutrino fluxes from point sources depends strongly on the extension of the spectrum to high energies. Many of the galactic TeV gamma sources observed, and in particular the supernova remnants, have a gamma spectrum with an energy cut-off

in the region from few TeV to tens of TeV. From these sources also a neutrino energy spectrum with a cut-off is expected.

The discovery for a neutrino flux proportional to $E^{-2} \exp(-E/E_c)$ has been assumed and calculated as a function of the cut-off energy E_c . Figure 2 shows the dependence of sensitivity and discovery fluxes on the assumed energy cut-off. When the cut-off energy decreases from 1 PeV to 10 TeV the sensitivity worsens by an order of magnitude.

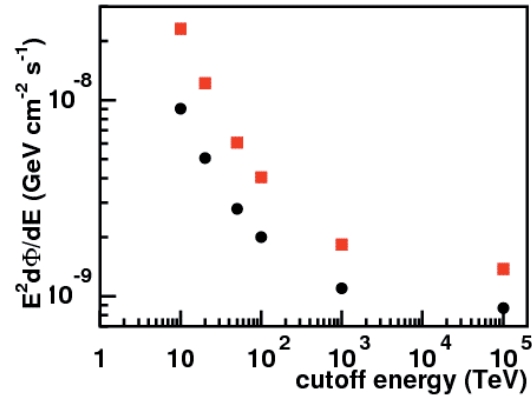


Figure 2: Evolution of the one year flux sensitivity (90% C.L., black dots) and discovery flux (5σ , 50% probability; red squares) for point sources at a declination of -60° as a function of the assumed cut-off of the energy spectrum

CONCLUSIONS

In this report the performance of the KM3NeT telescope for point-like neutrino sources is reported and compared with that one of IceCube. A preliminary result shows that applying the unbinned method for a search of point-like sources neutrinos an improvement of about 25% can be achieved for the 90% C.L. sensitivity flux.

The resulting sensitivity shows that KM3NeT extends substantially the visible region of the sky and even improves the discovery potential in the same field of view. This gain is due to the far larger instrumented volume possible with the project budget, together with the significantly better angular resolution achievable in water compared to ice.

Simulations aiming at the optimization of the detector layout to known Galactic sources (i.e. RXJ1713.7-39.46) are ongoing.

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Shear viscosity in hybrid stars

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The transport parameters in neutron stars (NS) have been calculated from the in-medium NN cross-section within the Brueckner theory [1]. In particular, it was found the shear viscosity to be a good candidate for the r-mode damping, requested to prevent the NS instability driven by the emission of gravitation radiation [2]. In fact, from the calculation of the density dependence of the shear viscosity in beta-stable nuclear matter it is possible to derive the time scale damping of r-modes sitting on a given stable configuration of neutron matter.

The previous calculation considered only pure NS, made of neutrons, protons and electrons. But it is well known that most of the EoS adopted to solve the Tolmann – Oppenheimer - Volkov structure equation predict a quite large NS mass [3]. This result along with the too large hadron density calculated in the NS central region indicated that a transition to quark matter could occur in the inner core. Hybrid neutron stars (hadron plus quark phases) calculated with different quark models predict in fact a NS mass quite close to the observed mean value.

Therefore it is interesting to recalculate the shear viscosity in hybrid stars because the contribution of the quarks can change the scenario of the damping mechanism of r-modes.

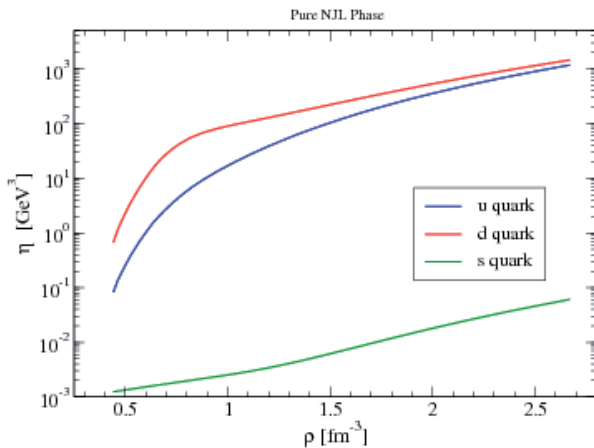


Fig.1 - Shear viscosity in pure quark matter from NJL model.

Within the linear response theory the quark viscosity can be calculated from the Kubo formula:

$$\eta(\omega) = i[\Pi(\omega) - \Pi(0)] / \omega$$

where $\Pi(\omega)$ is the quark polarization function [4]. Since in the present investigation the NJL model has been adopted for describing the quark phase, we calculated the quark shear viscosity within the same model [4]. The results in a pure quark phase are plotted in Fig.1.

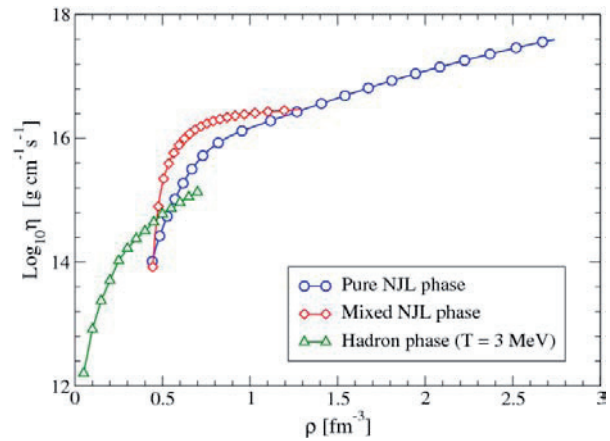


Fig.2 - Shear viscosity in hybrid neutron star.

The transition to the quark phase has been described within the Gibbs phase equilibrium conditions under the charge neutrality. From the entire hybrid star profile with hadrons in the inner NS core and the transition to the quark phase deep inside, the shear viscosity pattern can be established. This is shown in Fig.2. One can observe that the shear viscosity is further increasing from the hadron to the quark phase, so that in hybrid stars the viscosity damping turns out to be more efficient than in pure neutron stars. Quantitative estimates are on the way.

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A long term passive acoustic monitoring of sperm whales off Catania

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Abstract - An experimental deep-sea station named OvDE (within the activities of the NEMO Collaboration) has been deployed from January 2005 until December 2006 at the INFN – LNS Test Sea Site. The underwater Test Site is located at 25 km offshore Catania, at about 2,000 m depth. It is connected to a shore laboratory (in the harbour of Catania) through electro-optical cables, which allows real-time monitoring and data acquisition. During NEMO-OvDE operations, four calibrated broadband hydrophones, sampled at 96 kHz, sent digital data to the shore lab 24/24h. Data recording was made for 5 minutes every hour. The experiment provided long term data on underwater noise and a unique opportunity to study the acoustic emissions of marine mammals living in the area or transiting during their seasonal movements within the Mediterranean basin. This report deals with the analysis of sperm whales' detections performed by the NEMO OvDE station, providing first results on sperm whale group analysis and seasonal presence. Studies on deep-sea sounds will continue in 2011 at the NEMO Test Site, within the activities of the LIDO Demo Mission of ESONET and in Capo Passero (South – East Sicily) INFN – LNS Site, with the operation of the NEMO phase II and SMO projects.

INTRODUCTION

The NEMO-OvDE (Ocean Noise Detection Experiment) station was dedicated to the study of the acoustic underwater noise. It has been deployed on the sea floor 25 km offshore Catania (Sicily, Italy) at about 2,000 m depth [1]. It was connected to the shore laboratory, located at the harbour of Catania, through electro-optical cables to provide power feeding and real-time data monitoring. The station was deployed in January 2005; it steadily sent data since the end of March 2005 until December 2006 when the acoustic module was replaced by the NEMO Phase 1 experiment [2]. The acoustic experiment hosted by the station dealt with the study of the underwater acoustic environment to develop the strategies required for the detection of acoustic pulses generated by high energy

neutrino interacting with water. The experiment was highly interdisciplinary and besides providing long term

data on the underwater noise, it also provided an unique opportunity to study the acoustic emissions of marine mammals living in the area or transiting there during their movements within the Mediterranean basin [3].

EXPERIMENTAL SET-UP

NEMO-OvDE was equipped with four calibrated broadband hydrophones, with a -177 dB peak ref $1\text{V}/\mu\text{Pa}$ sensitivity and connected to a 24 bit AD board. The hydrophones were sampled at 96 kHz and sent digital data to the shore lab 24/24h, through optical fibre link. The continuous recording was not possible due to storage space constraints; recordings were, thus, performed for 5 minutes every hour. Data recording, totalling 2.5TB of scheduled recordings, and 1TB of free running recordings, was made with a custom developed 4 channels software recorder developed at CIBRA that reads and keeps in synch the two digital streams coming from the underwater station. Digital data were saved as standard Microsoft .wav files. Results of bioacoustics analysis shown in this paper were obtained with SeaPro, the sound analysis software developed at CIBRA Univ. of Pavia. In a first analysis stage sound were classified into known categories (biological sounds, ship noise, other). Results were then arranged to show, as a function of time, the occurrence of biological sounds and other relevant acoustic events.

NEW RESULTS ON SPERM WHALES

The NEMO-OvDE acoustic platform recorded several biological sounds especially produced by sperm whales. This marine mammal mainly produces an impulsive sound known as click (see Figure 1), arranged in a regular sequence (inter-click interval in the range 0.5 sec. to 2 sec.), or in special patterned sequences (chirrup -Figure 2-, codas, creaks). According to other studies in the Mediterranean Sea, sperm whales may dive to more than 1,000 meters depth, but normally travel at 800-1,000 meters depth. Their source level is greater than 200 dB at

1m on axis; the loudest clicks were received with sound pressure levels up to 170 dB. Clicks were often recorded with high Signal-to-Noise Ratio. The SNR, using high-pass filters, can be further increased to improve detection, count and analysis of the weakest click series. Detections indicate a presence of sperm whales more consistent and frequent than previously believed. Although the transiting of sperm whales is known since the end of XIX century [4], very few literatures are available for the area.

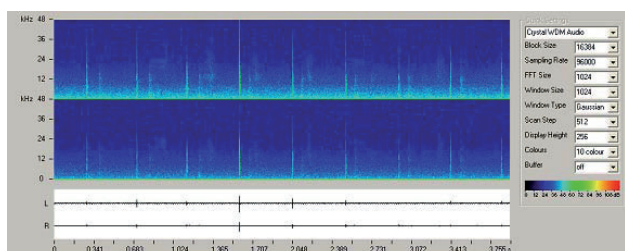


Fig. 1. Spectrographic display of a series of sperm whales' clicks recorded by NEMO-OvDE (2 channels).

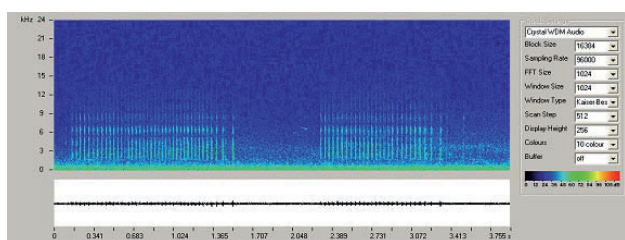


Fig. 2. Spectrographic display of sperm whales' chirrups.

The report of IFAW [5] presented a low sperm whale density in the Ionian basin with an encounter rate of 5.8 whale groups for 1,000 km of transect. Lewis et al. [6], based on the IFAW surveys, reports a total of 16 whales detected within the truncation distance of 20 km, along 3846 km of survey transects in the Ionian Sea. Panigada et al. [7] published a report about marine mammals presence in the area of the Strait of Messina and extending to South till 50 km North with respect to the the NEMO-OvDE station location. In the period from June 2005 to May 2006 they conducted 125 days of survey and sighted 80 marine mammals, of which 13.8% sperm whales and 1.2% Cuvier's beaked whales.

The NEMO OvDE acoustic platform has improved previous data with unprecedented statistics, detecting in 2005, sperm whales in 117 over 231 days (50.6%) and in 2006 in 35 over 100 days [8]. Although several periods of consecutive days were characterized by the presence of sperm whales, solitary whales or groups of several individuals were often detected for few hours only and this means they were just in transit (Figure 3). In some cases the presence of whales was constant for more than one day. In few occasions, other than clicks and creaks, chirrups and codas (the most common was the 3+1 type) [9], indicating socializing behaviours, were recorded (Figure 4).

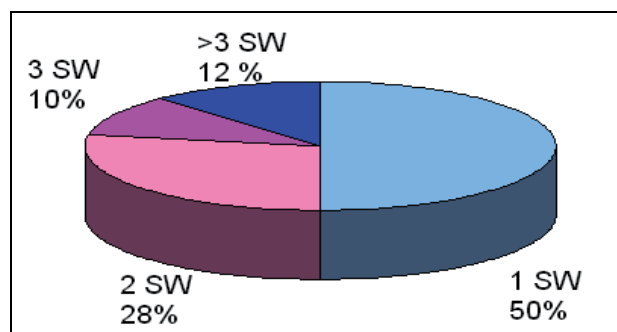


Fig. 3. Dimension of sperm whales' groups detected with NEMO-OvDE. In 50% of cases the animals were solitary.

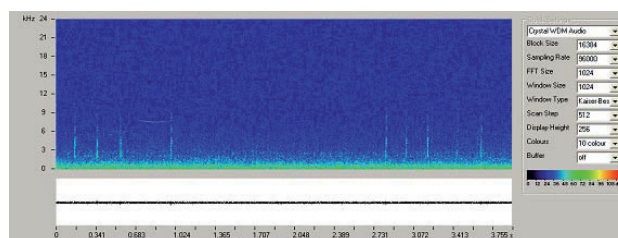


Fig. 4. Spectrographic display of two codas with the typical Mediterranean pattern 3+1 [9].

The marine biologists have also an ecological interest with regards to the seasonal transit of sperm whales near the Eastern Coast of Sicily. According to the NEMO OvDE data, spring is the period with the majority presence of sperm whales (Fig.5).

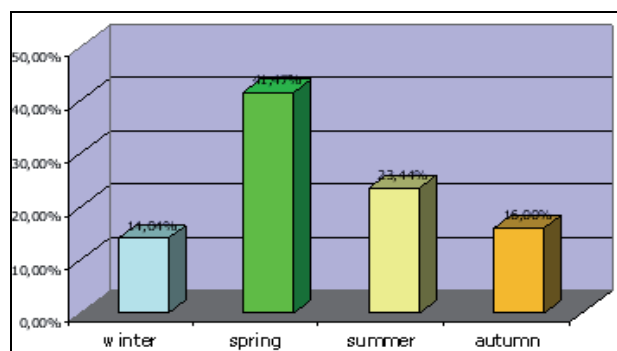


Fig. 5. Seasonal presence of sperm whales in the Gulf of Catania.

Analysis algorithms have been also developed to track the movements of impulsive acoustic sources to reveal the movement of sperm whales whilst in the detection range. By plotting TDOAs (Time Difference Of Arrivals) in a virtual 3D space it is easy to separate different sources and then, by projecting them in the real 3D space [10], to track the sources' movements. In some cases, when surface reflections are clearly linkable to individual clicks it is possible to exactly locate the animal, i.e. know the range and depth, instead of having only bearing and azimuth information [11]. The CNRS UMR LSIS (Information & System Sciences Lab.) of the University Sud Toulon Var (France) has developed a real-time system for tracking sperm whales. The algorithm is

mainly based on correlation techniques and TDOA computation for each couple of hydrophones to estimate the whales' position. F. Bénard et al. adapted this algorithm for the NEMO-OvDE platform [12]. The CNRS software algorithm detects clicks and determines the relative time delay between signal arrivals at the different receiver elements with cross-correlation techniques. Tracking algorithm consists in computing the position of each target, relative to the platform, using directly TDOA estimates, therefore resolving the acoustic model with a maximum likelihood estimator. They thus compute the Cramér-Rao Lower Bound (CRLB) for the given array geometry and the confidence ellipses. This method allowed localization of several sperm whales signals recorded by NEMO-OvDE. As an example in Figure 6 we shows the 2D result of the algorithm, tracking the dive profile of a sperm whales during a 5' NEMO-OvDE recording.

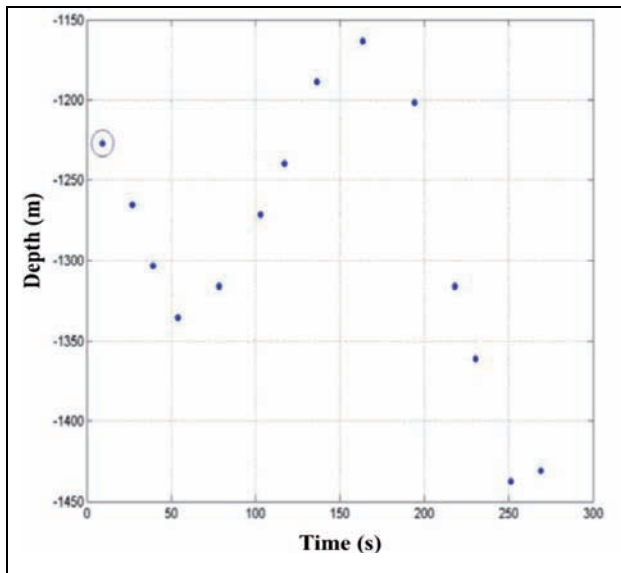


Fig. 6. Dive profile of one sperm whale recorded on 17 August 2005 at 16:00. The animal speed was ≈ 10 km/h.

Recorded clicks were also studied to measure the Inter Pulse Interval, i.e. the intervals among the pulses that constitute the sperm whale click [13]. According to the latest models on sound production [14] reliable IPI measures can be taken when a clean P0-P1, P1-P2 or P2-P3 (nominal IPIs) structures are available (Figure 7). If SNR is high enough, it is also possible to assess the orientation of the whale. By measuring the IPI [15] (that is the transit time of sound inside the sperm whale's head) it is possible to assess the whale size. If size is greater than 13m, the minimum size of mature males, the sex of the animal can be determined.

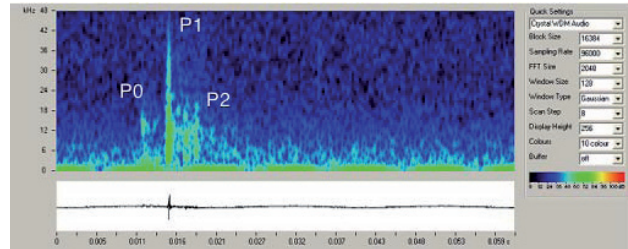


Fig. 7. Sperm whale click with clear multi-pulse structure: P0-P1-P2. In this recording the size has been estimated 9.94-10.27 meters, matching a young male or a female (females reach about 12 m, males reach 18 m).

Using this method we determined the size of about 50 sperm whales and, as shown in Figure 8, speculated the sex of the animals.

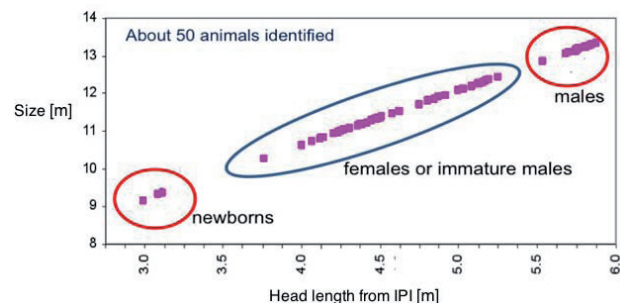


Fig. 8. Distribution of size of detected animals.

By combining the two data - TDOA and IPIs - it is possible to gain access to the number of transiting animals and the composition of the groups, to estimate with more accuracy the population dynamic of the species in the Mediterranean basin. With the long term tracking of sperm whale movements through the Ionian Sea it will possibly to reveal whether their transit is seasonal or not and if they are direct to/from the Strait of Messina, as already suggested by Bolognari [4].

WORK IN PROGRESS

In the same NEMO-OvDE underwater site, a project for a deep-sea multidisciplinary observatory (the LIDO Demo Mission of ESONET) [16,17] will be deployed in 2011. LIDO is a fully integrated system for multidisciplinary deep-sea science, capable to transmit and distribute data in real time to the scientific community. LIDO hosts a large number of sensors aimed at the monitoring and studying of oceanographic and environmental parameters, geophysical phenomena, ocean noise monitoring and identification and tracking of biological acoustic sources in deep sea. The latter will be performed using two tetrahedral arrays of 4 hydrophones, located at a relative distance of about 5 km, and at about 25 km from the shore lab, connected with the two deep sea cabled terminations named Test Site North (TSN) and Test Site South (TSS) respectively. The system presents an underwater technology that will allow to record any form of acoustic source in the bandwidth of 10 Hz – 70 kHz. It

will be real – time viewing and recording of the vocalizations of cetaceans present in the area. An identification and tracking of noisy ships can be achieved, to study the possible disturbance with marine mammals. Therefore the acoustic tracking of cetaceans from deep sea observatory increases the possibility to improve direct research techniques. According to the results of the NEMO OvDE experiment, we expect to obtain new data with regards to seasonal migration of sperm whales in the Mediterranean Sea.

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The East Sicily node of the LIDO demonstration mission

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Abstract - The LIDO (Listening to the Deep Ocean environment) Demonstration Mission of ESONET proposes to establish a first nucleus of a regional network of multidisciplinary seafloor observatory contributing to the coordination of high quality research. The LIDO demonstration mission (DM) is, in fact, carried out in two deep-sea sites: the first one is in Portugal, a stand alone mooring offshore Cadiz and the second one, located offshore Catania, is a cabled observatory in the East-Sicily Node. The main goal is to allow the real-time data transmission from the multidisciplinary observatories. These data are related with specific activities addressed to a long term geo-hazard monitoring (earthquakes and tsunamis) and characterisation of marine ambient noise with special attention to bioacoustics (mainly detection of marine mammals). In this report the work on the East-Sicily node is described highlighting the INFN activities in 2010.

THE LIDO DEMO-MISSION OF ESONET

LIDO is a demonstration mission of ESONET, a Network of Excellence (NoE) of deep-sea observatories, funded by EU, which includes 55 partners from 14 different European countries [1]. In particular, the LIDO Demonstration Mission (DM) foresees the installation of submarine observatories in two sites: offshore Cadiz and offshore Catania. The first one is an autonomous GEOSTAR class observatory that was deployed in November 2009 and operated for about 18 months. The second one, named LIDO-East Sicily, is composed of two cabled stations that will be deployed at the INFN Test Site North (TSN) and Test Site South (TSS). LIDO aims at fulfilling several scientific and technological objectives. Among these, acoustic sensors –managed by INFN- are installed to:

- evaluate the human and natural contributions to marine ambient noise and for the first time implementing tools to describe the long-term trends in ambient noise levels;

- allow real-time and near real-time long-term acoustic monitoring of marine mammals at regional level as well as noise propagation that could be soon correlated with the effects of anthropogenic impacts and climate changes;
- detect acoustic signals for the characterisation of tsunami warning system in the related areas with special regard to the definition of trans-national seismic and sea level monitoring networks.

LIDO-East Sicily will be installed using the Catania Test Site infrastructures installed and operated by the Laboratori Nazionali del Sud (LNS) of INFN, about 25 km offshore the Port of Catania [2]. The termination of the main electro-optical cable, connecting the deep-sea Test Site infrastructures to shore, is housed in the Catania Test Site Shore Laboratory of the LNS. The Shore Lab hosts the main power supply, and the on-shore data acquisition and data storage units. The Shore lab completely fulfils the requirements of power, physical space and logistics in general for the LIDO- East Sicily experiment. LIDO East-Sicily data will be continuously transmitted from deep-sea stations to the shore lab through the submarine main electro optical cable.

During 2010, integration of the LIDO East-Sicily observatories and extensive tests on the experimental devices have been carried out by INFN.

LIDO – EAST SICILY: TSN

LIDO TSN is an upgraded version of the former SN1 station, deployed by INGV [3]. This observatory hosts geophysical and environmental sensors and a tetrahedral array of hydrophones [4]. Mechanical parts of LIDO East Sicily TSN station have been refurbished with respect to the standard GEOSTAR class of sea-floor observatories. In particular the mechanical frame was modified in order to host deep-sea hydrophones and allow easily handling of seismometers and magnetometers with Remotely Operated Vehicles (ROV) for deep-sea operations; batteries and their container were removed, since power

feeding system relies only on MEOC power transmission; a new single pressure vessel (DACS – Data Acquisition and Control System Vessel) contains the power, DAQ and transmission systems; a 13’’ glass housing was added in order to host the electronics for data acquisition and transmission of the hydrophones. A photo of the LIDO TSN Station integrated at the Shore Laboratory of Catania is shown in Figure 1.



Figure 1: The TSN station, inside the LNS-INFN Shore Lab of Catania, ready for deployment.

Concerning the electronic system, the major modifications, with respect to SN1, were applied to the power feeding, data acquisition and data transmission systems: HVAC/LVDC power converters were added to permit power feeding directly from shore; full real-time data transmission was adopted via optical fibre link (MEOC); C/D-WDM compliant data transmission system was built; a new interface between acoustic data acquisition system and geo-seismic and environmental data acquisition system was designed and built.

Power electronics for LIDO TSN is composed of a shore power supply, a control unit and deep-sea power conversion subsystems hosted in the DACS and in the glass housing, as mentioned above. The shore power supply provides 500 VAC (single phase) power to the deep-sea installations. The primary AC/AC power converter is hosted in the DACS providing several low voltage AC output lines and a 230 VAC output line to the glass housing for the hydrophones read-out electronics. Low voltage AC/DC converter for environmental and geophysics instrumentation and front-end electronics are hosted inside the DACS. A dedicated low-noise power supply line is required for the hydrophone DAQ. The 230VAC/LowVoltage-DC converters are installed in the glass housing. The front-end electronics for seismic and environmental instruments is hosted in the DACS. Hydrophones’ electronic chain is hosted in the glass housing.

One of the main activities of INFN was test and characterisation of hydrophones and pre-amplifiers for LIDO TSN. Results demonstrate that design parameters are fully satisfied. On-shore electronics for hydrophones was improved adding on-shore GPS time-stamp capability.

The electro-optical data transmission chain of TSN has been designed in order ensure reliability and full redundancy of the optical data transmission channels. For this reason the data transmission system, based on bi-directional Ethernet electro/optical media converters, was built using e.o. Ethernet modems with 2 separated CWDM optical frequencies for uplink (shore to sea) and downlink (sea to shore). Hydrophones data are transmitted using e.o. CWDM media converters that utilise 2 CWDM frequencies for downlink. INFN has designed and built for LIDO TSN an “optical add/drop box” capable to add the 4 CWDM optical frequencies on a single channel, duplicated on 2 optical fibres to improve system redundancy and reliability.

The LIDO TSN integration and test were carried out by INFN, INGV and ENI-Tecnomare at the INFN shore Lab of Catania. The experimental set-up for tests included power rack, telemetry rack, data acquisition computers, and electro-optical cable simulator (28 km optical fibres, 28 km copper wire), as shown in Figure 2. The TSN station is now ready for deployment.

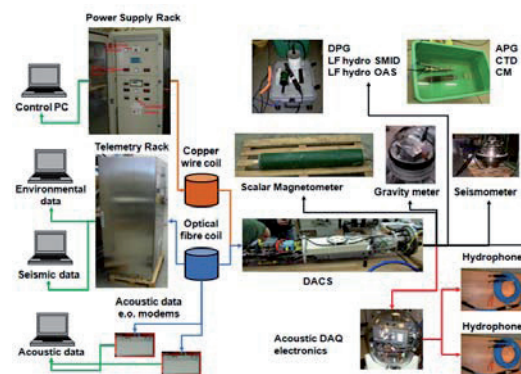


Figure 2: Scheme of the LIDO TSN deep-sea observatory.

LIDO – EAST SICILY: TSS

LIDO TSS is a deep-sea observatory equipped devoted to acoustic measurement, equipped with a tetrahedral array of four ultra-large bandwidth hydrophones [4].

Tests and integration of the LIDO TSS components have been carried out by INFN during the LIDO DM activity in 2010. For what concerns mechanical parts, frame, pressure vessel, connectors and cables have been designed and built to improve easiness of deployment and connection operations with ROV. The hydrophones are placed at the apexes of a tetrahedral frame. A pressure resistant aluminium vessel hosts the power, read-out and data transmission electronics (see Figure 3). A ROV mateable e.o. jumper cable was also installed to interconnect the LIDO TSS to the NEMO Junction Box (JB) [2].

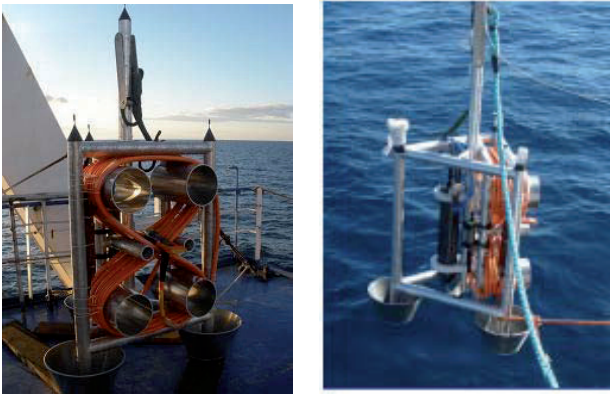


Figure 3: The mechanical frame hosting the LIDO TSS Observatory.

The power supply system for LIDO-TSS (220 VAC single-phase) is compliant with the output power supply (380 VAC -3 phase) provided by the NEMO JB. The system was tested demonstrating high reliability to input power overshoots and to sensors (output) short circuits. Moreover the request of low noise was fully satisfied as described in the following. The noise spectrum, of each hydrophone channel was measured; the total noise power is about -70 dB re 1VRMS over the frequency range 10 Hz-96 kHz. An innovative read-out electronics, capable of real underwater-GPS time-stamping of acoustic data, was designed and built by INFN [5,6]. The opto-electronic system for data transmission, based on bi-directional synchronous G-link and DWDM optical transmission, was fully tested and demonstrated to be capable to operate over more than 80 km optical fibre link. The actual optical budget of the connection (25 km of fibres at the Catania Test Site) is 37.5 dB (@800 Mbps data transmission). Also the LIDO TSS station is presently at the Catania Shore Lab, ready for deployment.

ON_SHORE DATA ACQUISITION ARCHITECTURE

A main activity of INFN was the design and construction of a IT system capable to sustain the intense data rate received from deep sea (about 50 Mbps) and distribute it over the internet (Figure 4). Acoustic data from deep sea will be acquired by Acoustic Data Servers (ADS) that will receive the acoustic raw data stream from the two stations (TSS and TSN) and will make it available on the local area network of the Catania Shore Lab. Each ADS is equipped with a professional audio card capable to sustain the underwater hydrophones data stream. Raw data is checked and sent to analysis clients using TCP-IP protocol.

A first analysis code was implemented for real-time data recording, visualization and listening. This code also provides real-time statistical measurements of the acoustic background, such as sound pressure density spectrum, that can be used in off-line analysis to locate acquisition time with presence of biological sounds. Other analysis codes-under development- will permit further

background analysis and detection, classification and 3D localization of acoustic sources.

Recorded raw data and first analysis results will be continuously transmitted to INFN-LNS through a dedicated 100 Mbps radio-link for storage. The expected data rate from the deep-sea acoustic detectors that will be installed on both cable terminations is about 36 Mbps of data payload (96 kHz sampling, 24 bit for TSN and 192kHz, 24 bit for TSS, each station has 4 channels). A limited bandwidth (few kbps) is required to transmit data from the geophysical sensors. The radio-link will also permit instrumentation control and setting from remote station managers at INGV and ENI-Tecnomare.

The Computer Centre of LNS, will host the Main Data Storage (MADS) Unit of the LIDO experiment- used to store acoustic and geophysical data- and another data storage unit, to be used also as a web server and file streaming server. The Main Data Storage infrastructure was set-up at LNS using a NetApp FAS2040 storage unit based on Fibre-Channel standard.

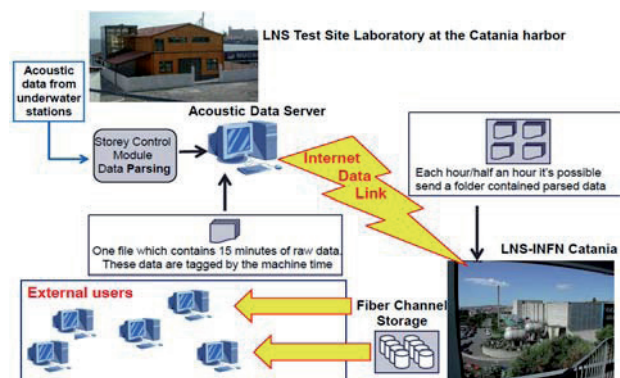


Figure 4: Architecture for the LIDO IT system.

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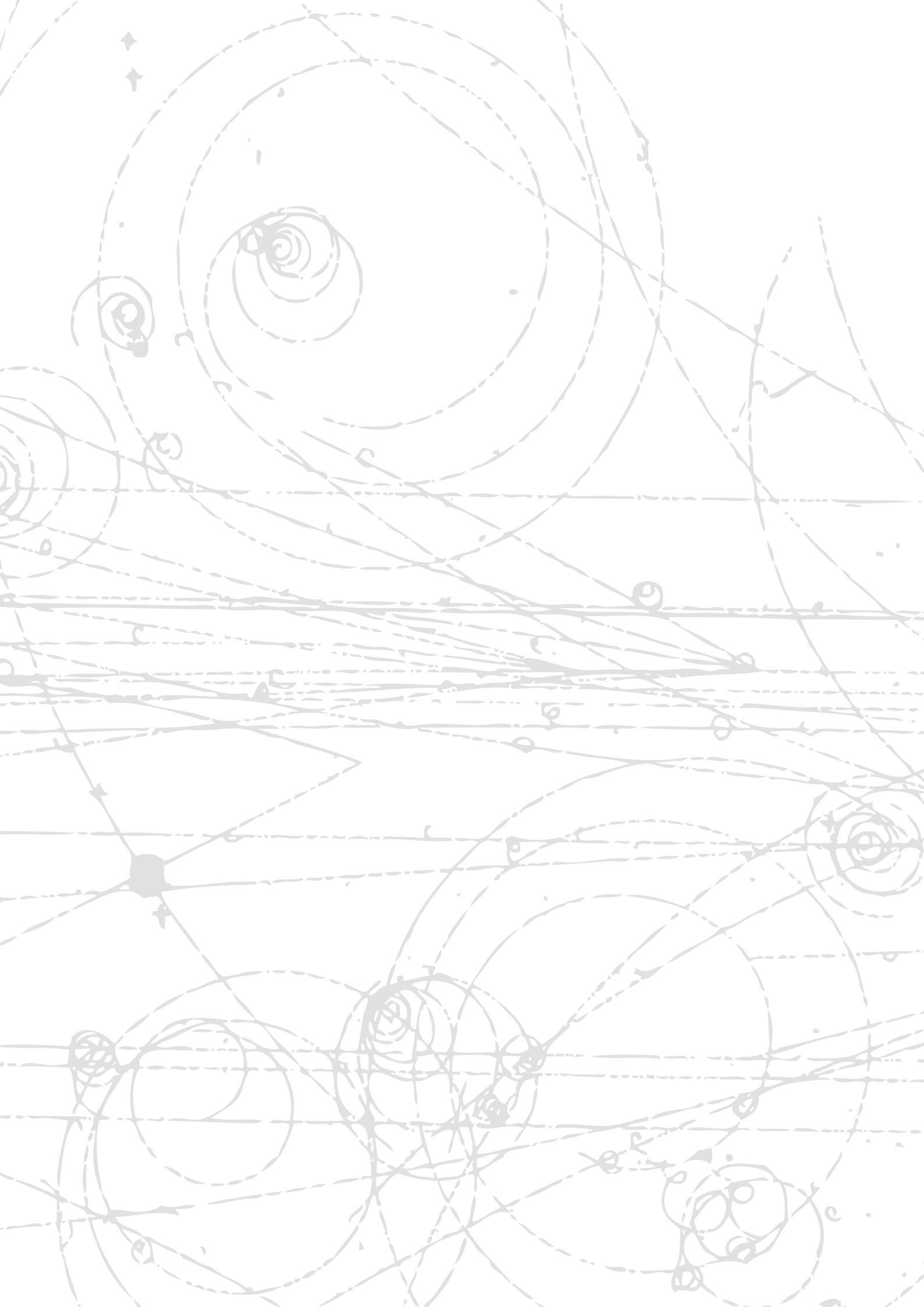
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ISTITUTO NAZIONALE DI FISICA NUCLEARE
LABORATORI NAZIONALI DEL SUD
ACTIVITY REPORT 2010

ION SOURCES AND ACCELERATORS



LNS ACCELERATORS ACTIVITY

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Abstract

The LNS Cyclotron and Tandem activity in 2010 is described, with some details on the beam time distribution among different research activities.

BEAM OPERATION

In 2010, 1940 hours of Cyclotron beams and 1706 hours of Tandem beams were delivered. These amounts can be considered moderately satisfactory as compared with the previous years.

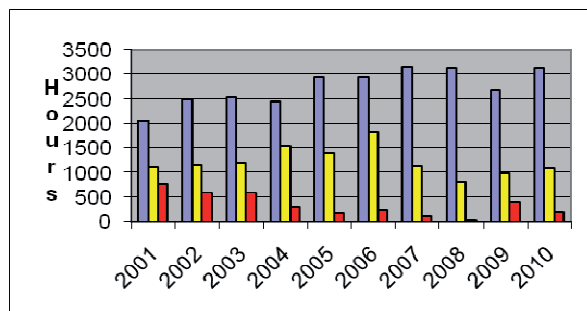


Figure 1: 2001-2010 Cyclotron beam statistics scaled to 8 months

In 2010, 3 sessions of proton therapy of ocular tumors (Catana) were accomplished, using the 62 MeV proton beam from the Superconducting Cyclotron, for a total of 23 treated patients. In total the protontherapy activity took approximately 440 Cyclotron hours.

In figures 1 and 2 the beam statistics for the years 2001 through 2010, scaled for a period of 8 months, are shown. The first column, in blue, displays the delivered hours, the second, in yellow, gives the preparation time, the third, in red, the number of failures. As evident from figure 1, the number of failures has a clearly decreasing trend from 2001 to 2008, which demonstrates the achieved good reliability of the Cyclotron, quite important for the experimental activity as well as for the development of new projects. However, in 2009 and the number of failures is quite big. This is mostly due to the high number of shut-down events of the Cyclotron

due to power failures. In fact in 2009 the UPS (Uninterruptable Power System) did not work properly, therefore there was no guarantee of electricity continuity over the whole year. In 2010 the UPS was fixed and the usual beam time distribution was recovered.

The amount of setting hours is still big, demonstrating that the Cyclotron is a quite complicated machine.

Concerning the Tandem, the amount of delivered beam time in 2010 is as small as in 2009, due to the correspondingly small demand from users.

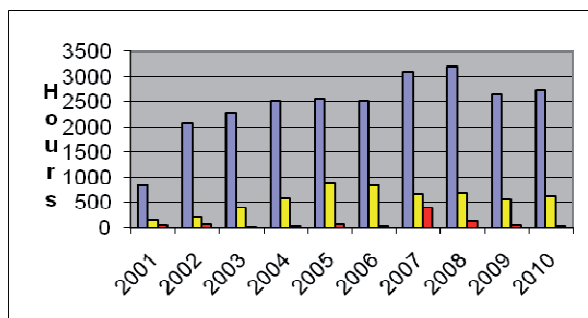


Figure 2: 2001-2010 Tandem beam statistics scaled to 8 months

Concerning the Excyt facility, during the year 2010 a 1 month session was performed to produce the ^9Li beam to be delivered to Chimera. Unfortunately, the electrostatic deflectors had a problem of voltage holding due to a cooling problem, and the Tandem had a problem of bad vacuum in the first accelerating tube. Therefore, after having made some successful tests of the PIS source, whose heater had been improved, the session ended without having accelerated a sufficient amount of ^9Li .

In the second half of 2010, from September to December, an important development operation was accomplished: the upgrading of the beam line for production of in-flight secondary fragments, called FRIBS. A reconfiguration of the Cyclotron extraction beam line was done to install new magnetic elements so as to increase the angular and momentum acceptance for radioactive beams. This upgrading is described in a dedicated report.

SUPERCONDUCTING CYCLOTRON

In 2010 Cyclotron beams were used for Nuclear Physics experiments (44%), proton-therapy (23%) and interdisciplinary experiments (29%) mainly investigating on interaction of ion beams with biological matter. 4% was dedicated to beam tests.

In figure 3 a plot of the experiments performed in 2010 with Cyclotron beams is presented, showing the beam time distribution (hours) among different experiments.

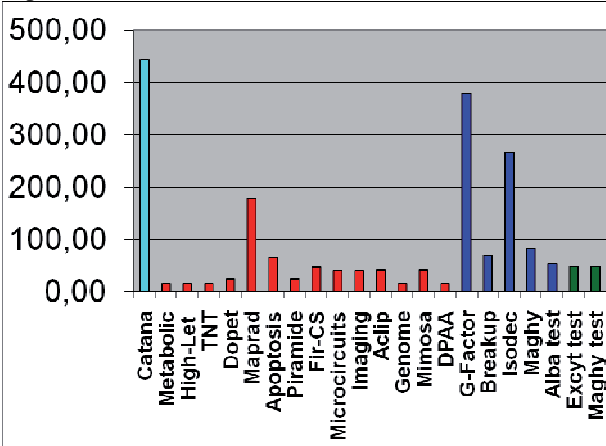
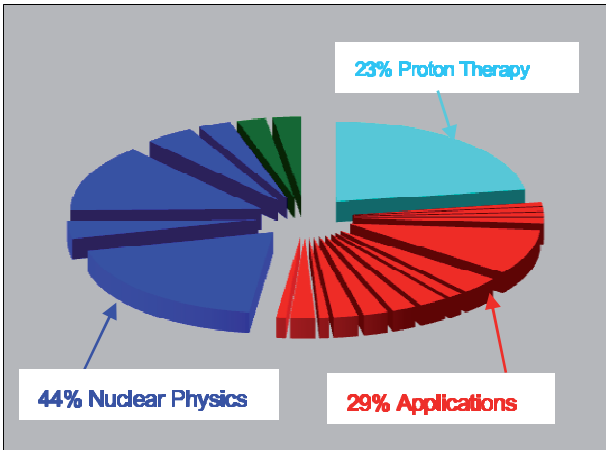


Figure 3: Cyclotron beam time distribution

In Table 1 a list of the experiments performed at the Cyclotron in 2010 is given.

Table 1: Experiments performed in 2010 at the Superconducting Cyclotron

Experiment	Research field
Catana	Hadrontherapy
Metabolic	Biology
High-Let	Biology
TNT	Biology
Dopet	Biology
Maprad	Rad. Hardness
Apoptosis	Biology
Piramide	Rad. hardness
Fir-CS	Superconductors
Microcircuits	Detectors
Imaging	Biology
Aclip	Accelerators
Genome	Biology
Mimosa	Dosimetry
DPAA	Archaeology
G-Factor	Nuclear Physics
Breakup	Nuclear Physics
Isodec	Nucl. Physics
Maghy	Nucl. Physics
Alba test	Nucl. Physics
Excyt test	Accelerators
Maghy test	Accelerators



TANDEM

In 2010 Tandem beams were used for Nuclear Physics experiments (84%) and applicative experiments (16%). In figure 4 a plot of the experiments performed in 2010 with Tandem beams is presented, showing the beam time distribution (hours) among different experiments.

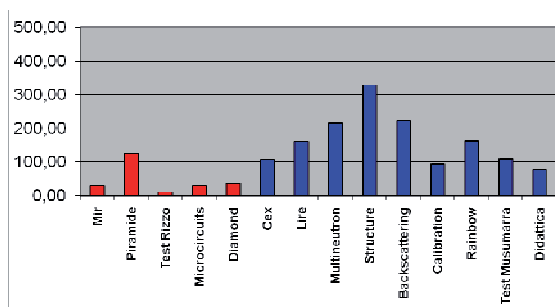


Figure 4: Tandem beam time distribution

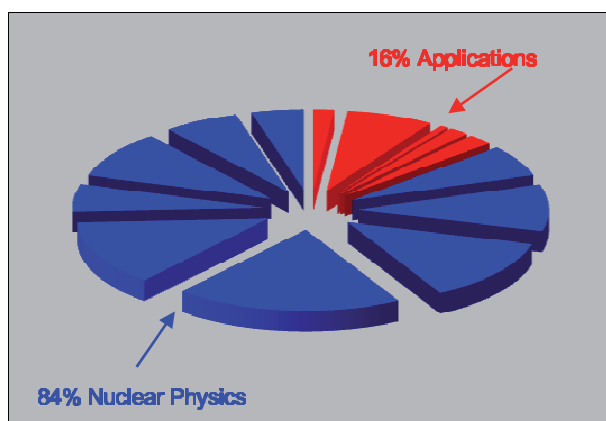


Table 2: Experiments performed in 2010 at the Tandem

Experiment	Research field
Mir	Detectors
Piramide	Rad. hardness
Test Rizzo	Cultural herit.
Microcircuits	Detectors
Diamond	Detectors
Cex	Nuclear Physics
Lire	Nuclear Physics
Multineutron	Nuclear Physics
Structure	Nuclear Physics
Backscattering	Nuclear Physics
Calibration	Nuclear physics
Rainbow	Nuclear physics
Test Musumarra	Nuclear physics
Didattica	Nuclear physics

In Table 2 a list of the experiments performed at the Tandem in 2010 is reported.



Refurbishing of the in-Flight Radioactive Ion Beam line

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Abstract - The beam line which transport the beam extracted from the cyclotron until to the Switching magnet inside the accelerator room has been fully dismantled and rebuild in the period September-December 2010. The main goal was to increase of a factor 20 the production yield of the radioactive beam produced by the in-flight method. A summary of all the operations is presented.

INTRODUCTION

At LNS radioactive ion beams are produced by the so called in-flight method. This technique joint with the tagging method, introduced at LNS by Giovanni Raciti, has proved the capability to provide useful rates of radioactive beams for nuclear physics experiments. The international relevance of some of these experiments [1,2,3] stimulate the management of INFN to assign for the 2010 an extra fund to improve the performance of our facility.

Indeed, in the past two possible upgrading of the extraction line to deliver higher intensities of in-flight produced RIB were developed [4]. The first project for an upgrading of the extraction beam line was proposed more than 15 years ago. That project was based on a high field (8 Tesla) superconducting solenoid ETNA. Due to an accident happened during the construction of the high field superconducting solenoid ETNA, at the constructor site, this project was stopped in the 2000. Later on the 2001, Slava Schepounov studied a new configuration based on conventional quadrupoles to increase the acceptance of the beam line. According to this study 4 magnetic quadrupoles and two magnetic sextupole, necessary to this upgrading, were bought in the 2002. Due to the previous program of the LNS to complete the EXCYT facility and due to the strong interference with the programmed schedule to deliver beams to the users, the project was postponed until the 2009 when according to the success of the experiment performed by the group lead by Giovanni Raciti the management of INFN accepted to fund the extra cost for the upgrading. The proposal of Slava Schepounov was a slightly modified to fit the real size of the beam line and to optimize the matching between the new extraction line and the existing beam transfer line to the experimental area. A further small adjustment was also necessary to leave enough room to install the existing High energy chopper and the under construction new 500-High Energy Chopper along the extraction line.

According to our study the new configuration should allow to increase the yields of the produced radioactive beams of a factor about 20 to the final users. Really this goal will be fully achieved when all the 30 mm diameter beam collimators, installed along the beam lines, will be removed. These collimators, installed in front the faraday cup of safety controlled by the health safety service, have the scope to prevent that the beam could reaches accidentally the experimental area. In near future the present faraday cup will be replaced by a new one with larger size and larger coarse ourselves made. These new Faraday cup when inserted fill fully the beam pipeline so the collimators will be unnecessary.

Here we report the operations of the beam line upgrading.

FRIB EXTRACTION LINE

The main changes requested to the beam line were:

- Insertion of 4 new magnetic quadrupoles;
- Insertion of 2 new magnetic sextupoles;
- Removing two existing magnetic quadrupoles;
- Repositioning of the existing 13 Quadrupoles;
- Repositioning of the diagnostic devices;
- Repositioning of the existing vacuum pump system;
- Upgrading of the vacuum control system;
- Repositioning of the existing power supplies;
- Installation of 4 new power supplies cabinet;
- Replacing of the old power cables to feed all the 17 Quadrupoles magnets with new power cables fire self extinguish;
- Alignment of the 17 quadrupoles, 3 Dipoles, 2 sextupoles and of all the diagnostic devices;
- Repositioning of the existing High Energy (H.E.) chopper;
- Site preparation for the future installation of the 500 H.E. Chopper;
- Installation of new cables for the diagnostic devices, for all the devices and for the vacuum system;
- cabling control system;
- Installation of a new production target for high power beam (<1 kW);
- Installation of neutron shielding, polyethylene made;
- Installation of the home made new diagnostic devices for the Radioactive ion beams.

The Fig. 1) show the layouts of the previous extraction beam line and of the new one. It is evident that the position of the three main dipole magnet

were unchanged. But all the other magnetic quadrupoles were moved. Also the steering dipole and the two quadrupoles, near the cyclotron, called respectively EXT, EQ1 and EQ2 were shifted of about 10 mm in horizontal plane, just to reduce the 5-10% beam losses detected in this region. Also the last two quadrupoles Q16 AND q17, after the dipole ED3, were realigned.

CONCLUSION

The refurbishing operation of the beam line was completed just at middle of January 2011 with less than one month of delay respect to the very tight schedule. The commissioning of the beam line was also performed in February. The measured experimental yield of the radioactive beam delivered at the end of the extraction beam line confirmed the results of the simulations.

We like to thanks all the services of the LNS for their collaboration. Special thanks are due to:

- Mechanical Workshop and to the welds people;
- apparatus design group ;
- Computer controls;
- Cyclotron vacuum group;
- Power supplies group.

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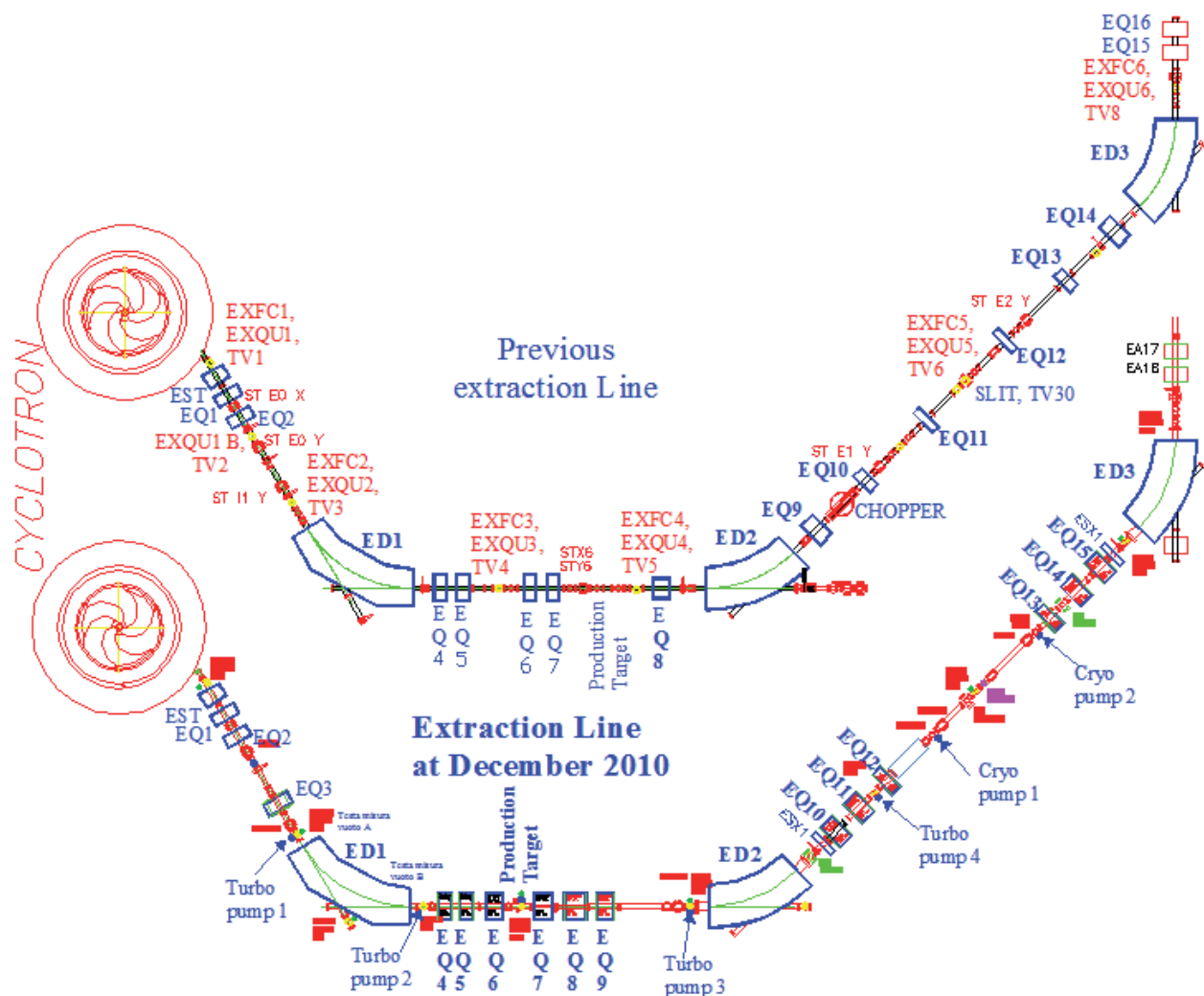


Figure 1: Layout of the extraction line from the cyclotron exit to the switching magnet, before August 2010 and after December 2010.



A multi megawatt cyclotron for DAEDALUS experiment

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Abstract - A Multi Megawatt Cyclotron complex able to accelerate H_2^+ to 800 MeV/amu is under study. It consists of an injector cyclotron to accelerate the injected beam up to 50 MeV/n and of a booster ring made of 8 magnetic sectors and 8 RF cavities. The advantages to accelerate H_2^+ and the main parameters of the injector and the ring cyclotron are presented.

INTRODUCTION

Scientists of MIT proposed recently a new experiment called DAE δ ALUS (Decay At rest Experiment for δ_{cp} At Laboratory for Underground Science) a new approach to search for CP violation in the neutrino sector [1,2]. They proposed to utilize high power proton accelerators able to supply a proton beam with about 800 MeV, 1.5 MW average power and a duty cycle of 20% (100 msec beam on, 400 msec beam off). DAE δ ALUS needs three sources of neutrino; located at 1.5, 8 and 20 km far from the underground detector. The beam power necessary to produce the neutrino fluxes at each site should be of 1, 2 and more than 5 MW respectively. The neutrino fluxes produced by the three sources are measured by the 300 KTons Cerenkov detector filled with water doped with Gd. The three sources have their beam time synchronised, so the detector will receive 100 msec beam bunch from each source in sequence, while for a 200 msec all the three sources will be kept off, to allow the measure of the background. This configuration allows measuring, how man oscillations $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ occur for each source.

Although the required average power for the first 2 sites is 1-2 MW, the 20% duty cycle has the consequence that the peak power is 5-10 MW and a peak current of about 9.5 mA is necessary. At current higher than 1 mA the space charge effects become more and more relevant both for the injection process and for the extraction process.

Accelerator complexes consisting of two or three cyclotrons have been proposed as drivers for energy amplifier [3,4,5]. The main features for these accelerator complexes are: current higher than 10 mA and energy as high as 1 GeV, minimum beam losses, high reliability and high conversion efficiency from electrical to beam power.

Accelerator driven systems (ADS) based on well known conventional cyclotrons accelerators are the most reliable and economical solution for a plant which requires a peak beam power of 1-5 MW [4,5]. To deliver higher peak power, i.e. 10 or more MW, the key points for the ring cyclotrons are the space charge effects, the extraction

devices and the power dissipated in each cavity. These problems are generally overcome increasing the radius of the cyclotron and the cavities number.

An alternative solution based on the acceleration of H_2^+ molecule has been proposed [6,7]. Extraction by stripping does not require well separated turns at the extraction radius and allows using lower energy gain per turn during the acceleration process. The extraction by stripper allows to extract beams with large energy spread (0.5÷1%) so the energy spread produced by space charge effect on the longitudinal size of the beam is not crucial for this kind of accelerator.

In the past, a layout for an accelerator complex able to supply a proton beam with energy of 1 GeV and a beam power up to 10 MW was presented by some of the authors [6], in the perspective to drive a sub critical reactor. This previous proposal is now updated to fit the requirement of the MIT scientists. Moreover the number of accelerators required by the experiments, at least 3-4, forces us to minimize the accelerator cost. The solution, here presented, consists in a two cascade cyclotrons complex. The injector cyclotron, a four sector machine, accelerates a beam of H_2^+ up to energy of about 50 MeV/n. The beam is then extracted by an electrostatic deflector and it is injected into a Superconducting Cyclotron Ring (SRC).

SPACE CHARGE EFFECTS

The space charge produces a repulsive force inside the beam bunches, which generate detuning effects. To evaluate the strength of this effect the parameter called "generalized perveance" has been introduced [8]. The generalized perveance is defined as:

$$K \propto \frac{qI}{m \cdot \gamma^3 \beta^3}$$

Where: q , I , m , γ and β are respectively the charge, current, mass and the relativistic parameters of the particle beam. From this formula it is evident that the proton beam has a perveance double as compared to the H_2^+ beam, if the two particles have the same speed and the same current. But if protons and H_2^+ are accelerated by the same electric field, they have the same energy but not the same speed. On the other hand a beam of H_2^+ delivers a number of protons which is double as compared to a proton beam with the same current.

In the first 3 rows of Table 1, we compare the perveance of H_2^+ beam and proton beam with a current of 5 mA and 10 mA respectively, at various energies.

Table 1: Perveance values of proton and H_2^+ beams at various energies.

	$E_p=E_{H_2}$ 30 keV	$E_p=E_{H_2}$ 800 MeV	$E_p=30$ keV $E_{H_2}=70$ keV
H_2^+ , $I=5$ mA	$0.881 \cdot 10^{-3}$	$0.151 \cdot 10^{-9}$	$0.247 \cdot 10^{-3}$
P, $I=10$ mA	$1.245 \cdot 10^{-3}$	$1.075 \cdot 10^{-9}$	$1.245 \cdot 10^{-3}$
K_{H_2}/K_p	0.707	0.141	0.198
P, $I=2$ mA	$2.491 \cdot 10^{-4}$	$2.15 \cdot 10^{-10}$	$2.491 \cdot 10^{-4}$
K_{H_2}/K_p	3.537	0.703	0.992

The ratio of perveance values shows that, concerning the space charge effects, to accelerate a H_2^+ beam is more convenient than a proton beam with a double current. This advantage is also more evident when energy increases. The last two rows of Table 1 show the perveance values of a proton beam with a current of 2 mA and the ratio vs. the perveance of H_2^+ beam with 5 mA.

INJECTOR CYCLOTRON

The injector here proposed is a mixing of the PSI injector II and of the compact commercial cyclotron. The central region of the proposed injector is a scaled up central region of the commercial cyclotron. To take account of the higher magnetic rigidity and to maintain the perveance of the H_2^+ beam similar to the perveance of the proton beam injected into a commercial cyclotron, both the injection energy and the energy gain per turn are doubled. Moreover, the energy gain per turn is supposed to increase along the radius up to the value of 1.8 MeV/turn at the extraction radius. This value is higher than the energy gain per turn in the PSI injector to compensate for the smaller extraction radius. Although the final turn separation at the extraction is 12 mm in the solution here proposed, while for the PSI injector II the turn separation is about twice, we believe that beam losses should be lower than 0.2%. This means that expected beam losses at the extraction should be lower than 200 W for a delivered average beam power of 100 kW. Lower beam losses could be achieved increasing the voltage of the cavities at extraction. Moreover the transverse and longitudinal emittances of the beam injected into the ring cyclotron can be larger than for the PSI ring cyclotron, indeed in our solution extraction is performed by strippers which do not need a single turn extraction to achieve extraction efficiency of 99.99%. The tentative parameters for the injector cyclotron are presented in Table 2.

Table 2: Parameters of the Injector Cyclotron

E_{inj}	35 keV/n	E_{max}	50 MeV/n
R_{inj}	50 mm	R_{ext}	1.85 m
$\langle B \rangle$ at R_{inj}	1.075 T	$\langle B \rangle$ at R_{ext}	1.133 T
Sectors N.	4	Cavities N.	4
RF	49.2 MHz	harmonic	6 th
V at R_{inj}	>70 kV	V at R_{ext}	250 kV
Injection eff.	15 %	Extraction eff.	99.8%
Extraction: Electrostatic Deflector + Magnetic Channels			
Deflector Gap	12 mm	Electric field	<50 kV/cm

RING CYCLOTRON

In Table 3 the main parameters of the preliminary study for the Ring Superconducting Cyclotron are presented. Our preliminary study was made using straight sectors with a spiral shape in the region $R > 4.5$. The pattern of the achieved magnetic field is shown in Fig. 1. The simulated configuration was able to produce a magnetic field near the required isochronous one with maximum differences lower than 1%, and vertical focusing > 0.5 . To achieve a good vertical focusing it is mandatory to spiral the magnetic field. This is achieved by a special shape of the iron hill, while the main coils have only a tilt, to avoid concave shape.

The magnetic field map was used to evaluate both the injection and extraction trajectories. To simulate the beam envelope and the trajectories we used the computer codes developed at MSU, with some minor changes. The results of our simulations demonstrate that it is possible to inject and extract the beam without interference among the stripper extractions and the injection trajectories. The vertical beam size is smaller than 2 and 1 cm respectively along the injection and extraction trajectories. The beam envelopes along these trajectories were also evaluated and are presented in Fig. 2. The normalised beam emittance in the transverse planes, used in the simulation, is 3.3π mm.mrad. The extraction by stripper was simulated simply changing the charge to mass ratio of the particles. The stripper was placed in a position where the magnetic field is in the range of 2-5 kGauss. The electrons removed by the stripper foil have a bending radius of about 8 mm, so it is possible to collect them on a copper made catcher.

This solution prevents the electrons to strike the stripper foil and reduce greatly the foil damage. The mean life of the stripper is expected to be longer than 180 hours in the operation condition.

The RF system of the DAEδALUS main ring cyclotron consists of 4 RF single gap cavities and 2 double gap cavities, see Fig.1). Both single gap and double gap cavities system were analysed. the combination of 4 single gap cavities and 2 double gap is chosen as better

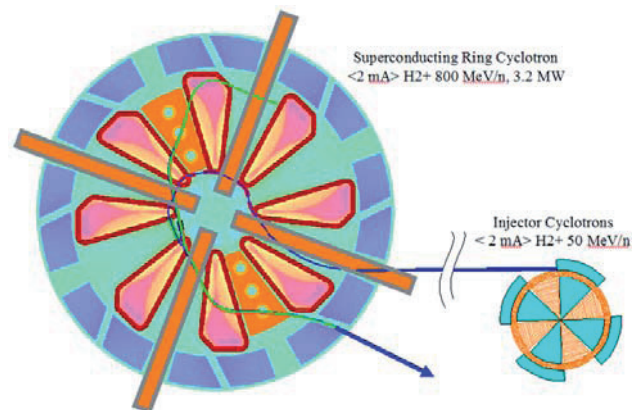


Figure 1: Layout of the complex accelerators, the average beam current in figure is evaluated with a 20% duty cycle

Table 3: Main parameter of the RSC

$E_{\max}$	800 MeV/n	E_{inj}	50 MeV/n
R_{ext}	4.05 m	R_{inj}	1.44 m
$\langle B \rangle$ at R_{ext}	2.28 T	$\langle B \rangle$ at R_{inj}	1.39 T
Bmax	<6.3 T	Pole gap	>50 mm
ξ_{spiral}	< 40°	Hill width	20°
Outer radius	≤ 6 m	Flutter	1.7÷1.27
Sector height	< 5 m	N. Sectors	8
Sector weight	< 300 tons	N. Cavities	8
Cavities $\lambda/2$	Double gap	harmonic	6 th
RF	59 MHz	V	250-300 kV
$\Delta E/\text{turn}$	3.2 MeV	RF Power	200 kW
ΔR at R_{ext}	1.5 mm	ΔR at R_{inj}	> 15 mm
Coil size	20 x 40 cm ²	Icoil	4300 A/cm ²

solution for the DAE δ ALUS SRC. Despite the double Gap Cavities have a lower voltage vs. the single gap voltage, they allow to be installed also in the valley where at the inner radii there are the magnetic channel necessary for the beam injection, moreover they allow the insertion of cryogenic pump just near to the median plane. This is a further advantage to increase the performances of the vacuum plant. An optimum operating vacuum, in the range of 10^{-8} Torr, is useful both to minimise the beam losses due to interaction of the H₂⁺ molecular beam with the residual gases and in order to increase the reliability of the RF cavities too.

CONCLUSION

A lot of work has to be done to achieve the final design of an accelerator complex to deliver H₂⁺ at 800 MeV/amu here presented shows that it is a realistic goal. In particular the sector magnets able to produce an average magnetic fields of 2 T with the right magnetic field shape for the DAE δ ALUS experiment. The preliminary study

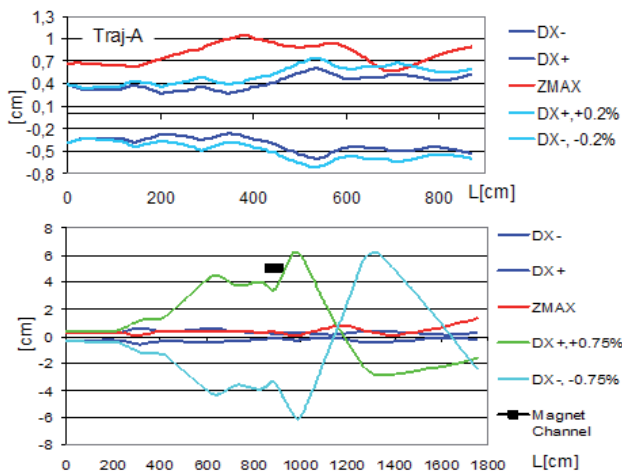


Figure 3: Beam envelope along the injection trajectory, upper, and along the extraction trajectory, lower. The 0° is the matching point on the equilibrium orbit at the injection or at the extraction radii; the 300° is outside the cyclotron.

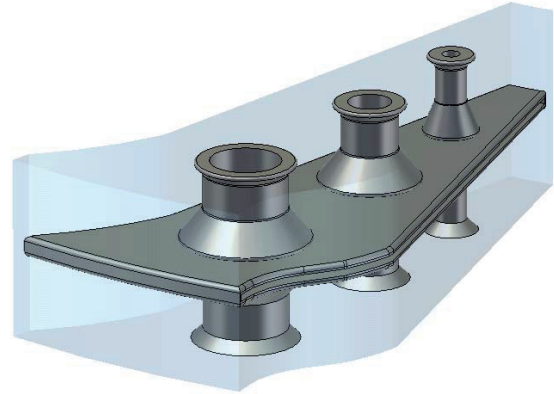


Figure 4: Layout of electrodes and stems of the proposed RF cavity. The three stems are useful for mechanical stability and to host the cryopumps to pump inside the vacuum chamber

and the necessary coils to drive these sectors seem to be feasible even with the present technology, but the optimisation of the magnetic shape and size of the sectors to avoid the spiral shape and to reduce the magnetic forces on the superconducting coils must be completed. Of course the advantage to have straight sectors allows installing RF cavities similar to that built for the PSI which achieves a maximum voltage of 1 MV. The use of these cavities will reduce the number of turns in the ring cyclotron and the beam losses due the interaction with the residual gases. Cyclotrons for DAE δ ALUS experiment need to guarantee a high level of reliability and high conversion efficiency from electrical to beam power.

We believe that extraction by stripping is a very powerful tool to increase the reliability and simplify the operation as demonstrated by the success of commercial cyclotrons.

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Investigations of laser produced plasmas dynamics by means of real and virtual Langmuir probe

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Abstract - In this paper we propose a novel technique for Laser Produced Plasmas investigation, combining high time resolved measurements using compact Langmuir probes (LP) with the output of a theoretical model called HYBLAS developed on purpose, which is able to simulate the charged particles collected by a so-called “virtual probe”.

It will be shown that with an appropriate experimental set-up and with the use of a Matlab software, laser plasmas can be investigated properly even if the probe is placed very close to the target surface.

The virtual probe method was moreover tested by comparing the numerical results with another numerical code, called MULTI, which simulate the expansion by combining the hydrodynamics equations to a multigroup method in order to include the radiation transport.

INTRODUCTION

Langmuir probes are widely used in order to characterize plasmas in different conditions of density and temperature and give also the opportunity to calculate the plasma parameters, i.e. the electron and ion densities, the electron temperature and the self-generated plasma potential. To avoid damaging and signal distortions, these devices are usually placed far away from the laser-plasma interaction area, allowing the investigation of the plume dynamics only at later time expansion stages. In this work, it will be shown that by using an appropriate reading circuit, the real current signals can be acquired with very low electrical noise and the probe can be placed very close to the target surface (few mm's), collecting information about plasma density and temperature, with a temporal resolution of few nanoseconds.

A theoretical model called HYBLAS (Hybrid Laser Ablation Simulations), able to simulate a virtual Langmuir Probe, is proposed. It is obtained by using and revising the numerical model proposed by Anisimov et al. [1] that solves the gas dynamical equations under the hypothesis that the plasma evolves adiabatically. The code was implemented in Matlab with the four Runge-Kutta method [2].

The reliability of our model was also tested by comparing the numerical results with the MULTI code, that takes into account also the radiative transport [5].

Comparisons with this code and with the experimental data show that HYBLAS is able to correctly describe the plasma bulk plume expansion in the nanosecond regime.

EXPERIMENTAL SET-UP

The complete experimental set-up is described in detail elsewhere [4, 6, 7]. A Nd:Yag laser operating at a power irradiance of $3 \cdot 10^{11}$ W/cm², with 6ns of pulse duration and FWHM of 1.064 μ m, was focussed on an aluminium target through a 250 mm focal length lens, placed inside a compact (diameter of 250 mm and 240 mm of height) cylindrical stainless steel vacuum chamber. The LP is an Analytical ESPion Advanced Langmuir Probe, consisting of a tungsten tip of cylindrical area of 2.43 mm² connected to a long coaxial cable. The probe was biased with a stable HP power supply (from -90 V to +90 V) and placed at different distances from the target surface (from 2 mm to 50 mm), parallel to the plasma expansion direction. The time of flight signals obtained at different voltages are then send through a particular RC circuit configuration and read out through the oscilloscope.

The data acquisition system permits to exactly evaluate the amount of current flowing through the LP and to obtain very low noisy current signals also when the LP is placed at few mm's from the target. Data are then processed through a Matlab code which analyzes the time of flight signals in order to obtain the current values. Once the current versus time values are calculated, the current signals versus probe potential are analyzed for different expansion times in order to estimate the time dependent plasma parameters [8].

THEORETICAL MODELS

The equations describing extensively the laser-matter interaction are numerous: many physical phenomena, such as the hydrodynamics motion, the radiation transport, the heat transfer and particles collisions, must be taken into account to completely describe the laser-target interaction and the subsequent plasma evolution.

One of the codes available in literature that considers these listed phenomena, is the MULTI code. It was developed by Ramis et al. [5] and is used especially for inertial fusion confinement calculations. The model combines hydrodynamics equations in the Lagrangian

coordinates to radiation transport and takes into account both opacities that non-LTE (local thermal equilibrium).

The MULTI approach consists in a discretization of the radiation transfer equation which is consistently simplified by neglecting scattering processes, and assuming that the plume velocity is much smaller than the speed of light. In this way opacity and the source function can be considered isotropic. A finite number of differential equation are solved with a finite time splitting scheme. The complete treatment can be found in [5].

On the other side, our theoretical model HYBLAS consists in a revised version of the Anisimov model which solves the gas dynamical equations under the basic hypothesis that the plasma expands selfsimilarly, adiabatically and isoentropically in vacuum: a special solution of the Eulero's equations gives out the plasma density and temperature profiles versus time. The density is described by the expression

$$\rho(x, y, z, t)_{th} = \frac{M}{I_1 X(t) Y(t) Z(t)} \times \left(1 - \frac{x^2}{X(t)^2} - \frac{y^2}{Y(t)^2} - \frac{z^2}{Z(t)^2} \right)^{\frac{1}{\gamma-1}} \quad (1)$$

where M is the plume mass, $X(t)$, $Y(t)$, $Z(t)$ are the spatial coordinates and γ is the adiabatic index. HYBLAS solves the equations of motion by adding two additional input parameters, in order to include the effect of the accelerating Coulombian field and the difference between the ion and the electron temperature.

The plasma evolution is strongly influenced by the charge separation of electrons and ions. The different mobility makes, typically the electrons faster than the ions. In the separation layer a self-generated electric field arises to compensate the charge discrepancy. In a free flowing plasma the electric field boosts the plasma mobility and it must be included in equation of motion of the plasma front. These improvements permitted us to successfully compare the numerical results to the ones in different experimental conditions [2, 3, 4].

The adimensional equations of motion of the plasma front are expressed in the form:

$$\xi \ddot{\xi} = \eta \ddot{\eta} = \left[\frac{\sigma}{\xi^2 \eta} \right]^{\gamma-1} \quad (2)$$

where $\xi(\tau) = \frac{X(t)}{R_0}$, $\eta(\tau) = \frac{Y(t)}{R_0}$, $\sigma(\tau) = \frac{Z(t)}{R_0}$, $\tau = \frac{t}{t_0}$ represent respectively the three spatial coordinates and the time expansion (R_0 is the crater spot diameter).

Equations 2 were then corrected by inserting an additional drift velocity term v_c , which takes into account the effect of the self-generated electric field [4]:

$$\xi_{shifted} = \xi + v_c = \xi + \sqrt{\frac{2\langle z \rangle e V_p}{M}} \frac{R_0}{t_0} \quad (3)$$

where $v_c = \frac{2\langle z \rangle e V_p}{M}$ is the contribution of the Coulomb

shift to the velocity term, $\langle z \rangle$ is the mean charge state, V_p is the plasma potential and M is the plume mass. The expansion in vacuum virtually reproduces the absorption of fast electrons in the plume front by a virtual wall placed close to the plasma at each time step.

Equations 3 have been solved numerically using a fourth order calculation Runge-Kutta Nystrm method by using a Matlab[®] code developed by Mascali et al. [2]. V_p can be roughly estimated by the electron temperature, according to the formula $V_p = c k_B T_e$ where the constant c lies usually in the range 1÷4 [4]. From thermodynamics considerations, the velocity of the adiabatic expansion can be expressed by the equation [9]:

$$v_\gamma = \sqrt{\frac{\gamma k_B T_e}{M_i}} \Rightarrow T_e = \frac{M_i v_\gamma^2}{\gamma k_B} \quad (4)$$

Once fixed the γ , from v_γ (estimated from equation 2 and depurated from v_c), we can extrapolate from equation 4 the initial electron temperature $T_e(0)$ and consequently also $T_i(0)$, since the electron-ion thermalization times are on the order of $\tau_{ei} \approx 100ps$, hence $T_e(0) \approx T_i(0)$. Due to the mass difference, during the expansion, electron and ions will evolve with a different kinetic energy and also with a different temperature. The high collisional rate determines that ions share the ordered, forward peaked energy changing it into disordered, thermal energy. The ion velocity will be of the same order of magnitude of the expansion velocity v_{exp} so that the ion temperature can be estimated as:

$$\frac{3}{2} k_B T_i \approx \frac{1}{2} M v_{exp}^2 \quad (5)$$

By taking into account equations 4 and 5 the ion to electron temperature ratio will be:

$$\frac{k_B T_i}{k T_e} = \frac{1}{3} [\sqrt{\gamma} + \sqrt{2\langle z \rangle}]^2 \quad (6)$$

where $v_{exp} = \xi_{shifted} + v_\gamma$. This relation can be seen also as the temperature ratio dependence on a given charge state inside a single plume [4]. It predicts not only that the ion temperature is consistently higher than the electron one, but also that the ratio grows with the charge state, that is in qualitative agreement with experimental results [10]. Using equation 6, the Anisimov model has been further improved by introducing the discrepancy between the ion and electron temperature. Two γ factors have been also introduced, one for electrons (γ_e) and the other one for ions (γ_i) [11], [4], whose values lie generally in the range of 1.1 to 1.4 [12]. Combining the numerical code described above to a second script, which simulate the virtual Langmuir Probe, every density mapping obtained with HYBLAS or with other hydrodynamics codes, can be used to calculate the current density at a fixed probe position.

THE VIRTUAL LANGMUIR PROBE

The virtualization of the Langmuir Probe consists in the definition of a two dimensional domain in the x - z plasma expanding plane where the probe characteristics can be "tuned" in relation to the experimental conditions, i.e. by taking into account the probe dimension, its orientation with respect to the plasma expansion direction and its distance from the target. The probe domain D is defined with a certain number of unitary cells; the current density on the probe is calculated from an overlapping between D and the plasma density mapping coming out from the resolution of the fluids equations. A mesh routine interpolates the density value in each numerical cell with the nearest cell at the plasma elliptical isosurfaces.

Figure 1 shows schematically the interaction between the plasma plume and the virtual probe placed parallel to the expansion direction at a fixed time of 20 ns of expansion calculated with the HYBLAS code.

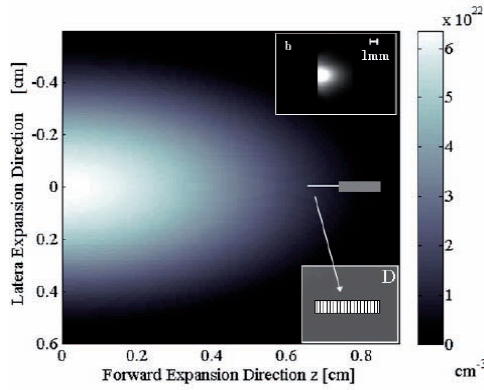


Fig.1 - 2D simulation of the density resolved Al plume at a fixed time expansion (20ns) with HYBLAS; the virtual probe is located at the same position where the real LP was placed; in (b) a real CCD image obtained also at 20ns of time expansion is reported.

The plasma density defined in equation 1, was simulated in the $y = 0$ plane; the horizontal axis represent the forward expansion direction z and the vertical axis represent the lateral expansion direction x (or equivalent y due to the hypothesis of axial symmetry). Simulation parameters are indicated in table 1. Figure 2.b shows a real CCD image obtained at 20 ns of time expansion: a first qualitative comparison with the simulation, shows a good agreement between the numerical and the experimental data.

Table 1: Simulation Parameters

E	600mJ
Crater depth	13.6 μ m
Crater diameter	100 μ m
Constant c	3.3
Adiabatic coeff.	$\gamma_e = 1.25, \gamma_i = 1.4$

VALIDATION OF THE VIRTUAL PROBE METHOD

This section reports the numerical simulations realized with HYBLAS and MULTI in order to test the validity of the virtual probe method. On this purpose, starting from the same initial conditions, a direct comparison of the bi-dimensional 2D density mapping obtained with the two codes at different expansion times was carried out.

Plasma density mappings

As observed in figure 1, the plasma can be simulated in the (x, z) plane in terms of density mapping. Comparisons were done for four fixed plasma expansion times: 10 ns, 30 ns, 50 ns and 70 ns (see figure 2).

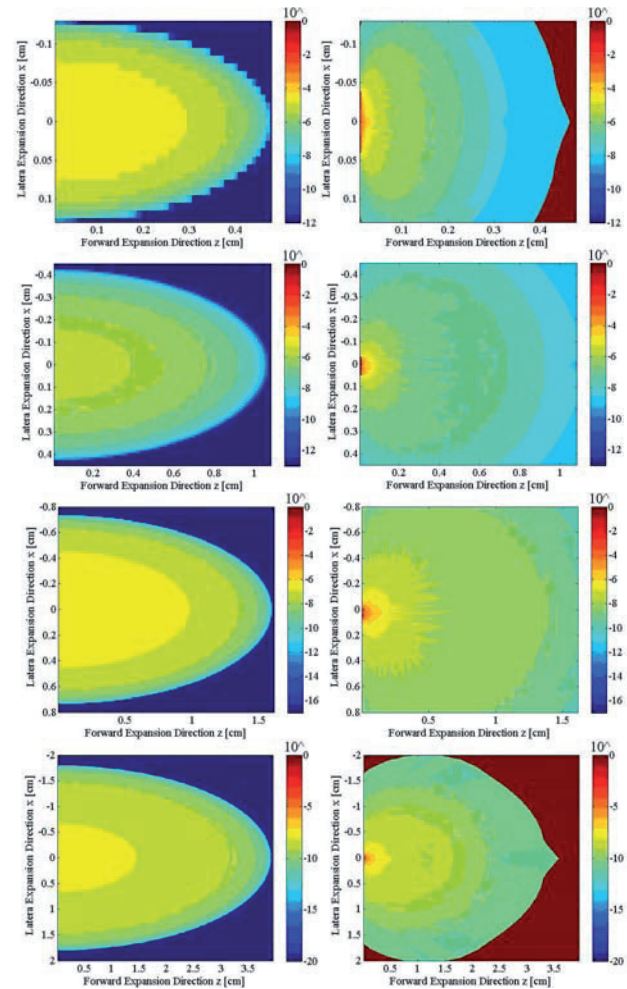


Fig.2 - Density mapping obtained with MULTI and HYBLAS code at four different expansion times: $t_1=10$ ns, $t_2=30$ ns, $t_3=50$ ns and $t_4=70$ ns; note that the density is normalized to the initial Al solid target density

The plasma maps obtained with the two codes are comparable but the maps obtained with MULTI display a higher density in regions close to the target surface. The front plume dimensions along the x -axis are similar for $t_1 = 10$ ns and $t_4 = 70$ ns while for $t_2 = 30$ ns and $t_3 = 50$ ns MULTI gives a front plume size respectively of 1.7 cm

and 2.1 cm (not visible in the figure). The main difference between the two dynamics is revealed along the lateral expansion dimensions. MULTI has a more "leaf" shaped structure, whilst HYBLAS gives a more elongated shape. This was expected since in this last case the special solution of the equations 3 gives an elliptically shaped density distribution; in addition, the presence of the Coulomb shifted velocity term accounts an additional contribution to the plasma elongation along the z direction. In any case, radiative losses are not taken into account in HYBLAS, so that the density distribution can be anyway different.

A more significative comparison is given by plotting the density profiles along the forward expansion axis for $y=0$. Results are reported in figure 3. They show that the disagreement between the two densities becomes less evident at higher time steps, even though they still remain at least one order of magnitude different.

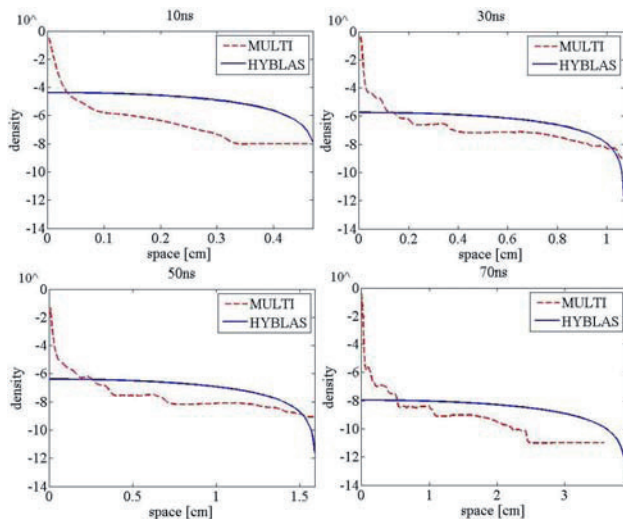


Fig.3 - Comparisons between densities obtained with MULTI and with HYBLAS in the $y = 0$ plane obtained at $t_1 = 10$ ns, $t_2 = 30$ ns, $t_3 = 50$ ns and $t_4 = 70$ ns.

Comparison with experiments

Previous versions of HYBLAS were already used to compare the numerical results to real time of flight signals using different types of metal targets [3], [11]. Results concerning the ion current signals of this work (comparison between experimental and theoretical trends) are reported in figure 4.

On the left, the experimental ion signal was obtained when the probe was placed at 14.5 mm from the target biased with a negative voltage of -50 V. Simulation predicts the width and the centroid position of the experimental signal, once depurated from the electron contribution tail.

On the right, it was tried to compare the data concerning the virtual probe signal with the real results in the electron current domain (with a positive voltage of $+60$ V). Initial conditions were the same of those used for

the ions. Calculations show that the simulated signal is able to reproduce the initial part of the real one, but not its entire shape. This discrepancy can be explained with the presence of a slow hot electrons tail produced by the recombination mechanisms that are not taken into account in the HYBLAS model [7].

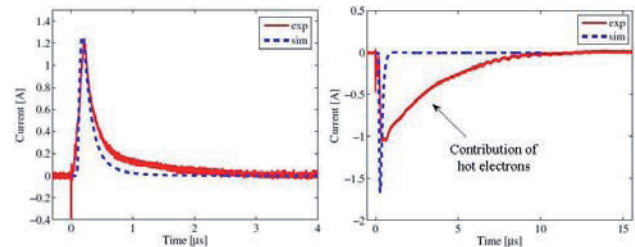


Fig.4 - Negative biased LP signal (-50 V) and positive biased LP signal ($+60$ V) compared with the simulated one, both detected at 14.5 mm from the target.

CONCLUSIONS

In this work we demonstrated that HYBLAS is a versatile code that is able to well reproduce the plasma dynamics in the nanosecond regime and that Langmuir Probes can be used as diagnostics tool for Laser Generated Plasmas. Future works will regard the possibility to include in HYBLAS recombination effects in order to take into account the presence of hot electrons tails at the later stages of the plume expansion.

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Investigation of laser produced plasmas for astrophysical applications

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Abstract - At the LNS-INFN of Catania we aim to reproduce in laboratory, via the laser ablation technique, plasmas of astrophysical interest for the study of fusions rates, in order to better understand astrophysical key parameters like the ES-Electron Screening effect. On this purpose we built up a new experimental apparatus, in order to realize measurements with laser plasmas in a laser power density regime on the order of 10^{10} - 10^{12} W/cm². Most of the results obtained up to now concern the characterization, in terms of density, temperature and temporal dynamics, of a single expanding plasma by employing a movable LP-Langmuir Probe. We observed, other than the classical hydrodynamics expansion, some non linear processes driven by the formation of Double or Multi-layers, whose dynamics has never been explained in detail up to now. On the other side, the characterization of the bulk plasma in terms of density and temperature obtained from the I-V curves (Current vs. applied probe potential) analysis, put in evidence the presence of a hot and a cold electron component, i.e a TET-Two Electron Temperature plasma which existence is related to possible plasma instabilities.

INTRODUCTION

LPP-Laser Produced Plasmas are employed in several fields of matter and nuclear physics, such as thin film deposition, ion acceleration and nuclear fusion [1,2]. In a low energy domain, like that of laser plasmas produced in irradiance regime of 10^{12} W/cm², the density is very low (on the order of 10^{19} - 10^{21} cm⁻³) if compared with stars and other fusion laboratory plasmas. However, the ion temperatures are high enough to ensure a not negligible number of fusion events (>100eV) and meanwhile clouds of cold electrons with temperatures on the order of few eV's can exist providing to a not negligible influence of the ES. In this sense, LPP's could result useful to study the ES and other astrophysical phenomena in a energy domain up to now mostly unexplored. At the LNS-INFN of Catania we designed a novel apparatus in order to carry the studies devoted to nuclear astrophysics by employing LPP [3]. We hereby will show the first experimental results carried out on a single plasma plume with the new apparatus. With an appropriate reading circuit, the Langmuir Probe can be positioned very close to the target surface and is able to measure very low noisy current signals, essential to evaluate the plasma parameters and to investigate the internal structure of the plume. We detected free layers of fast escaping plasma particles evolving very rapidly during the first 200nsec of the plume expansion and in a different manner respect to the bulk plasma. On the other side, the temperatures trends

obtained with the I-V curves analysis, put in evidence the presence of a hot and a cold electron component. The two electron populations evolve separately during the plasma propagation and their existence is related to possible plasma instabilities, such as DL-Double Layer or to the multiplicity of non-neutral plasma region layers formation [4,5].

EXPERIMENTAL SET-UP

The experimental set-up was fully described in the previous LNS-INFN Report 2009 [6]. It consists of a compact cylindrical stainless steel vacuum chamber, having a diameter of 250mm and 240 mm of height. The laser is a Nd:Yag operating at a power irradiance of $3 \cdot 10^{11}$ W/cm², with 6 ns of pulse duration and FWHM of 1.064μm focused on a Al target through a 250mm focal length lens. For the determination of plasma parameters a movable Hidden Analytical ESPion LP was used: it essentially consists of a tungsten 5mm long cylindrical thin tip, with a diameter of 0.15mm, connected to a rigid 300mm long coaxial cable, having a thickness of 3mm. The signal was read out with the RC circuit shown in fig.1.a permitting us to know exactly the current value (on the order of several of hundred mA) flowing through the probe, fundamental to correctly estimate the electron plasma density.

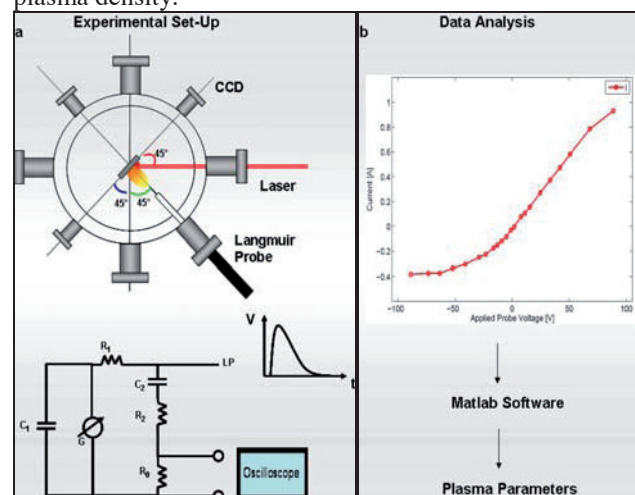


Figure 1: Experimental set-up and the RC circuit (a), typical I-V curve obtained at 400ns of expansion (b).

The Langmuir Probe was biased from -90V to +90V with steps of 5-10V at each laser shot, in order to reconstruct off-line the I-V curves (current vs applied voltage) in function of time. The probe was placed parallel to the plasma expansion direction at 0.5mm and 1.5mm from the target.

In a different set of measurements the unbiased probe was placed at different distances from the target: from 2.5mm to 50mm with spatial steps of few mm's. When $V=0$ the probe collects either electrons than ions: ions hit the probe attracted by a potential which is given by $V-V_p=-V_p$, where V_p is the plasma potential. The electrons are partially repelled whereas the ions are attracted. The LP signal can hence interpreted as follows: if $J_i > J_e$, the number of collected ions is larger than the electrons one, otherwise the probe shows a negative signal. Usually the ions dominates at such repelling voltages (V_p is typically around 30–80V, this means that electrons are repelled by a large negative potential). Therefore the total probe current at intermediate positive or small negative voltages will be $I(V)_{tot} = I_i + I_e$, where I_i and I_e are respectively the ion and the electron current collected by the probe.

The ion and the electron saturation current can be expressed by the formulas [7]:

$$I_i^S = ev_{tot} \sum_i z_i n_i A_p \quad (1)$$

$$I_e^S = \frac{1}{\sqrt{\pi}} ev_{th} n_e A_p \left(\frac{eV}{kT_e} + 1 \right)^{1/2} \quad (2)$$

$v_{tot} = v_B + v_{drift}$ is the sum of the Bohm velocity given by $v_B = \sqrt{\frac{kT_e + 2\gamma kT_i}{m_i}}$ and $v_{drift} = u + v_c$ is the sum respectively of the flow (or adiabatic) and the Coulomb $v_c = \sqrt{\frac{2zeV_{pl}}{m_i}}$

velocity term, z_i and n_i are respectively the ion charge state and the related ion density and A_p is the probe area. It must be noted that when the probe is placed parallel to the plasma expansion direction, the ion current contribution does not include the part accounting for the drift motion of the plasma flow. I_e is determined with the Orbital Motion Theory. According to equation 2 it is possible to determine the electron density n_e without any considerations about the temperature, thus reducing additional sources of errors. T_e is determined by applying the Langmuir Theory, since it is inversely proportional to the slope of $\ln(I)$ when $V < V_p$. The plasma potential, corresponds to the interception of the fits to the electron saturating and accelerating regions (i.e. where the knee of the $I(V)$ curve is located). The experimental I-V curves were processed by means of a Matlab code thus permitting us to obtain the plasma electron density and the electron temperature versus time [8].

RESULTS AND DISCUSSION

The set of measurements, carried out with unbiased LP, permitted us to investigate the plume dynamics without perturbing excessively its expansion. In figure 2 the time of flight signals for different d (where d is the Langmuir Probe - Target surface distance) are reported. Observing the different TOF-Time of Flight signals and more specifically the same signals in a shorter time window in

fig.2.b, for $d = 2.5$ mm we reveal at $t = 10$ ns a negative peak following the photopeak start signal.

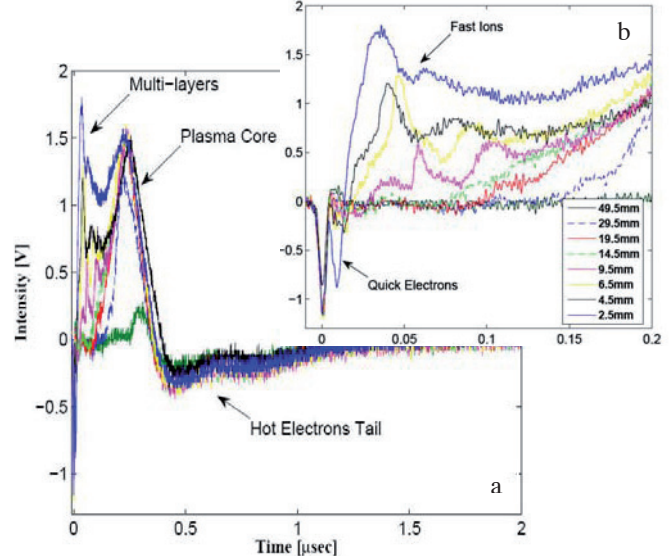


Figure 2: Time of flight signals vs. time for $V_p=0$ V and different probe positions in a larger timescale (a) and in a smaller timescale (b).

This signal can be attributed to a first layer of fast escaping electrons removed as first from the target surface, representing hence a first layer of free expanding particles. The fast electron peak is then followed by some fine structures in the current signal which can be interpreted as several positive ion peaks of different charge states (although we could not perform measurements able to distinguish among the different charge states, we can reasonably conclude that the peaks observed in the figure are similarly composed by ions with different charges) [9]. After 150ns, the bulk plasma expansion follows, with the expected dropping density decrease. At 400ns a hot electron tail expanding later on, impacts on the probe. This dynamics is favoured by the high three body recombination rate permitting to the hot electron to survive in the plasma at longer expansion times. The multi-peak are also detected for $d = 4.5$ mm and $d=6.5$ mm and disappears at $d = 14.5$ mm. This may be a consequence of the peculiar proprieties of the layers: if they are characterized by some excess of charges, they would be collected by the probe as a function of its geometrical cross-section, which in turn depends on the exposed solid angle (i.e on the distance). This means that at larger distances the transverse area of the probe would be too small to “see” the flying particles and also explains why the fine structure of the TOF spectra are invisible with Ion Collectors or Faraday Cups. The first 100ns of the plume expansion is therefore characterized by a multiplicity of ion bunches which were called ML-Multi-Layers, composing the coronal part of the plume, reaching for first the probe. Therefore, according with the data and to similar results reported in literature by Bulgakova et al [10], this phenomena is particular linked to the amount of energy deposited into the plasma. In this regime, the dynamics is strongly non-linear and the quasi

neutrality of the plume can be violated. The high laser fluence is then the principal activator of the ML structure. An estimation of the kinetic energy of the first layer of fast ions, evaluated from the LP-TOF signals peaks position gives: 700eV at 30ns of expansion (i.e. at $d=2.5\text{mm}$) and 3.5KeV at 60ns of expansion (at $d=9.5\text{mm}$). This self-acceleration process takes hence place in a timescale on the order of hundred of nanoseconds. Numerical calculations also show that the electric field developing during the ML expansion has a maximum value on the order of $3 \cdot 10^7 \text{V/m}$ [11]: this values is double with respect the ambipolar potential (evaluated experimentally from the ratio between the plasma potential and the Debye length) associated to the hot electrons expanding in the first instants of the core plasma propagation. It is the plasma potential developing in the DLs that produces in the plasma core an accelerating field which accelerate the ions and splits the different charge states. The splitting produces bunches separated by some Debye lengths and the electrons diffuse in the inter-bunches space accelerating also the lower charge state bunches. Therefore a plurality of charged layers is formed, approaching to each other during the propagation of the bulk plasma. Further investigations are needed on the purpose to fully understand the total evolution of the plasma.

Reporting the biased TOF signals in terms of current values determined at fixed times and plotting the different $I(t)$ vs V (probe potential) we obtained the characteristic $I-V$ curves reported in the previous LNS-INFN Report [6]. The current curves were analyzed by means of a Matlab code able to evaluate the electron density and the electron temperature from equation 2. In figure 3.a the electron density when the probe was placed at $d=4.5\text{mm}$ and $d=14.5\text{mm}$ is reported. As we can observe from the figure, we obtained densities on the order of $n_e=1.5 \cdot 10^{18} \text{m}^{-3}$ in the first instants of the plasma core expansion, then decreasing of one order of magnitude after $t=5\mu\text{sec}$, with the classical decreasing expansion trend. The electron density also shows a not significant decrease when the probe was moved from $d=4.5\text{mm}$ to $d=14.5\text{mm}$, although the distance was almost triplicated. This result contradicts the well know decreasing trend of the plasma density predicted by the theoretical models [12]. On this purpose we evaluated the density from the ion saturation current for different time expansion and for $d=4.5\text{mm}$ to $d=14.5\text{mm}$, by using equation 1 (v_{tot} was evaluated from the peak position of the LP-TOF signals and a mean charge state of $\langle z \rangle = 3$ was considered). Results are reported figure 3.b: as we can observe from the figure, the ion current shows a more significant decrease of the density when the probe was moved from 4.5mm to 14.5mm. This could indicate that the electron density evaluated by the OML theory is less reliable than the values extracted from ion saturation current (this is not new in LP measurements since a large number of experimental results demonstrate that the electronic part of the $I-V$'s could be affected by problems related to the

electron collection: it may be influenced by inner plasma magnetic fields, high collisionality, plasma waves etc).

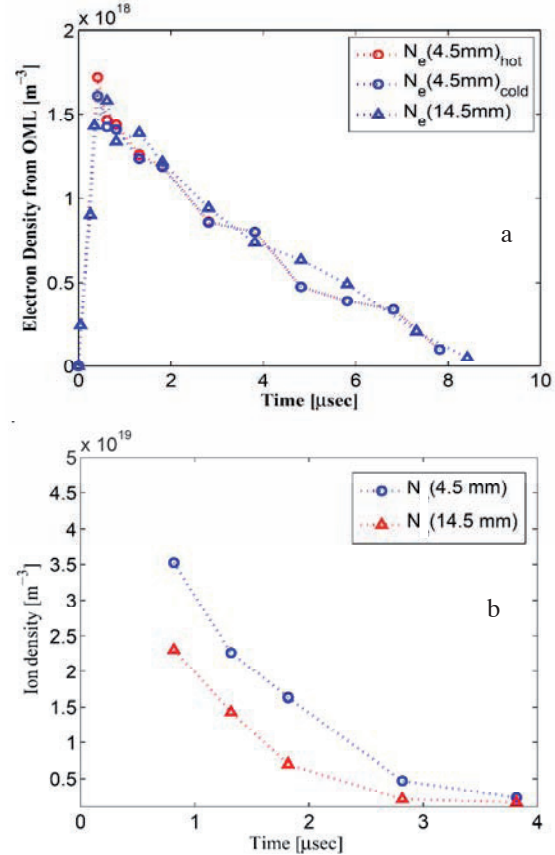


Figure 3: Electron (a) and Ion (b) density vs. time for $d=4.5\text{mm}$ and $d=14.5\text{mm}$.

In figure 4 the temperature trends are reported: a two plasma temperature, i.e a TET plasma (in terms of $I-V$ curve analysis two different $I(V)$'s slopes are detected), when the probe was placed at $d=4.5\text{mm}$. The TET plasma is due to the simultaneous presence of a hot (T_{hot}) and a cold electron plasma population (T_{cold}), evolving separately, starting with a temperature ratio (reported in figure 4.b) of $T_{\text{hot}}/T_{\text{cold}}=7\text{eV}$ in the first instants of the bulk plasma propagation, then decreasing to 1eV at $2\mu\text{s}$ (T_{hot} and T_{cold} become then comparable, because of the thermalization between the hot and the cold electrons component). At $d=14.5\text{mm}$ only and a SET (Single Electron Temperature) plasma for $d=14.5\text{mm}$ is detected. Some correlation between the TET plasma and the ML structure discussed previously can be found: looking again at the TOF signals reported in figure 2 we observe that the Multi-Layer structure disappears for $d=14.5\text{mm}$, i.e when also the TET plasma disappears. This indicates that TET plasma could be related to the DL formation as predicted by the theoretical models proposed by Hora et al. in [14]: in case of two electron plasma fluids Double Layer can manifest through the RSW-Rarefaction of Shock Wave.

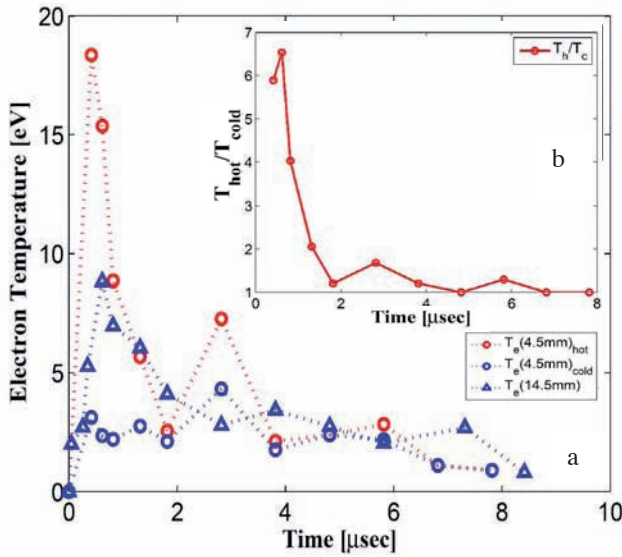


Figure 4: Electron Temperature vs. time for $d=4.5\text{mm}$ and $d=14.5\text{mm}$ (a), temperature ratio $T_{\text{hot}}/T_{\text{cold}}$ vs. time for $d=4.5\text{mm}$ (b) [4,13].

The theoretical condition of RSW is obtained by solving the hydrodynamics equations together with the Poisson equation: a singularity in the equations of state is then found existing only in anomalous fluids. We remind to literature to the complete mathematical treatment and remark here that by solving the hydrodynamics equations supposing a multiple electron fluid, if two electron fluids are considered, expanding respectively with two adiabatic coefficients of $\gamma_{\text{hot}}=1$ and $\gamma_{\text{cold}}=3$, the numerical condition for RSW is: $T_{\text{hot}}/T_{\text{cold}} \approx 5.4$ [14]. This value is very close to the experimental one reported in figure 4.b in the first instants of the bulk plasma expansion. This in turn leads to RSW, which may explain also the Multi-Layer structure observed in figure 2. However, the ML dynamics develops within few hundred of nanoseconds, instead measurements put in evidence that TET plasma survives for long times if compared with the laser pulse duration (i.e. with the typical times of plasma formation).

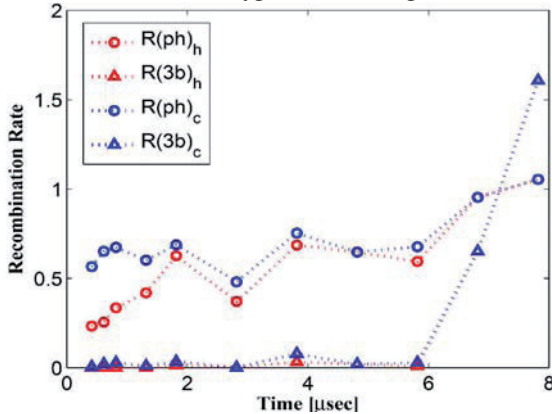


Figure 5: Three body and photo recombination rates vs. time calculated for the hot and the cold component at $d=4.5\text{mm}$.

This can be favoured by the recombination rate, becoming relevant during the core plasma propagation. On this

purpose, in figure 5 the $T^{-9/2}$ and the $T^{-1/2}$ trends are reported, representing respectively the threebody recombination and the photo recombination rate. As we can observe from the figure, R_{ph} and R_{3b} becomes significant at later expansion times. This means that in case of R_{3b} the hot electrons can take part in threebody recombination as third particle so that they get additional energy and they can survive in the plasma for more time. The hot electrons contribution is also visible in figure 2: it appears at $0.5\mu\text{sec}$ and determines the negative tail characterizing the final part of the plume dynamics.

CONCLUSIONS AND PERSPECTIVES

The investigation of the plasma structure, by means of the LP-TOF signals, permitted us to understand more in detail the overall plume expansion. Our experimental setups permitted us to locate the LP very close to the target surface and to detected the ML which develops in the first instants of the plume formation, then followed by the bulk plasma propagation were a TET plasma was detected. The high recombination rate finally explains the last part of the plasma dynamics. Additional investigations will be needed to clarify the ML formation mechanism to understand how it is definitively generated and what influence it has on the possible employment of such plasmas for astrophysical studies. According to preliminary fusion reaction rates calculations carried out with the HYBLAS code, plasma instabilities should be damped [3]. Otherwise, the contribution to the total number of fusions due to not-handled nonlinearities cannot be correctly evaluated, and we would be not sure of the correct determination of the screening contribution to the total rate. The experimental and numerical results obtained up to now demonstrate that in the laser regime of this work the plume dynamics begins to assume some characteristics which are more typical of plasma generated by high laser intensity, where any hydrodynamical approach fails, and only the microscopic kinetics are valid [15].

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Characterization of VIS performances in cw mode

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Abstract – The Versatile Ion Source (VIS) is an off-resonance microwave discharge ion source (MDIS) producing high intensity proton beams at 50 to 75 kV. The source, installed at INFN - LNS, is based on a 2.45 GHz microwave discharge and produces a proton current larger than 50 mA. Its beam characterization, in terms of proton fraction and beam emittance will be reported in the following.

Studies to optimize the extracted current, introducing an alumina cylinder embedded in the plasma chamber have been carried out and are reported in this paper. The know-how achieved with VIS source may be useful for the realization of a relevant project as the ESS European Spallation Source, to be built in Lund, Sweden, and other facilities using high power beams, so the characterization of the source here shown may be particularly relevant.

INTRODUCTION

The production of high current beams is a key point for different applications and this role is deemed to increase in the coming years, either for industrial applications and for research projects. High current and high brightness H^+ beams can be provided by 2.45 GHz MDIS, which present many advantages in terms of compactness, high reliability, ability to operate in CW mode or in pulsed mode, reproducibility, and low maintenance.

A compact version of MDIS called VIS, has been designed and built at INFN - LNS with the goal to produce with high reliability a cw proton current of some tens of mA with a rms normalized emittance lower than 0.2π mm mrad, for an operating voltage of 65 kV [1]. The VIS source, reported in figure 1, consists of a water-cooled copper plasma chamber (100 mm long and 90 mm diameter) surrounded by three rings of NdFeB permanent magnets, generating a 0.1 T almost flat magnetic field along the axis. A plasma is generated by means of the microwave provided by a 2.45 GHz Magnetron through a WR 340 (86.4 mm $\times$ 43.2 mm) waveguide excited in the TE_{10} dominant mode.

The ionic component of the plasma produced in the plasma chamber is then extracted by means of a four electrodes extraction system. The VIS extraction has been optimized to work around 40 mA and a theoretical value

of 0.1π mm mrad normalized emittance has been calculated, i.e. fulfilling the requirement of high brightness.

The low energy beam transport line (LEBT) allows the beam analysis and it consists of a focusing solenoid, a four-sector diaphragm to measure the beam misalignments, a Direct-Current Current Transformer (DCCT), a 30° bending magnet to separate the ion species and an insulated beam stop where the beam current is measured.

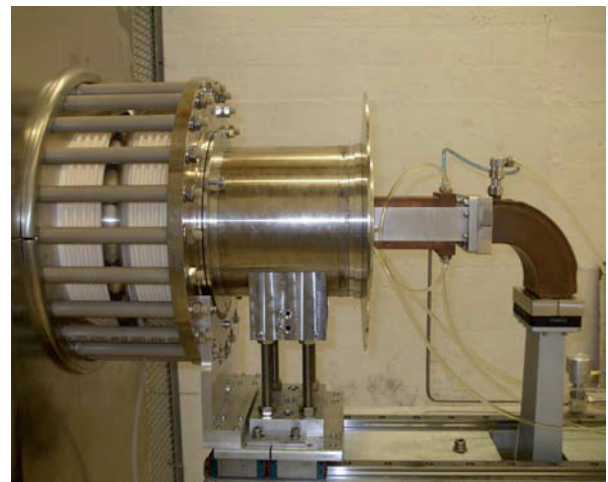


Figure 1: A picture of VIS source.

EXPERIMENTAL SET-UP

Several measurements have been carried out in 2010 to characterize and optimize the VIS source.

A characterization of the beam quality has been obtained by means of the Emittance Measurement Unit (EMU). This device, provided by the CEA/IRFU Saclay SILHI group, permits to determine the beam transverse emittance. The EMU is made of three parts [2]:

- a 0.2 mm diameter tantalum sampler within a water cooled copper block;
- a permanent magnet Wien filter with adjustable electric field;
- a wire for beamlet intensity measurements.

The device uses a stepper motor, so the sample is moved along a beam diameter. In order to make the emittance measurements, divergence is deducted from the electric field needed to collect the beam on the wire. The sampler position and the average potential value for the proton peak give the global divergence of the considered beamlet.

The emittance measurements have been carried out at different permanent magnets positions, corresponding to different magnetic fields; for each fixed position the puller voltage, microwave power and pressure have been changed. For different experimental set-ups the beam current varied from 30 to 45 mA with $\Phi_{\text{ext}} = 7$ mm.

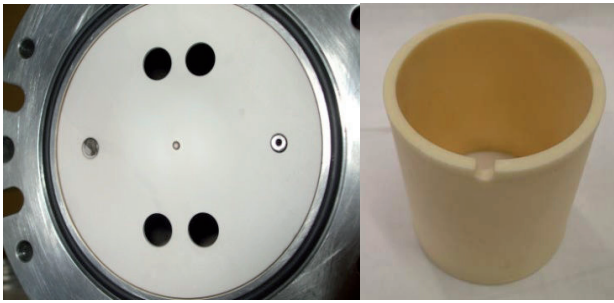


Figure 2: The BN disk in the injection flange (on the left), and the alumina tube inserted in the plasma chamber (on the right, inner diameter is 79 mm, the outer diameter is 89.5 mm, and its length is 95 mm).

The improvement of the extracted current and the proton fraction has been obtained by means of the use of Boron Nitride (BN) disk and a 5-mm-thick Al_2O_3 tube to increase the electron density. In plasma sources the output current depends linearly on the electron density n_e , according to the formula:

$$I \propto \frac{n_e}{\tau_i}$$

where τ_i denotes the lifetime of the ions in the plasma which is an evidence of quite low confinement time in comparison to ECR ion sources. The MDIS produce beams with low charges state (1^+ and 2^+). So in the VIS source the increment of ion beam current is connected mainly to the enhancement of electron density. High electron densities assure a more efficient ionization of the low-pressure plasma. Typical plasma parameters of proton sources operating in the off-resonance mode are: $T_e = 20$ eV (above the hydrogen ionization threshold), $n_e = 1\text{--}1.5 \cdot 10^{17} \text{ cm}^{-3}$ that is above the $n_{\text{cutoff}} = 7.5 \cdot 10^{16} \text{ cm}^{-3}$ for the frequency of 2.45 GHz.

The measurements can be divided in three different experimental set up:

- One BN disk in the injection side;
- Both BN disks located at the two extremities of the plasma chamber;
- Alumina tube and both BN disk.

Finally, an analyzing magnet was used to have precise proton fraction measurements; the H^+ and H_2^+ species were swept into two Faraday cups sequentially, by adjusting the 30° Bending Magnets. The different ion species are measured by the Beam stop located at 30° with respect to LEBT axis. For each species measurement, the electromagnetic solenoid current was adjusted to get the maximum beam current. In fact, the focus strength of the three species is approximately proportional to the square root of the mass.

The proton fraction has been calculated by means of these equation:

$$H^+(\%) = \frac{H^+}{H^+ + H_2^+} \quad H_2^+(\%) = \frac{H_2^+}{H^+ + H_2^+}$$

The fraction of H_3^+ molecular species was not measured because its amount was found to be negligible ($<1\%$), therefore our measurements are related only to the two ionic components H^+ and H_2^+ .

MEASUREMENTS

A typical emittance plot is shown in figure 3, obtained at 60 kV for a proton currents around 38 mA. The beam features a small emittance value, i.e. $0.125 \pi \text{ mm mrad}$, and a very low divergence.

Fixing the permanent magnets' position, additional measurements were done by changing the puller voltage, the microwave power and the hydrogen mass flow. In most cases emittance values lower than $0.2 \pi \text{ mm mrad}$ have been carried out; the increase of beam divergence, where observed, is due to the space charge forces in the beam. Space charge (SC) is the simplest and the most fundamental of the collective effects whose impact generally is proportional to the beam intensity [3].

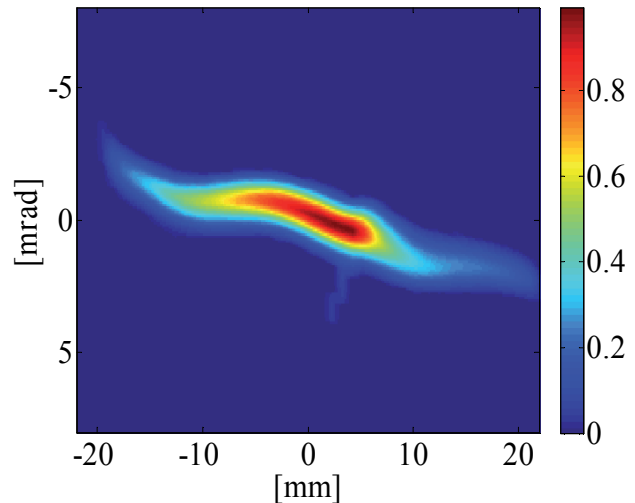


Figure 3: An emittance plot obtained at 700 W, $V_{\text{ext}} = 60$ kV.

Passive method to increase the electron density

The main limitation of MDIS consist of the so called electromagnetic cutoff, which fixes the upper boundary of the plasma density which can be reached at a given frequency. A passive technique (by using BN and Al_2O_3) has been used to overcome this limit.

For each different experimental set up we have changed the hydrogen mass flow from $0.6 \cdot 10^{-5}$ to $2.5 \cdot 10^{-5}$ mbar.

Figures 4 and 5 show the trends of the extracted current and the proton fraction as a function of microwave powers at $2 \cdot 10^{-5}$ mbar. At this pressure value the best experimental conditions for the extracted currents and the proton fraction have been observed when alumina tube has been inserted inside the plasma chamber.

The improvement of the performance with the use of the alumina tube and of the disk of BN disk can be explained by means of two different theories.

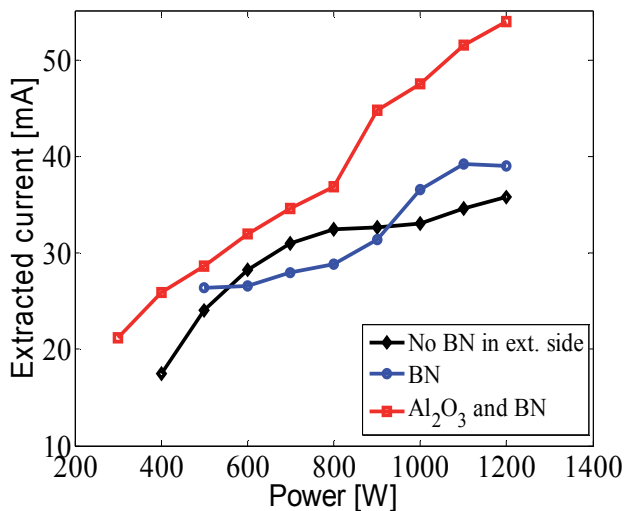


Figure 4: Extracted current vs. microwave power for three different experimental set-up.

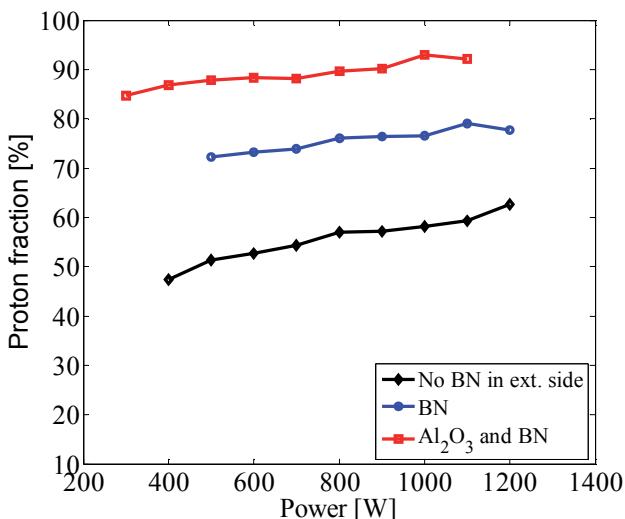


Figure 5: Proton fraction vs. microwave power for three different experimental set-up.

For the first one the BN and the alumina are electron donors that influence the plasma essentially by emitting cold electrons (called secondary emission). Being accelerated in the sheath by the plasma potential, they will enter the plasma generally with energies in the order of several tens of eV [4]. Alumina has the advantage to a high emission rate of secondary electrons even at low energy of the primary electrons [5].

The second one explains this phenomenon by introducing the Simon currents [6,7] within the plasma. In a magnetized plasma the loss fluxes of the electrons and the ions are not isotropic:

- The electrons diffuse along the axis because they must follow the lines of the magnetic field,
- the ion diffuse in each direction, they are mostly lost radially.

According to the quasi neutrality condition of the plasma, the loss fluxes of ions and electrons must be the same.

The balance of positive and negative charges flowing away from the plasma can be ensured only if the currents can freely flow through the plasma chamber walls. (This mechanism was named by Simon as “short circuit model”).

When we have inserted some insulators inside the plasma chamber, we have modified the loss flow of the two species. The insulator, in fact, stops the current flow along the plasma chamber walls and drives back the charged particles which are approaching to it.

In both the theories there is an increment of the electron density because of the reduction of the losses, and consequently higher proton current has been measured.

The beam current increases when enhancing the microwave power (fig. 4), conversely the proton fraction saturates at medium to high power levels (fig. 5). This trend can be understood if we consider the most important processes occurring in a hydrogen plasma [8]: the production of atomic hydrogen H^+ requires energies lower than 13 eV, instead the production of molecular hydrogen H_2^+ requires energies above 15 eV [8].

CONCLUSION

The VIS source is a practical device for generating dc proton beam with high current and low emittance. Proton beams up to 50 mA have been extracted through a plasma electrode of 7 mm at 50 to 75 kV. Proton fractions as high as 90% were generated at different hydrogen mass flow and microwave power. It was shown that these two parameters regulated the amount of the different species extracted from the source (H^+ , H_2^+) by affecting the electron temperature: in fact any variation of T_e modifies the Maxwellian distribution of the thermal electrons, that is correlated to the ionization rates.

The know-how gathered with the VIS source characterization may be useful for some relevant projects as: the ESS- European Spallation Source [9], to built in Lund, Sweden and the MYRRHA project to be installed in Mol (Belgium) [10]. A third project (DEDALUS) will

make use of MDIS as injector of a new high power cyclotron to be installed in USA [11].

In particular, the goal of the European Spallation Source (ESS) project is to construct and operate the next generation, high-intensity neutron source for Europe. The high beam brightness requested at ESS can be also useful to tackle challenges such as those set by the quest for more effective energy production and storage.

ACKNOWLEDGEMENTS

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Loss of light efficiency in CsI(Tl) scintillating screens

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Abstract - The demand of scintillating screens for ion beam imaging has been growing during the last years for several applications, including the real time monitoring of ion beam profiles in nuclear physics research laboratories. Research and development activities, started at INFN-LNS several years ago, have been focused on the development of ion beam diagnostic devices operating in a very low energy (< 100 keV) and intensity ($< 10^5$ particles per second) ranges. Scintillating crystals with high efficiency are available for such purposes, but a protracted beam irradiation induces radiation damage in the lattice, thus implying a decrease of its light yield. In this paper we report on the dependence of the light efficiency of a CsI(Tl) scintillating screen as a function of the fluence of low energy ^{16}O ions, by means of image analysis techniques.

INTRODUCTION

The most simple and efficient technique for ion beam monitoring is based on a scintillating screen intercepting the beam itself. This produces a light spot, whose shape corresponds to the 2-dimensional transverse beam profile. A CCD camera properly installed close to the screen allows to watch the profile in real time, that is extremely useful during the beam transport procedures. For radioactive ion beams produced with ISOL facilities, such as EXCYT at LNS [1], the typical beam conditions consist of energy below 100 keV and intensities below 10^5 particles per second (pps). Under these tough conditions the usual quartz or alumina screens can hardly produce enough scintillation light in order to be detected by a standard CCD camera. In these cases the adoption of high efficiency scintillating screens is necessary. This is why we chose to use thin screens made of CsI(Tl) [2-4], one of the most sensitive scintillating materials used as detectors in nuclear physics experiments.

In form of monocrystal its light yield when detecting gamma rays is above $6 \cdot 10^4$ photons/MeV, with the peak emission wavelength around 550 nm. The light emission basically proceeds according to two exponential decay laws, with time constants respectively of 0.73 and 3.2 microseconds, and a rather low afterglow. Like most scintillating materials, the CsI(Tl) light yield decreases by exposing it to radiation, and in particular to a flux of energetic ions, due to the production of quenching centers, whose number increases with the deposited dose. Such phenomena are widely under study since several years, typically for ions above the MeV range, in order to investigate the physics underlying the dependence of the

scintillation efficiency on the dose released in the CsI(Tl) [5-8].

EXPERIMENTAL SET-UP

In order to characterize the radiation hardness of the CsI(Tl), we irradiated a thin screen with a ^{16}O ion beam at 100 keV and measured the scintillation light intensity as a function of the fluence; we remark that at this energy the ^{16}O particles are implanted in a depth range of ~ 220 nm. The beam was produced by means of the injector of the Tandem Van Der Graaff accelerator installed at LNS. In fig. 1 a sketch of the experimental apparatus is shown. The Faraday cup allows to measure the beam intensity with a resolution of 0.1 pA, the pepper pot mask can be inserted across the beam path in order to reduce the total beam intensity to around 1 pA, to prevent the fast degradation of the screen.

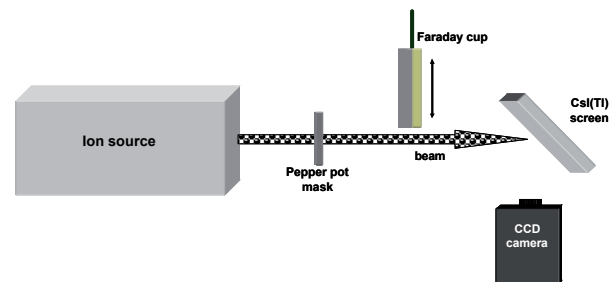


Figure 1: Sketch of the experimental set-up.

The CsI(Tl) screen we used, manufactured by Hilger crystals, has a thickness of 1 mm and was positioned at 45° with respect to the beam axis, in a typical configuration for the visualization of a 2D transverse beam profile. A high sensitivity 14-bit cooled CCD still camera (Chroma CX3 by DTA srl) was positioned at 90° , with a suitable lens objective in order to properly magnify the region hit by the beam. This camera, typically used in astronomical measurements of weak light sources, in ref [9] has shown a high reliability in terms of reproducibility and linearity, allowing accurate measurements of beam profiles and measurements of local beam intensities by means of image analysis. The advantage of using a CCD still camera is that it is possible to select regions of the scintillating screen where the local beam density is rather homogeneous, and thus to perform all the light yield analysis inside those regions of interest (ROIs). The pictures were acquired with an integration time of 5 seconds, long enough to get a sufficiently bright beam spot, and the CCD temperature was stabilized at -5°C to

reduce the noise. From each acquired picture a background image acquired with the shutter closed was subtracted, thus strongly reducing the systematic noise. The free software package ImageJ [10] implementing several advanced tools for image analysis was used, in order to extract the needed information from the pictures. The initial light yield was measured inside the selected ROIs by analyzing the gray levels in the first picture acquired immediately after the beam was switched on the fresh non-irradiated sample of CsI(Tl) screen, fig. 2. This image was not affected by efficiency degradations on the screen surface. This picture of the 2D beam profile shows a non-homogeneous structure that is due to the overall beam shape and to the round-holes geometry of the pepper pot mask. In the inset of fig. 2 the same profile is shown with the four selected ROIs where the distribution of the gray levels has a standard deviation within 5%, that was the statistical limit inherent with the local particle rate. This means that the beam fluence inside these ROIs, and hence the ensuing radiation damage, can be considered reasonably homogeneous. The fraction of beam intensity inside each ROI has been calculated by comparing the light intensity inside the region versus the overall intensity in the whole beam profile. Besides, by taking into account the spatial calibration of the imaging system, the beam intensity inside each ROI was expressed in pps/cm² in order to calculate the particle fluence in the ROIs.

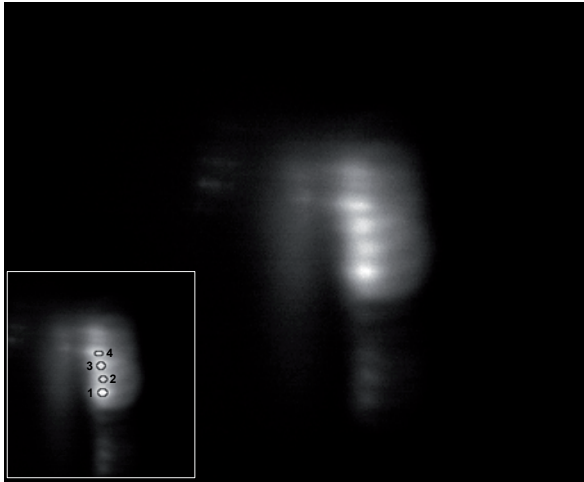


Figure 2: The first picture acquired with the non irradiated sample of the CsI (Tl) screen. In the inset the four selected ROIs are shown.

DISCUSSION

The screen was continuously irradiated for six hours, and a set of pictures was acquired while verifying that in the mean time the overall beam intensity was constant at the reference value of 1.3pA, as measured by means of the faraday cup. With ImageJ we measured the statistical parameters of the gray levels (mean and standard deviation) inside the ROIs in all the pictures, then we plotted the measured normalized values as a function of the particle fluence (ions/cm²), thus obtaining the light

loss curves corresponding to the four ROIs, as shown in fig.3. The error in the normalized efficiency has been quantified by propagating the standard deviation in the gray levels. The errors in the fluence take into account the various contributions, including the uncertainties in the measurement of the beam intensity inside the ROIs. Such experimental plots show a fast drop of the efficiency, that tends to a value below 10% of the initial one for fluence beyond 3·10¹² ions/cm². The curves have been fitted by

the equation $\frac{L_0}{L} = 1 + K \cdot \text{fluence}$, with L_0 and L the

light intensities of the non-irradiated and irradiated screen respectively, K the fit parameter that includes the quenching factor and the density of the quenching centers for fluence unit [8]. As an example in fig. 3b the light loss curve corresponding to the ROI 1 is shown; also shown is the fit that is in good agreement with the data, as for the other ROIs.

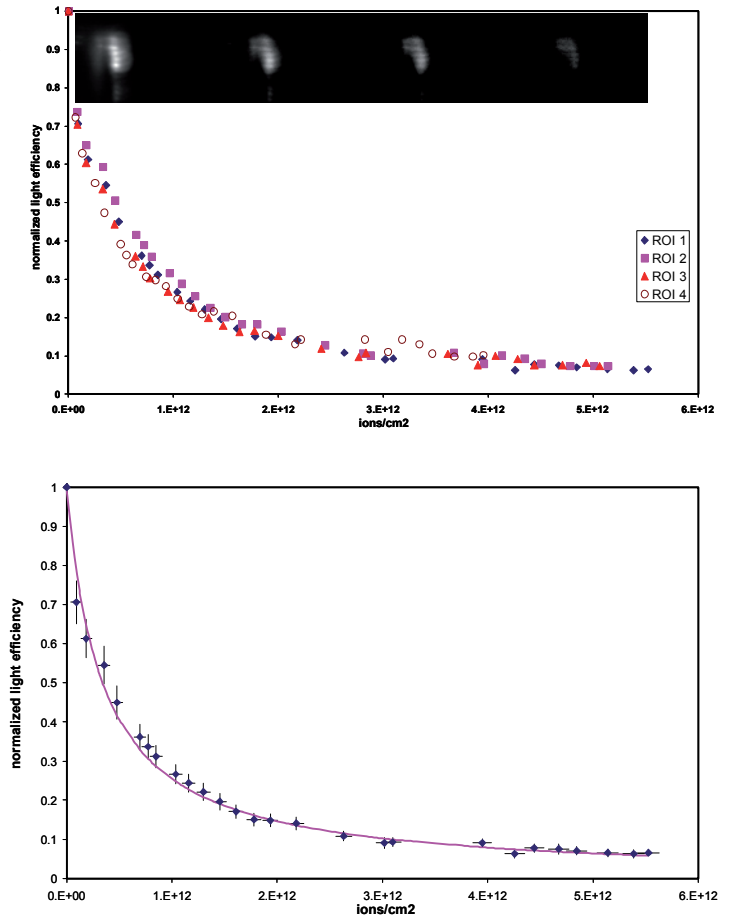


Figure 3: a) Plots of the measured efficiencies inside the ROIs, with some of the beam profiles acquired during the irradiation, where the loss in the brightness shows clearly. The error bars are omitted for better clarity. b) Data corresponding to the ROI 1 fitted with a function that takes into account the production rate of quenching centers.

CONCLUSION

We have tested the radiation hardness of a CsI(Tl) scintillating screen with a 100 keV ^{16}O beam, by acquiring the beam profiles by means of a high performance cooled CCD still camera. Image analysis has allowed to select the regions on the screen where the beam density was reasonably homogeneous and therefore to study the behaviour of the light yield inside these regions. We have found that the decrease of the luminosity as a function of the number of deposited particles is in agreement with the model of Quaranta et al. described in [8].

Acknowledgments

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Characterization of Silicon PhotoMultipliers at LNS

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Abstract - The Silicon PhotoMultiplier (SiPM) represents a new generation of photodetectors. The high sensitivity, compactness, low power supply, insensitivity to magnetic fields make them a valid alternative to the PMTs in several fields such as particle physics, medicine, space technology. At LNS a complete characterization of samples developed by different companies (Hamamatsu, STM, SensL) has been performed, in order to measure the most significant properties, consisting in the dark noise, cross talk probability, photon detection efficiency, charge and timing resolutions. Measurements have been performed also coupling the SiPMs with small size LYSO scintillators and using gamma sources, in order to investigate a possible application in the PET diagnostics.

INTRODUCTION

The Silicon PhotoMultiplier (SiPM) [1] represents an innovative photodetector sensitive to the single photons. It is constituted by a bidimensional array of single photon avalanche detectors (SPAD), whose number can be as many as 10^4 . Each SPAD, here simply called cell, is a small photodiode with square or circular shape, whose size is typically below $100\ \mu\text{m}$. Powering each cell with a bias voltage slightly over the breakdown makes it operative in Geiger mode, thus meaning that the cells stay quiescent until an electron-hole pair produced inside the depletion region generates an avalanche process, producing a fast pulse with a rise time below 1ns . Such an avalanche is immediately quenched by means of a feedback resistor integrated in the chip itself and the pulse falls to zero within some tens of nanosecond. It should be noted that an avalanche may be originated by the absorption of a visible photon as well as by a thermally generated e-h pair. In figure 1 an elementary cell of a SiPM is shown, with the surrounding integrated quenching resistor visible on top of it. The outputs of all the cells are connected together thus making the SiPM a device that can produce a discrete number of values at its output and allowing to deduce how many photons interacted with the detector. An important requirement is obviously that the pulse amplitude of all the cells must be the same. In the same figure a charge spectrum acquired by using a weak laser light source ($\lambda=408\text{nm}$) shows the very high resolution that allows to resolve the peaks produced by a small number of interacting photons.

The dimension of the SiPMs available now on the market are typically from $1\times 1\text{ mm}^2$ to $3\times 3\text{ mm}^2$ and they can also be arranged in array configuration of several elements. The typical bias voltage depends on the technology and can roughly vary between 30 and 75V.

Such characteristics, together with the insensitivity to magnetic fields, good timing resolution and sensitivity to a few photons, make the SiPM a quite promising photodetector for several applications, both for nuclear physics research and for applicative purposes.

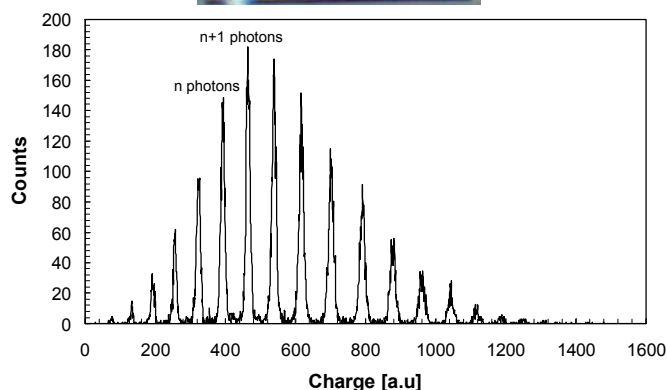
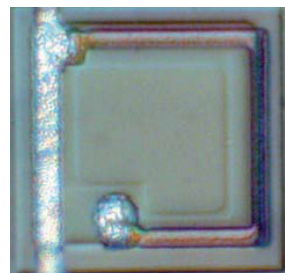


Figure 1: Elementary cell of a SiPM and charge spectrum generated by a weak light source.

THE MEASUREMENTS

At LNS-INFN in Catania we have tested several kinds of SiPM detectors, in order to study their main properties, with the typical values summarized in the table 1 [2]. The Gain corresponds to the total amount of carriers produced inside the cell as a consequence of the avalanche process. The dark count rate is the number of pulses per second, due to random thermal generation of pairs in the depletion zone that initiate avalanches. The Photon Detection Efficiency (PDE) is the fraction of detected over impinging photons onto the detector window. All of these parameters have been measured at LNS, also allowing to make a comparison between several devices available on the market produced by different manufactures. An estimate of the SiPM quality has been performed by studying in detail the dark noise and in particular the component that is due to correlated events, basically due to the physical processes described in the following.

Table 1 - Typical Properties of commercial SiPMs

Active Area	up to 10 mm ²
Cell size	25 – 100 micron
Gain	10 ⁵ – 10 ⁶
Operating Voltage	30 – 80 V
Dark Count	10 ⁵ - 10 ⁶ cps
PDE	< 50%

The first consists of spurious afterpulses produced as a consequence of main pulses, due to carriers produced during the avalanche process, trapped inside or near the depletion zone, and exponentially released within a few hundreds of nanoseconds. Such charge carriers can start avalanches giving rise to additional fake pulses. Fortunately the fraction of these events is typically below 1% and in first approximation can be neglected.

The second source of correlated noise is the cross talk between adjacent cells, mainly because of visible photons produced inside a cell during the avalanche process that can diffuse to the closest cells, be absorbed and thus starting other avalanches. Such a process can be relevant for those devices where no optical insulation has been implemented around each cell.

For all the devices we tested at LNS, the dark noise rate has been measured with the discriminator threshold set in order to have a value corresponding to about half of the single photon pulse amplitude. The measured rates strongly depend on the bias voltage, where the increase of dark noise is due to increasing probability of starting the avalanche as the bias voltage increases.

In order to estimate the amount of crosstalk affecting the SiPM, we operated by acquiring the dark noise rates for an increasing value of the threshold and calculating the ratio between the rates corresponding to 1.5 and 0.5 photons respectively. This ratio roughly represents the probability of double firing, that in case of pure random noise can be easily calculated to be generally below 1%. In the dark noise profile acquired with a 10x10 cell Hamamatsu SiPM (see fig. 2), the ratio dark(1.5 ph)/dark(0.5) is about 20%, thus meaning that a high cross talk is present in such a device. The same profile acquired with a 10x10 cell STM SiPM gave a ratio of 0.5%, a very low value that accounts for the presence of an optical trench around each cell, preventing the light propagation and hence the cross talk effects.

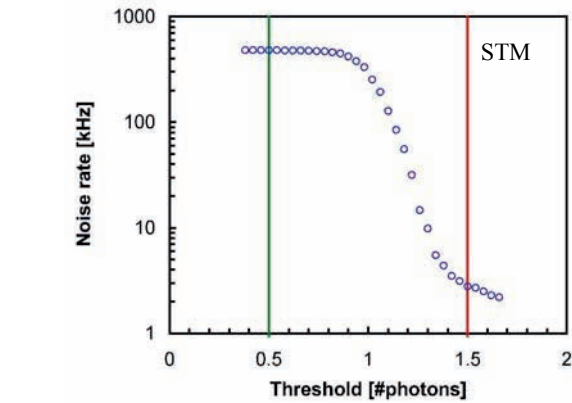
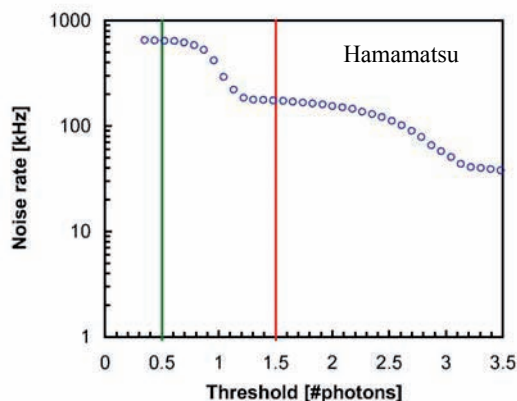


Figure 2: Dark rate measured by changing the threshold for Hamamatsu and STM 100 cells SiPMs.

The dark noise normalized profiles acquired for four SiPMs (see fig. 3) allow to compare the cross talk of such devices by comparing their slopes. In order to quantify the amount of the cross talk in the measured dark noise, we calculated by the difference between the measured noise and the expected value in case of poissonian random noise, and the values are shown in table 2. A further evidence of the effects due to cross talk comes from the analysis of the charge spectra acquired with a weak light source. Such spectra have been fit by using a Poisson multi-gaussian function,

$$F(x) = A \frac{dP}{dx} = A \cdot \sum_{n=1}^{\infty} \text{Poisson}(\mu, n) \cdot \frac{1}{\sigma_{\text{tot}}(n)\sqrt{2\pi}} \cdot e^{-\frac{[x-c(n)]^2}{2\sigma_{\text{tot}}^2(n)}}$$

with n the number of photons, $\sigma_{\text{tot}}^2(n) = \sigma_e^2 + n\sigma_l^2$ and μ the centroid of the poisson curve, corresponding to the average number of photons. Whilst for the STM the function fits the experimental values with a very good agreement, a large discrepancy is present for the Hamamatsu, as we expect because of the high contribution from correlated noise.

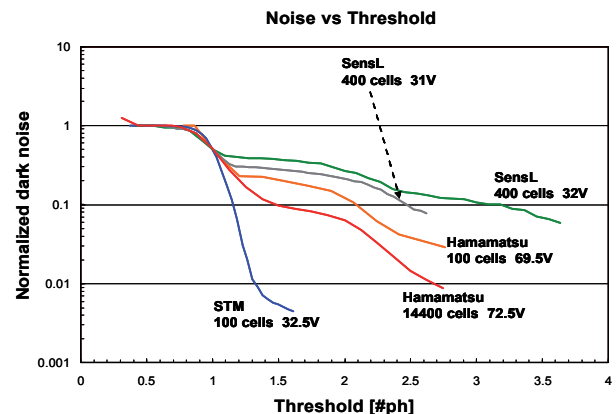


Figure 3: Profiles of normalized dark noise of four SiPM models.

For all the devices, the gain has been measured constructing the charge spectrum and dividing the charge corresponding to two adjacent peaks by the elementary charge, in order to obtain the number of carriers produced during the avalanche process. Also the dependence of the gain on the bias voltage has been measured, showing an almost linear behaviour.

Table 2 - Probability of correlated noise

SiPM	Probability
SensL 1x1 mm ² (V _{bias} 31V)	9%
Hamamatsu 1x1 mm ²	10%
Hamamatsu 3x3 mm ² (new)	1%
STM	<0.5%
FBK 1x1 mm ²	2%

One of the most relevant parameters characterizing a SiPM is represented by the PDE, whose value strongly affects the performance of the devices in terms of timing and charge (i.e. energy) resolution. It can be expressed by the following equation $PDE = QE \times fg \times Pa$, with QE the quantum efficiency of the single cell, fg the fill factor (i.e. geometrical efficiency) and Pa the avalanche probability, depending on the electric field configuration in the depletion zone. Several procedures can be followed in order to measure such a parameter. All of them make use of a calibrated reference detector (typically NIST certified [3]) mounted along with the SiPM onto an integrating sphere, that guarantees the homogeneity of the photon flux on its inner surface.

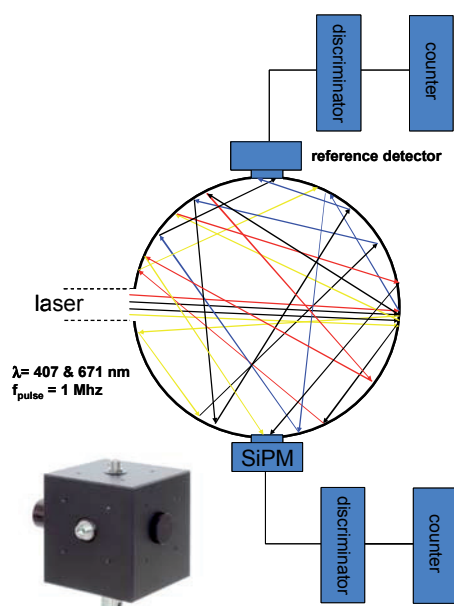


Figure 4 :PDE measurement set-up

In our first measurements [4, 5] we made use of a xenon lamp that has allowed us to measure the efficiency in the whole visible light spectrum, by means of a grating monochromator. The light is produced continuously and thus we have measured the efficiency by comparing the

current intensities read by both photodetectors. The limitation of such a technique is that the contribution of crosstalk and afterpulsing cannot be eliminated. Another technique that we are using now, makes use of pulsed laser light injected into the sphere. It implies that the SiPM must be used in pulse counting mode, in order to count the pulses whatever their amplitude. Maintaining the light intensity of each pulse as low as possible, the probability of double photons at the same time can be made negligible and the number of hitting photons can be easily measured by counting the pulses and subtracting the dark noise rate. If fig. 4 is a sketch of the apparatus for the PDE measurement and in fig. 5 the PDE vs. wavelength values measured for two Hamamatsu SiPMs 3x3 mm² are shown.

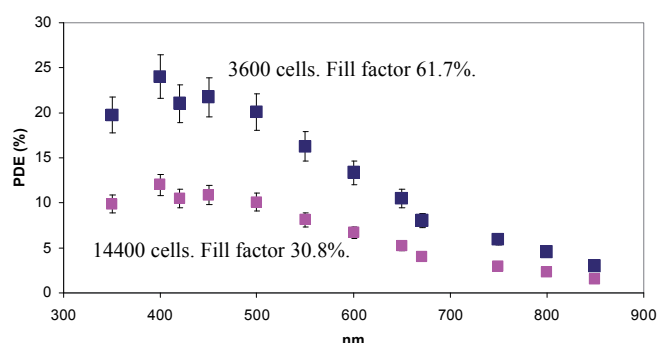


Figure 5: PDE values at different wavelengths for the 3x3mm² Hamamatsu SiPMs

POSSIBLE APPLICATIONS WITH SiPM DETECTORS

The peculiarity of the SiPM detectors, in particular their small size, the low bias voltage and the high sensitivity, make them very interesting for some applications we are developing at LNS, such as a mesh of counters for the monitoring of radioactive waste sites and a small TOF-PET probe for early diagnosis of the prostate cancer [6 - 8]. Within these projects we are pursuing, the SiPMs are coupled with organic or inorganic scintillators, that make them detectors suitable for charged particles, neutrons and gamma rays. A recently developed Hamamatsu SiPM 3x3 mm² has been tested by coupling it with a tiny LYSO scintillator 3x3x10 mm³ (40 ns decay time), in order to measure energy and time resolutions by using radioactive sources. In fig. 6 the spectra of three sources are shown. By using a couple of Hamamatsu SiPM coupled with two LYSO crystals, we measured the timing spectrum using the two 511 keV gammas produced by a ²²Na source, placed in between. The spectrum conditioned with the full energy events in both the detectors, is shown in fig. 6. Its FWHM of 350 ps is in agreement with the expectations and can be reduced to 250 by using the similar Hamamatsu SiPM with double fill factor and hence double PDE value, thus improving the resolution of a factor sqrt(2).

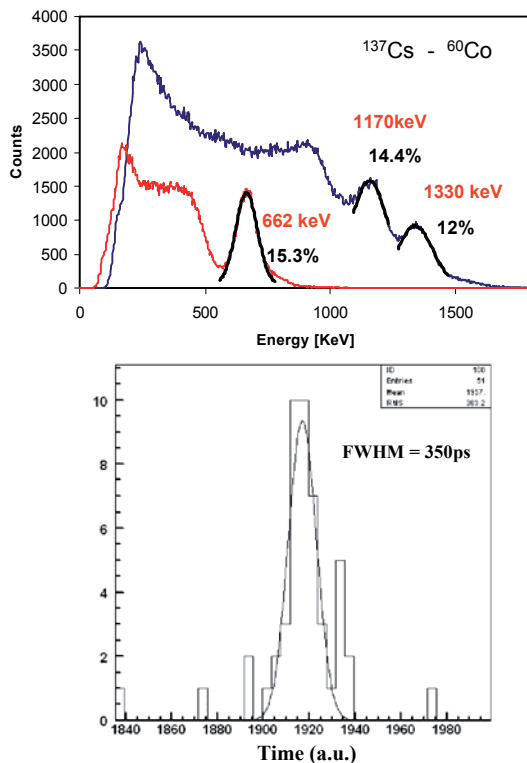


Figure 6: Energy spectrum acquired with the Hamamatsu SiPM $3 \times 3 \text{ mm}^2$ coupled with a LYSO scintillator. Timing spectrum of two SiPMs coupled with LYSO, using a ^{22}Na source.

CONCLUSIONS

We have characterized several samples of SiPM, in order to measure the most significant parameters to be taken into account in order to choose the suitable detectors for specific applications. The measured energy and timing resolution are in good agreement with the data reported in literature and make the SiPM a very good candidate to substitute the PMT in several applications.

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D + D fusion reaction rates in laser generated plasma

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Abstract - Thermonuclear reactions play a key role in astrophysics since they provide to the stellar energy production, determining then the stellar evolution. In such context the contribution of Electron Screening is crucial; it determines the increase of the fusion cross sections, changing the stellar evolution. At temperatures and densities that are typical of plasmas produced by lasers at power densities of $I > 10^{12} \text{ W/cm}^2$, the classical Debye screening factor in nuclear reactions becomes comparable with the one of the solar core: these plasmas are good candidate to reproduce astrophysical condition in laboratory. In this contribution we report some results of numerical simulations of D-D fusion reaction rates obtained by using a hydro-dynamical approach for the description of the fast expansion of a laser generated plasma.

INTRODUCTION

Electron Screening (ES) is a key parameter for the correct understanding of many astrophysical processes, from quiescent burning to the most spectacular events, like supernova explosions. In a naive picture, the electron cloud surrounding the interacting nuclei generates a potential screening so that the projectile “sees” a reduced Coulomb barrier, both in height and in its radial extension (metti la referenza di rolfs). This leads to a higher fusion reaction cross section. The bare-nucleus cross section and the shielded one are usually related in the literature via the “enhancement factor, f ”. Such parameter is defined as $f = \exp(\pi\eta U_e/E)$, being U_e the electron-screening potential and E the relative energy between the interacting particles. However, relatively small contribution coming from the screening effects can lead to significant errors in the extrapolation and evaluation of fusion cross sections. It should also be noted that, for stellar plasma, the screening effect could be very different from that one extracted from the study of nuclear reactions in laboratory. Actually the physical conditions of laboratory plasmas are very far from the astrophysical ones. In this sense, for a correct evaluation of the screening effects two essential considerations must be done: the extrapolation of the total cross section must be evaluated as close as possible to astrophysical conditions (including the ES effect) and the cross section bare nucleus must be taken into account. In the last decade, indirect methods have

been developed aiming to measure the bare nucleus cross section in a low energy domain (of astrophysical interest)[1]. The total cross section is generally extrapolated from high-energy direct measurements [2] performed by a low-energy particle beam incident on solid or gaseous targets. However these methods do not take into account the effects of plasmas.

In laboratory, plasma can be generated through several methods. The study of the fusion cross sections and the respective evaluation of ES influence, can be obtained through the investigation of nuclear reactions in plasmas generated by focusing the laser pulses at a high-medium power density regime on solid or gaseous targets. By following a methodology largely employed in plasma physics, it is possible to rescale plasma parameters (e.g. temperature and density) in order to make more similar to the real world our laboratory conditions. In our laser generated plasmas, in fact, the classical Debye screening factor (it depends somehow by the temperature over density ratio) becomes comparable with the one of the solar core. Laser Induced Plasmas (LIP) have a non-stationary nature, and their lifetime, depending on the experimental conditions, expires within few microseconds. However the tuneable experimental conditions (laser energy, pulse duration, ambient gas type and pressure, target type and composition etc.) lead to the generation of ions with thermal energies on the order of 100 to 1000 eV, and to the generation of electrons having thermal energies below 10 eV. The above mentioned energy regime opens the way to a new and interesting scientific scenario for the study of fusion reaction rates; in fact, it is well known that, from the classical Debye-Hückel theory, the effects of ES becomes important with increasing electron density and with decreasing electron temperature.

Typical expected plasma parameters, assuming laser power intensities $I > 10^{12} \text{ W/cm}^2$ are: supersonic expansion of the plasma plume with ion temperatures of several hundreds of eV, and densities around $10^{20} - 10^{21} \text{ cm}^{-3}$.

Preliminary calculations about the total number of fusion reactions are reported in [5], assuming a parametrization of the initial plasma temperature and density and following the evolution of such parameters by

means of an improved version of the “one fluid” hydrodynamical model of Anisimov *et al.* (1993) [3].

In this work we present an updated version of a numerical code which easily evaluates the 3D fusion rates, and finally the number of expected fusions per laser shot, including the electron screening. The new model predictions about the dependence of the plasma temperature and density on time, on the initial laser energy (fluence) and on type of ablated material are in good agreement with the experimental data collected in our laboratory during the last year [4].

THEORY AND MODEL

Among the various treatments existing in literature about fusion reactions (E. Rolfs and W.S. Rodney, (1998) [7]), we used the Gamow theory, which includes the tunnel effect of the nuclear Coulomb barrier. The reaction rate is then defined as:

$$\langle \sigma v \rangle = \left(\frac{8}{\pi \mu} \right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty S(E) \exp \left[-\frac{E}{kT} - \frac{b}{E^{1/2}} \right] dE$$

where $E = 1/2 m_r v^2$ is the energy of the particles pair with reduced mass m_r and relative velocity v , assuming a Maxwell Boltzmann distribution with temperature T . $\mu = m_r/m_p$ and $\sigma(E)$ can be obtained by the Gamow theory with an energy value $E_G = b^2 = (2\mu) \pi^2 e^4 (Z_1 Z_2 / \hbar)^2$; here Z_1 and Z_2 are the atomic numbers of the pair and $S(E)$ is the astrophysical factor.

For non resonant reactions $S(E)$ varies smoothly with energy and it can be developed in Mc-Laurin series, stopped at the quadratic term. By considering the d-d reaction, one obtains $S(0) = 0.05 \text{ MeV } b$, $S(0)' = 0.0183 \text{ } b$, $S(0)'' = 4.24 \text{ MeV}^{-1} b$ (NACRE website [6]). Therefore, assuming that the plasma is made of identical particles, the total number of fusions will be:

$$f_{TOT} = \frac{1}{2} N \langle \sigma v \rangle \int_0^\infty \rho(t) dt$$

where N is the total number of particles in the plasma and $\rho(t)$ is the plasma density. Note that f_{TOT} depends on the density and the temperature variation in space and time (in laser produced plasmas they both strongly vary, spatially and temporally), other than on their absolute values.

Hence eq. 2.2 must be discretized over small 3D cells in which density and temperature are evaluated step by step from the hydro-dynamical code. Time intervals of 0.5 ns have been chosen, integrating over $300 \times 300 \times 300$ cells, each one having a volume of $10 \times 10 \times 10 \text{ } \mu\text{m}^3$. ρ and T have been determined by the equations:

$$\rho(x, y, z, t) = \frac{M}{I_1 XYZ} \left[1 - \frac{x^2}{X^2} - \frac{y^2}{Y^2} - \frac{z^2}{Z^2} \right]^{\frac{1}{\gamma-1}}$$

$$T(x, y, z, t) = \beta \frac{\gamma-1}{2\gamma} \frac{m_p}{k_B} \left[\frac{X_0 Y_0 Z_0}{XYZ} \right]^{\gamma-1} \left[1 - \frac{x^2}{X^2} - \frac{y^2}{Y^2} - \frac{z^2}{Z^2} \right]^{\frac{1}{\gamma-1}}$$

where I_1 , β , γ , m_p , k_B are parameters connected with the adiabatic expansion of the plume, and X , Y , Z are the coordinates of the plasma front at a given time t , which can be calculated by the following set of second order differential equations:

$$\xi \frac{d\xi^2}{d\tau^2} = \eta \frac{d\eta^2}{d\tau^2} = \left(\frac{\sigma}{\xi^2 \eta} \right)^{\gamma-1}$$

where $\xi(t) = X(t)/R_0$, $\eta = Z(t)/R_0$, $\sigma = Z(t)/R_0$; $\tau = t/t_0$ denote the spatial and temporal dimensionless coordinates, and Z_0 , R_0 are the plasma dimensions at the end of the laser pulse.

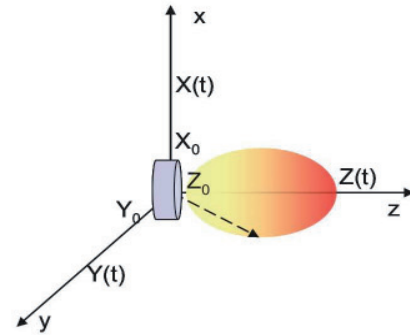


Figure 1: Sketch of plume expansion.

The model assumes a self-similar, iso-entropic expansion of the plasma plume, whose shape is half-ellipsoidal at $t =$. In our calculations we set $T_i \approx T_e$, with initial temperatures $T_{i0} \approx 450 \text{ eV}$ and $T_{e0} \approx 45 \text{ eV}$. This assumption is in agreement with empirical data; at power intensities comparable with the simulated ones, far from the target (i.e. in the free flight region) it is $T_i \leq 10^2 \text{ eV}$ (these numbers are consistent with our initial condition if one considers the adiabatic cooling, which goes like $T \propto \rho^{\gamma-1}$); T_e may be determined by optical emission spectroscopy or electrostatic probes, and it is usually a factor 5 to 10 lower [9]. This discrepancy is mostly due to the plasma acceleration mechanism, partially driven by self-generated electric fields. The resulting velocity of the moving plume is too small to give any appreciable contribution to the electrons' kinetic energy (because of their small mass), but large enough to give a contribution to the ion energy content, that is even larger of the electrons thermal energy (collisional temperature equalization should give $T_e \approx T_i$). The ordered, forward peaked energy of the ions is then transformed by the ion-

ion collisions in thermal motion, finally resulting in an effective ion temperature $T_i \gg T_e$.

The initial plasma density (that resulted to be around 10^{21} cm^{-3} , assuming the validity of the quasi-neutrality condition $\rho_e \approx \rho_i$) was self-calculated by the code, assuming a laser pulse of duration $\tau_L = 6 \text{ ns}$ and spot diameter of $200 \mu\text{m}$ impinging on a CD_2 thick target. Once known the temporal variation of ρ and T , the electron screening enhancement factor was calculated according to the well-known Debye-Hückel formula (Salpeter, 1954 [8]):

$$f_{scr} = \exp\left(\frac{Z_1 Z_2 e^2}{k T_e \lambda_D}\right)$$

where λ_D is the Debye length and T_e the electron temperature.

RESULTS

Data coming from simulations are reassumed in figures 2 and 3. Figure 2 shows the screening factor evaluated for the 3D plasma plume which is expanding in vacuum: f_{scr} smoothly varies either in time and along the spatial coordinates; this occurs because the ratio ρ/T remains almost unvaried, although ρ and T rapidly drop during the plasma expansion. The above mentioned discrepancy between electron and ion temperatures confers to laser generated plasmas at medium-low power intensity the unique property to have high enough ion temperature to favourite a consistent number of fusion events, but low enough electron temperature to ensure a non negligible screening factor.

About the absolute numbers, simulations results reported figure 3 reveal that if the laser is operated in the repetition rate mode (10 Hz), after 24 hours the accumulated number of fusion is increased of a factor 1.2 by the electron screening. The cumulated amount of fusion events overcomes 10^8 . Note that almost the totality of the fusion events takes place in the first 2-3 ns after each laser pulse (see figure 4). The calculated screening factor is very similar to the stellar ones [7].

The collected data put in evidence that an experiment with a deuterated target, and 4π detectors for fusion products like neutrons, is possible and physically meaningful; the strong temporal concentration of the significative events will help to adequately trigger the acquisition system, improving the experimental precision. The forecasted experiment will give the opportunity to calculate the electron screening in a stellar-like environment, to test the validity of the classical Debye-Hückel theory and finally to evaluate the astrophysical factor at energy domains of the order of hundreds of eV, never explored up to now by nuclear astrophysics.

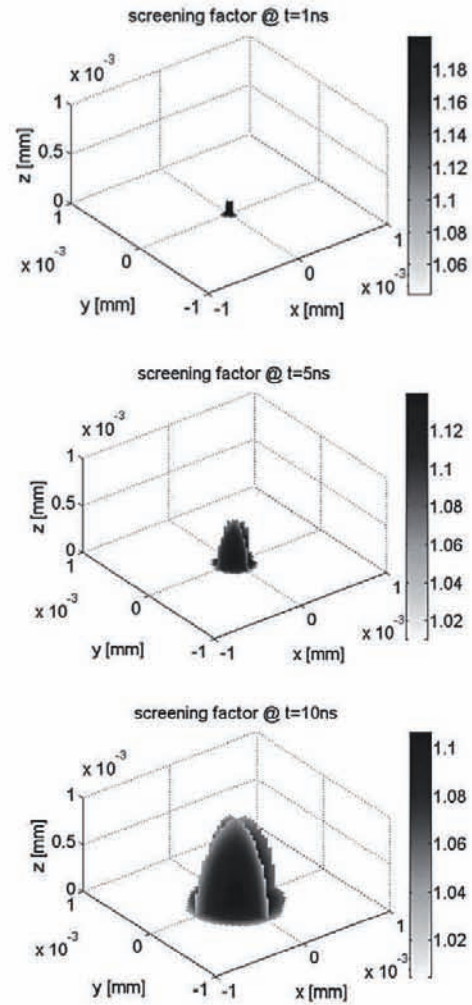


Figure 2: 3D calculation of the screening at different times after the laser shot.

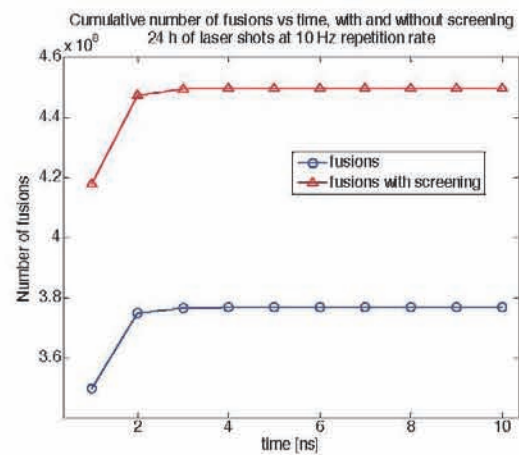


Figure 3: Cumulative number of fusions vs time, with and without screening collecting 24 h of laser shots at 10 Hz.

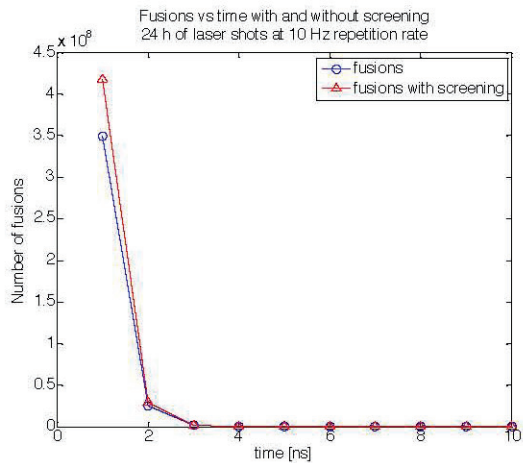


Figure 4: Cumulated number of expected fusion events versus the time elapsed from each laser shot.

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Dead time equations for time dependent sources

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Abstract - New equations for paralyzable, non paralyzable and hybrid DT models, valid for any time dependent sources are presented. We show how it's possible to correct DT losses in the case of time dependent sources. Montecarlo simulations were performed to compare the equations behaviour with the three DT models. Excellent accordance between equations predictions and Montecarlo simulation was found. We also obtain good results in the experimental validation of the new hybrid DT equation.

INTRODUCTION

Using an electronic signal counter, the Dead Time (DT) must be considered, to be sure that the measurement is free from losses or that the losses have been correctly calculated. Theoretical studies of the DT behavior are often used to infer the real amount of count rate from the measured one [1]. The greater part of literature has studied the DT influence on stationary sources [2] that is when the intensity variations of the source occur in time interval order of magnitude longer than the DT of the counter device. There are two elementary idealized models for DT, named paralyzable (P-DT) and non paralyzable (NP-DT). In the P-DT case all events occurring during the DT are not registered but are able to prolong the period during which the detector is not able to reveal further signals. In the NP-DT case, any event arriving during the DT is neither registered nor has any influence on the device. In the real equipments parallel or series combinations of these two kinds of DT can be found. One of the most important configuration is the hybrid model [3], a series of NP-DT followed by a P-DT, used for Geiger-Muller (GM) devices. Some studies have performed the analysis of short-lived time dependent source [4,5] but limited to the case of a well know shape dependency, for example in the case of decaying source with a single decay constant λ as $n(t)dt = (b + s_0 e^{-\lambda t})dt$, where n is the time dependent event rate, b is the constant background rate, s_0 is the starting pulse rate. Nevertheless there are many different types of source and many case in which such sources are mixed together in a non predetermined way or have a non predetermined shape. The relevance of this problem motivates the developing of complex electronic systems for DT compensation as reported in [5], but such complex solutions cannot be used in any condition. With our theoretical approach it is possible to evaluate the DT losses only by using a data

analysis process, apart from the time dependence of the source, and without the necessity of developing complex electronic systems.

MANUSCRIPTS

The goal of our study is to extend the dynamic range of our imaging device developed by using SPAD technology [6], and, in particular, passive quenched SPAD. The diodes used have been previously described [7], the DT configuration is hybrid model like, the total DT is 970 ns, 660ns NP-DT and 310 ns P-DT. As a reference counter a commercial active quenching device with 50 ns of NP-DT was used. As a matter of fact at the maximum rate used in our experimental setup this device can be considered free from losses. We realized a modulated light source using a commercial Light Emitting Diode (LED) powered by a pulse generator, model PB-4. The shape of the light source obtained is defined by an exponential grow, with a selectable characteristic time between 0.05 μ s and 10 μ s, and an exponential fall down with a selectable time between 0,5 μ s and 1,000 μ s. Both counter devices were contemporaneously enlighten by the same light source. The duration of the acquisition was 35 μ s and, to increase the statistics, about 10E6 run have been performed. The readout system has been designed to obtain a histogram of the measured count rate vs. time, with a time bins of 10 ns, even if the acquisition time precision is 0.1 ns.

NEW DEAD TIME EQUATIONS

Non Paralyzable Dead Time

As said, the signals that arrive during the NP-DT interval after a detected signal are lost. In the case of NP-DT the total inactive time of the sensor can be calculated by multiplying the measured count rate (m) and the DT extension (τ_{np}). The losses count rate are the real incident rate (n) in the total inactive time. So in this case the measured count rate is related to the real incident rate by the equation:

$$m = n \cdot (1 - m \cdot \tau_{np}) \quad (1)$$

that can be rewritten as:

$$m = \frac{n}{1 + n \cdot \tau_{np}} \quad (2)$$

Eq. 2 is the commonly used equation to describe the NP-DT regime [1]. This equation is valid for constant rate sources, while in the case of time dependent sources the

count rate m and n are functions of the time. Starting from this consideration we determine an equation valid for a time dependent count rates. We divide the total time in intervals of duration Δ and consider the average rate in each interval so obtaining two series of values m_i and n_i . With this time division the duration τ_{np} turns into a number T_{np} of intervals. For example, if it is $\tau_{np} = 500$ ns and the interval duration $\Delta = 10$ ns, then $T_{np} = 50$. Since the NP-DT losses are due to the measured counts in the previous DT interval (τ_{np}), to evaluate the measured rate in the i -th interval we sum the contribute of all the previous T_{np} measured rate values. Due to the finite duration of the i -th interval we must also consider the DT losses inside the same interval. The count rate at the end of the interval suffer of the losses due to the previous rate measured inside the same interval, whereas the rate at the first part of the interval are not influenced by the following part of the interval. So evaluating the average losses produced inside the interval, we obtain that the i -th interval must be considered like a source of DT losses, but half weighted. Applying these considerations to Eq. 1 we obtain:

$$m_i = n_i \cdot \left(1 - \left[\sum_{t=i-T_{np}}^{i-1} m_t + \frac{m_i}{2} \right] \cdot \Delta \right) \quad (3)$$

A deeper analysis of this equation allows to solve the problem of hybrid DT model. Inside the Eq. 3 we can separate the lost rate due to the NP-DT (L_{np}) from the original true rate n , being:

$$m_i = n_i - L_i^{np} \Rightarrow L_i^{np} = n_i \cdot \left[\sum_{t=i-T_{np}}^{i-1} m_t + \frac{m_i}{2} \right] \cdot \Delta \quad (4)$$

The quantity is characteristic of the DT type (np) and varies with the time position of the i -th interval. Eq. 4 shows that the lost rate is the incoming true rate multiplied by the probability of a measured event in the previous τ_{np} time interval.

Paralyzable Dead Time

Using the exponential distribution of time intervals between Poissonian random events occurring at a constant rate n , it is possible to show that the relation between measured rate and true rate in the case of P-DT is [1]:

$$m = n \cdot \exp(-n \cdot \tau_p) \quad (5)$$

In the case of time dependent count rate the two values of the true rate n appearing in Eq. 5 are different: the first one represents the true actual rate, the latter represents the true rate in the previous time intervals, source of DT losses. Taking into account the contribute of all previous T_p intervals, and half weighting the i -th interval as in the case of NP-DT previously analyzed, we obtain the equation:

$$m_i = n_i \cdot \exp \left(- \left[\sum_{t=i-T_p}^{i-1} n_t + \frac{n_i}{2} \right] \cdot \Delta \right) \quad (6)$$

Where T_p is the number of intervals contained in τ_p .

As before, we can separate the lost rate due to the P-DT (L_p) from the original true rate n :

$$L_i^p = n_i \cdot \left(1 - \exp \left(- \left[\sum_{t=i-T_p}^{i-1} n_t + \frac{n_i}{2} \right] \cdot \Delta \right) \right) \quad (7)$$

Hybrid Dead Time

In the hybrid DT model, introduced by Lee and Gardner [3], the DT configuration is a combination of P-DT and NP-DT. In constant regime the relation between true and observed count rates for this model is:

$$m = \frac{n \cdot \exp(-n \cdot \tau_p)}{1 + n \cdot \tau_{np}} \quad (8)$$

A detailed description and the derivation of this equation can be found in [3].

The count that arrives at the i -th interval generates a NP-DT followed by a P-DT, as shown in Figure 1(A). The two DT durations could be different.

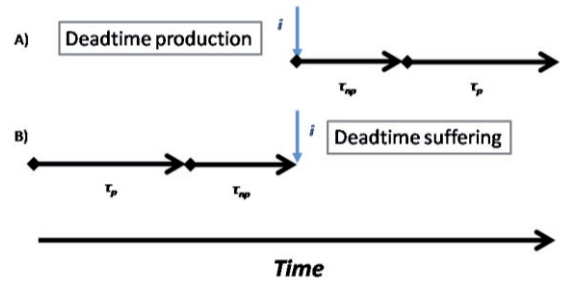


Figure 1. (A) Structure of the two DT produced in a hybrid DT model. (B) Time intervals rate that produces losses into the following i -th instant and type of DT losses actuated.

In the time dependent count rate, we must consider which previous intervals produce losses into the i -th interval and the type of the actuated DT losses. Due to the sequence of produced DTs reported in Figure 1B, the rates located inside the interval τ_p produce P-DT losses, while the rates located inside the interval τ_{np} produce NP-DT losses. Once identified the type losses produced by each previous interval we can write the equation for hybrid model valid for time dependent sources, starting from Eqs. 4 and 7:

$$m_i = n_i - L_i^p - L_i^{np} = n_i - n_i \cdot \left(1 - \exp \left(- \left[\sum_{t=i-T_p}^{i-1} n_t \right] \cdot \Delta \right) \right) - n_i \cdot \left[\sum_{t=i-T_{np}}^{i-1} m_t + \frac{m_i}{2} \right] \cdot \Delta \quad (9)$$

Note that the i -th interval generates NP-DT losses, so it must be considered only in the non paralyzable part of the equation. The symbol “*” indicates that last i -th term of Eq. 7 is not considered.

MONTECARLO SIMULATIONS

A code, developed in Matlab, was performed to simulate the behavior of the three DT types. We found that, in this simulation approach, a sharp increase of the

illumination from zero to a constant value, gives best information about the DT losses and the equation validity. The predictions of the three proposed equations (Eqs. 3, 6 and 9) were compared with the results of the simulation.

We chose that the illumination value started with zero and remained zero for a time interval longer than DT. In this way Eqs. 3, 6 and 9 can be calculated in an iterative mode ($i=t_0$, $i=t_0+1$, $i=t_0+2$, $i=\dots$), starting from the end of a zero illumination period, characterized by measured (m_i) and true rates (n_i) both equal to zero.

Montecarlo simulation uses the Poisson statistics to generate the source count distribution, and the DT laws to determine which counts are measured and which counts are lost. In the zero illumination zone no count is introduced. In the constant illumination region a Poisson distribution was used to extract the random values of photons that should be put into the illumination time window. The time position of these photons was randomly chosen inside the illumination time window. The histogram of the simulated photon source count rate is shown in Fig. 2. For the three DT simulations the three DT creation laws are used to determine the counted photons, the lost photons that arrive into DT, and the photons that produce or extend DT. Like in experimental setup, $1E6$ acquisition windows were simulated. The histograms of this three DT simulations are reported in Fig. 2. The time unit of the simulation is the interval duration $\Delta = 10$ ns, the total DT extension was chosen of 105Δ for all three simulations.

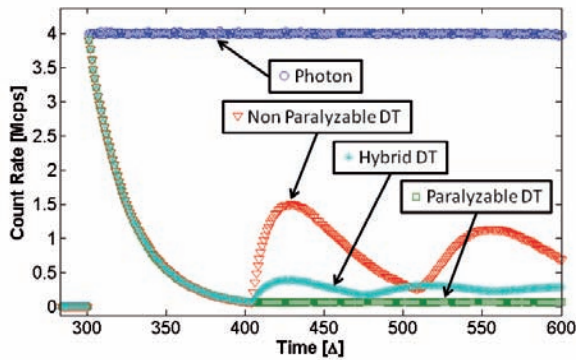


Fig. 2. Histograms of rate vs. time; blue circle, simulated photon source rate; dark green square, P-DT model simulation; red triangle, NP-DT model simulation; cyan asterisk, hybrid DT model simulation.

The agreement between the simulations and the data calculated with the Eqs. 3, 6 and 9, is better than expected, being deviation less than 0.2%. The equation predictions are not plotted in Fig. 2 because they overlap the simulation data.

In the simulation, the first 300Δ are defined without photons, after that the illumination source starts with a constant rate. In the following 105Δ , corresponding to the total DT duration, the shape of the three DT types are the same, because in this period, independently from the type of the occurring active DT, only one photon can be detected. Therefore this first part of the histogram shows

the arriving time position of the first photons. This shape represents the probability to have no photon in illumination condition. This probability drastically decreases on increasing the time. After a time equal to the total DT the type of DT generates changes in the shape of the response. The P-DT that takes into account all lost counts shows a constant output rate, due to the constant lost incoming rate. The NP-DT shows an increase of counts due to the end of the DT of the first measured count not extended by the others photons. The hybrid model shows a behavior in the middle of the two fundamental DT types, according to the proportion of the DT component of hybrid model.

The P-DT reaches the steady-state value of Eq. 5 after the first DT period, while the other DT types need few DT periods to reach their steady-state values, predicted from Eqs. 2 and 8. This is an important confirmation of the simulation goodness.

EXPERIMENTAL VALIDATION

To test the features of the proposed new hybrid DT Eq. 9 we used a Light Emitting Diode powered by a voltage which grows according to an exponential shape with a $0.05 \mu s$ time constant, and that falls down with a $100 \mu s$ time constant. The maximum photon rate that hit the detectors was about 500 kcps. The test device was a passive quenched SPAD with a measured 970 ns total hybrid DT [7]. In a constant illumination setup, at 500 kcps of photon rate, this device would be affected by 35% of losses. Instead the active quenching SPAD device, with a DT of 50 ns, at this rate can be considered free from losses, and it was used as reference counter.

Exposing the test device to a time dependent source we observed that the behavior changed with time (Fig. 3). At the beginning the device was affected only by the negligible DT losses produced by the previous darkcount rate, 1 kcps, so the measured rate was very close to real one. Immediately after the measured rate fell down for the DT losses produced by the first detected rate. When the DT losses production reached the maximum value, the measured rate continued with a slope different from that produced by the reference counter.

The Eq. 9 describes the relation between the true and the measured photon rates. Starting from the Eq. 9 it is possible to extract the equations of real count rate and measured count rate, as a functions of previous true and measured count rates:

$$n_i = \frac{m_i}{\exp\left(-\left[\sum_{t=i-T_{np}-T_p}^{i-T_{np}-1} n_t\right] \cdot \Delta\right) - \left[\sum_{t=i-T_{np}}^{i-1} m_t + \frac{m_i}{2}\right] \cdot \Delta} \quad (11)$$

$$m_i = \frac{n_i \cdot \left\{ \exp\left(-\left[\sum_{t=i-T_{np}-T_p}^{i-T_{np}-1} n_t\right] \cdot \Delta\right) - \left[\sum_{t=i-T_{np}}^{i-1} m_t\right] \cdot \Delta \right\}}{\left(1 + n_i \cdot \frac{\Delta}{2}\right)} \quad (12)$$

Assuming that during the dark state the count losses can be neglected, it is possible to evaluate the real true

rate from the measured one using the Eq. 11 and vice versa the measured rate from true rate using the Eq. 12. In Fig. 3B we compare the reference true rate with the predicted one using Eq. 11, and the measured rate affected by hybrid DT losses with the predicted one using the Eq. 12.

The difference between predicted and measured rate are in the first part of the light pulse because, due to the rapid change in the excitation rate, the device doesn't show exactly the hybrid DT behavior but something close. After a time double the DT duration the predicted and the measured rates show a very good agreement, being deviation less than 5 %.

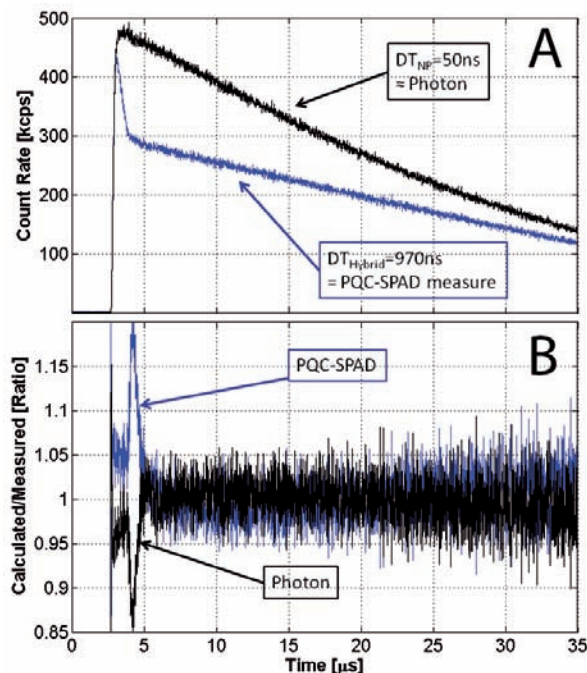


Figure 3. (A) black, true count rate, measured with active quenched SPAD; blue, measured count rate that suffer Hybrid DT losses (passive quenched SPAD). (B) Comparison between calculated rate and measured one; blue, calculated with Eq. 12; black, calculated with Eq. 11.

CONCLUSION

The presented new approach for evaluating DT losses is able to show how the two elementary DT types and their combination works with time dependent sources. The theoretical derivation, the completely accordance with the Montecarlo simulation, the inclusion of classic DT equation, and the experimental validation are a well-round presentation of this three new equations, that could be useful in all counting system devices and applications. Worth to note that our DT compensation technique

requires only a simple data analysis process, apart from the type of time dependent source and without the necessity of developing complex electronic systems.

Our theoretical approach can be also useful to deduce new equations for other series or parallel combinations of P-DT and NP-DT. The presented equations can be also used to predict the behavior of many devices in time dependent applications, so allowing to select the most appropriate device.

In particular we plan to use this technique in the development of a new time resolved single-photon imaging sensor (TRIS) [6], which uses passive quenched SPAD devices and shared readout channels for many diodes. Using a passive quenched SPAD device, instead of active quenched one, we increase the fill factor of the device and using the presented correction technique we take advantage from the DT losses that characterize this device. In fact, especially in scared readout configuration, the reduced measured rate due to the DT losses allows to not saturate the readout electronics.

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Proton generation from LIS at INFN-LNS (LIANA project)

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Abstract - The proton emission from laser-generated plasma is investigated in ambit of the LIANA (Laser Ion Acceleration for Nuclear Application) INFN project.

Hydrogenated targets are irradiated in high vacuum by laser pulses at intensities of the order of 10^{10} W/cm² in order to generate ion and proton emission.

The proton yield, energy and angular distribution, are analyzed through time-of-flight techniques.

A post acceleration system operating at 30 kV allows to accelerate the ions extracted form the LIS (Laser Ion Source) proportionally to their charge state.

Using 1-10 Hz laser repetition rates, proton currents in the order of 20 nA can be obtained.

The actual limitation for the proton current and energy is due to the used HV power supply.

INTRODUCTION

A LIS is becoming a system that for excellence allows to generate ions of each species, with high energy, charge state, current and direction. It can be used as ion source of many accelerator systems, because high flexible to produce any ion species, also for high boiling point elements, and to generate molecular and negative ions [1].

In particular, for the many applications in Nuclear Physics, a special attention is given to the proton and deuterium generation from hydrogenated targets.

To this aim special targets based on polymeric materials and on hydrates can be laser irradiated to produce non - equilibrium plasmas rich in hydrogen, to extract high energy and current protons and to post-accelerate these ions to higher energies.

By using laser pulse intensities of the order of 10^{10} W/cm², generally the ablation yield is of the order of $\mu\text{g/pulse}$ [1,2]. For polymeric targets this value corresponds to a yield of about 10^{16-17} ions/pulse and to production of about 10^{16} protons/pulse. Thus, operating at 10 Hz repetition rate a LIS may generate a proton current density higher than about 10 mA/cm² [3].

At this used laser intensity regime the target is thick and the plasma is generated in backward direction, while at intensities above 10^{15} W/cm² more directive and hot

plasmas can be produced in backward and forward directions. In these cases proton energies higher than 1 MeV can be produced without use of the post-acceleration systems [4, 5].

The interest for deuterium production from LIS and the D-D reaction induced by low energetic ions is described as one of the possible applications of the LIANA project.

EXPERIMENTAL SECTION

A Nd:Yag laser operating at 1064 nm at fundamental wavelength, 9 ns pulse width and 0.9 J maximum pulse energy, is employed to irradiate hydrogenated targets placed in vacuum (10^{-6} mbar). The incidence angle of the laser beam is 30° and the ion diagnostics are placed along the normal to the target surface.

Polyethylene based polymers, with different absorbing doping (carbon nanotubes CNT, Fe₂O₃ nanostructures, metallic powders,...) and metallic hydrates, such as TiH₂, were employed as 1 mm thick target.

The accelerating setup adopted for this experiment is reported in Fig. 1.

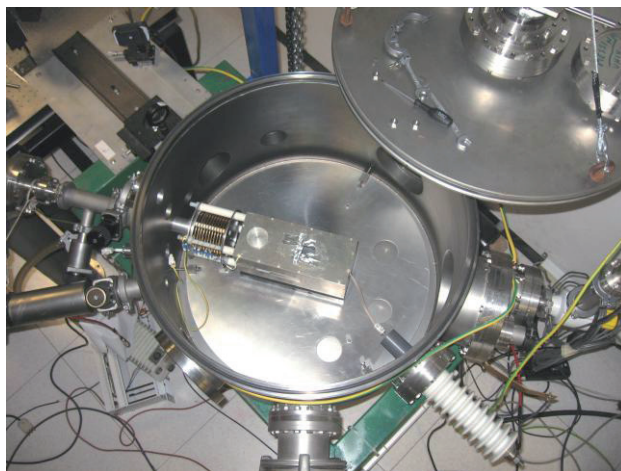


Fig. 1: Experimental set-up of LIANA at INFN-LNS.

It consists of a plasma expansion chamber, with a parallelepiped shape, at the centre of which is placed the

target, which is laser irradiated through a lateral input hole. Target and expansion chamber are placed at the same electrical potential, which can be set between 0 and +30 kV by a high voltage power supply (Heinzinger, 30 kV- 200 mA).

In order to permit the ion to exit along the longitudinal chamber axis, the frontal base of the parallelepiped chamber is opened by 8 mm diameter hole. Here 12 metallic disks, connected to the HV through different electric resistances, are aligned parallel along to the chamber longitudinal axis in order to distribute 30 kV on a distance of 60 cm, as described in a previous work [6].

The simulation code OPERA 3D [7] has demonstrated that only about 10 % of the total emitted ions from the target go through the collimator holes of the aligned disks and is submitted to the post acceleration process.

This current limitation, confirmed by the experimental measurements, is necessary in order to reduce the number of accelerated ions that may cause a voltage decrement of the HV power supply, due to possible arcs formation in the acceleration zone.

A ring ion collector (ICR) is fixed along the normal to the target surface (the direction of the maximum ion acceleration) at a target distance of 150 cm. TOF technique is employed by using as a start signal that of a photodiode detecting the laser shot, and as a stop signal that coming from the ICR detector. Signals are recorded on a fast Tektronics storage oscilloscope with 500 MHz frequency, 2 Gs/s sampling velocity and 50 Ω input resistance.

An electrostatic ion energy analyzer (IEA) is employed to measure the energy-to-charge ratio of the detected particles emitted from the plasma after their acceleration along the normal to the target surface. IEA spectrometer electro-statically deflects the ions by 90°, so that they are detected by means of a windowless electron multiplier (WEM). The first WEM dynode is 220 cm from the target, and TOF technique is employed for the ion energy measurements. Ion charge states and ion energy distributions were investigated with IEA, as reported in literature [8].

A Thomson parabola was also employed to analyze the produced low multi-energetic and multi-species ion beams at LNS. It consists of two ion input pin-holes at 10 cm distance, one of 1 mm and the other of 0.2 mm in diameter, followed by two polar expansions at 2000 Gauss magnetic field and to plate at 1 kV/cm electric field for the ion deflections. The cross-aperture of the magnetic field to the incident ions is 5 mm vertical and 25 mm horizontal and the magnet length is 25 mm; the electric deflection plates are parallel, 8 mm spaced and 25 mm long; the Thomson parabola focal plane, orthogonally to the target normal direction, is placed at 15 cm distance from the electric deflectors. A Gaf-chromic film dosimeter [9] is employed to record the ion parabola images on the focal plain.

A photo of Thomson parabola is reported in Fig. 2.

A surface profiler (Tencor P-10), with 1 nm and 1 μ m depth and lateral resolutions, respectively, is employed in

order to evaluate the crater volume produced by a known amount of laser pulses as a function of the laser fluence

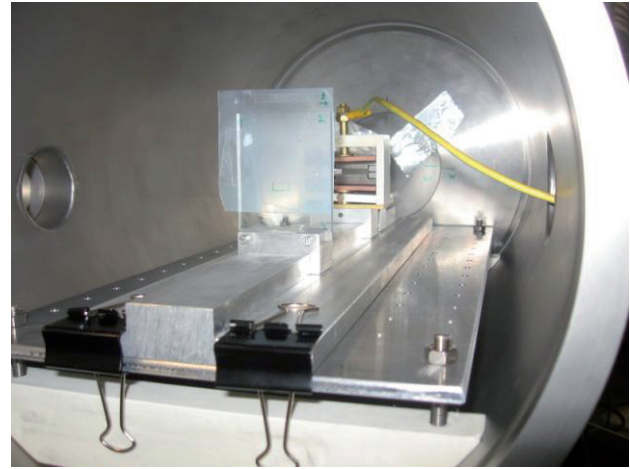


Fig. 2: The Thomson parabola set-up at LNS

(J/cm²). The measurement of the crater volume permits a precise calculation of the ablation yield in terms of removed atoms per single laser shot [10].

RESULTS

A typical IC spectrum relating to the ions emitted from the LIS by irradiating a TiH₂ target is reported in Fig. 3a.

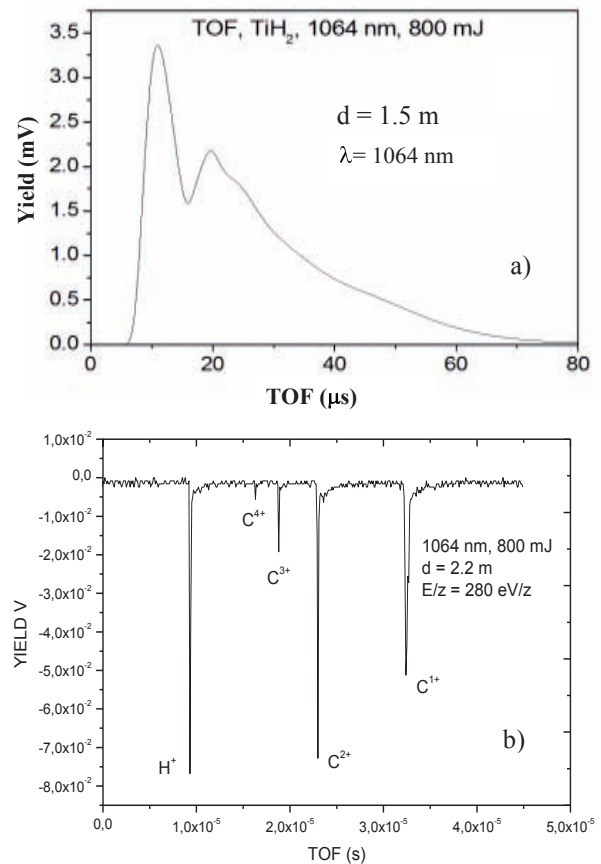


Fig. 3: Typical spectrum of IC (a) and IEA (b)

The spectrum shows a fast proton peak at an average kinetic energy of about 120 eV and a slower and large peak due to different charge states (up to 6+) of Ti atoms.

The Ti-peak corresponds to a kinetic energy of 1.4 keV. A typical IEA spectrum relating to the ions emitted from the LIS through irradiation of polyethylene target is reported in Fig. 3b. The spectrum shows a fast proton peak and four charge states of C ions at the E/z ratio of 280 eV.

At 800 mJ laser pulse the mean proton energy ranges between 100 eV for pure polyethylene to about 300 eV for polyethylene doped with 1% of Fe_2O_3 nanostructures.

At this used laser intensity the plasma temperature is about 10 eV for different targets, while the acceleration voltage, measured by the shift of the ion energy distributions, is about 100 V and the plasma density is of about $10^{16}/\text{cm}^3$. The mean proton yield in the investigated targets is of the order of 10^{10} protons/pulse. IC angular distribution measurements demonstrated that protons are emitted with an angular aperture of about $\pm 30^\circ$.

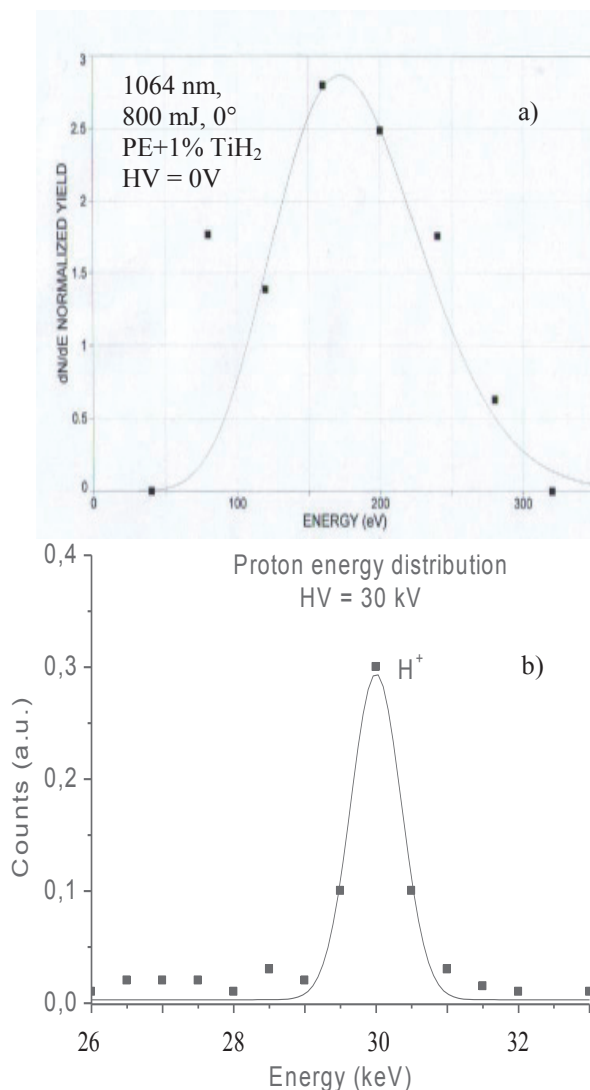


Fig. 4: Proton energy distribution ablation polyethylene doped with 1% TiH_2 without post acceleration (a) and with 30 kV post acceleration (b)

By changing the voltage of the IEA deflection plates it is possible to measure the ion energy distributions. As an example, Fig. 4a reports the proton distribution obtained by irradiating polyethylene with 1% TiH_2 doping. The experimental measurements (points) can be fitted with a "Coulomb-Boltzmann-shifted" distribution (line), as described by Torrissi's theory [11]. In this case the fit parameters, obtained by using the "Peakfit" code, give a kT temperature of 8 eV and a Coulomb acceleration voltage of 100 V.

The 30 kV post-acceleration system increases significantly the ion energy, proportionally to their charge state, thus in the case polyethylene ablation, for example, protons and carbon are accelerated at energies of 30 keV and 30 keV per charge state, respectively. The IEA analysis of the post accelerated proton beam demonstrated that the beam is well monochromatic with an energy straggling of about 3%, as reported in the experimental distribution of Fig. 4b.

The advantage of the Thomson parabola consists in the possibility to observe on its focal plane contemporary the different parabola shapes induced by ions having different energies, charge states and masses.

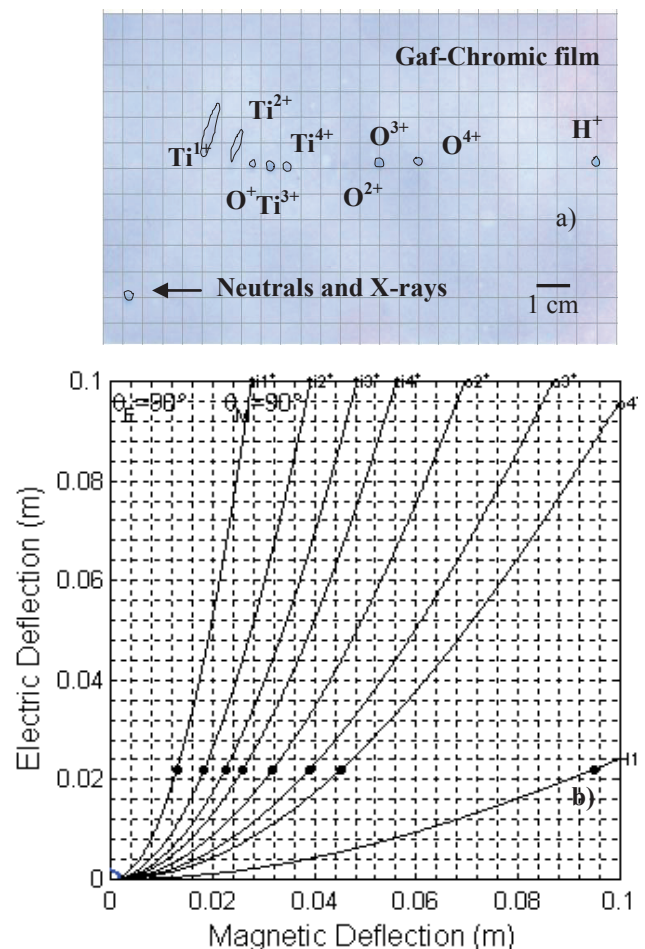


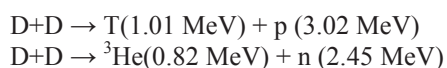
Fig. 5: Gaf-Chromic irradiated by 30 kV post-accelerated ions coming from a laser irradiated Ti target (a) and relative simulation plot (b).

Gaf-chromic detectors, employed in order to have a good contrast for parabola images, need to be irradiated by ions with energies above 10 keV. Thus Thomson parabola was employed only to monitor the post-accelerated ion beams. Fig. 5 shows a typical example of the images produced in the Gaf-chromic by 30 keV post-accelerated ions coming from a Ti target (a) and relative simulation plot (b). The image, obtained after 1000 laser shots at 10 Hz repetition rate, shows the presence of 30 keV protons, and four charge states of Ti and O ions (really Ti surface is rich of titanium oxide) with energies between 30 keV and 120 keV. The simulation plot puts in evidence the ion energies multiple of 30 keV (points) which are in well agreement with the experimental dots positions (blue points) reported by the film detector.

DISCUSSION AND CONCLUSIONS

The above describe experiments are using at LNS not only to prepare 30 keV protons and more energetic ions with high charge state but also to prepare 30 keV deuterium beams. To this aim, deuterated polyethylene (CD₂ monomer) targets are laser irradiated at 800 mJ pulse energy and at 10 Hz repetition rate and the produced ions are submitted to the post 30 keV acceleration system. Measurements are giving a deuterium yield of about 10⁹ D⁺/pulse, corresponding to an extraction current of about 2 nA.

This beam can be employed to induce D-D fusion reaction by irradiating a deuterated substrate, and to generate in equal probability protons and neutrons with an energy of 3.02 MeV and 2.45 MeV, respectively through the reactions [12]:



Each of these reactions have an equal fraction of branching. At 30 keV the cross section of the fusion reaction is low, it corresponds to 2 mbarns [10], but it is sufficient to induce a significant number of nuclear processes. By using a 10 micron thickness deuterated polyethylene film placed in front to a 300 mm² silicon surface barrier detector, with 100 micron depletion layer, and by irradiating the substrate orthogonally to its surface with 30 keV deuterium beam, it is possible to detect almost all generated protons. With our experimental set up, starting from the 2 nA deuterium current, the number of nuclear fusions generating 3.02 MeV protons corresponds to about 85 events/s.

This last represents only one of the numerous possible applications of the LIS and post-acceleration system to Nuclear Physics. In microelectronics other applications concern the surface implantation of the post accelerated ions which, at high doses, may change the physical and chemical properties (hardness, chemical reactivity, roughness, wetting ability, optical and electrical properties,...) of many materials [13]. In this field, the use of multi energetic and multi species ion beams

extracted from LIS and post accelerated may represent an advantage because simultaneously the implantation modifies different layer depths without change the energy and the specie of the traditional mono-energetic ion beam. In the field of Bio-medicine the laser ablation of biocompatible materials coupled to the LIS technique permits to deposit thin biocompatible films on the surface of different prostheses. Thin films of TiO₂, bioglasses, hydroxyapatite, calcium phosphates and carbon, for example, can be deposited very adherent to the substrate material thank to the action of the implanted ions [14].

Finally, the employment of the plasma extracted ion beams represents a powerful technique in order to investigate on Radiobiology effects of fast radiations inducing biological modifications due to very fast energy deposition in cells and tissues, a process which may generate non-linear phenomena with unexpected values of quality factors.

The increment of the post acceleration voltage up to 100 keV and of the extractible current density above 10 mA/cm² will permit to use this apparatus for other applications. Works are in progress in this direction.

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High intensity laser-generating plasmas in forward direction in thin films and Thomson parabola spectrometer monitoring

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Abstract - Asterix laser at PALS Laboratory of Prague, operating at 1315 nm fundamental wavelength, 300 ps pulse duration, 10^{16} W/cm² intensity and single pulse mode, was employed to irradiate thin hydrogenated targets placed in high vacuum. Non-equilibrium plasmas were obtained in forward direction, i.e. along the normal to the target surface on the rear of the irradiated thin films. Plasmas were monitored with different ion detectors, placed around the direction normal to the target. The main detector was a Thomson parabola spectrometer aligned along the normal in forward direction. This spectrometer permits to provide many plasma parameters concerning the involved ions (energy, charge state, mass, ...) obtained in a single laser shot. The spectrometer images, obtained by using a MCP coupled to a fast CCD camera, can be processed by a comparison with the simulation data obtained by a proper software. High ion energies and charge states have been obtained as a function of the laser parameters, target thickness and composition and irradiation conditions.

INTRODUCTION

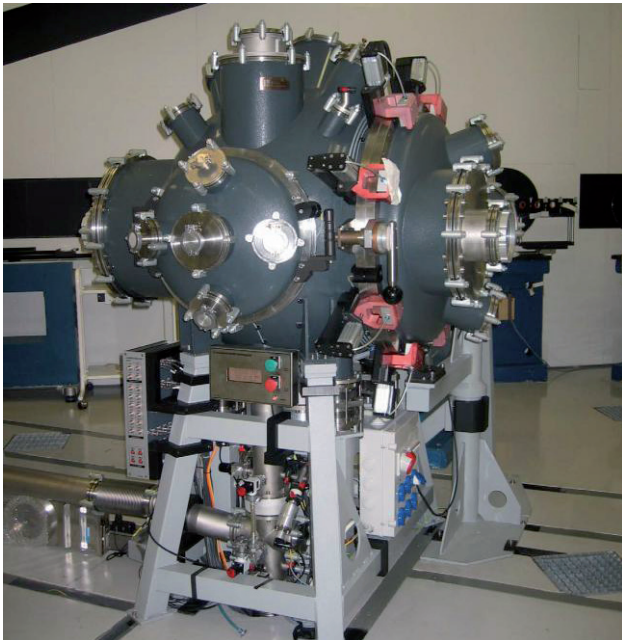
Ordinarily, at laser intensities of the order of 10^{16} W/cm², the laser pulse hitting thick targets generates plasma in the backward direction with respect to the target normal direction. Instead, by using thin target, of the order of 1 micron in thickness, the electrons, accelerated by the electromagnetic wave inducing ponderomotive forces, may cross the thin film permitting the generation of a spatial charge on the rear side of the target. The high positive charge in the film may induce Coulomb explosion with generation of plasma astride in backward and in forward directions.

In recent years, there has been a renewed interest in laser-driven ion acceleration due to the availability of high-intensity laser pulses with sub-picosecond duration, made possible by the introduction of chirped pulse amplification (CPA). Proton acceleration to tens of MeV energy and in low divergent beams of excellent quality has been demonstrated [1]. Heavier ions have also been observed, with energies up to hundreds of MeV [2]. Although this mechanism known as "Transverse Normal Sheath Acceleration (TNSA)" is employed with fs lasers at intensities of the order of 10^{20} W/cm², its investigation at lower intensities is interesting in order to understand the involved physical mechanisms responsible of high ion acceleration, up to kinetic energies above some MeV/charge state, and the threshold of occurrence of this peculiar phenomenon. The ions are produced in short bunches of high brightness with a measured efficiency of conversion from laser energy to ions as high as 12% [3].

To this, experiments were performed at PALS Laboratory of Prague [4], by using the 10^{16} W/cm² Asterix laser irradiating thin targets with different composition. In this paper, we discuss the aspects of our present understanding of the mechanisms leading to ion acceleration in the interaction of high-intensity laser pulses with thin foil targets, and highlight examples of some of the recent progress made in this research area near the threshold of occurrence for plasma forward generation. More properly, we discuss the influence of the laser pulse on ion acceleration with a special regard given to the proton acceleration, the ion stream more investigated in these last years due to its multiple employments in different scientific fields such as Medicine, Microelectronics, Radiobiology, Nuclear Physics and Astrophysics, where MeV protons represent the main MeV beam to be employed in different manners.

EXPERIMENTAL SECTION

The experimental studies were performed with the fundamental harmonic ($\lambda = 1.315 \mu\text{m}$), with laser energies up to 500 J in a pulse length of about 300 ps (laser intensity up to $5 \times 10^{16} \text{ W/cm}^2$, at 0° incidence angle, 80 micron spot size and at variable focus positions with regard to the target surface).



PALS

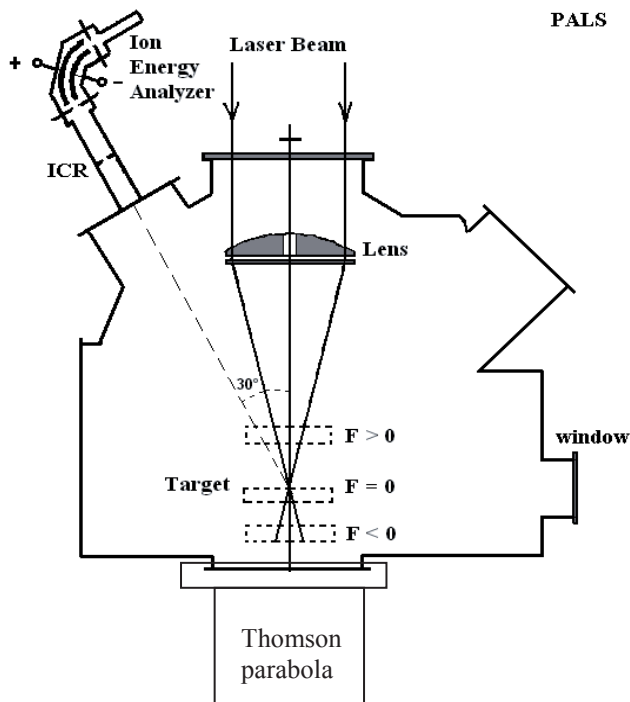


Fig. 1: Photo (upper) and scheme (bottom) of the experimental set-up at PALS Laboratory.

The vacuum chamber and a schema of the experimental arrangement are reported in Fig. 1a and 1b, respectively.

The produced ions were detected with a time-of-flight (TOF) technique at the angle of 30° , both in forward and in backward directions by using more of 20 kind of different devices like ring ion collectors (ICR), electrostatic deflection ion energy analyzer (IEA) and semiconductor SiC detectors [5, 6].

The ion emission in forward direction along the normal to the target surface was investigated through a Thomson parabola (TP) using a multi-channel-plate and a fast CCD camera to acquire the images [7]. Generally TP uses a magnetic and electric deflection with the values of 0.1 T/3.4 mm and 3kV/20mm, respectively.

Fig. 1 shows a photo and a schema of the employed experimental set-up at PALS laboratory.

Polymers arise from polyethylene, with different absorbing doping (carbon nanotubes CNT, Fe_2O_3 nanostructures, metallic powders,...), metals (Al, Au, Ti, Pd,...) and metallic hydrates, such as TiH_2 , were employed as thin films (thickness lower than $10 \mu\text{m}$) to be irradiated along the normal to their surface.

An expressly designed holder was employed in order to monitor the initial position of the plasma formation with a X-ray streak camera as a function of the different laser focal position (F). Negative focal position means that the laser is focused in front of the target surface and positive focal position that it is focused behind the target surface. Fig. 2 shows a photo of the TP spectrometer (a) and of the thin holder system during the target preparation (b).

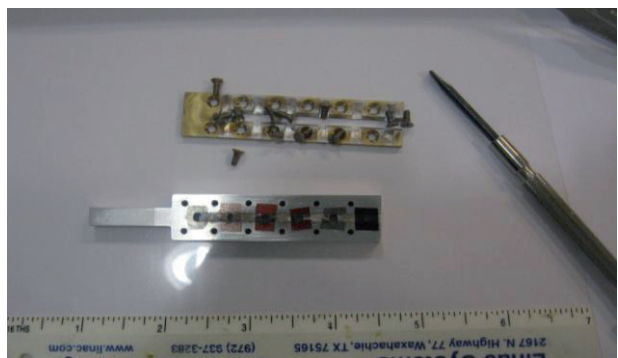
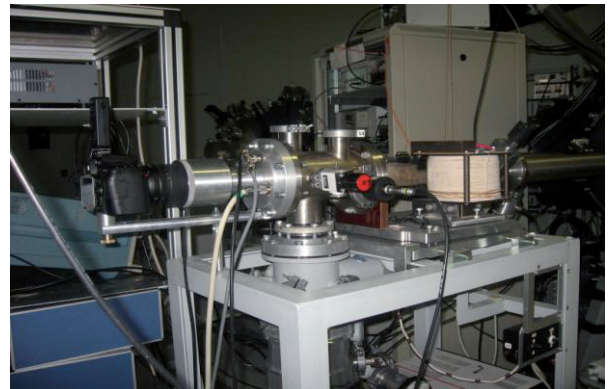


Fig. 2: Photo of the TP spectrometer (a) and of the thin holder system (b).

RESULTS

Two typical Thomson parabola spectra are reported in Fig. 3 concerning the forward plasma produced by single laser shots at a laser irradiation of 530 J pulse energy and -100 μm focal position, hitting 2.5 μm target thickness of gold (a) and 7 μm thickness of polymethylmetacrylate (PMMA) containing 1% carbon nanotubes (CNT) (b), respectively. The first TP is acquired with 0.056 T magnetic and 3kV voltage deflection; the second TP with 0.2 T magnetic and 3 kV voltage deflections.

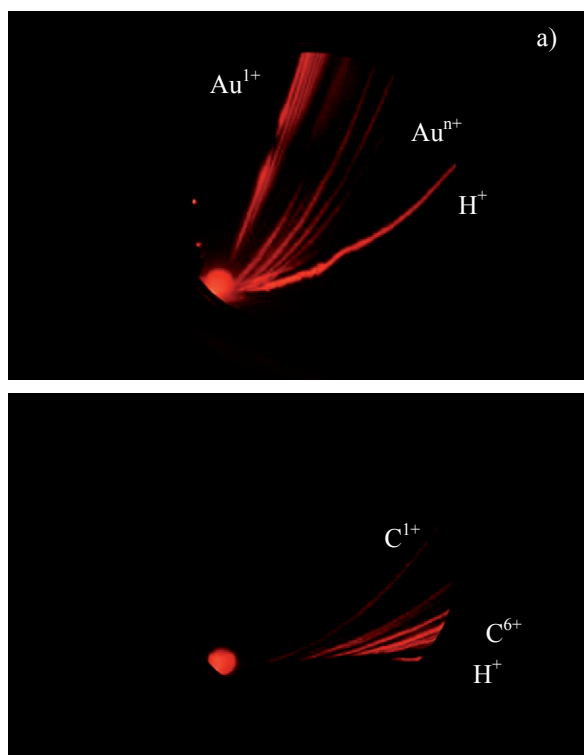


Fig. 3: TP images of the ions ejected from a plasma generated by 500 J laser pulse, -100 μm focal position, irradiating 2.5 μm thickness of Au (a) and 7 μm of PMMA(1% CNT) (b).

The figures, reporting in horizontal scale the magnetic deflection and in vertical scale the electric deflection, show the proton and the Au and C ion parabolae in agreement with a ratio between their charge state and momentum for the parabola's trend on X-axes and as a function of their charge state and kinetic energy for the electric deflection.

The minimum approach between the proton parabolae and the circular spot due to the X-ray detection is correlated to the maximum proton energy. In these two cases the maximum proton energy is approximately of about 1.5 MeV and 1 MeV, respectively, as confirmed by the code simulation obtained for the investigated plasmas and reported in the plots of Fig. 4a and 4b.

The maximum proton energy and the other ion energies and charge states were controlled simultaneously also by IC, SiC and IEA spectrometer. In particular the ICR

collector, placed along the normal to the target surface, subdivided in four sectors, permits to measure very well the proton energy by the TOF spectra comparison acquired through different Al absorbers (0 μm , 2.4 μm , 4.8 μm and 8 μm). The absorbers have the aim to decrease the background due to the fast photopeak and slower ions, in order to measure with precision the kinetic energy of the proton streams, such as reported in the spectrum of Fig. 5 indicating 3.1 MeV maximum proton energy ejected from a SiH target irradiation at 490 J pulse.

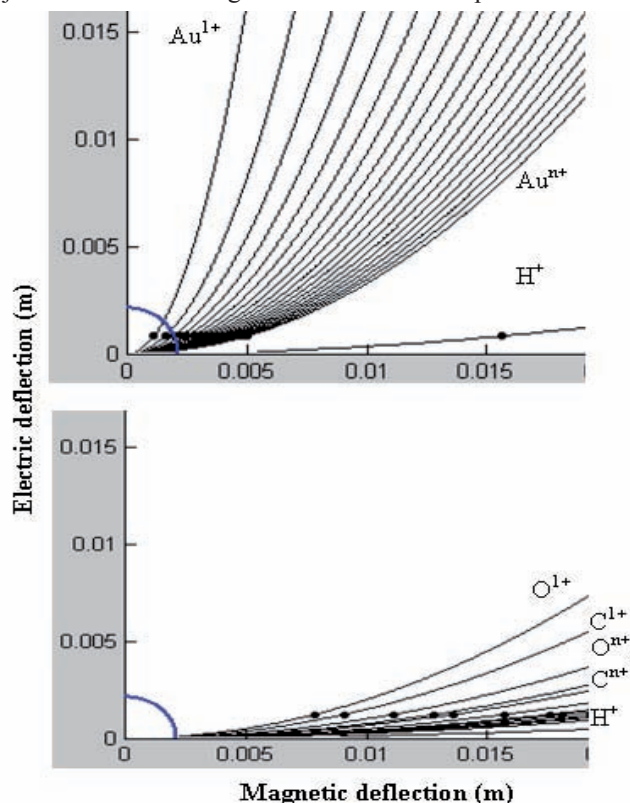


Fig. 4: TP simulation images of the ions ejected from a forward plasma obtained by irradiating 2.5 μm thickness of Au (a) and 7 μm of PMMA(1% CNT) (b), with the same experimental conditions reported in Fig. 3.

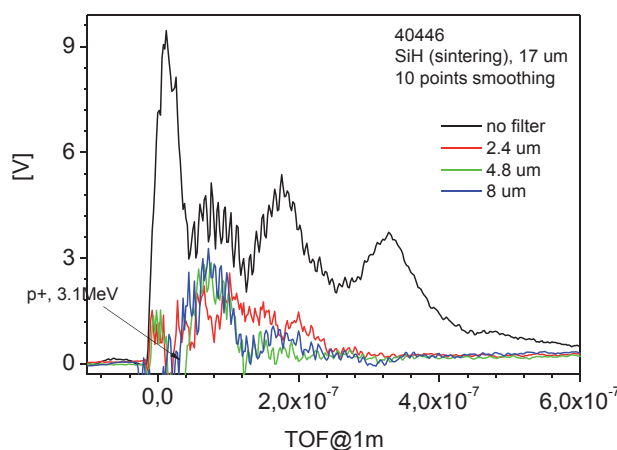


Fig. 5: ICR spectra obtained detecting the ions emitted from a SiH target, 17 μm thickness, laser irradiated at 490 J, as a function of the different Al filter thickness.

Also the fast SiC detector, placed at 30° angle with respect to the normal direction, permits to measure the proton and ion energies above 1 MeV from the TOF measurements. SiC detects not only ions but also UV, X-ray photons and energetic electrons. The angular distributions of the ejected particles indicate that, for thin films, the forward ion emission is narrow around the normal direction, while it is wider for the backward ion emission. A typical SiC spectrum, at 30° detection angle, is reported in Fig. 6, relatively to the laser irradiation at 332 J ad -92 μm focal position. The spectrum shows a fast proton peak at a TOF time of 50 ns corresponding to an average kinetic energy of about 1.83 MeV.

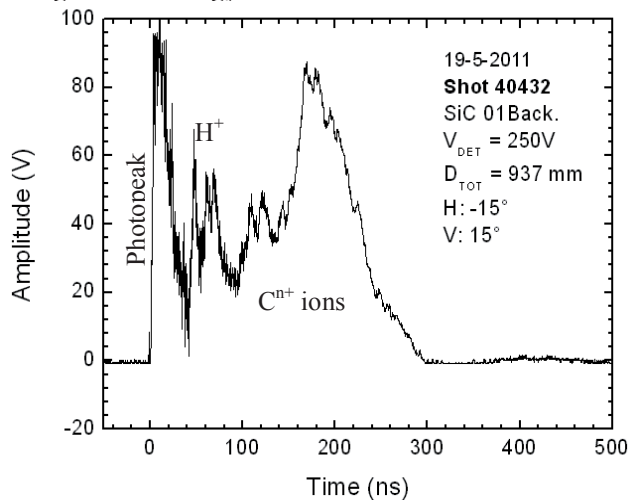


Fig. 6: Typical SiC spectrum of the ions emitted at 30° angle with respect to the normal to the target surface and relatively to PMMA (1% CNT) thin target.

A typical image of the streak camera of the plasma generated in forward direction is reported in the photo of Fig.7. The higher plasma temperature is represented by the red zone (central) of the plasma plume that reaches a value of about 28 keV, as measured by the electron emission detected with an energy calibrated plastic scintillator employed in the PALS measurements.

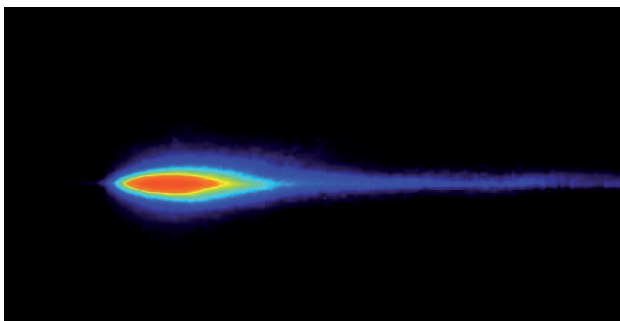


Fig. 7: Streak camera image of the plasma generated by irradiating a Mylar/Al target, 2.5 μm thickness, with 229 J pulse energy with +240 μm focal position.

DISCUSSION AND CONCLUSIONS

The above described experiments demonstrated that proton streams, with kinetic energy above 1 MeV, can be generated by laser-plasma in forward direction from irradiated thin hydrogenated films.

This result is particularly important because it indicates that the forward plasma can be obtained also at the relatively low laser intensity of the order of 10^{16} W/cm² by irradiating thin films with a thickness lower than 10 microns. The proton bunch acceleration, with a proton amount of the order of 1013/pulse, at energies above 1 MeV, opens new perspectives to the application of laser proton acceleration for nuclear physics. Protons and deuterons, in fact, may induce many nuclear reactions in different light elements. For example the D-D fusion process can be induced with high cross-section by accelerating deuterons from deuterated polymers and inducing fusion effects in thick targets. Such fusion processes generate monochromatic protons and neutrons at a characteristic energy of 3 MeV and 2.5 MeV, respectively [8].

The experiments at higher laser intensities, above 10^{19} W/cm² with terawatt lasers at fs pulse duration, in TNSA regime, are permitting forward protons acceleration from thin films at energies above 10 MeV, up to about 50 MeV [1]. These recent results are confirming that a new acceleration method, based on the fast generation of non-equilibrium plasmas, is possible, without the use of large traditional accelerators, and that new perspectives are reflecting on many other applications such as in Astrophysics, Engineering, Medicine and Protontherapy fields.

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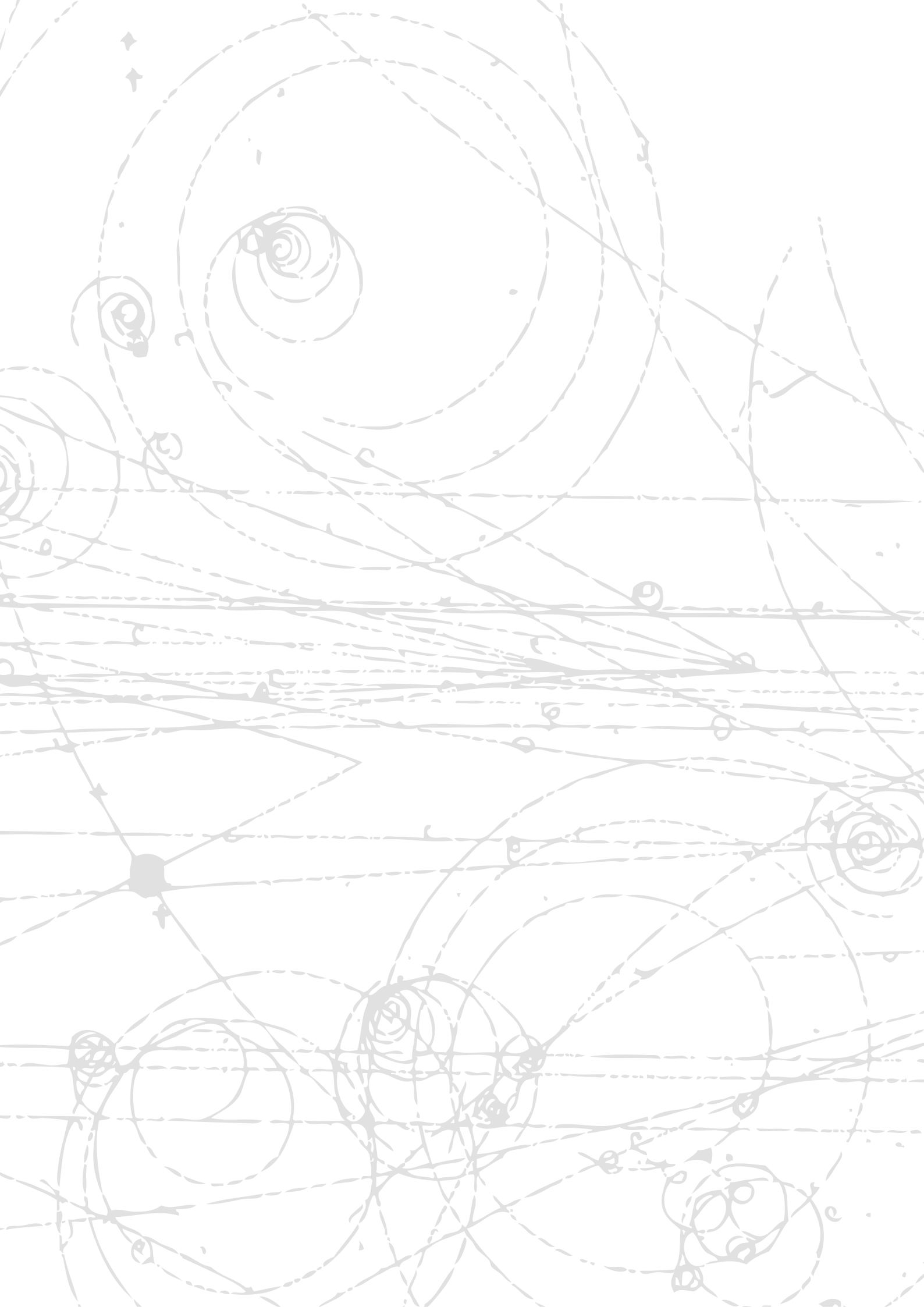
Authors thank Mr. C. Marchetta and Mr. E. Costa of INFN-LNS for the useful support given in the target preparation employed in the presented experiments.

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LABORATORI NAZIONALI DEL SUD
ACTIVITY REPORT 2010

**INTERDISCIPLINARY
PHYSICS**



The CATANA protontherapy facility: state of the art of the clinical and dosimetric experience

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Abstract - After nine years of activity, about 220 patients have been treated at the CATANA Eye Proton therapy facility. A 62 MeV proton beam produced by a Superconducting Cyclotron is dedicated to radiotherapy of eye lesions, as uveal melanomas.

Research and development work has been done to test different dosimetry devices to be used for reference and relative dosimetry, in order to achieve dose-delivering accuracy.

The follow-up results demonstrated the efficacy of proton beams and encouraged us in our activity in the fight against cancer.

INTRODUCTION

Since 2002 ocular tumors are treated with 62 MeV proton beams at LNS-INFN in cooperation with University Hospital of Catania; the goal of the Proton Beam Radiation Therapy (PBRT) is to achieve local tumour control and retention of organ and vision; uveal melanoma is the most frequent treated neoplasia, but other less frequent eye diseases have been treated by means of protontherapy, like choroid metastases, conjunctival and eyelid tumors [1, 2].

Physical properties make protons suited for the irradiation of eye tumours; proton therapy permits to use a single port to irradiate a defined eye target volume whilst sparing critical structures in its vicinity, as optic disk, macula, lens and anterior segment.

The 62 MeV proton beam, produced by a superconducting cyclotron, is passively prepared for conformal irradiation of the eye tumour.

The energy of 62 MeV confines maximal range of proton beam to about 30 mm, sufficient for the irradiation of intraocular tumours. The required maximum range for a specific treatment is set by a simple Perspex absorber, variable in thickness in steps of 0.2 mm. The sharp distal (< 1 mm) and lateral (< 1.5 mm) fall-offs of the SOBP improves sparing of the healthy eye tissue, demonstrating high dose conformity of eye proton therapy.

THE PROTON BEAM LINE

The CATANA passive proton beam line has been entirely built at INFN-LNS of Catania (Figure 1). The proton beam exits in air through 50 μ m kapton window placed at about 3 meters from isocenter. Just before the exit window the first scattering foil made of 15 μ m tantalum is placed in vacuum. The first element of the beam in air is a second tantalum foil 25 microns thick provided with a central brass stopper of 4 mm in diameter. The double foils scattering system is optimised to obtain a good homogeneity in terms of lateral off-axis dose distribution, minimizing the energy loss.



Figure 1: View of the CATANA beam line: 1. Treatment chair for patient immobilization; 2. Final collimator; 3. Positioning laser; 4. Light field simulator; 5. Monitor chambers; 6. Intermediate collimator; 7. Box for the location of modulator wheel and range shifter.

Range shifter and range modulator (for energy change and modulation) are placed inside a box, downstream of the scattering system. Two diode lasers, located orthogonally and coaxially to beam line, provide a system for the isocenter identification and for patient centring. A light field with cross-air, indicating the principal axis, simulates the radiation field. A key element of the treatment line is represented by two transmission monitor ionization chambers, which provide on-line control of the dose delivered to the patient. The last element before isocenter is the brass shaped patient collimator located 83 mm upstream of the isocenter [3, 4]. The mechanical staff of the LNS, also plays a fundamental role in the success

of any treatment. Modulator wheels and patient's collimators are in fact, fully realized inside the LNS machine shop. Patient collimators, specifically designed for each patient, are realized starting from brass cylinders catted with the tumour shape and with a sub-millimetric precision. The modulator wheels realisation requires even a bigger effort. Modulators have a topical function in the proton treatment: they have to transform the mono-energetic proton dose distribution (the pristine Bragg Peak) in a well-defined flat dose distribution (Spread Out Bragg Peak), according with the medical prescription. A modulator is, essentially, a plastic wheel composed by a given number of small steps, each step created with a well-defined angular aperture. A high precision (less than 50 μm for the steps height and 0.01 degree for the angular aperture) is required in the mechanical realisation of such devices, as the final dose differences in the SOBP must be less than 3% to ensure an high quality irradiation. Figure 2 shows one of the phases of the modulator realisation where a plastic block is catted by a milling machine. In Figure 3 the final modulator is shown.

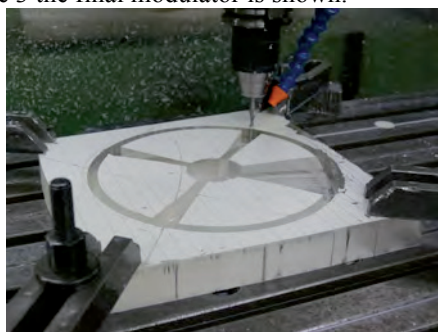


Figure 2: A block of plastic during the realisation phase of a modulator.



Figure 3: The modulator wheel in its final form, ready to be used in the for a proton treatment

PROTON DOSIMETRY AT THE CATANA FACILITY

As in conventional radiotherapy, clinical proton dosimetry includes reference dosimetry, consisting in determination of the absorbed dose at a reference point in the user's beam, and relative dosimetry, i.e. determination of dose distribution in a water phantom (x,y,z). The first is essential for monitor unit calculations and to verify the prescription of the

protocol, the second for planning and quality assurance purpose.

For reference dosimetry an Advanced Markus plane-parallel PTW Ion Chamber has been adopted, with an electrode spacing of 1 mm and a collection volume of 0.02 cm^3 . According to IAEA TRS 398 protocol [5], proton beam calibration is performed in a water phantom.

The absorbed dose to water per monitor unit (cGy/M.U.) is measured at the isocenter, for each combination of modulator and range shifter used in the clinical practice. Measurements are carried out at the depth of the middle of the SOBP, using the reference 25 mm diameter circular collimator [5]. The clinical proton beam calibration is performed just before each treatment fraction; the variation of beam calibration on the four consecutive days of treatment resulted to be within $\pm 5\%$.

As for all passive proton therapy facilities, the proton beam calibration resulted to be strongly dependent on the modulator and the range shifter adopted in the clinical practice; for the same modulator, the dose/(monitor unit) decreases of about 35% if the thickness of the range shifter increase from 6 to 12 mm.

To investigate whether narrow irregular fields used in clinical practice will affect the radiation output, output factors are experimentally determined, by using small-size detectors, as Scanditronix Hi-p Si stereotactic diode detector (0.6 mm detector diameter) and TN-502RDM micromosfet detector ($1 \times 1 \text{ mm}^2$ sensitive area) [6]. The *Output factor* is determined [5] as the ratio of small-size detector signals for the patient and reference collimators for the same M.U. setting.

Based on experimental results on several collimators, we can state that the dose delivered per monitor unit decreases by less than 3% for collimator areas in the range of 490 mm^2 (reference collimator) to 100 mm^2 , the latter representing the lowest limit of collimator areas associated to the clinical practice.

For mono-energetic and modulated proton beams, depth-dose distributions are measured in a home made motorized computer-controlled water phantom with a scanning resolution less than 0.1 mm in the Bragg peak region. Also in this case, an Advanced Markus chamber is used due to small electrode spacing and high electrical field (4000 Vcm^{-1}), the latter providing a collection efficiency close to 1 up to 100 Gy/min in the cyclotron continuous beam.

For the modulated clinical proton beams a set of physical beam parameters (Figure 4) are measured, according to the ICRU Report No 78, related to the clinical requirements:

A software, entirely developed at INFN-LNS, controls the data acquisition and provides data analysis.

Experimental depth dose profiles have been compared with a Monte Carlo simulation application, developed by us using the Geant4 toolkit [7]. The application reproduces in details all the elements of the CATANA proton beam line as well as the detectors used for dosimetric measurements, accurately simulating the tracking and physical interactions of protons with the

traversed materials. Results of these comparisons are extensively reported in some publications [8].

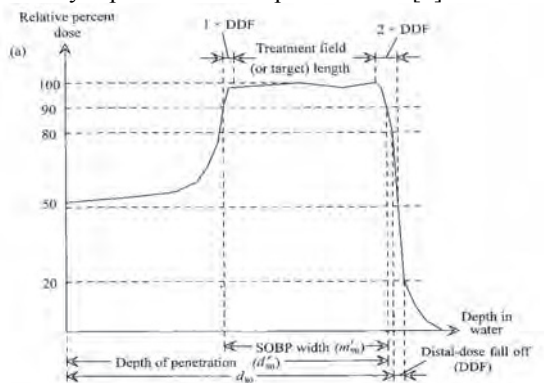


Figure 4: Physical beam parameters related to the clinical requirements for the modulated proton beam.

Lateral beam profiles are characterized in terms of *field size* ($W_{50\%}$), *lateral penumbra* (LP, $d_{80-20\%}$), *target* (or *treatment*) *width*, defined as the distance between two LP widths ($2 \cdot LP$) from the 50 percent dose level of the lateral profile, *flatness* and *symmetry* defined as in conventional radiotherapy and evaluated in the target width.

New EBT radiochromic films [9] have been chosen as reference detector for the measurement of lateral profiles; EBT film is nearly tissue equivalent [$(Z_{eff}/A)=6.98$], with a sensitive range between 0.1 Gy and 8 Gy, providing high spatial resolution up to 100 μm .

Preliminary in vivo dosimetry has been carried out on Catana patients, by using micro-mosfets; detectors are placed on the patient eyelid immediately before the treatments.

TREATMENT PROCEDURE

As explained before, protons allow a high dose deposition in a small deep-seated space, with precise irradiation of the target.

Treatment procedures have been modelled on the specific characteristics of the most frequent tumor of the ocular region, that is uveal melanoma: it is located most frequently in the posterior part of the eye, so it requires a surgical application of 4 tantalum clips around its base on the outer sclera to determine the tumor localisation. The other orbital tumors treated are clinically evident, so a prior surgical phase is not required.

During the ophthalmological work-up, the ophthalmologist defines the tumor position and dimensions, like transverse and longitudinal base diameters, elevation or height, distance to the optic disk, to the macula, to the limbus. Eye anatomical parameters (axial length, transverse diameter, thickness of the coats, distance between anterior cornea and posterior lens, limbus diameter) and clips measurements (distance between clips to limbus, clips to clips and clips to tumor) are also provided to the radiation oncologist. The final result is the draw of a precise fundus view model with

tumor and clips locations. After the surgical phase, the simulation procedure starts inside the treatment room. Here the patient is immobilized on a motorized computer controlled treatment chair by means of a customized thermoplastic mask and a bite block (Figure 5).

Two orthogonal X-ray pictures (axial and lateral) are taken with the Digital Acquisition System (DAS), consisting of two orthogonal X-ray tubes Philips Practix 33, two flat panels HAMAMATSU mod. C7921 CA02 and a PC Workstation connected to the treatment chair. A homemade software provides X-rays image acquisition and treatment chair movement.

In order to optimize the geometrical reconstruction of the eye and the tumor, 5 pairs of X-ray images for five different fixation angles of the eye are acquired. A measurement of the eyelid thickness and slope is also needed for the planning procedures. All the information are then elaborated by means of the 3-D treatment planning system EYEPLAN [10]. The software provides the treatment position of the clips, isodose curves, dose-volume histograms, the clinical beam range, the required modulation and the shape of the patient collimator. The DAS software matches the clip position provided by Eyeplan with the X-Ray images and sends the required movements (D_x , D_y , D_z) to the chair control program for the treatment position of the patient. For eye proton therapy 60 Gy (RBE) are delivered to uveal melanoma in 4 fractions on 4 consecutive days; a constant RBE of 1.1 is applied over the SOBP.

Before each treatment fraction the eye position is verified and compared to the planned position. A video camera is directed to the eye to verify its position outside the treatment room during the irradiation. The treatment time ranges are between 15 and 60 sec.

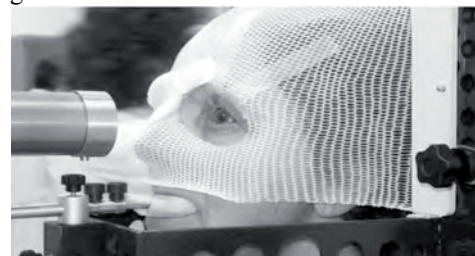


Figure 5: Lateral profile along the central axis performed with EBT film.

CLINICAL ACTIVITY AND RESULTS

Patients were affected by the following neoplastic diseases: uveal melanoma 192 patients, conjunctival melanoma 7 patients, conjunctival rhabdomyosarcoma 1 patients, conjunctival lymphoma 3 patients, conjunctival papilloma 1 patient, eyelid carcinoma 10 patients, lachrymal gland carcinoma 1 patient, choroideal metastases 3 patients. The majority of them came from the south of Italy, but at least one third came from north Italy, four patients came from outside Italy.

For many years the treatment of uveal melanoma has been the eye enucleation, but several studies have demonstrated no advantage of such an approach regarding

tumor control and metastatic spread compared to eye-sparing treatments, like PBRT. Proton beam radiation therapy (PBRT) has been applied for the treatment of uveal melanoma since the last 70s, and now is considered by most the treatment of choice for the high degree of tumor control and organ preservation obtained and the acceptable rates of side effects [11-14].

The follow-up ranges from 6 months to 9 years for all patients with uveal melanoma treated (192 patients). According to the international classification of malignant tumors TNM (tumor, node, metastases), the TNM staging of the patients at the recruitment was as follow: T1 for 11 patients, T2 for 58 patients, T3 for 123 patients. About 70 % of the lesions were posteriorly located, in close vicinity to the optic disc or to the macula.

The tumor thickness is reduced in 73% of patients, while 21% have a stable tumor elevation with increased reflectivity. Eight patients were early enucleated for radiation-induced toxicity, but only for four of them a tumor regrowth was detected. A local tumor control was obtained in 95% of patients treated.

A secondary end point of ocular tumor protontherapy is the maintenance of the eye, while the surgical alternative is, in most cases, the eye enucleation [12]. In our series, almost 90 % of patients have retained their eye. The remain patients have been enucleated at various follow-up time, the majority of them for radiation-induced toxicity, mainly neovascular glaucoma, due to the big tumor volume and the consequent large retinal surface irradiated.

The visual function was evaluated by the referring ophthalmologist during the follow-up; at the recruitment, only 65% of patients had an acceptable visual acuity, but, after treatment the percentage falls to 43 %, due to the location of the tumor, which in most cases was close to the optic disc or to the macula. For that reason, the treatment isodose must include those structures, causing the loss of the visual acuity [15, 16].

The development of radiation-induced damages is well known in ocular protontherapy. In our experience, an exudative retinal detachment of various degree has been detected in 35 % of patients, radiation retinopathy of various degree was seen in 22% of patients. A radiation-induced cataract or an increasing of a pre-existing cataract was detected in 35% of patients, most of whom underwent surgery. A neovascular glaucoma developed in 15 patients and 8 of them were enucleated for that reason. During the follow-up a metastatic disease was recognised in 35 patients after a median time of 23 months; almost all patient have been treated with chemotherapy with a median survival of 18 months. The cause-specific survival for uveal melanoma patients is 92 %, since 165/192 patients are still alive, taking in account that seven patients died from intercurrent disease. The other ocular tumors treated with PBRT are all alive and under local control, with the exception of squamous cell papilloma that relapse several times after 12 months and enucleation was required [17].

CONCLUSIONS

Clinical results show an high percentage of local tumor control with a limited acute and subacute toxicity and visual outcome according to the previsions. The results are in agreement with those reported in the literature, regarding the treatment of uveal melanoma by means of hadrons.

Even if CATANA should not be the clinical answer for all the Italian patients affected by this kind of disease, it represents the first successfully Italian example of the collaboration between Nuclear and Medical Physicists together with Medical Doctors in fighting tumors with hadrons. CATANA is the first milestone in Italy through the extensive use of hadrontherapy in cancer treatment.

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The activity of Monte Carlo simulation with the toolkit GEANT4 in the medical physics field

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Abstract

Monte Carlo (MC) methods are considered among the most powerful and precise approaches to study and solve issues in the medical physics field. They are more and more frequently used in several practical situations, such as the predictions of the dose distributions in radiotherapy with photon, proton and ion beams, the verification of the Treatment Planning Systems (TPS) and the simulation of devices for relative or absolute dosimetry. In particular, MC approach becomes necessary when a realistic response has to be known in complex configurations, like the reproduction of tissue inhomogeneity, the simulation of advanced medical devices and the evaluation of radiobiological effects. In this report, we relate particular applications of MC methods in different medical physics procedures, following the experience we gained by the use of the GEANT4 Monte Carlo toolkit.

INTRODUCTION

This first section is dedicated to the GEANT4 MC toolkit used for all the developed applications. These are described in details in the second section, where we dedicated a specific sub-section for each application.

The Monte Carlo GEANT4 toolkit

GEANT4 (*GEometry ANd Tracking*) is an object oriented toolkit for the simulation of particle interactions with the matter [1]. It provides advanced functionalities for all the typical domains of detector simulation: geometry and material modelling, description of particle properties, physics processes, tracking, event and run management, user interface and visualisation. The design as a toolkit and the adoption of the object oriented technology characterize GEANT4 with respect to other general purpose Monte Carlo codes. The object oriented technology allows multiple implementations for any of the object interfaces in the toolkit. This powerful technological feature is at the ground of a wide set of physical processes and models available in GEANT4. As a toolkit, it consists of a set of compatible components where a user can build his/her own application selecting the appropriate classes needed for each specific case. The flexibility of configuring an application by selecting the physical processes to be activated is a key feature for its usage in different experimental fields.

The Monte Carlo technique can provide, in principle, a very accurate prediction of the proton or ion treatment beams by taking into account all the physics processes involved, including electromagnetic energy loss, energy straggling, multiple Coulomb scattering, elastic and non elastic nuclear interactions as well as the transport of any generated secondary particles.

The accurate simulation of the energy deposition of protons and ions in water plays also an important role in oncologic radiotherapy and radiation protection: Monte Carlo methods are used for the optimisation of hadrontherapy beam line features and for the verification of patients treatment planning. In order to take full advantage of the Monte Carlo approach, the beam delivering system has to be simulated in detail and the initial beam parameters have to be known as accurate as possible.

The extension of physical interaction models down to low energies allows the use of GEANT4 for many kind of medical applications, both in the radiotherapy and diagnostic field [2].

In the following sections we describe the main applications we have developed and continue to maintain.

MONTE CARLO APPLICATIONS DEVELOPED WITH GEANT4

The 'Hadrontherapy' GEANT4 application

Hadrontherapy is a C++, free and open application developed for the simulation of the CATANA proton transport beam line. The CATANA project was born many years ago for the realization of a facility for the treatment of ocular tumours using 62 MeV proton beams accelerated by the Superconducting Cyclotron of LNS-INFN of Catania. CATANA is now a dedicated facility, in operation since 2002, where more than 200 patients have been treated so far, gaining a local control of the tumour in the 95% of cases [3]. The development of an hadron-therapy facility requires a long experimental work, where the choice of the most suitable solutions can sensibly influence the final quality of the treatment. The CATANA facility is a passive proton beam line, hence in this case the work mainly concerns with the realization of the passive scattering system (to obtain an homogeneous lateral distribution of the beam), of the modulation (to perform a correct energy modulation necessary for the spread out

Bragg peak) and of the collimation system.

Moreover, in addition to the proton irradiation room, a second experimental room at INFN-LNS is dedicated to *in-air* multidisciplinary irradiation studies. This second beam line is used by many research groups in different kinds of experiments (detector tests, irradiation of biological samples, etc.). Ion beams can be transported there with an energy ranging from 80 AMeV down to about 20 AMeV.

In order to improve the transport beam line, the dosimetrical calculations and to obtain a better understanding of the radiobiological effects of protons/ions, we realized a MC simulation, *Hadrontherapy*, using the libraries of the GEANT4 toolkit. Each element of the passive proton beam line has been carefully simulated and the detector used for the depth dose distribution has been also reproduced in the application [4].

The application has been publicly released in 2004 inside the GEANT4 distribution and today it is furnished in two different versions: a *basic* one, still contained inside GEANT4 in the advanced examples category, and a *full* one, more complete and separately distributed by the authors at a specific web site [5]. The *Hadrontherapy* application offers large flexibility: it permits, in its simplest version, the simulation of a typical beam line for proton/ion therapy including all the necessary transport elements: the diffusion and modulation systems for the particles spatial and energy distribution, the collimators, the transmission detectors as well as detectors for the dose distribution measurements, which can be simulated and activated via simple and external macro commands.

The *full* version offers many other features with respect to the *basic* one. Among them the most important are: the modularization of the geometry, that gives the possibility to change the simulated apparatus interactively and externally, without changing the code but only via script commands; the possibility to easily calculate stopping powers and ranges in simple geometrical configurations and for any couple of ion-material combinations; the presence of specific algorithms for the calculation of the average 3-dimensional LET (Linear Energy Transfer); a new graphical user interface, implemented using the QT libraries, that can be chosen (if installed) in order to have a more simple interaction with the program. Moreover, a future version of the application will include the possibility to use DICOM interfaces in order to take into account the different tissue densities.

The *Hadrontherapy* application has been validated against experimental data acquired by us, as reported elsewhere [6]. In Figure 1 the comparison between the experimental and the GEANT4 Bragg peak is showed for carbon ion beams incident in a water phantom at 62 AMeV. A good agreement has been found between the experimental and calculated curves for both proton and carbon beams, which confirm the accuracy of the simulation procedures implemented in the *Hadrontherapy* application.

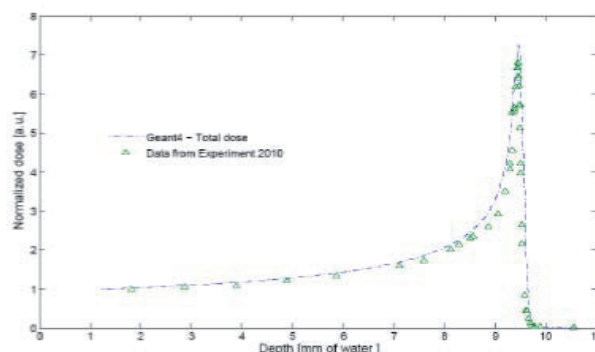


Figure 1 - Simulated (line) and experimental (dots) depth dose profiles of a 62 AMeV carbon beam in water. Experimental curve have been acquired using a plane parallel ionisation chamber (Markus Chamber type) [7].

Proton Computed Tomography (pCT)

A precise radiation modality, as the proton therapy, requires very accurate Quality Controls (QA) of the treatment procedures. In proton therapy, QAs are mainly related to the patient positioning and to the dose calculations with a treatment planning software. In existing proton treatment centres, positioning and dose calculations are currently based on x-ray radiographs and x-ray computed tomography (xCT), respectively. A new challenge, in the next years, could be the direct use of the proton beam for the tomographic imaging of the patient body, developing a proton Computed Tomography (pCT) system. This technique will make the proton radiation procedure more precise by defining the position of the Bragg peak more accurately (allowing the verification of patient and tumour position with respect to the proton beam) and by permitting a direct measurement of the electron densities (and hence of the stopping powers values) of the involved tissues. Indeed, stopping powers are actually indirectly derived from the conversion of the linear attenuation coefficients measured with a conventional x-tomography of the patient. This conversion is not error free and can produce, in many cases, uncertainties in the stopping power values and, consequently, in the calculated dose deposition. The main task for any imaging system is to obtain images with a sufficient density ($\leq 1\%$) and spatial ($\leq 1\text{mm}$) resolutions. Recent works, based on analytical methods and Monte Carlo simulations, have demonstrated the possibility to obtain a proton tomography with a good density resolution and to realize, in the next years, a real pCT device. On the other hand many limitations must be still investigated. In our work we investigated the possibility to overcome one of the main limitations of the pCT: a poor spatial resolution due to the effect of Multiple Coulomb Scattering (MCS) inside the body of patient [8]. One possible solution for the spatial resolution improvement is the use of the so-called 'single tracking technique' whose principle is based on tracking each single proton in coincidence as they enter and exit the specific object. We have studied and verified the single tracking approach, using the Monte Carlo method and also by means of experimental measurements with a first prototype of a pCT system.

Gamma Knife® Stereotactic Radiosurgery

Stereotactic Radiosurgery represents at present one of the best clinical solution for the brain radiotherapy with external beams. In this field, the Gamma Knife®, manufactured by Elekta, is one of the most used device, thanks to its geometrical precision. Gamma radiation, emitted by 201 ^{60}Co sources arranged in a hemispherical shape, converges through a collimation system on the isocentre, where the target volume has to be positioned [9]. With this technique, malignant tumours and brain disorders of different kind are treated delivering high amount of dose only in a single session. The Treatment Planning System (TPS) devoted to the dose distribution computation is the Leksell ‘GammaPlan’ (LGP), which calculates the isodose curves obtained combining many shots of different diameter at the isocenter (four available collimators: 4, 8, 14, 18 mm). With this method, tumours with very complex shapes can be treated. In order to plan the treatment in a reasonable time, the TPS has been designed on the base of analytical algorithms, which include some approximations. The most crucial consists on considering the patient’s head composed only of water, neglecting the presence of different densities. Hence, the aim of our work has been the evaluation of the TPS GammaPlan accuracy, simulating the device with the GEANT4 toolkit. The work has permitted to evaluate how the included approximations may influence the calculated dose. An application has been developed, which accurately reproduces all the Gamma Knife features (both from the geometrical and physical point of view), in order to simulate with an high level of accuracy the dose deposited in a spherical phantom [10] (Figure 2). To simplify the code, in place of the reproduction of hundreds of sources and collimators we have simulated only one source, exploiting the spherical symmetry of the device. Therefore, the source with the correspondent collimation system is placed in the X axis and the spherical phantom is rotated at 201 different angular positions. In such a way the original angular positions of the sources have been reproduced we have in an alternative way, implementing time-dependent geometries in the application.

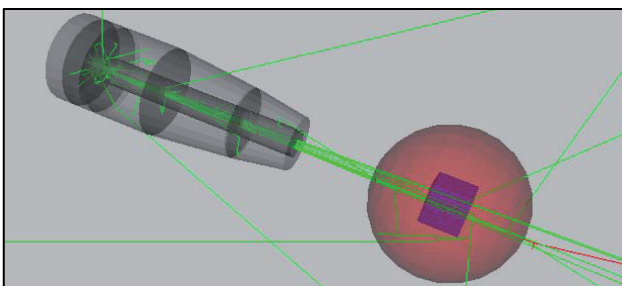


Figure 2 – Gamma Knife GEANT4 application

The Monte Carlo simulation has been validated for the four available collimators in the standard configuration (homogeneous phantom). GEANT4 dose distributions have been compared with experimental ones, which have been obtained by radiochromic film dosimetry measurements inside a water phantom (HS GafChromic films).

After the validation procedure of the implemented code, we have used the Monte Carlo simulation to verify the dose distributions calculated by the TPS, firstly in standard conditions (homogeneous phantom) and, afterwards, in more real conditions, characterized by the presence of different density materials (inhomogeneous phantom). As regards the first configuration, results show that, considering the statistical uncertainties, the TPS calculates accurately the delivered dose.

On the other hand, concerning the case of inhomogeneous phantom, we found a discrepancy of about 4% between Monte Carlo and TPS dose distributions. These differences probably arise from the TPS approximations about the density. The obtained results clearly show the importance of the application of Monte Carlo methods in radiotherapy, especially in case of special radiotherapeutic techniques, where the level of complexity increases.

The Gamma Knife application has been proposed, and recently accepted by the GEANT4 international collaboration, as a GEANT4 ‘advanced example’. Thus, it will be freely distributed to the interested Users and included in the future public releases of the toolkit.

Validation of GEANT4 nuclear models in the energy range of interest in hadrontherapy

The inverse depth dose profile, i.e. the increase of the dose with penetration depth makes heavy charged particles a powerful tool for the radiotherapy of deep-seated tumours close to radiosensitive organs. Beyond a good dose profile, carbon ions are also characterized by a small lateral scattering and a higher biological effect, especially at the end of the particle range, where the Bragg peak overlaps the target region.

Even if heavy ions present the discussed advantages, a drawback has to be taken into account in their clinical use: the projectile fragments produced by fragmentation reactions can cause a significant amount of undesired dose to the healthy tissues beyond the Bragg peak (tail dose) and create a ‘mixed field’ composed of secondary ions with different biological effects. Therefore, a detailed knowledge of fragmentation processes is quite important to accurately calculate the dose distribution [11].

After many years of studies about the effects of different ions, scientific community has accepted the carbon ions as the best compromise between local control of the tumour and negative side effects for healthy tissues, even if further studies are still going on about the possibility to use lighter ions [12].

In this context, Monte Carlo simulations are considered a suitable tool for such a kind of study, thanks to their realistic predictions. The accuracy of their predictions strictly depends on the reliability of the nuclear models implemented in the codes, which need to be rigorously validated. A detailed physics validation for GEANT4 fragmentation models, at the energy range of interest in hadrontherapy (60 - 400 AMeV), has been carrying out by our group. Unfortunately, few updated data are present in literature for carbon ions incident at this energy range. In order to cover the gap of data, an experimental campaign has been carried out at LNS-INFN

of Catania. The measurements aimed to measure the production cross sections of charged particles for different angles and target materials [13], using a carbon ion beam accelerated by the Superconducting Cyclotron at 62 AMeV on thin targets of ^{197}Au , ^{12}C and CH_2 . Nuclear fragments have been detected using two hodoscopes (Hodo-small and Hodo-big), respectively composed by two-fold and three-fold telescope detectors covering an angle of about 20 degree.

We have started simulating part of the experimental apparatus with the toolkit GEANT4 and the production cross sections obtained with the simulations have been compared with the experimental data. Preliminary results show that the trend of angular cross sections is quite well reproduced, even if differences in the absolute values have been found.

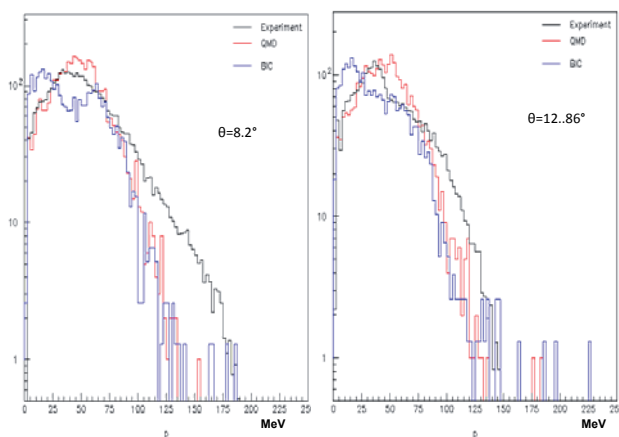


Figure 3 - Spectra of secondary protons at two different polar angles. In black: experimental data; in red: QMD; in blue: BLI.

Simulations were performed implementing two different physics lists of GEANT4: Shielding and QGSP_BIC, which respectively use the Quantum Molecular Dynamic (QMD) model and the Binary Light Ion Cascade (BLI) model for ion physics. In Figure 3 are showed preliminary comparisons between experimental data (C + C @ 62 AMeV) and simulations performed with the GEANT4.9.4 version. So far the QMD seems to show, respect to the experimental data, a better agreement than BLI.

In order to further test the reliability of fragments emission predictions of GEANT4, we have investigated also the de-excitation models to understand how they affect the simulation output at low energy. GEANT4 native de-excitation models include several semi-classical alternative/competitor models: evaporation of nucleons and light fragments, evaporation of photons, fission, statistical multifragmentation and Fermi break-up [14]. The de-excitation process is repeated iteratively until cold fragments and/or nucleons are produced according to specific rules. At our energy, simulations showed that only evaporation and Fermi break-up are responsible of the de-excitation, because practically multifragmentation is never activated.

This study has led to an improved knowledge of the models and of their predictions and represents a first step for a complete and exhaustive validation of the inelastic nuclear models implemented in GEANT4.

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An "In-Beam PET" prototype for proton therapy. Preliminary results on the accuracy of the activity distal fall off localization

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Abstract

The DoPET (Dosimetry with a Positron Emission Tomograph) project is focused on the development and characterization of a dedicated, scalable, dual-head PET prototype for in-beam treatment planning verification of the proton therapy. A dedicated PET design is necessary for this application in order to avoid interference between the proton beam and the PET detectors and to fit different patient sizes.

In this note, we report the results obtained with our current prototype, by measuring the β^+ -activation induced by 62 MeV proton beams at Catana facility (LNS, Catania, Italy) in a water phantom. Experiments were performed to evaluate the capability of the system, operating for a limited acquisition time, to keep unchanged the accuracy in the localization of activity distal fall off.

INTRODUCTION

The necessity for treatment verification in hadron beam radiotherapy is gaining widespread recognition especially if hypo-fractionated radiotherapy is planned to be used. In fact, cancer therapy using hadrons offers several advantages with respect to traditional radiotherapy with photons due to hadron physical and radiobiological properties that on one hand bring high precision but on the other hand make the treatment sensitive to delivery uncertainties.

We have developed an in-situ monitor system, based on Positron Emission Tomography (PET), to measure the induced β^+ -activity (i.e., ^{15}O (half-life of 122 s) and ^{11}C (half-life of 1218 s) produced by the projectile and/or target nuclei fragmentations), to extract in-beam information about the effective ion path [1,2,3]. In fact, a correlation exists between dose and induced-activity and is in use in clinical trials [4,5]. An on-line measurement, i.e. immediately after patient irradiation, is the only way to collect the maximum statistics, by detecting also the activity contribution provided by short lived isotopes, i.e. ^{15}O and ^{13}N .

Several test beams were already performed at the CATANA beam-line at LNS and the results are reported in this note.

EXPERIMENTAL RESULTS

The experimental prototype is based on two planar heads with an active area of about $5 \times 5 \text{ cm}^2$. Each head is made up of a multi anode photomultiplier coupled to a square matrix of the same size of LYSO ($1.9 \times 1.9 \times 16 \text{ mm}^3$ pixel dimensions). A dedicated electronic board performs signal amplification and digitization. A specific calibration procedure is applied and a 3D reconstruction algorithm using an adaptive version of the iterative ML-EM (Maximum Likelihood Expectation Maximization) algorithm is used [6, 7, 8, 9,10].

We have investigated the dose reduction effect on the accuracy of activity distal fall off localization. The variability in the reconstructed activity depends mainly upon the number of protons impinging onto the phantom. Decreasing the dose (i.e. the number of projectiles) results in an increase of the statistical uncertainty, thus in a loss of accuracy in determining the exact position of 50% or 20% peak value of normalized activity profiles. Four solid water phantoms were irradiated with 30, 15, 10 and 5 Gy, maintaining unchanged the dose rate. The phantoms were parallelepipeds realized assembling 7 solid waters slabs, each with a dimension of $5 \times 5 \times 1 \text{ cm}^3$, for a total thickness of 7cm. They were irradiated using 62 MeV protons and a collimator with a 25 mm diameter at CATANA beam line. The long side of the parallelepiped was positioned aligned to the proton beam line. The acquisition time was fixed at 20 minutes starting from the end of irradiation, for all the measurements.

The activity distributions were reconstructed and the longitudinal profiles were extracted for each irradiation. The shape of the 4 activity profiles, as reported in figure 1, are perfectly overlapping when normalized profiles are plotted, confirming that the penetration depth is the same as expected.

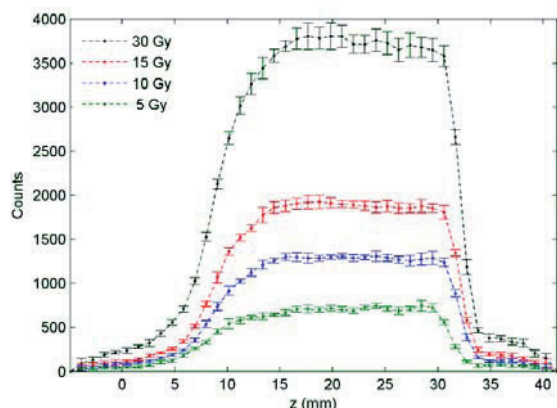


Figure 1: Activity distribution longitudinal profiles for solid water phantoms irradiated with 30, 15, 10 and 5 Gy

For each reconstructed activity volume we plotted the distributions of 20% and 50% fall off positions evaluated for each profile within the irradiated volume as the distance between the position corresponding to a fixed percentage activity in the leading edge and the same percentage in the trailing edge of the distribution. As expected, the spread of the distribution increases with decreasing the dose. However, even at doses as low as 5 Gy, it doesn't get bigger than 1 mm as reported in table 1

We have also investigated the effect of the PET acquisition time on the accuracy of the fall off position: using the 5 Gy irradiation data, we reconstructed the activity for increasing time intervals: the distributions of 20% and 50% fall off positions, evaluate as described above, is reported in table 2

The results indicate that an in-situ acquisition of about 6 minutes is sufficient to get a reliable number of coincidences to obtain a good signal to noise PET image.

In order to verify the linearity of our prototype we performed a decay analysis on all the reconstructed activities. We separated the contributions of ^{11}C and ^{15}O from the total activity and calculated the total isotope density. Then, we tried to quantitatively evaluate the relative activity concentration produced during the irradiations as a function of the delivered dose. By plotting the results, we observed a good linearity for both ^{11}C and ^{15}O isotopes down to few Gys, with both intercepts near to zero. In figure 2 we report the plot only for ^{11}C .

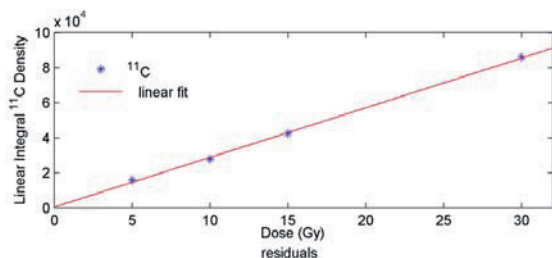


Fig. 2: ^{11}C contribution to the total activity as a function of dose

CONCLUSIONS

The reported results prove that the detection system based on the PET technique is a valuable monitoring method for hadrontherapy. The localization of the leading edge has an uncertainty lower than 1mm also for a low dose irradiation and for an in-situ limited time acquisition. Short acquisition, that starts immediately after the treatment, without move the patient, is a requirement necessary to have the possibility to treat several patient in the same beam line on the same day. We have also started the study for a quantitative analysis of the reconstructed data: the linear response of the system in terms of the relative activity concentration produced during the irradiations as a function of the delivered dose is a promising results. Nevertheless, the low β^+ emitter production and their short half-lives lead to a request for a high sensitivity PET system: a new prototype with an increased active area was realized and will be tested soon.

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	30 Gy	15 Gy	10 Gy	5 Gy
50%	(17.5 ± 0.2) mm	(17.2 ± 0.3) mm	(17.2 ± 0.6) mm	(17.5 ± 0.6) mm
20%	$(20. \pm 0.3)$ mm	(20.8 ± 0.3) mm	(20.9 ± 0.5) mm	(21.3 ± 0.7) mm

Table 1: Distribution of the 50% and 20% fall off positions of the normalized activity profiles, evaluated within the irradiated volume for different doses for an acquisition time of 20 minutes after the irradiation end. The error reported for each position corresponds to the sigma of the distribution

	Acquisition time ≈ 1 min	Acquisition time ≈ 2 min	Acquisition time ≈ 3 min	Acquisition time ≈ 6 min	Acquisition time ≈ 11 min	Acquisition time ≈ 20 min
50%	(15.9 ± 1.9) mm	(16.5 ± 1.6) mm	(17.2 ± 1.2) mm	(17.6 ± 0.7) mm	(17.6 ± 0.7) mm	(17.5 ± 0.6) mm
20%	(20.1 ± 2.4) mm	(21.6 ± 2.3) mm	(21.2 ± 2.0) mm	(20.5 ± 1.0) mm	(21.5 ± 0.8) mm	(21.3 ± 0.7) mm

Table 2: Distribution of the 50% and 20% fall off positions of the normalized activity profiles, evaluated within the irradiated volume for different acquisition time for the 5Gy irradiation.



An upgraded version of the LNS PIXE-alpha spectrometer

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Abstract - The LNS PIXE-alpha spectrometer has been upgraded by the use of a new 20mm² SDD droplet detector coupled to the preamplifier and pulse-shaping amplifier realised by the Department of Electronics of the Milano Politecnico. The power supply has been realised by the electronics staff of the LNS. The main objective was to improve the energy resolution in order to distinguish the x-lines of S(K) from those of Pb (M) and the Hg (M).

INTRODUCTION

The PIXE-alpha portable spectrometer [1] is based on the use of 1 mCi ²¹⁰Po radioactive source that emits pure alpha particles of 5.307 MeV energy. In the present version, it works with a 10 mm² SDD detector associated to an electronics device produced by the EIS (Roma) company. The X-ray energy resolution of the systems is 145 eV at the 5.9 keV @ Mn-K α .

For the application in the C.H. field a better energy resolution is required especially in the energy region from 2 to 3 keV in which important X-lines, as the 2.308 keV S(K), 3.345 keV Pb(M) and 2.194 keV Hg(M), are present. In fact, S and Pb are dominant in some pigments used in the antiquity as, for example, the Gypsum (CaSO₄·2H₂O) and White Lead (2PbCO₃·Pb(OH)₂). Hg is present in Cinnabar (HgS) or as natural element in some Roman Nummi surfaces [2]. Recently, a new 20mm² SDD droplet Peltier cooled detector with internal collimator has been produced by the PNDetector Company with a 128 keV energy resolution at 5.9 keV. Also, the Department of Electronics of the Milano Politecnico has realized and produced a preamplifier and SDD biasing and a pulse-shaping amplifier particularly suited to be associated with the SDD droplet detector. Then, a collaboration has been started to modify the present LNS PIXE-alpha spectrometer in order to improve its characteristics and in particular the energy resolution. The power supply and the mechanical assemblage has been realised by the technical and electronic staff of LNS. A second Peltier has been also added to the system.

THE DEVICE DESCRIPTION

The spectrometer device consists of two main components: *The Detector Holder* and the *Electronic Control Box*.

The Detector Holder includes: the SDD detector, the preamplifier and the cooling system.

-The SDD detector

“PNDetector GmbH: SD3-20-128pnW-BeW-iC. Active volume 20mm²×450 μ m. TOX socket. Internal collimator ϕ =4,6 mm”.

-The preamplifier and SDD biasing (Milano Politecnico)

“Allows the best resolution tested down to 124eV @ Mn-K α ; very low degradation at high counting rates: <4eV at 150Kcps; very high peak stability at high counting rate<0.1% at 300kcps; very high bandwidth; rise time 50 ns; automatic biasing of any SDD; Internal or external pulse-reset”.

Fig.1 shows a schematic view of the *Detector Holder*.

The SDD detector is assembled on a copper cold finger which is in thermal contact with a second Peltier. The typical working temperature is -20° C.

The *Detector Holder* is connected to the *Control Box* by shielded multiwire cable that feeds out the preamplifier the output signal, the control signal, the power supply and the detector bias supply.

The Control Box contains the power supplies, the controls and the monitor systems developed by the LNS electronics staff.

-The low noise preamplifier and pulse shaping amplifier power supply, was realized to fulfil the requirements of energy resolution. Special toroidal transformer, low noise voltage regulator and low pass filter have been used.

- The Peltier Power Supply was designed to take into account the vicinity of Peltier 2 to the detector and the large current required.

-The High Voltage Detector Bias was realized by the use of a “floating common” electronic configuration followed by a 3 cell 6 DB/decade low pass filter.

- The voltage start-stop control was realized to avoid detector damage. Besides, an “Interlock circuit” was designed to prevent power failure.

- The temperature monitoring is shown on digital display, that allows a continuous detector temperature control.

The *Control Box* contains also:

- The Pulse shaping amplifier board (Milano Politecnico) “5th order semi-gaussian shaper; Two shaping time resolution: 1 μ s, 25ns. Gain regulation; Base line restorer.

Interface with MCA-POLI, MCA8000 Amptec, FAST M. “

RESULTS

Fig.1 shows a schematic views of the upgraded spectrometer. The second Peltier is visible on the top and the new alpha source, produced by the LNS Alpha Laboratory [3], is applied on the front of the apparatus. The Peltier current (temperature) can be controlled. Also, it is possible to connect directly the preamplifier exit to an external spectroscopic amplifier.

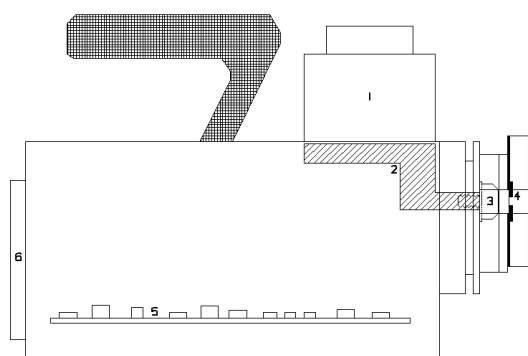


Fig. 1: The detector holder. 1) the second Peltier; 2) the copper cold finger; 3) the 20mm² SDD droplet detector; 4) the ²¹⁰Po alpha source; 5) the pre-amplifier; 6) input-output connector.

The system has been assembled, tested and the energy resolution optimized with the assistance of the Electronics Department of the Politecnico and of the XGLAB, a spin off of the Milano Politecnico, staff.

The energy resolution of 128 keV @ Mn-K α and 82 keV @ Si- K α has been easily achieved.

CONCLUSIONS

The use of a new SDD droplet detector, associated to the suitable electronics and a double Peltier, has allowed the spectrometer PIXE-alpha to reach the 128 keV X-ray energy resolution. This result would substantially improve the analytical capabilities of the system.

ACKNOWLEDGEMENTS

Thanks are due to dr. R. Alberti of the Electronics Department of the Milano Politecnico and of XGLAB for the invaluable contribution given in all the phases of realization and test of the present system.

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A new version of the 210-Polonium source realised at the LAB-alpha laboratory of the LNS-INFN

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Abstract – In this contribution we describe a new version of the portable 210-Po source realised at the LAB-alpha laboratory of the LNS-INFN of Catania (Italy).

The new geometry of the 210-Po source was designed in order to improve the counting statistics of the acquired x-ray spectra in comparison to the previous versions.

Table 1 reports the dimensions of the new source compared to the ones of the previous source. The designed geometry was preliminary simulated by performing Montecarlo calculations; the estimated gain factor was equal to 9-10.

A schematic view of the new source is shown in Figure 1.

INTRODUCTION

Since many years the LANDIS group of the LNS started to study the feasibility of a low-activity 210-Po source for PIXE applications in the Cultural Heritage field [1,2]. The research activity allowed to realise an innovative portable PIXE-alpha spectrometer particularly suited for the quantitative analysis of pigments and precious covering in ancient metals (gilded and silvered artefacts)[2]. The portable PIXE-alpha system of the LANDIS laboratory was successfully used in many in situ measurements [2-7].

In this contribution we describe a modified version of the portable 210-Po source presenting an high geometrical efficiency. The new geometry was designed in order to have an high count rate during the measurements and, due to the large spot size of the source, to analyse large and homogenous surfaces.

The new source was entirely realised at the LAB-alpha facility of the LNS laboratories.

DESIGN AND REALISATION OF THE NEW 210-Po SOURCE

The aim of this research was the development of a 210-Po source with a large geometrical efficiency to be used in PIXE measurements at the LANDIS laboratory.

The annular geometry of the source, and in particular the annulus in which polonium is deposited, was maintained with respect to the previous sources [2]; the internal/external diameters of the 210-Po deposit as well as the source-sample and sample-detector distances were opportunely changed.

Moreover, the source was designed in order to be coupled to a large active area SDD detector (50-100 mm²); this will allows to obtain a gain factor (in terms of counting statistics) equal to 8-10 compared to the previous versions.

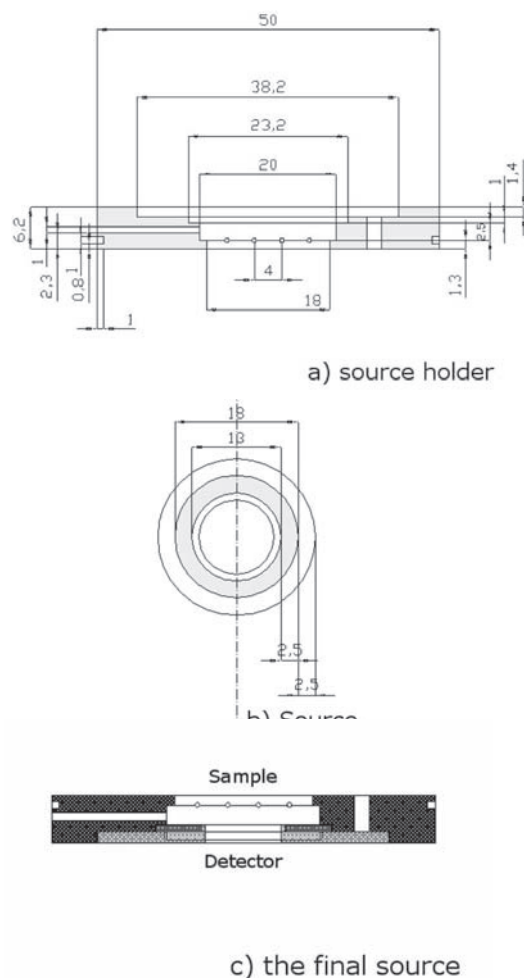


Figure 1 – The schematic view of the Large 210-Po source (all dimensions are in mm): a) the holder of the source; b) the annular source. The area in which polonium is deposited is visible; c) the final packaging of the source.

Distances	Large PIXE-alpha (mm)	Standard PIXE-alpha (mm)
Source-sample distance	3.8	4.3
Sample-detector distance	6.2	6
Internal/external diameter of the 210-Po deposit	13/18	5.5/10
Spot size diameter	18	7

Table 1 – Dimensions of the new 210-Po source in comparison with the previous one.

The ^{210}Po source was realised at the LAB-alpha laboratory by using the manipulation procedure already developed and optimized during the collaboration INFN-CEA for realising the previous radioactive sources [8].

The procedure is based on the spontaneous deposition of the polonium (in liquid solution with 2M HCL furnished by the Eckert & Ziegler Isotope Products Laboratories) on a silver backing (0.2 μm thick) previously evaporated on a Mylar support. Typical efficiency for the deposition are 95-98% of the initial activity of the liquid radioactive solution. In the case of the new source the deposition was performed by using a polonium solution with a starting activity of about 55MBq.

At the end of the deposition - lasting about 1 hour - the source is sealed by using a 2 μm thick KAPTON foil, glued on the deposited polonium by means of an epoxy resin. Finally, the source is encapsulated on its own package.

Figure 2 shows the manipulation of polonium in the glove boxes of the LAB-alpha laboratory. The source in its final packaging is visible in figure 3; the annular ring in which polonium is deposited is clearly visible.



Fig. 2 – The manipulation of the source into the glove-box of the LAB-alpha laboratory



Fig. 3 – The polonium source in its final packaging

In order to test the new source, measurements on geological standard were performed. The source was coupled to a 50 mm² active area SDD detector (139 eV energy resolution); the acquisition chain consisted of a standard spectroscopy amplifier (mod. 672 by ORTEC) and portable MCA analyser (MCA8000A by AMPTEK). Figure 4 shows the characteristic x-ray spectrum obtained in 30 minutes by measuring the Sco-1 geological standard.

The compact geometry of the source and the presence of the He atmosphere, allow the detection of the low energy lines of light elements starting from Na; also, the Ar-K α line at 2.957 keV - visible when operating in air - is strongly reduced.

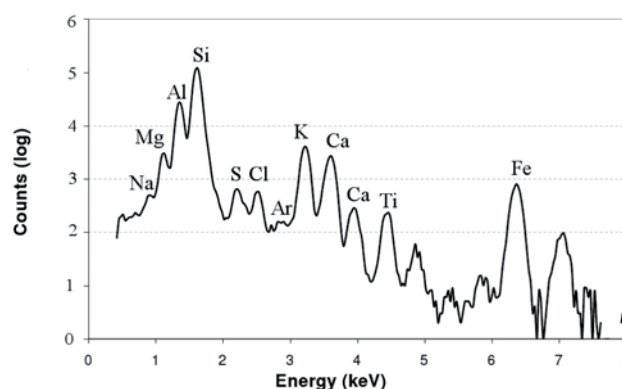


Figure 4 – The PIXE spectrum of the SCo-1 geological standard

The net counts obtained by fitting the x-ray spectrum, were compared with those measured, at the same measurement time, with the previous version of the source.

Table 2 summarizes the results of elements emitting characteristic x-rays at different energies; a gain factor of 11-12 was obtained.

Element/x-ray energy	Portable L-PIXE alpha	Portable PIXEalpha	Gain Factor
Si-K α (1.74 keV)	486396 $\pm$ 714	37950 $\pm$ 202	12
Ca-K α (3.69 keV)	11053 $\pm$ 111	959 $\pm$ 34	11.5
Fe-K α (6.40 keV)	4101 $\pm$ 61	368 $\pm$ 20	11.2

Table 2 – The net counts of x-rays coming from element of different atomic number present in the SCo-1 standard. Data are compared with those obtained by the standard PIXE-alpha.

CONCLUSIONS

A new version of the ^{210}Po sources, realized at the LAB-alpha facility of the LNS-INFN, was described. The source was tested by measurements on reference standards. A gain factor (in terms of counting statistics) equal to 11-12 was obtained in comparison to the previous version of the system. It must be evidenced that, due to the large spot size, the use of the present source should be limited to perform PIXE measurements on large and homogeneous surfaces.

ACKNOWLEDGEMENTS

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Quantitative analysis by using the XPIXE-alpha spectrometer of the LNS-INFN

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Abstract - The XPIXE-alpha (X-ray Fluorescence and Particle Induced X-ray Emission) is a portable spectrometer, developed at the LNS-INFN laboratories, that makes use of a ²⁴⁴Cm radioactive source as alpha particles and X-ray emitter [1]. In this contribution we present a preliminary method to perform quantitative analysis of thick homogeneous samples.

INTRODUCTION

Dedicated software to perform quantitative analysis for the PIXE mechanism (es. Gupix code) [2] or XRF mechanism [3, 4] are well known. In the case of the XPIXE-alpha spectrometer both alpha particles and X-rays are used as incident beams and standard software cannot be used. Some attempts have been made [5, 6, 7] to produce a specific software for similar spectrometric systems used in Mars Exploration Rover mission and some limitations have been evidenced [6, 8].

In ref. [1] we suggested an approach in which, after a first measurement, a second one is performed by using a 25 microns Kapton foil to absorb the alpha particles: the obtained data are subtracted from the previous ones, therefore the resulting spectrum is due only to the alpha interaction and can be then analysed by the GUPIX software. This method has two limitations: a) two independent measurements must be done exactly in the same conditions; b) the differences between large net counts are affected by a large statistical uncertainty.

In the following we describe a method which is based on the comparison of an unknown sample spectrum with a set of geological reference standards spectra.

THE METHOD

First of all we have assured a reproducible [9] geometrical apparatus as it is shown in Fig.1. The positioning is assured within a ± 0.2 mm. The samples are powdered and pellets are obtained by using the standard procedure as in the traditional XRF measurements of geological samples. The reproducibility of the beam current and the incident energy is assured by the use of the ²⁴⁴Cm radioactive source.

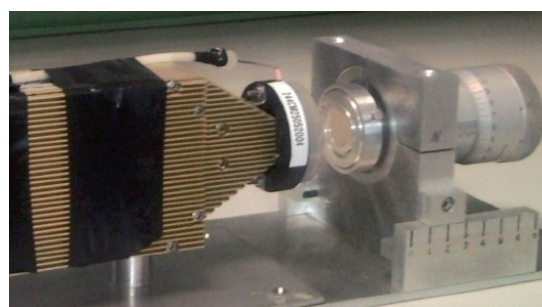


Fig. 1: The micrometric system for ensuring the geometrical reproducibility

We have measured the X-ray energy spectra of the following 22 reference geological samples (later on the indicated as RGS) produced by USGS (United State) and CNRS (France). They are named as AGV-2, AN-G, BCR-2, BE-N, BIR-1, BR, BX-N, DNC-1, DR-N, FK-N, G-2, GA, GS-N, GSP-2, MAG-1, MA-N, MICA-Fe, MICA-Mg, SDC-1, STM-1, W-2, SCO-1.

The measuring time was 3600 seconds. Much care has been devoted to ensure the same positioning between the sample and the hole of the spectrometer head.

The intensities of the X-ray lines were extracted by using the fitting procedure implemented in the QXAS AXIL code [3, 4]. To evaluate the concentrations we proceeded through the following steps:

- i) we assumed as unknown sample one of the 22 reference samples;
- ii) we calculated the square of the relative deviations between each peak intensities of the unknown sample and the corresponding ones for each of the above RGS;
- iii) we defined as similarity index (SQM) between the unknown and each of the reference samples, the square root of the mean value of the above results;
- iv) we obtain the elemental concentrations of the unknown sample by considering a linear dependence between its line intensities and the ones of the RGS that evidenced the lower SQM.

The above procedure has been repeated for each of the reference samples.

Fig. 2 (a-d) shows the calculated concentration values for all the elements of overall samples compared to the certified ones at different SQM ranges. As it is expected a

better fit is obtained for the lowest similarity index (see Fig. 2d).

However it is evident from the data of Fig. 2d that, to improve the agreement, a larger number of standards must be used. Also, attempts will be undertaken to better take into account the matrix effects [8] and to estimate the effects of counting and fit errors.

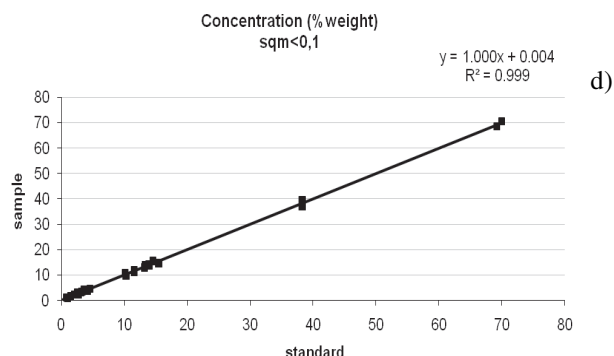
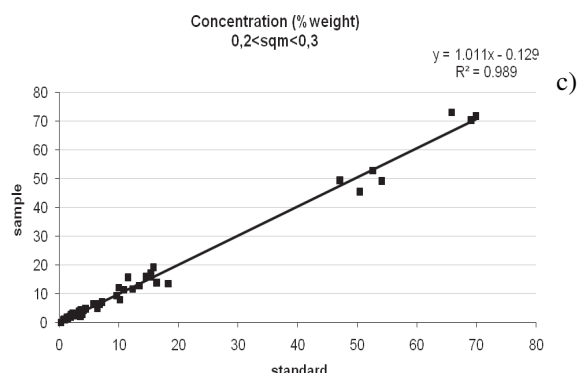
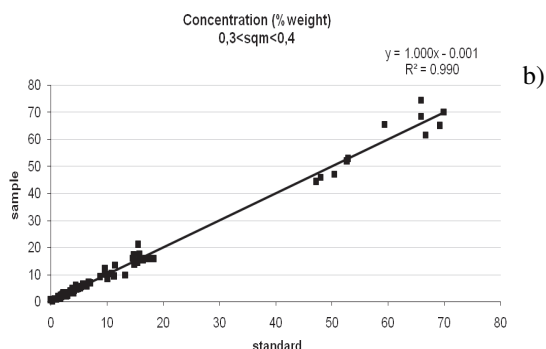
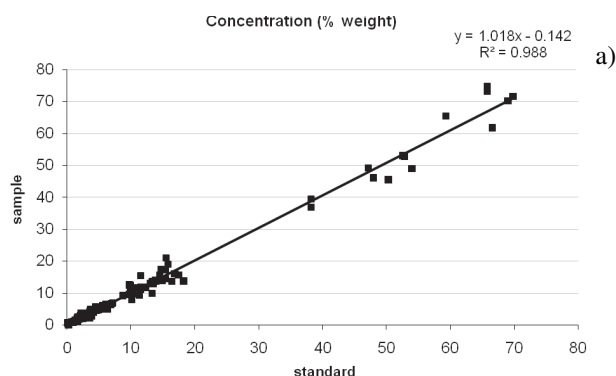


Figure 2 (a-d): Comparison between the samples concentration (y axis) obtained with the described method and the certificated values (x axis).

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Investigation of a new method based on High Energy Proton Induced Gamma Emission (HEPIGE) for the non-destructive global analysis of ancient alloys of archaeological interest

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Abstract — The paper describes the preliminary results of a new method based on the use of 62 MeV energy protons to perform a non-destructive global analysis of archeological metals. It is well known that ancient alloys are characterized by strong in-homogeneities and their global composition is difficult to measure with the some of most used non destructive methods (XRF, PIXE or PAA).

The new technique - named HEPIGE method - consists in the detection of prompt γ rays emitted in (p,p' γ) inelastic reactions occurring during the irradiation of 1-1.5 mm thick metallic samples.

The cross sections for inelastic processes at such incident energies are constant across the target even if the energy loss of protons is up to 10-12 MeV.

Due to this cross section behavior and to the energies of the induced γ -rays, the HEPIGE technique allows to determine the global concentration of the elements composing the alloy even in the case of in-homogeneous samples.

INTRODUCTION

It is well known that the analysis of ancient metals can give useful information to archaeologists and conservators: for example, the knowledge of the chemical composition of the alloy allows the study of the techniques used to produce the artefacts; the determination of the trace elements, especially in objects realised with native metals, helps to determine the provenance of the raw materials; besides, the study of the noble metals content allows to obtain information about the economic evolution of a region.

The investigation of metal concentration is affected by the presence of in-homogeneities which, in some cases, could be very important. The corrosion and oxidation patinas in copper-based alloys; the manufacturing techniques and their associated metallurgical processes; the presence of enriched coverings (gilded or silvered objects) can induce strong variation of the surface composition up to a depth of 200 microns [1-3].

Even if a destructive approach allows to obtain accurate and detailed quantitative information about the composition and structure of the alloy under investigation, the use of non destructive techniques is mandatory when a large number of artefacts must be analysed or when the analysis deals with objects that must be preserved for their historical and artistic value.

The most used non-destructive techniques are either surface techniques like Particle Induced X-ray Emission and X-Ray Fluorescence (PIXE and XRF) [4-5] or techniques like the Proton Activation Analysis (PAA) [6-7] which can be strongly influenced by the surface composition. In general, their results cannot be considered representative for the original alloy composition.

In the last years, at the LNS Laboratories, many efforts have been dedicated to the developing of new complementary non-destructive methods – i.e. the PIXE-alpha technique [5] and the Deep Protons Activation Analysis (DPAA) [8] - allowing to investigate and characterise the surface (a layer 3-5 microns thick) and the interior (a region from about 350 to 650 microns inside the body) of the alloy composing archaeological objects [5,8,9].

These techniques have been successfully applied to the determination of the Ag content in the patina and in the core of bronze Roman *nummi* (a typology of coin presenting a thin silvered patina on the surface) dating back to the 294-333 A.D. and belonging to the Misurata Treasure (Libya), still under study by the LANDIS group of the LNS in collaboration with the Italian CNR and the Libyan Department for the Antiquities [9].

However, that protocol of analysis does not allow to obtain information about the global elemental composition of the alloy. In fact, the region between the surface (about 5 microns) and the interior (about 350 microns) cannot be properly investigated by those techniques and therefore no information about the total content of each element can be obtained. The new HEPIGE method is devoted to solve this lack in the analytical results.

The HEPIGE can be considered as an alternative method to other techniques - i.e. NAA or PGAA - devoted to the bulk analysis of samples. The method gives the possibility to analyse artefacts of large dimensions; however, neutron based techniques present detection limits that, at the present time, are difficult to obtain with the HEPIGE.

THE HEPIGE METHOD: PRINCIPLES AND PRELIMINARY EXPERIMENTAL TEST

A 62 MeV protons beam opens up the possibility to investigate, in a new non-destructive way, the chemical composition of metals.

In the case of ancient objects, the most widespread alloy was bronze, composed of Cu, Sn, Pb at different

concentrations; often the presence of others metals, like Ag (in silvered bronze) or Zn (in brass) were used to realise artefacts.

The global weight concentration of each of the above elements can be investigated by means of high energy protons since they allow to excite uniformly the target nuclei across the whole thickness of samples under analysis. This gives the possibility to correctly take into account the in-homogeneities present in ancient metals.

Using a 62 MeV proton beam different nuclear reactions can take place. However, direct nuclear reactions, and in particular the (p,p'X) inelastic processes (being X = γ , p, n, 2n,...), are particularly suitable to perform the elemental analysis of the thick metallic targets. At such incident energies these processes present high cross sections [9] almost constant across a target of about 1-1.5 mm. The energy loss of protons in such a thickness is about 10-12 MeV.

Then target nuclei are uniformly excited by protons across the target and prompt γ -rays are emitted in their decay processes. The detection of these photons gives a clear signature of the elements composing the target and allows to investigate their global concentration also in case of in-homogeneous samples. Since the energy of these prompt γ -rays is up to 1-1.5 MeV, the absorption in the target can be neglected and no corrections are necessary in the data analysis.

A feasibility test of the HEPIGE measurements was performed in the 2010. In order to select among the large γ yield the photons produced in direct inelastic processes, p'- γ coincidence measurements were planned to be performed.

Preliminary GEANT 4 simulations of the inelastic cross section across a pure copper target 2mm thick using 62 MeV incident proton are shown in figure 1. The results show that the inelastic cross section is reasonably constant up to a thickness of 2 mm, supporting the validity of the method.

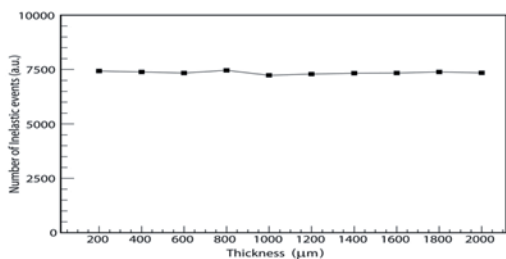


Figure 1 – The simulated inelastic cross section of (p,p'X) reactions across the thickness of a pure copper target.

The HEPIGE method was tested experimentally by irradiating a 2 mm thick copper target with the 62 MeV protons delivered by the CS accelerator of the LNS-

INFN. The beam current used was about 50 pA; the irradiation time lasted 30 minutes for each sample.

The experimental set-up consisted of a DE-E telescope (Si-CsI(Tl)), placed at forward angles at about 30°, and two HPGe detectors placed at backward angles. The telescope was used to detect protons in coincidence with γ -rays emitted in the de-excitation process of the alloy nuclei following the inelastic reactions.

Figure 2 shows a schematic view of the experimental set-up.

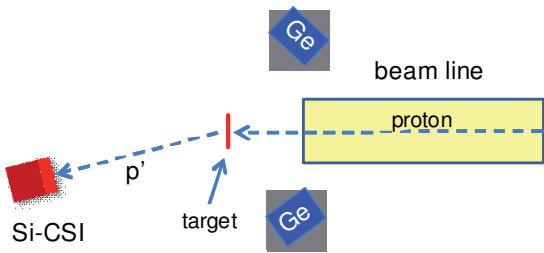


Figure 2 – The schematic view of the experimental set-up

Table 1 summarizes the effect of the set-up geometry on the beam energy loss and straggling. Energy loss has been determined by using the LISE code. The exit window of the beam line was made of a 75 μ m thick Kapton foil; the proton energy loss in this windows is about 0.1 MeV.

	Thicknesses	Energy Loss	Straggling
Kapton -Target (air path)	71 cm	0.81 MeV	0.065 MeV
Target (pure copper)	2 mm	10.3 MeV	0.36 MeV
Target-Telescope (air path)	45 cm	0.62 MeV	0.051MeV
Target-HPGe's (air path)	35 cm	Detection of γ -rays	n.d.

Table 1 – The experimental parameters used to perform the HEPIGE test.

Inclusive and coincidence data were acquired during the experiment. The analysis of coincidence data is still in progress and will be completed by the data of the new measurements scheduled in 2011.

As a preliminary result, the inclusive data were studied. The gamma spectra measured with the HPGe detectors were filtered by selecting only the events where an inelastic proton was detected in coincidence. This procedure allowed to improve the peak/background ratio

and helped to better identify the γ lines to be used for the analysis of unknown samples. However, some background events can be present in the filtered data.

Figure 3 shows the energy spectrum of inclusive protons detected by the CsI detector. The elastic/inelastic peak is clearly visible in the spectrum; it should be noted that, due to the large energy loss of protons in the thick copper target, the contribution of the elastic process can not be separated from the inelastic one. In any case, elastic processes do not produce γ -rays. The window chosen for filtering the inclusive γ -rays spectra is also shown in the figure.

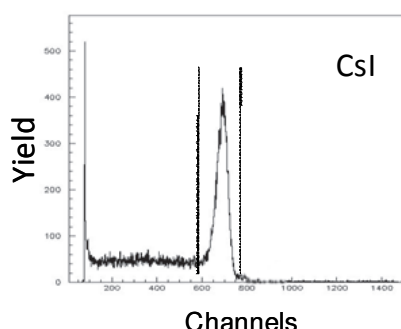


Figure 3 – The protons energy spectrum acquired by the CsI detector

Figure 4 shows the γ spectrum obtained in the HPGe detectors by using the above mentioned filter.

Gamma-ray spectrum detected in coincidence with inelastic protons

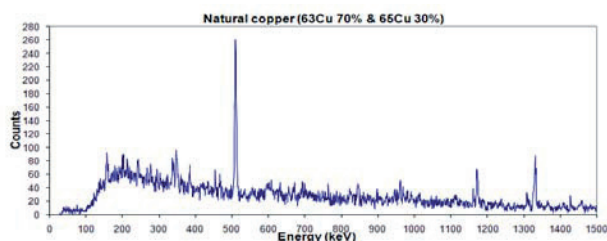


Figure 4 – The filtered γ spectrum

The γ lines visible in the spectra represent the main candidates for the HEPiGE analysis of pure copper.

Figure 5 shows the identification of the γ lines of both low and high energy regions of the γ spectrum of figure 4.

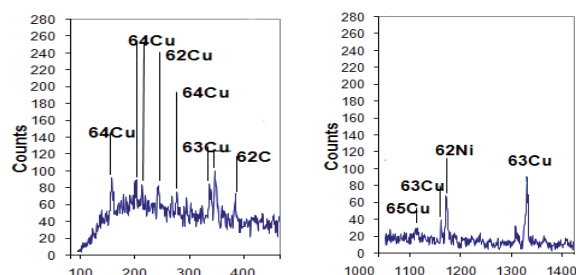


Figure 5 – The low energy region (left) and high energy region (right) of the filtered γ spectrum of fig. 4.

Finally, the residual activity of the measured samples was monitored at the Radioprotection Service of the LNS. This allowed to estimate a quarantine time of 10-15 days in order to consider the irradiated objects as radiologically irrelevant.

CONCLUSIONS

The feasibility of the HEPiGE method, devoted to the analysis of archaeological metals, was investigated through a preliminary experiment performed by using a 62 MeV proton beam delivered by the CS accelerator of the LNS.

A 1.5 mm thick copper target was irradiated with 50 pA current and for 30 minutes.

Due to the behavior of the cross sections of the (p,p') inelastic processes in the irradiation of thick target, p'- γ coincidences were selected as a tool for the compositional investigation.

The preliminary analysis of the γ spectra, properly filtered by the events where inelastic protons were detected, shows the presence of γ lines useful to perform the analysis. The quantitative analysis of the irradiated samples is in progress.

The latter will be performed in the next experiment, scheduled in 2011, and it will be based on relative measurements of unknown samples with references standards, irradiated at the same experimental conditions.

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The non destructive analysis of Nasca pigments from Cahuachi (Peru) by using the PIXE-alpha and XRD portable techniques

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Abstract — An analytical protocol based on the combined use of the portable PIXE-alpha and XRD non destructive techniques developed at the INFN-CNR LANDIS laboratory of Catania (Italy), was applied for the characterisation of the surface paints of some archaeological fragments of Nasca pottery from the site of Cahuachi (Peru).

Measurements were carried out on the black, white, red, orange, red grey pigments; quantitative information on the chemical composition as well as on the mineralogical phases present on the paints were obtained.

Results allowed to make some considerations about the materials and the manufacturing technique used to realise such fired pigments.

It should be noted that during firing the precursor minerals composing the pigments undergo a phase transformation and their identification present some difficulties.

INTRODUCTION

The analysis of ancient mineral pigments provides information to archaeologists both on the technology and on the materials used in antiquity to realise artworks; moreover analytical results can be used to evidence the differences in the artistic and cultural evolution occurred during the time at different geographical regions.

The polychrome Nasca pottery, realised at the Ica and Nasca valley in south coastal Peru from the 100 B.C. to A.D. 650, represents one of the most interesting cases in which different minerals and a well established technology were used to produce a large variety of color shades [1,2].

The ceramic production of the Nasca have been largely investigated in the past [3-5]. However, only a few analyses, performed by using destructive methods, concern the chemical composition of the fired pigments [6].

A non-destructive approach and the use of portable instruments for determining both the chemical and to the mineralogical composition of pigments, should be mandatory when a large number of samples must be investigated or when the analysis refers with well preserved artworks that can not be moved, due to their artistic and historical value, to the laboratories.

In the last years at the LANDIS laboratory of the LNS-INFN and IBAM-CNR of Catania (Italy) many efforts have been dedicated in order to realize innovative

portable PIXE-alpha and XRD systems for in situ applications in the cultural heritage field [7-9].

Recently, these systems have been combined for the quantitative investigation of ancient mineral pigments [10].

The PIXE-alpha technique, due to its analytical depth of a few microns, (about 15 microns in a clay-based matrix as in the case of the Nasca pigments), is particularly suited for the elemental analysis of the painted surfaces. This way the investigation concerns mainly the pictorial layer and the substratum contribution is strongly reduced. In addition, the mineralogical nature of pigments can be investigated by the use of our portable XRD technique.

By combining results obtained by both non-destructive methods it is possible to quantitatively determine the paints composition.

In the present work the pigments present in some fragments of Nasca pottery from Cahuachi (Peru), have been analysed.

The PIXE-alpha and XRD measurements focused on the chemical and mineralogical characterization of the different shades of white, black, red, orange and grey pigments.

The research has been performed within the scientific activities carried out by the ITACA mission (Italian mission of heritage Conservation and Archaeogeophysics) of IBAM-CNR in Peru.

In view of a systematic in situ analysis of the polychrome Nasca artworks at Cahuachi, the present results allowed to evidence the potentiality and the limits of using the cited non-destructive techniques for the analysis of fired pigments.

EXPERIMENTAL

The non-destructive analysis of ancient mineral pigments should be performed by using appropriate methods.

Fired pigments are painted on the pottery surface in a layer of about 20 μm thickness or more, depending on the pottery typology [11,12]; however, variations down to a few microns can be observed even if they usually can be attributed to irregularities of the painted surface [13].

In order to minimize the substratum contribution in the experimental data, measurements must be performed by using techniques with a sharp analytical depth. Moreover, pigments are minerals and the use of elemental techniques can not suffice for a correct identification; the chemical characterization of the

pigments should be combined with the mineralogical analysis.

Finally, the fired pigments (like in the case of the Nasca pottery) change their mineralogical phases during firing and the resulting minerals can not be the same as the original ones [12,14]. In this case data interpretation should be performed with particular attention in order to typify correctly the precursor materials.

Recently, many efforts have been made at the LANDIS laboratory, in order to develop complementary non-destructive methods for performing the quantitative analysis of ancient pigments. An analytical protocol based on the combined use of the portable PIXE-alpha and portable XRD systems was developed and used in some archaeometrical applications [10].

Such systems were used for the analysis of the Nasca pigments of the present paper.

The portable PIXE-alpha system [7] consists of a low activity ^{210}Po radioactive source emitting alpha particles of 5 MeV energy coupled to a 20 mm² active area SDD detector with 138 eV energy resolution at the reference line of 5.9 keV. The spot size of the alpha beam on the irradiated sample is 7 mm diameter allowing the analysis of small dimension samples. Finally, the presence of an helium flux during the measurement allows to detect the low energy x-rays up to about 1 keV.

At the present time the polonium PIXE source is entirely developed and realised at the LAB-alpha facility of the LNS-INFN.

The portable PIXE-alpha system is particularly suited to perform the quantitative chemical analysis of the elements composing painted surfaces. As mentioned above, its analytical depth in a clay-based matrix is limited to about 15 microns (such a value was estimated by means of SRIM calculation). Typical measurement time is about 30 minutes. The spectra detected by the portable PIXE-alpha system can be quantified by using the standard GUPIX code [15].

The portable XRD system was realised by installing on a commercial goniometric system a microfocus x-ray source equipped with modular x-ray optics and a Si-PIN detector, placed in a theta-theta geometry [8-9]. The 2 θ angular range allowed to be investigate is 24°-140°.

The x-ray source consists of a Fe anode microfocus tube (produced by the German IFG) with a 50 μm spot sizes; it is coupled to a polycapillary semi-lens that allow to obtain a parallel x-ray beam with high intensity and a reduced divergence of 0.26°. Such a x-ray source allows to operate the diffraction of the samples with an angular resolution of 0.12° (that can be compared with the ones of laboratory XRD system) and rapid measurement time (40-60 minutes) [9]. However, due to the very low power of the compact x-ray microfocus source (only 10 W), such a system can be used mainly to determine the major phases of the

sample under investigation, being the detection limit about 2-4%.

The x-ray spot emitted by the modular polycapillary semilens is 6 mm in the normal direction. However, the illuminated area at the lowest diffraction angles is significantly larger (about 2 cm) limiting the possibility of performing analysis of small dimension samples.

Recently a new modular slightly-focusing polycapillary optics was added to the portable XRD system; the spot size at the normal direction is limited 100 μm . The new optics allows the analysis of small dimension samples (up to 5 mm) even if measurement time is longer (about 2 h).

The detection of the diffracted x-rays is performed by using a 25 mm² active area Si-Pin detector (190 eV energy resolution) equipped with a 1 mm wide slit.

The portable XRD has been successfully characterised to be used in the mineralogical investigation of the pigments most used in the antiquity [9]. Moreover, thanks to its goniometric geometry the samples can be placed externally to the system and whole artworks (like frescoes or wall paintings) can be easily analysed *in situ*, without the necessity to perform destructive sampling from its surface.

The analytical protocol used for the chemical and mineralogical characterization of the pigments is detailed in ref. [10]. It is briefly summarized in the following.

A preliminary PIXE-alpha measurement on a unknown sample allows to qualitatively identify its chemical elements (starting from Na).

Since the matrix composition (composed of light elements in the case of pottery) is not known, the quantitative analysis is not allowed.

Then, an XRD measurement, in the same position of the previous PIXE-alpha one, is performed. The search/match of the obtained diffraction pattern is carried out by limiting the analysis to those phases containing the chemical elements already evidenced by PIXE-alpha. Such a filter allows to reduced the search only to a few phases, limiting the uncertainties during the identification of the minerals.

Finally, the XRD data are used to estimate the matrix composition of the pigments that, in turns, can be used to quantify the PIXE-alpha spectra.

The analytical protocol was tested by measuring a reference material constituted by 50% of SiO₂ and 50% of CaSO₄ [10]: the PIXE spectrum clearly evidenced the presence of Si, S and Ca characterising quartz and gypsum. Oxygen is not detectable by PIXE. The subsequent XRD measurement allowed to identify the mineralogical phases (quartz and gypsum as expected) and to establish the presence of light elements (oxygen) to be used, with the correct stoichiometry, in the quantification of the PIXE spectrum. The final GUPIX calculation of the PIXE measurement resulted 50.9 $\pm$ 3% for SiO₂ and 48.3 $\pm$ 4 % for CaSO₄.

PIXE-ALPHA AND XRD ANALYSIS OF THE NASCA PIGMENTS

The different pigments of Nasca pottery fragments, analysed by combining the portable PIXE-alpha and XRD non destructive techniques, are shown in Figure 2.

The elemental composition of the pigments was obtained by the PIXE-alpha measurements.

In all the samples the presence of major Al and Si, minor Mg as well as the presence of K, Ca and minor Ti was detected.

The presence of these elements, typically composing clay pastes, can be attributed to the manufacturing technique [1,2].

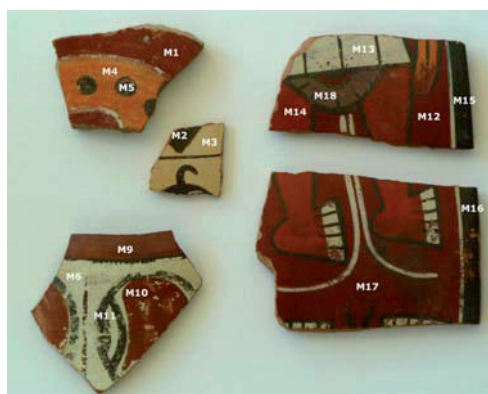


Figure 2 – The investigated pigments present on the Nasca fragment from Cahuacy (Peru). The position of the PIXE-alpha and XRD analyses is indicated.

In fact, as already established by other authors, the Nasca introduced the thick slip paints technology made by mixing the finely ground mineral pigments to a fine suspension of clays; these slip were applied before firing in order to ensure their adherence with the pottery surface [1,2]. However, irregular thickness or in homogeneities on the painted layer can not be excluded especially for buried objects.

In all the samples, the white pigments are characterized by an high Ca content; the black ones by Fe and minor Mn; the red, orange and grey by high Fe content.

The XRD patterns obtained in the subsequent measurements (performed on the same positions of the PIXE-alpha ones) were analyzed using the PIXE-alpha qualitative data as chemical filter in the phases recognition. This approach allowed to significantly reduce the number of phases to be investigated in the search/match procedure, strongly reducing the possibility of erroneous attribution.

Calcium was the main component characterizing the white pigments. Gehlenite was systematically present in the XRD data; it forms completely at 850-900°C by firing a mixture of calcite and clays [12,16]. A comparison of the diffraction pattern of M3, M6 and M13 samples is shown in figure 4.

Such a mineral was observed in the analysis of similar fired white paints of pottery from the Aguada culture (Argentina) [12].

It should be evidenced that the above estimation of the firing temperature must be considered only qualitative in the case of our portable XRD. As mentioned in the previous section, our instrument is able to detect mainly the major phases; consequently the coexistence of gehlenite with minor phases of calcium minerals at lower temperature (like calcium oxides or carbonates) can not be detected. Also, higher firing temperature can not be a priori excluded.

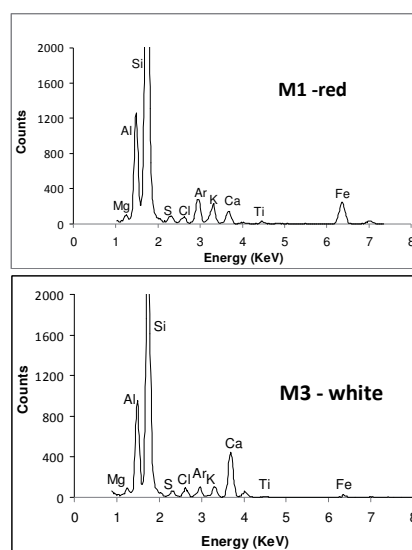


Figure 3 – The PIXE-alpha spectrum of a white and of a red pigment. White is characterized by calcium; red by the iron presence.

Black pigments (M2, M1, M5, M15 and M16), characterized in the PIXE-alpha spectra by the presence of Fe and Mn, resulted composed of hematite and minor Mn oxides. The latter probably induce the dark shade to the pigment. The diffraction pattern of a black (M2) is shown in figure 5; the overlap between some diffraction lines of the Mn oxides to the ones of quartz and hematite make difficult the mineralogical identification.

Red paints (M1, M9, M10, M1 and M17) as well as orange pigments (M4 and M14) and grey pigment (M18) are clearly characterized by hematite.

The extensive use of iron oxides for producing pigments was already established during the Nasca period [17].

However the identification of the original coloring minerals is difficult to be performed in the fired pigments. In fact, as clearly evidenced in ref. [14], the most of the iron oxides used in antiquity for producing pigments change their mineralogical phase to hematite during firing.

Red paints were most probably realized by using a red ochre. Orange pigment by the use of goethite or

jarosite; in fact these oxides maintain a yellowish/red color when are fired mixed with clays below 900°C [14].

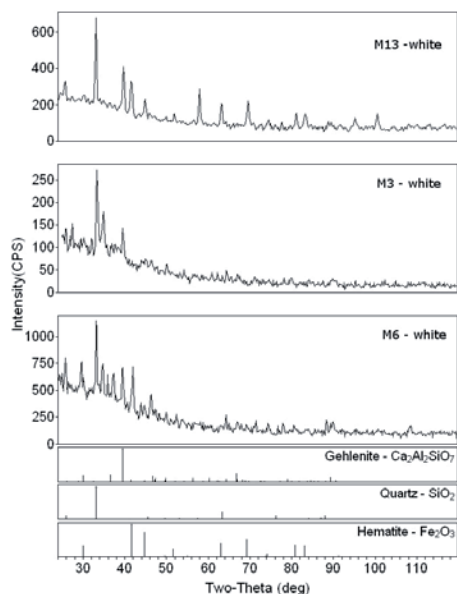


Figure 4 – Diffraction patterns of the white pigments. Gehlenite is present and suggest the use of calcite as precursor mineral. Also, hematite is present in the M13 sample.

Finally, the XRD analysis of the grey pigment (M18) showed the presence of both hematite and ghelenite; the use of the specular hematite (in this case mixed with calcite) have been already cited in ref. for the mineral used by the Nasca for producing their grey and light blu pigments in the slip paints [1,2].

The mineralogical phases indentified by the XRD analysis were used to construct the matrix needed to perform the quantitative analysis of the PIXE measurements.

Sample	Pigment	Al2O3	SiO2	SO3	K2O	CaO	TiO2	MnO	Fe2O3
M2	black	9.8	28.5	3.2	2.1	5.2		4.3	35.5
M5	black	13.1	36.7	1.2	2.0	4.3	0.5	3.5	34.6
M11	black	10.0	31.6	1.8	1.3	7.7	0.6	3.4	35.6
M15	black	10.1	29.9	1.8	2.5	3.6	0.3	2.6	39.3
M16	black	11.0	30.1	3.5	2.0	5.4	0.3	2.8	37.2
M18	blu/grey	13.4	35.7	2.7	1.9	7.2	0.4		28.3
M14	orange	14.2	48.9	1.4	3.5	4.6	1.1		16.2
M1	red	13.0	46.0	1.2	2.5	2.5	0.9		32
M9	red	12.3	44.8	1.5	2.1	7.0	0.8		24.4
M10	red	19.2	43.4	1.0	2.5	5.8	0.4		7.8
M12	red	9.8	31.1	1.2	2.1	3.5	1.4		38.7
M17	red	8.4	25.5	4.8	1.7	6.3	1.3		44.8
M3	white	16.6	51.0	1.7	2.6	17.6			5.1
M6	white	16.4	47.2	0.9	1.3	19.1	0.6		5.4
M13	white	14.5	44.6	1.3	2.0	9.6	0.7		6.0

Table 1 – Quantitative results obtained by the PIXE analysis. Errors are about 5-10%

Calculation have been performed by using the GUPIX code. Results are reported as oxides in table 1; since the investigate samples are fired this hypothesis can be

considered a working approximation. The errors on the concentrations are about 5-10% for the major elements. They are mainly due to the counting statistics and the fitting procedure. Mg and Na (only in few pigments) were detected but, due to the large errors, were not quantified

CONCLUSIONS

The combined use of the non destructive and portable PIXA-alpha and XRD techniques of the LANDIS laboratory, was applied for the chemical and mineralogical investigation of the fired pigments present on the surface of some Nasca fragments from Chauachi (Peru).

Results allowed a chemical and mineralogical characterization of different pigments –white, red, black, orange and grey - present in the investigated fragments. Moreover, by combining PIXE and XRD results, a quantitative analysis of the paints was possible.

White pigments were characterized by gehlenite, that forms by firing calcite mixed with clays. A systematic analysis of the white produced during the Nasca period is necessary in order to assess the use of other white pigments (mainly kaolin as suggested in previous work); black pigments were characterised by Mn and Fe minerals. Red, orange and grey by iron oxides (resulting in hematite phase after the firing).

The results obtaine evidenced the potentiality of using portable non destructive instrumnts for performing a systematic investigation *in situ* of the fired pigments in Nasca artworks. Limits (mainly due to the technology used to realised the fired pigments) have been also discussed in the text.

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Non destructive determination of the mercury content in the Roman *nummi* of the Misurata treasure (Libya) by using the portable BSC-XRF spectrometer

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Abstract — This paper reports the research activities performed by the LANDIS group at the Leptis Magna Museum (El-Khoms, Lybia) for the non-destructive characterisation of the Roman *nummi* belonging to the Misurata Treasure. These coins were produced in different official mints of the Roman empire in the period 294–333 A.D.

Measurements started in 2007 and continued as far as 2010. They were performed by using the portable non-destructive BSC-XRF spectrometer (the Beam Stability Controlled XRF) developed at the LANDIS laboratory. The main aim of the research was the determination of the trace elements in the alloy of the silvered *nummi*. The presence of Hg was systematically observed in the coins produced in a few specific mints and manufactured in the late period. This results can be considered as a preliminary evidence of the use of the mercury silvering technique to produce the silvered covering of the Roman *nummi*.

INTRODUCTION

The application of non-destructive techniques and the use of portable instrumentation developed at the LANDIS laboratory of the LNS-INFN and IBAM-CNR at Catania, has allowed in the last years, the characterization of the Roman *nummi* belonging to the Treasure of Misurata (Libya) [1-3].

The Treasure, preserved at the Leptis Magna Museum in El-Khoms (Libya), is one of the most important finding of coins in the Mediterranean area.

It is composed of approximately 108 thousand of Roman *nummi* in good condition. *Nummus* is a typology of Roman coin presenting a 1-2 μm thick silvered-enriched covering and a bronze core with a low content of silver.

Since coins produced in 12 Roman mints are present in the Misurata treasure, their analysis give the possibility to deal with some archaeological questions: a) the study of the silver content in the coins during the time; b) the study of the manufacturing techniques.

It is well known that the analysis of ancient metals present some complications related to the presence of strong in-homogeneities that are observed up to a depth of 200 microns from the surface [4-8]. They are due mainly to the corrosion and oxidation occurred during the burial (especially in copper-based alloys); to the presence of covering in silver or gold; to metallurgical processes associated to the manufacturing techniques. Even if a destructive approach allows to obtain accurate and detailed quantitative information about the composition

and structure of the alloy under investigation, the use of non destructive techniques is mandatory when a large number of artefacts must be analysed.

The non-destructive techniques frequently used for the analysis of metals are either surface techniques like Particle Induced X-ray Emission and X-Ray Fluorescence (PIXE and XRF) [1-2] or techniques like the Proton Activation Analysis (PAA) [3] which can be strongly influenced by the surface composition. In general, their results cannot be considered representative for the original alloy composition.

In the last years, at the LNS Laboratories, many efforts have been dedicated to the developing of new complementary non-destructive methods – i.e. the PIXE-alpha technique [3] and the Deep Protons Activation Analysis (DPAA) [2] - allowing to investigate and characterise the surface (a layer 1-3 microns thick) and the interior (a region from about 350 to 650 microns inside the body) of the alloy composing the *nummi*.

These techniques have been successfully applied to the determination of the Ag content in the patina and in the core of bronze Roman *nummi* [1-3,9].

Recently, the general interest has been devoted to the study of the manufacturing technique of *nummi*, and in particular to determine the process used to realise the thin silvered patina.

Previous metallographic studies supposed that copper segregation was probably the used process [10,11]. However, some XRF measures on the same typology of coins have evidenced, in a few isolated cases, the presence of traces of Hg, addressing the attention to the mercury silvering technique [12,13].

To better clarify this aspect a systematic study of the Roman *nummi* composing the Misurata treasure was undertaken by the LANDIS group from 2007. The activities continued annually up to the 2010.

Measurements were performed in situ, at the Leptis Magna Museum by using the BSC-XRF spectrometer (Beam Stability Controlled - XRF), equipped with a control of the energy and intensity stability of the x-ray beam used to irradiate samples [14].

The stability and reproducibility of the BSC-XRF measurements give the possibility to obtain accurate quantitative analysis without the necessity to perform continuous calibration with reference standards – to this day the system operates with a unique preliminary calibration. Moreover, the x-ray beam used to irradiate sample is particularly suited to excite both the major elements composing the *nummi* (i.e. Cu, Sn, Pb and Ag)

and some characterising trace element present in bronze alloy (i.e. Sb, As or Hg).

In this report we present the results obtained from the analysis of some trace elements (Hg in particular) of the 400 samples investigated up to this day.

THE PORTABLE BEAM STABILITY CONTROLLED XRF SPECTROMETER (BSC-XRF)

The new portable XRF spectrometer with the energy and intensity stability control is shown in figure 1, during the measurements of the coins at the Leptis Magna Museum.

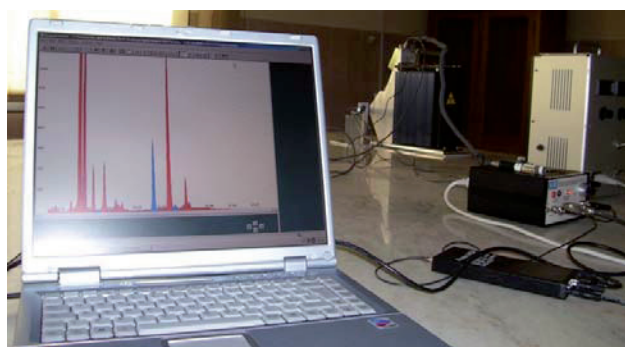


Figure 1 – The portable BSC-XRF spectrometer during the measurements at the Leptis Magna museum (Lybia)

A schematic view of the stability-control system is shown in figure 2.

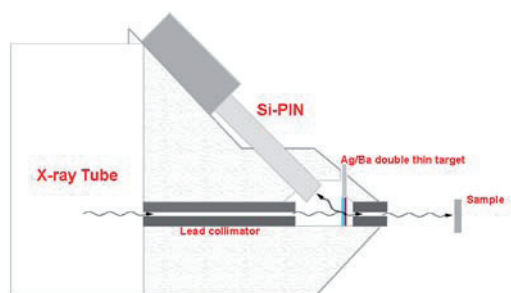


Figure 2- A schematic view of the stability-control system.

The spectrometer consists of a tungsten-anode portable x-ray tube (EIS company, $V_{\max}=50\text{kV}$; $I_{\max}=1\text{ mA}$) with a 0.8 mm Al output window coupled to an ancillary Si-PIN detector (AMPTEK company, XR-100CR) to control both the energy and intensity stability of the beam and of a second Si-PIN detector (AMPTEK company, XR-100CR) to acquire the characteristic x-ray spectra emitted by the sample being analysed. The system works in a fixed and compact geometry; both the tube-sample and sample-detector distances and the incident and take-off angles are fixed. A 3 mm diameter lead collimator is provided in order to focus the beam on a small area of the sample.

During a measurement the x-ray beam crosses the double thin target of Ag and Ba placed between the x-ray tube and the sample.

The method used to control the stability of the x-ray beam is not based on a electronic device operating on the applied high voltage and current; it consists on a direct intervention on the beam through suitable parameters obtained from the fluorescence emitted by the double Ag/Ba thin target arranged in transmission mode (see the schematic view in Fig. 2).

Monitoring the relative intensity of the characteristic K_{α} lines of silver and barium, and in particular by determining the parameters $R=\text{Ag}(K_{\alpha})/\text{Ba}(K_{\alpha})$ and I (the time integral of the sum $\text{Ag}(K_{\alpha})+\text{Ba}(K_{\alpha})$), it is possible to register every energy and intensity fluctuations of the excitation beam; in fact the ratio R is sensitive to variations of the maximum energy of the beam – i.e. to variations of the applied high voltage - and I depends on the flux of photons incident on the target – i.e. on the operating current.

The target was realised at the Servizio Bersagli of the LNS-INFN laboratories by coupling a 1.5 mg/cm^2 thick Ag foil and a 100 mg/cm^2 thick $\text{BaCl}_2 \cdot 2\text{H}_2\text{O}$ target obtained in a mixture with a resin binder. Due to its small thickness the variation of the spectral distribution emitted by the tube is negligible.

Monitoring continuously the characteristic K_{α} lines of silver and barium by using the Peltier cooled Si-PIN detector (25 mm^2 active surface, $500\text{ }\mu\text{m}$ active depth, 250 eV energy resolution at 5.9 keV) it is possible to evidence every variation of the energy and of the intensity of the excitation beam. The Si-PIN detector is coupled to a Pocket 8000A MCA produced by the AMPTEK company.

The control of the stability is operated by a specific software developed at the LNS-INFN laboratories by using the own libraries distributed by the AMPTEK company for its instrumentation.

The stability-control software allows to set all the operative conditions of the SI-PIN detector; to acquire and record the Ag/Ba-target spectra; to automatically extract after a specific, but adjustable, interval of time the net counts of the Ag and Ba peaks; to provide the above defined ratio R and the integral I ; to set the range of stability by fixing two limiting values of R and to set the total amount of photons by fixing the value of the integral I .

Finally it also provides an alarm signal when R differs from the range of values determined by a preliminary calibration of the system. It can be noted that a variation on the ratio R larger than the statistical fluctuations means a meaningful variation on the energy of the x-ray beam emitted by the tube; in this case an adjustment on the applied voltage must be operated or the measurement being performed could be rejected.

The sample measurement is performed by using a 25 mm^2 active surface Si-PIN detector with 180 eV energy resolution at 5.9 keV and $25\text{ }\mu\text{m}$ thick Be window. The

Si-PIN detector is coupled to a Pocket 8000A MCA produced by the AMPTEK company for the data acquisition.

The stability-control software gives the start command to the Maestro acquisition software and the end one when the sum I reaches the initial fixed values. Further, it gives a delay command in order to wait the necessary time to allow the tube reach the operative conditions when it starts to operate after an off-time period.

THE QUANTITATIVE ANALYSIS OF THE ALLOY COMPOSING THE ROMAN NUMMI OF THE MISURATA TREASURE

During the *in situ* campaigns performing from 2007 to 2010, about 370 coins were analysed by using the BSC-XRF spectrometer. Measurements were performed at the Restoration Laboratory of the Leptis Magna Museum at El-Khomes.

The *nummi* to be analysed were carefully chosen in order to have sample representing different mints in different historical periods.

Table 1 summarize the analysed samples, the production mint and historical period.

Figure 3 shows a typical x-ray spectrum obtained by irradiating the coins with the BSC-XRF spectrometer.

The major and trace (Hg) elements composing the alloy are evidenced in the spectrum. Hg is clearly evidenced in the enlarged view of figure 4. Measurements lasted about 900 sec

The quantification is obtained by using the IAEA QXAS code in the Fundamental Parameters option [15]; the x-ray beam emitted by the BSC-XRF spectrometer was determined by using the QXAS algorithm and taking into account all the absorption layers due to the experimental set-up. The instrumental constant, preliminary to the analysis, was determined by measuring pure thick targets of different atomic number. Analysis is performed under the hypothesis that samples under investigation are homogeneous and that the matrix is composed only of visible elements.

However the presence of the Ag-enriched patina on the coins surface represents a strong in homogeneities of the alloy and, consequently, XRF measurements should be used only for semi-quantitative considerations.

Mint name	Historical period (A.D.)	Number of analysed nummi
Siscia	318-321	28
Siscia	326-329	17
Siscia	330-333	14
Roma	294-316	83
Roma	324-329	57
Roma	330-333	40
Thessalonica	330-333	39

Arelate	332-333	8
Costantinopoli	330-333	25
Alessandria	330-333	25
Alessandria	before 320	3
Cartagho	before 320	17
Costantinopoli	before 320	8

Table 1 – the *nummi* sampled for the analysis with the indication of the manufacturing mint and the period of production.

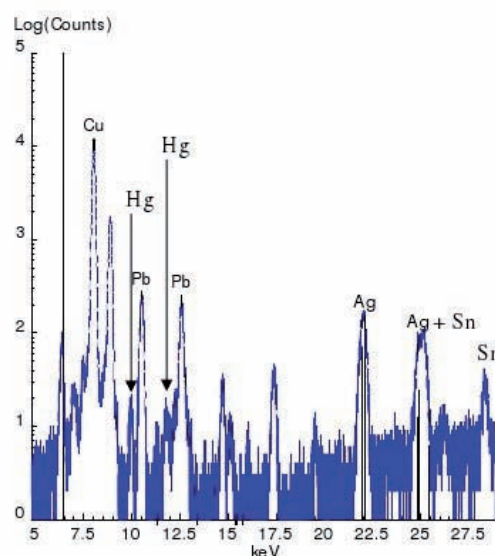


Figure 3 - A typical XRF spectrum of a Roman *nummus*. Mercury traces are evidenced.

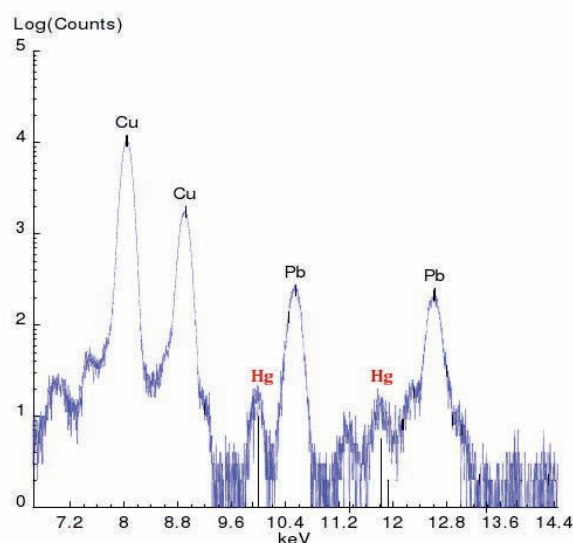


Figure 4 – The evidence of the presence of Hg in one of the analysed coins (enlarged view of figure 3).

mint name/period A.D.	Cu (%)	Ag (%)	Sn (%)	Pb (%)	Hg (%)
SISCIA 318-321	89.8	3.6	3.1	3.5	-
SISCIA 326-329	89.8	3.6	3.1	3.5	-
SISCIA 330-333	95.3	1.3	1.3	2.1	-
ROME 294-316	87.6	5.1	3.5	3.8	-
ROME 324-329	88.5	2.7	3.9	4.8	-
ROME 330-331	90.6	1.2	2.9	5.3	0.2
THESSALONICA 330-333	92.7	1.4	2.4	3.5	-
ARELATE 332-333	91.2	1.1	3.3	4.4	-
COSTANTINOPLE 330-333	95.4	1.1	1.4	2.1	0.1
ALESSANDRIA 330-333	90.8	2.0	3.6	3.6	-

Table 2 – Results of the analysis of the alloy composition of the *nummi* belonging to the different mints and produced in different periods. Mean values are reported for each investigated mint.

Tables 2 summarizes the results of the analysis.

For each of the investigated mints at different historical periods, the average values of the major elements are reported. Also, the presence of Hg was evidenced in the mints of Rome and Constantinople in the late period from 330 to 333 A.D.

It should be observed that Hg was systematically present in this two mints, suggesting the possible use of the mercury silvering to produce the patina of the coins. In the others mints and periods, mercury was not observed in no other samples.

Finally, the major elements composition the Romani *nummi* is reported in the table 2. Even if they are semi-quantitative results, it is evident the general trend of the silver content during the time. In fact, the data of the mints of Rome and Siscia from 318 to 333 A.D. show a systematic debase of the alloy.

CONCLUSIONS

The analyses of the about 370 *nummi* belonging to the Misurata treasure (Libya) were presented and discussed. Analyses have been performed *in situ* from 2007 up to 2010, at the Leptis Magna Museum of El-Khoms (Libya).

In order to investigate about the use of the mercury silvering technique for producing this typology of coins, measurements were addressed to the detection of trace of Hg.

Measurements were performed by the BSC-XRF spectrometer equipped with a system to control the energy and intensity stability of the x-ray beam.

The system allows to obtain accurate quantitative results and it is particularly suited for the trace element analysis. Samples were carefully chosen in order to study in a systematic way, the different mints and the different historical periods.

Results confirmed a systematic presence of Hg in Rome and Constantinople production from 330-333 A.D., suggesting in this case the possible use of mercury silvering to produce the *nummi* patina.

Others samples manufactured in others mints and in different period do not contain mercury.

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DL measurements and water structures

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Abstract - The physical properties of water are essential for the life on Earth. Even if water is the most studied molecule in science and many models have been developed to explain its anomalous properties, it still does not exist a description of water that is universally recognized by the scientific community. In this context, we started a series of measurement of Delayed Luminescence on water in order to get new experimental information about water structures. Some of the obtained results will be discussed in the present work.

INTRODUCTION

Due to the relevant role of water in biological systems it is interesting to explore new experimental techniques that can give more hints in the observation of water structures. Here, it is investigated the possibility to get pieces of information about the ordered structure of water by measuring Delayed Luminescence (DL), i.e. the prolonged and low intensity emission of light from a system, after optical excitation.

Literature presents several experimental results of DL measurements from both solid-state systems and various kinds of living organisms [1-4]. These experiments show a general characteristic of DL: it appears to be dependent on the order parameters of the system. To explain the DL experimental evidences, a theoretical model [5] has been developed. It connects DL with the excitation and subsequent decay of non-linear coherent localized electron states (excitons or solitons), whose presence is favoured in low-dimensional macromolecules, which are present both in solid

state and biological systems (see for instance alpha-helical polypeptide proteins, actin filaments, etc.)

Recently, DL has been successfully used to investigate the role of water in collagen [6,7], where water appears to be structured in regular chains along the collagen fibrils [8]. Such collagen water chains are reminiscent of those seen in carbon nanotubes [9], which are thought to represent an entirely new phase of water. Furthermore, a Debye-like slow relaxation has been observed in water, and it has been associated to structural and/or dynamical inhomogeneities on length scales quite larger than previously thought (of the order of 0.1 mm) [10]. These observations indicate the possibility that the distorted hydrogen-bonded structures proposed by Huang et al. [11] are connected to chainlike structures with a polymer-like dynamics.

Results of spectroscopic measurements [12] have shown that a structural polymorphism of water (quasi-crystalline structures) should exist also in salt solutions where water structuring is expected and in the solute-free zone, that water forms in vicinity of various hydrophilic surfaces. This region has a width of 100 μm and it is stable for days once formed.

Among the several theories proposed to explain the peculiar properties of water, the two-state model describes the liquid water as consisting of two kinds of rapidly exchanging microdomains of different densities, low-density water (LDW) and high density water (HDW) clusters, in dynamic equilibrium [13-15]. The equilibrium point can be shifted by the presence of specific ions in water.

Guided by these considerations, we have performed DL measurement of aqueous salt solutions that stabilize LDW structures on varying the temperature. Moreover DL was measured on pure water at ambient pressure in the super-cooled region because, following theoretical predictions, the structure of liquid water changes toward LDW structure when liquid is in the supercooled regime.

MATERIALS AND METHODS

Salt solutions

Previous results have shown that a significant DL signal was detected only for those solutions that favour LDW domains over the HDW ones [16,17]. So, aqueous solutions of NaClO_4 and $(\text{NH}_4)_2\text{SO}_4$ were chosen for their capacity to stabilize LDW [18].

The salt solutions were prepared in bidistilled water (Carlo Erba), using $(\text{NH}_4)_2\text{SO}_4$ by J.T.Baker, NaClO_4 by Sigma Aldrich. The saturated solutions were prepared, and dilutions were then performed. DL was measured at first on aqueous solutions at 9:10 dilution of the saturated ones at a constant temperature of 20°C. For two fixed dilutions, behaviour on changing temperature was investigated. NaClO_4 and $(\text{NH}_4)_2\text{SO}_4$ solutions were diluted at concentration respectively 4:10 and 5:10 of saturated ones at room temperature, in order to have a good signal to noise ratio and, in the mean time, to prevent solution saturation at lower temperatures.

Supercooled water

Bi-distilled water was placed inside the holder used for DL measurements 12 hours before the experiment. The holder was completely filled by 177 ml of water, and it was partially submerged in a thermal bath (Haake C25) to assure the right temperature of water. The temperature inside the holder was measured with a Pt100 temperature sensor (TP472 I.O; type: diving; field of use: -50°C - +400°C, accuracy: $\pm 0.25^\circ\text{C}$) connected with a thermometer RTD HD2107.1 produced by Delta OHM.

To reach the supercooled regime, the temperature of the thermal bath was decreased very slowly. For each studied temperature, DL

measurements started after 20 minutes from the reaching of equilibrium between the thermal bath and the water in the holder.

Delayed Luminescence

DL was measured, in the time interval from 10 μs up to 1 s. A high-intensity pulsed nitrogen laser (Laserphotonic LN203C, $\lambda = 337 \text{ nm}$, pulse width 5 ns, energy per pulse $120 \pm 5 \mu\text{J}$) was used to illuminate the sample via a bifurcated optical fiber bundle (lot Oriel LLB-321). After the switching off of the laser pulse, the DL signals were collected by the same fiber and revealed by a photomultiplier (Hamamatsu R-7206-1) in single photon regime. A PC implemented with a multi-channel scaler (Ortec MCS PCI) plug-in card was devoted to data acquisition.

The samples were placed in a special holder specifically designed for each kind of samples. The geometry of the holders and the parameters used during the different samples measurements were optimized to reduce as much as possible the background noise.

RESULTS

DL measurements were firstly performed on aqueous salt solutions at dilution of 9:10 with respect to the saturated ones. The measured DL time trends were modelled by a sum of two power law functions:

$$I(t) = I_1 / (1 + t/t_1)^{m_1} + I_2 / (1 + t/t_2)^{m_2}$$

Looking at the luminescence kinetics as the convolution of a continuum distribution of exponential decays, the previous equation can be also considered as the Laplace transform [19] of a $p(\gamma)$ function expressing the probability of an exponential decay characterized by a lifetime $\tau = \gamma^{-1}$:

$$\begin{aligned} I(t) &= I_1 \int_0^\infty p_1(\gamma) e^{-\gamma t} d\gamma + I_2 \int_0^\infty p_2(\gamma) e^{-\gamma t} d\gamma = \\ &= I \int_0^\infty p(\gamma) e^{-\gamma t} d\gamma \end{aligned}$$

The result from this analysis is shown in figure 1, where the lifetime distribution function $f(\tau)$ such that $p(\gamma)d\gamma=f(\tau) d\log(\tau)$ is shown [17]. It appears that the probability distribution of decay times presents a maximum at 1.7 μs for $(\text{NH}_4)_2\text{SO}_4$ and at 2.2 μs in the case of NaClO_4 . In this last case a secondary maximum appears at about 25 ms even if with an extremely low intensity, as shown in the inset of Fig.1.

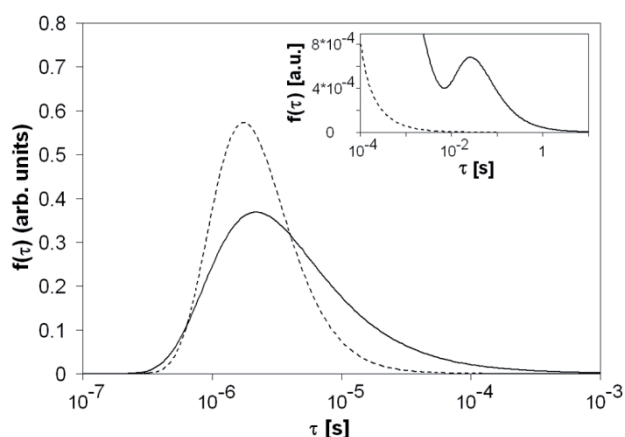


Figure 1: Lifetimes distribution for NaClO_4 (solid line) and $(\text{NH}_4)_2\text{SO}_4$ (dotted line).

Further investigations of DL from $(\text{NH}_4)_2\text{SO}_4$ and NaClO_4 solutions on varying the temperature have shown an Arrhenius trend of the DL intensity (N_{tot}), characterized by an activation energy, evaluated by trend gradient, of $\Delta E = 0.12 \pm 0.02$ eV ($R^2 > 0.96$) for NaClO_4 and $\Delta E = 0.13 \pm 0.01$ eV ($R^2 > 0.98$) for $(\text{NH}_4)_2\text{SO}_4$, as shown in figure 2. This energy can be interpreted as the specific amount of energy requested to displace the LDW/HDW equilibrium.

Nevertheless, the specificity of each salt in inducing LDW domains was evidenced when the dependence of DL intensity from salt concentration was investigated. Indeed, NaClO_4 showed a cooperative effect in LDW domains formation while the opposite behaviour was present for $(\text{NH}_4)_2\text{SO}_4$ solution.

As prevalence of LDW domains is foreseen in water at supercooled condition, DL measurements were performed on pure water at ambient pressure on varying the temperature from 18°C down to -6°C. Even in this case, preliminary studies show an increment of DL signals when

an increased presence of LDW is expected, and below the temperature of 4°C DL intensity shows an Arrhenius trend (see figure 3). The activation energy results equal inside the

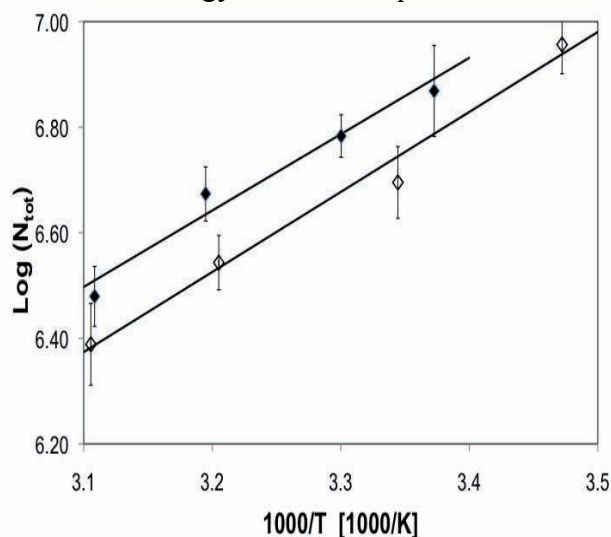


Figure 2: Arrhenius plot of the total number of emitted photons: (♦) NaClO_4 , (◇) $(\text{NH}_4)_2\text{SO}_4$. Solid lines represent fit according to an Arrhenius trend. Bars denote standard deviation from average values.

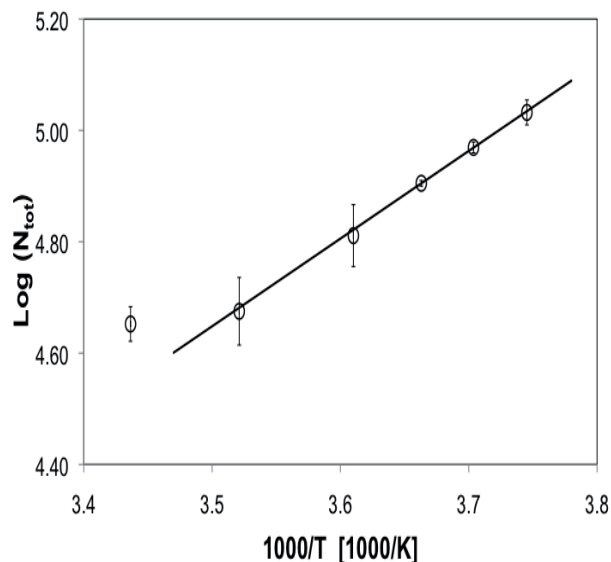


Figure 3: Arrhenius plot of the total number of emitted photons for pure water. Solid line represents fit according to an Arrhenius trend. Bars denote standard deviation from average values.

experimental errors to what obtained for the salt solutions at higher temperatures: $\Delta E = 0.136 \pm 0.003$ eV ($R^2 > 0.99$). Further measurement on pure water on varying the temperature are still in progress.

CONCLUSIONS

The strong dependence of DL from the long-range structures of the whole systems suggests the possibility to use DL as a tool to investigate the properties of water in general and water role in biology in particular. In this respect, DL measurements have been performed on salt solutions and pure water as a function of temperature.

All the presented results can be interpreted in the framework of the two state model of liquid water, claiming the presence of LDW and HDW domains. A clear DL signal is present only for $(\text{NH}_4)_2\text{SO}_4$ and NaClO_4 solutions or for pure water in the supercooled regime, where prevalence of LDW domains is foreseen. However, once formed the water structures seem to have analogous characteristics for the two salt solutions. Indeed they show a similar distribution of the lifetime of LDW domains, having a maximum in the microsecond range. Moreover the same energy is requested to promote the displacement of the LDW/HDW equilibrium. This value of the activation energy is confirmed by the measurement performed on pure water in supercooled region, where an equal activation energy value is deduced by the Arrhenius behaviour of the DL intensity.

The result about the lifetime probability distribution of the water structures gives values surprisingly higher than previously thought. This long lasting lifetime of the order of microseconds, as found by DL analysis, lets to think that water structuring could be used in biological processes as a tool to store and transfer energy.

Further measurements of DL from pure water are still in progress, with the aim to get new insight into the peculiar characteristics of liquid water.

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Effects of ion irradiation on mung bean growth

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Abstract - In the last decades the possibility to induce mutations in plants by using ion irradiation has been demonstrated, so enhancing the biodiversity and clarifying the underlying plant physiology. To add a contribution to these researches, green soya seeds (Mung bean) were irradiated with a ^{12}C beam of energy 62 MeV/A by using the automatic set-up designed and made at LNS to optimise the beam time use. Growth of seeds after irradiation was checked and compared with that of untreated seeds, used as control. Moreover, the Delayed Luminescence (DL) of seeds after ion irradiation was measured in order to test the possibility to identify the mutated samples inside the irradiated set.

Irreversible damage of seeds appeared for high radiation doses, together with a change in DL parameters.

Seeds of green soya (Mung bean), characterized by quite high (about 98%) germination performances and high growth speed, have been irradiated by using a ^{12}C beam at energy of 62 MeV/A to test the effects of ion irradiation on the their growth. Mung beans are largely used as sprouted beans and gamma radiation treatment at doses of the order of 1 kGy is recommended for insect disinfestations [7].

After ion irradiation the seedlings growth under controlled conditions has been followed.

With the aim to use a non invasive method for finding a physical variable correlated with the induced mutation, that could be measured immediately after the irradiation, the Delayed Luminescence (DL) (i.e. the prolonged emission of light coming from a sample after illumination) of each irradiated seed has been measured. Indeed, the viability of several kinds of seeds has been successfully correlated to the DL [7-12].

INTRODUCTION

The use of ion irradiation with high linear energy transfer (LET) to enhance biodiversity by inducing mutations in plants has been widely studied [1-6], both in the high (about 100 MeV/nucleon) and in the low (few keV) energy regions, also with the aim of clarifying the underlying mechanisms. As a matter of fact the proposed mechanisms for the interaction of accelerated ions with biological samples are not yet clearly explained. The proposed models use combination of energy absorption, mass deposition and charge exchange of energetic ions in the organism, but differences exist for the two energy regions. Indeed, in the high energy region the ions penetrate the whole organism with a constant LET, while in the low energy region the ions are stopped inside the sample and their energy is released essentially at the end of the path following the Bragg's law.

The facility built up at LNS has allowed to extend the analysis of the interaction between ion beam and biological samples to the intermediate energy region, i.e. few tens of MeV/nucleon, not so intensely investigated up to now. This novel investigation can give a better understanding of the interaction mechanism responsible of the induced mutations.

MATERIALS AND METHODS

The remote controlled irradiation system suitably designed in the frame of the IENBIO experiment (Ion beam application in the ENhancement of BIODiversity) [13] to automatically irradiate in air a great number of samples was used for the experiment. About 300 seeds of Mung bean were placed in the experimental hall at once, and seeds were set in suitable holders [14], each containing 12 seeds, so to be all inside the irradiated region (beam uniformity about 85%). By moving the irradiation system, each set of 12 seeds was placed in the ion beam position, until the chosen dose was delivery on it. A shield with a collimator of 20 mm in diameter defined the irradiation zone avoiding also the irradiation of seeds in the other holders. This procedure allowed to optimising the use of beam time, reducing the entrances in the experimental all for sample changing. Doses were evaluated by using a proportional chamber previously calibrated with a reference one. According to the calibration, the Bragg's peak occurred just in correspondence of the embryonic axis of the seed.

Seeds have been selected in order to have similar size: about 5.0 mm in the larger dimension and about 3.0 mm in the other dimension. They were exposed to a ^{12}C ion beam at energy of 62 MeV/A, delivered by the LNS K800 Superconducting Cyclotron, and doses of 50, 100, 300, 500, 1000, 5000 or 7000 Gy were deposited on seeds.

The growth of seeds has been carried out under controlled conditions inside a chamber, provided with a forced ventilation unit and characterized by a temperature of $25 \pm 0.5^\circ\text{C}$ and a relative humidity of $60 \pm 5\%$. Each seed was placed inside a single cell (dimensions: $1\text{cm} \times 1\text{cm} \times 23\text{cm}$) of a polycarbonate alveolar plate (see Fig.1), containing the whole group of 12 seeds of each irradiated sample, plus 11 untreated seeds as reference. The cells bottoms were closed with a rolled up sheet of filter paper and inserted in a Plexiglas framework (see Fig.1). The plates were partially dipped into distilled water contained in a suitable vessel.

Temperature and humidity values have been recorded with two Escort Logger (mod.60D32), everyone with 0.3°C accuracy and medium resolution 0.1°C , placed as close as possible on the left and right side of the water containing vessel.

Growth has been monitored regularly by catching photographs of the plates every 24 hours (see Fig.1). The length of every seedling was calculated from the pictures and the entire procedure carried up for six days. In this period about all native seedlings became longer than 23 cm and came out from the cells of the plate with fully developed leaves at unifoliate node.

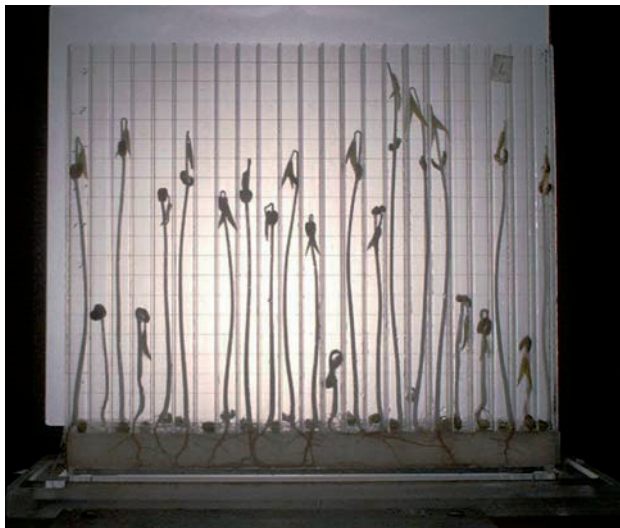


Figure 1: Photographs of the polycarbonate alveolar plate in which the seeds have been grown under controlled conditions.

Delayed Luminescence of seeds after UV laser illumination was measured by using the ARETUSA apparatus developed at LNS [14] in the improved version for single seed measurement [11]. The results obtained for irradiated seeds were then compared with that of untreated seeds.

Previous experiments [11, 12] showed that the time trend of the DL spectral components from seeds depends on the emission wavelength λ . In particular there are two different decay slopes in the two regions of the emission spectra at $\lambda < 600\text{ nm}$ and $\lambda > 600\text{ nm}$ respectively. For this reason only two spectral components characterizing the two regions (460 nm and 645 nm) were measured for all the seeds.

Starting from the time-dependent DL intensity $I(t)$ observed at emission wavelength λ , the relaxation kinetics was evaluated considering the probability $p(t)$ that Δn levels of the n excited ones decay radiatively:

$$p_{\lambda}(t) = \frac{\Delta n_{\lambda}}{n_{\lambda}} = \frac{\int_t^{t+\Delta t} I_{\lambda}(t') dt'}{\int_t^{\infty} I_{\lambda}(t') dt'} \quad (1)$$

After $p_{\lambda}(t)$, the following parameter, which reflects spectral properties of DL, was evaluated :

$$R_p = \frac{1}{t_F - t_S} \int_{t_S}^{t_F} \frac{p_{460}(t)}{p_{645}(t)} dt \quad (2)$$

Worth to note that according to Eq. (2) R_p is a dimensionless parameter, as those largely used in Literature in the field of autofluorescence measurements because they are independent of experimental parameters that often remain largely unknown. Moreover R_p is sensitive to differences in the decay probability $p_{\lambda}(t)$ between two spectral components, so it is actually a spectrum-dependent parameter.

RESULTS AND DISCUSSION

The evaluation of the irradiation damage has been performed on the basis of the pictures taken six days after that seeds have been bedded out. During this period it is possible to follow the first part of the growth phases of the Soybean development, that is the vegetative stages that cover development from emergence through flowering.

It is known in Botany that the primary root, or radicle, is the first organ to appear when a seed germinates. It grows downward into the soil, anchoring the seedling. In dicotyledons as mung bean, secondary roots grow laterally from radicle. The soybean plant exhibits epigeal (above the surface) emergence. During germination, the cotyledons are pushed through the soil to the surface by an elongating hypocotyl. After emergence, the green cotyledons open and supply the developing leaves with stored energy: the first leaves to develop are the unifoliate leaves.

According to the observed pictures, at the sixth day only four conditions were revealed: seeds not germinated

(NG) at all, seeds that had formed only the primary root (PR) without any secondary roots, seeds in the vegetative emergence (VE) stage where the cotyledons emerged above the hypothetical soil surface and leaflets emerged from cotyledons, and plants in the vegetative cotyledon (VC) stage where unifoliate leaves were unrolled sufficiently so that the leaf edges were not touching. Figure 2 shows the pictures of the four vegetative stages observed.

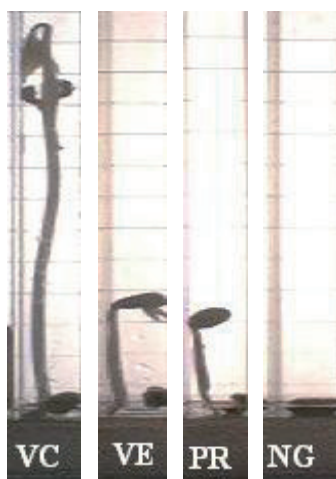


Figure 2: Photographs of the four vegetative stages (see text) considered in order to evaluate radiation damage.

Considering all the seeds that have been subjected to a fixed radiation dose, the percentage of seeds that were found in each of the previously defined vegetative stages have been calculated. Results are reported in fig.3, where, for the sake of simplicity, four ranges of radiation dose were considered: no radiation (0 Gy, control sample), radiation dose less than 500 Gy, radiation dose between 500 and 1000 Gy, radiation dose greater than 1000 Gy.

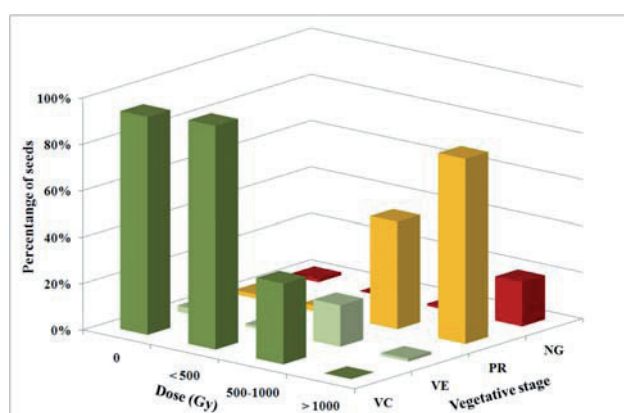


Figure 3: Percentage of seeds at each vegetative stage (see Fig.2) as a function of the radiation dose.

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It appears that no significant effect has been caused by low doses: seedlings grew as the untreated (control) ones and only a slight lowering in the relative elongation was observed (data not shown). At the intermediate doses the percentage of seeds that showed only a primary root is nearly equal to the percentage of germinating seedlings (considering the VC and the VE stages). On the opposite, at high doses seeds that showed only a primary root constitute the most populated class and a considerable number of seeds did not germinate at all.

Table 1: Spectral Delayed Luminescence parameter R_p Eq.(2) for seeds irradiated at different doses. Average value $\pm$ standar error.

Dose (Gy)	R_p
0	1.21 ± 0.01
< 500	1.22 ± 0.02
500 ÷ 1000	1.27 ± 0.02
> 1000	1.66 ± 0.03

Correspondingly, the four classes of seeds exposed to the same radiation dose showed different behavior as it regards the DL measurements. Table I reports the average values of the parameter R_p , evaluated according to Eq.(2), for each class of seeds, corresponding to the four ranges of radiation dose considered in Fig.3.

On increasing the damage, related to the radiation dose, the R_p parameter increases. The same behavior was observed in seed artificially aged [10], so confirming the possibility of using DL measurements to investigate and foresee the damage.

CONCLUSION

In conclusion the green soya seeds exposed to ion irradiation exhibited a very high resistance to radiation damages. Indeed, most of the seeds exposed to low and intermediate doses germinated as well as the control, even if we are not able, at this stage, to evaluate if the growing seedlings could show further mutations after cultivation in field. Up to now, we are able to reveal only an irreversible damage, as it occurred at high doses exposition. Interestingly, a correspondence is still present between DL parameter and vegetative performances of seeds. The DL result continues therefore to show its predictive capability.

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Real-time online monitoring of radwaste storage: proof-of-principle tests

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Abstract - Tests of a few DMNR fiber sensors were performed on the lab bench with radioactive sources and in a real radwaste storage site. Quite promising results were obtained, pointing towards a next step consisting of setting up a pilot full system in a real radwaste storage site.

THE TESTS

Several tests were performed with the fiber sensors on the bench with and without laboratory sources, in order to verify the capability of gamma detection, the sensitivity, the stability, to measure the noise level and the ambient radiation count rate. As an example we show in Fig. 1 the result of a 4-day data acquisition with the L30-2 sensor. The counting rate is rather stable with respect to night-day temperature fluctuations of a few degrees. After about 40 hours we placed a small box containing three radioactive sources (^{60}Co , ^{137}Cs , ^{152}Eu , total activity 2.7MBq) at about 8cm from the fiber, leaving it there for two hours and then removing it again.

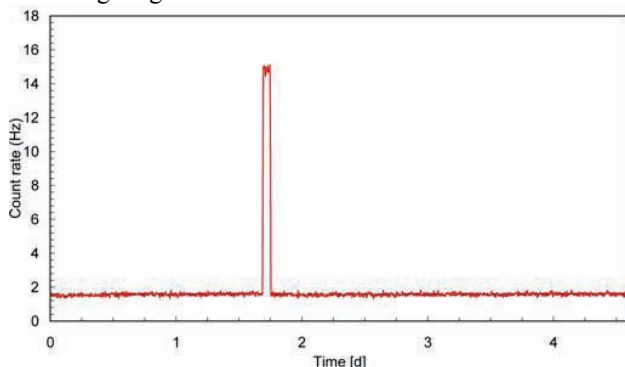


Fig. 1. Bench test of the fiber sensor L30-2 over four and a half days. Three radioactive sources (^{60}Co , ^{137}Cs , ^{152}Eu) with a total activity of 2.7MBq were placed at $\approx 8\text{cm}$ from the fiber during two hours.

A step further with realistic bench-tests was the construction of a prototype, shown on the left-hand side of Fig. 2. The phantom drum was made from an empty plastic bottle 40 cm high placed at the center of an array of five fibers. The fibers with their sensors were arranged three vertical and two horizontal. The counting rate versus time was reported for a short test where the same multi-source mentioned above was placed at the position marked with a red "X" in Fig. 2 left. In Fig. 2 right a simple 3D image is shown, roughly representing activity

levels around the drum, obtained by combining the horizontal and vertical information from the log data. This proves that a geometry with crossed fibers can actually provide position information.

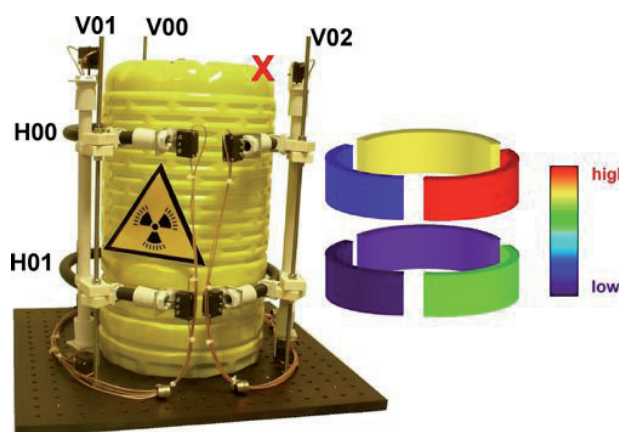


Fig. 2. The prototype mini-drum with two horizontal and three vertical fibers. The red "X" indicates the position where the gamma source was placed. The graph on the right side represents the 3D rough activity levels obtained by combining the horizontal and vertical information from the log data.

Gaining position information could be quite useful under several cases, for instance with liquid waste or in the occurrence of a leak caused by corrosion and gas pressure buildup inside a drum.

The most important test, however, was to be performed in a real environment of radwaste. This is why we decided to perform a measurement inside a temporary storage site at a Sogin installation in Sessa Aurunca (CE) Italy. For this purpose we installed four of our fiber sensors onto a pushcart, along with a geiger counter to be used as cross-check. The same cart also hosted the front-end electronics, whereas the output digital pulses travelled on 40m long cables towards the FPGA data acquisition system, placed outside, in order to be counted and recorded. The measurements were done in seven positions according to Table 1, where we also report the corresponding dose rate as measured by the on-cart geiger counter.

We remark that the six positions P1-P6 are known only roughly, as each displacement was performed in just a few seconds by operators who then moved quickly away. In Fig. 3 we show the pushcart with the four detectors and the related front-end electronics; highlighted is also the

position where the geiger counter was installed. In Fig. 4 we show the P5 and P6 positions with respect to the closest drums.

Table 1. Measurement positions and geiger readings

Position	Description	Dose rate ($\mu\text{Sv/h}$)
P0	ambient level outside the storage site	0.07
P1	at the entrance of the storage	40
P2	near a perimeter wall, facing an aisle between drums	42
P3	near a perimeter wall, facing some drums	45
P4	at the entrance of the aisle	150
P5	in the aisle, between two drum rows	170
P6	in the aisle, close to a row of drums	310
cart removal	while moving the cart outside	decreasing

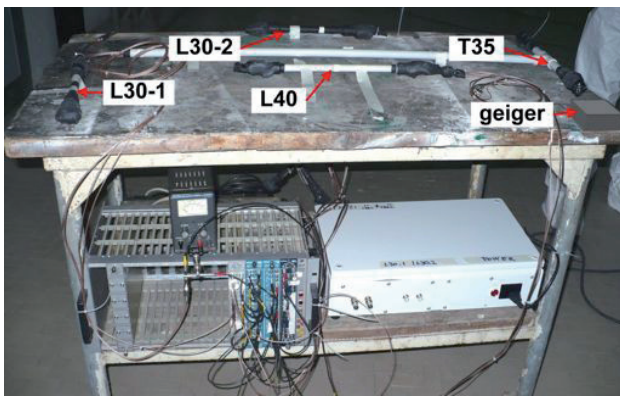


Fig. 3. The pushcart equipped with the four fiber detectors, the related electronics, the geiger counter.

The detectors, as indicated in Fig. 3, were:

- two identical L30, whose length is 30cm, with fiber cleanly cut and coupled to the photosensor window;
- one T35, 35cm long, fiber cleanly cut and coupled to the photosensor window;
- one L40, 40cm long, fiber cut and polished and coupled to the photosensor window.



Fig. 4. The positions P5 and P6 of the pushcart with respect to the drums. The grey square indicates the position of the geiger counter on the cart.

In Fig. 5 we show the counting rate of three of the four fiber sensors as a function of time during the initial phase of the test. The sampling time was set at 1 second. The pushcart was placed in position, kept there for a while and then moved to the next position. Unfortunately during this phase the sensor L30-1 was not operating due to a loose contact, but we were able to recover it for the following phase.

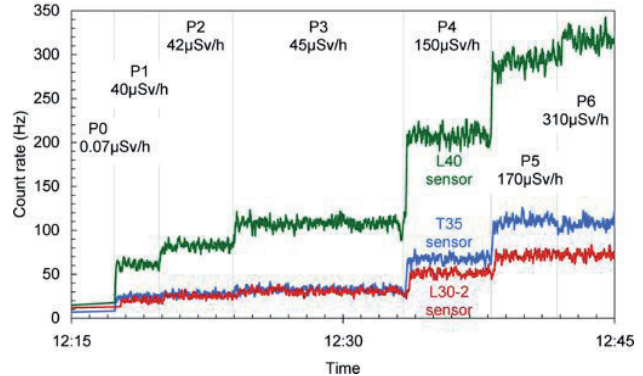


Fig. 5. The initial phase of the test, with the counting rates reported by each sensor in each position. The L30-1 sensor was not operating during this phase.

The measured counting rates with respect to the dose on the reference geiger counter are not easily disentangled, as one should know precisely the radiation field in each sensor position and keep into account also the different detector geometries and placement. However, the counting trend of Fig. 5 is quite reasonable, including the slight decrease of T35 when rotating the pushcart from P5 to P6. Interesting to be noticed is that the fiber sensor with polished ends (L40) showed a much better efficiency, well above what one can ascribe to its slightly longer fiber. The slight initial decrease of the counting rate on the L40 sensor when starting to move the pushcart from P3 to P4 and from P4 to P5, was due to the operator standing in front of the sensor thus partially screening it for a while.

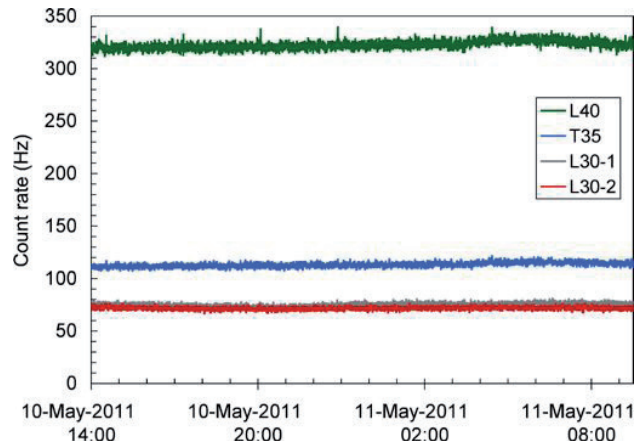


Fig. 6. Overnight counting rate as a function of time with the pushcart in position P6.

The second phase of the test consisted in leaving the cart in position P6 overnight with the sampling time set at 10 seconds. The corresponding plot is shown in Fig. 6.

The third phase of the test, a quick one as it lasted about thirty seconds, consisted in the removal of the pushcart with the sampling time set again at 1 second. Fig. 7 shows the counting rate during the quick displacement from P6 to P1. In P1 the power was then switched off to allow disconnecting the cables, verifying the absence of contamination of the equipment and transporting it out of the radwaste storage hall.

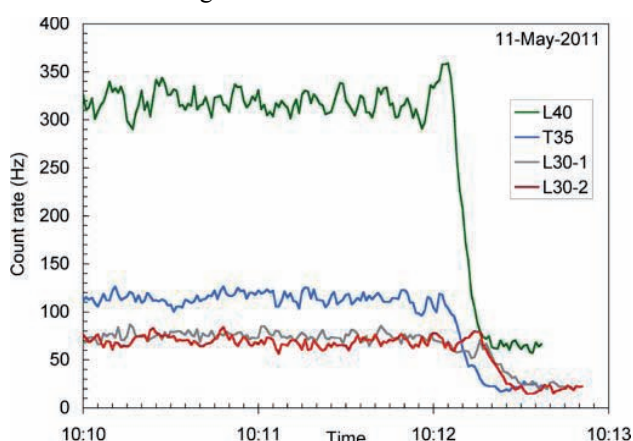


Fig. 7. Final test phase: the pushcart was quickly displaced from P6 to P1. The measured counting rates followed accordingly.

As we were performing a test in a site not easily accessible, we decided to split the electronics and the data acquisition into two independent systems, in order to have some redundancy in case of failure of some component. Therefore we handled two fiber sensors with each console, and later we merged the acquired data to produce the data plots reported on this paper.

DISCUSSION

Following a phase of study, simulation, prototyping and characterization of these new fiber sensors, we performed a long series of laboratory tests employing radioactive sources. The important step to be undertaken was a realistic test with real waste drums in a real storage. This was done and the result shows quite clearly that the fiber sensor can play the promised role in the monitoring process. Moreover, what came out of this test is that the realistic dose rate around the tested drums (hundreds of $\mu\text{Sv/h}$) was a factor 100 to 1000 smaller than our initial assumptions based on rough (pessimistic) estimates from private communications with operators in this field. This increases the initially expected lifetime of the sensors due to radiation damage (100 to 1000 years) by a corresponding amount. Under these conditions the lifetime of the sensors will actually be dominated by electrical and electronic failures.

Due to a lower dose rate than expected, the useful dynamic range of the sensors is better than foreseen: the “normal” counting rate resulted of the order of hundreds

of Hz, with a detection upper limit of 100MHz, thus meaning a range of 10^5 to 10^6 .

The sensitivity limit of the fiber sensors, for example the detector L40 in Fig. 5 and Fig. 7, is about 18 over 320 (5.5%) with a sampling time of 1 second. If we assume that L40 was measuring the same dose rate as the geiger counter, this sensitivity would correspond to $\approx 20 \mu\text{Sv/h}$. By increasing the sampling time, or by averaging several consecutive samples, the sensitivity can be enormously improved, as it was done by the employed geiger counter.

The fiber sensors can be mass replicated with a considerable economy of scale, and we estimate that the cost could easily reach below €100 per sensor channel, including the electronics. The fiber length can be chosen as a tradeoff between the drum size and the desired detection efficiency, without any influence on the cost, on the readout electronics, on the production process.

CONCLUSION

The DMNR project has shown that a real time online monitoring system for radwaste is feasible. The test performed on real waste drums inside a storage site has shown performance beyond expectation. The next step, that is the installation of a pilot system inside a radwaste storage site for an extended period of time, is currently under discussion and likely to start quite soon.

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DMNR: a system for real-time online monitoring of radwaste storage

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Abstract - A prototype array of modular sensors for online monitoring of radioactive waste was developed at INFN-LNS. We implemented a new kind of gamma mini-sensor, based on Silicon PhotoMultipliers and scintillating fibers, that behaves like a cheap scintillating Geiger-Muller counter. It can be placed in shape of a fine grid around each single waste drum in a repository. After simulating the counting response of thin scintillating fibers to gamma radiation, we verified our simulation results with measurements using radioactive sources. Front-end electronics and an FPGA-based counting system were developed to handle the field data, also implementing data transmission, a graphical user interface and a data storage system.

INTRODUCTION

One of the main topics in decommissioning and storage of radioactive waste is its monitoring in the short, medium and long term. Whereas for the long term waste the geological disposal is foreseen, or better the use of new “cleaner” reactors, the short and medium term waste is currently packed into drums and either kept inside the production site or transported to dedicated storage sites. In any case special care must be devoted to the prompt detection of possible leaks due to structural weakness or accident [1].

Whichever the topological arrangement or the physical structure of the drums, the goal would be measuring the radioactivity around each single drum. Detector Mesh for Nuclear Repositories (DMNR) is a project for a prototype demonstrator of the online monitoring of short-medium term radioactive waste, currently under development at INFN-LNS Catania. Such a system is planned to be distributed, fine-grained, robust, reliable, and based on low-cost components.

With the main purpose of counting gamma radiation, a new kind of mini-detector was implemented that behaves like a scintillating Geiger-Muller counter. It has to be replicated in shape of a grid around each single waste drum. This system could also open new perspectives on the modality of waste packaging and storage [2]. What was proposed is cheap scintillating detectors, readout by means of SiPM (Silicon PhotoMultiplier) photosensors capable of detecting the tiny light signals of few photons ([3], [4] and references therein). This way one can easily place grids of 5-10 radiation sensors around each waste drum, and record continuously the measured activity in order to know its instant rate as well as its history.

In order to build such a system one needs to perform a characterization of the photosensors to be employed, and this was done for several families of SiPM in terms of gain, photon resolution, overall efficiency, noise, cross-talk. The cross talk evaluation, in particular, is crucial in order to determine the lowest threshold attainable. This is why a simple yet powerful analytical method was developed to measure it [2].

Front-end electronics and an FPGA-based counting system were developed, in order to handle the data flow coming from the field sensors. Such a system also deals with the redundant data transmission toward a console with a graphical user interface and a data storage system. The redundant transmission is to be done simultaneously on differential cables and wireless, using powerful low-cost units.

A robotic arm is being developed for remote ad-hoc inspection, both visual and by using high resolution radiation detectors; other operations around the waste drums should also be possible using the same robotic arm.

Test results of a small demonstrator system with radioactive sources, as well as with real radioactive waste drums, showed very encouraging performance in terms of sensitivity, as it is going to be shown below.

REAL-TIME MONITORING

From a technical point of view a real-time monitoring of radwaste packages was already possible years ago, even though with some limitations. Ambient radiation monitors are typically installed in several locations inside the storage sites. What one should do is replicating these systems in form of a mesh of detectors (i.e. Geiger counters) to be deployed all over the storage site around the packages and interconnected with an overall transmission and control system. This could work in principle but posing a set of operational issues, first of all the cost. The main requirements to such a system of radiation sensors, along with the basic features of the DMNR system we are proposing are listed in Table I.

Moreover, the system should feature a robot, or robotic arm, providing remote visual inspection of the drums and capable of high resolution radioactivity measurements by means of a more sophisticated and specialized radiation detector. The robot could also be able to replace failing sensors and/or electronic modules and batteries.

As for the acquired data, the system should exploit some redundancy on the transmission from the sensors to

the control station, possibly making use of batteries to make up for power failures and to keep the monitoring in operation also during possible displacements of the platforms.

Table 1. Requirements vs. features of the DMNR system

Requirement	Feature
mesh of detectors on platforms	yes
radiation hardness	>10 years close to a drum with 10–100 mGy/h
robustness & flexibility	yes, plastic scintillators; SiPM not damaged by ambient light exposure
low intrinsic efficiency	yes, 1 mm thick round plastic fibers
linear sensor shape, 1-2m long	yes
geometrical efficiency can be chosen by length or thickness	yes, fibers can be freely cut from spool
high sensitivity	yes, SiPM can detect down to single photons
reliability	yes, simple system
possible position sensitivity	yes, by crossing fibers
ease of handling	yes, only plastic cases
low cost	yes (for mass production)

Under these conditions it could be possible to achieve a real-time three-dimensional radioactivity map, capable of monitoring the expected decrease of radioactivity over time on a drum-by-drum basis. Alarm levels and leak detection would be an additional benefit of such a configuration.

Downstream from the hardware and the data acquisition software, the system should feature a high-level software for graphical user interface (GUI) and a powerful database engine for archiving/retrieval of all the information related to the waste packages, along with the history of the monitored counting rates.

All of the features listed above are the basis for the DMNR project. In this framework we developed and tested several proof-of-principle prototypes.

BASIC SENSOR UNIT AND ELECTRONICS

Each radiation sensor consists of a scintillating optical fiber, 1-2 m long and 1 mm diameter, which can be arranged around each drum in longitudinal and/or ring geometry. If both geometries are adopted, the most likely leak position can be determined by combining the increased activity measured by a longitudinal and a ring fiber. Each fiber can intercept radiation coming off the drum wall, mostly gamma rays, so that the energy released inside its active volume is converted into scintillation light, that propagates to both ends of the fiber itself to be detected by the photosensors.

Simulations were performed using the GEANT code, which included the fiber material and geometry, the

poissonian production of the scintillation photons, the response of the SiPM. Not being able to evaluate the real properties of the optical contact between the fiber and the SiPM face, it was assumed it contributed in a systematical way. In other words, one expected to find a proportionality between the simulated and the measured data, with a scaling coefficient independent of the gamma source type.

The efficiency measurements were done using ^{60}Co (1.333 and 1.173 MeV) and ^{137}Cs (0.662 MeV) sources. Fig. 1 reports the results of simulations and measurements; the simulated data points were rescaled by a unique systematical constant, to account for the unknown effect of the optical contact, of the effective light yield of the particular fiber (in the simulation the nominal value was used), and of the SiPM detection efficiency [6].

Moreover, by assuming a point-like source and an infinite fiber length, one can easily calculate the fiber solid angle as seen from the source, either by solving a simple integral or even by elementary geometrical considerations. The geometrical efficiency thus resulting, i.e. the ratio between the fiber solid angle and the 4π total solid angle, is $d/2\pi r$ where d is the fiber diameter and r is the distance from the source. Two curves proportional to $1/r$ were reported on the same plot (Fig. 1) after normalization to the first data point of each series. The conclusion, as can be easily verified on the plot, is that both the simulation and the $1/r$ behavior reproduce pretty well the measured data.

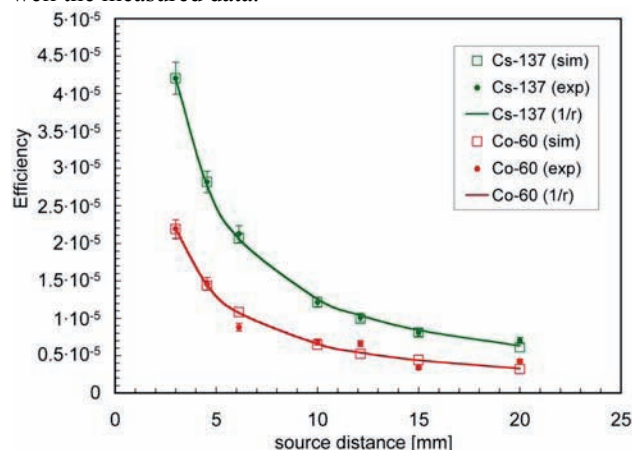


Fig. 1. Detection efficiency of the fiber sensor to gamma radiation, as a function of the source distance, for two different sources: ^{60}Co and ^{137}Cs . Open squares: simulation; full circles: measured data; line: calculation assuming a $1/r$ dependence.

Despite the physical amplification due to the avalanche multiplication, the output signal of a SiPM is generally small and needs further amplification. The first tests were done using a commercial high-level linear amplifier, namely ORTEC FTA810B, featuring a linear gain around 200 with a bandwidth of 350 MHz. It was then decided to design a dedicated amplifier, that was developed at LNS

in discrete components SMD technology, featuring a linear gain around 200 and a bandwidth of 4GHz.

Employing this amplifier allowed a much more comfortable handling of the analog to digital electronics, without recourse to a dedicated ASIC (Application Specific Integrated Circuit). In particular a discrimination circuit was developed, in order to generate a digital output pulse whenever an input pulse overcomes a predefined threshold value, along with a fast digital coincidence circuit that only generates a digital output pulse when its two digital inputs are true.

Each of the two SiPM outputs from a fiber is fed to an amplifier, whose output goes into a discriminator. The outputs of the two discriminators are combined by the coincidence unit, that will thus produce an output pulse only when a predefined amount of light is detected at both fiber ends.

Fig. 2 shows a sketch of the front-end electronics architecture for one fiber. The output signal shape and type (analog or digital and polarity) are represented near each component. It is worth to remark that a single FPGA can handle many fibers at once.

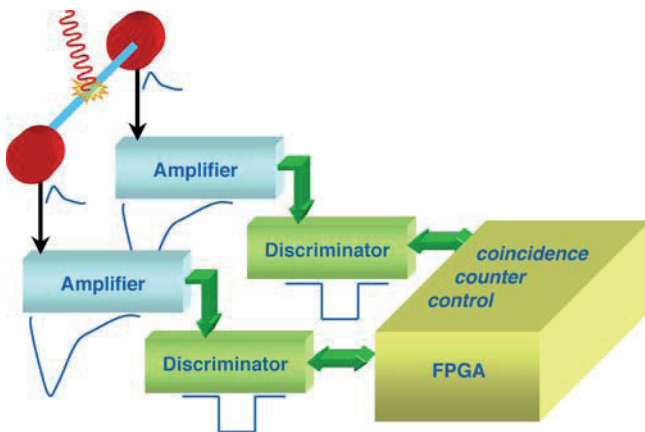


Fig. 2. Scheme of the front-end electronics for one fiber. The output signal shape and type are represented near each component. It is worth to remark that a single FPGA can handle many fibers at once.

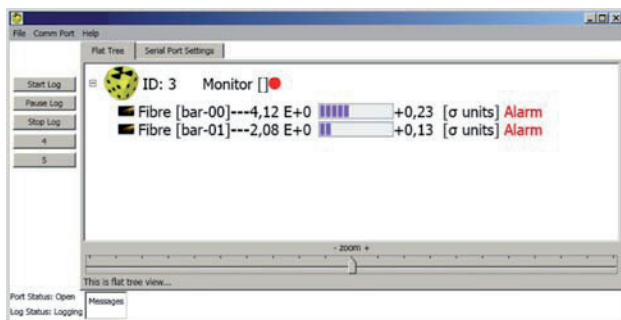


Fig. 3. A screenshot of the graphical user interface.

The FPGA implements a set of digital counters, along with a clock and the USB interface towards a computer where the graphical user interface allows the online control and the log data storage.

CONCLUSION

The DMNR project has shown that a real time online monitoring system for radioactive waste is feasible.

Several tests with radioactive sources have allowed to validate the simulations, as well as to prove that the detectors and the associated electronics are suitable for the monitoring task we aim for.

ACKNOWLEDGEMENT

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Characterization under proton beam of a complete proton computed radiography apparatus

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Abstract - Proton Computed Tomography (pCT) is a medical imaging method based on the use of proton beams with kinetic energy of the order of 250 MeV, aimed at directly measuring the stopping power distribution of tissues (presently calculated from X-rays attenuation coefficients) to improve the accuracy of treatment planning in hadron therapy. A pCT system should be able to measure tissue electron density with an accuracy better than 1% and with a spatial resolution better than 1 mm. The blurring effect due to multiple Coulomb scattering can be circumvented by single proton tracking. As a first step toward pCT, during year 2010, we manufactured a proprietary apparatus to undergo proton computed radiography (pCR). The system, able to carry out single projections, is characterised by a field of view of about $5 \times 5 \text{ cm}^2$ and an acquisition time of the order of 10s (10 kHz, 10^5 events). It includes a tracker, made of silicon microstrip detectors, to measure proton trajectory, and a calorimeter, made of four YAG:Ce optically separated crystals, to measure the residual energy. In 2010 the complete system has been characterized with 62 MeV protons at Laboratori Nazionali del Sud (LNS-INFN). Results from these experiments are presented in this contribution and first radiographies shown.

INTRODUCTION

One of the main advantages in using protons to treat tumors is the possibility to tightly shape the radiation dose to the target volume, thanks to the peculiarities of the interaction of hadrons with matter. However, the spatial accuracy of proton therapy is still presently limited by the uncertainty in the stopping power distribution, which is calculated from photon attenuation coefficients measured by X-ray tomography [1]. This uncertainty could be reduced by directly measuring stopping powers with a proton beam [2] by means of a proton tomography (pCT) apparatus. The basic idea of pCT is to reconstruct

stopping power distribution by measuring the protons energy loss along their path through the matter. The main difficulty is the blurring effect introduced in tomographic projections by multiple Coulomb scattering. A possible solution is to track the trajectory of each proton, by measuring its direction upstream and downstream the imaged volume.

Aim of our project [3] is to design, manufacture and test a pCT prototype for small objects analysis where single proton tracking is performed with segmented silicon sensors. The final pCT system should be able to measure electron density with an accuracy better than 1% and with a spatial resolution better than 1 mm. The project is carried out in the framework of the PRIMA (PRoton IMAGING) experiment of CSN5-INFN. In detail, main objectives of our research activity are: a) to develop a proton computed radiography (pCR) prototype capable to carry out a single projection; b) to develop a time-effective data analysis algorithm suitable to account for multiple scattering; c) to conceive a configuration for a complete pCT system.

As a first step, we designed and manufactured in 2010 a complete apparatus for proton computed radiography (pCR), to detect protons with initial kinetic energy high enough to transverse a human trunk (in the range 250 to 270 MeV) in order to collect data within a time of the order of 10s.

THE PCR SYSTEM

Figure 1 reports an overview of the pCR system design, which includes a tracker and a segmented calorimeter (a). The tracker is composed of 4 xy planes (p1 to p4) capable to measure x and y coordinates of the particle trajectory. Protons emerge from the beam pipe (g). Planes p1 and p2 measure entrance angle and position; the object under

study (a phantom in this case) is placed in the gap between planes p2 and p3; planes p3 and p4 measure exit angle and position. The distance between entrance (or exit) planes is about 1cm and could be changed to optimize the measurement quality. Beyond the last plane (p4), protons stop inside the calorimeter (a), which measures the particle residual energy.

Each xy plane is composed of two identical tracker modules, each including a 256-channels silicon microstrip detector (c), analog front-end ASIC and digital electronics for data acquisition and transmission. One of the two tracker modules within the same xy plane is flipped upside down and rotated by 90° to measure both the x and y local trajectory coordinates. Each tracker module communicates with the control terminal (PC) by an Ethernet connection. Each tracker module includes two electronics boards: a front end board (b), carrying the silicon microstrip detector (c) and readout ASICs, and a tracker digital board (d). The latter board is mounted piggyback to the former.

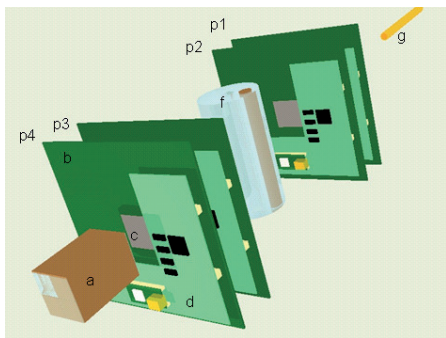


Figure 1: Sketch of the pCR system in the typical test arrangement. The Si telescope composed by the xy planes p1 to p4, the calorimeter (a) and a phantom (f) are shown. Protons emerge from beam pipe (g).

A $200\ \mu\text{m}$ detector thickness provides a good compromise between low multi-Coulomb scattering and low energy loss in the device and high signal to noise ratio. The ASIC, which contains 32 channels readout in parallel, has been developed in the framework of the INFN PRIMA experiment. The calorimeter is made of four YAG:Ce optically separated crystals, with size $3\times 3\times 10\text{cm}^3$, arranged as a 2×2 matrix. This material has been selected due to its short decay time (70 ns) and because its scintillation light is in the photodiode sensitivity range. Photodiodes are simpler to use than photomultiplier and are not sensitive to the magnetic field usually present near the beam line. More details on the system can be found in recent publications [4-9].

RESULTS OF THE PROTON TEST BEAM

The pCR system has been tested with a 62MeV proton beam at LNS in May 2010. A photograph of the complete

pCR system installed at the CATANA proton beam of LNS-INFN Catania is shown in figure 2.



Figure 2: Photograph of the pCR system, composed by four Si x -y planes and a YAG:Ce calorimeter with front-end electronics, installed at CATANA beam in LNS INFN.

In the 62MeV proton beam test the pCR hardware was fully characterised and first radiographic images of a non-homogeneous phantom were taken. Fig. 3 shows the scheme of the setup used during data acquisition. The phantom has been positioned between P2 and P3. Planes alignment has been done on the pCR prototype using a sample of about 3×10^5 tracks taken when no phantom is inserted in the system. The off-line alignment procedure is based on the chi-squared minimization of the reconstructed tracks with respect to the alignment parameters (transverse and longitudinal shifts and plane tilt angle of the tracker planes). During the test beam 300'000 events were acquired to obtain radiographies. Radiographic images have been reconstructed using both spatial coordinates and residual energy values. An image of the non homogeneous phantom taken with the PRIMA apparatus at LNS INFN Catania on May 2010 is shown in fig. 4.

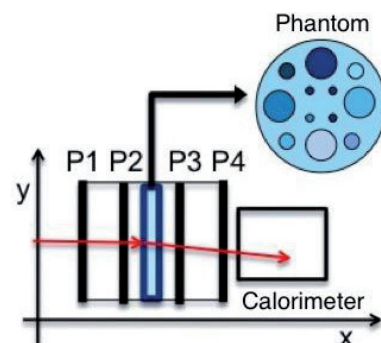


Fig. 3. Sketch of the pCR experiment carried out at LNS-INFN with a 62MeV proton beam. A non homogeneous phantom is placed in between the silicon microstrip modules P2 and P3 of the PRIMA apparatus.

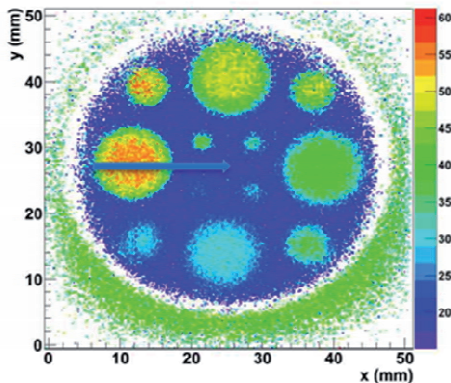


Fig. 4. Proton radiography of the non homogeneous phantom taken with the PRIMA pCR apparatus at LNS INFN.

To get information on the accuracy of the image reconstruction the profile of the radiography was studied on a slice of fixed Δy along the x-coordinate, as indicated by the arrow in fig. 4. Results, shown in fig. 5, give indication that a standard deviation σ of 3strips (600 μ m) is achieved in the high contrast region between 55MeV and 22MeV. These results show that in case of high contrast a sub millimeter precision is achieved by the PRIMA apparatus.

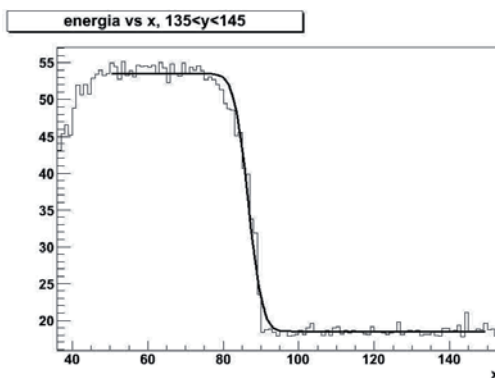


Fig.5 Plot of the energy profile along x-coordinate in the on a slice of fixed Δy along the x-coordinate, as indicated by the arrow in fig. 4.

As a further test, the radiography of a little object (walnut) was also performed, image is shown in fig. 7.

CONCLUSIONS

A system for proton radiography, made of silicon microstrip detector modules and a YAG:Ce calorimeter, has been designed, manufactured and tested by the PRIMA INFN collaboration. The complete system has been tested in 2010 with a 62MeV proton beam at LNS-INFN. First results obtained demonstrate the quite efficient apparatus functionality.

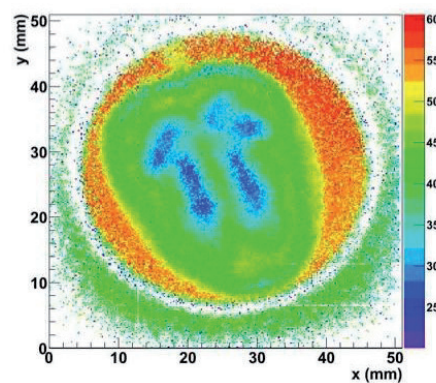


Fig. 7. Proton radiography a little object (walnut) taken with the PRIMA pCR apparatus at LNS INFN.

Radiographic images of a non-homogeneous phantom and of a little object have been reconstructed using spatial coordinates and residual energy values. Accuracy of the image reconstruction in case of high contrast proves to be in the sub-millimeter range. Presently, we are in the process of measuring and analyzing first pCT tomographic analysis with this system. In near future we plan to perform studies with proton beams at higher energy. Further, our collaboration is planning to design and manufacturing a novel prototype of pCT system with increased active area and data acquisition speed, for realistic pre-clinical applications.

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Ion-beam nanostructuring of superconducting YBCO FIR photodetectors

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Abstract – In the framework of the INFN-Mo.Na.De. experiment, we investigated the possibility of modifying $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ superconducting films by high energy heavy ion irradiation for developing position-sensitive far infrared detectors. In this report, we describe the activity during the year 2010, which was devoted to fulfil the last targets of the Mo.Na.De. experiment: engineering the prototype device for suitable portable liquid nitrogen housing and understanding the role of high energy heavy ion irradiation on the single crystal substrate, where the superconductor is deposited. For the latter purpose, irradiations with Au ions at several energies and fluencies are needed, and the analysis is still in progress.

INTRODUCTION

Since the discovery of high temperature superconductors, many efforts have been done for developing high performance devices working above the liquid nitrogen temperature. For optical detectors, the challenging task is to obtain comparable noise and responsivity characteristics which can compete with well assessed technology of low temperature superconductors and, for what concerns far infrared detectors, with low temperature silicon or germanium based sensors.

The Mo.Na.De. experiment is devoted to exploit the heavy ion lithography technique for developing a novel type of position-sensitive detectors of far-infrared radiation (FIR), based on the high temperature superconductor $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ (YBCO). The local irradiation of YBCO films with high energy heavy ions yields to a controlled reduction of the critical temperature, therefore a new material is formed inside a continuous, superconducting as-grown film. This local reduction of the critical temperature was already exploited in the INFN-Di.S.Co.L.I. experiment for developing a position sensitive magnetic field detector [1,2].

The same approach, as demonstrated in [3], is useful for detecting the infrared radiation, down to the sub-millimetre wavelength range, i.e., the far infrared. A prototype device was tested with suitably filtered black body sources and the far infrared induced signal was detected only in the irradiated part of the sample, under suitable bias conditions. This device can be operated above the liquid nitrogen temperature and therefore with the perspective to be used in light weight, portable cryostats. Moreover, since only a selected part of the

superconducting film (the irradiated one), is brought into the dissipative state, the noise performances can be tuned in order to meet stringent requirements of critical applications, which now must rely only on low temperature bolometers.

In this report, we describe the activity of the last year of the Mo.Na.De. experiment. In order to accomplish the project milestones, we conducted separate activities for engineering the prototype layout for use of the detector in a portable liquid nitrogen cryostat (a solution chosen e.g. in the frame of INFN-TERASPARC experiment, that authors are currently involved in), and for studying the effects of high energy heavy ion irradiation of the single crystal substrates, where the superconducting films are deposited and which constitute the thermal resistance of the device.

EXPERIMENTAL DETAILS

Device preparation

YBCO films were deposited by thermal co-evaporation [4], both on CeO_2 buffered yttria stabilized zirconia (YSZ) and on MgO single crystal substrates. Thickness of the superconducting films were 300 nm for YBCO on YSZ and 250 nm for YBCO on MgO.

The device layout was discussed in the previous LNS report [5]. Basically, a couple of meanders are connected in series. One of them is uniformly irradiated (see the following section), in order to obtain a sensitive element for thermal radiation slightly above the liquid nitrogen temperature. Standard UV photolithography and wet etching were used to pattern the devices.

Heavy Ion Lithography

The heavy ion lithography technique was developed for controlling the spatial distribution of swift ions colliding on solid samples. The apparatus is described in details in [6]. A micro-collimator is placed across the beam line in order to shape a uniform ion beam. A moving sample holder (with crossed optical encoders) enables to irradiate the sample with arbitrary patterns. For the production of the devices, we scan one of the meander in order to locally irradiate it with the maximum uniformity. Same procedure was adopted for the bare substrates.

The irradiation of YBCO films with relatively high fluences of swift ions reduces its critical temperature [1,2]. This finding is at the basis of the Mo.Na.De. device

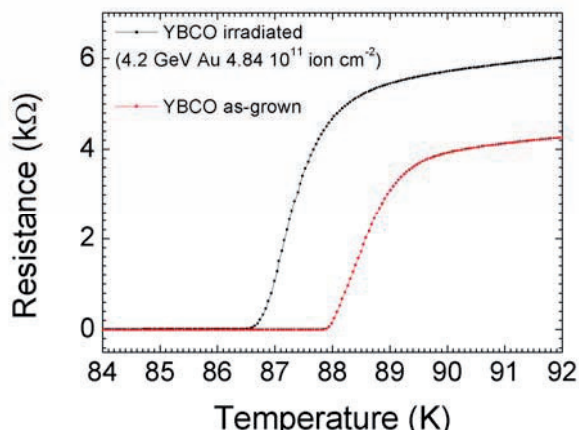


Figure 1: resistance vs. temperature curves of the two meanders in a device irradiated with 4.2 GeV ^{197}Au ions, at a fluence of $4.8 \cdot 10^{11} \text{ cm}^{-2}$.

[3]. With respect to other techniques which are degrading the superconducting properties, the heavy ion lithography has the advantage not to reduce the slope of the resistance versus temperature curve. This parameter is critical for every bolometer application. In order to understand the role of ion energy in this process, we irradiated samples at different energies. The result for 4.2 GeV ^{197}Au ion irradiation is presented in Fig. 1. Even if the critical temperature shift is smaller with respect to the effect of lower energy (e.g., 250 MeV), the slope is steeper: from 3.32 kΩ/K, as-grown YBCO, to 4.85 kΩ/K, irradiated YBCO.

Sample characterization: devices and substrates

The devices are electrically measured in a modified optical cryostat from Oxford Instruments Ltd^(TM). The device has two current leads and three voltage contacts. By means of a dual-channel voltmeter, the complete characterization of as-grown and irradiated YBCO is performed simultaneously.

Substrate optical characterization was performed by a commercial Varian^(TM) spectrometer for the near ultraviolet-visible wavelength range (transmission and reflection), while a FTIR Bruker^(TM) spectrometer was used for the measurement of optical absorption for 2.5 - 25 μm wavelength range.

LIQUID NITROGEN HOUSING

The Mo.Na.De. device was thought for operating at relatively high temperature with respect to other far infrared sensors. Its low power consumption and low mass are suitable for working in light weight and portable liquid nitrogen dewars. We used a commercial product from Kadel^(TM).

A high resistivity silicon window was used in order to stop the electromagnetic radiation below about 1 μm wavelength. The cryostat appears as in Fig. 2(a). In order

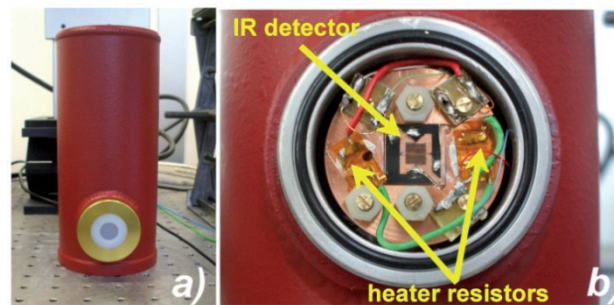


Figure 2: a) full view of the portable liquid nitrogen dewar; b) close-up of the device housing, onto the copper cold finger. Contacts arrangements and heater resistors can be clearly seen.

to keep the device at the required base temperature, we developed a cold finger of copper equipped with Teflon^(TM) insulating spacers and a resistive heater, which can be powered by two external wires. The device mounted on the cold finger is visible in Fig. 2(b).

ROLE OF THE IRRADIATED SUBSTRATE

Creation of color centers

It is well known that irradiation of ionic crystals produces colour centers [7]. In the past, irradiation of MgO single crystals with fast neutrons, protons and alpha particles has shown to induce a coloration of the crystal in well defined absorption bands [8]. In particular, as-grown crystals generally show an intrinsic absorption band near 250 nm that is attributed to a small content of Fe impurities (of the order of a ppm). In addition, particle irradiation creates two major absorption bands peaked at 350 and 575 nm. The macroscopic effect in the visible spectrum is a blue coloration of the crystal.

In order to understand the role of ion modification into the device substrate, we studied the coloration of MgO crystals due to high energy Au ion irradiations. The results are resumed in Fig. 3, where the transmission/reflection spectra are reported for several crystals (as-grown and irradiated), in the near ultra-violet and visible wavelength range. It is clearly evident that irradiation with high energy Au ions produces color centers at the same positions as lighter particles. Therefore, this effect can be ascribed to the elastic collision of Au ions on Mg sites and the consequent formation of ionic vacancy, with the localization of an electron (F^+ colour center [9]). The amount of elastic scattered ions depends both on energy and fluence, as can be seen from the data. Moreover, at the highest energy (4.2 GeV), the UV absorption band is strongly enhanced and photoconductivity could be turned on in that wavelength range.

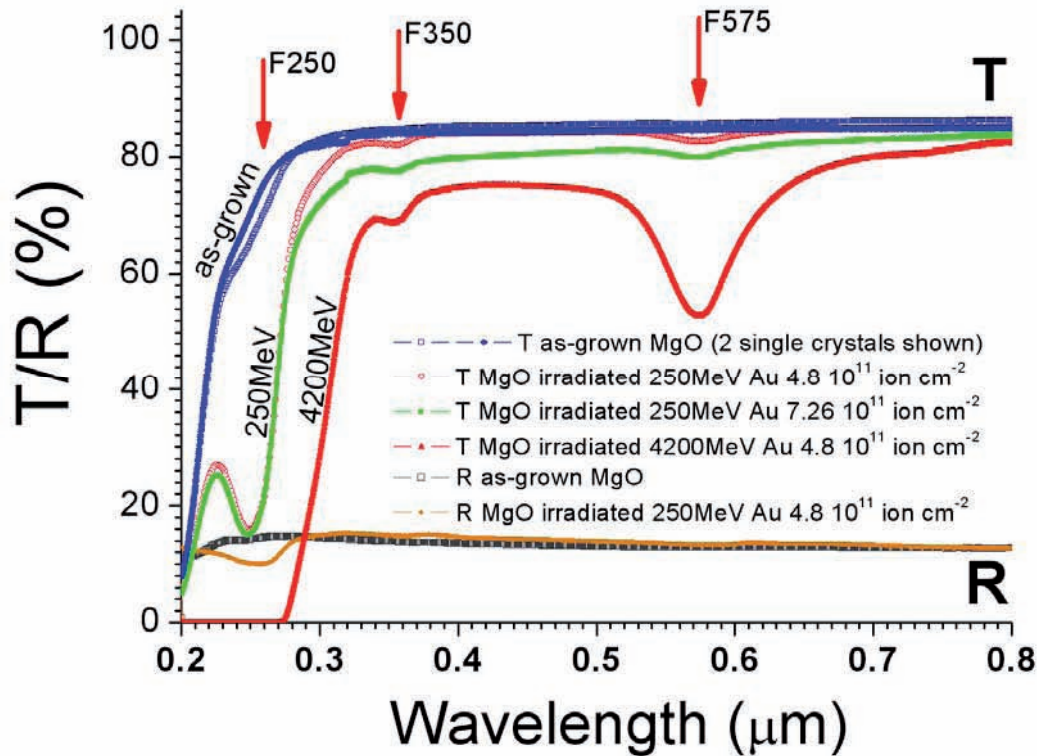


Figure 3: Transmission/Reflection spectra of several MgO crystals (as-grown and irradiated). The color centers are indicated by an arrow (the number following the F is indicating the central wavelength of absorption)

Phonons

In order to check if the thermal properties of the substrate are changed too, we measured the near to medium infrared absorption of irradiated crystals (both MgO and YSZ). Results for samples irradiated with 250 MeV Au ions are plotted in Fig. 4. No detectable difference can be appreciated in both materials, therefore the high energy Au ion irradiation, in that energy and fluence ranges, does not alter the phonon spectrum. This conclusion allows us to model the detector performances taking into account the measured thermal conductivity of the as-grown substrates, for irradiation energies up to 250 MeV ($3.4 \text{ Wcm}^{-1}\text{K}^{-1}$ for MgO and $0.015 \text{ Wcm}^{-1}\text{K}^{-1}$ for YSZ). For what concerns higher energy (e.g., CS energy), a further study is necessary in order to understand the role of phonon softening in the substrate.

CONCLUSIONS AND PERSPECTIVES

In summary, we presented results about the effect of high energy Au irradiations of YBCO patterned samples for what concerns Mo.Na.De. FIR detector performances, the engineering of a portable liquid nitrogen housing and the study of irradiation induced modifications of the detector substrates. It turns out that high energy Au ions can enhance the responsivity of the device, while the thermal properties of the substrates at high energy must be carefully investigated (despite coloration, the phonon spectrum is unchanged up to 250 MeV Au irradiation).

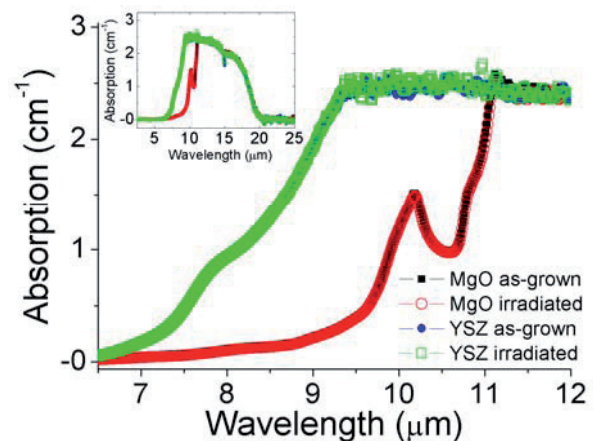


Figure 4: Near infrared spectra showing the phonon absorption edge of MgO and YSZ crystals (irradiated with 250 MeV ^{197}Au ions, at a fluence of $4.8 \cdot 10^{11} \text{ cm}^{-2}$ and as-grown), in the $6.5\text{--}12 \mu\text{m}$ range. Full spectra are shown in the inset.

ACKNOWLEDGEMENTS

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Effect of *NBS* gene mutations on stable chromosome aberration in ¹²C-ions irradiated-lymphoblastoid cell lines

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INTRODUCTION

Ionising radiations, induce cytogenetic damage that may represent useful markers for radiation exposure. In particular, stable chromosome aberrations, such as reciprocal translocations, do not result in the loss of chromosome material and do not disappear from the cell population in the same way as unstable aberrations do; therefore, they are considered heritable. Due to their stability and the potential for altered gene expression regulation because of position effects, translocations are very important for biodosimetry.

Fluorescence *in situ* hybridization (FISH) with chromosome-specific DNA probes, known as chromosome painting, can be used to quickly and accurately detect stable aberrations [1, 2, 3].

This approach, however, has not been extensively used to analyse the induction of translocations after high-LET radiation.

Another aspect that may possibly affect the response to radiation is the genetic background of cells/organisms. Mutations in genes encoding MRE11, RAD50, NBS1 proteins, members of the MRN complex are responsible for rare autosomal recessive disorders characterized by chromosomal instability and hypersensitivity to DNA double-strand break-inducing agents, like ionizing radiations and proneness to malignancy [4, 5].

With the aim to study the relationship between high-LET radiation, *NBS1* gene (responsible of the Nijmegen Breakage Syndrome, NBS) and chromosome instability, we have assessed the capability of 2 Gy of high-LET radiation (¹²C-ions, 50 keV/um) to induce stable chromosomal aberrations using chromosome painting. Experiment were carried out on lymphoblastoid cells derived from normal individuals and from individual heterozygotes or homozygotes for the *NBS1* gene.

MATERIALS AND METHODS

Human lymphoblastoid cell lines (LCLs) established from normal individuals, heterozygous and homozygous for mutations in the *NBS1* gene (*NBS1*+/+, *NBS1*+/- and *NBS1*-/-, respectively), were irradiated with 2 Gy ¹²C-ions (62 MeV, 50 keV/μm at the cell entrance; INFN-LNS facility). Samples were harvested after 48 hours from irradiation. To evaluate stable aberrations, chromosome painting staining was performed on calyculin-A-premature condensed chromosomes with FITC and Cy3-labelled probes (Metasystems, Germany) specific for whole chromosomes 1, 2 and 4. The slides were incubated in denaturing solution (NaOH 0,07 N) for 1 min. Denatured slides were dehydrated through a series of 3 min ethanol washes (70%, 85%, 100%) and air-dried. The DNA probes were denatured 5 min at 75°C, pre-annealed 30 min at 37°C. After the adding of the probes the slides were covered with a coverslip and sealed with rubber cement. After an overnight incubation in a humidified chamber at 37°C, the slides were washed 2 min in 1X SSC at 75°C and 1 min in 2X SSC at room temperature, followed by counterstaining with 4'-6'-diamidino-2-phenylindole (DAPI). Spreads were viewed with a fluorescence microscope equipped with DAPI/Cy3/FITC filters and a CCD camera.

RESULT AND DISCUSSION

In fig. 1 are shown examples of a normal metaphase (A) and a metaphase with translocation (B). In fig. 2 A, B and C, are reported the results obtained from chromosome painting analysis in the three genotypes (*NBS*+/+ , *NBS*+/- and *NBS*-/-, respectively). We can observe that translocation is the more frequent type of aberration irrespective of genotype. As expected, the yield of aberrant metaphases and total aberrations is higher in *NBS*-/- irradiated cells compared to normal and heterozygous counterparts. Interestingly, ¹²C-ions

produced a higher percentage of cytogenetic damage in NBS+/- in comparison with NBS+/+ cells, suggesting that a more severe DNA damage, as that expected to be induced by high-LET ^{12}C -ions, may cause difficulties to the DNA repair systems of NBS heterozygous cells. Data in the literature reporting on chromosome radiosensitivity of NBS cells to high-LET radiation are limited to experiments with high-energy iron ions (LET=151 keV/um; [6]). Results obtained with both ^{12}C - and ^{56}Fe -ions are in good agreement with the behaviour of NBS cells irradiated with low-LET radiation [7,8]. It should be recalled that differences in the complexity of DSBs are expected to be induced by high-LET radiations [9]. An interesting, and still open question, is whether there is a possibility of a genetically based radiosensitivity for high-LET induced damage in carriers of radiosensitive disorders as Ataxia telangiectasia (AT) and NBS.

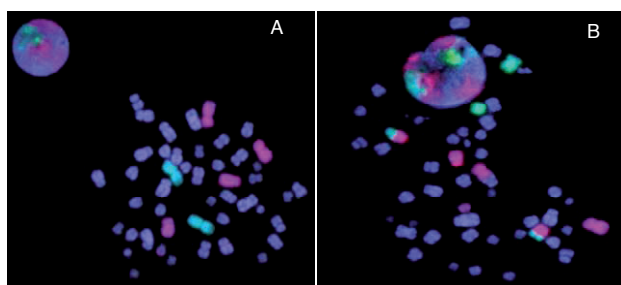


Figure 1: Examples of metaphases with 2, 4 (red staining) and 1 (green staining) painted chromosomes. Metaphases with normal painted chromosomes (A) and translocated chromosomes (B) are reported as representative. DNA was counterstained with DAPI.

This topic is of particular relevance for manned missions in deep space due to the unique radiation environment (mostly high-LET radiations) and in adrontherapy, for the possibility of a higher radiosensitivity of carriers subjected to treatment. In this respect it should be said that using chromosome painting Neubauer and coworkers (2002) were able to demonstrate intermediate sensitivity of NBS heterozygotes respect to γ -ray-induced aberrations [7]. To our knowledge, this is the only paper on this topic and no data are available in the literature for high-LET radiations. The results so far collected irradiating cells from a NBS heterozygotes with ^{12}C -ions, indicate that both the frequency of translocations and the frequency of total aberrations are increased with respect to the normal individual, though not to a dramatic extent. Therefore, since, such differences may be only of slight extent, the analysis on the NBS heterozygotes need to be increased in terms of metaphase scored and/or in a higher number of individual.

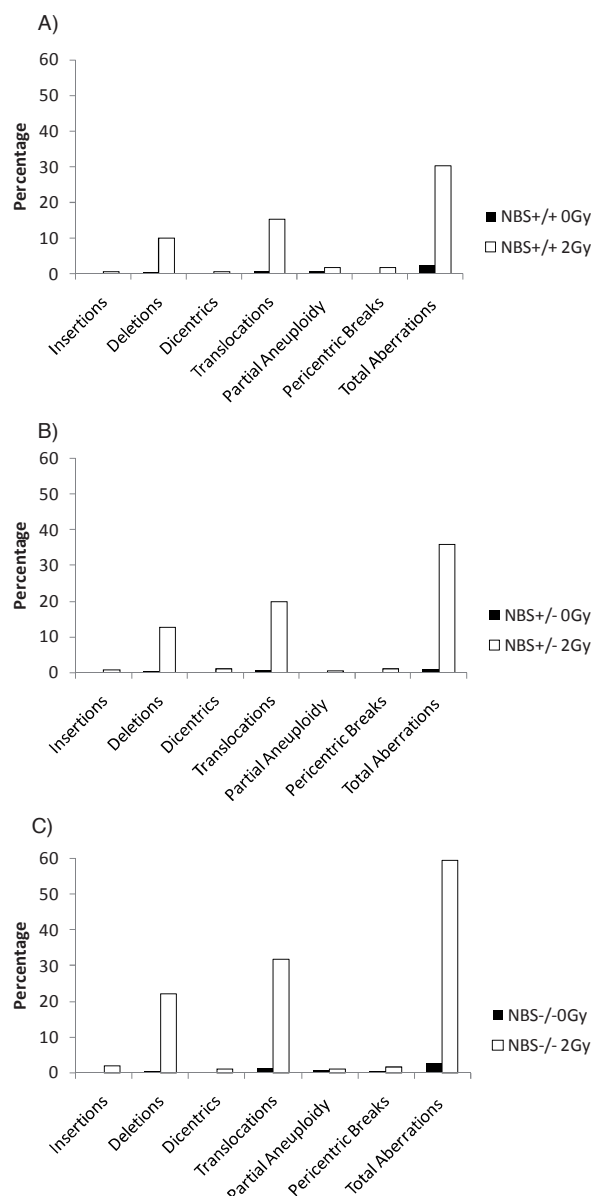


Figure 2: The yield of chromosome aberrations in NBS+/+, NBS+/- and NBS-/- cells.

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Melanoma cells along a carbon ion Bragg curve

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Abstract

The results presented were obtained after a series of irradiations of human HTB140 melanoma cells along the Bragg curve of the 62 MeV/u ¹²C ions. Irradiation positions were at the plateau, the peak and the distal fall off part of the Bragg curve. In this way different values of liner energy transfer (LET) were applied. The dose range was from 2 to 16 Gy. Radiobiological parameters confirmed high radio-resistance of the cells, showing also better effectiveness of ¹²C ions, due to higher LET, than that of protons and particularly γ -rays. For the five irradiation positions the surviving fractions at 2 Gy (SF2) were 0.72, 0.61, 0.57, 0.67 and 0.73, respectively along the curve. The corresponding relative biological effectiveness ranged from 4.56 through 7.06, 7.69 and 5.58 to 4.23. Numerical simulations with the GEANT4 code provided distributions of dose, fluence and LET, as functions of depth.

INTRODUCTION

Heavy ion beams have been commonly used in radiotherapy because they produce good radiobiological response in killing malignant growth. When traversing matter, high energy charged particles loose their energy through interactions with atoms, with a large increase in energy loss at the end of their track - the Bragg peak. The energy deposited per unit of length along the particle track, which is the linear energy transfer or LET, explains induced biological effects to radiation damage. Since LET depends on particle species, as well as on its energy, heavier particles have higher energy loss per unit length. It is assumed that these physical and biological properties might improve radiotherapy, particularly for radio-resistant tumours. However, it has been shown that the largest biological effectiveness was achieved at intermediate LET values of ~ 200 keV/ μ m [1, 2]. A number of studies revealed that the relative biological effectiveness (RBE) depends on LET, but also on ion species and cell types.

The effects of proton irradiations, at the Bragg peak as well as along the plateau of the spread out Bragg peak (SOBP), including the distal fall off part of SOBP, on the human HTB140 melanoma cells were extensively analysed. Although rather high RBE values, with respect to γ -rays, were obtained in all cases, surviving fractions at 2 Gy (SF2) revealed that these cells are among the most radio-resistant cell lines reported [3, 4]. Due to such a position on the wide scale of cellular radio-sensitivity,

HTB140 cells were exposed to the beam of ¹²C ions at five positions within the Bragg curve. Radiobiological effects corresponding to these different LET values were analysed. The irradiations were performed with the 62 MeV/u carbon ion beam in Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali del Sud (INFN – LNS), Catania. Radiobiological characterisation of the HTB140 cells after irradiations with carbon ions was done using clonogenic assay as well as proliferation assay that particularly enabled better insight of the distribution of the radiation damage that was produced.

MATERIALS AND METHODS

Cell Culture

The HTB140 cells were maintained in RPMI1640 medium supplemented with 10 % foetal calf serum, penicillin/streptomycin and L-glutamine (all from Sigma-Aldrich Chemie GmbH, Steinheim, Germany). Cells were grown in 25 cm² plastic tissue culture flasks at 37 °C in a humidified atmosphere with 5 % CO₂ (Heraeus, Hanau, Germany). Under these conditions, the plating efficiency for the cells was 62 ± 7.3 %.

Irradiation Conditions

Exponentially growing cells were irradiated with 62 MeV/u ¹²C ions produced by the superconducting cyclotron in INFN – LNS, Catania. Five positions for irradiation, as shown in Figure 1, were obtained by interposing Perspex plates (Polymethyl methacrylate - PMMA) of different thickness in front of the cell monolayer. The thicknesses of Perspex were 6.0, 7.7, 7.8, 7.9 and 8.0 mm, giving relative doses of 22.1 ± 1.4 , 49.0 ± 3.9 , 64.0 ± 4.4 , 87.5 ± 5.7 and 32.8 ± 7.2 % for positions A, B, C, D and E, respectively. Single doses delivered to the cells at each irradiation position were 2, 4, 8, 12 and 16 Gy, at the dose rate of 11.03 ± 0.27 Gy/min. Reference dosimetry was performed using plane-parallel PTW 34045 Markus ionization chamber calibrated according to IAEA code of practice [5]. The precision of positioning of the chamber was 50 μ m [4, 6]. Since the range of the 62 MeV/u carbon ions is short, with a very narrow Bragg peak, the precision of positioning of cells was checked by placing GafChromic HS films (ISP Technologies, Wayne, New Jersey, U.S.A.) before each irradiation. Flasks with cell monolayers were fixed vertically in a special device, facing the horizontal beam. Prior to irradiations culture medium was discarded. Controls were maintained under the same conditions.

Irradiations with γ -rays, at the same dose levels and conditions, were performed using ^{60}Co source in the Vinča Institute of Nuclear Sciences in Belgrade, at the average dose rate of 1 Gy/min. Dosimetry calibration was performed according to IAEA code of practice [5]. Cell survival, estimated after ^{12}C ion irradiations was carried out in INFN - LNS, while that after γ -rays in the Vinča Institute.

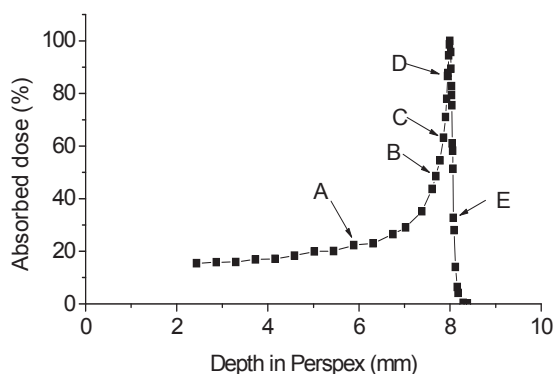


Figure 1: Measured depth dose distribution in Perspex of the 62 MeV/u ^{12}C ion beam. Arrows indicate irradiation positions.

Clonogenic Assay (CA)

After irradiation cells were harvested by trypsinization, seeded into 25 cm² flasks at a suitable number for colony assay and incubated at 37 °C for 7 days. This time corresponds to the clonal survival of the HTB140 cells [3]. Cells were then fixed with methanol and stained with 10 % Giemsa solution. More than 50 cells per colony were scored as a surviving cell. Survival was calculated by comparing the number of colonies in irradiated samples with controls. Three independent experiments were done and each dose level was tested three times per experiment.

Proliferation Assay (BrdU)

The cell proliferation and the DNA synthesis were measured using a 5-bromo-2-deoxyuridine (BrdU) assay (Roche Diagnostics GmbH, Mannheim, Germany). The cells were grown in 96-well plates (four wells per dose in each of three independent experiments, Nunclon™, Amex Export-Import) and BrdU labeling was performed according to the manufacturer's instructions. The absorbance was measured at 550 nm using a microplate reader (Wallac, Victor2 1420 Multilabel counter, PerkinElmer, Turku, Finland).

GEANT4 code

The GEANT4 code based on the Monte Carlo method was used to reproduce the transport beam line of carbon ions at INFN - LNS. Physical models and data libraries used were those valid for radiotherapy energy range. For numerical simulations the PMMA phantom was divided in 10 μm thick slices orthogonal to the beam axis and the

depth distributions of dose, fluence and mean LET were obtained [7, 8].

RESULTS

Response to irradiations with the doses ranging from 2 to 16 Gy, were analysed at five positions within the depth dose distribution in Perspex of the 62 MeV/u ^{12}C ion beam. Experimental data were fitted using the linear-quadratic equation: $S = \exp(-\alpha D - \beta D^2)$, where S is the surviving fraction for the dose D , while α and β are the fitting parameters. Surviving fractions were evaluated from the best fit survival curves. Data obtained by the clonal assay and the resulting survival curves are given in Figure 2. Since the β parameter was very small for all fitted curves, fitting to the linear-quadratic equation was reduced to its linear term.

Figure 2 shows that the levels of cell inactivation produced by carbon ion irradiations are stronger than that of γ -rays in the whole dose range and for all irradiation positions. When changing the irradiation position from A through B to C the dose dependent killing ability of carbon ions increases, while it decreases for D and E. The effectiveness of each position is illustrated by α parameter, ranging from 0.163 Gy⁻¹, through 0.246 Gy⁻¹, 0.278 Gy⁻¹ and 0.201 Gy⁻¹ to 0.154 Gy⁻¹, respectively. The corresponding value for γ -rays is 0.036 Gy⁻¹.

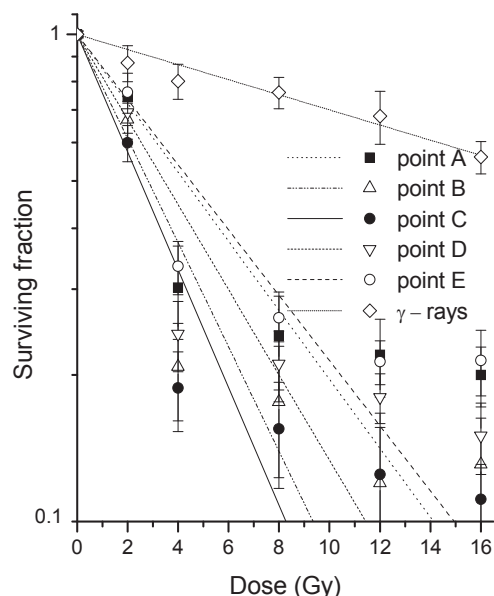


Figure 2: Dose dependent surviving fractions of HTB140 cells irradiated with γ -rays and ^{12}C ions at five irradiation depths in Perspex (A, B, C, D and E).

Considering the survival data inside each irradiation position, there is a relatively high gradient of cell inactivation for the doses below 8 Gy. As the dose increases cell inactivation is further improved although less than for lower doses. The described fall off rate of

survival data at lower doses increases when irradiation positions are changed from A to C. Inside each irradiation position, the survival data do not differ to a great extent for higher doses. The strong fall off rate of the survival data for lower doses has an important contribution to the decrease of the fitted curves. The two rather different gradients of cell inactivation, one for lower and the other for higher doses are the cause of reduced fitting precision of the curves. For the positions A, B, C, D and E the coefficient of determination (r^2) is 0.87, 0.93, 0.94, 0.89 and 0.88, respectively.

The levels of cellular radio-sensitivity assessed by surviving fractions at 2 Gy (SF2) were estimated from the fitted curves. Its highest value, i.e., 0.93 ± 0.01 is obtained for γ -rays. Rather high values are also obtained throughout the carbon irradiation positions (A, B, C, D and E) and are 0.72 ± 0.01 , 0.61 ± 0.02 , 0.57 ± 0.02 , 0.67 ± 0.02 and 0.73 ± 0.01 , respectively.

The biological effect of carbon ions with respect to γ -rays was estimated by relative biological effectiveness at 2 Gy, RBE (2 Gy, γ). It represents the ratio of 2 Gy γ -ray dose and the carbon ion dose generating the same inactivation level as that given by 2 Gy of the reference γ -rays. The values of this parameter increase along irradiation positions from A to C, and are 4.56 ± 0.16 , 7.06 ± 0.18 and 7.69 ± 0.14 , respectively. For positions D and E RBE (2 Gy, γ) decreases having values 5.58 ± 0.12 and 4.23 ± 0.13 , respectively.

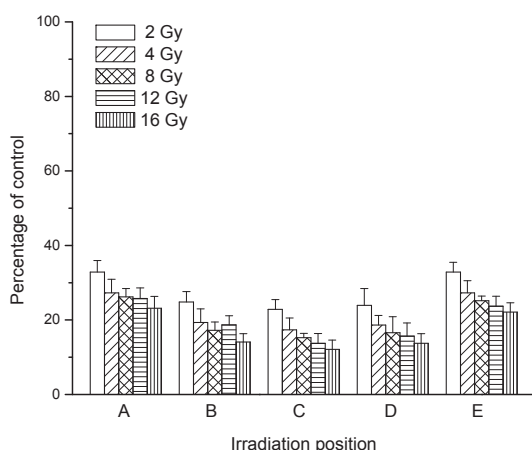


Figure 3: Dose-dependent cell proliferation at irradiation positions A, B, C, D and E.

Figure 3 gives the levels of cell proliferation as a function of dose at five irradiation positions along the carbon Bragg curve. At all irradiation positions there is a strong drop of cell proliferation with respect to controls, reaching values below 40 %. The lowest cell proliferation is attained at positions B and C while it is somewhat higher at position D. The highest cell proliferation is detected at position E and a slightly lower at position A. For doses higher than 4 Gy, at all irradiation positions, there is a relatively small decrease of cell proliferation

with the rise of the doses applied. However, there is not a considerable statistical difference between irradiation positions in the range of the delivered doses.

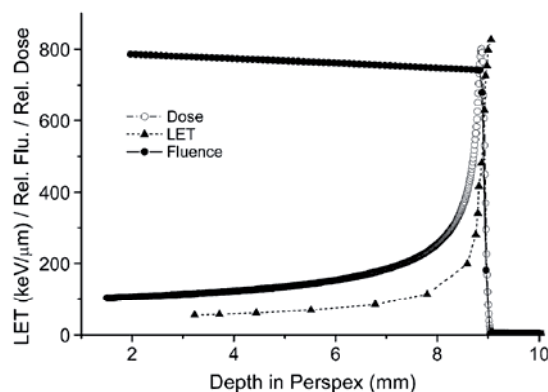


Figure 4: Numerical simulations with the GEANT4 code: relative dose, relative fluence and mean LET distributions as functions of depth.

The GEANT4 code was used to simulate a number of physical parameters that characterize the carbon beam in the performed experiment. Very good agreement, practically overlapping, was obtained for the experimental (Figure 1) and the simulated dose-depth distributions. Figure 4 gives the distributions of primary carbon ion relative dose, mean LET and relative fluence as a function of depth in Perspex obtained by simulations. Curves of relative dose and fluence were normalized to the maximum at 800, which is practically the maximum value of mean LET given in keV/ μ m. Contribution of secondary particles at the carbon energy used is small, thus neglected in the figure. From the simulated data it is clear that the fluence is practically flat and falls sharply at the very end of carbon range. Along the carbon path mean LET rises very slowly until close to the end of range when it increases very fast exponentially. LET values at the positions A, B, C, D and E were ~ 84 , 197, 258, 382 and 742 keV/ μ m.

DISCUSSION

Carbon ion beam, produced at the INFN – LNS was tested on the resistant human HTB140 melanoma cells. A number of parameters describing the level of cellular radio-sensitivity were presented. Irradiation position was moved along the Bragg curve of the 62 MeV/u ^{12}C ions, enabling investigation of the level of cell survival at different Perspex depths. Chosen positions belonged to the plateau, the peak and the distal fall off part of the Bragg curve, having rather different LET values.

The effect of the two quite different gradients of cell inactivation, one for smaller and the other for higher doses (Figure 2) resembles the low-dose hypersensitivity, but on the dose scale that is an order of magnitude larger. Due to the two gradients, the HTB140 cells reveal a kind

of saturation of the inactivation capacity with the rise of doses. This might be regarded as a kind of overkill appearing with the increase of doses. After proton irradiations along the SOBP this conduct was also observed and discussed [4]. Very high radio-resistance of the HTB140 cells is probably at the origin of this shift of the dose scale [9].

The obtained values of surviving fractions at 2 Gy (SF2), throughout the whole Bragg curve, indicate rather high level of radio-resistance of these cells [10]. They decrease when changing irradiation position along the major part of proximal section of the Bragg curve, when they start moderately to rise. Still all these values, when compared to those obtained with 62 MeV protons, are lower [3]. This is the consequence of higher LET values and different track structure in the case of carbon ions than in the case of protons. Although for carbon irradiation positions from A to C, LET rises from ~ 84 to $258 \text{ keV}/\mu\text{m}$ there is not a big decrease of SF2 values (from 0.72 to 0.57). When moving irradiation position to the proximal side close to the Bragg peak maximum (position D) and further to the distal fall off part of the Bragg peak (position E), the SF values increase (from 0.67 to 0.73) although LET rises from ~ 382 to $742 \text{ keV}/\mu\text{m}$. Such behaviour is in agreement with the reported fact that the highest efficiency of carbon ions is at $\sim 200 \text{ keV}/\mu\text{m}$, since for higher LET values there is an overkill of the cell population [2].

The efficiency of carbon ions to inactivate cells with respect to conventional radiation (γ -rays) is analysed through relative biological effectiveness at 2 Gy (RBE). Even though it was shown that HTB140 cells are among the most radio-resistant cells, the obtained RBE values indicate significant level of carbon induced cell inactivation, which is higher than for protons. Moving the irradiation position from A to C, RBE (2 Gy, γ) increases from 4.56 to 7.69, while slightly decreases to 5.58 and 4.23 when further moving to positions D and E. Such high RBE values are the consequence of low inactivation that was attained by γ -rays. Similar RBE values for the corresponding carbon LET were obtained for more radio-sensitive cell lines [11, 12]. Also close RBE values were attained in the case of fractionated dose irradiations [13]. However, small variations in ion beam production and transport at different facilities can influence the radiobiological outcome [2].

It might seem that due to two gradients the linear-quadratic model underestimates the inactivation effect at lower doses, but it is so both for γ -rays and carbon ions and therefore does not affect the evaluation of RBE. When the RBE was evaluated only from the fitted curves for γ -rays and carbon ions up to 4 Gy there was no considerable difference.

Proliferation capacity of the HTB140 cells illustrates the quality of life of the cells by distinguishing those that are in the stage of the DNA replication from those that are either dead or are stopped for a time period in order to repair the lesions induced by radiation. Parallel examination of the two biological endpoints, the survival

and the proliferation capacity, along the chosen irradiation positions enables better insight of the distribution of the radiation damage that was produced by carbon ions. Following the results of the two assays it appears that the number of survived cells and those that have active proliferation are quite similar. Therefore, the large majority of the cells that are not in proliferation are the cells killed by carbon ions, meaning that there are practically no cells stopped in order to repair the lesions induced by radiation. Moreover, regardless the LET values cell surviving fractions are similar for all irradiation positions. They all express weak dose dependence. This is even more pronounced for cell proliferation values.

CONCLUSIONS

Radiobiological parameters, evaluated after irradiations with carbon ions, have revealed high resistance of human HTB140 melanoma cells. Still, these parameters, due to higher LET of carbon ions, have shown better effectiveness compared to protons and particularly to γ -rays. Significant cell inactivation was observed along the whole Bragg curve.

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Response of human lung adenocarcinoma cells to proton irradiation

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Abstract

The prognosis of patients with lung cancer is still poor despite recent advances in surgery, radiation, and chemotherapy. Therefore, the development and application of new therapeutic strategies are essential for improving the prognosis of this disease. Proton radiotherapy is a mode of treatment that has an inherent advantage over photon radiotherapy, because of its good dose localization and high biological effectiveness on the tumour. The aim of this *in vitro* study was to investigate the inactivation effects of protons on human lung CRL5876 adenocarcinoma. Irradiations were performed in the middle of the 62 MeV therapeutic proton spread out Bragg peak. The mean energy of protons was 34.88 ± 2.15 MeV, corresponding to the mean linear energy transfer value of 4.7 ± 0.2 keV/ μ m. Irradiations were performed with single doses ranging from 2 to 16 Gy. Cell survival was assessed 7 days after exposure to protons. Flow cytometric analyses of apoptosis were performed after 48 h, while the cell cycle phase distribution was analyzed both 48 h and 7 days post-irradiation. The obtained results indicated that irradiation induced dose-dependent inhibition of cell survival, with higher effectiveness of protons than γ -rays, used as reference radiation. The CRL5876 cells showed low apoptotic cell death (4.49 – 9.05 %). The flow cytometric analysis of cell cycle distribution revealed that protons provoke accumulation of the CRL5876 cells in G2 phase.

These preliminary results showed high radio-resistance of human CRL5876 lung adenocarcinoma cells and indicated that proton radiation induced higher level of inhibition of cell survival than γ -rays. Antitumour effect of protons is accomplished through induction of G2 arrest.

INTRODUCTION

Lung cancer is the leading cause of cancer death throughout the world, claiming more than 1 million lives each year [1]. This type of cancer can roughly be separated into small cell lung carcinoma (SCLC) or non-small cell lung cancer (NSCLC) [2]. SCLC represents 15 % of all lung cancers diagnosed and displays neuroendocrine features. It is very responsive to chemotherapy alone or combined chemo-radiotherapy [3].

NSCLC accounts for 85 % of lung cancers and includes the histopathologic subtypes: adenocarcinoma, squamous

cell carcinoma and large cell carcinoma. Treatment of NSCLC differs between stages. Surgery is the standard approach to early stage disease while radiotherapy, with or without chemotherapy, is the main treatment option in non-resectable, locally advanced disease. Finally, in metastatic disease chemotherapy remains the only available treatment [4]. Although significant progress has been made in understanding of the molecular mechanisms of lung carcinogenesis, the therapeutic interventions for lung cancer have achieved only modest benefits [5].

The major reasons for limited effectiveness of radiotherapy of NSCLC are the radio-resistance of the tumour and radiation-induced toxicity to the normal tissues [6]. Another important reason why lung cancer still results in a poor prognosis is the frequent incidence of distant metastasis. In addition, therapeutic intervention might augment the metastatic potential of cancer cells. Several authors have reported that photon beam irradiation at sublethal doses enhanced metastatic processes of malignant tumour cells and angiogenesis [7].

Proton radiation is a promising modality because of distinct physical advantages over conventional beams. Protons produce little side scatter and stop abruptly at any prescribed depth. The pattern of energy deposition is characterized by the Bragg peak, wherein the dose is minimal on entry and reaches a maximum at the stopping region, which is planned to occur in the target volume [8]. Since the Bragg peak is only a few millimetres wide, for the needs of cancer therapy to encompass the treatment volume, it has to be spread-out by modulating the proton energy [9]. Proton beams can be shaped to deliver homogeneous radiation doses to irregular three-dimensional volumes such as those required for lung tumors. These characteristics enable the reduction of the dose delivered to the normal tissue [10].

Clinical experience confirms the feasibility of proton radiation for early-stage lung cancers, while on the other hand indicates that proton radiation should be further explored [11].

One of the hallmark features of cancer cells is their ability to avoid apoptosis. Alterations in pro- and anti-apoptotic pathways are common in cancer cells and defects in regulation of apoptosis have been implicated in both lung tumorigenesis and resistance to therapy. Therefore, understanding the mechanisms of apoptosis induction in lung cancer cells is very important for lung cancer therapy [12]. Apoptosis is tightly connected with

the regulation of cell cycle progression [13]. The disturbance of the cell cycle can also influence the resistance to different therapeutics and reduce the efficiency of anti-cancer therapy [14].

The aim of this study was to further investigate the inactivation of resistant human cells using high linear energy transfer (LET) radiation. Preliminary results regarding the effects of proton irradiation on the CRL5876 human lung adenocarcinoma cell survival, induction of apoptosis and cell cycle redistribution are presented.

MATERIALS AND METHODS

Cell Culture

Human NSCLC CRL5876 cells were obtained from American Tissue Culture Collection (ATCC, Rockville, MD, USA) and cultured in the RPMI 1640 medium supplemented with 10 % foetal calf serum (FCS, Sigma-Aldrich Chemie GmbH, Steinheim, Germany) and penicillin/streptomycin (Sigma-Aldrich Chemie GmbH), in a humidified atmosphere of 5 % CO₂ at 37 °C (Heraeus, Hanau, Germany).

Experimental Conditions

The CRL5876 lung adenocarcinoma cells were exposed to proton irradiation 48 h after seeding. The evaluation of cell survival was performed 7 days after irradiation. Number of apoptotic cells was calculated after 48 h while the cell cycle phase distribution was analyzed both 48 h and 7 days post-irradiation.

Irradiation Conditions

Irradiations with the therapeutic 62 MeV proton beam were performed at the CATANA (Centro di Adro Terapia e Applicazioni Nucleari Avanzati) facility at Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali del Sud (INFN - LNS), Italy. Delivered single doses were 2, 4, 8, 12 and 16 Gy, at the dose rate of 15 Gy/min. Irradiation position in the middle of the spread-out Bragg peak (SOBP) was simulated by inserting 16.3 mm thick Perspex plate (Polymethyl methacrylate - PMMA) between the final collimator and the cell monolayer. Relative doses were 99.42 ± 0.58 %, with the mean energy of protons 34.88 ± 2.15 MeV. Corresponding LET value was 4.7 ± 0.2 keV/ μ m. Mean energy and LET values were obtained by the numerical simulations carried out with the GEANT4 code [15]. Reference dosimetry was performed by the plane-parallel PTW 34045 Markus ionization chamber (Advanced Markus Chamber, 0.02 cm², Type 34045, PTW Freiberg, Germany), calibrated according to the International Atomic Energy Agency (IAEA) code of practice [16, 17]. Irradiations with ⁶⁰Co γ -rays were performed at the Vinča Institute of Nuclear Sciences, Belgrade, Serbia, within the same dose range as for proton irradiations, at the dose rate of ~ 1 Gy/min. All cell irradiations were carried out in air at room temperature.

Clonogenic Assay

For the clonogenic assay, cells were harvested immediately after irradiation and seeded at a suitable number into the 25 cm² flasks. After the incubation for 7 days, cells were fixed with methanol (Zorka Pharma, Šabac, Serbia) and stained with 10 % Giemsa solution (Alkaloid A.D., Skopje, Macedonia). More than 50 cells per colony were scored as surviving cells. Survival was calculated by comparing the number of colonies in irradiated samples with control.

Quantification of Apoptosis

For quantification of apoptotic cells, the flow cytometric analysis with Annexin V-FLUOS Staining kit (Roche Diagnostics GmbH, Mannheim, Germany) was performed according to the manufacturer's instructions. In brief, cells were trypsinized, washed in ice-cold phosphate-buffered saline (PBS) and resuspended in 100 μ l Annexin V FLUOS labelling solution (containing Annexin - V - Fluos labelling reagent and propidium iodide (PI)). After incubation for 30 min in the dark, 500 μ l of incubation buffer was added per sample. Samples were analyzed on a FACSCalibur (Becton Dickinson, Heidelberg, Germany). For each sample, 10 000 cells were analyzed. The number of apoptotic cells was calculated using ModFit software (Verity Software, Becton Dickinson).

Cell Cycle Analysis

For flow cytometric evaluation of the cell cycle status, cells were washed with PBS, fixed overnight with cold 70 % ethanol and stained with PBS solution containing 50 μ g/ml PI (Sigma-Aldrich Chemie GmbH) and 50 μ g/ml ribonuclease A (RNase A, Sigma-Aldrich Chemie GmbH). After incubation at room temperature for 30 min, cells were analyzed by flow cytometry (FACSCalibur; Becton Dickinson) using ModFit software.

Statistical Analysis

Measurements were made in triplicate during each experiment, while each experiment was repeated three times. The significance of differences among the experimental groups was assessed by the independent Student's t-test, with the level of significance set at $p < 0.05$. The results were presented as the Mean $\pm$ S.D. (standard deviation).

RESULTS AND DISCUSSION

Effects of γ -rays and Protons on CRL5876 Cell Survival

Clonal survival as the most important parameter that describes the level of cellular radio-sensitivity was analyzed 7 days after irradiation. Experimental data were fitted using the linear-quadratic equation: $S = \exp(-\alpha D - \beta D^2)$, where S is the surviving fraction for the dose D , while α and β are the fitting parameters. Data obtained by the clonogenic assay are presented in Figure 1 and

revealed the dose-dependent inhibitory effects of γ -rays and protons. The level of cell inactivation produced by proton irradiation is stronger than that of γ -rays in the whole dose range. Described behaviour suggests that CRL5876 cells are resistant both to γ -rays and protons, with corresponding surviving fractions at 2 Gy (SF2) of 0.86 and 0.71. Although these cells are rather resistant, trend of increased inactivation with rise of dose was observed, especially after proton irradiation. Commonly used parameter for comparison of effects of protons vs. γ -rays is the relative biological effectiveness, RBE (2Gy, γ). This value represents the ratio of 2 Gy γ -rays and the proton dose that has the same inactivation level as that of γ -rays. The obtained RBE for CRL5876 cells of 2.13 indicated that protons induced significant level of cell inactivation even on this resistant cell line. Several authors also reported that protons have better inhibitory effect on lung cancer cells than γ -rays [18].

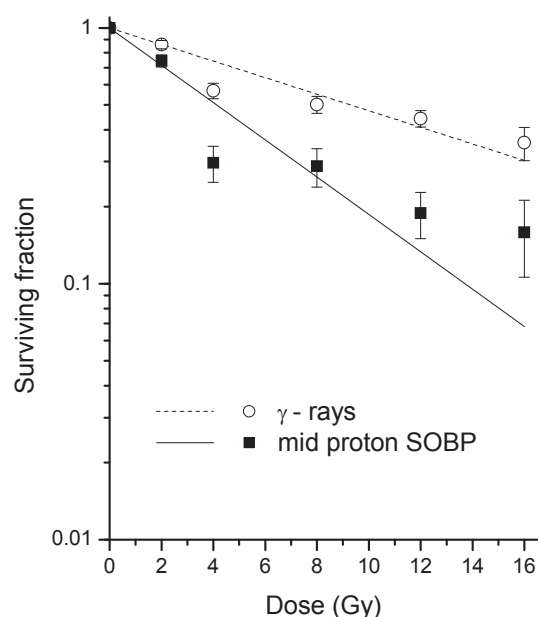


Figure 1: Dose-response curves of human CRL5876 lung adenocarcinoma cells exposed to γ -rays or protons, obtained by clonogenic assay 7 days after irradiation.

Since proton radiation has shown higher level of inhibition of CRL5876 lung adenocarcinoma cells than conventional γ -radiation, in further experiments the attention was on the effects of this radiation type. In order to study mechanisms of proton induced inhibition of CRL5876 growth, the induction of apoptosis and changes in cell cycle distribution were investigated.

Effects of Protons on Induction of Apoptosis

The percentage of apoptotic cells was evaluated 48 h after irradiation. The obtained values are given in Table 1. Flow cytometric analysis showed that the level of apoptosis induced by protons ranged from 4.49 to 9.05 %, with the maximal effect accomplished after irradiation with 8 and 12 Gy.

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Table 1: Percentage of apoptotic nuclei in the CRL5876 cells 48 h after proton irradiation

Dose (Gy)	Percentage of apoptotic nuclei
0	4.17
2	4.49
4	5.21
8	9.05
12	8.43
16	4.71

Time point of 48 h after irradiation was selected for the analysis of apoptosis because usually maximal number of apoptotic cells after irradiation in *in vitro* conditions was observed at this time point [13]. However, in the CRL5876 cells even at this time point the level of apoptosis was low, confirming the radio-resistant feature of this cell line. The level of apoptosis was lower than in PC3 prostate adenocarcinoma, MCF7 breast adenocarcinoma as well as in highly radio-resistant human HTB140 melanoma cells [19, 20]. It was reported that the percentage of apoptosis for the HTB140 cells after irradiation with 12 or 16 Gy protons was 18 and 17 %, respectively [20].

Effects of Protons on Cell Cycle Distribution

The analysis of the cell cycle phase distribution of the CRL5876 cells irradiated with protons is presented in Figure 2. Cells were analyzed 48 h and 7 days after irradiation. In the first case, control cells were dominantly accumulated in the G1+S (~79 %), while the percentage of cells in G2 phase was ~ 21 %. Protons induced G2 arrest with the highest percentage of G2 cells detected in samples irradiated with 8 and 12 Gy (39.5 – 45.4 %) (Figure 2A).

The data obtained for the prolonged incubation period of 7 days suggested that the control sample contained ~ 73.5 % of cells in the G1+S and 26.5 % of cells in G2 phase. At this time point protons also induced G2 cell accumulation. With the rise of the dose within the dose ranges applied, there is a trend of increase of G2 cells, reaching the maximum after irradiation with 12 Gy (Figure 2B).

It is known that after ionizing radiation a delay in G2 phase is the most frequent event, but significant arrest could also occur in G1 phase [21]. These delays allow reparation of the damage before DNA synthesis (G1 arrest) and/or before mitosis (G2 arrest) [22]. The central element of the radiation induced G1 block is the stabilization of the p53 protein and the activation of its transcriptional activity. Cells that have intact p53 protein, such as melanoma cells, could respond to radiation by

apoptosis or activation of G1 arrest [23]. However, if the p53 protein is mutated or inactivated, cells were accumulated in G2 phase. Lung carcinoma cells usually have altered p53 [23]. This may be the reason for the different response of analyzed CRL5876 lung adenocarcinoma cells to radiation, than previously investigated HTB140 melanoma cells [20, 24].

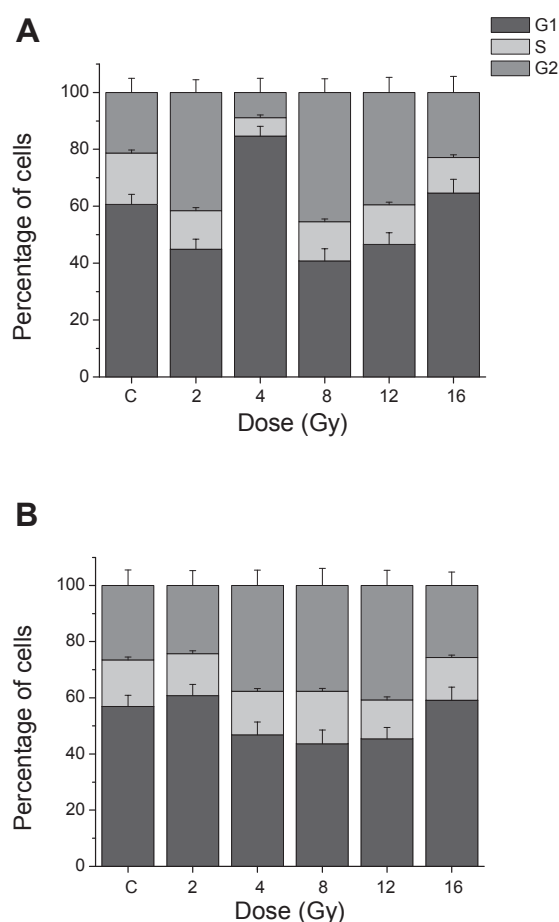


Figure 2: The cell cycle analysis of human CRL5876 lung adenocarcinoma cells irradiated with protons determined by FACS analysis 48 h (panel A) or 7 days (panel B) after irradiation. Irradiation doses were 2, 4, 8, 12 and 16 Gy. C – control. The percentage of cells in G1, S and G2 phase was obtained with the Mod Fit software. Data obtained from 3 experiments are presented as means $\pm$ S.D.

Comparison of the obtained results for CRL5876 and HTB140 cells suggested that protons reveal better antitumour effects on the CRL5876 human lung adenocarcinoma than on HTB140 melanoma cells, especially on the level of survival and cell cycle arrest. This is in agreement with SF2 values evaluated after proton irradiation of 0.71 for CRL5876 and 0.86 for HTB140 cells [24], illustrating different but high cellular radio-resistance of the two cell lines. Dissimilar response to radiation of these cell lines may be related to different features of these cells. The CRL5876 cells have shown typical radiation induced G2 block, while HTB140 cells induced signalling pathways characteristic for apoptosis.

CONCLUSIONS

The obtained results indicated that the human CRL5876 lung adenocarcinoma cells are radio-resistant with SF2 values for γ -rays and protons of 0.86 and 0.71, respectively. Protons have better inhibitory effect on cell survival than conventional radiation. This inhibitory effect is based on ability of protons to induce accumulation of the CRL5876 cells in G2 phase of cell cycle.

ACKNOWLEDGMENTS

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Back-side He irradiation of power devices used as carriers lifetime killing technique for improving their switching characteristics

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Abstract – He irradiation has been used to introduce a well defined reduction of the carrier lifetime into the vertical structure of a 1200V-20A MOS-GTO in order to improve its switching performances. For the first time the irradiation was performed from the back side of the device in order to avoid the degradation of the surface gate oxide. A reduction by a factor ~ 4 in the storage time and more than 30% decrease in the turn-off energy losses have been measured on irradiated samples with respect to not irradiated ones without affecting the on-state characteristics.

INTRODUCTION

High voltage silicon power devices like Gate Turn-Off Thyristors (GTO), Insulated Gate Bipolar Transistor (IGBT), Insulated Gate Controlled Transistor (IGCT) [1] etc. are widely used in high power conversion applications. These electronic switches include a low doped and wide N- base region in their vertical structure in order to sustain the required high voltage in the off-state. Fortunately, this region does not significantly worsen the on-state voltage drop thanks to the injection of carriers from the terminal regions. In fact, this injection creates and sustains a large population of carriers in the N- base and largely increases its conductivity thus keeping reasonably low the voltage drop during the device forward conduction [1]. However, the presence of the conductivity modulated region in the on state is paid during the device commutation because it is slowed down by the removal of the stored charge. To limit this effect, carriers lifetime killing techniques are used in order to speed up this charge removal. Techniques like electrons or gamma irradiations [2] produce a uniformly distributed reductions of carriers lifetime along the vertical structure and, consequently, reduce the amount of carriers available and their mobility in the N- base during forward conduction thus worsening the on state characteristics. Much better performances can be achieved by He irradiation [3] which is able to localize the lifetime reduction at depth where it is very effective in assisting the charge removal without degrading the characteristics elsewhere.

Recently, a new power device, the MOS-GTO (Metal Oxide Semiconductor Gate Turn-Off thyristor), has been presented [4]. It shows very interesting characteristics,

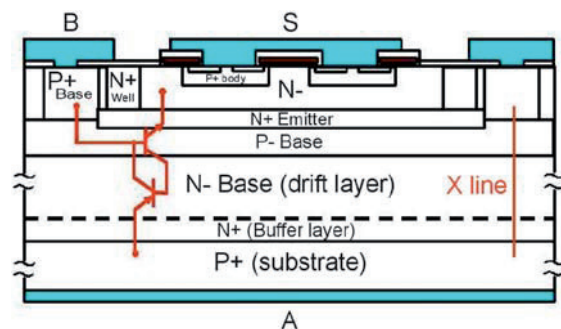


Figure 1: Elementary cell of the MOS-GTO.

especially in high voltage applications, thanks to a very low voltage drop and good switching performances. As for the other bipolar devices, the switching performances of a MOS-GTO are affected by the carriers lifetime in the N- base and a trade off between on-state and switching performances can be achieved thanks to the implementation of lifetime killing techniques.

The objective of this paper is to present the results of a study executed on 1200V-20A MOS-GTO samples irradiated with He in order to improve their switching performances. It is shown that irradiation can be executed from the back side of the die in order to avoid any degradation of the gate oxide and of the active region of the structure. Simulation and experimental results show much better performance of the irradiated devices in terms of storage time, switching losses and voltage drops, compared to not irradiated.

MOS-GTO STRUCTURE

Fig. 1 shows the monolithic structure of the MOS-GTO elementary cell. It is obtained by integrating low-voltage diffused MOS (DMOS) cells inside the emitter region of the high voltage thyristor. Each DMOS cell is surrounded by N^+ wells that have the function of inhibiting the action of the lateral PNP parasitic transistor. The presence of an N^+ buffer layer makes this device a PT (punch through) version, however it is possible to fabricate non-PT devices without the buffer layer. In spite of MOS-GTO apparent complexity, the perspective cost of the device is expected to be comparable with that of similar ratings IGBTs. In fact, the fabrication process of the MOS-GTO requires only slight modifications of the flowchart used to

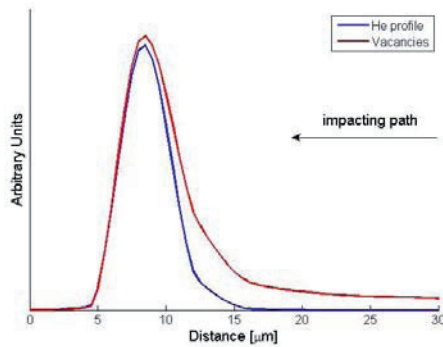


Figure 2: Typical He distribution and vacancies profile in a silicon target

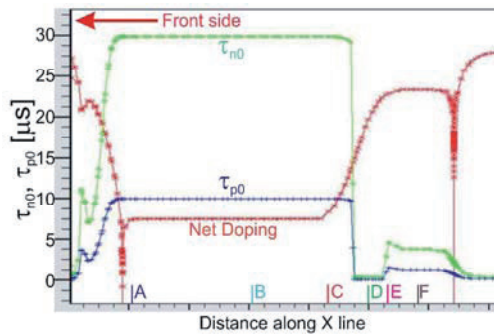


Figure 3: Lifetime and doping profile inside the elementary cell along the X line marked in Fig. 1.

fabricate the commercially available emitter-switched bipolar transistor (ESBT) [5].

OPTIMIZATION OF THE MOS-GTO PERFORMANCES BY HE IRRADIATION

A preliminary study has been performed by means of the 2D SILVACO ATLAS software [6] in order to study the effects of He irradiation on the performances of a 1200V-20A MOS-GTO. As well known, this lifetime killing technique can be used to modify the carrier lifetime in a very localized region whose depth can be chosen by using a proper energy of the impacting particles [7]. Typical He profile and primary vacancies distribution in the silicon target, obtained by SRIM [8] simulations, are reported in Fig. 2.

The doping profile of the simulated device, reported in Fig. 3, was obtained by ATHENA [6] process simulator applied to the fabricated device. The profile refers to the X line marked on the cell of Fig. 1, starting from the P⁺ Base region. In Fig. 3, the lifetime profiles of holes and electrons for one of the simulated cases are reported too. The width of the modified lifetime region has been chosen of about 6 μm according to SRIM simulations and experimental results reported in [7]. A reduction of two orders of magnitude in the lifetime profile of majority and minority carriers was imposed according to the results shown in [9] for common dose values used in lifetime killing techniques. Six different positions of the He peak

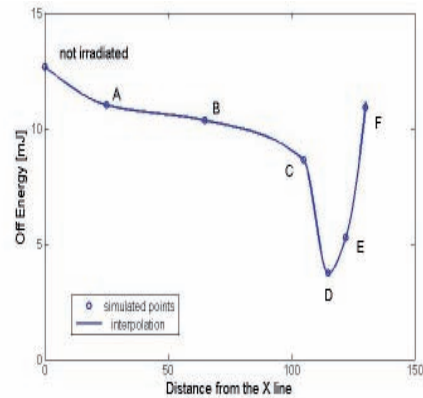


Figure 4: Turn-off energy losses as a function of the position of the He peak concentration.

concentration, indicated from A to F in Fig. 3, were considered in the simulations.

For each position switching simulations have been performed using the circuit presented in [4] and the turn-off energy was extracted.

The results are summarized in Fig. 4, where the simulated turn-off energy losses are reported as a function of the peak position. The minimum corresponds to the case when the lifetime is reduced at the N/N⁺ interface (position D). In this case, a reduction of about 75% of the turn off energy is observed with respect to the not irradiated device.

Further simulations, not reported here for brevity, have shown that He irradiation has almost no effects on the on-state characteristics and on the turn-on switching performances of the device, respect to not irradiated ones.

THE EXPERIMENTAL SETUP

A ⁴He, 10 MeV/nucleon beam generated by the CS facility has been used to irradiate the samples, with a beam current of 110 pA. The experiments have been done at the 0° beam line, where a Kapton window has been installed to allow irradiations at free air conditions. Fig. 5 depicts the experimental setup.

A polystyrene rough collimator, 3 cm thick and 4cm holed, has been used to shield-off the beam from the unwanted devices. Behind it in the beam direction, a transmission chamber has been used to measure the fluency during each experiment. Finally, a round sample holder has been placed, which can be manually rotated in order to irradiate different device sets by simply rotating it by a given angle (see Fig. 6).

Samples have been grouped by four, in order to gain beam time, without appreciably loosing in terms of uniformity. The sample holder is made of a typical stick foil, and the samples have been glued at the front side, thus ensuring a back irradiation.

Irradiations at several energies and/or fluencies have been done. The impacting energy has been modulated basing on SRIM simulations, with a degree of confidence of 5%, by varying the free air space between the Kapton window and the sample under test, whereas the fluency

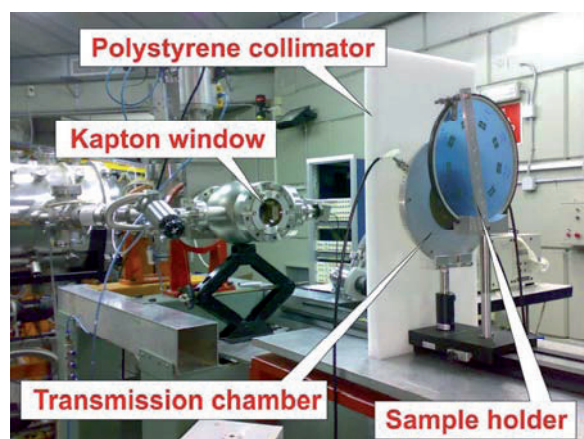


Figure 5: Picture of the setup.

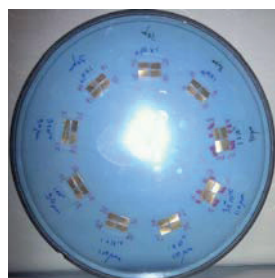


Figure 6: Detail of the sample holder.

has been regulated by using a shuttering system based on the transmission chamber and a programmable counter set at the required fluency. Three dose points have been done for each energy (except for the last energy due to a lack of time), in such a way to evaluate the dose effect on the lifetime control.

The complete set of experiment is reported in Table I, note that energy at the target refers to the energy the ion has when impacts the surface (the back side) of the target.

Table I reports the complete set of experiments.

Free air thickness [cm]	Energy at the target [MeV]	Penetration range from the front surface of the device [μm]	Dose [atoms/ cm^2]
63	16.4	110	$1.0 \cdot 10^{10}$
63	16.4	110	$3.0 \cdot 10^{10}$
63	16.4	110	$1.0 \cdot 10^{11}$
58	17.6	90	$1.0 \cdot 10^{10}$
58	17.6	90	$3.0 \cdot 10^{10}$
58	17.6	90	$1.0 \cdot 10^{11}$
54	18.7	70	$1.0 \cdot 10^{10}$
54	18.7	70	$3.0 \cdot 10^{10}$
54	18.7	70	$1.0 \cdot 10^{11}$
51	19.7	50	$1.0 \cdot 10^{10}$
51	19.7	50	$3.0 \cdot 10^{10}$

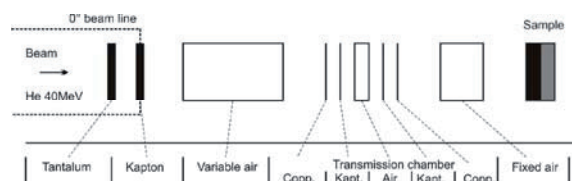


Figure 7: Simulated structure of the beam line.

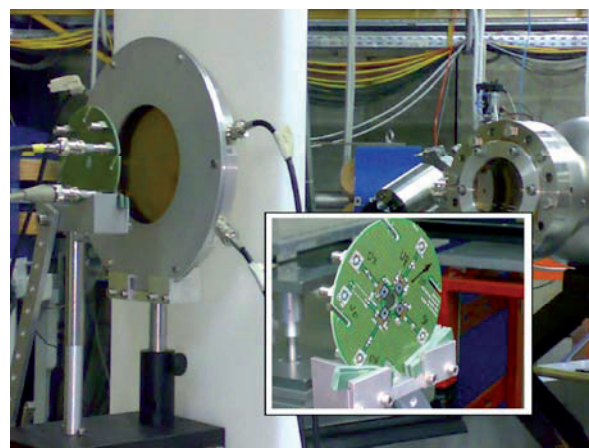


Figure 8: Calibration of the transmission chamber.

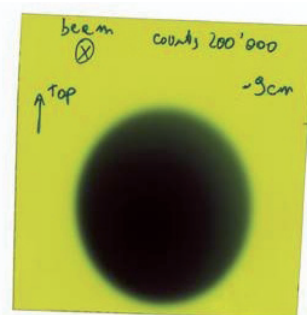


Figure 9: Typical Gafchromic® response obtained during experiments.

Energy estimation

The set of chosen energies refers to the expected positions of the damage peak inside the irradiated device.

SRIM calculations have been done to evaluate the required penetration energy at the target to reach the given depth. At the given acceleration energy of 40 MeV, the unknown is the air thickness able to precisely decrease the energy to the wanted value. The simulated structure is reported in Fig. 7.

The estimated degree of confidence is 5%, corresponding to 1.8 MeV at the target surface. Such uncertainty leads to a penetration uncertainty of 20 μm , which is acceptable to the aim of the experiment.

Three dose points have been done for each energy, (except for the last energy due to a lack of time), in such a way to evaluate the dose effect on the lifetime control.

Fluency estimation

A transmission chamber has been used to accurately estimate the fluency onto the target device (see experimental detail in Fig. 8). The transmission chamber has been placed behind a rough polystyrene collimator, in such a way to well define the counting area.

The output of such diagnostic system is a counter, whose ticks are proportional to an arbitrary amount of charge flown through the chamber. For this reason, a calibration procedure has been required, in order to measure the absolute value of the fluency. To this aim, a set of silicon detectors have been used for counting the total number of the impacted particles (see the inset of Fig.8). The beam current has been reduced up to three orders of magnitude, in order to not saturating the silicon detectors.

The calibration points are here omitted, though the transmission chamber exhibited a very good linearity (error<1%) in the range 10 pA - 100 pA.

Beam uniformity

A Gafchromic® analysis done at each experimental point gave a beam uniformity less or equal to 10%, which is widely acceptable to the aim of the measurements. Fig. 10 reports a typical scan obtained during irradiations.

EXPERIMENTAL RESULTS

Some preliminary experimental results are summarized in Figs. 10 and 11, which report storage time and turn-off energy, respectively, as a function of the irradiation dose for three values of the anode current. These results demonstrate that He irradiation is very effective in improving the switching characteristics of the MOS-GTO. In fact, the storage time is reduced by a factor ~4 and the turn-off energy losses are reduced by about 30% at the maximum irradiation dose for all collector currents. As expected, the on-state characteristics of the MOS-GTO, not reported here for brevity, are practically independent of the He irradiation dose.

Spreading resistance measurements, which are sensitive to the local reduction of the mobility induced by He implantation [9], executed on the samples used to obtain Figs. 10 and 11, show that the reduction of the lifetime was localized at about the position B of Fig.3. This result is in agreement with the simulation of Fig. 4 which shows in that case a 30% reduction of the turn-off energy. Much better performances are expected for the localization of the He peak concentration at the N/N^+ transition.

CONCLUSIONS

The paper demonstrates that it is possible to perform He irradiation from the back side of the wafer thus avoiding any damages at the gate oxide of MOSFET placed on the device surface. Experimental results show that He irradiation can significantly improve the turn-off switching performances of the MOS-GTO without affecting its on-state and turn-on switching characteristics. Simulation results indicate that a proper

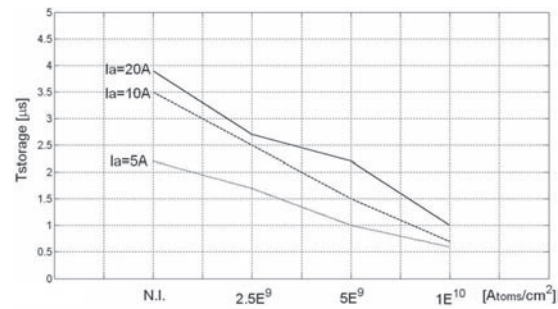


Figure 10: Storage time at different irradiation doses.

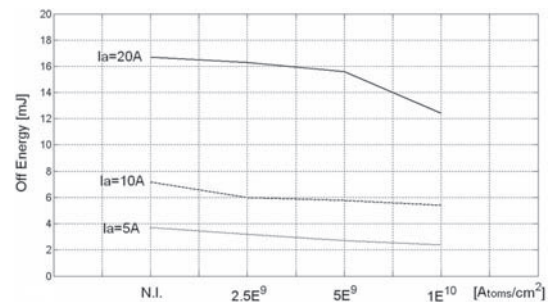


Figure 11: Turn off energy at different irradiation doses.

localization of He peak concentration, obtained by changing the parameters of the irradiation (energy and dose), can be used to optimize the device characteristics and to improve significantly its switching performances. A reduction by more than 70% of the turn off energy losses compared to not irradiated devices can be expected thanks to He irradiations.

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FPGA based Motion Control System with high performance PID

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Abstract – In this paper, the implementation of a software module using 'VHDL' for Altera FPGA (Cyclone II) based PID controller for the DC motor speed control system is presented. The tools used for building and testing the software modules are Altera Quartus II, Altium Designer and Matlab-Simulink. The Motion control systems usually use MCU to achieve the control. We have developed a method of using an FPGA in the control system instead of MCU. It can control more units and even has little response time. It can achieve high resolution PID control and Profile speed control in DC motors with an incremental relative encoder.

IndexTerms - Field Programmable Gate Array (FPGA), Proportional-Integral-Derivative (PID) controller, Very High Speed Integrated Circuit Hardware description Language (VHDL), Pulse Width Modulation (PWM), Micro Controller Unit (MCU), Graphic User Interface (GUI)

INTRODUCTION

VHDL is used to describe hardware from the abstract to the concrete level. Many of the Electronic Design Automation (EDA) vendors are standardizing on VHDL as input and output from their tools.

The PID is used extensively in the field of servo motor control, robotics, temperature control and power electronics. It has a long history of development and very mature tuning rules. Overall, the PID is an important tool for the embedded real-time digital control designer. They are usually implemented either in hardware using analog components or in software using computer-based systems. The emergence of field programmable gate arrays and hardware description languages allows for a added dimensions of digital PID controllers, Parallelism, Programmable bit widths and absolute determinism. Building PID controllers on Field Programmable Gate Arrays (FPGA) improves speed, accuracy, power efficiency, compactness and cost-effectiveness.

With the growing complexity of motor and motion control applications, it becomes apparent that an FPGA offers significant advantage over the off-shelf Application Specific Standard Product (ASSP) solutions in the areas of performance, flexibility and inventory control.

SIMULATION

Before verifying the design on FPGA, the complete design is simulated using Matlab-Simulink tool. With this simulation, we can choose and set up the parameters of the motor and of the PID controller. Figure 4, shows the schematic of the simulation project. The result of the simulation is in figure 1.

In the figure, it shows that it could reach the speed as high as 2000RPM, it could reach in a short time and keep stable. But it is simulated without loading, so we must recalculate the parameter of controller in different loadings.

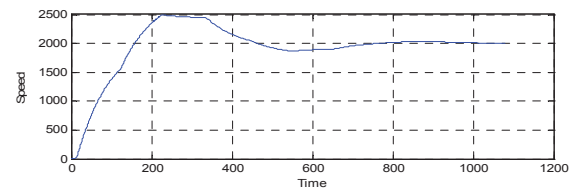


Figure 1: The simulation result.

III. DESIGN

The motion control system includes three parts such as console (remote control unit), local control module and power motor driver.

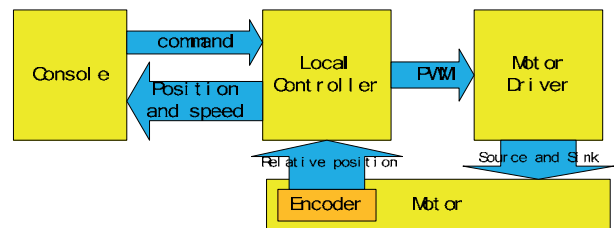


Figure 2: General design of the project

Console

The GUI is used to communicate with the local controller. It sends the commands to the local and gets the parameters from it.

Figure 3 shows the software that the user can use to enter both the speed and the position, and can get all the information as position, speed and state of the motor. The user can change some configurations to the system, too. In addition, it is possible to set up IP address, home position and so on. Generally, it is a very friendly interface to the user and is easy to use.

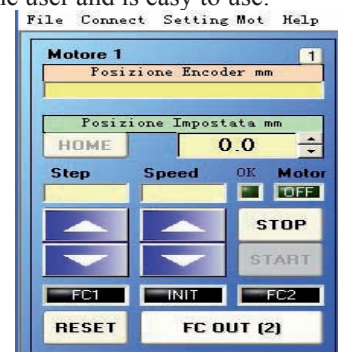


Figure 3: The GUI Console.

Local controller

In our old projects, the local controller has always used MCU. But one MCU can only control one or two motors. In this project, we use FPGA instead of MCU. One FPGA can control up to eight motors with a lower response time than MCU.

In Figure 5 we can see that the local controller includes four blocks such as communication module, control unit, PWM module and motor position monitor. The

communication module is used to communicate with the GUI Console. It can get commands from the console and send out the information console desired. The control unit is used to calculate the PWM value with the position of the motor, and the command PWM module is just as a PWM chip; with the value input it can output PWM duty-cycle waveform. The position monitor can send the position of the motor with the encoder signal.

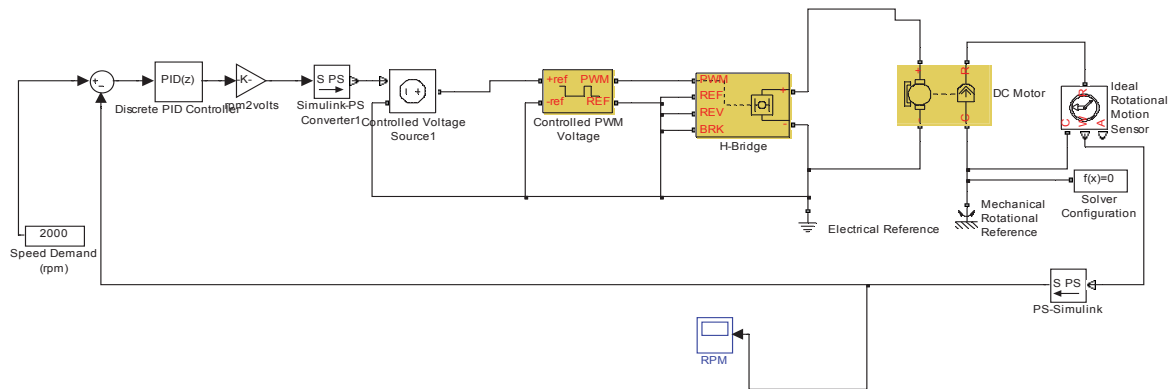


Figure 4: The simulation of the project in Matlab Simulink

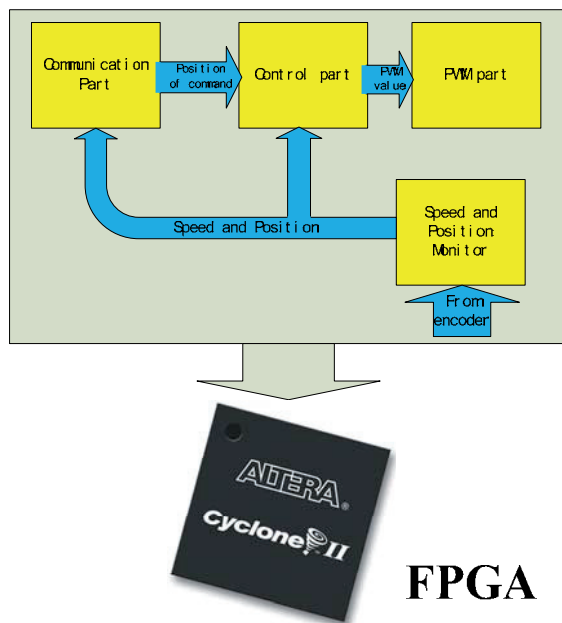


Figure 5: The diagram of the local controller.

Communication module

In the FPGA program, communication is always a problem. It is must to write the agreement of RS232 (or other communication protocol) with FPGA. So in this

project, we have used Altium IPcore Task 51. It has the same function as 8051 series MCU. It means that we can simulate the MCU in the FPGA.

We can program the firm ware source and com pile in the Altium Design to transfer to the chip.

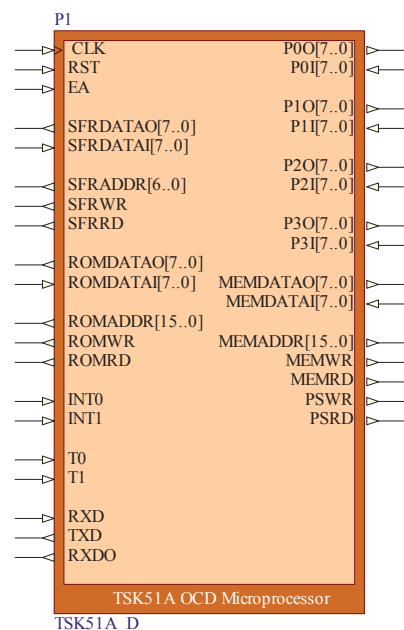


Figure 6: The Altium IPcore TASK51.

Control unit

The control unit contains the PID controller and the Profile control module. The profile controller knows the position of the motor and the value of the position we have decided. After calculation, it gives out the speed to the PID controller. The speed is transferred to the PWM value through the PID controller and sent to the PWM module.

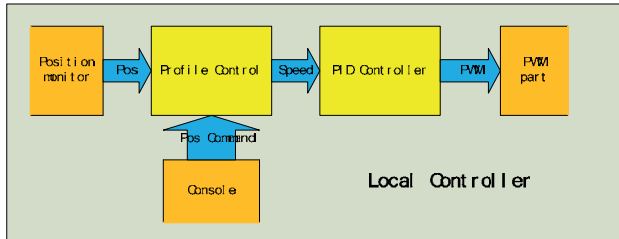


Figure 7: The diagram of control unit.

Profile Controller

The profile controller is used to control the moving track of the motor. It means we can move the motor to any position with any track we want. In this project, we just want to make the motor to increase speed slowly when start and end. We can also change the max speed and ramp acceleration of the speed to move the motor more smoothly and stably.

With the simulation, we can see the waveform of the position and speed. The speed reaches the maximum at the position we decide, and it decreases at the same ramp.

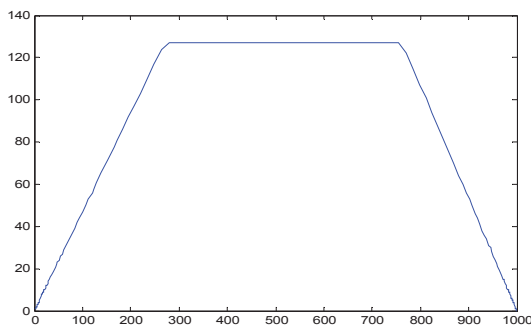


Figure 8: The simulation of profile control.

PID Controller

The PID controller is a traditional control module in motion system. It is a control algorithm with a proportional-integral-derivative as figure 9.

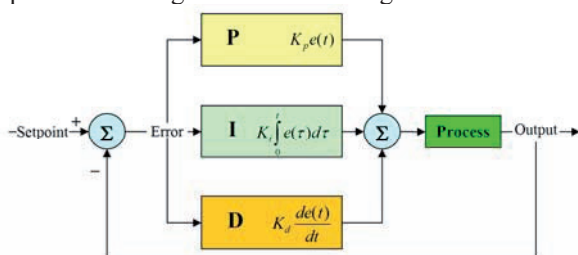


Figure 9: The block diagram of PID controller.

A PID controller calculates an "error" value that is the difference between a measured process variable and a desired set point. The controller attempts to minimize the error by adjusting the process control inputs. The final form of the PID algorithm is:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + k_d \frac{d}{dt} e(t) \quad (1)$$

But FPGA is a digital circuitry Device; it can not calculate the continuous functions. We must make a discretization. So after discretization, we finally obtain:

$$u(t_k) = u(t_{k-1}) + K_p \left[\left(1 + \frac{\Delta T}{T_i} + \frac{T_d}{\Delta T} \right) \cdot e(t_k) + \left(-1 - \frac{2T_d}{\Delta T} \right) \cdot e(t_{k-1}) + \frac{T_d}{\Delta T} \cdot e(t_{k-2}) \right] \quad (2)$$

After we have programmed the function in the VHDL, we get the simulation as figure 10. We can see that the speed gets stable in a very short time. But the simulation is simulated without loading. With loading, we should work for new PID parameters.

PWM module

PWM waveform is usually output by PWM chip or motor driver chips with the PWM. We have designed a PWM module in VHDL to make the project more modular. With the PWM value which the control unit input, it can output different 16-bit resolution duty-cycle PWM waveform.

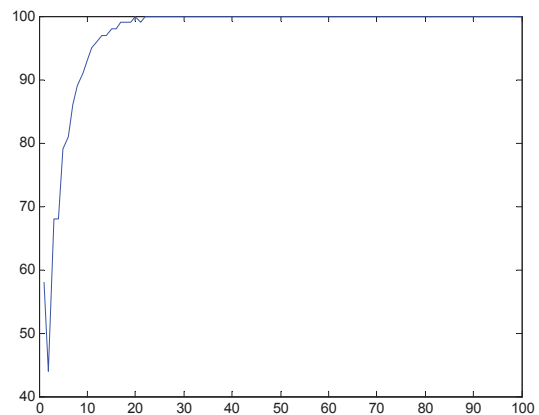


Figure 10: The simulation of PID control.

Speed and Position Monitor

The speed and position monitor module is used for transferring the signal from encoder to the position and speed. The monitor part includes three modules which are shown in figure 11. The Quartus Decoder is a state machine. It can detect if the encoder signal has finished a step. If the encoder has finished a step, it will send a counter signal to the position counter and speed counter. The position counter will add the step to the old position to calculate new position. And the speed counter is counting position step in a fixed period of time to calculate the speed.

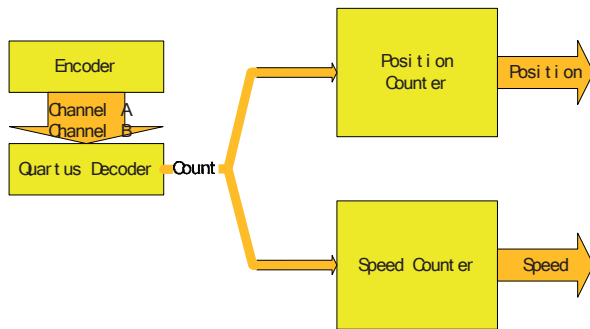


Figure 11: The block diagram of Position and Speed Monitor

The power motor driver

For the power motor driver we have chosen the chip L6203. L6203 is a CMOS full-bridge driver. It has more power than usual driver chips and it does not need external free-wheeling diodes. It has not PWM and PID controller. We have merged the PWM and PID in to the FPGA. With this chip, we can make the project more modular and easy to change. The chip L6506 is a current controller chip, and it is used to protect the current not overflow.

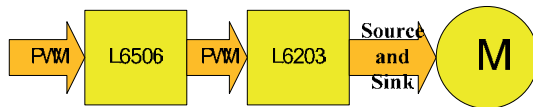


Figure 11: The block diagram of Motor driver board.

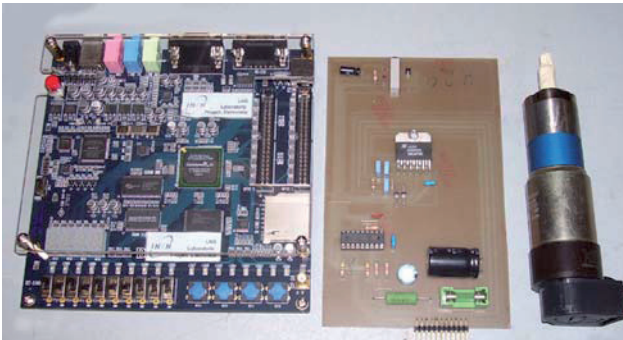


Figure 12: Photograph of the experimental working model of FPGA based motion control system.

response time than a usual control system with MCU. In this project we have merged all parts in to FPGA like PID controller, Profile controller, communication, and PWM. The FPGA has completely used instead of MCU even in the math program which MCU always has adventures. The mathematic program in FPGA is also a highlight in this project.

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CONCLUSIONS

A digital PID controller is successfully implemented using the FPGA and its performance is verified and tested on a DC motor speed control system for real-time control. The test results show that with PID controller added, the steady-state error is eliminated and the desired output speed is obtained. The implementation of controller has reduced the total hardware complexity and cost.

This project was designed to develop a motion control system with FPGA which could control up to 8 motors for a multi-degree of freedom (D.O.F.) in mechanical systems (robotic arm, real-time diagnostic beam). It also has lower

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Antonelli Francesca	Italy	Chbihi Abduh	France
Ardid Miguel	Spain	Chen Huan	China
Arena Nicol�	Italy	Cherubini Roberto	Italy
Ashwood N.	UK	Chiarusi Tommaso	Italy
Aslanoglou X.	Greece	Chiorboli Massimiliano	Italy
Attanasi Francesca	Italy	Cicioni Michele	Italy
Attili Andrea	Italy	Circella Marco	Italy
Auditore Lucrezia	Italy	Civinini Carlo	Italy
Azaiez Faical	France	Col� G. L.	Italy
Balabanski Dimiter	Bulgaria	Condorelli Daniele	Italy
Baran Irina	Rumania	Consoli Fabrizio	Italy
Baran Virgil	Rumania	Consorti Rita	Italy
Barbarino Giancarlo	Italy	Corso Domenico	Italy
Barbarito Elio	Italy	Costanzo Evelina	Italy
Barn� Renato	Italy	Crema E.	Brasil
Barone Salvatore	Italy	Crispino Adalgisa	Italy
Barresi V.	Italy	Crupi Isodiana	Italy
Bartolotti Alessia	Italy	Curr� Giuseppe	Italy
Bedogni Roberto	Italy	Curtis N.	UK
Belcari Nicola	Italy	D'agostino Michela	Italy
Belias Anastasios	Greece	D'alesio Valentina	Italy
Belli Mauro	Italy	D'andrea Maurizio	Italy
Bellou Nikoleta	Greece	D'angelo Giovanni	Italy
Beranzoli Laura	Italy	Dal Corso Flavio	Italy
Berardinelli Francesco	Italy	Das Gupta Shinjinee	India
Berceanu Ionela	Rumania	De Bonis Giulia	Italy
Bisogni Maria Giuseppina	Italy	De Domenico Emilio	Italy
Blagus S.	Croatia	De Filippo Enrico	Italy
Blasi Nives	Italy	De France G.	France
Blazhev Andrej	Germany	De Luca Massimo	Italy
Blokhintsev Leonid	Russia	De Martinis Carlo	Italy
Bo Liu	China	De Nadal Viviana	Italy
Bohlen Till	Germany	De Napoli Marzio	Italy
Boiano Ciro	Italy	De Notaristefani Francesco	Italy
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Bonori Maurizio	Italy	Delory Eric	Spain
Borderie Bernard	France	Di Bartolo Federico	Italy
Borrelli Antonella	Italy	Di Franco Ivana	Italy
Boscagli Lucia	Italy	Dini Valentina	Italy
Bruni Federico	Italy	Emanuele Leonora	Italy
Bruzzi Mara	Italy	Emanuele Umberto	Italy
Bubak A.	Poland	Embriaco Davide	Italy
Bucciolini Marta	Italy	Esposito Adolfo	Italy
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Feng Zhaoqing	China	La Torre Francesco	Italy
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Filippescu D.	Rumania	Lahmann Robert	Germany
Finocchiaro Valentina	Italy	Laisne Andre	France
Fiore Enrico	France	Lanzalone Gaetano	Italy
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Porcellato Anna Maria	Italy	Siwek-Wilczynska K.	Poland
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Randisi Giacomo	Italy	Stefan Iulian	Rumania
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Testa Lorella	Italy
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Trasatti Luciano	Italy
Trifirò Antonio	Italy
Trimarchi Marina	Italy
Trippella Oscar	Italy
Tucciarone Aldo	Italy
Tumino Aurora	Italy
Tuvè Cristina	Italy
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Ursu I.	Rumania
Uva Carlo	Italy
Valastro Lucia	Italy
Valentini S.	Italy
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Van Hees Hendrik	Germany
Variale Vincenzo	Italy
Varoli Vincenzo	Italy
Velardi Francesco	Italy
Verde Giuseppe	Italy
Vernin Pascal	France
Verona Claudio	Italy
Verona Gianluca	Italy
Veselsky Martin	Slovakia
Vigilante Mariano	Italy
Viti Vincenza	Italy
Vivirschi Bodgan	Russia
Waldmann Christoph	Germany
Wen Lipeng	China
Wieleczko	France
Wiesermann Klaus	Germany
Wilczynski Janusz	Poland
Wolter Hermann	Germany
Wyss Jeff	Italy
Yurish Sergey	Ukraine
Zadro Mile	Croatia
Zakula Jelena	Serbia
Zerbini Livio	Italy
Zerva Kostadina	Greece
Zetta Luisa	Italy
Zhang Hong Fei	China
Zhang Shisheng	China
Zhang Yingxun	China
Zhanov Akram	Usa
Zhao Feng Shou	China
Zielinska-Pfabe Malgorzata	Poland
Ziman V.	UK
Zipper Wictor	Poland
Zotto Pierluigi	Italy
Zuo Wei	China

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AIP Conference Series, 1213, 232, 2010

Cherubini S, et al.

AIP Conference Series: 1269, 98, 2010

La Cognata M, et al.

AIP Conference Series: 1269, 369, 2010

PROCEEDINGS OF CONFERENCES, WORKSHOPS AND MEETING

Puglia SMR, et al.

AIP Conference Series, 1269, 375, 2010

Pizzone, RG, et al.

AIP Conference Series, 1304, 202, 2010

La Cognata M, et al.

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Lombardo I, Agodi C, Alba R, Amorini F, Anzalone A, Berceanu I, Cardella G, Cavallaro S, Chatterjee MB, Coniglione R, DeFilippo E, DiPietro A, P.Figuera P, E.Geraci E, G.Giuliani G, L.Grassi L, A.Grzeszczuk A, LaGuidara E, Lanzalone G, LeNeindre N, Maiolino C, Pagano A, Papa M, Pirrone S, Politi G, Pop A, Porto F, Rizzo F, Russotto P, Santonocito D, Sapienza P, Verde G
Mirror nuclei emission and isospin transport at intermediate energies

CERN-Proceedings-2010-001, 1, 151-158

Romano F

"Report on WP5 starting activity"

"ESA AO6041 Progress Report Meeting #2", Bordeaux, Francia, 1 Dicembre 2010.

Colonna M

Testing the behavior of n-rich systems away from normal density

EURORIB10, Lamoura 2010

Mukhamedzhanov AM, La Cognata M, Spitaleri C, Tribble RE

*CNR*09 - Second International Workshop on Compound Nuclear Reactions and Related Topics, Bordeaux, France, Edited by Bonneau L, Dubray N, Gunsing F, Jurado B*

EPJ Web of Conferences: 2, id.13001, 2, 13001, 2010

Romano FP, Pappalardo G, Pappalardo L, Rizzo F

A new upgrade of the portable PIXE-alpha spectrometer and of the portable XRD system at the LANDIS laboratory of the LNS-INFN and IBAM-CNR of Catania (Italy) and their integrated application for the non destructive characterization of ancient pigments

First Research Co-ordination Meeting (RCM) of the Co-ordinated Research Project (CRP), invited lecture

On Micro-analytical Techniques Based on Nuclear Spectrometry for Environmental Monitoring and Material Studies IAEA HQ, Vienna 2010

Romano FP, Pappalardo G, Pappalardo L, Rizzo F

Determinazione non distruttiva della composizione del corpo della lega mediante la tecnica DPAA (Deep Proton Activation Analysis)

Giornata di studio "La Panoplia della Colchide: L'armatura ritrovata", invited lecture. Cento, 2010

Romano FP, Garraffo S, Pappalardo G, Pappalardo L, Rizzo F

Analisi non distruttive sui nummi romani del Tesoro di Misurata (Libia)

IV Giornata di Studi su Archeologia, Numismatica e Archeometria, relazione orale, Messina 2010

Romano FP, Pappalardo G, Pappalardo L, Rizzo F

L'attività del Laboratorio LANDIS dei LNS nel settore dei Beni Culturali

Incontri di Fisica Applicata, Isola d'Elba, relazione orale, 2010

Romano F

Relazione su invito dal titolo "Applicazione dei metodi Monte Carlo per lo studio di tecniche speciali di radioterapia"

"Incontri di Fisica Applicata", La Biodola, Isola d'Elba, 23-28 Maggio 2010

Calabretta L, Maggiore MM, Piazza LAC, Rifuggiato D

"A Multi MegaWatt Cyclotron Complex to Search for CP Violation in the Neutrino Sector",

International Conference on Cyclotron and their Applications, invited lecture

PROCEEDINGS OF CONFERENCES, WORKSHOPS AND MEETING

Ristić-Fira A, Korićanac L, Žakula J, Keta O, Cuttone G, Petrović I.

Cellular response to therapeutic hadrons

International Symposium One Hundred Years of Ivan Djaja's (Jean Giaja), Belgrade school of physiology, Belgrade, Book of abstracts, 82, September 10-14, 2010

I. Petrović I, G.A.P. Cirrone GAP, L. Korićanac L, J. Žakula J, O. Keta O, F. Di Rosa F, F. Romano F, G. Cuttone G and A. Ristić-Fira A,

VINČA – LNS Collaboration: Radiobiological Effects of Protons and Carbon Ions on a Resistant Melanoma Cell Line. La Radiobiologia degli adroni carichi con acceleratori INFN: ricerca, sviluppo, applicazioni

Istituto Superiore di Sanità, June 7-8, 2010, invited lecture, Rome, Italy

Ristić-Fira A, Korićanac L, Žakula J, Keta O, Cirrone GAP, Valastro L, Privitera G, Cuttone G, Petrović I

VINČA – LNS Collaboration: Biomedical Effects of Combined Treatments with Protons and Anticancer Drugs. La Radiobiologia degli adroni carichi con acceleratori INFN: ricerca, sviluppo, applicazioni

Istituto Superiore di Sanità, June 7-8, 2010, invited lecture , Rome, Italy

Mukhamedzhanov AM, et al.

JPCS: 202, 012017, 2010

Pizzone, RG, et al.

JPCS: 202, 012018, 2010

La Cognata M, et al.

JPCS: 202, 012019, 2010

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JPCS: 202, 012021, 2010

Tumino A, Spitaleri C, Cherubini S, La Cognata M, Lamia L, Pizzone RG, Puglia SMR, Rapisarda GG, Sergi ML

The Trojan Horse Method as indirect approach for nuclear astrophysics studies

JPCS: 205, 012048, 2010

Lamia, L, et al.

Memorie della Societa Astronomica Italiana Supplementi, 14, 39, 2010

Puglia SMR, et al.

Memorie della Societa Astronomica Italiana Supplementi, 14, 43, 2010

La Cognata M, et al.

Memorie della Societa Astronomica Italiana Supplementi: 14, 111, 2010

Sergi et al.

Memorie della Societa Astronomica Italiana Supplementi, 14, 131, 2010

Spitaleri C, Cherubini S, La Cognata M, Lamia L, Mukhamedzhanov A, Pizzone RG, Romano S, Sergi ML, Tumino A

Trojan Horse Method: Recent Applications In Nuclear Astrophysics

Nuclear Physics A: 834, 639, 2010 - Proceedings to the 10th International Conference on Nucleus-Nucleus Collisions, August 16-21, Beijing, China

Lamia L, Spitaleri C, Carlin N, Cherubini S, Del Szanto MG, Gulino M, La Cognata M, Munhoz MG, Pizzone RG, Puglia SMR, Rapisarda GG, Romano S, Sergi ML, Szanto de Toledo A, Tudisco S, Tumino A

Indirect study of $^{11}\text{B}(p, \alpha_0)^8\text{Be}$ and $^{10}\text{B}(p, \alpha)^7\text{Be}$ reactions at astrophysical energies by means of the Trojan Horse Method: recent results

Nuclear Physics A: 834, 655, 2010 - Proceedings to the 10th International Conference on Nucleus-Nucleus Collisions, August 16-21, Beijing, China

La Cognata M, Spitaleri C, Mukhamedzhanov A, Goldberg V, Irgaziev B, Lamia L, Pizzone RG, Sergi ML, Tribble RE

DWBA momentum distribution and its effect on THM

Nuclear Physics A: 834, 658c–660c, 2010

PROCEEDINGS OF CONFERENCES, WORKSHOPS AND MEETING

Pizzone RG, Spitaleri C, Cherubini S, La Cognata M, Lamia L, Romano S, Sergi ML, Tumino A, Li C, Wen Q., Zhou S, Burjan V, Kroha V, Mrazek J, Carlin N, Gimenez Del Santo M, Szanto De Toledo A, Kubono S, Wakabayashi T, Yamaguchi H, Rolfs C

Trojan Horse Method: An Useful Tool For Electron Screening Effect Investigation

Nuclear Physics A: 834, 673, 2010 - Proceedings to the 10th International Conference on Nucleus-Nucleus Collisions, August 16-21, Beijing, China

Sergi ML, Spitaleri C, Coc A, Mukhamedzhanov A, Burjan SV, Gulino M, Hammache F, Hons Z, Irgaziev B, Kiss GG, Kroha V, La Cognata M, Lamia L, Pizzone RG, de Serevillé N, Somorjai E

The 65 keV resonance in the $^{17}\text{O}(p,\alpha)^{14}\text{N}$ thermonuclear reaction

Nuclear Physics A: 834, 676c-678c, 2010

Cavallaro M, Cappuzzello F, Cunsolo A, Foti A, Carbone D

The MAGNEX large acceptance spectrometer

Proc. "5th European Summer School on Experimental Nuclear Astrophysics", S.Tecla, Italy, 20-27 September 2009, published in AIP Conf. Proc., 1213, 198-200, 2010, Doi: 10.1063/1.3362574

Keta O, Korićanac L, Žakula J, Popović N, Cuttone G, Petrović I, Ristić-Fira A

Radio-sensitivity of human melanoma, ovarian and lung carcinoma cells to gamma radiation

Proc. 10th International Conference on Fundamental and Applied Aspects of Physical Chemistry, 322-324, Belgrade, 21-24 September 2010,

Žakula J, Korićanac L, Keta O, Cirrone GAP, Cuttone G, Ristić-Fira A, Petrović I

Carbon ion beam as inducer of melanoma cell apoptosis

Proc. 10th International Conference on Fundamental and Applied Aspects of Physical Chemistry, 376-378, Belgrade, 21-24 September 2010

Cavallaro M, Cunsolo A, Cappuzzello F, Carbone D, Foti A, Orrigo SEA, Rodrigues MRD, Schillaci M, Borello-Lewin T, Petrascu H

Preliminary study of the $^{19}\text{F}(^7\text{Li}, ^7\text{Be})^{19}\text{O}$ reaction at 52 MeV with MAGNEX

Proc. "12th International Conference on Nuclear Reaction Mechanisms", Varenna, Italy, 15-19 June 2009, published in CERN-Proceedings-2010-001,1, 181-185, 2010

Cappuzzello F, Cavallaro M, Cunsolo A, Foti A, Orrigo SEA, Rodrigues MDR, Borello-Lewin T, Carbone D, Schillaci M

States of ^{15}C via the $(^{18}\text{O}, ^{16}\text{O})$ reaction

Proc. "12th International Conference on Nuclear Reaction Mechanisms", Varenna, Italy, 15-19 June 2009, published in CERN-Proceedings-2010-001,1, 187-191, 2010

Odorici F, Cuffiani M, Malferrari L, Rizzoli R, Veronese GP, Celona L, Gammino S, Mascali D, Miracoli R, Romano FP, Gambino N, Castro G, Ciavola G, Serafino T

Enhancement of ECR performances by means of carbon nanotubes based electron guns

Proc. 19th Workshop on ECR ion Sources, Grenoble 2010

Gammino S, Celona L, Miracoli R, Mascali D, Castro G, Ciavola G, Maimone F, Gobin R, Delferrière O, Adroit G, Senèe F

Tests of the Versatile Ion Source (VIS) for high power proton beam production

Proc. 19th Workshop on ECR ion Sources, Grenoble 2010

Mascali D, Gammino S, Celona L, Ciavola G, Neri L, Miracoli R, Gambino N, Castro G, Maimone F

Some considerations about frequency tuning effect in ECRIS plasmas

Proc. 19th Workshop on ECR ion Sources, Grenoble 2010

Toivanen V, Celona L, Ciavola G, Galatà A, Gammino S, Jones P, Koivisto H, Mascali D, Peura P, Ropponen T, Tarvainen O, Arje J

Effects of microwave frequency fine tuning on the performance of JYFL 14 GHz ECRIS

Proc. 19th Workshop on ECR ion Sources, Grenoble, 2010

PROCEEDINGS OF CONFERENCES, WORKSHOPS AND MEETING

Rizzoli R, Veronese GP, Odorici F, Malferrari L, Cuffiani M, Gammino S, Celona L, Mascali D, Gambino N, Miracoli R, Serafino T
Carbon nanotubes based electron guns to improve the performances of Electron Cyclotron Resonance Ion Sources

Proc. CARBOMAT workshop, Catania, 2010

Lindroos M, Bousson S, Calaga R, Danared H, Devanz G, Duperrier R, Eguia J, Eshraqi M, Gammino S, Hahn H, Jansson A, Oyon C, Pape-Møller S, Peggs S, Ponton A, Rathsmann K, Ruber R, Satogata T, Trahern G

The European Spallation Source

Proc. ECAART, Athens, 2010

Gammino S, Celona L, Mascali D, Gambino N, Maimone F, Miracoli R, Torrisi L, Ciavola G
Increase of beam brightness by means of improved ECR heating in ECRIS - Electron Cyclotron Resonance Ion Sources

Proc. EPS conference on Plasma Science, Dublin, 2010

Gambino N, Mascali D, Tudisco S, Anzalone A, Gammino S, Grasso R, Miracoli R, Musumeci F, Neri L, Privitera S, Spitaleri A
Investigation of laser generated plasmas expanding in vacuum and in a background gas by means of Time-Of-Flight measurements

Proc. EPS conference on Plasma Science, Dublin, 2010

Cappuzzello F, Carbone D, Cavallaro M, Cunsolo A, Foti A, Orrigo SEA, Rodrigues MRD
States of ^{15}C via the $(^{18}\text{O}, ^{16}\text{O})$ reaction

Proc. "EXON2009: International Symposium on Exotic Nuclei", Sochi, Russia, 28 September – 2 October 2009, AIP Conf. Proc. 1224, 94-99, 2010

Cavallaro M, Cappuzzello F, Cunsolo A, Foti A, Carbone D, Lenske H
Study of the ^{19}O States via the $(^7\text{Li}, ^7\text{Be})$ Reaction at 52 MeV

Proc. "EXON2009: International Symposium on Exotic Nuclei", Sochi, Russia, 28 September – 2 October 2009, AIP Conf. Proc. 1224, 112-117, 2010

Celona L, Gammino S, Ciavola G, Mascali D
Modeling of electron and ion dynamics in the electron cyclotron resonance ion source by means of PIC-self consistent numerical simulations

Proc. High Brightness workshop, Morschbach, 2010

Mascali D, Tudisco S, Gambino N, Anzalone A, Bonanno A, Musumeci F, Gammino S, Scordino A
Calculation of fusion reaction rates at extremely low energies in laser generated plasmas

Proc. IAU workshop, Giardini-Naxos, 2010

Odorici F, Cuffiani M, Malferrari L, Rizzoli R, Veronese GP, Gammino S, Celona L, Mascali D, Gambino N, Miracoli R, Serafino T
The CANTES experiment: a carbon nanotubes based electron gun to improve performances of Electron Cyclotron Resonant Ion Sources

Proc. IPRD, Siena, 2010

Gammino S, Celona L, Mascali D, Ciavola G
New tools for the improvement of beam brightness in ECR ion sources

Proc. Int. Conf. Cyclotrons and Appl, Lanzhou, 2010

Toivanen V, Aho V, Kauppinen J, Koivisto H, Tarvainen O, Arje J, Celona L, Ciavola G, Gammino S, Mascali D, Galatà A, Ropponen T
Studies of ECRIS ion beam formation and quality at the Department of Physics, Univ. Jyväskylä

Proc. Int. Conf. Cyclotrons and Appl, Lanzhou, 2010

Peggs S, Bousson S, Calaga R, Danared H, Devanz G, Duperrier R, Eguia J, Eshraqi M, Gammino S, Hahn H, Jansson A, Lindroos M, Oyon C, Pape-Møller S, Ponton A, Rathsmann K, Ruber R, Satogata T, Trahern G

Plans for the ESS LINAC

Proc. LINAC conference, Tsukuba, 2010

PROCEEDINGS OF CONFERENCES, WORKSHOPS AND MEETING

Gammino S, Celona L, Ciavola G, Mascali D, Maimone F, Miracoli R
Study of the frequency tuning effect for the improvement of beam brightness in ECR ion sources
Proc. LINAC conference, Tsukuba, 2010

Gammino S, Celona L, Maimone F, Miracoli R, Mascali D, Ciavola G
Tests of the Versatile Ion Source (VIS) for high power proton beam production
Proc. LINAC conference, Tsukuba, 2010

Gammino S, Celona L, Maimone F, Mascali D, Gambino N, Miracoli R, Ciavola G, Torrissi L
Increase of beam brightness by means of improved ECR heating
Proc. Symp. on Plasma Physics and Tech., Prague, 2010

Maggiore M, Calabretta L, Cavallaro S, Cirrone GAP, Cuttone G, Gammino S, Giuffrida L, Torrissi L
Thomson Spectrometer Design for Laser Plasma Facilities
Proc. Symp. on Plasma Physics and Tech., Praga, 2010

Colonna M
Symmetry Energy Effects in Heavy Ion Collisions at Low Energies
SPES 2010 International Workshop, INFN - Laboratori Nazionali di Legnaro 2010

Colonna M
Reaction Mechanisms with Exotic Beams: Exploring the Density Behavior of the Symmetry Energy
Summer School V on Nuclear Collective Dynamics, Istanbul 2010

Gammino S, Calabretta L, Celona L, Ciavola G, Cuttone G, Maggiore M, Piazza L
R&D of ion sources and cyclotrons for hadron therapy facilities
Workshop on Physics & Health, Geneve 2010

Pappalardo G, Pappalardo L, Rabin I, Rizzo F, Romano FP
PIXE studies of the Dead Sea Scrolls
Workshop on the Archaeometry of the Dead Sea Scrolls, BAM Federal Institute for Materials Research and Testing, invited lecture, Berlin, 2010

Rizzo F, Pappalardo G, Pappalardo L, Rabin I, Romano FP
Studio dei Rotoli del Mar Morto con la tecnica PIXE.
XCVI Congresso Nazionale della Società Italiana di Fisica, relazione orale, Bologna, 2010

DEGREES THESES

Student: : Saletta Marco

Caratterizzazione delle proprietà di timing e di count rate di un sistema di in-beam PET per adroterapia

Tutor: V. Rosso

Student: Rapisarda Giuseppe

Sub-Coulomb proton-proton scattering via the Trojan Horse Method: suppression of the Coulomb effects

Tutor: C. Spitaleri

Student: Romano Francesco

Monte Carlo simulations of carbon ions fragmentation in hadrontherapy

Tutor: S. Lo Nigro, G. Cuttone

Student: Politi Giacomo

Controlli di qualità e verifica con metodo Monte Carlo dei radiofarmaci utilizzati a scopo diagnostico

Tutor: G. Burrafato

Student: Giacoppo Francesca

Nuclear structure studies at the FRIBs facility of LNS

Tutor: R. Barnà, C. Sfienti

Student: Nicolosi Dario

Studio della Frammentazione $^{12}\text{C}+^{12}\text{C}$ a 62 AMeV per applicazioni in adroterapia

Tutor: M. Lattuada, G. Cuttone, M. De Napoli

Student: Neri Lorenzo

Time Resolved Single Photon Imaging Sensor with Single Photon Avalanche Diode

Tutor: F. Musumeci, S. Tudisco

Student: Scuderi Valentina

Peculiarities of nuclear reactions induced by light neutron-rich beams at energies around the coulomb barrier

Tutor: M. Lattuada, A. Di Pietro

Student: Fiori Enrico

Measurement of the magnetic moment of the 2^+ state of ^{72}Zn via extension of the high-velocity transient field method

Tutor: G. Audi, G. Georgiev

Student: Hanif Muhammad

Nanostructuring Superconducting YBCO Thin Films towards Photosensors Applications

Tutor: E. Mezzetti, G. Ghico

Student: Mulaosmanovic Halid

Analisi e caratterizzazione sperimentale di preamplificatori di tensione e di carica per rivelatori di radiazione

Tutor: C. Guazzoni

Student: Marini Algert

Preamplificatori di corrente e di carica per tecniche di discriminazione in forma per segnali provenienti da rivelatori in silicio in esperimenti di multiframmentazione

Tutor: C. Guazzoni

SEMINARS

15-Jan-2010

G. Perdikakis

Low Energy Radioactive Ion Beams from the ReA3 re-accelerator at the National Superconducting Cyclotron Laboratory. Instrumentation and a view on possible experiments

2-Mar-2010

L. Zerbini

L'armatura della Colchide: problematiche storico-archeologiche e di analisi

23-Mar-2010

D. Jaccarino

Dissociazione di Quarkonia pesanti in QGP

2-Apr-2010

D. Margarone

Laser-Plasma Acceleration: the future tool for the High Energy Physics

13-Apr-2010

A. Shotter

Quantum tunnelling of exotic nuclei

15-Apr-2010

P. Gomes

Breakup effects on near barrier reaction mechanisms

16-Apr-2010

N. Fornengo

Particles in astrophysics and cosmology: a dark connection

12-May-2010

A. Laisnè

Metodi analitici per la progettazione dei campi magnetici dei ciclotroni

31-May-2010

B. Balantekin

Nuclear Astrophysics and Neutrinos

31-May-2010

T. Borello-Lewin

Resonances excited by the $^9\text{Be}(^6\text{Li},d)^{13}\text{C}$

3-Jun-2010

T. Stanev

Ultrahigh energy cosmic rays and neutrinos

21-Jun-2010

S. Yurish

Smart Sensor Systems Design: New Challenges

24-Jun-2010

E. Palmieri

Stato dell'arte del progetto Cuore (Cryogenic Underground Observatory for Rare Events)

SEMINARS

15-Oct-2010

Z.Q. Feng

Dynamics of Heavy Ion Collisions from near barrier to 1AGeV energies

18-Oct-2010

H. Laqua

The Wendelstein Project at Max Planck Institute-IPP, Greifswald

19-Oct-2010

H. Laqua

Experiences of Bernstein wave excitation at WEGA stellarator and possible applications to ion sources

22-Oct-2010

S. Gammino

The European Spallation Source Linac and the prospective contribution of INFN to its Design Update.

22-Oct-2010

N. Masini

Metodologie integrate per l'archeogeofisica e la conservazione. Le ricerche a Nasca (Peru) e Tiwanaku (Bolivia)

28-Oct-2010

M. Grasso

Nuclear structure far from stability

4-Nov-2010

P. Finocchiaro

Un sistema per il monitoraggio in tempo reale di rifiuti radioattivi a breve/medio termine

24-Nov-2010

L. Calabretta

Un Ciclotrone di alta energia e alta potenza per l'esperimento DAEDALUS (Decay At rest Experiment for delta Cp At the Laboratory for Underground Science)

3-Dec-2010

K. Wiesemann

Plasma containment in ECR Ion Sources

9-Dec-2010

E. Pollacco

Towards a Charge Particle Spectroscopy program

EVENTS

January 20

LabVIEW 2009 & Big Physics Meeting

February 1

Giovanni Raciti International Memorial Meeting

February 11

Olimpiadi della Fisica

February 24

Open Discussion on CS beams upgrade

March 1 – 5

ICARO 2010

March 3

Workshop MICOS

March 12 – 13

NuPECC meeting

March 15 – 19

20th Scientific Week

March 29 – 31

GIANTS 2010

April 1

Stato dei lavori dello spettrometro TP dei LNS INFN

April 12 – 3

Commissione Scientifica Nazionale 2

April 24 – May 3

Mostra "Donne alla guida della più grande macchina mai costruita dall'uomo" ovvero la complessità di LHC in mano alle donne." Museo Civico Castello Ursino Catania

May 21 - 24

ASY-EOS 2010 Grand Hotel Sofia Noto

June 16

User Group Meeting

June 17 – 18

LNS Scientific Committee

EVENTS

September 13 – 17

CRIS 2010 Palazzo dei Chierici Catania

October 11 – 13

CVI Meeting 2010

November 25 – 26

II edizione Caffè-Incontro con gli studenti di fisica ai LNS INFN

December 13 – 14

INFN Course on C++, Root and GEANT

December 14 – 16

MAGNET 2010 - Nuclear Physics with Modern Magnetic Spectrometers.

**ISTITUTO NAZIONALE DI FISICA NUCLEARE
LABORATORI NAZIONALI DEL SUD
ACTIVITY REPORT 2010**

**LNS
ACTIVITY
PHOTO
GALLERY**

Giovanni RACITI
International Memorial Meeting



Physics and Astronomy Department
University of Catania

Main Hall

1 February 2010

Scientific Committee
M. Lattuada
A. Pagano
F. Porto

Invited Speakers
B. Borderie
T. Bressani
G. Casini
G. Cifone
M. De Nappoli
U. Lynen
G. Pappalardo
P. Petronici
E. Rappasarda
U. Schroeder
C. Siletti
W. Trautmann
B. Tsang





ICARO 2010

Intensive Course on Accelerators and
Reactors Operation

INFN-LNS
1-5 march 2010



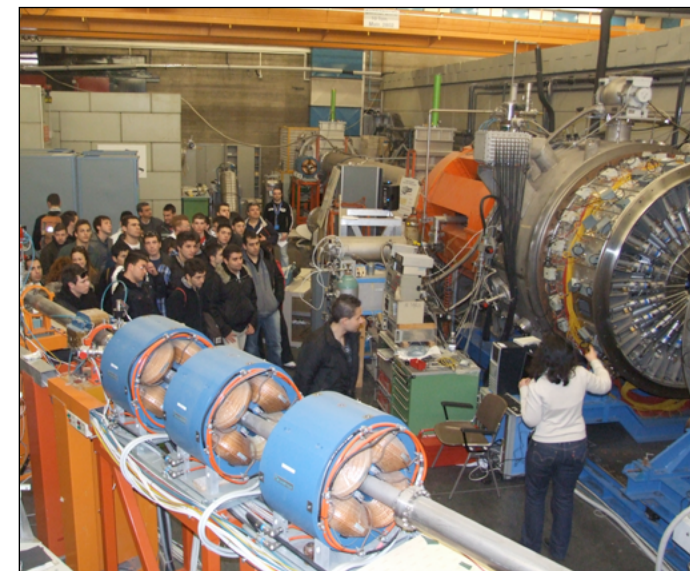
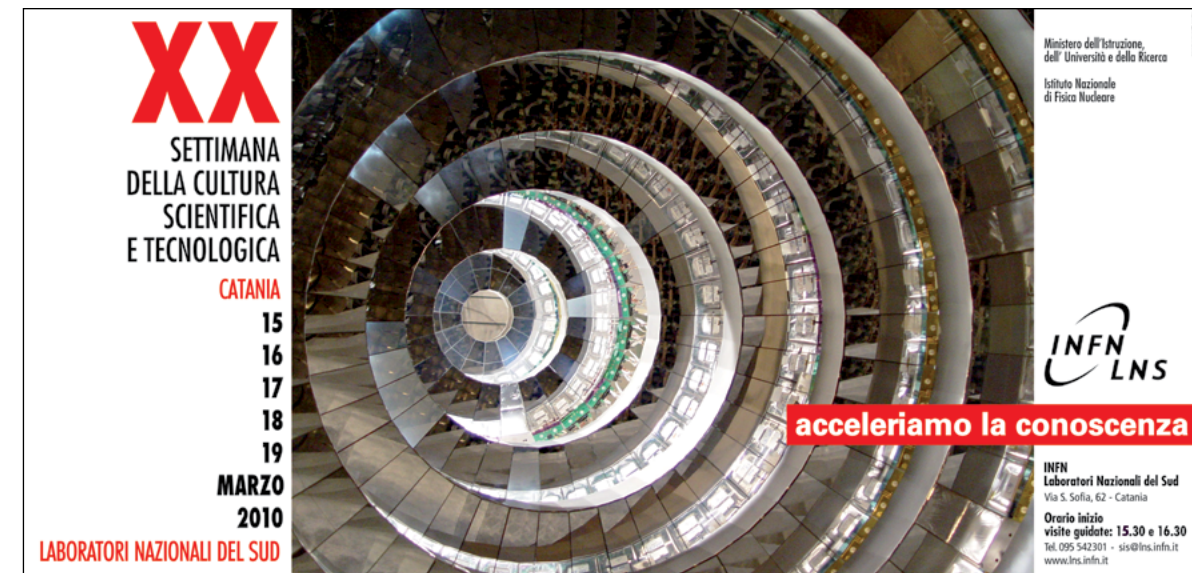


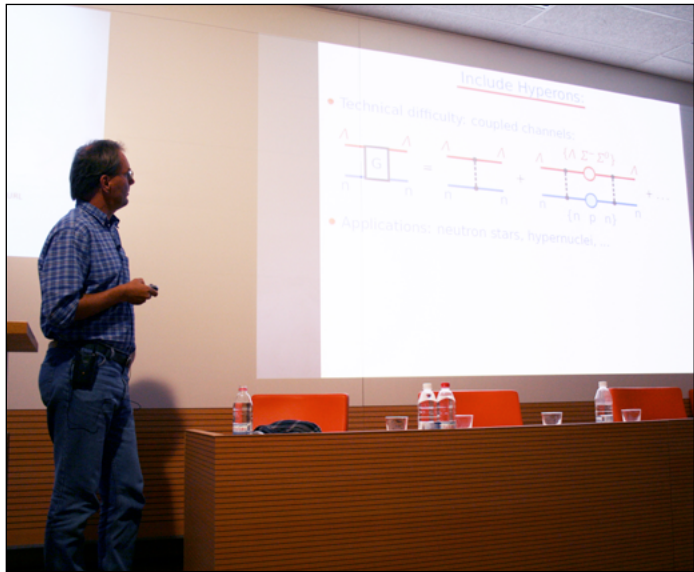


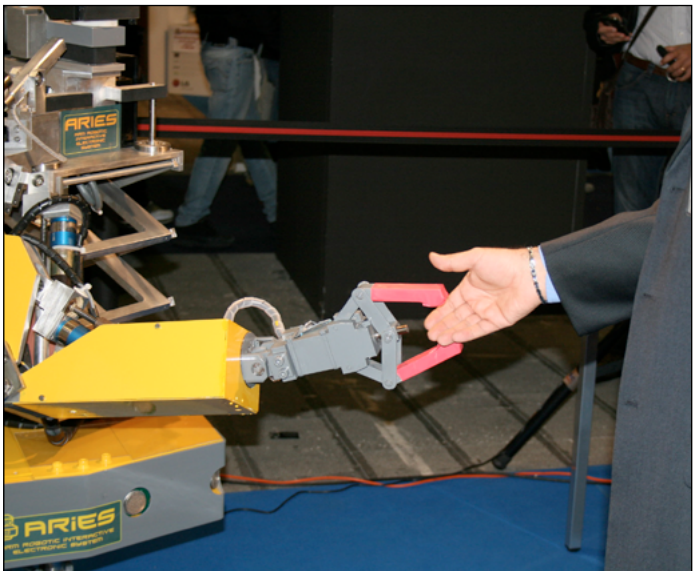
NuPECC meeting in Catania

Programme – morning 12 March 2010
Site: LNS

Brief overview of INFN activity in Nuclear Physics







Sei uno studente in cerca di tesi di laurea?

Il Caffè Incontro

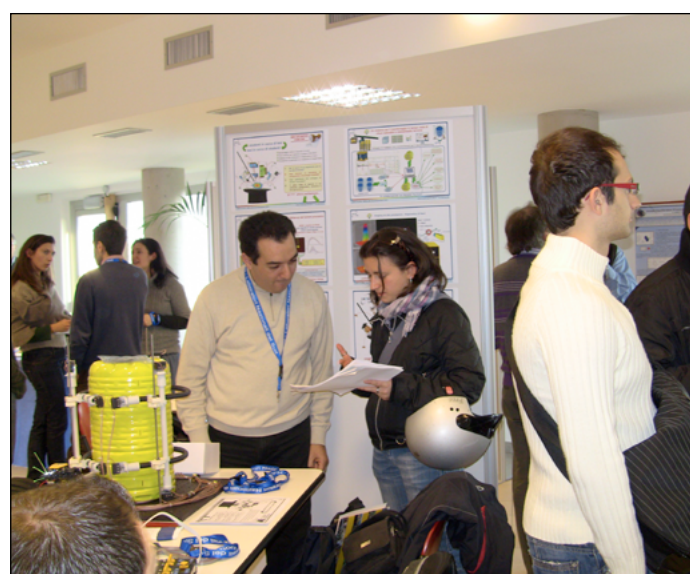
Physics at INFN - LNS

La tua tesi ai Laboratori Nazionali del Sud

25 - 26 Novembre 2010
ore 15 - 18 Sala Mensa

Presentazione temi di ricerca per lo svolgimento di tesi di laurea

info: www.lns.infn.it - sis@lns.infn.it - 095542301

Dipartimento di Fisica e Astronomia, Università di Catania
13 - 14 Dicembre 2010




CORSO BASE DI PROGRAMMAZIONE IN C++ E APPLICAZIONI (ROOT E GEANT4)

FINALITA'

- Fornire i fondamenti di base della programmazione ad oggetti in C++ e presentare due applicazioni: il tool per l'analisi dati ROOT e il toolkit di simulazione Monte Carlo, GEANT4, per il tracciamento di particelle nella materia

Comitato organizzatore:

- G. Andronico
INFN - Sezione di Catania
- G. A. P. Cirrone
INFN - LNS
- G. Cuttone
INFN - LNS
- E. Mazzaglia
INFN - LNS
- L. Pandola
INFN - LNGS
- F. Romano
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- P. Rusotto
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- D. Sardinia
INFN - LNS
- G. Verde
INFN - Sezione di Catania






<http://www.lns.infn.it/link/C++Course2010>
<http://workgroup.lns.infn.it/geant4lns>

