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ISTITUTO NAZIONALE DI FISICA NUCLEARE
LABORATORI NAZIONALI DEL SUD

ACTIVITY REPORT 2009

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The background is a complex, abstract pattern of thin, light gray lines. These lines form a dense network of overlapping circles, spirals, and intersecting paths, creating a sense of movement and depth. Small, dark gray dots are scattered throughout the composition, some appearing as isolated points and others as part of the line patterns. The overall effect is reminiscent of a technical drawing or a scientific visualization of a complex system.

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Cover figure:

the primordial nucleosynthesis and the element and energy production mechanisms accompanying the evolution of stars are the main subjects of nuclear astrophysics studies that are carried out worldwide in the nuclear laboratories with the aim of understanding the structure and the history of the Universe. At LNS a large number of experiments concerning central problems of nuclear astrophysics have been performed either by directly measuring reaction cross sections of astrophysical interest or by applying alternative methods, like the Trojan Horse one, able to give indirect information on such cross sections. Stable Tandem beams as well as the radioactive ^8Li beam produced by EXCYT have been used for this purpose.

The background of the entire page is a complex, abstract pattern of thin, light gray lines. These lines form a series of overlapping circles, spirals, and intersecting paths, creating a sense of dynamic movement and geometric complexity. The lines vary in thickness and density, with some areas appearing more crowded than others. The overall effect is reminiscent of a technical drawing or a scientific visualization, such as particle tracks or orbital paths.

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Foreword

The main mission of the INFN Laboratori Nazionali del Sud (LNS) consists in fundamental research in nuclear and astroparticle physics, as well as in applications of physics technologies and methodologies in different fields of human activities.

Following this traditional path, in 2009 several experimental studies on nuclear structure, reaction mechanisms and nuclear astrophysics processes have been performed taking advantage of the ion beam accelerators and particle detection systems like Chimera and Magnex, available at LNS.

The recently developed pulse shape analysis implemented on Chimera enhanced its performances, allowing detection of charged particle with much lower identification thresholds than before and revealing new opportunities of experimental research with low energy beams as the ones produced by EXCYT. Also for Magnex a powerful method has been developed for identification of particles detected in the spectrometer, that improved the peculiar features of the magnetic spectrometer. Also thanks to those improvements the two big detection systems have been fruitfully exploited during 2009. Chimera was specially used for experiments on the multifragmentation process whilst experiments with Magnex mainly concerned the structure of neutron-rich nuclei produced by multineutron transfer. Many other experiments performed with Tandem and Cyclotron beams, concerning, for instance, the role of the symmetry term in the nuclear equation of state, the structure of weakly bound nuclei, the rate production of elements in stars and so on, complete the articulated panorama of nuclear research topics addressed at LNS. It is to be stressed that in many cases the close collaboration of the experimentalists with the theoretician group of LNS was very helpful in designing the experiments and interpreting their results.

As in the past, a significant fraction of the accelerators beam time has been devoted to interdisciplinary experiments, mostly related to radiation hardness of materials and to the response of biological tissues to irradiation with ionizing particles. In the same framework of applications a primary and most visible role is played by the treatment of the ocular melanoma by means of the cyclotron proton beam, that now has become a routine operation; new sessions have been performed in 2009 leading to a total number of about 190 patients treated from the beginning of this activity.

In the field of technological research special mention is deserved by the development of innovative ion sources and of the beam diagnostics systems, a issue specially crucial for low intensities, as well as the exploitation of simple systems of scintillating fibers as versatile, cheap detectors for nuclear waste repository monitoring. Moreover, as a support to the activity on in situ analysis of archaeological samples, a new laboratory (LAB-ALFA) has been set up where the sources of ^{210}Po used for the portable systems developed at LNS can be produced with the required intensities.

LNS is committed to participate in the big challenge represented by the Italian radioactive ion beam facility SPES, that will be installed at the Laboratori Nazionali di Legnaro, the other low energy nuclear laboratory of INFN. The experience and the knowledge acquired at LNS during the design and realization of the EXCYT facility have been put at the disposal of this new project.

The medium/long term future of LNS relies on the project of the undersea telescope for cosmic neutrinos and many steps forwards have been done in 2009, connected to several aspects of the project.

At Capo Passero, the Italian candidate site for the installation of the telescope, the on-shore laboratory has been completed and is now operational. Moreover, the submarine infrastructure located at a depth of 3500 m has been enriched with the deployment of the DC-DC Medium Voltage Converter.

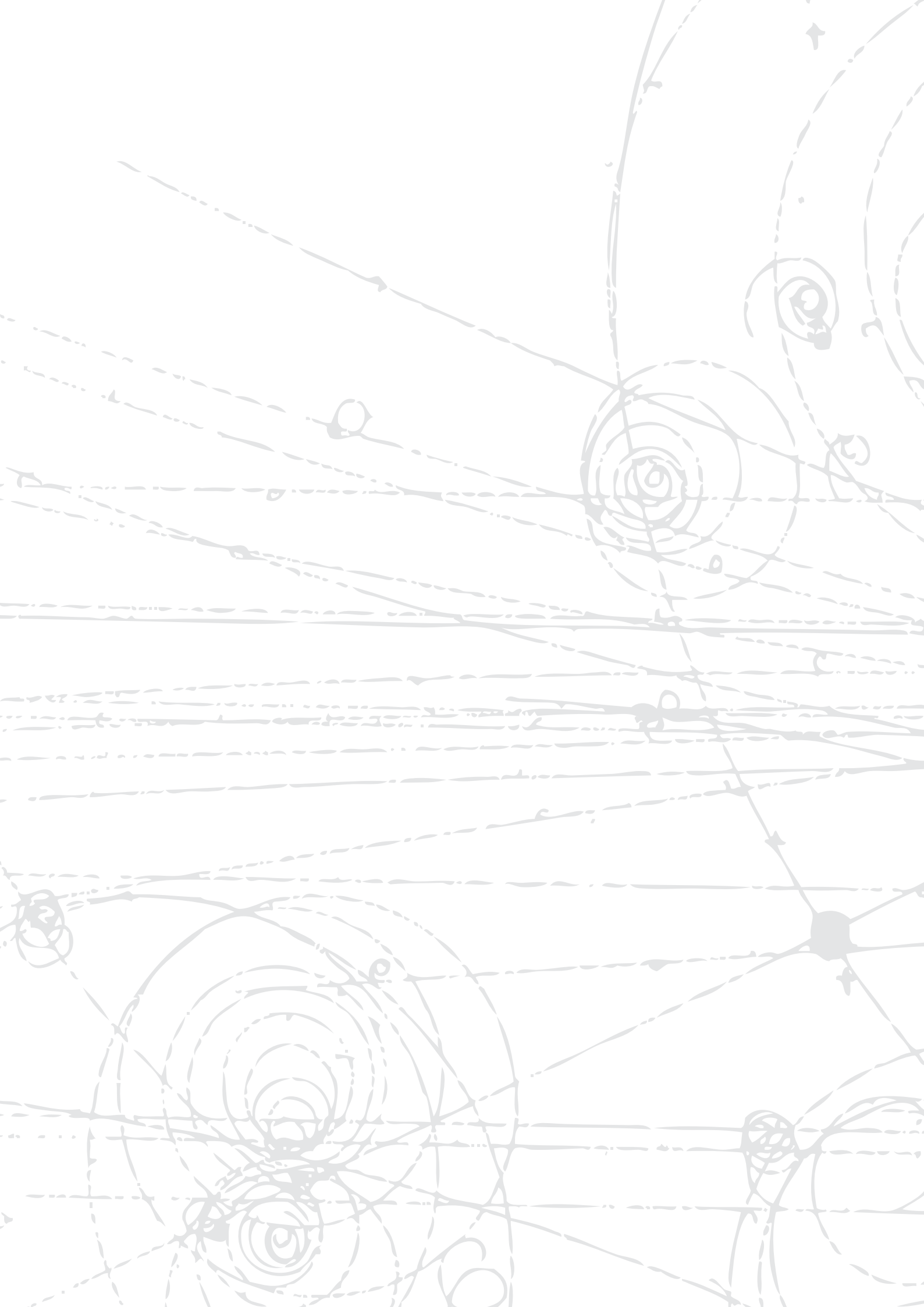
Noticeable advances towards the design of the final detection unit have been made with the realization and test of a full scale demonstrator of the NEMO tower. At the same time the development of a new mechanical structure that puts together the best aspects of the different solutions proposed by the KM3NeT partners is in progress. In the framework of the KM3NeT Consortium, LNS is active in many technological aspects including mechanical design, deep sea operations, power feeding, front-end electronics, opto-electronics for data transmission, calibration and acoustic positioning system.

In parallel with the development of the technologies required by the project, attention has been paid also to the physics that can be done with the presently available small scale detectors, by analyzing the data taken by ANTARES and NEMO-phase1, and to the physics that will be done with the KM3NeT telescope, by comparing the simulated response of different configurations of the whole detector.

Among the multidisciplinary activities exploiting the observatory infrastructures, an impulse was given in 2009 to the LIDO-ESONET project aimed at the realization of a system for acoustic and geophysical monitoring of deep sea environment. Sensors and electronics have been tested in view of the future deployment of the whole equipment in the so called test site, off the coast of Catania.

Finally a warm thank has to be given to the LNS staff and to the whole community of LNS users. The continuous interest of users in the growth of the Laboratory pushed us to give our best in improving day by day the reliability and the performances of our facilities.

Marcello Lattuada
INFN-LNS Director



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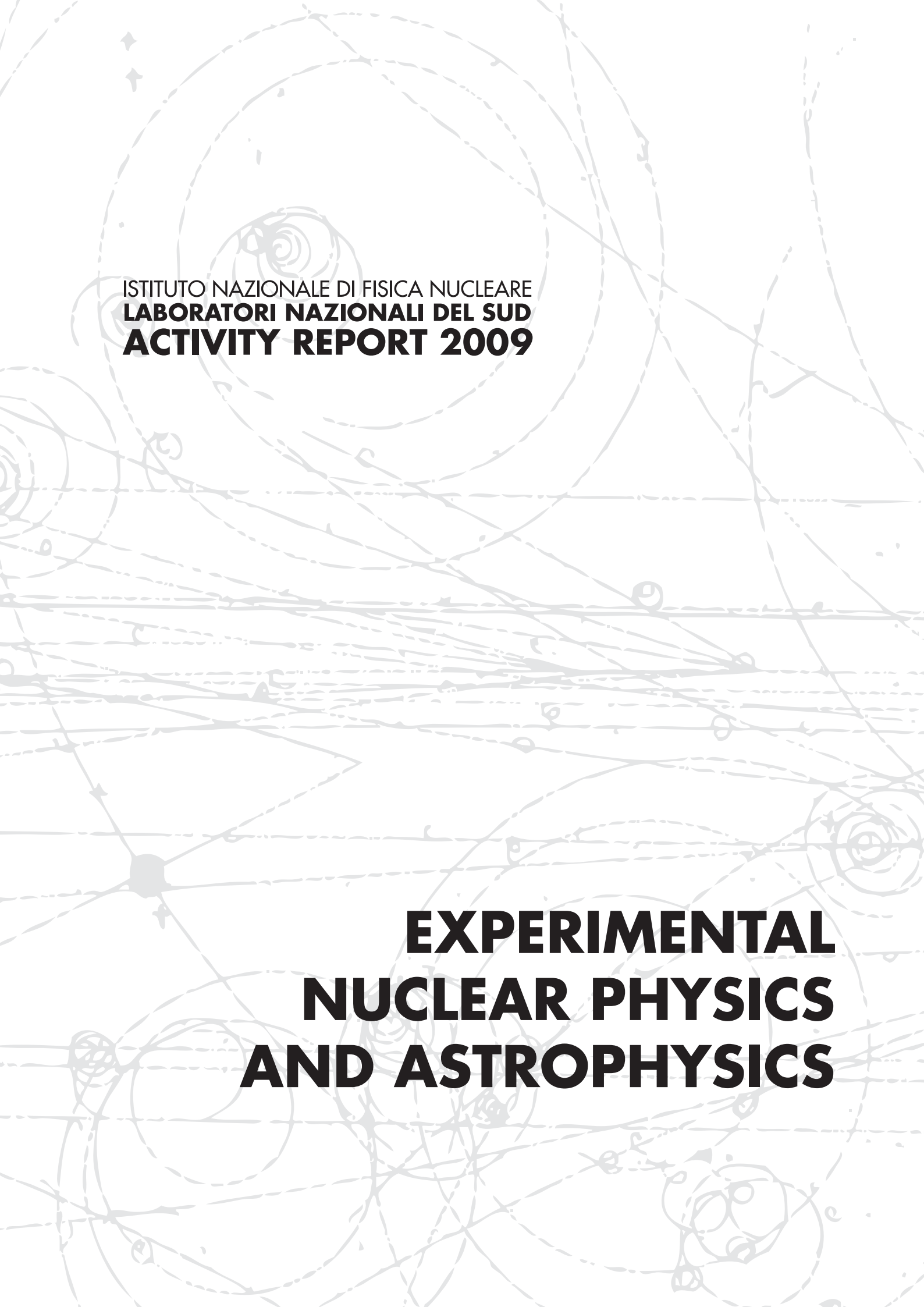
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ACTIVITY REPORT 2009

**EXPERIMENTAL
NUCLEAR PHYSICS
AND ASTROPHYSICS**

STUDY OF ^{12}B LEVELS BY ELASTIC SCATTERING OF ^8Li ON HELIUM

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Abstract

In the framework of the study of cluster states in neutron rich light nuclei (see [1-3] and reference therein), ^{12}B levels have been studied by using ^8Li elastic scattering on ^4He in inverse kinematics [4]. The initial ^8Li beam energy, provided by EXCYT, was $E_b=30.6$ MeV and ^4He elastic scattered particles have been detected around $\theta_{\text{lab}}=0^\circ$ as previously reported in [1]. Preliminary results regarding the elastic scattering excitation function, obtained in the energy range $E_{\text{cm}}=2.7\text{-}5$ MeV for alpha particles stopped in the ΔE detector, will be shown.

The MCP signal provides a reference for time of flight measurements and a measurement of the beam intensity, which was about $\sim 5 \cdot 10^4$ pps.

The acquisition trigger was generated by events from the ΔE detectors. The time interval (ΔT) between the signal produced by the ΔE and the delayed signal coming from the MCP (inverse logics) has been measured.

The time measurement is crucial for the discrimination of elastic from inelastic scattering (see [1]).

EXPERIMENTAL SET-UP

As reported in [1], the ^8Li beam, produced by EXCYT, after passing through an aluminized Mylar foil ($0.8 \mu\text{m}$ thick) of a Micro Channel Plate (MCP), reaches the scattering chamber, filled with ^4He gas. The ^4He gas acts as target and beam energy degrader at the same time.

The pressure inside the scattering chamber was $P=702 \pm 5$ mbar. A kapton foil ($13 \mu\text{m}$ thick) isolated the chamber from the beam line. Four detector telescopes were placed in the chamber. Each one consists of a four quadrant Silicon Pad detector ($47\text{-}60 \mu\text{m}$ thick) and a E DSSS Detector, with 16×16 strips ($500\text{-}1000 \mu\text{m}$ thick).

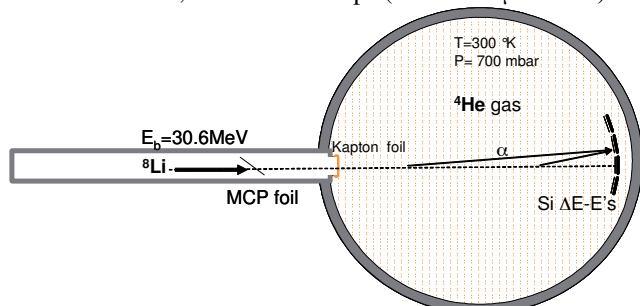


Figure 1: Experimental set-up. Detectors are inside the CT-2000 scattering chamber which is filled with ^4He gas.

PRELIMINARY RESULTS

In the following we will focus the attention on results obtained from the most forward detector $\Delta E\text{-}E$, placed at 0° with respect to the beam direction. For this telescope, the ΔE nominal thickness is $47 \mu\text{m}$.

In figure 2, a typical $\Delta E\text{-}E$ scatter plot is shown. We can distinguish the alpha particles from the other hydrogen isotopes, like tritons, that are produced most probably in ^8Li break-up.

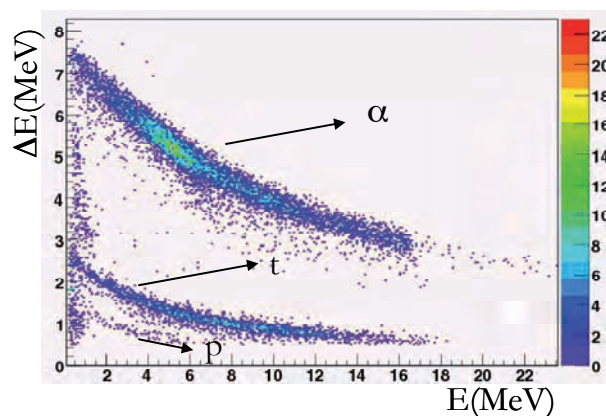


Figure 2: $\Delta E\text{-}E$ scatter plot.

In Fig. 3, the time ΔT is shown as a function of the energy measured by the ΔE detector.

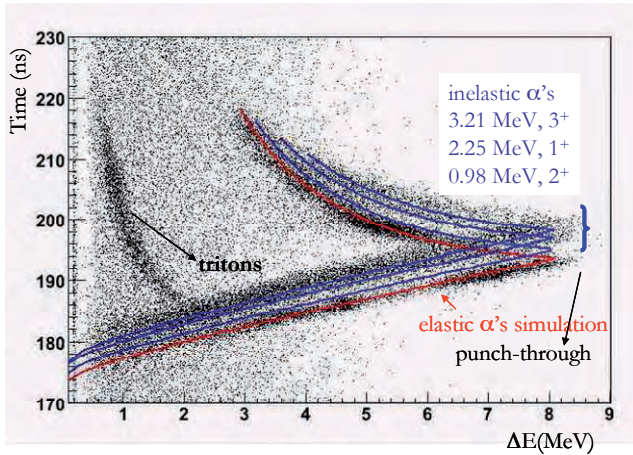


Figure 3: ΔT vs ΔE energy. Red and blues lines represent the simulation of elastic and inelastic scattering respectively.

As one can observe, the elastic events are clearly distinguished from the inelastic events. We have simulated the correlation between ΔT and energy for the elastic and inelastic events (first three excited levels). The calculation includes the kinematics and the energy losses of ${}^8\text{Li}$ and α in ${}^4\text{He}$ gas. It can be seen that the simulation which concerns the elastic events is in agreement with the data. As regards the inelastic events, we can notice that the 2^- level is scarcely populated.

In the same plot one can also observe a large yield of tritons as well as alpha background events (for $\Delta E < 5\text{MeV}$). The former are due, as previously mentioned, to ${}^8\text{Li}$ break-up, while the latter, which are uncorrelated in time, are produced in the ${}^8\text{Li}$ decay (${}^8\text{Li} \rightarrow {}^8\text{Be}^* + 2\alpha$).

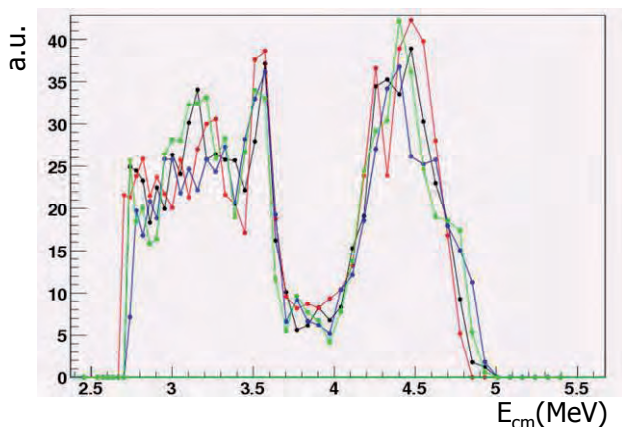


Figure 4: Preliminary centre-of-mass elastic cross section in arbitrary units at $\theta_{\text{lab}}=0^\circ$. The four lines represent the spectra obtained separately for the four quadrants of the ΔE detector.

Graphical contours on the elastically scattered α -particles stopping in the ΔE detectors allow to project the scatter plots on the ΔE axis. For these

events the centre-of-mass energy has been reconstructed and the preliminary cross section is plotted in Fig.4.

The excitation function obtained for the four quadrants of the ΔE detector are in agreement. The spectra show evidence of pronounced peaks.

CONCLUSION

The preliminary results of the ${}^8\text{Li}+{}^4\text{He}$ elastic scattering cross sections have been shown for $E_{\text{cm}}=2.7\text{--}5\text{MeV}$. The evaluation of the absolute cross section and a more precise reconstruction of E_{cm} , including the angular and energy straggling for projectiles and alpha recoils, is in progress. Moreover, before deducing resonance parameters, the background of α events for $\Delta E < 5\text{MeV}$ has to be evaluated and subtracted.

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ELASTIC BACKSCATTERING MEASUREMENTS FOR

 ${}^6,{}^7\text{Li}+{}^{58}\text{Ni}$, ${}^6,{}^7\text{Li}+{}^{118,120}\text{Sn}$, ${}^6,{}^7\text{Li}+{}^{208}\text{Pb}$ AT NEAR BARRIER ENERGIES

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Abstract

We have performed, elastic backscattering measurements for the weakly bound nuclei ${}^6,{}^7\text{Li}$ on the medium and heavy mass targets ${}^{58}\text{Ni}$, ${}^{118,120}\text{Sn}$, ${}^{208}\text{Pb}$ at sub- and near-barrier energies (0.6 to 1.3 $E_{\text{C.b.}}$). Excitation functions of elastic scattering cross sections have been measured at $\pm 160^\circ$ and $\pm 170^\circ$ and the corresponding ratios to Rutherford scattering and relevant barrier distributions have been extracted. These measurements will complement recent work on a ${}^{28}\text{Si}$ target for probing the potential at sub- and near barrier energies and relevant reaction mechanisms.

INTRODUCTION

As it is well known in heavy ion reactions, approaching the vicinity of the Coulomb barrier, couplings between various channels increase in importance. Describing elastic scattering, either these couplings have to be taken into account through coupled channel theories, or the energy dependence of the various optical model parameters has to be considered explicitly. In well bound nuclei, the term "threshold anomaly" was invoked to describe a rapid variation of such model parameters appeared as a sudden increase of the real part of the potential approaching the barrier, which is connected via dispersion relations with a decrease of the imaginary part.

Moving to weakly bound nuclei the situation becomes more complicated due to the influence of breakup and/or transfer effects leading to a new type of anomaly [1-5]. In principle, the lack of sensitivity for obtaining the energy dependence of optical potential parameters, at energies below and near the coulomb barrier, leads occasionally to vague conclusions. Therefore, to improve our understanding on the energy dependence of the optical potential especially at sub-barrier energies and the relevant processes involved in the threshold anomaly, other complementary means should be adopted. We have shown in [6] that a very promising method to probe the potential and relevant reaction mechanisms is that of elastic backscattering. Into this context we will describe

below our measurements on ${}^6,{}^7\text{Li}+{}^{58}\text{Ni}$, ${}^6,{}^7\text{Li}+{}^{118,120}\text{Sn}$, ${}^6,{}^7\text{Li}+{}^{208}\text{Pb}$

EXPERIMENTAL DETAILS AND RESULTS

Beams of ${}^6,{}^7\text{Li}$ ions were delivered by the SMP Tandem accelerator of LNS in Catania. at 0.5 energy steps in the energy range 0.6 to 1.3 $E_{\text{C.b.}}$. Beam currents were of the order of 5 to 20 nA depending on energy. The beams impinged on 200 $\mu\text{g}/\text{cm}^2$ thick self-supporting ${}^{58}\text{Ni}$, ${}^{118,120}\text{Sn}$, ${}^{208}\text{Pb}$ targets with the target frame fixed perpendicular to the beam direction. Excitation functions of (Quasi)-elastic backscattering events were recorded in four telescopes consisting of 10 μm and 2000 μm silicon detectors, set at 160 and 170 degrees. The beam flux was estimated via a measurement of the Rutherford scattering in two silicon detectors set at 20 degrees.

Cross sections were extracted via the relation

$$\sigma_{q170} = \frac{N_2}{N_1} \frac{\Omega_1}{\Omega_2} \sigma_{R(30)}$$

where N_2 and N_1 are the yield on the backward and forward detectors respectively while Ω_1 and Ω_2 are the solid angles of the forward and backward detectors respectively. The ratio of the solid angles was determined from the data at the lowest energies where the scattering is Rutherford for both forward and backward detectors eliminating most of the assigned error in the above relation.

Barrier distributions were formed by using the relation for elastic scattering [7]

$$D(E) = \frac{d}{dE} \left[\sqrt{\frac{d\sigma_{el}}{d\sigma_{Ruth}}(E)} \right]$$

Preliminary results of barrier distributions are compared for ${}^6\text{Li}$ on the the three targets ${}^{58}\text{Ni}$, ${}^{120}\text{Sn}$, ${}^{208}\text{Pb}$ in Figure 1, while for ${}^7\text{Li}$ on the four targets ${}^{58}\text{Ni}$, ${}^{118,120}\text{Sn}$, ${}^{208}\text{Pb}$ in Figure 2. From the above systematic it is seen that the

barrier heights are larger for the lower mass targets than for the heavier ones and this variation is more obvious for the ${}^6\text{Li}$ projectile. Additionally to that the barrier distribution widths and heights are larger for the lighter targets and larger for the ${}^6\text{Li}$ projectile than the ${}^7\text{Li}$ one. Another interesting result is that there is no isotopic target dependence as sought for ${}^7\text{Li}+{}^{118,120}\text{Sn}$, since the barrier distributions are almost identical for the two targets. The above results will be further explored in the future via theoretical calculations in order to probe any relation with the reaction mechanisms involved. Also theoretical analysis is under way to probe and map till very low energies the optical potential.

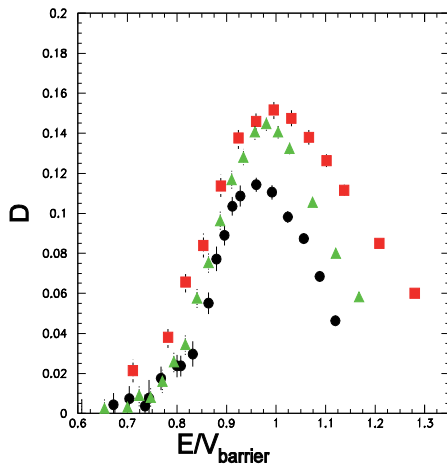


Figure 1: Barrier distributions for ${}^6\text{Li}$ on ${}^{208}\text{Pb}$ (solid circles) ${}^{120}\text{Sn}$ (triangles) and ${}^{58}\text{Ni}$ (solid boxes).

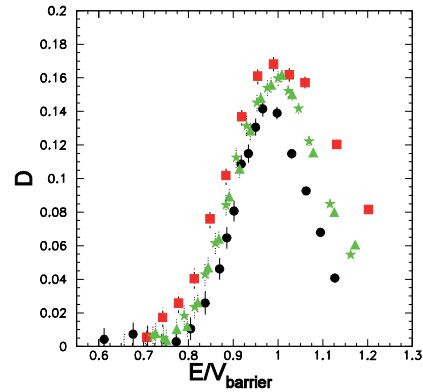


Figure 2: Barrier distributions for ${}^7\text{Li}$ on ${}^{208}\text{Pb}$ (solid circles), ${}^{118}\text{Sn}$ (stars), ${}^{120}\text{Sn}$ (triangles) and ${}^{58}\text{Ni}$ (solid boxes).

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FUSION EXCITATION FUNCTION IN THE COLLISION ${}^6\text{Li}+{}^{64}\text{Zn}$ AROUND THE COULOMB BARRIER

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An increasing number of experimental and theoretical papers are being published about the reaction mechanisms in collisions involving weakly bound and/or halo nuclei around the Coulomb barrier. We recently started a new systematic investigation of the various reaction mechanisms for the ${}^6,7\text{Li}+{}^{64}\text{Zn}$ systems, looking for possible effects due to the different binding energies and structure of the projectiles. In this paper we report the preliminary results for the fusion cross sections obtained for the ${}^6\text{Li}+{}^{64}\text{Zn}$ system.

1. INTRODUCTION

Several efforts have been undertaken, in the last years, to understand the reaction mechanisms around the coulomb barrier in collision induced by weakly bound nuclei (see ref. [1] and references therein). The ground state energy for these particular nuclei is very close to the particle emission threshold; therefore, in order to properly describe the reaction dynamics, direct processes and the coupling to different bound and unbound states must be considered.

From a semiclassical point of view, direct processes like break-up or transfer may be favored by the low binding energies and one might also expect suppressed fusion cross section due to the competition with the breakup. However, according to the Coupled Channel calculations (CC), it is well known that the presence of strong open reaction channels can be responsible for a fusion cross-section enhancement.

The reaction mechanisms in collisions induced by weakly bound, stable and unstable nuclei have been investigated from both the experimental and theoretical point of view to study the effects of the breakup channel on fusion and elastic scattering at energies around the Coulomb barrier. Recently, much work has been devoted to the study of the threshold anomaly (TA) in elastic scattering of weakly bound nuclei, such as ${}^6\text{Li}$ and ${}^7\text{Li}$. For these projectiles the breakup channel is expected to be important at energies around the Coulomb barrier and the usual TA may disappear.

For the above discussed reason we recently studied different reaction channels for the collision of ${}^6\text{Li}+{}^{64}\text{Zn}$ at energies around the Coulomb barrier.

Elastic scattering angular distributions were measured at eight beam energies from below to above the Coulomb barrier, $12.0 \leq E_{\text{lab}} \leq 22.0$ MeV. The experimental data were analyzed within the optical model in order to study the energy dependence of the interaction potential and to obtain total reaction cross-sections. The energy dependence of the real and imaginary parts of the optical potential shows that no usual TA is present for the ${}^6\text{Li}+{}^{64}\text{Zn}$ system. These result are discussed elsewhere in this annual report.

Moreover, we have also extended to sub-barrier energies the fusion excitation function for ${}^6\text{Li}$ on ${}^{64}\text{Zn}$, previously measured by Gomes et al. [2] at energies close to and above the barrier. Comparison of the deduced reaction cross-section and total fusion cross-section in [2,3] showed a reaction cross-section larger than the total fusion one at energies around the barrier and the authors concluded that the elastic break-up has significant cross-section at these energies. However, there are indications [4] that there may have been problems with the ${}^6\text{Li}+{}^{64}\text{Zn}$ fusion data in [2] and this could change this conclusion.

We measured fusion cross-sections for the system ${}^6\text{Li}+{}^{64}\text{Zn}$ using an activation technique, detecting off-line the delayed X-ray activity emitted by the evaporation residues decaying by electron capture. The explored energy range was $E_{\text{c.m.}} = 9-28$ MeV.

2. FUSION CROSS-SECTION MEASUREMENTS

The fusion excitation function has been measured using the technique fully described in [5]. Briefly, we detect off-line the X-rays following the electron capture decay of the evaporation residues (E.R.) after activation of a target.

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The setup used for the activation is sketched in figure 1. Inside the reaction chamber has been placed a thin ($\sim 200 \mu\text{g}/\text{cm}^2$) Au target for beam current monitoring by measuring the Rutherford scattering using two detectors placed at 30° with respect to the beam axis. On the beam axis, following the thin Au target, has been placed the ^{64}Zn target (200-500 $\mu\text{g}/\text{cm}^2$ depending on bombarding energy), followed by a Nb or Au catcher. We bombarded a different Zn target at each different beam energy ($E_{\text{lab}} = 9, 11, 13, 17, 20, 24, 31, 40 \text{ MeV}$).

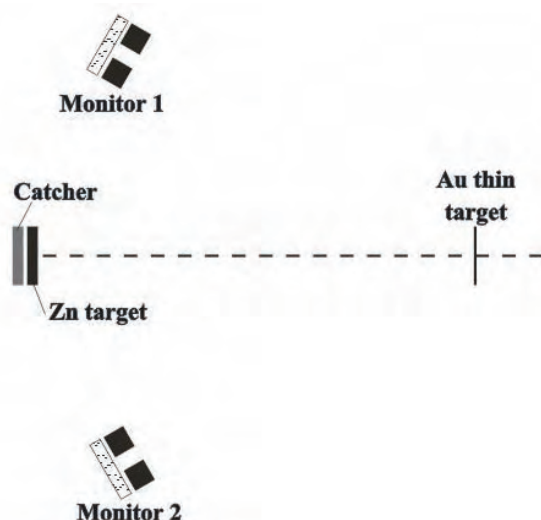


Figure 1. The experimental setup for the activation of the Zn target. A thin Au foil is placed before the Zn target to reconstruct the beam current as function of time by measuring the Rutherford scattering with two monitors.

The catcher thickness was chosen in order to stop the E.R. produced in the previous ^{64}Zn target. The analysis of Rutherford scattering on the thin Au target allows reconstructing the beam current as a function of time during the activation.

The activity of the irradiated targets has been measured off-line using Pb shielded large area Si(Li) detectors which a very low background allowing counting rates that can go down to 0.5 counts/h. Different elements has been discriminated by the X-ray energy. Although different isotopes of the same element are not separated in the X-ray spectra, they have been identified by their half-lives following the activity curves as a function of time for each peak in the X-ray energy spectrum.

For example, in figure 2 one can see a typical X-ray spectrum measured about six days after a 13 MeV activation showing a peak for each element found in the target.

In figure 3 is shown the activity curve corresponding to the decay of the Ga isotopes into the Zn ones for the same

target. Different slopes correspond to the half-lives of different identified Ga isotopes. Note the presence of a 270 half-live contribution that is not corresponding to the direct decay of a Ga isotope but to the ^{68}Ge decaying into ^{68}Ga , which intern decays into ^{68}Zn .

From the analysis of the activity curves, knowing the beam current as function of time during the activation, the X-ray fluorescence probabilities, the detection efficiency and taking into account the self absorption probability, the partial and total fusion cross-sections can be extracted.

In figure 4 is shown the production cross-section of each E.R. at 13 MeV.

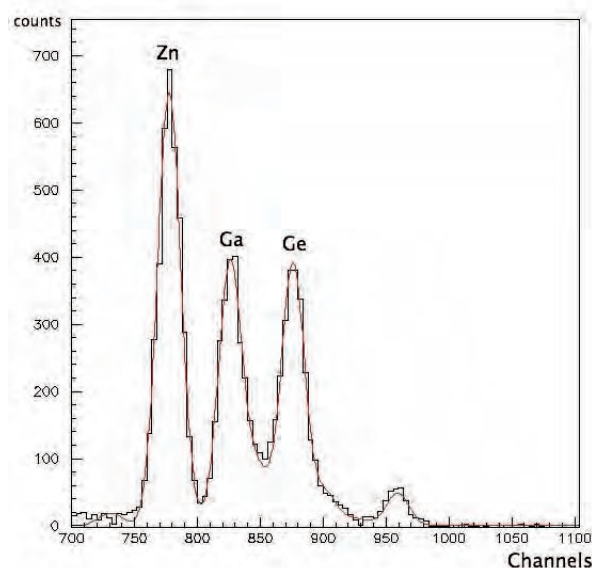


Figure 2. A typical X-ray spectrum in which we can identify each E.R. by the X-ray energy of the daughter nucleus. For each element there is a dominant emission (K_α) and a less intense emission (K_β) visible for instance on the right of the Ge K_α .

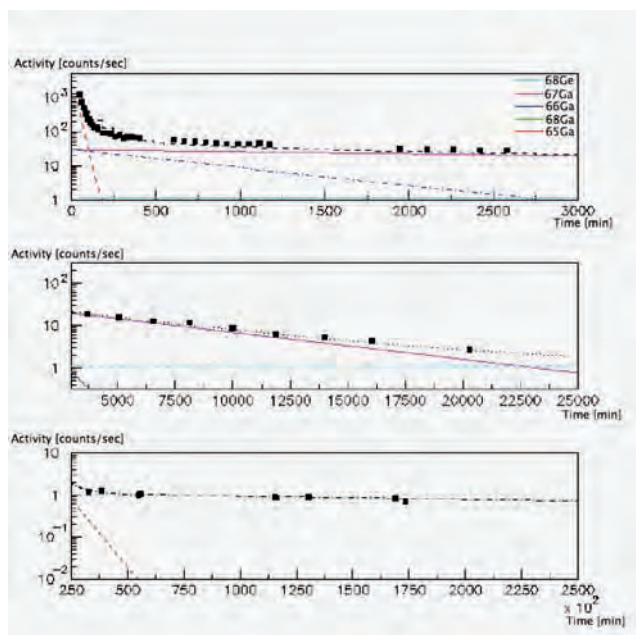


Figure 3. Activity curves as a function of time for the $Ga \rightarrow Zn$ decay in logarithmic scale. The sum of all curves, displayed as a black dashed line, fits the experimental dots. Note the ^{68}Ge presence due to the "feeding" ($^{68}Ge \rightarrow ^{68}Ga \rightarrow ^{68}Zn$)

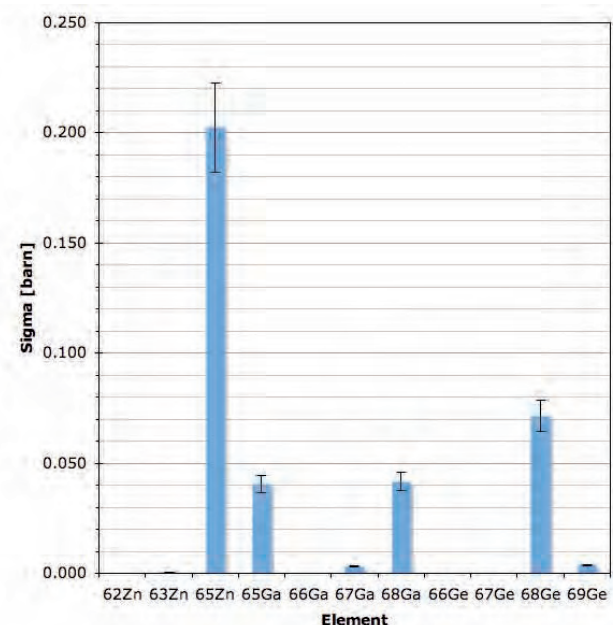


Figure 4. Production cross-section of each E.R. at 13 MeV.

2. RESULTS AND CONCLUSION

Our preliminary fusion cross sections are reported in figure 5 together with the total reaction cross section measured in an other experiment [6], the reaction cross sections and the fusion cross section of [2]. From our new preliminary results the large difference, observed by Gomes et al. [2,3], between the reaction and the total fusion cross-section is reduced. This seems to confirm possible experimental problems in the fusion cross sections measured in [2] as suggested in [4].

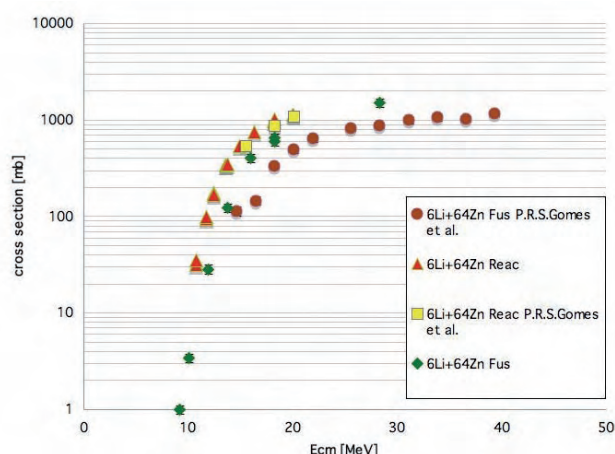


Figure 5. Fusion and reaction cross-sections as a function of the center of mass energy. The green diamonds and the red triangles are respectively the fusion and total reaction cross-sections measured by us. The red circles and the yellow squares are respectively the fusion cross-section and the reaction cross-section measured by P.R.S. Gomez [2,4].

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PRODUCTION OF RADIOACTIVE NUCLEI VIA NUCLEAR FRAGMENTATION OF ^{13}C , $^{16,18}\text{O}$ AT 55 MEV/A

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Abstract

Two runs of the Unstable experiment at LNS were performed on 2009. The production of neutron and proton rich light nuclei was tested. The optimum transmission was measured only in few cases for which it was possible to produce pilot beams. Preliminary results on elastic scattering of ^{16}C on proton target are reported

INTRODUCTION

Fragmentation beams are produced at LNS since many years [1]. During 2009 we have performed various test experiments in order to understand the opportunities offered by such beams using a 4π detector like CHIMERA [2], looking both to proton and neutron rich light nuclei production. The identification of such nuclei was performed by using the tagging system developed for CHIMERA [3]. It consists of a large area microchannel plate (MCP) used as start detector for time of flight (TOF) measurements and a double side silicon strip detector (DSSSD) 16×16 strips providing the stop signal for TOF measurement, energy loss (ΔE) and position of the impinging beam. For the test of beam production we have used as primary beams ^{13}C , ^{18}O and ^{16}O , at 55 MeV/A. The first two beams were used to produce neutron rich nuclei while ^{16}O was used for the production of nuclei on the proton rich side.

PRODUCTION OF NEUTRON RICH NUCLEI

The main effort was dedicated to the production of beams in the region of ^{11}Be . We verified that the most suited primary beam for ^{11}Be production is the ^{13}C . With this primary beam we were able to produce a ^{11}Be beam quite intense (of the order of 10^4 p/s using 100 W ^{13}C beam 55MeV/A) and quite pure (around 50% of the

produced beam was ^{11}Be). The measured identification scatter plot (ΔE -TOF) is reported in fig 1.

The same isotope can be also produced by using ^{18}O however with less intensity (3kHz using 100 W ^{18}O 55MeV/A beam) and with much more contaminants. However most of the contaminants produced with ^{18}O are quite useful neutron rich beams. Therefore also this choice is good for some experiments. In fig. 2 we can see the same beam identification plots of fig.1 but obtained with ^{18}O primary beam.

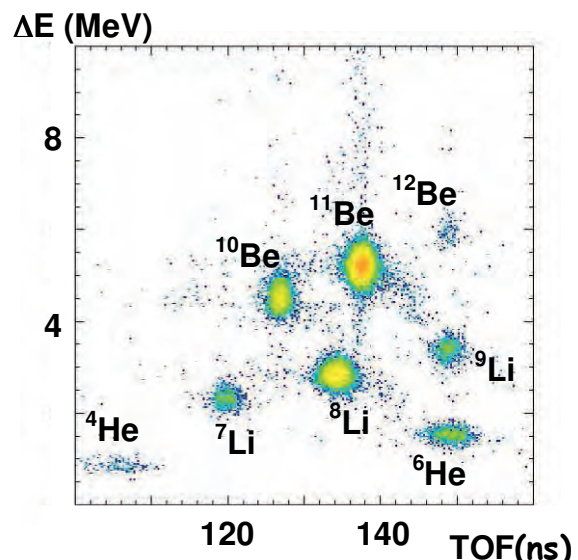


Fig.1 Identification scatter plot for the fragmentation beams obtained using a primary beam of ^{13}C 55 MeV/A on a 1.5mm ^9Be target

As can be also evaluated looking to the production rate reported in table 1, we see that while with ^{13}C one is able

to produce mainly $^{11,10}\text{Be}$ and ^8Li , with ^{18}O beam we have also intense beams of $^{16,17}\text{C}$, $^{13,14}\text{B}$.

With both beams one produces also very neutron rich nuclei even if with rather low intensity at list with the bp selected for ^{11}Be production. $N=2Z$ nuclei like ^6He , ^9Li , ^{12}Be are produced with ^{13}C , with ^{18}O also ^{15}B and ^{18}C can be observed.

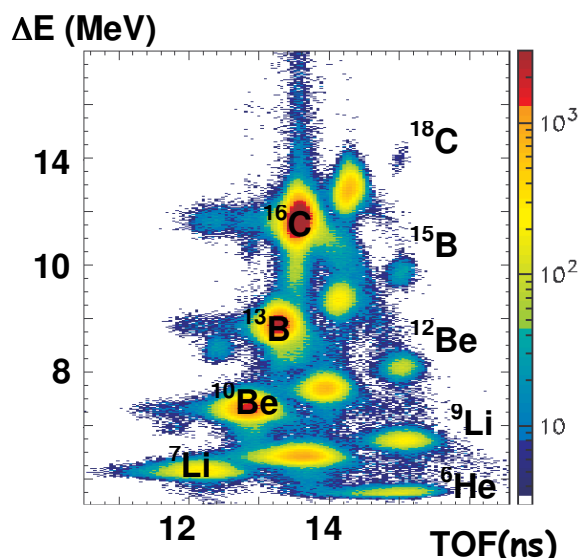


Fig.2 Identification scatter plot for the fragmentation beams obtained using a primary beam of ^{18}O 55 MeV/A on a 1.5mm ^9Be target

For all these very neutron rich nuclei it was not possible to investigate on the maximum production yield, mainly due to transmission problems. At the time of the tests it was in fact still not available the new beam monitoring system developed for the transport along the CHIMERA and MAGNEX beam line [4]. To optimize the transport of the beam the only available technique was that of pilot beam. With this technique, a stable beam with the same magnetic rigidity of the searched radioactive beam is used to set the beam line. While for proton rich nuclei the pilot beam can be easily obtained using degraders of the opportune thickness, so decreasing the beam energy of the primary beam, with neutron rich beams this is impossible. We can get a pilot beam for such nuclei only in few special cases. The pilot beam is in such cases the primary beam itself. This was for instance obtained with ^{11}Be produced with a ^9Be target 1.5mm thick both for the $^{13}\text{C}^{5+}$ and $^{18}\text{O}^{7+}$ beams 55 MeV/A. Such beams are in fact characterized by a bp of 2.817 and 2.785 Tm respectively, very near to the optimum bp calculated with LISE [5] (2.780 and 2.710 Tm).

Without a pilot beam the transmission of the fragmentation beams up to the CHIMERA scattering chamber is quite inefficient therefore, for the most neutron rich elements it was not possible to measure the maximum available beam current but only to test the

production capability. In this respect it is very interesting the plot of fig.3 showing the production and identification of nuclei as ^8He , ^{11}Li , ^{14}Be , and again ^{15}B .

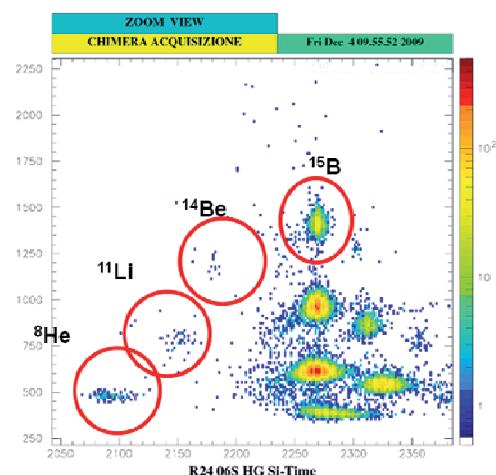


Fig.3 Identification scatter plot for the fragmentation beams obtained using a primary beam of ^{18}O 55 MeV/A on a 1.5mm ^9Be target with a setting useful to produce very neutron rich nuclei.

New measurements after the upgrading of the beam lines will be necessary to definitively test the possibility to use such beams.

Table 1 Characteristics of the produced fragmentation beams. Intensity is normalized to a primary beam of 100 Watt.

Primary beam (55 MeV/A)	^9Be production target thickness (mm)	Secondary beam and energy	Intensity (kHz)	Abundance
^{13}C	1.5	^{11}Be 48 MeV/A	10 *	50%
^{13}C	1.5	^{12}B 47 MeV/A	160	80%
^{16}O	1.5	^{15}O 31 MeV/A	5	10%
^{16}O	1.5	^{14}O 36 MeV/A	0.7	1.5%
^{16}O	2.5	^{17}F 24 MeV/A	10	20%
^{18}O	1.5	^{16}C 49.9 MeV/A	9	30%
^{18}O	1.5	^{13}B 52 MeV/A	4.5	15%
^{18}O	1.5	^{11}Be 48 MeV/A	3*	10%
^{18}O	1.5	^{10}Be 56 MeV/A	4.5	15%
^{18}O	1.5	^8Li 51 MeV/A	3	10%

THE PROTON RICH SIDE

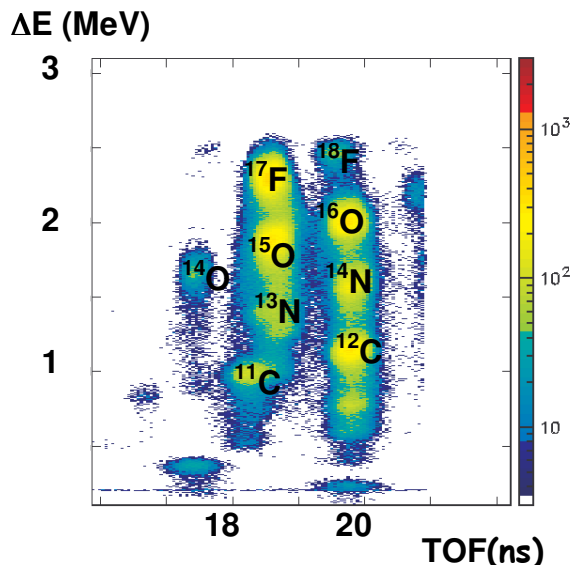


Fig.4 Identification scatter plot for the fragmentation beams obtained using a primary beam of ^{16}O 55 MeV/A on a 2.5mm ^9Be target. A 70 μm thick DSSSD detector was used to measure the beam energy loss.

The ^{16}O beam 55 MeV/A was used as primary beam in order to investigate on the production of proton rich nuclei. The main aim was to observe the production yield for nuclei in the region of ^{13}O . Therefore a 2.1 mm Al degrader was used in order to prepare the opportune pilot beam. However the production yield of ^{13}O was quite low (less than 1 kHz) and for this reason is not reported in table 1. $^{15,14}\text{O}$ are produced with reasonable rate, the surprise was the rather large yield measured for the ^{17}F . This finding confirms what was observed in previous runs with ^{20}Ne beams, the large probability to observe not only fragmentation reactions at this energy but also proton pickup from the ^9Be target, raising the production of ^{17}F in the case of ^{16}O beam and of ^{21}Na in the case of ^{20}Ne beam. In fig.4 one of the identification scatter plot obtained with ^{16}O beam on a 2.5 mm thick ^9Be target is shown. In this case we have used a DSSSD detector 70 μm thick. The identification is less good than in the case of the 140 μm DSSSD detector used for the ^{13}C and ^{18}O primary beams. This less clear identification is due to some non uniformity of pixels of the 70 μm thick detector. A pixel by pixel correction for the detector thickness is necessary to recovery this problem.

ELASTIC SCATTERING DATA

Reactions were performed using as primary beams ^{13}C and ^{18}O with the setting useful for ^{11}Be production. As shown in fig.2 one of the most intense beam produced

during the ^{18}O experiment was ^{16}C , therefore we concentrated on the analysis of such beam in order to understand the data quality. In fig. 5 we plot the residual energy spectrum detected in a telescope at 2.4° in single and in kinematical coincidence with a telescope at 84° .

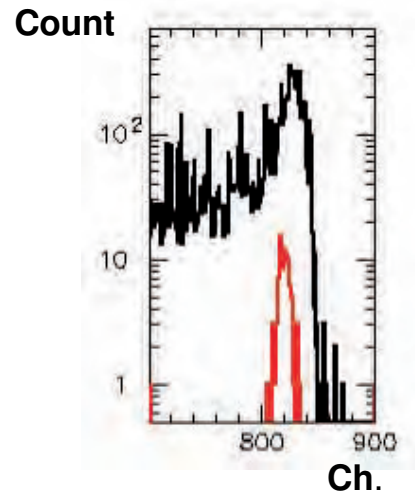


Fig.5 Particle energy detected in a telescope at 2.2° . The shaded area spectrum are the events detected in kinematical coincidence with a telescope at 84° .

We observe in coincidence ^{16}C and protons produced in elastic scattering reactions. Due to the cleaning effect of kinematical coincidence, we can rather simply integrate the peak without any need for background correction.

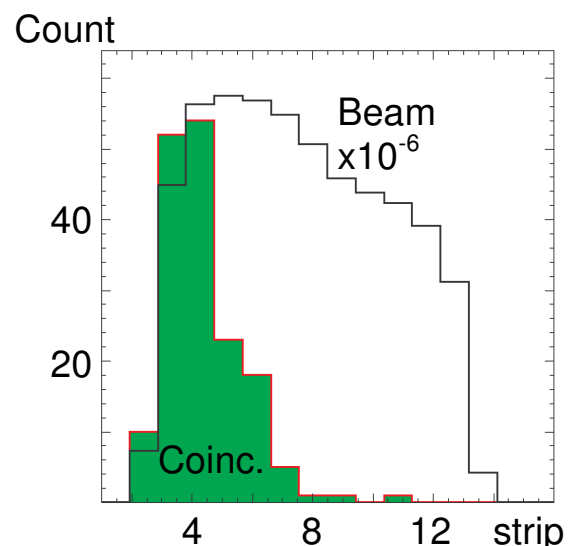


Fig.6 Distribution along the X direction of the ^{16}C beam (scaled) impinging on the tagging strip. The filled histogram is the distribution of the beam generating the coincidence events of fig.5.

To measure the cross section we have to compare such events to the beam intensity used. We measure event by

event the beam therefore we have a very precise evaluation of its intensity. However we must perform corrections because of the impinging beam angle and position. In fig.6 it is reported the x distribution of the beam (scaled by a factor 10^6) and as dashed spectrum the position of the beam producing the coincidences observed in fig.5. We note that only beam particles impinging on the left side of the spectrum generate reactions producing particles detected in kinematical coincidence. After the trajectory correction we can evaluate the effective angle of the detected ^{16}C and proton, and the beam intensity for the cross section evaluation. A preliminary cross section in arbitrary units is plotted in fig.7 (less than 10% of the available statistics was used)

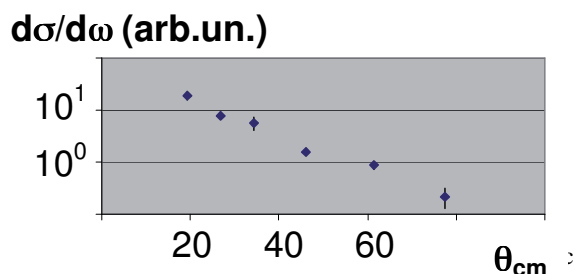


Fig.7 Center of mass angular distribution of the elastic scattering $p+^{16}\text{C}$.

CONCLUSION

The production yield of proton and neutron rich light nuclei has been investigated in order to evaluate the reactions that can be studied in the next future with the CHIMERA detector. Some of these beams have been already used and preliminary results on elastic scattering cross section have been obtained checking also the beam trajectory reconstruction. After the upgrading of the production beam line, programmed for the second half of 2010, and with the availability of the new diagnostic system for the radioactive beam transport monitoring, most of the investigated beams will have a very interesting production yields from some kHz up to 10^5 p/s.

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FIRST RESULTS OF $^{48}\text{Ca}+^{48}\text{Ca}$ REACTION AT 25 MeV/NUCLEON

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Abstract

We show the first physics data obtained from analysis of $^{48}\text{Ca}+^{48}\text{Ca}$ reaction at 25 MeV/nucleon, studied by means of Chimera array. The preliminary results seem to confirm the strong influence of N/Z degree of freedom on the competition between heavy residue production and binary-like mechanisms.

INTRODUCTION

On June 2009 we performed the *isospin-I* experiment at INFN-LNS. It consisted of two nuclear reactions $^{48}\text{Ca}+^{48}\text{Ca}$ and $^{42}\text{Ca}+^{54}\text{Fe}$ at 25 MeV/nucleon. We used the Chimera 4π array as detection device [1]. The fundamental aim of the experiment was to analyze the influence of the N/Z degree of freedom on the competition between different reaction mechanisms [2,3]. We had already shown in our recent papers [4,5] that the production of heavy residues by means of incomplete fusion mechanisms is enhanced when we collide nuclei in the Ca region having large neutron asymmetries. In particular, we have seen a large probability to produce heavy residue in $^{40}\text{Ca}+^{48}\text{Ca}$ reaction (N/Z=1.2). On the contrary, for the N/Z symmetric reaction $^{40}\text{Ca}+^{40}\text{Ca}$ a large probability to observe binary-like mechanisms has been reported.

The competition between this two kind of mechanisms could be related to the interplay between Coulomb and Symmetry term in nuclear Equation of State; for this reason we were able to extract information about the density dependence of the symmetry potential by comparing mass related observables with CoMD-II calculations [6].

In order to investigate deeper this kind of effect, we performed the key reaction $^{48}\text{Ca}+^{48}\text{Ca}$ at 25 MeV/nucleon. This system has N/Z value of the entrance channel equal to 1.4, the highest value obtainable with stable beams and

target populating entrance channels near to A=100. The data analysis, involving energy calibrations, ΔE -E identification, fast-slow analysis and time of flight identification has been performed in very short time (about 8 months), due also to improvements of the software dedicated to identification procedures [7].

We want to underline the very good working condition of the experimental device during the data acquisition; just as an example, we reported in Figure 1 a ΔE -E matrix, allowing mass identification up to Z=13.

In the following sections we will show some preliminary data belonging to complete events detected by the Chimera telescopes.

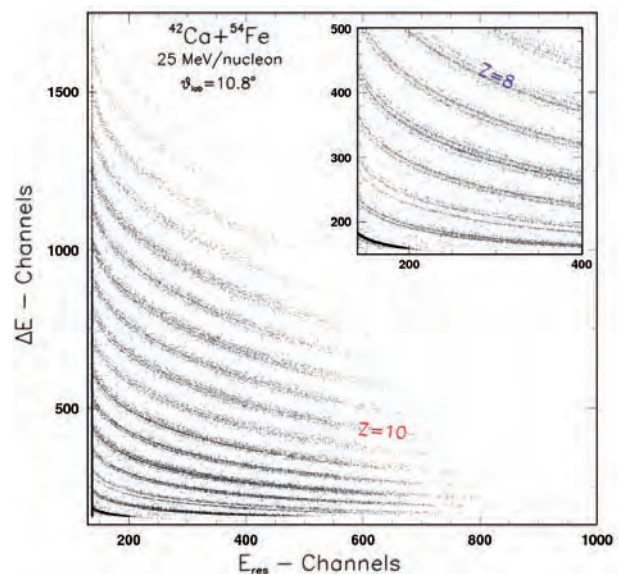


Figure 1: ΔE -E matrix obtained during the $^{42}\text{Ca}+^{54}\text{Fe}$ shift, for the telescope number 230. The inset shows a zoomed plot of ΔE -E correlation for the lightest isotopes.

INCLUSIVE RESULTS

Analogously to the previous analysis performed in Refs. [4,5], we selected almost complete events by means of constraint on the total mass or charge detected in each event by the Chimera array. In particular, we studied only those events where we detect at least the 80% of the total charge in the entrance channel (i.e. $Z_{\text{tot}} \geq 32$). Pile-up events are discarded by analyzing only events having $Z_{\text{tot}} \leq 40$.

The first relevant physical observable that we have obtained from the analysis of complete events is the multiplicity of charged particles (m_{cp}), shown in Figure 2. The global behaviour of this m_{cp} distribution is similar to those obtained in the reaction $^{40}\text{Ca}+^{48}\text{Ca}$, as described elsewhere [4].

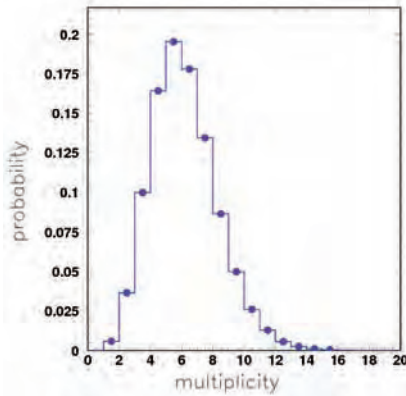


Figure 2: Charged particle multiplicity distribution obtained selecting complete events in $^{48}\text{Ca}+^{48}\text{Ca}$ reaction.

The good resolving power of Chimera telescopes allows to extract elemental distributions of light particles emitted in inclusive events. In particular, Figure 3 shows the relative yields of Lithium and Beryllium isotopes emitted at forward angles ($\theta = 8.5^\circ$). It is interesting to observe that n-rich isotopes as ^9Li and ^{10}Li are emitted more abundantly compared to the n-poor isotopes ^6Li and ^7Be .

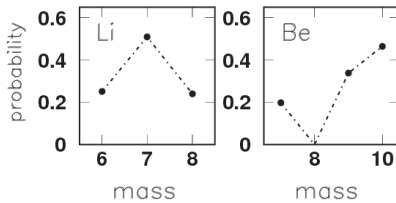


Figure 3: Relative yields of emission of Lithium and Beryllium isotopes in $^{48}\text{Ca}+^{48}\text{Ca}$ reaction at polar angle $\theta = 8.5^\circ$, as obtained by ΔE -E identification technique.

Taking inspiration from previous analysis conducted on $^{40}\text{Ca}+^{40,48}\text{Ca}$ reactions about the subject of isospin transport [8], we focused our attention to the emission of ^7Li and ^7Be isobars. In this respect, we show in Figure 4 kinetic energy spectra of ^7Li nuclei emitted at various polar angles, going from 5.8° up to 66° . The spectral shape is continuously varying as a function of the polar

angle. The good statistics collected during the experimental shifts will allow detailed studies of the spectral shape by means of multi-component moving sources analysis.

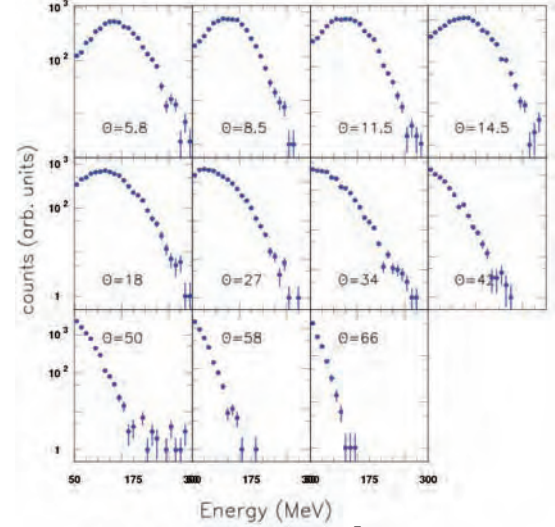


Figure 4: kinetic energy spectra of ^7Li isotopes emitted in inclusive events of $^{48}\text{Ca}+^{48}\text{Ca}$ reaction, at different polar angles ($\theta = 5.8, 8.5, 11.5, 14.5, 18, 27, 34, 42, 50, 58, 66^\circ$).

MASS AND VELOCITY DISTRIBUTIONS IN INCOMPLETE FUSION EVENTS

As previously seen with the *limiting* experiment ($^{40}\text{Ca}+^{40,48}\text{Ca}$, ^{46}Ti reactions at 25 MeV/nucleon), the competition between heavy residue production and binary-like mechanisms (that dominates semi-central events of reactions at 20-30 MeV/nucleon bombarding energies, for systems having total mass $A \sim 100$) can give useful information about the role played by Coulomb and Symmetry term in the Equation of State of nuclear matter [3-6]. We have now the possibility to extend the previous results to the very n-rich system $^{48}\text{Ca}+^{48}\text{Ca}$.

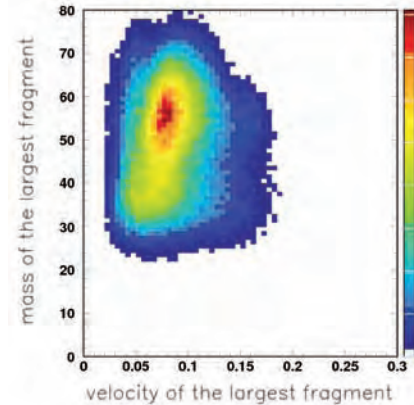


Figure 5: mass-velocity correlation for the largest fragment emitted in incomplete fusion events, selected according to the constraint established in Refs. [4,5]. The centre of mass velocity is $v_{\text{cm}} = 0.115 c$, the beam velocity is $v_{\text{beam}} = 0.23 c$.

First of all, we selected incomplete fusion events [4,5] by looking at semi-central events ($m_{cp} \geq 5$) where the second or third largest fragment emitted was a projectile remnant (having velocity larger than $0.13c$). Under these constraints, that optimize selection of incomplete fusion mechanisms, we plot in Figure 5 the correlation between mass and velocity of the largest nucleus emitted in each event of reaction.

The bump around mass 55 and velocity $0.08c$ (near to the centre of mass velocity) indicates an abundant production of heavy residue compared to binary-like emission (region of mass 40).

Similar arguments can be drawn by looking at the correlation between the masses of the two largest fragments emitted in incomplete fusion events, as shown in Figure 6.

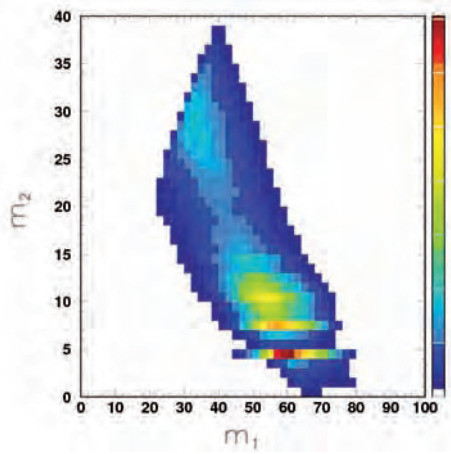


Figure 6: correlation of the masses of the two largest fragments (m_1 , m_2) emitted in incomplete fusion events of the reaction $^{48}\text{Ca}+^{48}\text{Ca}$ at 25 MeV/nucleon.

The $\{m_1, m_2\}$ correlation shows a bimodal behaviour that is typical of light systems below the limiting temperature [9,10]. The bump around masses $\{m_1 \approx 30, m_2 \approx 30\}$ is clearly due to binary-like mechanisms, while the strong populated bump around masses $\{m_1 \approx 55, m_2 \approx 10\}$ can be associated with heavy residue production in incomplete fusion events.

Figure 7 shows the mass spectrum for the three largest fragment (m_1 , m_2 , m_3) emitted in ICF event of reaction. The m_1 distribution is composed by two Gaussian-like contributions; the first one, having the highest probability, is peaked around $A=55$ and is associated to the heavy residue production; the second one is due to binary mechanisms and peaks around $A=35$.

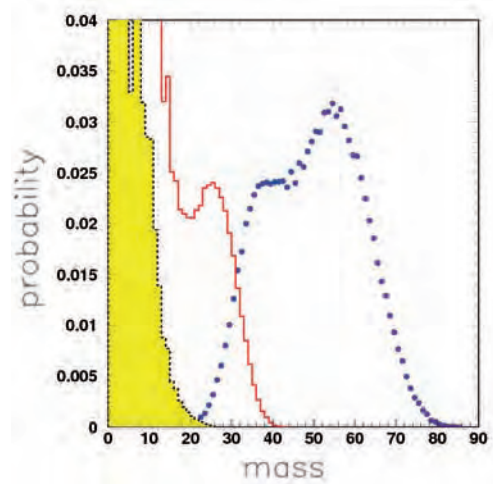


Figure 7: mass distribution of the three largest fragments emitted in the analyzed event of reactions. Blue dots: mass of the largest fragment (m_1). Red solid histogram: mass of the second largest fragment (m_2). Filled area-dashed histogram: mass of the third largest fragment (m_3).

COMPARISONS WITH PREVIOUS EXPERIMENTAL FINDINGS

It is interesting to compare the obtained preliminary mass and velocity distribution with the results obtained with the *limiting* experiment. For example, in Figure 8 we plot the mass-velocity distributions for the largest fragment emitted in the *limiting* and *isospin-I* experiments. Obviously we have used the same criteria for event selection, as described in the previous section.

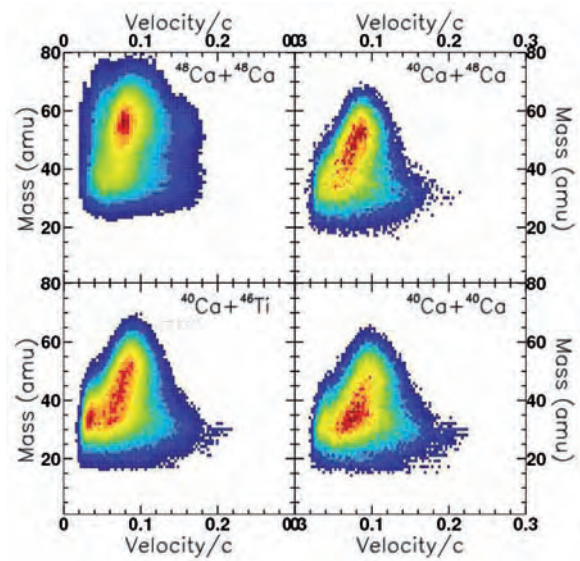


Figure 8: mass-velocity correlations for the largest fragment emitted in incomplete fusion events of reactions $^{48}\text{Ca}+^{48}\text{Ca}$ ($N/Z=1.4$), $^{40}\text{Ca}+^{48}\text{Ca}$ ($N/Z=1.2$), $^{40}\text{Ca}+^{46}\text{Ti}$ ($N/Z=1.05$) and $^{40}\text{Ca}+^{40}\text{Ca}$ ($N/Z=1.0$).

Confirming the conclusions drawn in our recent papers [4,5], the balance between production of heavy residues and binary-like mechanisms is strongly regulated by the N/Z degree of freedom. In particular, nuclear reactions characterized by high N/Z values in the entrance channels shows a larger probability of producing heavy residues by means of incomplete fusion.

Following the suggestion of Ref [4], this effect can be better seen by looking at mass distributions of the largest fragment emitted in the selected incomplete fusion events, by putting a gate on velocity in order to exclude target-like or projectile-like contaminations ($0.04 < v/c < 0.15$).

Figure 9 shows mass distributions obtained for the four systems analyzed in the *limiting* and *isospin-I* experiments. We underline that our data refer to a very wide range in N/Z spanned by the studied systems (going from $N/Z=1$ for $^{40}\text{Ca}+^{40}\text{Ca}$ reaction of the *limiting* experiment up to $N/Z=1.4$ for $^{48}\text{Ca}+^{48}\text{Ca}$ reaction of the *isospin-I* experiment).

From Figure 9 we can clearly see how the N/Z values of the entrance channels influence the interplay between the production of heavy residue and binary-like mechanisms; by increasing the N/Z the Gaussian component associated to heavy residue production is enhanced, while the binary-like mechanisms are suppressed.

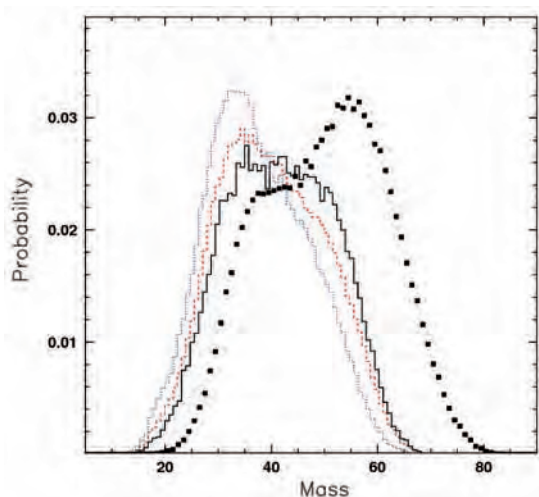


Figure 9: mass distribution for the largest fragment emitted in incomplete fusion events for the reactions: $^{48}\text{Ca}+^{48}\text{Ca}$ ($N/Z=1.4$, squared point histogram), $^{40}\text{Ca}+^{48}\text{Ca}$ ($N/Z=1.2$, black solid line histogram), $^{40}\text{Ca}+^{46}\text{Ti}$ ($N/Z=1.05$, red dashed histogram) and $^{40}\text{Ca}+^{40}\text{Ca}$ ($N/Z=1.0$, blue dotted histogram). A gate on the largest fragment velocity has been imposed ($0.04 < v/c < 0.15$) following the prescriptions of Ref. [4].

CONCLUSIONS AND PERSPECTIVES

In this report we discussed very recent preliminary data obtained by studying the reaction $^{48}\text{Ca}+^{48}\text{Ca}$ at 25 MeV/nucleon. We used the 4π Chimera array as detection device. Inclusive data belonging to well reconstructed events have been shown; in particular multiplicity of charged particles, relative yields of Lithium and Beryllium isotopes and ^7Li spectra have been discussed.

Due to the performances of the detector, we selected semi-central incomplete fusion phenomena. For this class of events, we performed mass and velocity distributions, in order to learn about the interplay between heavy residue production and binary-like mechanisms. The comparison of these preliminary data with previous distributions obtained by means of the *limiting* experiment seems to confirm the strong role played by the N/Z degree of freedom on the fate of hot nuclei formed by means of incomplete fusion mechanisms at bombarding energies near to the multi-fragmentation threshold.

Experimental results obtained with the neutron rich system $^{48}\text{Ca}+^{48}\text{Ca}$ will be compared, as soon as possible, with results obtained for $^{42}\text{Ca}+^{54}\text{Fe}$ reaction. This system has the same mass of the studied reaction but quite different N/Z ratio.

In parallel with analysis of experimental data, we started calculations with CoMD-II model; for the *limiting* data, a comparison of experimental distributions with CoMD-II calculations has allowed the extraction of information about the stiffness of the symmetry potential at near saturation densities.

We acknowledge gratefully Dr. D. Rifuggiato and co-workers for delivering ^{48}Ca beams with very good timing properties. We thanks also Mr. C. Marchetta and Mr. E. Costa for providing ^{48}Ca targets of excellent quality.

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MIRROR NUCLEI EMISSION AND ISOSPIN TRANSPORT PHENOMENA IN NUCLEAR REACTIONS AT 25 MeV/NUCLEON

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Abstract

Isospin effects are studied in reactions induced by ^{40}Ca projectiles at 25 MeV/nucleon on ^{40}Ca , ^{48}Ca and ^{46}Ti targets. The N/Z of projectile-like, target-like and mid-velocity sources are probed by measuring isobaric ($^7\text{Li}/^7\text{Be}$) yield ratios. The presence of isospin transport phenomena is observed.

INTRODUCTION

Nuclear reactions at intermediate energies (20-50 MeV/nucleon) offer a unique opportunity to explore the equation of state of infinite nuclear matter [1-3]. An interesting physical case is constituted by nuclear collisions where the projectile and target nuclei have similar masses but noticeably different N/Z values. In an used picture, the interacting nuclei are seen as being constituted of a mixture of two different types of fluids (neutrons and protons), and their exchange can be studied by means of transport physics (isospin transport) [2-4].

Isospin transport phenomena have two different facets, commonly called isospin diffusion and isospin drift. Isospin diffusion is related to the differences in concentration of neutrons and protons in the interacting projectile and target nuclei. If the interaction time between projectile and target is long enough the nucleon exchange process leads to a uniform distribution of the N/Z asymmetry throughout the di-nuclear system.

The second facet of isospin transport phenomena is represented by isospin drift. Dynamical calculations suggest in fact that the strong compression-expansion mechanism occurring in the overlap region during the first phase of the collision may lead to a neutron

migration from the spectators to the low density neck regions, inducing a neutron enrichment of light fragments emitted at mid-velocity [5].

Experimentally, the N/Z values of the quasi-projectile (QP), quasi-target (QT) and MV sources can be probed by measuring isotopic distributions of produced fragments. These approaches are based on the assumption that isotopic and isobaric ratios reflect the initial neutron/proton composition (N/Z) of their emitting sources [6-8]. The use of these yield ratio observables allows one to infer the N/Z of primary emitting sources with reduced contaminations from secondary decays [9].

EXPERIMENTAL APPARATUS

The experiment was performed at the INFN-LNS Super Conducting Cyclotron facility in Catania (Italy). A beam of ^{40}Ca at 25 MeV/nucleon impinged on self-supporting isotopically enriched targets of ^{40}Ca (1.24 mg/cm²), ^{48}Ca (2.87 mg/cm²) and ^{46}Ti (1.06 mg/cm²). Emitted fragments were detected by the CHIMERA 4π array. It is constituted by 1192 Si-CsI(Tl) telescopes. Details about the array are described in Refs. [10-11].

We analyzed only events where the total detected charge was between 80% and 100% of the total charge. Quasi-elastic reactions were removed during the experiment by the chosen electronics trigger condition, requiring the detection of at least 3 charged particles with $Z > 1$.

MIRROR ISOBAR NUCLEI EMISSION

Figure 1 shows ^7Li and ^7Be kinetic energy spectra measured at polar angles $\theta=11.5^\circ, 14.5^\circ, 18^\circ, 22^\circ, 27^\circ, 34^\circ, 42^\circ, 50^\circ, 58^\circ, 66^\circ$ in the laboratory frame for the

three studied reactions. We performed our data analysis looking at inclusive events, taking into account that, for geometrical reasons, the bulk of events belonging to such a class is widely dominated by semi-peripheral collisions.

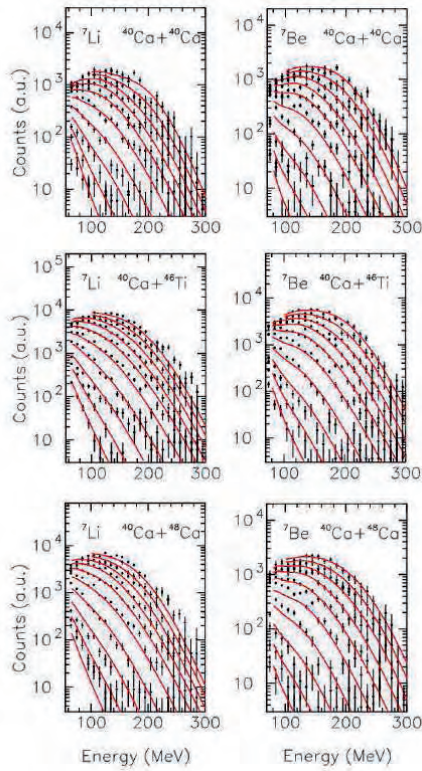


Figure 1: Inclusive energy spectra for ${}^7\text{Li}$ and ${}^7\text{Be}$ emitted in the ${}^{40}\text{Ca}+{}^{40,48}\text{Ca}$, ${}^{46}\text{Ti}$ reactions, at different values of polar angle in the laboratory frame (respectively 11.5° , 14.5° , 18° , 22° , 27° , 34° , 42° , 50° , 58° , 66°). The solid red line is the result of the three components moving sources fits, described in the text.

We studied these energy spectra by means of multi component moving source analysis. The data are well reproduced by assuming that they originate from the superposition of three Maxwellian distributions. The solid red lines on Figure 1 show the results of the fitting procedure. The overall agreement with the measured energy spectra is satisfactory. The obtained fit parameters are in reasonable agreement with values reported in the literature for heavier reaction systems at slightly higher beam energy [12].

The velocities of the three moving sources determined by the fit with experimental data are about $v=0.06c$, $0.13c$ and $0.19c$, with uncertainties of $\approx 15\%$. The value obtained by the fit for the velocity associated to the QT emission is higher compared to that expected for perfect binary kinematics ($\approx 0.04c$). This effect is probably due to identification thresholds that do not allow a good reconstruction of the QT emission. The slope parameters ($T \approx 5$ MeV) for projectile-like and target-like sources are

comparable, simply reflecting the overall mass symmetry in the entrance channels of the three studied reactions.

${}^7\text{Li}$ and ${}^7\text{Be}$ production cross sections, $\sigma_i({}^7\text{Li})$ and $\sigma_i({}^7\text{Be})$, for the i^{th} source can be deduced from the best-fit analysis shown on Figure 1. Then, we calculate the isobaric ratios, $r_7 = \sigma_i({}^7\text{Li})/\sigma_i({}^7\text{Be})$, for each reaction and each source. In Figure 2 we show the r_7 values obtained with the fit procedure, for all the reactions and QP and MV emitting sources

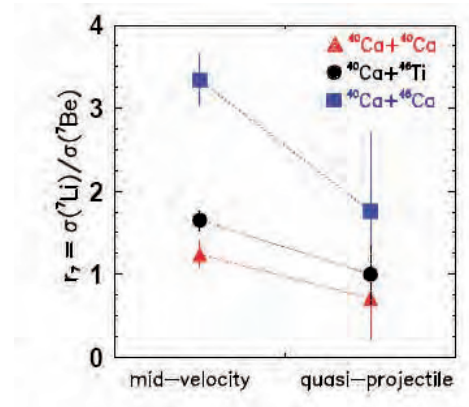


Figure 2: Isobaric yield ratios ${}^7\text{Li}/{}^7\text{Be}$ for the three different reactions, as obtained from the moving source analysis. QP and MV emissions are indicated.

In Figure 2 we see that mid-velocity emission is characterized by r_7 values higher than the QP emission ones, also for the isospin symmetric reaction ${}^{40}\text{Ca}+{}^{40}\text{Ca}$. Therefore it seems that neutron rich isobars are emitted with more probability in the mid-velocity region of the phase-space.

If we look at the isobaric emission for the QP sources, we observe that even if the projectile used was the same for the three reactions (${}^{40}\text{Ca}$), r_7 values increase by increasing the N/Z content of the *target* nucleus. This effect testifies that, before the re-separation, isospin diffusion takes place between the projectile and target interacting nuclei. In particular, the greater is the difference in N/Z between projectile and target nuclei, and the greater is the net neutron diffusion along the whole di-nuclear system formed during the nuclear reaction.

CONCLUSIONS AND PERSPECTIVES

Isospin diffusion and drift phenomena involving nuclear reactions at 25 MeV/nucleon have been investigated looking at the emission of light isobars (${}^7\text{Li}$ and ${}^7\text{Be}$) by means of the CHIMERA multi-detector. A neutron enrichment of the nuclear clusters emitted at mid-velocity is observed, in agreement with the isospin drift theory for nuclear reactions at intermediate energies. Isospin diffusion phenomena are observed, especially for the reaction ${}^{40}\text{Ca}+{}^{48}\text{Ca}$, having strong difference of N/Z between projectile and target.



In the future it could be interesting to perform the same collisions with more statistics; in this way we will be able to disentangle the impact parameter dependence of isospin diffusion and charge equilibration related phenomena.

Moreover with the recent tuning of the pulse shape technique for CHIMERA silicon detectors it will be possible to lower considerably the isotopic identification thresholds (up to $\approx 3\text{MeV/nucleon}$ for Li and Be isotopes) [13]; this improvement will allow a better reconstruction of the quasi-target emission.

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DYNAMIC PRODUCTION AND STATISTICAL EMISSION OF INTERMEDIATE MASS FRAGMENTS FROM CA+SN COLLISIONS AT 45 AMEV

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Abstract

A study of intermediate-mass fragment production was performed using asymmetric heavy-ion reactions of $^{40}\text{Ca} + ^{112}\text{Sn}$ and $^{48}\text{Ca} + ^{112,124}\text{Sn}$ at 45 AMeV. Projectile-like fragments were measured in coincidence with intermediate-mass fragments and light-charged particles in a semi-exclusive study with the 4π multi-detector array CHIMERA. A significant fraction of the measured events show production characteristics appearing consistent with a dynamical formation mechanism, while the remainder is consistent with statistical decay of an excited PLF. This assignment is made by comparison of the data with a standard sequential decay model.

not yet reached thermal (shape) equilibrium, then the observed fragments may maintain a memory of the reaction entrance channel and thus be characterized as dependent on the collision dynamics.

Numerous authors have investigated the possibility of a dynamic IMF origin [5-12]. The data in these studies are often interpreted with the aid of reaction models which predict the dynamic evolution of the reacting nuclei [8,9]. In the present work, the opposite approach is considered. The data are compared to a standard two-step reaction model. This comparison suggests that the neglect of the dynamic evolution in these degrees of freedom is not consistent with the data.

INTRODUCTION

At medium bombarding energies (25-100 AMeV) collisions of heavy ions have been found to produce an unexpectedly high yield of fragments with atomic numbers ($3 \leq Z \leq 10$) termed intermediate-mass fragments (IMFs) [1]. Models used to predict these yields often rely on the assumption that the primary nuclei produced in heavy-ion collisions at medium bombarding energies are internally equilibrated and decay with little regard for their history of formation; rather the probability of decay is dependent, in a statistical fashion on the total available phase space [2-4]. However, if the IMFs are produced in a prompt (non-equilibrium) dis-assembly (break-up) of either the interacting projectile-target system or the separated (distinct) primary reaction products which have

EXPERIMENTAL DETAILS

Heavy-ion beams of $^{40,48}\text{Ca}$ (45 AMeV) were provided by the superconducting K800 cyclotron of the Laboratori Nazionali del Sud (LNS), Catania. Beam currents of 10^8 pps for ^{40}Ca and 10^7 pps for ^{48}Ca were bunched with a repetition rate of 120 ns. The projectiles impinged on self supporting targets of $^{112,124}\text{Sn}$ with thicknesses 627 and 689 $\mu\text{g}/\text{cm}^2$, respectively. The targets were placed in the CHIMERA multi-detector array in the CICLOPE scattering chamber at the LNS. The specifics of the array, the signal processing electronics and acquisition system are described in detail elsewhere [13].

The aim of the experiment was to perform an exclusive study of IMF production in an intermediate-energy heavy-ion collision. Therefore, the CHIMERA array used a

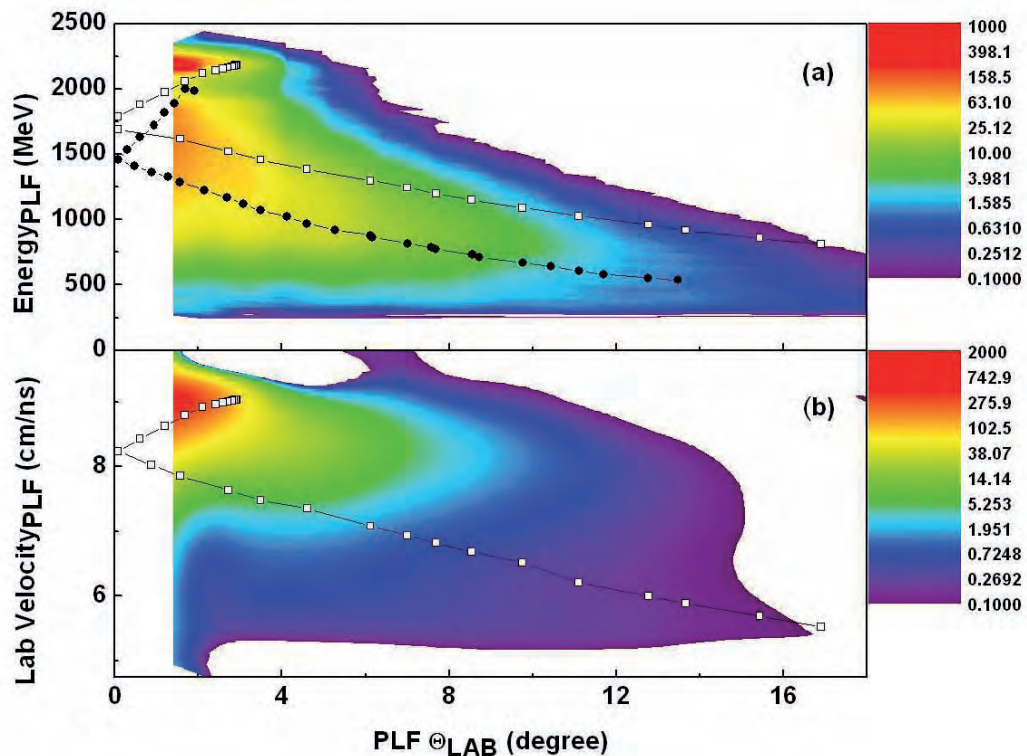


Figure 1: (a) Logarithmic contour diagram of the double-differential cross section (b / Sr MeV) of PLFs ($Z \geq 10$) plotted versus their laboratory kinetic energy and laboratory scattering angle. The data were measured in the reaction $^{48}\text{Ca} + ^{124}\text{Sn}$. Symbols connected by curves represent the mean predictions of simulations. Open squares represent the results of only the first step of the two-step reaction model. Solid circles represent the predictions of the two-step decay model and include the experimental filter. (b) Logarithmic contour of the double-differential cross section (b ns / Sr cm) of PLF laboratory velocity and scattering angle.

minimum-bias trigger condition requiring the detection of at least two charged particles. Specifically, the acquisition electronics were triggered when two silicon detectors measured a charged particle within a coincidence time of 250ns. Of note in the analysis is the possibility that reaction/elastic-scattering event(s) from a subsequent beam burst are accepted by the wide ($> 3\mu\text{s}$) common QDC gate. These pile-up events are the main source of background but easily recognized as such. The cross sections reported here were measured with respect to a monitor detector placed forward of the grazing angle. They are subject to uncertainty of at least 20%.

TWO-STEP REACTION MODEL

The data are compared to semi-classical simulations approximating the adiabatic response of projectile and target along their classical trajectory (CLAT) [14] in peripheral collisions. In the model the kinetic energy of relative motion is transferred to internal (thermal) degrees of freedom through the mechanism of nucleon exchange

(NEM)[15-17]. The simulations predict distributions for the properties of the primary reaction products, e.g., distributions in kinetic and excitation energies, elemental and isotopic identities, as well as their mean asymptotic scattering angles and intrinsic angular momenta. The simulations were performed for an angular momentum (l) window covering the most peripheral 65% of the reaction cross section. The results of the dynamical simulations for the average properties of the primary reaction products were used as input for the statistical decay code GEMINI++[2]. In the model predictions presented here, the spins of the two primary reaction products were both set to $J=0$.

The results of the two-step reaction model described above were adjusted to account for the inefficiency and geometric acceptance of the CHIMERA multi-detector and the response of electronics. A software filter of the CHIMERA multi-detector was used to predict its response to a reaction in the target foil.

RESULTS

The data are first investigated with respect to the general reaction characteristics. The double-differential cross section of PLFs, here defined as fragments with ($Z \geq 10$), is plotted in Fig. 1(a) with respect to their laboratory kinetic energy and scattering angle (Θ_{LAB}). The solid symbols represent the mean predictions of the two-step reaction model. The data appear consistent with a mid-peripheral damped reaction trajectory. The quantitative agreement in Fig. 1(a) is not observed in Fig. 1(b) where the double-differential cross section is now plotted with respect to the laboratory velocity and scattering angle. This suggests that the two-step model over-predicts the amount of dissipation and likewise the internal excitation of the two primary reaction products.

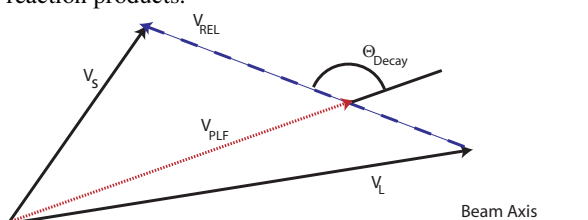


Figure 2: Definition of the decay angle (Θ_{decay}) from the two-body event components.

The kinematical region accessible to the break-up of the primary projectile-like fragment was selected by placing a software cut on the forward angular region ($\Theta_{\text{LAB}} < 18^\circ$). The velocity of the primary PLF was reconstructed from events in which two massive fragments ($Z \geq 3$) were detected within this forward angular region. The masses of the two fragments were inferred from their measured atomic number and the "attractor line" describing the most likely endpoint in an evaporation chain[18]. The inferred masses are combined with the measured asymptotic velocity to determine the momenta of the two massive fragments. The reconstruction of the primary PLF velocity assumes that the inferred momenta are consistent with those of the nascent break-up fragments. The decay angle (Θ_{decay}) is defined in Fig. 2 as the angle between the measured relative velocity of the two fragments and the reconstructed primary PLF velocity. The angular distribution with respect to this angle is shown in Fig. 3. The data (solid symbols) are compared to predictions of the two-step model (solid histogram). With respect to these predictions, the data show both an increased two-body fragment ($Z \geq 3$) production rate and an asymmetry in the angular distribution. The former could result from the model's restriction to peripheral collisions, while the latter discrepancy is difficult to reconcile with sequential emission of IMFs from fully accelerated PLFs.

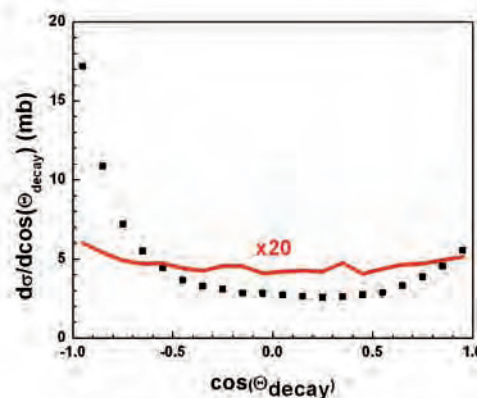


Figure 3: Measured differential cross section (mb) for two-body events versus the cosine of the decay angle for reactions of $^{48}\text{Ca} + ^{124}\text{Sn}$ (solid symbols). The cross section predicted by the two-step reaction model is represented by the solid line. The model predictions have been increased by a factor of twenty to allow a better comparison of the shape of the angular distributions.

DISCUSSION

As demonstrated in the previous section, the data disagree with the two-step model featuring IMF production from sequential decay of hot primary reaction products. The discrepancy is manifest in two important ways. The first involves the interplay between the magnitude of energy dissipation and the evaporation yield. Two explanations for the observed discrepancy come to mind. If the first step of the reaction model were modified to better represent the observed dissipation (Fig. 1(b)), it would likely also require a modification of GEMINI++ to increase the evaporation probability and maintain the quantitative agreement visible in Fig. 1(a). Another possibility is that the violent interaction between projectile and target leads to the break-up of either or both primary reaction products before they reach asymptotic velocity and shape equilibrium. The latter explanation is clearly favored after comparison with the data and model predictions presented in Fig. 3 because sequential decay of a single source should lead to a symmetric angular distribution in its rest frame[19]. This is the second significant discrepancy. Therefore, the data are consistent with a process which occurs more rapidly than the time-scale associated with the rotation of the primary projectile-like fragment.

CONCLUSIONS

Comparison of the data measured in reactions of Ca + Sn at 45 AMeV with a two-step reaction model suggests that a significant fraction of the IMFs resulting from the break-up of the primary projectile-like fragment could result from a process other than sequential decay.



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CHARGING OF INSULATORS UNDER MULTIPLY-CHARGED ION IMPACT PROBED BY SLOWING DOWN OF FAST ELECTRONS

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Abstract

Charging dynamics of insulating foil targets (Mylar, polypropylene PP) irradiated with swift ion beams (C, O, Ag, Xe at 40, 23, 40 and 30 A MeV, respectively) was studied via the slowing down of fast binary encounter electrons. Fast electron spectra were measured by the time-of-flight method with the ARGOS multidetector. The charge build-up leads to target material dependent potentials of the order of 6 kV for Mylar and 2 kV for PP. Surprisingly, sandwich targets (Mylar covered with a thin Au layer on both surfaces) show the same behavior as the insulating targets, whereas a single Au layer strongly suppresses the charging phenomenon. The accumulated number of projectiles needed for charging up (exponential function time constant) is found to be inversely proportional to the projectile's electronic energy loss.

INTRODUCTION

Since more than 10 years, the ARGOS multidetector has been used with great success in the domain of atomic collision physics, since it allows studying the emission of fast electrons [1]. The studies focussed on binary encounter-, convoy- and Auger electrons from the in-flight deexcitation of electron-carrying projectiles [2,3]. Recently, after a pilot experiment at GANIL [3,4], dedicated experiments on charging and discharging phenomena were conducted at the CS (Superconductor Cyclotron) of LNS in 2007 and 2009 with insulating foils such as Mylar [5] and polypropylene (PP). Here, we report on the dependence of charging up of insulators, measured via slowing down of binary encounter electrons, on the target material and on the amount of energy deposited in the target by the fast projectiles. Charging-up under multiply charged ion irradiation are at present under investigation in connection with guiding phenomena in nano-capillaries with the possible application of nano-focused beams [6]. Generally,

charging renders many methods of materials analysis based on particle beam impact difficult to use in the case of insulators. Examples include methods using ion scattering, secondary particle emission (ions, electrons) and even fluorescence (PIXE).

EXPERIMENT

The experimental details including modified scintillation detectors of the ARGOS multidetector were reported in [5]. Briefly, beams of swift C^{4+} (40 A MeV), O^{4+} (23 A MeV), O^{5+} (23 A MeV), Ag^{30+} (40 A MeV) and Xe^{31+} (30 A MeV) delivered by the superconducting cyclotron CS were used to irradiate insulating polymer foil targets (Mylar, polypropylene PP) in the large scattering chamber CICLOPE and in the CHIMERA chamber of LNS. Also, Au-My-Au sandwich targets (Mylar of $\approx 100 \mu g/cm^2$ covered with a thin Au layer of $\approx 10 \mu g/cm^2$ on both surfaces), as well as Au-My foils (Mylar covered with a thin Au layer on one surface) were used. Figure 1 shows a sketch of the experimental set-up. In CICLOPE, 26 detectors were placed at a distance of 400 cm in a plane at observation angles between $\theta=1^\circ$ and $\theta=24^\circ$. Another 10 detectors covered the backward angles between $\theta=30^\circ$ and $\theta=155^\circ$. The Chimera chamber experimental set-up is described in [5].

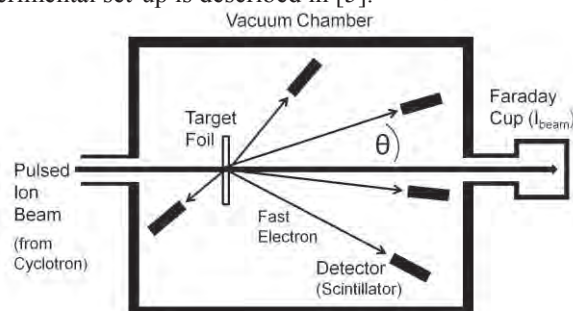


Figure 1: experimental set-up (schematically).

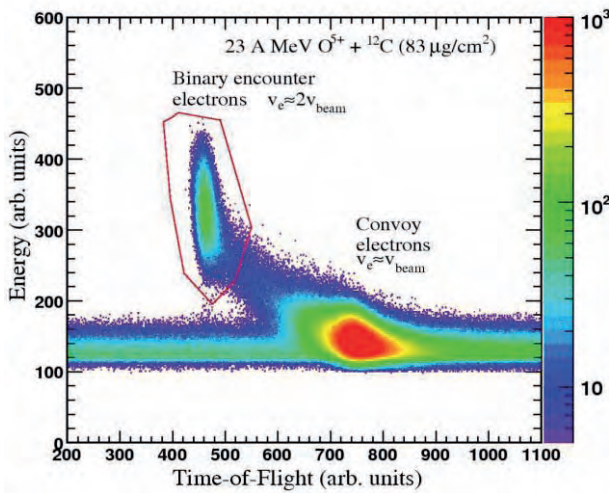


Figure 2: energy of the emitted electrons (23 A MeV oxygen on C foil) as a function of their time-of-flight.

The beam current, which was measured in a Faraday Cup, was varied over orders of magnitude from about 3 pA to 300 pA depending on the beams. The electron energy can be determined by the output of the scintillation detector which corresponds to the deposited energy. The electron velocity can be measured from their time of flight, with respect to the pulsed beam of CS. The time resolution, given mainly by the burst width of the pulsed beam, was about 1 ns. Figure 2 shows a plot of the energy deposited in a carbon target (which is a conductor) as a function of the time-of-flight. Figure 3 shows the corresponding electron velocity distribution; here, also a spectrum obtained with a Mylar target (insulator) is included). One observes two prominent structures: 1) binary encounter electrons (BEE) at about twice the projectile velocity from a knock-on ionization of target electrons by the projectile nucleus (in other words, a Rutherford scattering of a target electron in the projectile's Coulomb field), and 2) convoy electrons (CE) from capture- or loss to low lying projectile continuum states (with kinetic energies close to zero in the projectile frame thus travelling with the same velocity as the projectile). For projectiles below, say, 30 MeV/u, after charging-up induced slowing-down, CE fall below the detection threshold of the scintillators, as can be seen from figure 3. Therefore, and since some features observed with CE were already discussed in [4,5], in the following we concentrate on BEE as probe of charging dynamics.

CHARGING UP DYNAMICS

As the insulator is irradiated, a charging-up occurs either on the surface or in the bulk. The electrical field slows down the fast electrons. This can be seen from Fig. 4, which shows the mean time-of-flight (TOF) of BEE as a function of irradiation time t . One clearly observes how the TOF increases with t : the electrons are slowed down. The t -dependence follows an exponential increase with a certain time constant, which depends on the ion beam current and the target material.

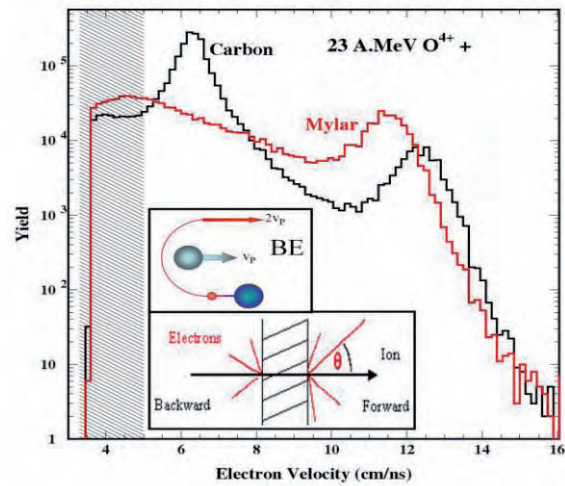


Figure 3: velocity the emitted electrons for a C-Foil (conductor) and a Mylar target (insulator).

In contrast, with a conducting C foil, the TOF remains constant. Figure 5 shows the corresponding shift of the BEE energy as function of irradiation time. The energy shift is equal to the induced slowing-down potential. A striking result here is that the charging dynamics observed with a Au-Mylar-Au sandwich target closely resembles that of the pure insulator Mylar. A single Au layer on the electron (and ion beam) exit surface strongly reduces the peak shift and the slowing down. This may indicate that in contrast to what was believed until now, the charging-up is a bulk- and not a pure surface phenomenon.

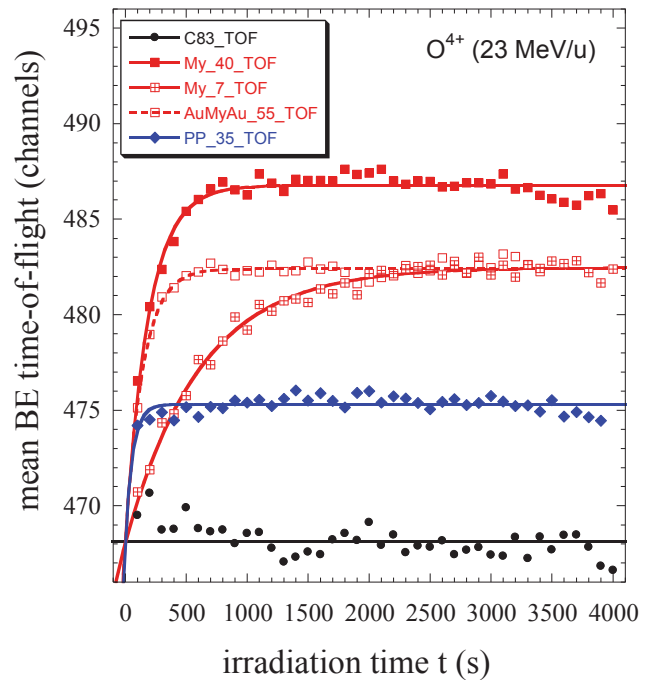


Figure 4: mean time-of-flight (TOF) of BEE as a function of irradiation time t ; for 1) Mylar targets (open squares) at two different ion beam currents of 7 pA (full curve) and 40 pA (dashed curve); 2) a polypropylene (PP) target (diamonds); and 3) a C-Foil (conductor).

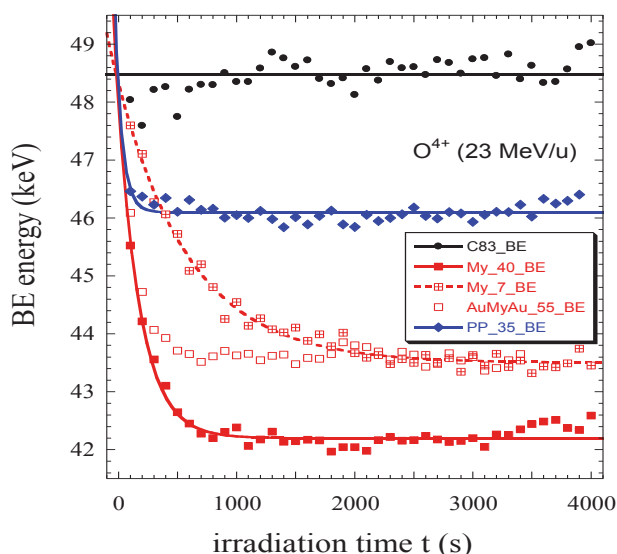


Figure 5: BEE energy shift (corresponding to the data of figure 4) as a function of irradiation time t ; for 1) Mylar targets (open squares) at two different ion beam currents of 7 pA (full curve) and 40 pA (dashed curve); 2) a polypropylene (PP) target (diamonds); and 3) a C-Foil (conductor, no shift).

PROJECTILE DEPENDENCE

Swift heavy ions loose energy in matter mainly due to inelastic collisions with target electrons (electronic energy loss dE/dx). A basic question is how observed effects (defect creation, particle emission, structural changes etc.) evolve with the amount of deposited energy. Therefore, we performed experiments with several swift ions covering a large range of dE/dx values.

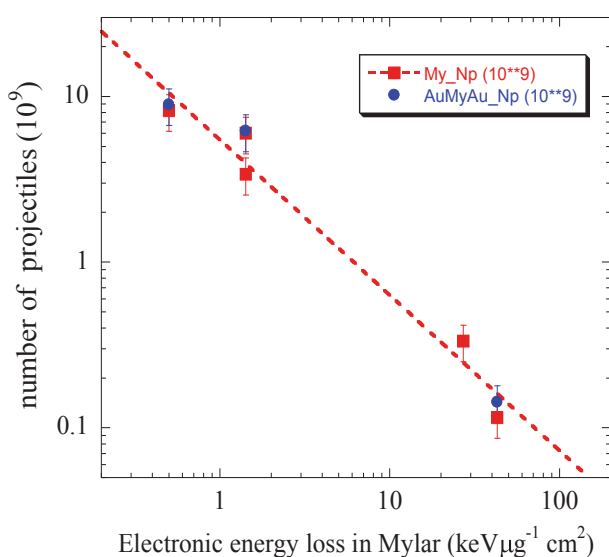


Figure 6: number N of accumulated projectiles needed to charge up the as a function of the energy loss dE/dx for Mylar and Au-My-Au sandwich targets. The dashed line is a power law fit to the Mylar data

A simple observable for the charging dynamics is the number N of accumulated projectiles associated to the charging time constant of the exponential functions of figures 4 and 5. This number N of accumulated projectiles needed to charge up the target is shown in figure 6 as a function of the energy loss dE/dx . A simple power law is observed:

$$N \sim (dE/dx)^{-(0.94 \pm 0.08)}$$

Thus, in a good approximation, N is inversely proportional to dE/dx . Finally, figure 7 shows us that the BEE energy shift ΔE does not depend on dE/dx , but on the target material (PP: $\Delta E \approx 2.8$ kV, Mylar: $\Delta E \approx 6$ kV).

The puzzling result that the sandwich targets behave in the same way as pure insulators remains, nevertheless, unexplained. This may be an indication that the charging-up does not only occur and remain located at the very surface, but is in fact a bulk phenomenon.

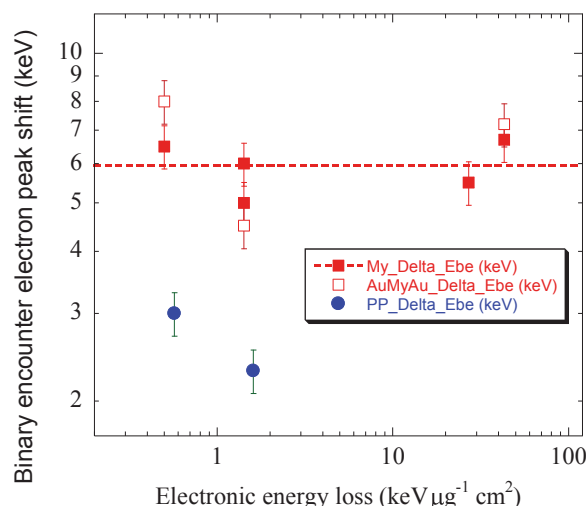


Figure 7: BEE energy shift ΔE as a function of the energy loss dE/dx for Mylar, Au-My-Au sandwich targets, and polypropylene.

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ASY-EOS EXPERIMENT AT GSI: CONSTRAINING THE SYMMETRY ENERGY WITH NEUTRON AND PROTON ELLIPTIC FLOWS

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Abstract

The determination of the equation of state of asymmetric nuclear matter is fundamental for both nuclear physics and astrophysics. The ASY-EOS experiment at GSI is going to measure elliptic flows (squeeze-out) of neutrons, protons and light complex particles in reactions of isospin asymmetric systems at pre-relativistic energies, in order to provide quantitative information on the density dependence of symmetry energy at value bigger than the saturation one.

INTRODUCTION

A key question in nuclear physics is the knowledge of the equation of state (EOS) for asymmetric nuclear matter away from saturation density [1]. The EOS can be divided into a symmetric matter contribution, that is independent of the isospin asymmetry and an isospin term, also known as the Symmetry Energy (SE), that is proportional to the square of the asymmetry $I=(N-Z)/N+Z$ [2], where N and Z are neutrons and protons numbers respectively; besides its importance in nuclear physics (structure of exotic nuclei and dynamics of nuclear reactions) several aspects of neutron star physics and supernovae collapse rely on the density dependence of the SE. Recent measurements of the Giant Monopole, Giant Dipole and

Pygmy Dipole resonances [3], isospin diffusion and neutron/proton emission [4], isospin dependence of incomplete fusion reactions [5] and fragment isotopic ratios [6] have provided initial constraints on the density dependence of the SE at sub-saturation densities. It results that the best description of experimental data is obtained with a SE $S(u)=C_{s,kin}(u)^{2/3}+C_{s,pot}(u)^\gamma$ with γ in the range 0.6-1.1 [4] ($u=\rho/\rho_0$ is the reduced nuclear density). In the near future, refinement of these measurements with both stable and rare isotope beams will provide further stringent constraints at sub-saturation densities. In contrast, very few experimental constraints exist on the SE at supra-saturation densities ($u>1$). This is the domain with the greatest theoretical uncertainties and the largest impact on the understanding of neutron stars [2]. The theoretical models propose several experimental observable as sensitive probes to the behaviour of the SE at supra-saturation densities, such as neutron and proton direct and elliptic flows [7,8,9], neutron/proton ratios [4,7,10], π/π^+ ratios and flows [7,8], K^+/K^0 [11] and Σ/Σ^+ [12] ratios. It is likely that consistent measurements of all of these will be necessary to provide definitive constraints on the SE. From the experimental point of view, recently, the single ratio π/π^+ measured in Au+Au collisions from 400 to 1500 AMeV using the FOPI detector at GSI [13]

has been compared to the hadronic transport model IBUU04 [14]. The comparison suggests a super-soft behaviour (SE reaches its maximum at a density between ρ_0 and $2\rho_0$ and then decreases at higher densities) not consistent with the results obtained at sub-saturation densities. Recently, the same set of FOPI data has been analysed in the framework of the Improved Isospin dependent Quantum Molecular Dynamics (ImIQMD) [15]; preliminary results favour a stiff SE of the potential term proportional to u^γ with $\gamma = 2$, just the opposite of [14] results. It follows that for the π/π^+ ratio further works are needed to establish the effectiveness in probing the SE, clarifying which density phase is explored using pions signal, and how in medium absorption and reemission can distort such signal. This suggests that more works, possibly including additional observable and focusing on the consistency among them, will be needed in order to arrive at firm conclusions regarding the SE at high density.

NEUTRON AND PROTON ELLIPTIC FLOWS

One of the most interesting observable predicted to be sensitive to the strength of the symmetry term at supra-saturation density is the neutron and proton (or hydrogen) elliptic flows [16]. As an example, Fig. 1 shows UrQMD [12,17] calculations for the rapidity dependence of the elliptic flow parameter v_2 for neutrons, protons and hydrogen isotopes in the $^{197}\text{Au}+^{197}\text{Au}$ reaction at 400 AMeV, integrated over an impact parameter range of $5.5 < b < 7.5$ fm. The calculations are made using both stiff ($\gamma=1.5$) and soft ($\gamma=0.5$) potential symmetry energies [12,17]. A characteristic inversion of the relative strengths of the elliptic flow for neutrons and protons/hydrogen isotopes between the stiff and soft parameterization is clearly seen.

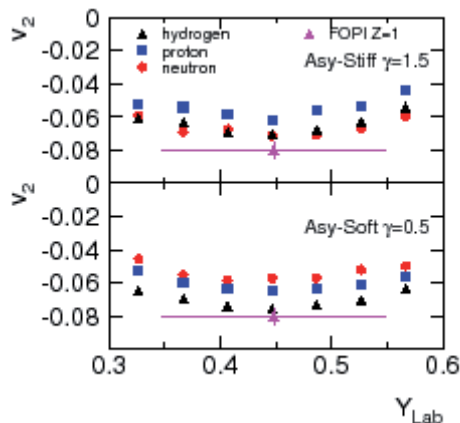


Figure 1: Elliptic-flow parameters v_2 for neutrons, protons and hydrogen isotopes for midperipheral ($5.5 < b < 7.5$ fm) collisions of $^{197}\text{Au}+^{197}\text{Au}$ at 400 AMeV as a function of the rapidity y (in lab frame) as predicted UrQMD model, for stiff and soft SE; the star with horizontal bar is the elliptic flow of hydrogens at midrapidity as experimental measured with FOPI [18].

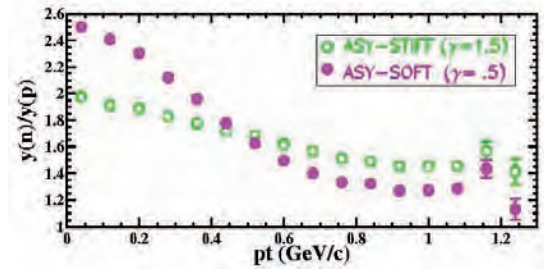


Figure 2: UrQMD predictions for the neutron/proton yield ratio, as a function of transverse momentum pt in Au+Au central ($b < 3$ fm) collisions, for stiff and soft SE.

Squeezed-out nucleons in the direction perpendicular to the reaction plane escape mostly from the high density region formed during an earlier stage of the reaction, and they are thus not much affected by the spectator nuclei. The difference of the elliptic flow of neutrons and protons can then be correlated by the amount of repulsion/attraction experienced by the particles in the high density region. For comparison, also the hydrogen ($Z=1$) elliptic flow parameter v_2 at mid-rapidity, and over the same impact parameter range, measured in the Au+Au system with FOPI [19] is shown. Neutron and proton directed and elliptic flows were measured in Au + Au collisions from 400 to 800 AMeV using the LAND neutron detector and the FOPI Phase 1 forward wall [18]; we are currently analyzing the data to extract the neutron and proton directed and elliptic flows; a preliminary value of $\gamma = 0.94 \pm 0.21$ [16] is obtained, in agreement with the finding at sub-saturation densities. However the poor experimental statistics of these data set severe limits to this conclusion.

ASY-EOS EXPERIMENT AT GSI

Comparison between experimental data and theoretical predictions has driven us to propose a new experiment at GSI (exp. S394 [20]) devoted to a new measure of neutron and proton elliptic flows in a neutron rich system, such as Au+Au at 400 AMeV (getting an higher statistics of data required for an accurate comparison between experimental data and theoretical predictions), and to enlarge available experimental data investigating SE effects, by comparing neutron rich and neutron poor systems $^{96}\text{Ru}+^{96}\text{Ru}$ and $^{96}\text{Zr}+^{96}\text{Zr}$ at 400 AMeV. Simultaneous measurements of neutron and proton elliptic flows, neutron-proton ratios, light fragment flows and ratios will be made. This will allow comparisons of the SE extracted using several different nucleon-based observables. As an example, fig. 2 shows UrQMD predictions for the neutron/proton yield ratio, as a function of transverse momentum pt in Au+Au central ($b < 3$ fm) collisions, for the two different parameterizations of symmetry energy.

The experiment will use LAND calorimeter for neutron and charged particle detection; LAND will be positioned around polar angle $\theta_{\text{lab}} \sim 45^\circ$ covering the midrapidity kinematic region for suitably high transverse momenta pt .

Kinetic energies are obtained from the measured time of flight. The determination of impact parameter and the orientation of the reaction plane will be achieved measuring the atomic number Z and the azimuthal direction of fragments emitted) at small angles, by using a detection system with high effective granularity at forward angles consisting of several CsI(Tl) rings of the CHIMERA multidetector[21] and the ALADIN Time-Of-Flight wall. In addition, the flow of light fragments will be measured with the Krakow telescopes array positioned opposite from LAND at angles $\theta_{lab} > 30^\circ$. Since the experiment will be mounted in air, an additional hodoscope (MICROBALL), positioned in a backward angle, will be used to distinguish interactions of the incoming beam with air.

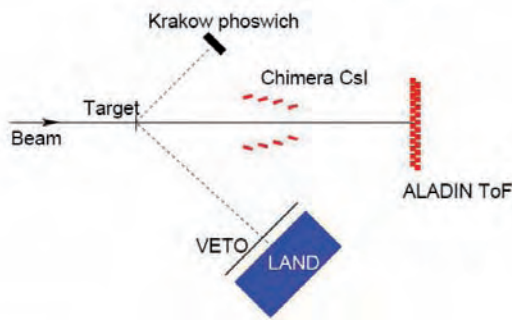


Figure 3: Schematic view of experimental setup.

RESULTS OF THE TEST EXPERIMENT

In September 2009 we have tested performances of CHIMERA Si-CsI(Tl) telescopes at SIS energy using a U+Pb reactions at 350 A.MeV in Cave C at GSI. The telescopes have been operated in air, shielded from light by means of an aluminium box, with an entrance window made by a black plastic foil and a thin aluminium layer, as schematically shown in the following figure.

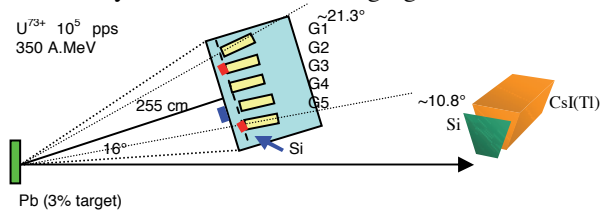


Figure 4: Schematic view of experimental setup.

In the test we have evaluated time resolution and charge discrimination capabilities; as an example, in Fig. 5 are reported Fast vs Slow and ΔE -E scatter plot as obtained using analogical acquisition in Si-CsI(Tl) telescope; charge discrimination up to $Z=3$ is obtained in Fast vs Slow plot; isotopic identification up to $Z=2$ is obtained using the ΔE -E technique.

When the energies of $Z=1$ and $Z=2$ ions exceed those corresponding to their ranges in 12 cm CsI(Tl) crystals they appear as punch-through lines as it is indicated on Fast vs Slow scatter plot of Fig. 5; as their energies increase, the corresponding lines display a back-bending behavior.

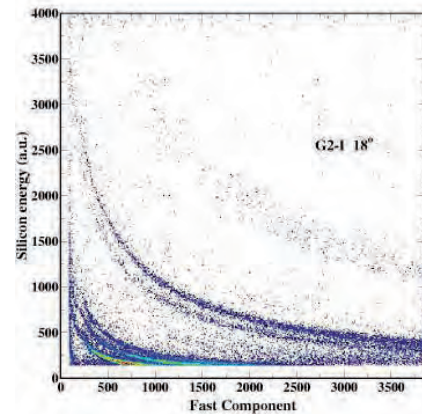


Figure 5: ΔE -E and Fast vs Slow scatter plots as obtained in CHIMERA telescopes for the $^{238}\text{U}+\text{Pb}$ at 350 A.MeV using analogical acquisition.

Moreover, in parallel to the standard analogical acquisition, we have also used Digital Pulse Shape Acquisition (DPSA) and Digital Signal Processing (DSP) [22] techniques to the pulses collected from Si and CsI(Tl). The analysis, based on pulse characterization algorithms, has been of fundamental importance in understanding detector response and performances; obtained results can be found in [23].

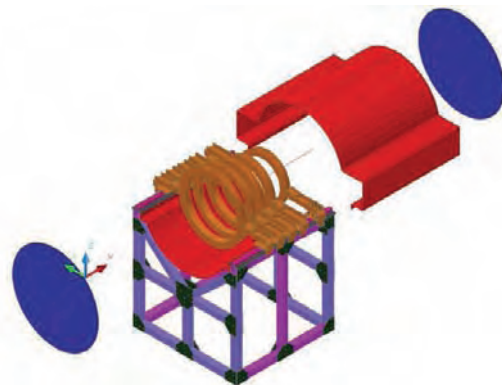


Figure 6: Schematic view of mechanical structure that will be used in the ASYEOS experiment at GSI.

Thus, the test proved capabilities of CHIMERA telescopes to work at GSI energies and in conditions completely different from the ones used at LNS.

In view of the main experiment we are building a new mechanical structure for CHIMERA's wheels, schematically shown in figure 6.

CONCLUSIONS

The ASY-EOS experiment at GSI will be an unique opportunity in order to investigate density dependence of the Symmetry Energy at supra-saturation density. The experiment aims to collect the high statistics of data required for a meaningful comparison to the predictions of theoretical models. Simultaneous measurements of neutron-proton yield ratios, light fragment flows and ratios will be performed. This will allow to compare the SE extracted using several different nucleon-based observables.

The on beam test at GSI in September 2009 proved capabilities of CHIMERA telescopes to work at GSI energies and in conditions completely different from the ones used at LNS. Moreover, The DPSA results [23] demonstrate that it is possible to perform an efficient discrimination of Light Charged Particles in charge and mass also using Energy and Rise-Time computation, instead of the Fast and Slow components computation.

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HIERARCHY EFFECTS IN LIGHT FRAGMENTS AT MID-VELOCITY EMISSION

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Abstract

Intermediate mass fragments (IMF) emitted with multiplicity $M_{\text{IMF}} \geq 3$ at mid-velocity in semi-central reactions induced by ^{124}Sn projectile (35 A.MeV) on ^{64}Ni target have been studied. The results show a clear correlation between the fragment sizes and the corresponding transverse velocities. We interpret this correlation as signature of hierarchy effects in nuclear multifragmentation. A correlation with the fragments isospin contents is also found. Qualitative comparisons with SMF calculations suggests that these correlations are good observables for the symmetry term of the EOS at sub-saturation density.

INTRODUCTION

In the study of the reactions $^{124}\text{Sn}+^{64}\text{Ni}$ and $^{112}\text{Sn}+^{58}\text{Ni}$ with the Chimera detector, the time-scale for fragments formation has been recently investigated [1], in order to disentangle between prompt dynamical and sequential statistical emission. In semi-peripheral reactions prompt emitted light particles ($Z \leq 9$) are mainly originated by the fragmentation of the neck in a short time within 40-80 fm/c after the re-separation of the two main partners PLF (projectile-like) and

TLF (target-like) of the reaction. Dynamical IMFs emission is characterized by larger N/Z ratio and angular anisotropies respect to particles produced in sequential statistical emission [2]. Fast emission of heavier fragments ($Z \geq 10$) happens generally at later stage of the neck fragmentation process. Recently [3] has been shown that this last process can be interpreted in the framework of the so-called “dynamical fission” of a projectile-like fragment. The aim of this report is to study the transition between peripheral and central collisions in dissipative process. When going towards more central collisions, progressively a multifragmentation decay with higher IMFs multiplicity takes place with respect to the peripheral collision where the coexistence of prompt emission and sequential decay was observed [4]. In order to better explore this transition region we have analysed semi-central collisions in the $^{124}\text{Sn} + ^{64}\text{Ni}$ reaction looking at events in which together with a PLF and TLF residue fragments a further multiplicity $M \geq 3$ of light IMFs are present.

RESULTS

For the class of events in which the total charge Z_{TOT} and the total parallel momentum are respectively greater than 70% of the total charge and projectile momentum of the colliding nuclei we have considered three different bins of the total charged particle multiplicity M , going from semi-peripheral reactions ($M \leq 6$, $b/b_{\text{max}} > 0.7$), to the most dissipative collisions ($M > 12$, $b/b_{\text{max}} < 0.1$). For the intermediate total multiplicity bin $7 \leq M \leq 12$ we have analysed the class of events in which after selection of PLF and TLF residue fragments, a multiplicity $M \geq 3$ of IMFs are present (thus, for the selected events total IMF multiplicity is $M_{\text{IMF}} \geq 5$). For these fragments, in the c.m. system, the parallel and the transverse velocity components respect to the separation axis $V_{\text{PLF}} - V_{\text{TLF}}$ vector have been evaluated. The parallel and the transverse velocity of the IMFs were evaluated event by event and, thus ordered according to their size. Fig 1 shows the parallel a) and transverse velocities b) distributions. The result shows a clear tendency to some “hierarchy” effect in the transverse velocity distribution: the greatest

transverse velocity is reached by the lightest fragments. In contrast, a such effect is not evidenced for the parallel velocity distribution.

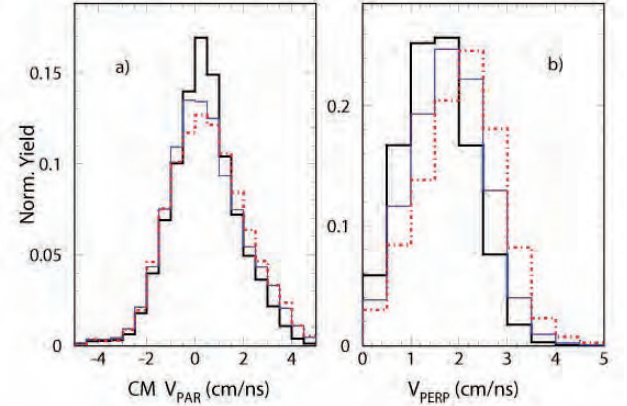


Fig. 1: a) Parallel velocity distributions for events with 3 IMFs sorted as a function of fragment charge. Black thick line (biggest charge), thin blue line (intermediate), red dot-dashed (smallest charge); b) the same for the IMFs transverse velocity.

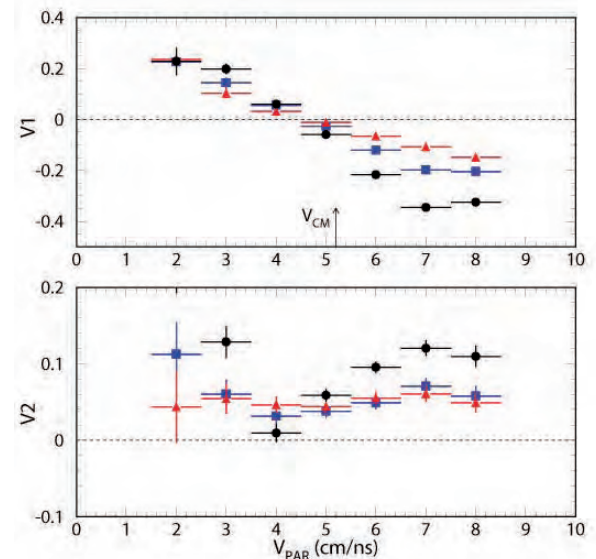


Fig. 2: Transverse flow V_1 a) and elliptic flow V_2 b) as a function of the parallel velocity for fragments ordered in a rank based on charge: biggest fragment (circle), intermediate fragment (squares), smallest fragments (triangles).

In order to get more insight into this “hierarchy” effect we have constructed, for the selected events, the IMFs azimuthal angular distributions respect to the reaction plane defined as the normal vector to the plane defined by $\mathbf{n} = (\mathbf{V}_S \times \mathbf{V}_{\text{CM}})$ where $\mathbf{V}_S = \mathbf{V}_{\text{PLF}} - \mathbf{V}_{\text{TLF}}$ and $\mathbf{V}_{\text{CM}}$ is the

beam velocity direction in the center of mass reference system.

Flow observables are obtained from the Fourier expansion of the azimuthal distributions:

$$dN/d\phi = 1 + V_1 \cos(\phi) + 2V_2 \cos(2\phi)$$

where V_1 and V_2 are the transverse and elliptic flow respectively. V_1 gives indication of the azimuthal anisotropy in the reaction plane. Fig 2a) shows V_1 as a function of laboratory parallel velocity respectively for the biggest fragment (black circle), the intermediate one (blue square) and the smallest one (red triangle). The largest slopes for V_1 are reached by the biggest fragment indicating the tendency for emission in the reaction plane in an aligned configuration with PLF or TLF. The slope becomes less steeper following the rank in the charge hierarchy. This behaviour is confirmed in fig. 2b) where V_2 is shown for the same particles as a function of laboratory parallel velocity. A positive V_2 values indicates a preferential emission in the reaction plane. We note also a tendency for the lightest particles in the rank to have a flat distribution, probably indicating the competition of different reaction mechanisms in their formation.

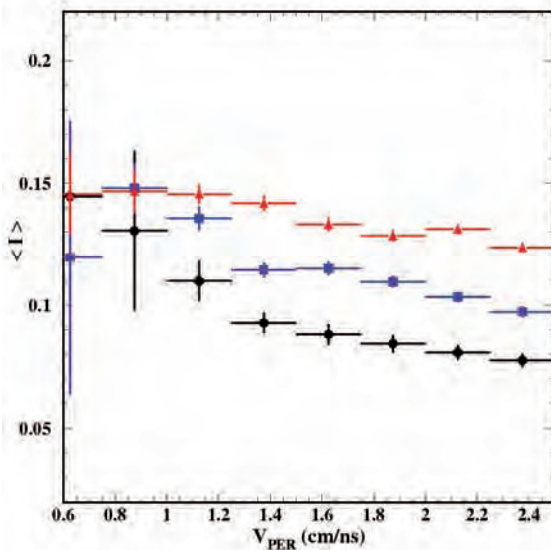


Fig. 3: Isospin asymmetry $(N-Z)/A$ as a function of the transverse velocity. Biggest fragment (circle), intermediate fragment (squares), smallest fragments (triangles).

Fig. 3 shows the isospin asymmetry distribution as a function of the transverse velocity for the biggest fragment (black circle), the intermediate one (blue square) and the smallest one (red triangle) in the charge rank. We note the tendency for the isospin asymmetry to lowering at increasing of the transverse velocity. For all transverse velocities the lighter fragments have always the largest asymmetry.

It is interesting to compare the experimental data with the results of SMF [5] simulations, performed for neutron rich and neutron poor Sn+Sn symmetric reactions at 50 A.MeV [6]. In these simulations a similar hierarchy effect in transverse velocity is shown and interpreted as an interplay between neck fragmentation and the onset of the multifragmentation. The calculations show a sensitivity to the choice of different symmetry term behaviour in the nuclear EOS. For example, in the calculation for a soft symmetry term of the EOS no difference in the isospin content of the fragments is found as a function of the rank hierarchy. In contrast, a stiffer symmetry term EOS produces a marked difference: the asymmetry increases following the rank in hierarchy.

The preliminary experimental results shown here indicate a first evidence of a correlation between the fragments isospin contents and the transverse velocity suggesting a valuable input for future analysis for studying the symmetry term of the EOS.

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DISSIPATIVE BINARY COLLISION AND ISOSPIN FORCES

Angular distributions measurement of the $^{28}\text{Si}+^{64}\text{Ni}$, $^{27}\text{Al}+^{58}\text{Ni}$ dissipative collisions at $E_{\text{lab}}=136$ and 130 MeV

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Abstract

A comparison between the angular distributions of dissipative binary collisions induced on the systems $^{28}\text{Si}+^{64}\text{Ni}$, $^{27}\text{Al}+^{58}\text{Ni}$ at the Tandem energy has been performed. The results suggest that the charge/mass asymmetry of the two Di-Nuclear intermediate Systems, which are produced under rather similar conditions, can affect the reaction time. According to COMD-II calculations, this last variable, in turn can sensitively depend on different parameterizations of the Iso-vectorial interaction.

INTRODUCTION

In the past, dissipative binary collisions between heavy ions were studied extensively [1] from few MeV up to some tens of MeV per nucleon. The reaction mechanisms were investigated mainly through mass, charge and kinetic energy distributions of the projectile-like (PLF) and target-like (TLF) fragments. Most of the features displayed by one of the main processes were explained through the so called “deep inelastic collisions” essentially produced by the decay of an excited, fast rotating, and strongly deformed intermediate system: the Double Nuclear System (DNS). Since 1988 [2,3] the study of the average angular distribution and excitation functions of deep inelastic processes allowed to estimate the characteristic times of the processes and to explain the visibility of the fluctuations in the excitation function, as the results of channel-channel correlations produced through the excitation of overlapped, low density, “door-way states” of the DNS. The results of these studies were interpreted through the POMLM[3] model (essentially a Random Matrix approach [4] for Heavy Ion Collisions), which allows to characterize the DNS through information concerning both its dynamical evolution and its structure. The excitation of these intermediate structures corresponds to the excitation of states located at about 10-20 MeV above the Yrast line and can represent the natural evolution of the well known molecular states excited in collisions between light ions (see for example [5]). These states are usually identified as isolated

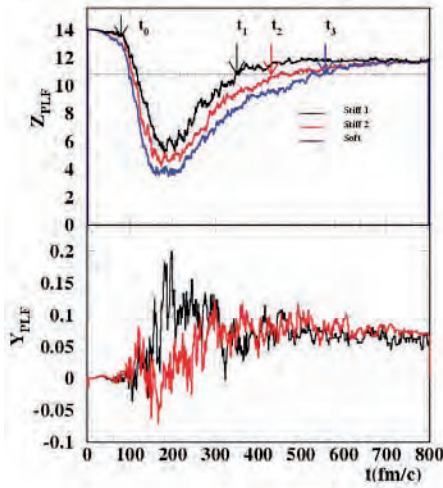
resonances at excitation energy near the ground state molecular band. In particular, an intriguing subject related to the Heavy Ion Collisions, still investigated also at Fermi energy, concerns the equilibration of the charge/mass ratio between the PLF and TLF[6]. The interest on this phenomenon is associated to the link of this process with the forces related to the asymmetry term V_{asym} of the equation of state.

At low energies, as the one reachable by means of the Tandem accelerator, the main fragments are produced with low excitation energy and with a density near the saturation value. Therefore the physics ruling this process has to be almost exclusively determined by the dynamics and the structure of the DNS (clusterization – surface effects etc.).

In particular in Fig.1 we present, as an illustrative example, results of semi-classical CoMD-II [7] calculations (Constrained Molecular Dynamics) performed by using different options for the symmetry interaction V_{asym} . From this calculations it is possible to clearly appreciate how the Isospin forces affect the characteristic times of the process leading to the charge/mass equilibration. The same calculations suggest also that this dependence is linked with non-stationary structures formed during the DNS life time.

According to the studies described in [3] and based on the scattering theory of heavy collisions, these differences in the PLF formation time (or DNS life time) could be appreciable already by looking at the average angular distributions (see [3] and Fig.10b therein). In fact, the ratio between the cross section related to the Near-Side (N.S.) (usually it reaches the maximum value around the Grazing angle) and the Far-Side (F.S.) contributions (for this system it could become the dominant one around 50°-60°) can change by a factor 3 up to a factor 8 for variation of the DNS life time of the order of 30% and 50%.

Figure 1 :-CoMD-II calculations for the $^{28}\text{Si}+^{64}\text{Ni}$ system at $E_{\text{lab}}=140$ MeV; Upper- panel, Charge of the PLF fragments as function of time for different asymmetry potential. Bottom panel, -related charge/mass asymmetry parameter $Y_{\text{PLF}}=(N_{\text{PLF}}-Z_{\text{PLF}})/A_{\text{PLF}}$ as function of time.



THE EXPERIMENT

With the aim to start a preliminary investigation on these subjects, the angular distributions of deep inelastic processes for the collisions $^{28}\text{Si}+^{64}\text{Ni}$, $^{27}\text{Al}+^{58}\text{Ni}$ were studied at the SMP Tandem accelerator of the Laboratori Nazionali del Sud in Catania. The two systems are able to form similar excited intermediate system with a different Charge/Mass asymmetry. $^{27}\text{Al}^{9+}$ and $^{28}\text{Si}^{9+}$ beams were used impinging on ^{58}Ni and ^{64}Ni $300\mu\text{g}/\text{cm}^2$ thick target respectively. The beam energy was set to 130.6 MeV and 136 MeV for the two beams respectively.

To explore a wide angular range we used monolithic silicon detectors and ionization chambers to detect and identify in charge the produced fragments. In particular in the forward region between $\Theta_{\text{lab}}=8^\circ$ and $\Theta_{\text{lab}}=27^\circ$ we placed 6 units of monolithic silicon detectors originally belonging to the TRASMA apparatus. Each of these telescopes is a device having 5 independent ΔE strips ($3 \times 4 \text{ mm}^2$) implanted on a common residual energy stage. The first and second stage are about $1 \mu\text{m}$ and $500 \mu\text{m}$ thick respectively. Two such units mounted on a common ceramic package form a single detection module. The 3 modules were placed at a distance of 17 and 34 cm from the target on opposite side of the beam. The region at larger angles was covered by 2 telescopes consisting of a first stage transverse field ionization chamber followed by $1000 \mu\text{m}$ thick silicon position sensitive detector. The position sensitive detectors were placed at a distance of

19 cm from the target. Their spatial resolution was ± 0.5 mm.

RESULTS

In Fig.2 as an example, we show in the upper panel a ΔE -E bi-dimensional histogram corresponding to the monolithic telescope placed at $\Theta_{\text{lab}}=26^\circ$. In the bottom panel a Q-Value spectrum associated to the production of Z=13 and Z=12 element in the $^{28}\text{Si}(E_{\text{lab}}=136 \text{ MeV})+^{64}\text{Ni}$ collision is shown. The Q-Value is estimated starting from the measured project-like fragment (PLF) energy by taking into account two-body kinematical (TBK) relationships and assuming PLF masses equal to 27 and 24 for Aluminium and Magnesium isotopes respectively.

As an example in Fig.3 and Fig.4 we show a comparison between angular distributions obtained for the two investigated systems. The integrated yields take into account the Z=12 and Z=11 elemental production in the ^{27}Al induced reactions while for the ^{28}Si one the Z=13 and Z=12 production. Centre of mass (c.m.) angles have been estimated by using TBK relationships. The horizontal error bars represent the related uncertainty.

The angular distributions for the dissipative collisions are integrated on the indicated Q-Value bin.

Figure 2 :- Upper panel; ΔE -E scatter plot for a monolithic telescope placed at $\Theta_{\text{lab}}=26^\circ$ for the $^{28}\text{Si}+^{64}\text{Ni}$ collision. Bottom panel; For the same collision, Q_value spectrum obtained taking in to account the observed yield, at different angles for the Z=13 and Z=12 elemental production (see the text).

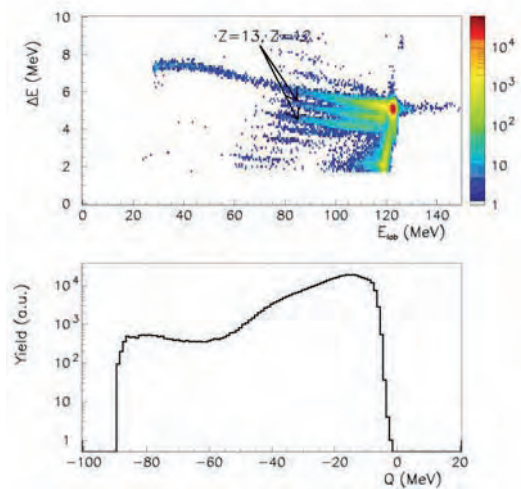


Figure 3 :- Angular distribution for the dissipative collisions induced by the two investigated systems. $Z=13$ and $Z=12$ elemental production are integrated for the $^{28}\text{Si}+^{64}\text{Ni}$ system. $Z=12$ and $Z=11$ yield are integrated for the system $^{27}\text{Al}+^{58}\text{Ni}$.

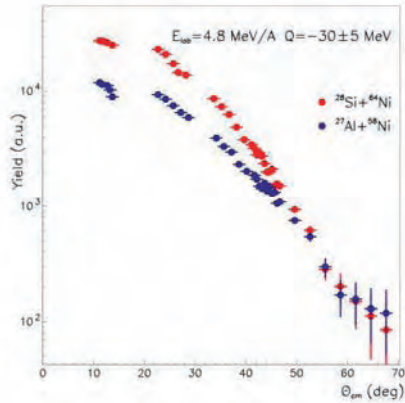
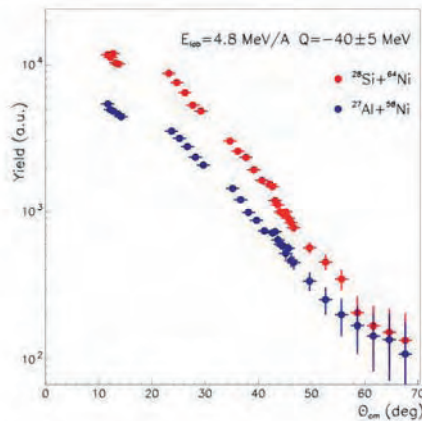


Figure 4 :- Same like Figure 3 but for a Q-value window from -45 to 35 MeV



REMARKS

As can be seen by looking at Figures 3 and 4, the analyzed angular distributions show a change of slope around 50° , 55° degree in c.m. reference frame.

Typically, this change of slope at large angles indicates a dominance of the Far-Side (F.S.) scattering with respect the N.S. one. This last contribution in fact dominates in the forward region. Moreover, the comparison between the two angular distributions show that the balance between the N.S. and F.S. scattering is larger for the most charge asymmetric system. According to what briefly discussed in the introductory section, this could suggest a fast transfer of 1 or 2 unit of charge from the PLF to the TLF in the case of the neutron reach target with respect to the case related to the almost symmetric ^{58}Ni targets. Clearly the results presented in this report have to be considered as preliminary ones

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PARTICLE IDENTIFICATION IN LARGE ACCEPTANCE MAGNETIC SPECTROMETERS WITHOUT TIME OF FLIGHT

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Abstract

A technique to identify the heavy ions produced in nuclear reactions, based on the use of a hybrid detector mounted in the focal plane of a magnetic spectrometer, is presented. In particular it is based on the measurement of the energy loss, the residual energy, the horizontal position and angle of the ions at the focus. Experimental results with the MAGNEX spectrometer show a remarkable resolution of about 1/100 in the mass parameter.

INTRODUCTION

The Particle Identification (PID) capability of a large acceptance magnetic spectrometer is a crucial feature for its successful application to modern nuclear physics [1-4]. A standard way to identify reaction products by a magnetic spectrometer is to measure the energy loss (ΔE) and the residual energy (E_r) by the focal plane detector and to additionally determine the Time of Flight (TOF) of the particle while moving along the spectrometer. This requires the generation of a Start signal for the TOF , that can be obtained exploiting the discrete beam time structure, if present, or can be produced by the use of an appropriate Start detector mounted close to the target. The latter could also be used to get position measurements useful for the application of trajectory reconstruction methods [5-10]. Nevertheless some limitations on the use of the spectrometer itself are directly determined by the presence of such a Start detector. As an example it is not possible to use it at very forward angles (including 0°) under beams more intense than $10^5 - 10^6$ pps, which represents a major drawback in several cases. In addition one should consider the degrading effect produced by the detector active materials and dead layers on the overall achieved energy and angular resolution, which could overcome the positive effects of the position measurement. Finally one should also consider questions as the limited detector efficiency, that is particularly important when dealing with low count-rate experiments, and the geometrical encumbrance of the device, that could limit the use of ancillary detectors.

Thus it is worthwhile to develop advanced PID techniques which avoid the use of the TOF measurement. A possibility is offered by the simultaneous measurement of the kinetic energy T and the magnetic rigidity $B\rho$ of the detected ions. These parameters are in fact connected by the general non relativistic relation

$$m^{0.5} q^{-1} = B\rho * T^{-0.5} \quad (1)$$

where m and q are the charge state and mass of the ion, while ρ is the radius of curvature of the ion trajectory inside a dispersive element (dipole) with field B . In practice the $B\rho$ measurement is directly connected to the horizontal position at the focal plane x_{foc} . The kinetic energy T is reconstructed by adding the energy loss measured by special ΔE detectors to the residual energy, typically measured by large plastic scintillators or ionization chambers. In this way the energy loss in the dead layers crossed by the ions along the track is ignored.

Nevertheless due to the poor energy resolution of the detectors typically used, the techniques based on the application of the eq.1 have been always limited to the identification of light particles, leaving that of the heavy ions to precise TOF determination. In a recent article [11] mass resolving powers as high as 1/160 have been achieved without TOF by use of the trajectory reconstruction algorithms. In this document a simplified version of such technique, is proven still useful to identify ions up to mass 100 avoiding TOF measurements and ray-reconstruction algorithms.

EXPERIMENTAL RESULTS

A beam of Li^{3+} at 52 MeV incident energy, delivered by the INFN-LNS Tandem Van de Graaff accelerator of Catania, was sent to a AlF_3 target 100 $\mu g/cm^2$ thick mounted on a 20 $\mu g/cm^2$ Al backing. The outgoing ejectiles, produced in the different reactions, were momentum analysed by the MAGNEX spectrometer [1-2] located at 12° central laboratory angle (actual spanned interval $7^\circ - 19^\circ$, solid angle 50 msr) and detected by the focal plane detector FPD [12-13]. The magnetic field was set in order to transport the 7Be ejectiles corresponding to the population of the ground

state of the ^{19}O in the $^{19}\text{F}(^7\text{Li}, ^7\text{Be}^{4+})^{19}\text{O}$ reaction, 8% above the central analyzed momentum, thus exploring the excited states of ^{19}O up to about 13 MeV excitation energy.

The FPD is a large ($\sim 1600 \times 255 \times 500 \text{ mm}^3$) gas-filled hybrid detector with a wall of 45 large area Silicon detectors ($50 \times 70 \times 0.5 \text{ mm}^3$) at the back. The detector measures the horizontal and vertical coordinates of each incident particle at four sequential planes crossed by the ion trajectory, thus determining the angles. It also measures the energy loss in the gas and the residual energy released in the silicon detectors wall. In the standard operation the signals of the silicon detectors give also the stop for the Time Of Flight (TOF) of the particles through the spectrometer, the start being provided by a specific detector, which is located in front of the target and is based on a micro-channel plate electron amplifier [14].

As shown in Fig.1 many different ejectiles are produced in the experimental conditions mentioned above. In Fig.1a ΔE_{corr} represents the energy loss corrected by the measured horizontal angle θ_f , thus accounting for the different path length of the ionization track within the gas as a function of the horizontal angle [15]. The effect of the vertical angle is negligible since this is always within $\pm 2^\circ$. From an inspection of the $\Delta E_{\text{corr}} - E_r$ two-dimensional histogram some of the detected ions can be easily identified, mainly due to the favorable matching between kinematics conditions and magnetic rigidity, while others can only be grouped in terms of the atomic number and electric charge.

In Fig.1b an example of the $\text{TOF} - E_r$ histograms is presented, after gating on the Boron isotopes with charge 5^+ in the $\Delta E_{\text{corr}} - E_r$ spectrum as shown in Fig.1a. A clear separation is achieved between ^{11}B and ^{10}B , even without correcting for the observed dependence on θ_f , but at the price of a reduction of the overall efficiency of about 30% in the full spectrometer acceptance.

In Fig.1c an example of the PID is shown in terms of the $x_{\text{foc}} - E_r$ two-dimensional spectrum gated on the $\Delta E_{\text{corr}} - E_r$ one. The performance of the technique in discriminating the Boron isotopes is evident, clearly showing the presence of $^{12}\text{B}^{5+}$ ions. Similar results are obtained for all the other detected ions. The observed cleaner identification compared to the TOF technique is mainly due to the fact that this latter has not been corrected for the different trajectory lengths of the detected ions. For a non isochronous device like MAGNEX, such a procedure requires a full trajectory reconstruction, since these are complex functions of the broadly varying scattering angle and momentum, other than of the motion of the ions along the non dispersive plane. A detailed discussion of such high order corrected technique for TOF is beyond the scope of this paper and will be presented elsewhere. To get an estimate of the achieved resolution in Fig.2 the selected data are projected into a one-dimensional spectrum of $\bar{E}_r$ obtained by rotating the $x_{\text{foc}} - E_r$ reference frame around the point ($x_{\text{foc}} = 0 \text{ cm}$; $E_r = 35 \text{ MeV}$) in order to

minimize the projection of the Boron loci over the horizontal axis. A resolution of about 1/100 in the mass of the Boron isotopes is measured. The same result is got for all the detected ions.

One can note that the high resolution determination of the $x_{\text{foc}} - E_r$ spectrum, as well that of the TOF , does not help in improving the resolution in the measurement of the atomic number Z . This latter remains mainly connected to the quality of the ΔE_{corr} measurement and, more precisely, to the resolution on the ΔE and the θ_f parameters. In the case of the MAGNEX spectrometer the resolution on the ΔE_{corr} parameter is limited to about 2%, corresponding to about 1/50 in Z , principally depending on the gas pressure and on the voltage applied to the multiplication wires. On the other hand, since these latter quantities do influence the electron drift velocity and the signal to noise ratio in the x_f measurement, the best set-up for PID purposes could not correspond to the best condition for the measurement of the ions positions and angles at the focal plane. Thus a compromise has to be found depending on the ions to be detected and the required resolution of the phase space parameters. When the emphasis is on the measurement of phase space quantities, such as in a recent experiment [16] where Oxygen ions were detected, the resolution on the ΔE_{corr} parameter is limited to about 3%, corresponding to about 1/30 in Z .

To summarize we developed a technique that allows for the identification of heavy ions in a dispersive magnetic spectrometer based on the sole use of high resolution detectors located in the region of the focal plane. The main requirement for the significant application of this is the good reconstruction of the ions kinetic energy, since the magnetic rigidity is normally measured with high resolution. The major achievement is the possibility to avoid the measurement of the TOF parameter, still getting enough resolution to unambiguously identify ions in most of the cases where a spectrometer is intended to be used. This greatly improves the flexibility of a spectrometer, especially when large solid angles are covered, since the problems connected with the use of a Start detector for the measurement of the TOF are overcome. In particular it becomes possible to measure at very forward angles (including zero degree). Moreover the degrading effects due to the Start detector active materials are avoided, thus improving, especially at low energies, the final achievable momentum resolution. In addition it becomes much easier to couple ancillary detectors to the spectrometer for coincidence measurements.

The technique discussed in this paper could be easily extended to other modern spectrometers with large acceptance as VAMOS or PRISMA [3-4].

To conclude we believe that new generation spectrometers could be designed since the very beginning in a way that could avoid the use of the TOF measurement, providing that a particular attention is paid in refining the methods presented in this paper.

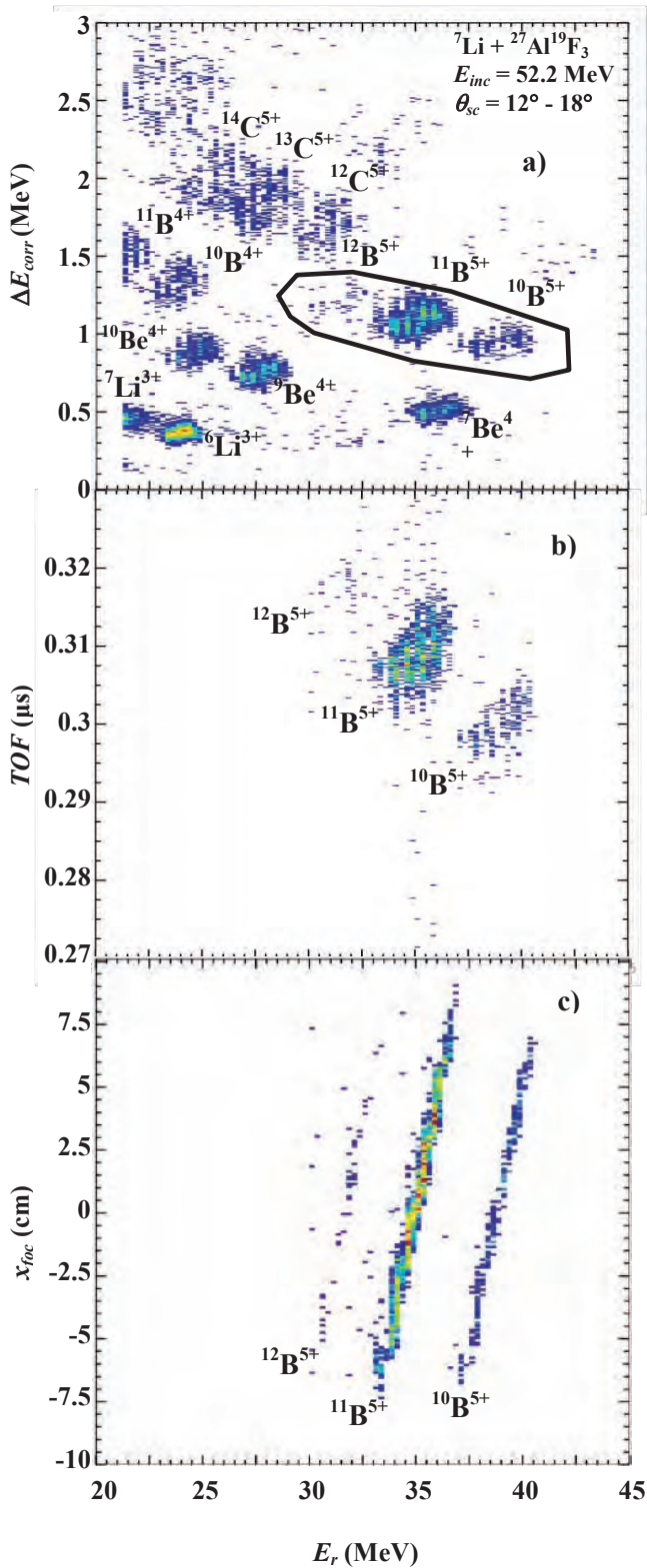


Fig.1: Two-dimensional spectra measured in the ${}^7\text{Li} + {}^{27}\text{Al}^{19}\text{F}_3$ reaction at 52.2 MeV and scattering angle of $\theta_{sc} = 12^\circ - 18^\circ$. Panel a) shows the $\Delta E_{corr} - E_r$ spectrum for unselected events. The contour line represents the graphical selection on the Boron isotopes. Panel b) shows the $TOF - E_r$ spectrum gated on the Boron isotopes. Panel c) shows the $x_{foc} - E_r$ spectrum gated on the Boron isotopes.

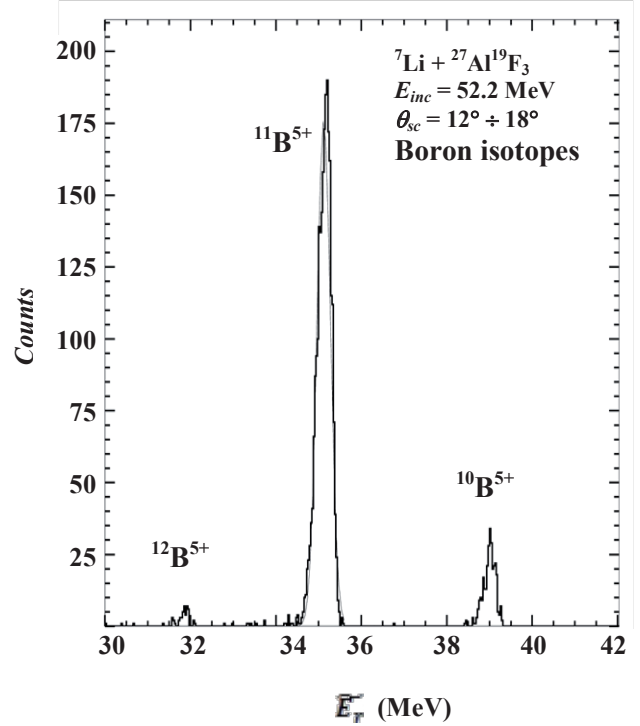


Fig.2: One-dimensional spectrum of E_r gated on the Boron isotopes as indicated in Fig1a.

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E0 TRANSITION STRENGTH IN ^{160}Er

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ABSTRACT

In this experiment we studied the decay of the first 0^+ excited state of ^{160}Er by measuring the ratio of the transition probability of the 836 keV, $0_2^+ \rightarrow 0_1^+$ ($E0$) transition and the $0_2^+ \rightarrow 2_1^+$ ($E2$) transition. $E0$ transitions are possible only through conversion electrons.

Gamma rays are measured by a coaxial HPGe detector and the conversion electrons are detected by means of a Mini-Orange spectrometer.

INTRODUCTION

$E0$ electric monopole transitions are forbidden by the gamma decay selection rule and can only occur via emission of conversion electrons. When the spin is non-zero $E0$ and $E2$ transitions compete with each other but the conversion electron process is the only way by which a state with spin $I=0$ can decay to another $I=0$ state.

Church and Weneser [1] showed that $E0$ transition probabilities can be factorized into electronic and nuclear terms,

$$W = \Omega \rho^2$$

$$\rho = \sum_p \int \psi_f^* \left[\left(\frac{r_p}{R} \right) + \dots \right] \psi_i d\tau$$

where the sum is over the protons, R is the nuclear radius and additional terms inside the brackets are usually neglected.

Considering a simple collective geometrical model, Rasmussen [2] estimated the $E0$ transition probability theoretically. He also defined a dimensionless ratio of the reduced $E0$ and $E2$ transition probabilities as,

$$X(E0/E2; 0_2^+ \rightarrow 0_1^+) = \rho^2 \frac{(E0; 0_2^+ \rightarrow 0_1^+) \cdot e^2 \cdot R_0^4}{B(E2; 0_2^+ \rightarrow 2_1^+)} = 4 \beta^2$$

Empirically, the $E0$ transition strength has particularly large values in the transitional region between spherical

and deformed nuclei [3]. This fact can be explained by strong mixing of states with different deformation or, within the Interacting Boson Model picture, with different number of d bosons [4]. The shape phase transition from a spherically harmonic vibrator to an axially deformed rotor has been described analytically by Iachello introducing a dynamic symmetry, denoted as $X(5)$ [5].

Experimental signatures of the $X(5)$ symmetry are some features of the level scheme (in particular the position of the first excited 0^+ state with respect to the first 2^+ level) and a characteristic pattern of the $B(E2)$ values.

Another interesting quantity is the $E0$ transition strength in the decay of the excited 0^+ state. This quantity has been previously measured by our group in ^{156}Dy , considered a good candidate of $X(5)$ symmetry [6]. However, the resulting X value [7] turned out to be compatible with a rather vibrational nucleus. Following that experiment, we measured the $E0$ strength in another good candidate of the $X(5)$ symmetry, ^{160}Er .

A partial level scheme of ^{160}Er is shown in figure 1. The two grey arrows show the two measured transitions. Energies are given in keV unit.

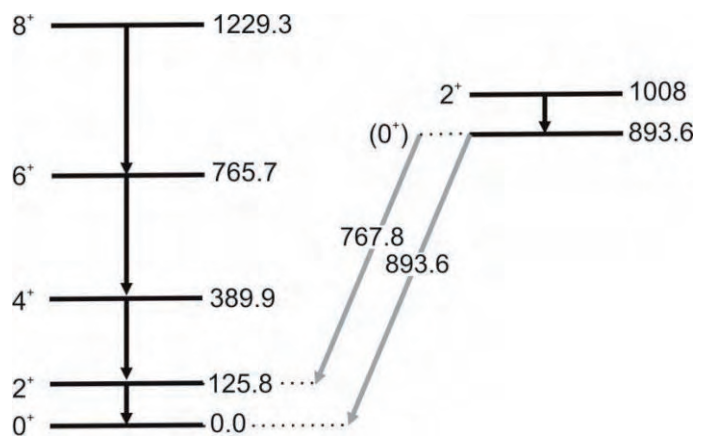


Fig1:- Partial Level Scheme of ^{160}Er

EXPERIMENTAL PROCEDURES

The experiment was performed at the INFN *Laboratori Nazionali del Sud* (LNS) in Catania.

Levels of ^{160}Er were populated by the EC decay of

^{160}Tm : ^{160}Tm (9.4 min) $\rightarrow$ ^{160}Er .

^{160}Tm was produced by the ^{150}Sm ($^{14}\text{N},4n$) reaction at $E_{\text{beam}} = 72$ MeV; the ^{14}N beam was provided by the LNS tandem accelerator and the target was a self-supporting foil having a thickness of ~ 0.612 mg/cm². A beam-pulsing device, consisting of a fast switching shutter, was used in order to irradiate the targets every 10 minutes for 10 minutes. Data were taken only during beam-off interval.

The γ -rays were measured with a coaxial HPGe detector having an energy resolution of 3.0 keV at 1332 keV and positioned at 90° with respect to the beam direction.

Conversion electrons were measured by a Mini-Orange spectrometer, consisting of a magnetic lens (made by permanent Sm-Co magnets) and of a 3mm-thick Si(Li) detector. The electron spectrometer was placed at a fixed position at 45° with respect to the beam in the backward direction.

The energy resolution of the mini-orange spectrometer is entirely due to the properties of the silicon detector while the magnetic field produced by the permanent magnets has the only purpose of transporting the electrons to the detector. The efficiency of the Mini-Orange spectrometer is therefore strongly energy dependent. The position and the width of the transmission window depend on the type and number of the magnets and on the distance between the magnets and the source and between the magnets and the silicon detector.

The efficiency calibrations of the HPGe detector and the Mini-Orange spectrometer were required to obtain the ratio of the transition probabilities of E0 and E2.

In order to calibrate the Mini-Orange spectrometer in-beam measurements of gamma and conversion electron were performed simultaneously through the $^{150}\text{Sn}(^{12}\text{C},4n\gamma)^{132}\text{Ba}$ reaction at $E_{\text{beam}} = 60$ MeV, since in this case stretched E2 transitions with well known conversion coefficients are populated in our desired energy range of 650-850 keV [8].

The efficiency of the Mini-Orange spectrometer as a function of the electron energy can be evaluated from the measured areas of the electron peaks corresponding to lines whose relative γ -ray intensities are known. Indicating by ε_e the efficiency of the of the electron spectrometer, by A_e the area of the electron peak, by I_γ the γ -ray intensity, by α the conversion coefficient and by B the electron binding energy, we have for two lines of energy E1 and E2,

$$\frac{\varepsilon_e(E_1 - B)}{\varepsilon_e(E_2 - B)} = \frac{A_e(E_1 - B) \cdot \alpha(E_2) \cdot I_\gamma(E_2)}{A_e(E_2 - B) \cdot \alpha(E_1) \cdot I_\gamma(E_1)}$$

If the γ -ray relative intensities are not known, they can be derived from the areas of the peaks in the γ spectrum

by measuring the relative efficiency of the γ -ray detector using a standard source. In our case we used the standard sources Eu and Ba.

In the off-beam measurements the energy resolution of the Si(Li) detector was 6.5 keV at 673 keV.

RESULTS

Figure 2 shows the relevant part of the off-beam gamma and conversion electron spectra. The arrow in the lower panel indicates the peak corresponding to the expected E0 transition; the arrow in the upper panel shows the position where a peak should appear in the γ -ray spectrum if the supposed E0 transition were instead a K line of higher multipolarity in one of the Erbium isotopes.

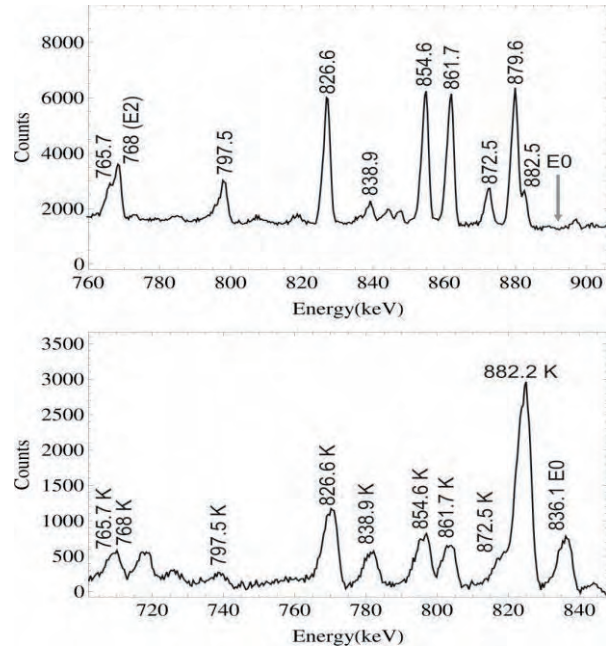


Fig 2. Partial off-beam γ -ray (upper panel) and conversion-electron (lower panel) spectra

After a careful inspection of the γ -ray spectrum we could also exclude a significant contribution from K lines of any identified contaminant or from L lines.

The area of the peak corresponding to the $0_2^+ \rightarrow 2_1^+$ transition at 768 keV in ^{160}Er turned out to be contaminated by a transition belonging to ^{160}Dy , however we were able to estimate it to be:

$$A_e(\text{Er}) = \frac{A_\gamma(\text{Er}) \cdot \alpha_k(\text{Er})}{[A_\gamma(\text{Er}) \cdot \alpha_k(\text{Er}) + A_\gamma(\text{Dy}) \cdot \alpha_k(\text{Dy})]} \times A_e(\text{E2}) = 2728 \pm 898$$

Following T. Kibedi et.al.[9] the relation between the theoretically estimated X value based on the Rasmussen model and the experimental value can be expressed as:

$$X(E0/E2; 0_2^+ \rightarrow 0_1^+) = 2.54 \times 10^9 A^{4/3} E_\gamma^5 \cdot q^2 \cdot \alpha_K(E2) / \Omega$$

where, E_γ is the energy of the E2 transition in MeV, $\alpha_K(E2)$ is the K-conversion coefficient for E2 transition and Ω is the electronic factor, and q^2 is given by:

$$q^2 = \frac{W_{e,K}(E2, 0_2^+ \rightarrow 0_1^+)}{W_{e,K}(E2, 0_2^+ \rightarrow 2_1^+)} = \frac{A_{e,K}(E0)}{\varepsilon_{e,K}(E0)} \times \frac{\varepsilon_{e,K}(E2)}{A_{e,K}(E2)}$$

From our data, we obtain $q^2 = 4.8(1.6)$.

The theoretical k-conversion coefficient is [10], $\alpha_K(E2; 768 \text{ KeV}) = 0.00487(7)$, and the electronic factor, calculated via the method used by Kantele [11] is $\Omega = 7.04 \times 10^{10} \text{ s}^{-1}$.

Thus, finally we obtained the X-value as,

$$X(E0/E2; 0_2^+ \rightarrow 2_1^+) = 0.19(7)$$

Since the theoretical X value in the Rasmussen model is $X = 4\beta^2$, we estimated the equilibrium deformation value,

$$\beta = 0.218(132)$$

In the framework of the CBS rotor model [12] one can theoretically estimate the minimum deformation value from the B(E2) value.

For a $\Delta K = 0$ transition [13],

$$B(E2; J_i \rightarrow J_f) = q_{E2}(\beta_M) \cdot \left(C_{J_i 0 2 0}^{J_f 0} \right)^2 \cdot \left[m_{L, r_\beta}(J_i \rightarrow J_f) \right]^2$$

Where $q_{E2}(\beta_M) = \left(\frac{3}{4\pi} \right)^2 \cdot \beta_M^2 \cdot Z^2 \cdot e^2 \cdot R^4$ is a scaling constant,

$C_{J_i 0 2 0}^{J_f 0}$ is the Clebsch-Gordan coefficient and $[m_{L, r_\beta}(J_i \rightarrow J_f)]$ is the nuclear matrix element. Since $\beta_m = r_\beta \beta_M$ and for ^{160}Er , $r_\beta = 0.204$ [14], considering the adopted $B(E2; 0_2^+ \rightarrow 2_1^+) = 4.38(20)$ [from National Nuclear Data Center, Brookhaven], one can obtain $\beta_m = 0.209(142)$, in good agreement with the value deduced by our measurement.

CONCLUSIONS

We measured the $X(E0/E2)$ branching ratio for the decay of the first 0_2^+ excited state of the beta band to the 0_1^+ and 2_1^+ state of the ground band in ^{160}Er . Our result agrees, within the experimental error, with the predictions of the CBS rotor model which is a generalization of the X(5) model.

ACKNOWLEDGEMENT

We like here to give a last farewell to Nanni, who left us unexpectedly last September. He has been an excellent teacher and collaborator for all of us.

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INDIRECT STUDY OF THE ${}^2\text{H}(\text{d},\text{p}){}^3\text{H}$ VIA THE TROJAN HORSE METHOD

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Abstract

The ${}^2\text{H}(\text{d},\text{p}){}^3\text{H}$ reaction has been indirectly studied by means of the Trojan Horse Method applied to the quasi-free ${}^2\text{H}({}^3\text{He},\text{p}){}^3\text{H}$ reaction at 18 MeV of beam energy, off the proton in ${}^3\text{He}$. For the first time in the application of the THM, the reaction channel was reconstructed from the detection on the spectator. This has several advantages. Analysis is underway for the determination of angular distributions and excitation function within a d-d relative energy from 1.5 MeV down to 2 keV. Preliminary results will be presented.

INTRODUCTION

The ${}^2\text{H}(\text{d},\text{p}){}^3\text{H}$ reaction is of interest for nuclear processes in the early solar system and early universe and for fusion energy applications. In particular this reaction belongs to the network of processes which will be used to fuel the first magnetic- and inertial-confinement fusion reactors. These reactors are expected to operate in the temperature range of $kT = 1$ to 30 keV.

Available data in the literature are below a d-d relative energy of 200 keV or above 1 MeV [1-5]. In particular, several experiments have been performed below 200 keV, but available data are not always in agreement within each other. Indeed, an evaluation of past work on both reactions [6,7] indicated the possibility of large systematic errors in some of these data sets (50% and more). Another weak point is that available data below 10 keV, region of interest for the future fusion power plants as well as for burning deuterium in the Pre-Main Sequence phase, are affected by the "electron screening" that is responsible for a 12% overestimate of the low energy fusion cross section. As regards the Standard Big Bang Nucleosynthesis (SBBN), the region of interest ranges from 50 to 300 keV and experimental data at least up to 1 MeV are required for an accurate calculation of the

reaction rate. Due to the lack of data in the intermediate region up to 1 MeV, the reaction rate has been calculated using a theoretical curve to interpolate the behaviour of the low energy data with that of the available higher energy data [7]. There is a recent experimental work where the relevant SBBN cross section is measured up to 300 keV, but there are several concerns on the way the reaction rate is calculated [8]. For these reasons, it was recommended by the astrophysical community a new experimental campaign in order to provide new data in the full range of interest for pure and applied physics.

Recently, we have carried out a new investigation of the ${}^2\text{H}(\text{d},\text{p}){}^3\text{H}$ as well as of the ${}^2\text{H}(\text{d},\text{n}){}^3\text{He}$ reactions (see contribution by A. Tumino to the Book of Proceedings to GIANTS2010) by means of the Trojan Horse Method (THM) applied to the quasi free ${}^3\text{He}+\text{d}$ interaction. The break-up is in the projectile, thus the spectator will be forwardly focussed.

As known, the THM [8-10] brings directly to the extraction of the low-energy bare nucleus cross section overcoming the problems of Coulomb suppression and electron screening enhancement. Note that for a plasma the value of the bare nucleus cross section must be known because screening in plasma can be quite different from that in the laboratory nuclear reaction studies at low energy [4].

In addition, the investigation of both reaction channels of the d+d interaction will allow us to perform another test concerning the suppression of Coulomb effects in the two-body cross section at sub-Coulomb energies. In particular we expect that the cross sections for the two processes should appear the same within the experimental errors. This would strengthen the results we have recently obtained concerning the suppression of the Coulomb amplitude in scattering processes studied via the THM [5].

THE EXPERIMENT

The $^2\text{H}(^3\text{He},p^3\text{H})^1\text{H}$ experiment was performed at the Nuclear Physics Institute of ASCR in Rez near Prague. A 18 MeV ^3He cyclotron beam with a spot size on target of 1.5 mm and intensities up to 2-3 pA, was delivered onto a CD_2 target of about $150 \mu\text{g}/\text{cm}^2$.

The experimental set up consisted of a telescope (20 μm silicon detector as ΔE - and 1000 μm position sensitive detector (PSD) as E -) placed on one side with respect to the beam direction, covering angles from 5° to 15° , and of other two telescopes (similarly assembled) placed on the opposite side at angles 5° to 15° and 24° to 36° . The trigger for the event acquisition was given by the coincidences between the two symmetric PSD's (with off-line selection of p - ^3H coincidences) as well as between any two of them detecting a proton, and the less forward PSD dedicated to the detection of ^3H .

For the first time in the application of the THM we have detected the particle which acts as a spectator to the $^2\text{H}(d,p)^3\text{H}$ binary process, namely the proton particle. This was mandatory for the reconstruction of the $n+^3\text{He}$ channel, allowing us to overcome all the experimental problems usually connected with the detection of neutrons, such as the limited detection efficiency and the poor energy and angle resolutions. For the $p+^3\text{H}$ system, the detection of the proton spectator at forward angles makes sure that the proton comes from projectile break-up, ruling out those events proceeding from target break-up. The bulk of the quasi-free contributions for the break-up process of interest was expected to fall inside the angular regions covered by the detectors, and the investigated range of proton momentum values allowed us to test the existence of the quasi free mechanism.

DATA ANALYSIS AND RESULTS

The energy and position calibration of the telescopes was performed using data acquired in preliminary runs of the $^3\text{He}+^{197}\text{Au}$, $^3\text{He}+^{12}\text{C}$ and $^3\text{He}+^2\text{H}$ elastic scattering and reactions. A standard three-peak α source was also used.

In order to identify the channel of interest and to choose the kinematical conditions where the quasi-free process is dominant, ^3H and proton loci were selected in the ΔE - E two-dimensional plots. An example of ΔE - E two-dimensional plot from this experiment is shown in Fig.1. One can easily recognize the hydrogen loci (proton and triton loci) and the helium ones (^3He and α loci).

The kinematics were reconstructed under the assumption of a proton as undetected particle, leading to the Q -value spectrum shown in Fig.2. A peak shows up around -1.5 MeV, closely reproducing the expected theoretical value of -1.47 MeV.

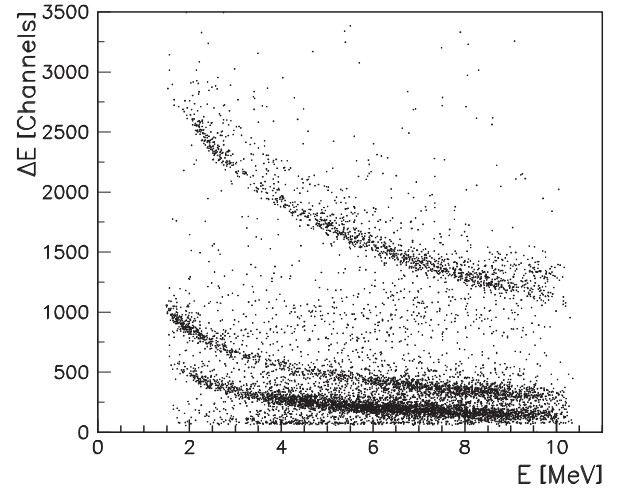


Fig.1: Example of ΔE - E two-dimensional plot from this experiment

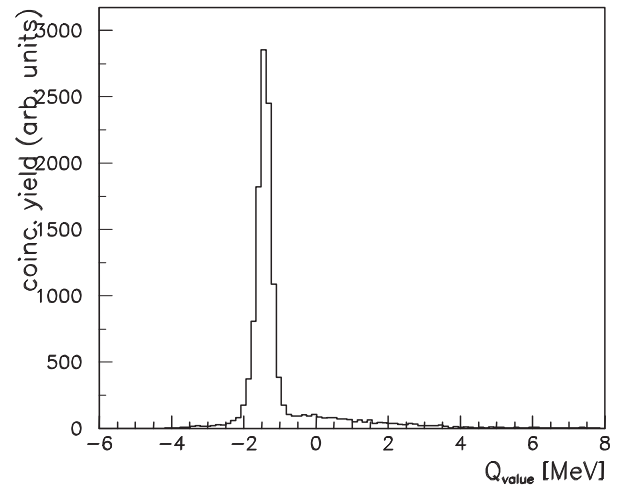


Fig.2: Experimental Q -value spectrum

The resulting spectra make us confident on the quality of the performed calibration, and on the possibility to well identify the $^3\text{H}+p+p$ channel.

In order to investigate the reaction mechanism involved a shape analysis of the experimental momentum distribution for the deuteron was performed. The experimental momentum distribution was reconstructed by applying the energy sharing method [8-10] to our coincidence data selecting d - d relative energy windows of 100 keV. The Plane Wave Impulse Approximation (PWIA) was employed, which factorizes the three-body cross-section into two terms corresponding to the two vertexes of the known pole diagram representing the quasi free mechanism (see ref.[8-10]).

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

where $d\sigma/d\Omega$ is the half-off-shell differential cross-section for the two-body ${}^2\text{H}(d,p){}^3\text{H}$ reaction of interest, KF is a kinematical factor depending on masses, momenta and angles of the outgoing particles and containing the final phase-space factor [8-10], and $\Phi(\vec{p}_s)$ is the Fourier transform of the radial wave function for the p-d intercluster motion inside ${}^3\text{H}$, described in terms of a Eckart function.

Dividing the three-body coincidence yield by the kinematical factor, we are left with a quantity proportional to the product of the momentum distribution with the differential d-d cross-section. Since in the restricted relative energy ranges of 100 keV, the differential two-body cross-section can be considered constant, the quantity above reflects the behaviour of the experimental momentum distribution in arbitrary units. The result is shown in Fig.3.

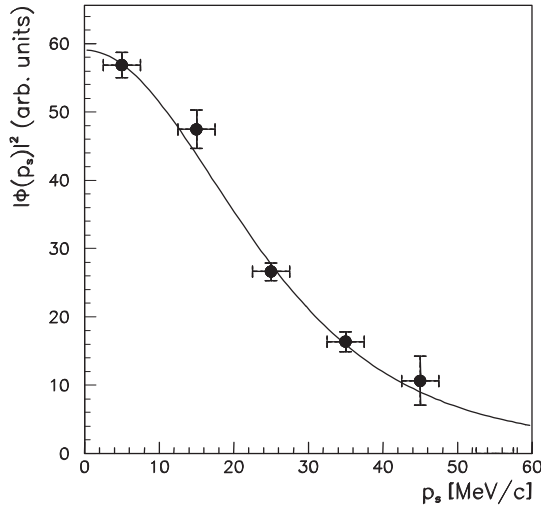


Fig.3: Experimental momentum distribution for the proton (full dots) compared with the theoretical behaviour (full line) given in terms of the Eckart function in momentum space.

Here we present the final results in terms of angular distributions and S(E)-factor. We recall that the plane wave impulse approximation (PWIA) was employed, which factorizes the three-body cross-section into two terms corresponding to the two vertexes of the known pole diagram representing the quasi free mechanism (see ref.[1-4]).

$$\frac{d^3\sigma}{dE_c d\Omega_c d\Omega_c} \propto KF \frac{d\sigma}{d\Omega} |\Phi(\vec{p}_s)|^2 \quad (1)$$

where $d\sigma/d\Omega$ is the half-off-shell differential cross-section for the two-body ${}^2\text{H}(d,n){}^3\text{He}$ reaction of interest, KF is a kinematical factor depending on masses, momenta and angles of the outgoing particles and containing the final phase-space factor [8-10], and $\Phi(\vec{p}_s)$ is the

proton momentum distributions given as the Fourier transform of the radial Eckart wave function for the p-d intercluster motion inside ${}^3\text{He}$. The further analysis was performed by considering coincidence events with a proton momentum window of 40 MeV/c. This makes sure that in selected kinematical region, the quasi-free mechanism gives the main contribution to the ${}^3\text{He}+d$ reaction. Following the PWIA approach the two-body cross-section was derived dividing the selected three-body coincidence yield by the result of a Monte Carlo calculation reproducing the behaviour of the KF $\Phi(\vec{p}_s)$ product (see eq.(1)). The geometrical efficiency of the experimental setup as well as the detection thresholds were accounted for in the calculation.

In order to derive angular distributions from the THM binary data the emission angle for the neutron in the ${}^3\text{H}$ -n center-of-mass system was calculated according to the relation:

$$\theta_{c.m.} = \arccos \frac{\vec{p}_t \cdot (\vec{v}_3\text{He} - \vec{v}_n)}{p_t (v_3\text{He} - v_n)} \quad (2)$$

where the velocities refer to the particles in the exit binary channel and the momentum is that of the transferred particle, namely the deuteron in the present case. The center-of-mass angular ranges covered in the present experiment are 60° to 120° and 140° to 180° .

The angular distributions were reconstructed throughout all the d-d relative energy range investigated in steps of about 100 keV (± 30 keV). Some examples are reported in Fig.4.

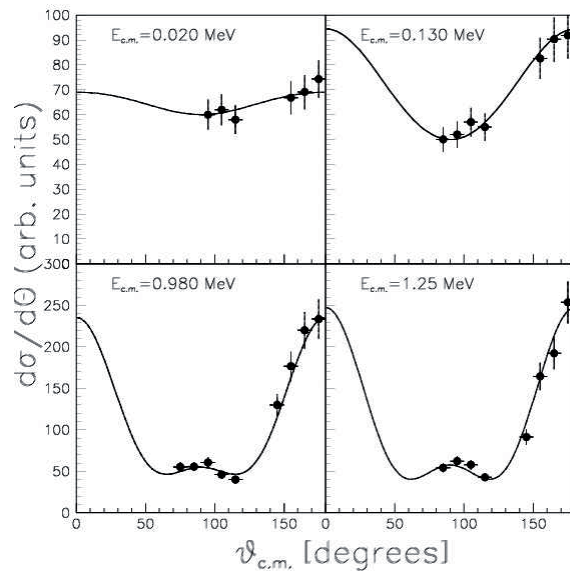


Fig.4: examples of experimental angular distributions (full dots), throughout the d-d relative energy range investigated. Solid lines refer to Legendre polynomial fits on the direct data.

The solid lines correspond to the Legendre polynomial fit performed on the direct data reported in ref.[6]. Owing

to the identical boson character in the entrance channel, the distributions are symmetrical about $\theta_{\text{cm}} = 90^\circ$, and thus only even Legendre polynomials enter the fit. As far as the energy increases higher order Legendre polynomials become more important and the angular distributions appear no longer as flat as in the ultra low relative energy region. Fits to the distributions have shown that the data can be described with a maximum order of 6.

A fair agreement with indirect data shows up, providing a first test on the validity of the IA for the present experimental conditions.

Next step will be to check whether the off-energy-shell binary cross section multiplied by the Coulomb penetration function [8-11] and integrated over the full $\theta_{\text{c.m.}}$ range is consistent with direct data. Since the THM angular distributions appear to be in good agreement with the direct ones over the entire energy range explored, their behavior will be extrapolated to the range not covered in the experiment, assuming the same trend of the direct measurement. Moreover, after the extraction of the bare nucleus $S(E)$ factor, we will be able to check the close connection with the one extracted from the $^2\text{H}(d,n)^3\text{He}$ counterpart, as well as the absence of screening effects.

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THE $^{18}\text{O}(p, \alpha)^{15}\text{N}$ REACTION RATE AT HIGH TEMPERATURES

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Abstract

The $^{18}\text{O}(p, \alpha)^{15}\text{N}$ reaction is of great importance in several astrophysical scenarios, as it influences the production of key isotopes such as ^{19}F , ^{18}O and ^{15}N . In this work, a high accuracy $^{18}\text{O}(p, \alpha)^{15}\text{N}$ reaction rate is proposed, based on the simultaneous fit of direct measurements and the results of a new Trojan horse experiment. Indeed, current determinations are uncertain because of the poor knowledge of the resonance parameters of key levels of ^{19}F . In particular, we have focused on the study of the broad 660 keV $1/2^+$ resonance corresponding to the 8.65 MeV level of ^{19}F . Since $\Gamma = 100 - 300$ keV, it determines the low-energy non-resonant contribution to the cross section and dominates the cross section at higher energies. Here we provide a factor 2 larger reaction rate above $T = 0.5 \cdot 10^9$ K based on our new improved determination of its resonance parameters, which could strongly influence present-day astrophysical model predictions.

INTRODUCTION

The $^{18}\text{O}(p, \alpha)^{15}\text{N}$ reaction is of great importance in several astrophysical scenarios, as it influences the production of key isotopes such as ^{19}F , ^{18}O and ^{15}N [1, 2, 3]. Fluorine is synthesized in the intershell region of asymptotic giant branch stars, together with s-elements, by radiative capture on ^{15}N , which in turn is produced in the ^{18}O proton-induced destruction. Peculiar ^{18}O abundances are observed in R-Coronae Borealis stars, having $^{16}\text{O}/^{18}\text{O} < 1$, hundreds of times smaller than the galactic value. In the framework of the double degenerate scenario, a quantitative account of such abundances can be provided if H-rich material is ingested and the $^{18}\text{O}(p, \alpha)^{15}\text{N}(p, \alpha)^{12}\text{C}$ chain is activated. Finally, there is no explanation of the $^{14}\text{N}/^{15}\text{N}$ ratio in presolar grains formed in the outer layers of asymptotic giant branch stars.

Again, such an isotopic ratio is influenced by the $^{18}\text{O}(p, \alpha)^{15}\text{N}$ reaction that might increase the ^{15}N yield during non-convective mixing episodes.

About ten resonances contribute to the $^{18}\text{O}(p, \alpha)^{15}\text{N}$ reaction cross section below 1 MeV [4, 5]. Particular attention has to be devoted to the broad $1=2^+$ resonance at about 660 keV. Our present knowledge allows us to state that it is comparatively broad, Γ_{tot} ranging from 100 to 300 keV according to the different measurements [4, 6, 7]. As a consequence, such a broad resonance at 660 keV gives strong contributions both at low and high temperatures [5] and its accurate determination is crucial to pin down both the reaction rate and its uncertainty. More in detail, these measurements are in agreement regarding the proton width, $\Gamma_p = 5$ keV, but not for the α -particle width ($\Gamma_\alpha = 317$ keV [4], 150 keV [7] or 90 keV [6]). To account for the large discrepancy, in the NACRE compilation [5] the contribution of the 660 keV resonance to the reaction rate has been evaluated by averaging out the rates resulting from the numerical integration of the cross sections obtained from the two sets of widths available, namely from [6] and [4]. The presence of such untenable discrepancy spoiling the cross section accuracy in the energy region of interest for astrophysics, the resonance being so broad to provide the non-resonant contribution down to zero energy. This has motivated the present indirect study by means of the THM.

THE EXPERIMENT

The $^{18}\text{O}(p, \alpha)^{15}\text{N}$ has been studied by applying the THM to the $^2\text{H}(^{18}\text{O}, \alpha^{15}\text{N})n \ 2 \rightarrow 3$ reaction. The experiment was performed at Laboratori Nazionali del Sud, Catania (Italy). A detailed description can be found in [8, 9, 10]. The SMP Tandem Van de Graaf accelerator provided a 54 MeV ^{18}O beam which was accurately collimated. The intensity was 5 enA on the average and the relative beam energy spread was about 10-4. Thin self-supported deuterated polyethylene (CD₂) targets, 100 $\mu\text{g}/\text{cm}^2$ thick, were used to minimize energy and angular straggling

(about 0.06 deg) and were placed at 90 deg with respect to the beam direction. The detection setup consisted of a telescope (A), devoted to ^{15}N detection, made up of an ionization chamber (IC) and a silicon position sensitive detector (PSD A) on one side with respect to the beam direction. Three additional silicon PSD's (B, C and D) were placed on the opposite side with respect to the beam direction. The distances were chosen to keep the intrinsic angular resolution better than 0.08 deg. Angular conditions were selected in order to maximize the expected QF contribution. To decrease detection thresholds, no ΔE detectors were put in front of PSD's B, C and D. Energy and position signals of the PSDs were processed by standard electronics together with the TAC signal for each coincidence event.

The resulting $^2\text{H}(^{18}\text{O}, \alpha ^{15}\text{N})\text{n}$ reaction cross section is shown in Fig. 1 (full circles). The error bars account for the statistical uncertainty (about 6%, on the average) and for the uncertainties coming from the adopted procedure to disentangle the contribution of each resonance to the reaction yield. The 4π integrated cross section in Fig. 1 is given in arbitrary units, thus no normalization error is included. Besides the resonances lying below 200 keV, the two resonances corresponding to the 8.65 MeV and to the 8.793 MeV state in ^{19}F are clearly seen.

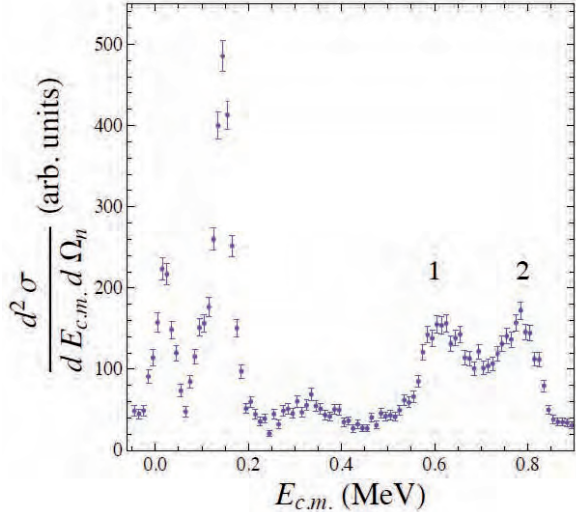


Figure 1: Cross section of the $^2\text{H}(^{18}\text{O}, \alpha ^{15}\text{N})\text{n}$ THM reaction, integrated over the whole solid angle using the measured angular distributions inside the range covered by the THM experiment and the trend deduced from [4] outside. Below 200 keV, the same cross section as in [8, 9, 10] is recovered. Labels 1 and 2 mark the position of the 660 and 799 keV resonances.

R-MATRIX FITTING

The experimental THM and direct data from [4] have been simultaneously fitted by means of an exact two-

level, two-channel calculation as discussed in [11]. Such an approach is well suited to reproduce the experimental data, in particular the contribution of the 660 keV and 799 keV resonances, since the effect of the interfering 145 keV narrow resonance ($\Gamma_{\text{tot}} < 0.3$ keV) can be neglected at such energies while the 8.629 $7/2^+$ state in ^{19}F adds up incoherently to the $S(E)$ factor. The proton and alpha reduced widths γ_{1p} , $\gamma_{1\alpha}$, γ_{2p} and $\gamma_{2\alpha}$, for the 660 keV and 799 keV resonances (marked as resonance 1 and 2, respectively, in Fig. 1) and the corresponding resonance energies E_{R1} and E_{R2} , have been deduced and the resulting partial and total widths are given in Tab. 1. To take into account the virtual nature of the transferred proton, the same approach discussed in [12] is adopted, including in the fitting procedure the ratio M_{12} (compare Eq. 12 of [12]) of the exact amplitudes for the direct transfer reaction $^{18}\text{O}(d, n)^{19}\text{F}$ populating the 8.65 MeV and the 8.793 MeV state of ^{19}F . Indeed, no $^{18}\text{O}(d, n)^{19}\text{F}$ transfer data are available to fix this ratio in contrast with the $^{15}\text{N}(d, n)^{16}\text{O}$ case in [11, 12]), that is why a fit is necessary.

If the same procedure is repeated for the [7] and [13] combined data, to cover the whole 0.5-0.9 MeV range, no reasonable simultaneous fitting of direct and THM data have been possible, though the possible shift in energy in data from [13] was considered in the fitting. This suggests that a consistent picture of the $S(E)$ factor for the $^{18}\text{O}(p, \alpha)^{15}\text{N}$ reaction in the 0.5-0.9 MeV energy interval can be found only if [7] data set is not included in the fitting, on the basis of the present THM measurement and the independent one in [14]. Following this recommendation, the reaction rate has to be calculated to evaluate its impact on astrophysics.

Table 1: 660 keV and 799 keV resonance parameters from the simultaneous fitting of Lorentz-Wirzba et al. (1979) and THM data

	E_R (keV)	Γ_p (keV)	Γ_α (keV)	Γ_{tot} (keV)
1	609 $\pm$ 2	11.1 $\pm$ 1.1	188 $\pm$ 3	199 $\pm$ 3
2	813 $\pm$ 2	27 $\pm$ 10	40 $\pm$ 10	67 $\pm$ 13



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Indirect study of the $^{19}\text{F}(\text{p},\alpha)^{16}\text{O}$ reaction through the Trojan Horse Method applied to the $^2\text{H}(^{19}\text{F},\alpha^{16}\text{O})\text{n}$ three-body reaction

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Abstract

Preliminary data of the $^2\text{H}(^{19}\text{F},\alpha^{16}\text{O})\text{n}$ THM reaction are discussed. This reaction has been performed at LNS-INFN with the aim of extracting the resonance parameters of the $^{19}\text{F}(\text{p},\alpha)^{16}\text{O}$ reaction, of great importance for the study of AGB star nucleosynthesis.

ASTROPHYSICAL MOTIVATIONS

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 justify 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. Anyway since the highest values of the observed ^{19}F enhancements in the stellar atmosphere are not matched by the models, 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 adopted reaction rates and the treatment of the mixing phenomena and the associated nucleosynthesis at the bottom of the convective envelope ([1], [2] and reference therein). In particular in this proposal we focus on the

$^{19}\text{F}(\text{p},\alpha)^{16}\text{O}$ reaction which represent the main fluorine destruction channel in this low-temperature, proton-rich environment.

The reaction rate is determined by the contribution of several resonances, about 10, which show up below 1 MeV, and by the non-resonant contribution. Direct measurements of the cross section stop at about 500 keV for both the α_0 and the α_1 channel ([3], and references therein), thus only theoretical estimates or spectroscopic studies are available elsewhere. In the case of extra-mixing phenomena, which are characterized by a maximum temperature of about 10^7 K, the energy region below 500 keV is of key importance, thus requiring further investigation to make clear on one hand the weight of the occurring resonances, on the other the exact contribution of the non-resonant cross section, which should dominate the reaction rate at the lowest temperatures. Indeed a careful review of the available measurements ([3], and references therein) shows that because of the estimate of the non-resonant contributions the uncertainty on the reaction rate increases up to the 50% at the lowest temperatures. As regards the resonances, their strength are based on very old data from the early 50's, thus an improved as well as up-to-date study would be very important also to establish the relative normalization of the different peaks. Finally an

investigation of the subthreshold region is crucial because it can strongly influence the cross section at very low energies.

A new experimental study through the Trojan Horse Method (THM) is important because the method is particularly suited for the study of low-energy and subthreshold resonances. This method (whose basic features are shortly discussed in the next section) has been already applied to several reactions involved in the analysis of the fluorine problem in AGB stars, including the $^{15}\text{N}(p,\alpha)^{12}\text{C}$ [4,5], the $^{18}\text{O}(p,\alpha)^{15}\text{N}$ [6,7] and the $^{19}\text{F}(\alpha,p)^{22}\text{Ne}$. Here we discuss the indirect study of the $^{19}\text{F}(p,\alpha)^{16}\text{O}$ through the $d(^{19}\text{F},\alpha^{16}\text{O})n$ ($Q=5.889$ MeV) three-body reaction by applying the THM.

THE METHOD

The THM [8,9,10,11] is an indirect technique through which astrophysically relevant two-body reactions can be measured down to the Gamow peak energy region. A three-body reaction is performed at a beam energy that allows to overcome the Coulomb barrier in the reaction entrance channel as well as the electron screening due to atomic electrons. In recent years the THM has been successfully applied to a number of reactions, including neutron-induced reaction.

In the THM approach, the two-body cross section for the process of interest, $a+x \rightarrow c+d$, is determined by selecting the quasi-free (QF) contribution of a three-body reaction, $a+b \rightarrow c+d+s$, the nucleus b being chosen because of its $x \oplus s$ cluster structure. In a restricted phase space region, that is for small transferred momenta, particle s can be regarded as a spectator in the three-body process while x constitutes the participant to the astrophysically relevant two-body reaction $a+x \rightarrow c+d$ (QF mechanism). The beam energy is compensated for by the $x \oplus s$ binding energy so that the two-body reaction can take place at very low $a-x$ relative energies. Moreover a single beam energy is required to get the full excitation function thanks to the $x-s$ inter-cluster motion allowing to measure a wide range of $a-x$ relative energies and to the wide covered angular range.

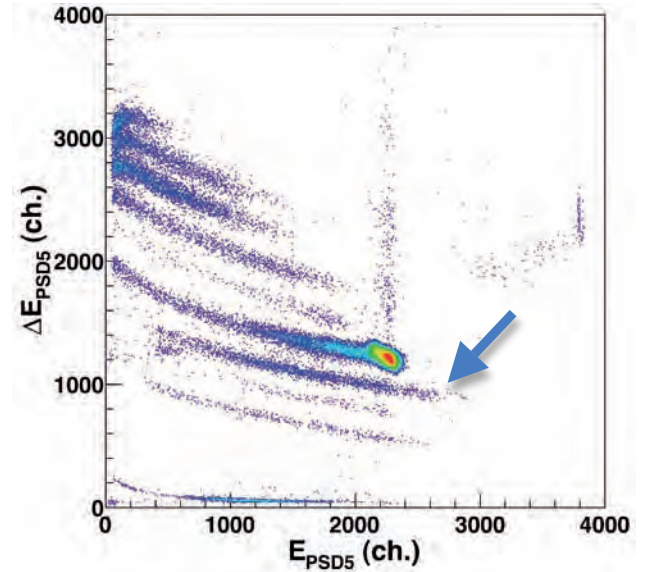


Figure 1: ΔE - E 2D spectrum for oxygen selection. The red spot marks ^{19}F elastic scattering while the arrow marks the oxygen locus.

THE EXPERIMENT

We have investigated the 0-1 MeV $^{19}\text{F} - p$ relative energy range in order to compare the behaviour of angular distributions and cross section extracted via the THM with direct data (from [3] and reference therein), in the case of the α_0 channel. To this aim, a 50 MeV ^{19}F beam was used, with a spot size on target of about 1 mm and intensities of about 1 pA, impinging onto a $100 \mu\text{g}/\text{cm}^2$ deuterated polyethylene target.

Five silicon position sensitive detectors (PSD) have been used in order to cover the 0-1 MeV ^{19}F - p relative energy range and a wide $\theta_{\text{c.m.}}$ angular range (here $\theta_{\text{c.m.}}$ is two-body reaction c.m. angle). A first 500 μm thick PSD detector (A) covered the 4° - 13° angular range, its position being optimized for ^{16}O detection from the $d(^{19}\text{F},\alpha^{16}\text{O})n$ QF reaction. An ionization chamber (IC) was placed in front of the PSD to discriminate oxygen nuclei via the $\Delta E - E$ technique.

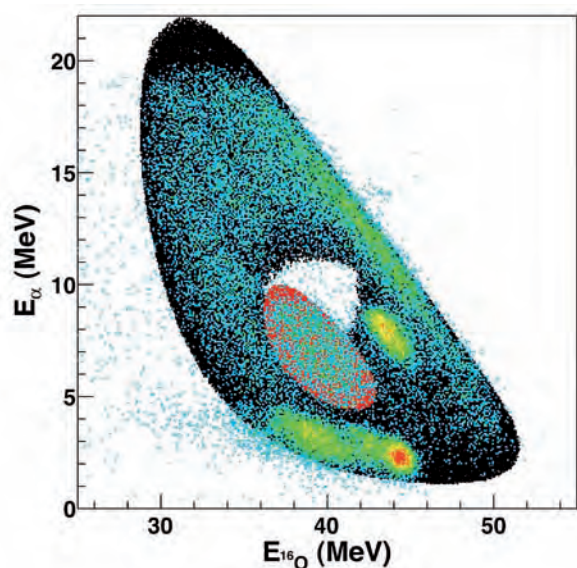


Figure 2: Selection of the reaction channels. The black locus is the simulated kinematic region spanned by the $d(^{19}\text{F}, \alpha ^{16}\text{O})n$ events (^{16}O ground state) while the red region delimitates the $d(^{19}\text{F}, \alpha ^{16}\text{O})n$ locus when ^{16}O is emitted in the first excited state. The experimental data are superimposed on the simulated loci. Besides the $d(^{19}\text{F}, \alpha ^{16}\text{O})n$ reaction, additional reactions contribute, which have to be disentangled to single out the channel of interest.

Fig. 1 shows the measured ΔE - E 2D spectrum that has been used for oxygen selection. The corresponding locus, marked by an arrow in this figure, is very well separated from any other. An overall elastic scattering counting rate of 3 keps was measured on detector A (full range), which is placed at the most forward angles. Four 1000 μm PSD's were placed on the opposite side with respect to the beam direction, their positions being optimized for the detection of the α particles from the QF reaction. The four PSD's (B, C, D and E) covered the angles: 5° - 15° , 20° - 30° , 35° - 45° and 50° - 60° respectively (see fig. 1, left panel). ^{16}O nuclei were detected in coincidence with α particles thus allowing for a complete kinematical identification. The $E_{4\text{He}}$ vs $E_{16\text{O}}$ two-dimensional plot is reported in Fig.2, showing the emission energy intervals of

the two fragments. The full kinematics is displayed with no gates on the neutron momentum, for the PSD 1-5 coincidence condition. The presence of a ΔE detector for particle identification in front of PSD A did not introduce any detection energy threshold, while a negligible threshold was present on the α particles spectrum, due to dead layers in the detectors, since no ΔE detector was used. Identification of the proper kinematical locus is also shown in Fig.2. The black and red regions delimitates the energy intervals corresponding to the $d(^{19}\text{F}, \alpha ^{16}\text{O})n$ reaction leaving ^{16}O in the ground and first excited states, respectively, as deduced from a Monte Carlo simulation. The experimental data are superimposed to the simulated loci, showing that besides the reaction channels of interest, additional loci show up corresponding to two-body reactions. The first step of the analysis will be selection of the $d(^{19}\text{F}, \alpha ^{16}\text{O})n$ channel.

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CORRECTION-FREE ${}^8\text{Li}(\alpha, n){}^{11}\text{B}$ CROSS SECTION AT ASTROPHYSICAL ENERGIES

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Abstract

The ${}^8\text{Li}+{}^4\text{He}\rightarrow{}^{11}\text{B}+n$ reaction inside the centre-of-mass energy region $E_{\text{cm}} = 0.5\text{--}2.5$ MeV, corresponding to the temperature range $T_9 = 1\text{--}5$, is of relevant interest in the fields of cosmology and r-process nucleosynthesis. In this experimental work, the cross section, summed over all ${}^{11}\text{B}$ final bound states, at the centre-of-mass energy of 1.05 MeV, is investigated by a correction-free projectile-correlated inclusive neutron measurement. The radioactive ${}^8\text{Li}$ beam delivered by the EXCYT facility at LNS-Catania is used to induce the inverse-kinematics reaction process.

INTRODUCTION

Observations extended over high-redshift astrophysical objects have shown evidences of the presence of a non-negligible abundance of heavy nuclides ([1] and references therein). Such results might be explained if heavy-element production has taken place during the very early stages of the universe, namely during the Big Bang nucleosynthesis. Since the standard Big Bang model cannot allow to overcome the $A=8$ mass gap, several models have been introduced, one of the most effective being the inhomogeneous Big Bang scenario [2, 3, 4, 5]. According to this inhomogeneous model (IM), soon after the QGP-to-hadron transition, neutron-rich high-baryon-density regions formed where heavy-element production could have taken place. In particular, nuclei beyond the $A=8$ mass gap should have been produced primarily following the ${}^1\text{H}(n,\gamma){}^2\text{H}(n,\gamma){}^3\text{H}({}^2\text{H},n){}^4\text{He}({}^3\text{H},\gamma){}^7\text{Li}(n,\gamma){}^8\text{Li}({}^4\text{He},n){}^{11}\text{B}(n,\gamma){}^{12}\text{B}(\beta+){}^{12}\text{C}\dots$ reaction chain [1, 2, 3, 4, 5, 6, 7]. Such a pathway, transiting through the zero-energy-threshold ${}^8\text{Li}+{}^4\text{He}\rightarrow{}^{11}\text{B}+n$ reaction, involves the unstable ${}^8\text{Li}$ isotope which is short lived, with $T_{1/2}=840$ ms.

The ${}^8\text{Li}+{}^4\text{He}\rightarrow{}^{11}\text{B}+n$ reaction could also play a crucial role in the r-process, in particular to constrain the physical conditions characterizing the r-process site. Indeed, this has not been soundly established yet, neutron-star mergers, gamma-ray bursts and core-collapse supernovae

(e.g. type II) being commonly considered among the most likely candidates [8, 9]. Concerning type II SNe, the necessary high neutron flux required for an effective r-process can be produced in the hot-bubble region formed by a neutrino driven wind, between the nascent neutron star and the shock front ([9] and references therein). A second necessary condition for the r-process to occur is the presence of seed nuclei, which are eventually burnt to heavier elements in fast neutron-capture reactions. These are nuclei in the mass range $70 < A < 120$ (e.g. the doubly magic ${}^{78}\text{Ni}$) that are made through the so-called α -process [10]. The ${}^8\text{Li}+{}^4\text{He}\rightarrow{}^{11}\text{B}+n$ reaction plays a key role to constrain the astrophysical environment where the r-process takes place because it implies a more efficient production of these seed nuclei, so that a larger neutron-to-seed ratio is necessary for the r-process.

Table 1: Summary of the cross sections values

Ref.	E_{cm} (MeV)	Cross section (mb)
[12]	1.03 ± 0.07	531 ± 63
[15]	1.05 ± 0.05	570 ± 185
[16]	1.05 ± 0.05	285 ± 100
[14]	1.05 ± 0.05	122 ± 28
[17]	1.05 ± 0.16	516 ± 111

THE MEASUREMENTS

In the ${}^{11}\text{B}$ inclusive measurements [11, 12], an active target consisting of a multisampling ionization chamber, the detector gas being mostly ${}^4\text{He}$, was used. The resulting cross section is given in the first line of Tab. 1. The procedure to discriminate ambiguous events in such a ${}^{11}\text{B}$ inclusive measurement approach was not considered clearly described and was criticized in [13]. To suppress such undistinguished contaminants, ${}^{11}\text{B}$ -n kinematical

coincidence measurements were then introduced [13, 14, 15, 16]. A multiple-sampling and tracking proportional chamber surrounded by modular neutron counters consisting of plastic scintillators was used. The results at $E_{cm} = 1.05$ MeV by [14, 15, 16], obtained using the same set-up, are shown in Tab. 1 (lines 2,3 and 4). Such a variety of results, differing even by a factor 4.7, well outside the statistical uncertainty, demonstrates the complexity of the approach adopted in [14, 15, 16].

These contradicting results have motivated a new analysis of the ${}^8\text{Li}+{}^4\text{He}\rightarrow{}^{11}\text{B}+n$ reaction data to reach a recommended cross section to be used in astrophysical calculations. Details of the data analysis are given in [17], while here the most important facts are given.

In our new neutron inclusive measurement [17], the background contribution has been carefully identified and evaluated. In comparison to the ${}^{11}\text{B}$ inclusive measurements [12] different sources of systematical uncertainties and of background are involved. Therefore, the resulting cross section at $E_{cm} = 1.05$ MeV, $\sigma=516\pm111$ mb (compare line 5 in Tab. 1) strongly confirms and supports the complementary inclusive ${}^{11}\text{B}$ data [12] in Tab. 1. Opposite to the ${}^{11}\text{B}$ -n coincidence approach [14, 15, 16] we have shown in [17] that a single correction is required to extract the cross section, namely the one for the detection efficiency, and that all the possible sources of systematic uncertainties give a negligible contribution. The present new cross section value differs from the one in [18] by about 10% thanks to the new improved data analysis performed in [17].

It is also worth to underscore that by focusing on the cross section value recommended in [14] (Tab. 1) by no means a factor of 5 difference with our result can be recovered by radically changing the Polycube detection efficiency [17]. As discussed in Ref. [19], in the study of the ${}^8\text{Li}+{}^4\text{He}\rightarrow{}^{11}\text{B}+n$ cross section the role of the detection threshold in determining the detection efficiency at low neutron energy is of fundamental importance. For the detector used in this work, the efficiency curve in [17] shows how suited the Polycube detector design [18] is to detect low energy neutrons. This makes the experimental setup more sensitive to high ${}^{11}\text{B}$ excited states yielding the lowest energy neutron as in the kinematics examples shown in Fig. 1. Conversely, in the measurements using plastic scintillators [14, 15, 16], which are typically characterized by a threshold of several hundreds keV, high ${}^{11}\text{B}$ excited states are experimentally inaccessible (Fig. 1, right panel) and the requested cross section summed over all ${}^{11}\text{B}$ final states cannot be obtained.

A second crucial point of the present approach is that the effects of the new branching ratio pattern in [19] are taken into account in the present data analysis [17]. The detection efficiency required to calculate the total cross section is given by the average of all level detection efficiency weighted by the ${}^8\text{Li}+{}^4\text{He}\rightarrow{}^{11}\text{B}+n$ reaction branching ratios. In Ref. [18] an uniform feeding of ${}^{11}\text{B}$ excited states has been adopted for simplicity.

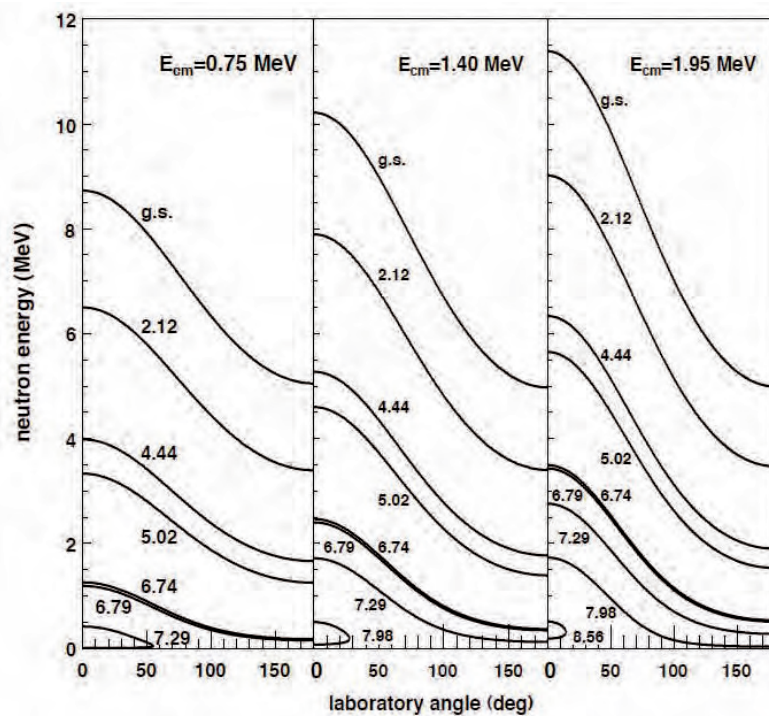


Figure 1 The laboratory energy ranges spanned by the ${}^8\text{Li}+{}^4\text{He}\rightarrow{}^{11}\text{B}+n$ reaction neutrons for each of the involved ${}^{11}\text{B}$ final states at the indicated E_{cm} values.



Indeed, two determinations of the branching ratio pattern are available in the literature: the mean branching ratios from [14], which result from an average extended over the broad $0.75 < E_{\text{cm}} < 2.55$ MeV range; the recent set given in [19], where the relative population of the different energy states as a function of E_{cm} is deduced from the comparison of the inclusive data [20, 18, 11, 12] with the n - ^{11}B coincidence data in [14]. A lower detection efficiency, and a corresponding larger cross section $\sigma = 637 \pm 138$ mb, is obtained if the branching ratios from [14] are assumed, with respect of the uniform population. This is mainly due to the fact that a seemingly weak non-uniformity of the branching ratios privileges the lower excited levels of ^{11}B and, consequently, smaller values of the detection efficiency. On the other hand, a larger efficiency and a correspondingly smaller cross section $\sigma = 516 \pm 111$ mb result if the branching ratio pattern from [19] is considered, with respect of the uniform population. In this case, a significant branching ratio non-uniformity right at $E_{\text{cm}} = 1.05$ MeV privileges the higher excited levels of ^{11}B and, consequently, larger values of the detection efficiency.

Since the branching ratio pattern at the appropriate centre-of-mass energy is available [19], we recommend $\sigma = 516 \pm 111$ mb as the $^8\text{Li} + ^4\text{He} \rightarrow ^{11}\text{B} + n$ cross section value at $E_{\text{cm}} = 1.05 \pm 0.16$ MeV.

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THE $^2\text{H}(\text{d},\text{p})^3\text{H}$ REACTION AT ASTROPHYSICAL ENERGIES STUDIED VIA THE TROJAN HORSE METHOD AND POLE APPROXIMATION VALIDITY TEST

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Abstract

In order to understand primordial and stellar nucleosynthesis, we have studied $^2\text{H}(\text{d},\text{p})^3\text{H}$ reaction at 0,5 MeV down to astrophysical energies. Knowledge of this S-factor is interesting also to plan reactions for fusion reactors to produce energy. $^2\text{H}(\text{d},\text{p})^3\text{H}$ has been studied through the Trojan Horse Method (THM) applied to the three-body reaction $^2\text{H}(^3\text{He},\text{pt})\text{H}$, at a beam energy of 17 MeV. Detecting protons and tritons in coincidence and selecting quasi-free events, the obtained S-factor obtained has been compared with direct reactions results, and reaction rate as well as the screening potential U_e have been evaluated. Obtained data are in agreement with the direct ones, and a pole invariance test has been obtained comparing the present result with another $^2\text{H}(\text{d},\text{p})^3\text{H}$ THM one, $^6\text{Li}(\text{d},\text{p})^4\text{He}$, performed with a different spectator particle (see fig. 1).

INTRODUCTION

Like it has been shown in [1], that the $^2\text{H}(\text{d},\text{p})^3\text{H}$ reaction is important in the framework of primordial nucleosynthesis (from its cross section is possible to obtain a reliable value for baryon density, since deuterium is the best baryometer). It is also relevant for the Pre Main Sequence phase of stellar evolution as well as to produce energy in fusion reactors. In these frameworks energy range of interest goes from 150 down to zero keV.

In order to study these environments it is necessary to extract the bare nucleus S-factor, so it will be possible to take into account the shielding of the electrons present in astrophysical plasma (especially with the Debye-Hückel theory) that is in general

really different from the typical shielding of the laboratory conditions [2].

Indirect methods, and in particular for charged particles induced reactions the Trojan Horse Method (THM) [3,4,5], are powerful tools to obtain bare nucleus cross section. With THM it is possible to obtain a cross section free from Coulomb and screening effects.

Because of the pole invariance this method must be independent from the third particle, the so called spectator. This feature of the method was already seen for the deuterium and ^3He used as Trojan Horse nuclei in the case of the reaction $^7\text{Li}(\text{p},\alpha)^4\text{He}$ [6],[7]. The same will be done with the present work with the results arising from $^2\text{H}(^3\text{He},\text{pt})\text{H}$ and the ones from $^6\text{Li}(\text{d},\text{pt})^4\text{He}$ [8]. The break-up schemes in those experiments are reported in fig. 1; the THM requires that data extracted from the two three body reactions should be in agreement.

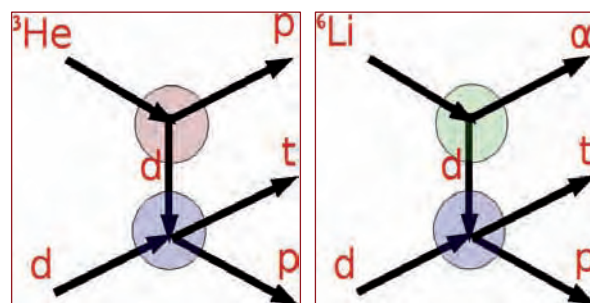


Fig.1: three body reaction scheme for the present work (first panel) and the $^6\text{Li}(\text{d},\text{pt})^4\text{He}$ [8] (second panel). The two body reaction of interest is identical but the spectator is different in the two cases.

EXPERIMENT AND DATA ANALYSIS

The experiment was performed at the Cyclotron Institute of the ASCR in Rez, Praha. The ^3He beam provided with an energy of 17 MeV and it impinged on a deuterated polyethylene target ($200 \mu\text{g}/\text{cm}^2$ thick). The experimental set-up consisted of three telescopes, each one formed by a ΔE silicon detector (about $20 \mu\text{m}$ thick) and a Position Sensitive Detector (PSD). The experimental apparatus is reported in fig. 2.

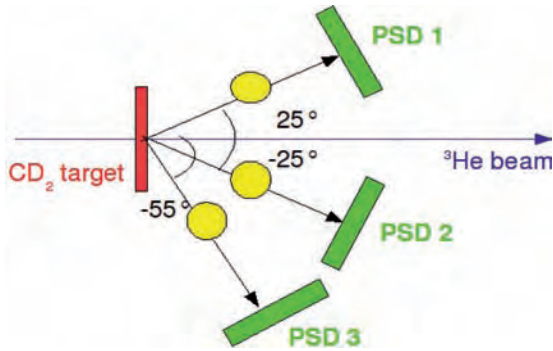


Fig. 2: experimental set-up adopted for the experiment discussed in the text.

Calibration of the telescopes and selections on proton and tritons have been discussed in [9]. The Q-value spectrum for these events shows a peak at about -1.4 MeV (see fig. 4), which refers to the $p+t+p$ channel of interest (whose calculated Q-value is -1.458 MeV). In the following the present study will focus on the events under this peak. In fact the kinematics were reconstructed under the assumption of a proton as third particle, leading to the locus of events in the E_H vs. E_{3H} plane shown in fig. 5.

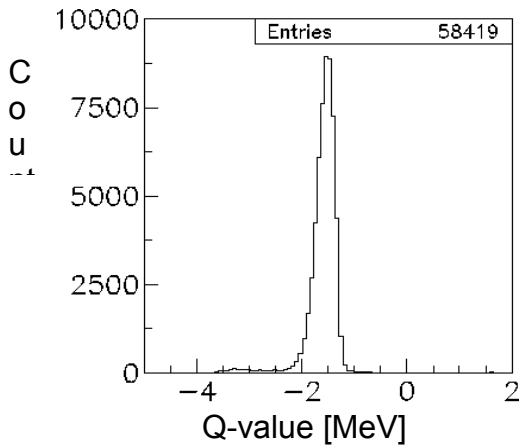


Fig. 4: Q-value spectra for the $^2\text{H}(^3\text{He},pt)p$ reaction.

The further step of the analysis has been the selection of the quasi-free mechanism, which is accomplished via the study of the spectator proton momentum distribution p_s for all coincidence events,

that is an observable very sensitive to the reaction mechanism. This has been reconstructed in Plane-Wave Impulse Approximation (PWIA) by applying the energy sharing method [5] to our coincidence data selecting a narrow t - p relative energy windows where the differential two body cross section can be considered almost constant.

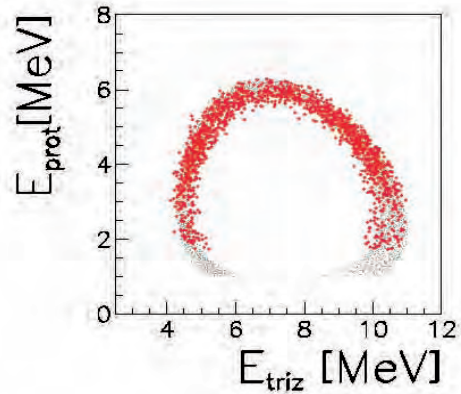


Fig. 5: kinematic locus for the $^2\text{H}(^3\text{He},pt)\text{H}$ reaction (red dots) compared with calculated locus (black dots). A nice agreement shows up.

The good agreement of the result with the theoretical Eckart spectator momentum distribution (which is evident in fig. 6) will make us confident that in the experimental selected kinematical region, the quasi-free mechanism gives the main contribution to the $^3\text{He} + ^2\text{H}$ reaction in the kinematical conditions described above and it can be selected without significant interference with contaminant sequential decay processes.

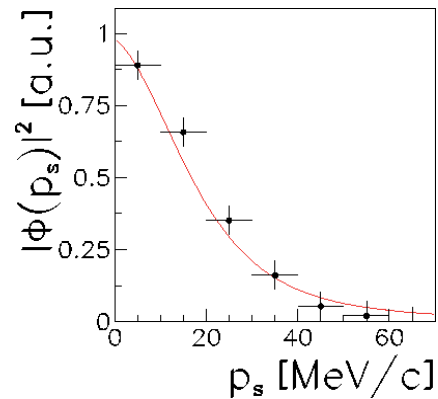


Fig. 6: inter-cluster momentum distribution for proton inside ^3He . The Eckart function is reported for comparison as a solid line.

The absence of other reaction processes is due to the choice of ^3He as Trojan Horse nucleus, instead of the previous choice of ^6Li , in whose data the presence of sequential mechanisms, and their necessary elimination, has dropped statistic substantially, as is evident in fig. 10.

RESULTS

In the Plane Wave Impulse Approximation approach the three-body cross section can be written as [10]

$$\frac{d^3\sigma}{dE_1 d\Omega_1 d\Omega_2} \propto (KF) |\Phi(p_s)|^2 \left(\frac{d\sigma}{d\Omega} \right)^N.$$

In order to get the on shell two-body cross section that must be compared with the directly measured one, it is necessary to multiply $(d\sigma^N/d\Omega)_{cm}$ by the penetrability function through the Coulomb barrier, given in terms of regular and irregular Coulomb functions. By introducing this penetrability function P_l , as described in [5] it was possible to extract the two-body cross-section $\sigma(E)$ and therefore the bare-nucleus $S(E)$ -factor.

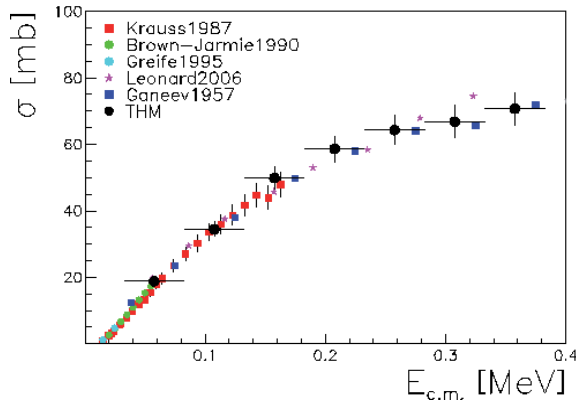


Fig. 8 : two-body cross section obtained from present data (black dots) compared with direct data results.

In fig. 8 the bare nucleus cross section and in fig. 9 the S -factor for the $^2\text{H}(d,p)^3\text{H}$ reaction is reported and compared with direct data from [11]. The agreement of the two data sets seems nice within the experimental errors, except in the energy range of 0-50 keV, that is the object of further studies. The normalization of indirect data to the indirect ones was performed in the energy window 300-400 keV.

This new data set has been compared with the previous Trojan Horse one, obtained through the selection of quasi-free channel of the $^6\text{Li}(d,pt)^4\text{He}$ reaction [8], even if in that case the spectator was an α particle instead of a proton.

The agreement of the two results in fig. 10, within experimental errors, shows clearly the pole invariance of the quasi-free mechanism and that the polar approximation in THM is reliable.

Reaction rate has been calculated in the temperature range of interest for astrophysics ($T=0.07-1 \cdot 10^9$ K) from the polynomial fit of the $S(E)$ -factor (in which 0-

50 keV energy range result has been excluded), that is given by the expression:

$$S(E) = S(0) + \dot{S}(0)E + \frac{1}{2}\ddot{S}(0)E^2,$$

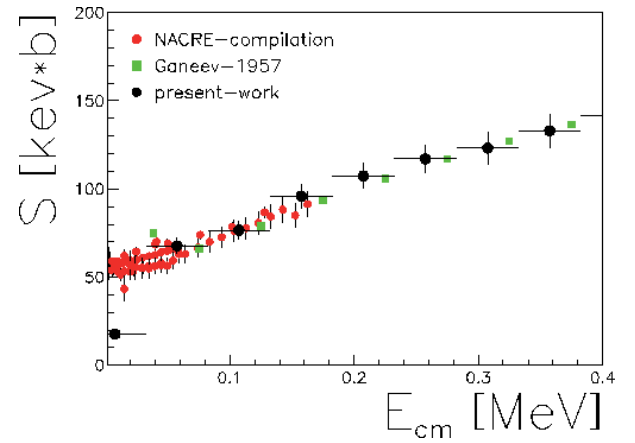


Fig. 9: bare nucleus cross section for the $^2\text{H}(d,p)^3\text{H}$ reaction (black dots) compared with direct data (red dots and green squares) from [11,12].

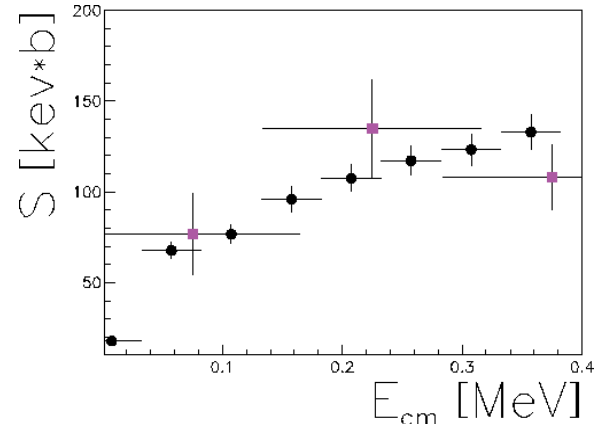


Fig. 10 : $d\sigma^N/d\Omega$ for the $^2\text{H}(d,p)^3\text{H}$ reaction extracted in present work (solid dots) compared with data from [8] (pink dots).

and with the parameters:

$$S(0) = 48.412 \pm 8.370 \text{ [keV*b]}$$

$$\dot{S}(0) = 322.14 \pm 97.51 \text{ [b]}$$

$$\ddot{S}(0) = -323.23 \pm 223.4 \text{ [b/keV]}.$$

The expression obtained for the reaction rate is



$$r_{dd} = \exp \left(a_1 + \frac{a_2}{T_9} + \frac{a_3}{T_9^2} + a_4 T_9^{\frac{1}{3}} + a_5 T_9 + a_6 T_9^{\frac{5}{3}} + a_7 \ln T_9 \right)$$

expressed in $\text{cm}^3/\text{mol} \cdot \text{s}$ and with the fitted parameters:

$$\begin{aligned} a_1 &= -0,418 \cdot 10^2 \\ a_2 &= +0,337 [\text{K}^{-1}] \\ a_3 &= -0,365 \cdot 10^{-2} [\text{K}^{1/3}] \\ a_4 &= +0,107 \cdot 10^3 [\text{K}^{-1/3}] \\ a_5 &= -0,147 \cdot 10^2 [\text{K}] \\ a_6 &= -1,920 [\text{K}^{-5/3}] \\ a_7 &= -0,352 \cdot 10^2 \end{aligned}$$

The result compared with the one extract from direct data is shown in fig. 11.

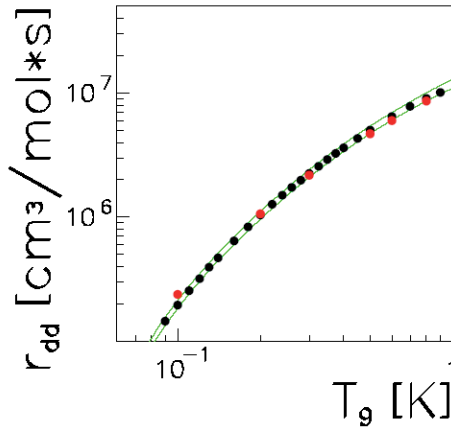


Fig 11 : Reaction rate for the ${}^2\text{H}(\text{d,p}){}^3\text{H}$ reaction obtained by the present data (black dots) inside the error bars (green lines) and compared with the direct data result (red dots) [11].

The value of the screening potential has been evaluated from the expression:

$$S_s = S_b \frac{E}{E + U_e} \exp \left(\frac{\pi \eta U_e}{E} \right),$$

where $S_b(E)$ is polinomial fit shown previously and S_s is the S-factor fit of the direct data [9], and U_e is the free parameter. A best fit procedure leads to a value of $U_e = 35 \pm 15$ eV, that is compatible with the results given by literature [13,14,15], as shown in table 1.

Source	U_e [eV]
Present work	35 ± 15
[11]	14 ± 9
[12]	25 ± 5
Adiabatic limit [13]	52

Table 1 : present work value of the electron screening potential compared with literature values, with the result of a nice agreement.

In order to improve statistics and try to solve the discrepancy of $S(E)$ under 50 keV, it's been performed a new measure run, in the same laboratory and with a very similar experimental setup, with a ${}^3\text{He}$ beam at 18 MeV. This data set is currently under analysis.

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VALIDATING THE POLE APPROXIMATION IN THE STUDY OF THE ${}^6\text{Li}(\text{D}\alpha){}^4\text{He}$

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Abstract

The Trojan Horse Method (THM) was applied to the ${}^3\text{He}+{}^6\text{Li}$ interaction in order to investigate the quasi-free ${}^6\text{Li}(\text{d}, \alpha){}^4\text{He}$ reaction. The experiment was performed at 17 MeV at the Cyclotron Institute of the Czech Academy of Science.

The extracted ${}^6\text{Li}(\text{d}, \alpha){}^4\text{He}$ quasi-free cross-section was compared with the behavior of direct data. A good agreement between data sets shows up throughout the energy range investigated, providing a very important validity test of the pole approximation for the THM above the Coulomb barrier.

INTRODUCTION

The study of nuclear reactions induced by charged particles at astrophysical energies has shown the presence of many experimental difficulties, mainly connected to the presence of the Coulomb barrier and the electron screening effect. For this reason several indirect methods have been applied. Many of them are based on direct reactions. Among them, an important role is played by the Trojan Horse Method (THM). It has been applied to several reactions in the past decade [1-8] at the energies typical of the astrophysical applications, which usually are far below the Coulomb barrier. In recent years many tests have been made to deepen the knowledge of the method and its possible ways of application: the target-projectile break-up invariance, the polar invariance [8] and the possible application for neutron beams. The Trojan Horse Method (THM) allows the extraction of the low energy behaviour of an astrophysically relevant binary reaction by applying the well known theoretical formalism of the Quasi-Free processes. Basically these 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). In particular these processes have three particles in the exit channel one of which can be thought as "spectator". In case of a PBU and referring to

Fig.1, the picture is that of an interaction between the impinging nucleus a and fraction of the nucleons forming the target (called "participants", x), while the other counterpart does not participate to the reaction. The spectator s will be then "free" from any effect due to the interaction between the incoming nucleus and the participants, keeping in the exit channel the same momentum distribution for the intercluster x - s motion inside A it had before the occurrence of the QF break-up.

In this framework an important test, the so-called "polar invariance", should be verified. It means that the study of a binary reaction of astrophysical interest, $a(x,c)C$, via a QF process with three particles in the exit channel, can proceed whatever the spectator particle is. It means that instead of studying the binary reaction through the $a(b,c)C$ reaction, one can study it by means of the $a(b',c)C$ reaction. This represents substantially the invariance of the upper vertex with respect to changes in the lower one (break-up of Trojan horse nucleus).

In a recent work [8] the pole approximation validity test was performed for the ${}^7\text{Li}(\text{d}, \alpha\alpha)\text{n}$ studied via the ${}^7\text{Li}({}^3\text{He}, \alpha\alpha){}^2\text{H}$.

In the paper it was shown that there was good agreement between data of the ${}^7\text{Li}(\text{p}, \alpha){}^4\text{He}$ binary reaction extracted from the two reactions. The excitation function was reproduced below and above the Coulomb barrier, confirming the applicability of the polar approximation in that case.

THE EXPERIMENT

The present experiment was aimed to study the ${}^6\text{Li}(\text{d}, \alpha){}^4\text{He}$ reaction by means of the THM applied to the ${}^6\text{Li}({}^3\text{He}, \alpha\alpha)\text{H}$ three-body reaction (Fig.1 left). The experiment was performed at the cyclotron Institute of the ASCR in Rež (Praha). The experimental details are

extensively reported in [9]. We will now focus the attention on the more recent results obtained in this study.

Among the first steps of the standard THM analysis we can put the investigation on the evidences of the QF mechanisms. Among all the observables that can be sensitive to the involved reaction mechanism is the shape of the momentum distribution $\phi(p_s)^2$. Thus the tests that allow to discriminate the QF contribution from all the others are based on the study of this quantity. In order to extract the experimental momentum distribution of the

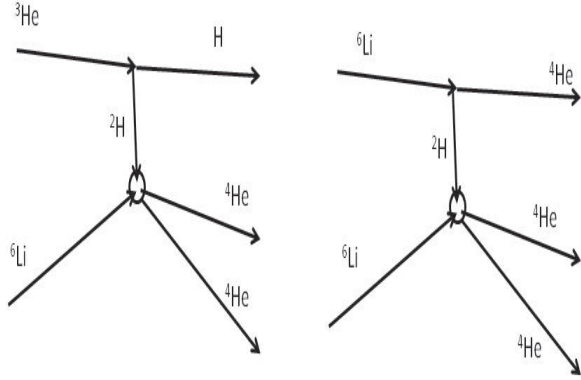


Figure 1. Quasi free reactions studied in the paper.

spectator, the energy sharing method can be applied to each pair of coincidence detectors, selecting narrow energy and angular windows, ΔE_{cm} and $\Delta \theta_{cm}$, as reported in [9].

Keeping in mind the factorization of typical of the PWIA and assuming $d\sigma/d\Omega^{HOES}$ is nearly constant in a narrow energy and θ_{cm} range one can get the shape of the momentum distribution of the undetected proton (after this test we can stress its role as a spectator to the QF process). The obtained momentum distribution for proton in ^3He is reported in picture 2. This result is consistent with what has been observed for the ^3He nucleus in [6-7] as regards the correlation between the transferred momentum ($q_t \approx 230$ MeV/c in the present case) and the width at half maximum of the experimental momentum distribution (in this case it is around 64 MeV/c).

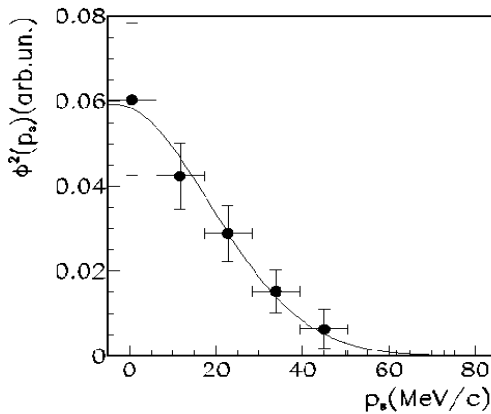


Figure 2. Momentum distribution for spectator measured in energy sharing

An alternative way was adopted to measure the momentum distribution of the spectator particle and therefore to test the presence of the QF mechanism. In fact the correlation between the coincidence yield projected on the E_{cm} variable for different spectator momentum intervals in a fixed center-of-mass angle $\Delta \theta_{cm} = 90^\circ \pm 5^\circ$. The obtained distribution is consistent with the one obtained with the standard method thus confirming the presence of the QF mechanism (its FWHM is about 62 ± 6 MeV/c). According to the prescription assumed in [1-8] the data in the $|p_s| < 30$ MeV/c range were chosen and used in the further analysis.

The results were compared with recent results on distortion effects in reactions induced by light nuclei [7]. The expected FWHM of the p momentum distribution in ^3He is around 66 ± 5 MeV/c. In figure 3 the good agreement of these results is shown thus confirming what was observed for ^3He in [7].

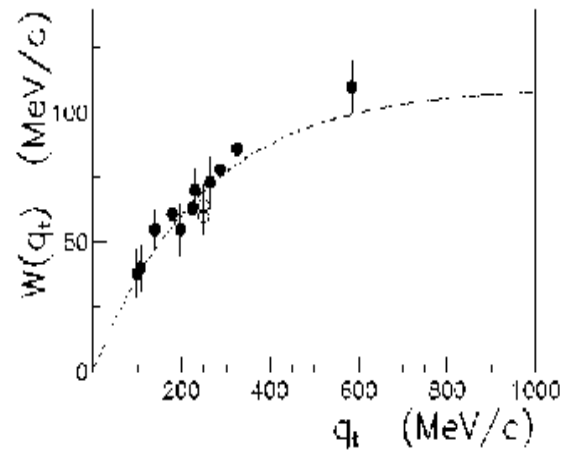


Figure 3. FWHM of the momentum distribution for spectator as a function of transferred momentum. Present data are plotted as empty dots.

RESULTS

In the standard THM analysis the two body cross section is derived by dividing the experimental three-body one for the Monte Carlo simulation which is used to calculate the product $KF \phi(p_s)^2$. The width of the momentum distribution was set to the experimentally measured value in order to account for the distortion effect which can arise at low transferred momenta [7].

In our case the angular distribution was extracted for $E_{cm} = 2.940$ MeV which corresponds to direct data present in literature [10].

In figure 4 the present data are compared with direct data extracted from [10] and a nice agreement shows up in the angular range where overlap is present. The good agreement is a necessary validity test, required by the prescription of THM.

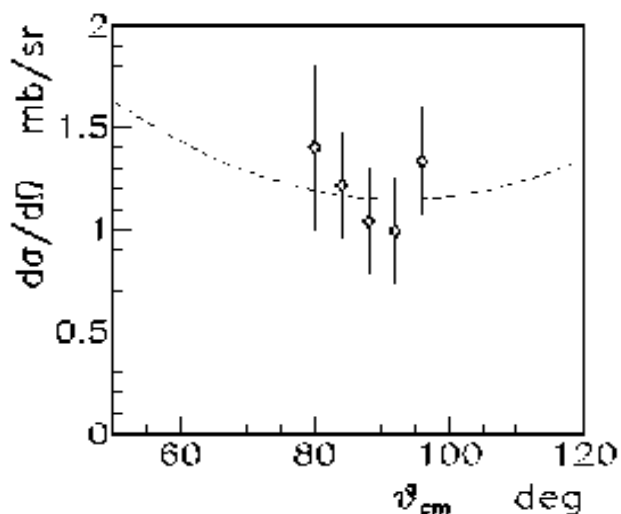


Figure 4. Indirect angular distribution obtained by means of THM (see text for details)

The reproduction of the direct excitation function both below and above the Coulomb barrier is another important check for the validity of the method.

Once the THM cross section is corrected for the penetrability factor (below the Coulomb barrier) which also make it possible the comparison of half-of-shell data and on-shell one. The penetrability factor is, as usual, described in terms of the regular and irregular Coulomb functions [2]. The measured cross section, extracted by the THM, is compared in the $E_{cm}=0.4 - 5$ MeV energy range with several data sets present in literature [10-14] (figure 5). The agreement is very good throughout the whole energy range after normalization of the indirect data to the direct ones. Moreover the resonance at about 3 MeV (corresponding to the $25.2 \text{ MeV}, 2^+$, status in ^8Be) is clearly reproduced.

Another interesting aspect of this analysis is the possibility to study the pole invariance of the quasi-free mechanisms [8].

This has been already done in the case of the $^7\text{Li}(p,\alpha)\alpha$ studied through the ^3He break-up as reported in [8]. Once again the agreement is both above and below the Coulomb barrier.

It is assumed, in fact, that changing the spectator particle in the quasi-free process (on which is founded the THM) doesn't give any change to the binary reaction of interest. This effect has been already explored in the case of the $^7\text{Li}(p,\alpha)\alpha$ reaction [8] where it was seen such an effect. If we zoom out the present data in the $0.4-1$ MeV energy range we can compare data for the $^6\text{Li}(d, \alpha)^4\text{He}$ arising from the $^6\text{Li}(^3\text{He}, \alpha\alpha)^2\text{H}$ reaction with the ones extracted from $^6\text{Li}(^6\text{Li}, \alpha\alpha)^4\text{He}$ [3] (see fig. 6), as sketched in figure 1 (right).

The agreement is very good within the experimental errors.

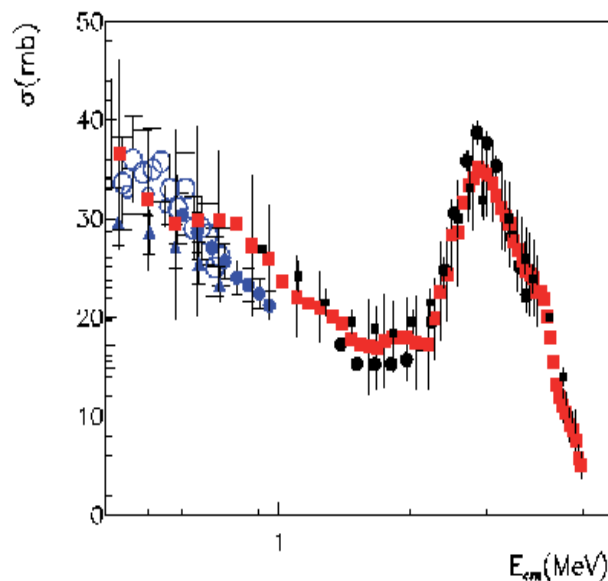


Figure 5. Indirect excitation function obtained by means of THM compared with direct data from [10-14] (see text for details)

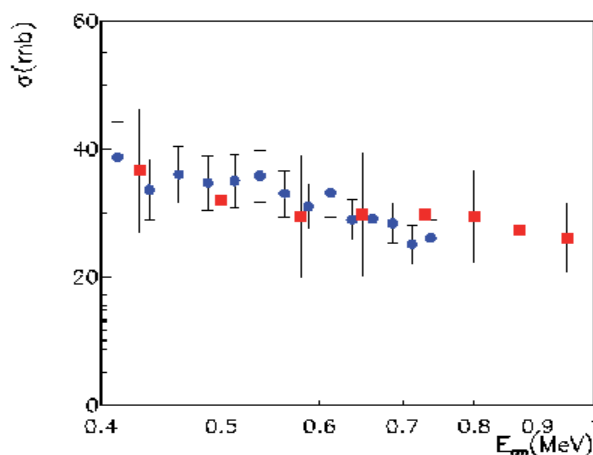


Figure 6. Excitation functions for the $^6\text{Li}(d, \alpha)^4\text{He}$ from ^6Li break-up (blue) and ^3He one (red) [11-15] extracted by means of THM

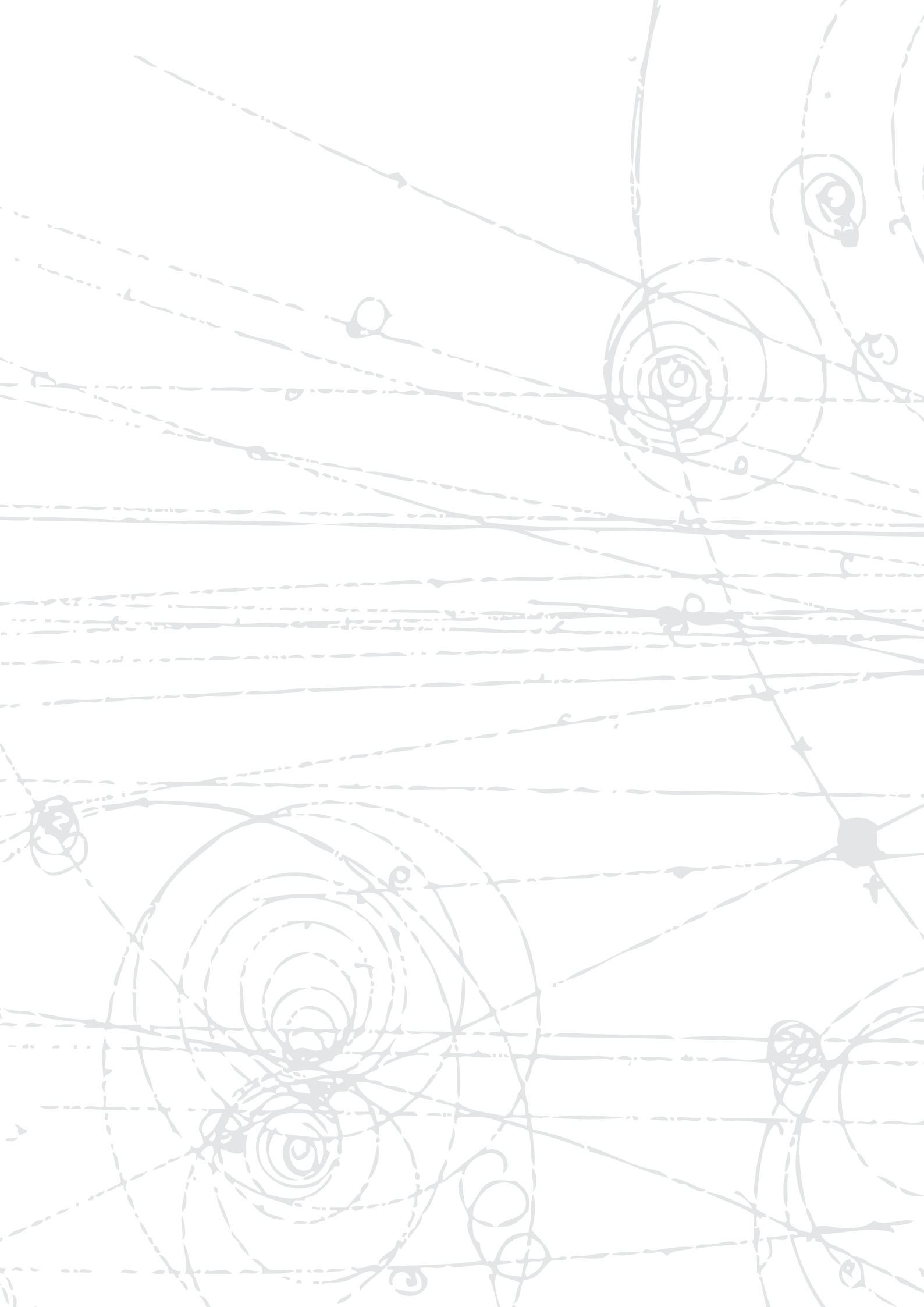
We can conclude by saying that the pole approximation is verified also in this case thus giving to the standard approach to the THM a stronger validation. Moreover in the examined, wide, energy range, the validity test is performed and the studied resonance in ^8Be reproduced.

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**THEORETICAL
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PHYSICS**

ISOSPIN OBSERVABLES IN THE FERMI ENERGY DOMAIN

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Abstract

We review recent results obtained for charge asymmetric heavy ion collisions at Fermi energies. Observables sensitive to the isospin dependent part of nuclear interaction are discussed, providing information on the symmetry energy behavior below normal density.

INTRODUCTION

The behavior of nuclear matter under several conditions of density and temperature is of crucial importance for the understanding of a large variety of phenomena, ranging from the structure of nuclei and their decay modes, up to the life and the properties of massive stars. Different mechanisms involving nuclear processes at fundamental level can be linked by the concept of nuclear Equation of State (EOS). In particular, over the past years, many efforts have been devoted to the investigation of the isovector part of the nuclear interaction, aiming at constraining the density dependence of the symmetry energy E_{sym} (Iso-EOS) [1, 2]. Transient states of nuclear matter far from normal conditions can be created in heavy ion collisions at Fermi and intermediate energies. Hence reactions with neutron-rich/poor systems and, in perspective, with exotic beams can be seen as a suitable tool to explore this issue. Our strategy to constrain the nuclear interaction is to implement effective density functionals, usually employed to model the nuclear potential, into transport codes, devoted to simulate the collisional dynamics. Here we follow the Stochastic Mean Field (SMF) approach [3]. Then predictions can be compared to experimental data for specific reaction mechanisms, and related observables, particularly sensitive to isospin effects. We will focus on collisions at Fermi energies, where one essentially explores the low-density behavior of E_{sym} . We will test an asy-soft parametrization, with an almost flat behavior of the symmetry energy below normal density ρ_0 , or an asy-stiff behavior, with a faster decrease at lower densities [4]. Hence, in the density domain of our interest, the symmetry energy is higher in the soft case, while the derivative of the symmetry energy is larger for the stiff parametrization.

ISOSPIN DIFFUSION IN SEMI-PERIPHERAL REACTIONS

We consider semi-peripheral reactions between two nuclei (denoted by H and L) having different N/Z and we investigate the diffusion of the initial isospin gradient. This process involves nucleon exchange through the low density neck region and hence it is sensitive to the low density behavior of E_{sym} [5–7]. Within a first order approximation of the transport dynamics, the relaxation of a given observable x towards its equilibrium value can be expressed as: $x_{P,T}(t) - x^{eq} = (x^{P,T} - x^{eq}) e^{-t/\tau}$, where $x^{P,T}$ is the x value for the projectile (P) or the target (T) before the diffusion takes place, $x^{eq} = (x^P + x^T)/2$ is the full equilibrium value, t is the elapsed time and τ is the relaxation time, that depends on the mechanism under study. The degree of isospin equilibration reached in the collision can be inferred by looking at isospin dependent observables in the exit channel, such as the asymmetry β of projectile-like (PLF) and target-like (TLF) fragments. It is rather convenient to construct the so-called imbalance ratio [5]:

$$R_{P,T}^x = (x_{P,T} - x^{eq}) / |x^{P,T} - x^{eq}| \quad (1)$$

Clearly, this observable measures the difference between the actual asymmetry of PLF (or TLF) and the full equilibrium value, normalized to the initial distance (i.e. to the conditions before the diffusion process has started). In the calculations the latter can be evaluated by looking at the asymmetries of PLF (or TLF), as obtained in the symmetric reactions HH and LL (where diffusion does not take place), after fast particle emission is over. Within our approximation, the imbalance ratio simply reads: $R_{P,T} = \pm e^{-t/\tau}$. According to this expression, the observable $R_{P,T}$ is actually independent of the initial asymmetry distance between the reaction partners and isolates the effects of the isodiffusion mechanism, whose strength is determined by the relaxation time τ , related to the symmetry energy. However the degree of equilibration reached in the reaction crucially depends also on the contact time t , i.e. on the reaction centrality. To pin down the information on E_{sym} we study the correlations between isospin equilibration and the kinetic energy loss, that is adopted as a centrality selector [6, 8]. The simple arguments developed above are confirmed by the simulations of ^{124}Sn (H) + ^{112}Sn (L) collisions at 35 and 50 MeV/u, that have been

carried out employing the SMF treatment with momentum dependent (MD) and momentum independent (MI) interactions [6]. In fig.1 we report the

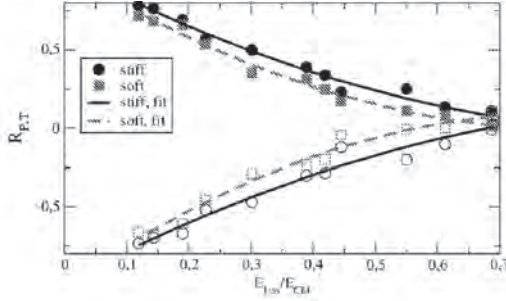


FIG. 1: Imbalance ratios as a function of relative energy loss for stiff (circles) and soft (squares) Iso-EOS, for calculations employing two parametrizations of the isoscalar part of the interaction: MD and MI (see text). Results are shown for the projectile region (full symbols) and the target region (open symbols). The lines represent quadratic fits to all points for the stiff (solid), resp. soft (dashed) Iso-EOS.

correlation between $R_{P,T}$ and the total kinetic energy loss, normalized to the total energy available in the center of mass E_{cm} , for the full set of calculations performed. One can see that all the points essentially follow a given line, depending only on the symmetry energy parametrization adopted. A larger equilibration (smaller R) is observed in the asy-soft case, corresponding to the larger value of E_{sym} at low density. We mention that, according to its definition, the imbalance ratio does not change if one considers as observable x , instead of the asymmetry of PLF and TLF, other observables that are linearly correlated to it and more accessible from the experimental point of view, such as isoscaling coefficients, ratios of production of light isobars [9] or isotopic content of light particle emission [10].

An experimental study of isospin diffusion as a function of the dissipated kinetic energy has been recently performed by the Indra collaboration [10]. Two systems, with the same projectile, ^{58}Ni , and two different targets (^{58}Ni and ^{197}Au), at incident energies of 52 MeV/u and 74 MeV/u have been considered, with the aim to study isospin diffusion between Ni and Au nuclei. An isospin-dependent variable, correlated to the PLF asymmetry, is constructed from the isotopically identified light particles emitted from the PLF, namely their average isotopic content, $(N/Z)_{CP}$. The analysis of this observable in terms of imbalance ratios is not possible for this set of reactions. Hence, in fig. 2 we plot directly the results of the SMF simulations concerning the variable $(N/Z)_{CP}$ (lines), calculated after de-exciting the hot primary PLF's with the help of the SIMON code [11]. One can notice (see top-left

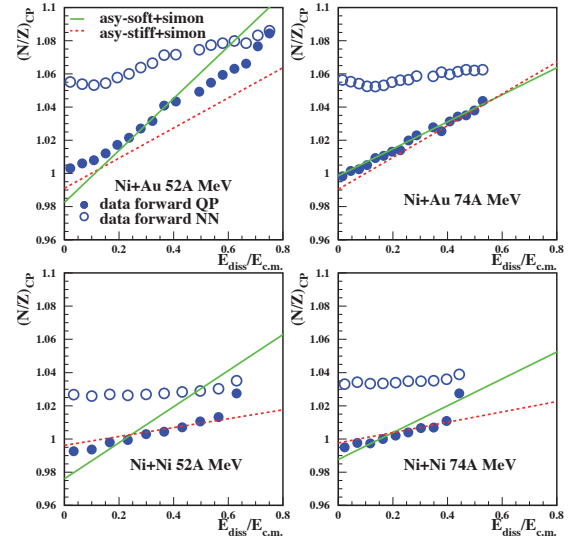


FIG. 2: Isospin ratio of complex particles for Ni quasi-projectile vs dissipated kinetic energy, for the two reactions and the two energies. Circles correspond to the experimental data, open for data forward of the N-N velocity, full for data forward in the PLF frame. Dotted lines are for asy-soft calculations and full lines for asy-stiff. Adapted from ref.[10].

panel) that isospin diffusion effects are larger in asy-soft case (full line), as expected. In fact, due to the larger value of the symmetry energy, the diffusion mechanism is more effective and the quasi-projectile becomes more neutron-rich. For the symmetric Ni + Ni system, isospin effects are only due to pre-equilibrium emission. Concerning the experimental data, open points show the values obtained forward in the nucleon-nucleon (NN) frame. In this case mid-rapidity particles and those coming from the PLF de-excitation are mixed up. The close points in fig.2 are related to the values of $(N/Z)_{CP}$ forward in the PLF frame. They are more representative of the isotopic content of the particles emitted from the PLF and can be compared with the results of the simulations. When looking globally at the results for the four cases treated here, the agreement is better when the asy-stiff EOS is used. However for Ni+Au at 52 MeV/u, where isospin transport effects are dominant, the close points lie in between the simulated results with the two iso-EOS. To conclude, this analysis points to a symmetry energy behavior in between the two adopted parametrizations, in agreement with other recent estimates [12, 13].

ISOSPIN DYNAMICS IN NECK FRAGMENTATION

It is now quite well established that the largest part of the reaction cross section for dissipative

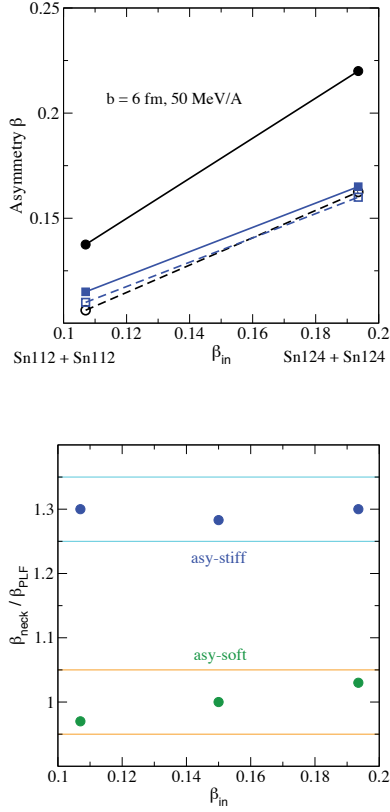


FIG. 3: Top panel: asymmetry of IMF's (circles) and PLF-TLF (squares), as a function of the system initial asymmetry, for two Iso-EOS choices: Asy-stiff (full lines) and asy-soft (dashed lines). Bottom panel: Ratio between the neck IMF and the PLF asymmetries, as a function of the system initial asymmetry. The bands indicate the uncertainty in the calculations.

collisions at Fermi energies goes through the *Neck Fragmentation* channel, with intermediate mass fragments (IMF) directly produced in the interacting zone in semiperipheral collisions on very short time scales [14]. It is possible to predict interesting isospin transport effects for this fragmentation mechanism since clusters are formed still in a dilute asymmetric matter but always in contact with the regions of the projectile-like and target-like remnants almost at normal densities. In presence of density gradients the isospin transport is mainly ruled by drift coefficients and so we expect a larger neutron flow to the neck clusters for a stiffer symmetry energy around saturation [1]. This is shown in fig.3 (top), where the asymmetry of the neck region is plotted for the two Iso-EOS choices, compared to the PLF-TLF asymmetry, for Sn + Sn reactions at 50 MeV/u, $b = 6 \text{ fm}$. In order to build observables less affected by secondary decay effects, in fig.3 (bottom) we consider the ratio of the asymmetries of the IMF's to those of the residues for stiff and soft iso-EOS. This quantity can be estimated on

the basis of simple energy balance considerations. Starting from a residue of mass A_{res} and a neck of mass A_{IMF} we assume that the mass A participating in the isospin exchange is approximately equal to the mass of the neck, while it is small relative to the mass of the residue. This will lead to the asymmetry $(\beta + \Delta\beta)$ of the neck, and to a total asymmetry $\beta_{res} = [\beta(A_{res} - A) + (\beta - \Delta\beta)A]/A_{res} = \beta - \Delta\beta A/A_{res}$ of the residue, with $\Delta\beta$ to be determined by minimization of the symmetry energy. The corresponding variation of the symmetry energy is equal (apart from a constant) to:

$$\Delta E_{sym} = A_{res} E_{sym}(\rho_R)(\beta - \Delta\beta A/A_{res})^2 + A E_{sym}(\rho_I)(\beta + \Delta\beta)^2, \quad (2)$$

where ρ_R and ρ_I are the densities of the residue and neck regions, respectively. The minimum of the variation of ΔE_{sym} yields

$$\frac{\beta_{IMF}}{\beta_{res}} = \frac{E_{sym}(\rho_R)}{E_{sym}(\rho_I)} \quad (3)$$

From this simple argument the ratio between the IMF and residue asymmetries should depend only on symmetry energy properties and, in particular, on the difference of the symmetry energy between the residue and the neck regions, as appropriate for isospin migration. It should also be larger than one, more so for the asy-stiff than for the asy-soft EOS. It is seen indeed in fig.3, that this ratio is nicely dependent on the iso-EOS only (being larger in the asy-stiff case) and not on the system considered. If final asymmetries were affected in the same way by secondary evaporation in the case of neck and PLF fragments, then one could directly compare the results of fig.3 (bottom) to data. However, due to the different size and temperature of the neck region with respect to PLF or TLF sources, de-excitation effects should be carefully checked with the help of suitable decay codes.

CONCLUSIONS

We have reviewed some aspects of the phenomenology associated with nuclear reactions at Fermi energies, from which new hints are emerging to constrain the EOS of asymmetric matter below normal density. A considerable amount of work has already been done in this domain. We note also recent confirmations from structure data, see for instance the study of monopole resonances in Sn-isotopes [15]. In the near future, thanks to the availability of both stable and rare isotope beams, more selective analyses, also based on new exclusive observables, are expected to provide further stringent constraints.



ACKNOWLEDGEMENTS

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NUCLEON-ION OPTICAL-MODEL POTENTIAL

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Abstract

The theoretical optical potential (elastic and absorptive bulk components) derived within the microscopic theory of nuclear matter, is compared with the empirical one. The isospin splitting is discussed, based on the analysis of the neutron and proton scattering in a large range of target nuclei and bombarding energies.

Theoretical model

Let us consider a nucleon travelling in nuclear matter. Its energy E and momentum p are connected by the mass shell relation

$$E = \frac{p^2}{2m} + S_t(E, p(E)), \quad (1)$$

where $\sum_\tau$ is the nucleon self-energy and τ the isospin. The self-energy is a complex quantity: its real (imaginary) part describes the optical potential of elastic (absorption) collisions. In this theoretical model it is made of three terms

$$S_t = U_t + iW_t = S_t^{bhf} + S_t^{cpol} + S_t^{3bf}, \quad (2)$$

where the first contribution is the self-consistent mean field, the second one is due to the medium polarization, and the third one comes from the three body force. In isospin asymmetric nuclear matter, namely $\beta = (N-Z)/A \neq 0$, the optical potential is isospin dependent. The isovector component, i.e. the shift $U_n - U_p$, between the neutron and proton potentials is plotted in Fig.1 as well as the corresponding imaginary part $W_n - W_p$. In both cases the deviation is linearly increasing with the neutron excess and it should become observable in the comparison between neutron and proton cross sections in the collisions with neutron-rich ions.

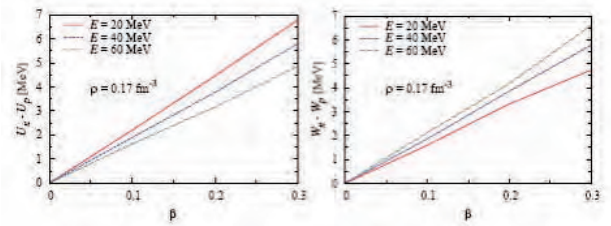


Fig.1 Elastic (left) and absorptive (right) part of the optical potential vs. isospin parameter for three

This theoretical prediction can be tested from the comparison with the empirical optical potential built up with a fit of the experimental elastic and absorption cross sections [2]. A selected number of results are reported in Figs.2-3. The agreement is satisfactory for the elastic component U of the optical potential, but less satisfactory for the absorption component W . However one should take into account that there is no any adjusted parameter in the theoretical model.

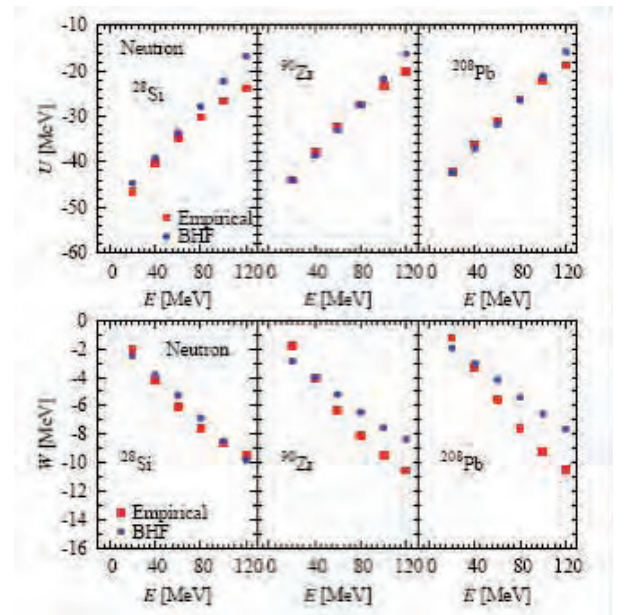


Fig.2 – Comparison between the empirical and theoretical optical potential for neutron-ion collisions.

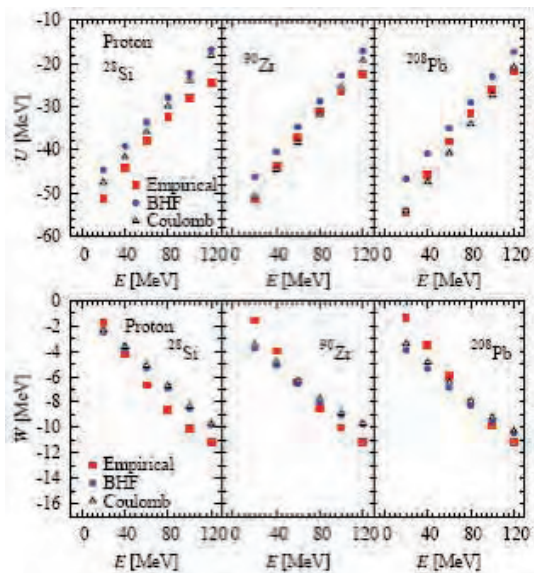


Fig.3 – Comparison between the empirical and theoretical optical potential for proton-ion collisions. The Coulomb correction is emphasized.

From a suitable folding of the volume term one can build up the nucleus-nucleus optical potential to describe heavy ion collisions, including the fusion of heavy and super heavy elements where phenomenological models are still used. The extension to the nucleus-nucleus potential would be of some interest also in the fit of elastic scattering data with halo projectiles.

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TRANSPORT PARAMETERS IN NEUTRON STARS

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Abstract

A calculation of the shear viscosity and thermal conductivity of β -stable nuclear matter is performed in the framework of the Brueckner theory. The results permit to make predictions on the damping time scales of non radial modes in neutron stars.

Introduction

Neutron stars are a unique laboratory for studying the equation of state (EoS) of nuclear matter at high density and isospin asymmetry, far above the typical range of heavy ion collisions and nuclei far from stability. But the observation data are still largely insufficient to constrain the EoS. The detection of gravitational waves could open prospects of investigation, because they drive the instability of neutron star oscillations, including non radial modes, and then rise the problem of the damping mechanisms necessary to stabilize the star rotation [1].

Good damping candidates are the viscosity and the thermal conductivity of the neutron star constituents. Their calculation within microscopic, i.e. based on bare interactions, models of nuclear matter [2] requires to know the nucleon effective masses and the medium renormalized nucleon-nucleon (NN) interaction. The nucleon effective masses are plotted in Fig.1 in different configurations of neutron matter, including the β -equilibrium one that simulates the neutron star interior structure. The reduction of the effective masses leads to a reduction of the states available to nucleons before and

in the forward and backward directions is due to the effective NN-interaction as a consequence of the medium correlations particularly strong in the two particle S-wave channel. As shown in Figs.2-3, the effect in the angular distribution of the NN cross sections is not only a sizable quenching, but also a flattening.

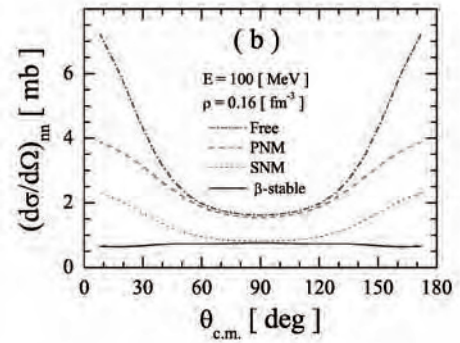


Fig.2 – Neutron-neutron cross section at the NM saturation density and $E=100$ MeV in the lab frame.

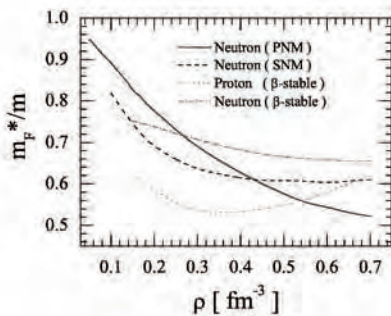


Fig.1 – Neutron and proton effective masses.

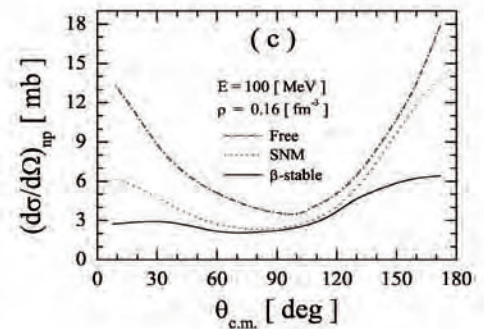


Fig.3 – Neutron-proton cross section as in Fig.2.

after their collisions and then the NN cross section turns out to be reduced either. Additional quenching, specially

Transport parameters

The phenomenological equations of thermal and mass transport in a viscous fluid are, respectively, the

following ones [3]:

$$\frac{2}{3} \rho \left(\frac{\partial}{\partial t} + u \cdot \nabla \right) \theta = -\rho (\nabla \cdot u) \theta + K \Delta \theta$$

$$\rho \left(\frac{\partial}{\partial t} + u \cdot \nabla \right) u = f - \nabla \left(p - \frac{\eta_v}{3} \nabla \cdot u \right) + \eta \Delta u$$

where the conductivity K drives the temperature gradients and the volume and shear viscosity, η_v and η , drive the collective motion. All transport parameters in a nuclear fluid are determined by the nucleon-nucleon collisions in the medium. The thermal conductivity K , calculated from

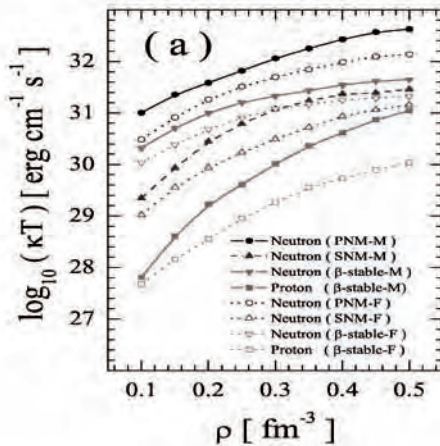


Fig. 4 – Thermal conductivity of nucleons vs. density in different states of nuclear matter.

the above described in-medium NN cross sections, is plotted in Fig.4 at zero temperature. As expected K is an increasing function of density, including the neutron and proton K in β -stable nuclear matter. The latter was calculated for the sake of application in the neutron star interior, where the baryons are supposed to be in equilibrium with leptons (electrons and muons). The equilibrium condition is such that the neutron fraction is much larger than the proton one at low density, less at higher density but still dominant. This effect can be also seen in the behaviour of K vs. density. The shear viscosity, plotted in Fig.5 for the same configurations of nuclear matter, exhibits similar features.

The transport parameters, viscosity and thermal conductivity, calculated for β -stable nuclear matter, can be used to determine the respective time scales of various configurations of nuclear

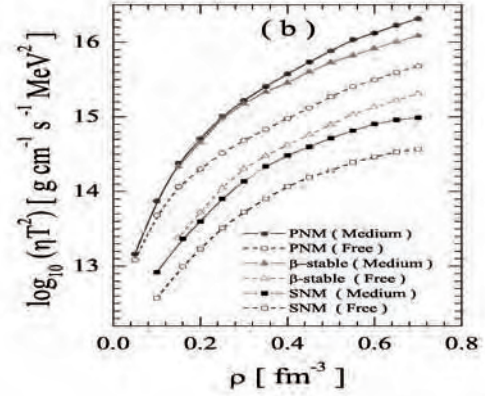


Fig.5 – Shear viscosity of nucleons vs. density in various states of nuclear matter.

energy dissipation τ_v and τ_T during the oscillations of neutron stars. This requires to integrate $\eta(\rho)$ and $\kappa(\rho)$ weighted on the density profile $\rho(r)$ of the neutron star in the range $0 \leq r \leq R$, R being the neutron star radius. The latter can be obtained solving the Tolman-Oppenheimer-Volkov (TOV) equation with a given equation of state of nuclear matter. Besides the density profile, the TOV solutions provide the all possible stable configurations of the neutron stars, namely the mass radius plot, giving for each radius the corresponding mass. In Table I the damping time scales of the Y_{22} non radial modes are reported for a number of neutron star mass-radius configurations. These data are taken from Ref.[4], where the TOV equation was solved using the EoS derived from the theoretical model used to calculate in medium cross sections. The low temperature results show that the energy dissipation mechanism due to the neutron viscosity is of the same order of magnitude of the time scale associated to gravitational waves (~ 100 sec), at least at high density.

The proton contribution is much less important, since the time scale is proportional to the density. In other words the instability driven by gravitation radiation is prevented for cold neutron stars. This theoretically supports the observations of rotating neutron stars in the long era stages. On the contrary, the high temperature time scales are too large by several order of magnitude and no help can be expected by superfluidity since the critical temperature is much less than that of the newborn star.

Conclusions

The calculation of the nucleon transport parameters was performed in beta-stable nuclear matter for the sake of application to neutron stars. The theoretical framework was the fully microscopic theory of nuclear matter based on the realistic NN interaction. The main result is the remarkable enhancement of the transport coefficients due

to the suppression of the cross sections for nucleon-nucleon collisions in the medium. A preliminary estimate of time scales of non radial mode damping shows that only in cold stars the dissipation times due to viscosity are

M/ M _⊙	R (Km)	ρ(gr/cm ³) x 10 ¹⁴	t _η (sec)		t _κ (sec)
			10 ⁶ K	3x10 ¹¹ K	
0.8	12.8	1.8	1865	3 x 10 ¹⁴	0.54x10 ¹⁶
1.4	12.5	3.4	1680	1.68x10 ¹⁴	1.5x 10 ¹⁶
1.8	12.2	4.7	883	8.8 x 10 ¹³	3 x 10 ¹⁵
2.3	11.0	8.25	317	3.2 x 10 ¹³	6 x 10 ¹⁵

Tab.1 - Time scales of damping of Y₂₂ non radial modes due to the energy dissipation via neutron viscosity and thermal conductivity.

on the realistic NN interaction. The main result is the remarkable enhancement of the transport coefficients due to the suppression of the cross sections for nucleon-nucleon collisions in the medium. A preliminary estimate of time scales of non radial mode damping shows that only in cold stars the dissipation times due to viscosity are comparable with the gravitational radiation time, whereas the effect of thermal conduction is negligible.

For the application of the transport properties to neutron stars, one should also include strange matter in the beta-stable nuclear matter. In fact the strange particle fractions are increasing with density in the inner core, where they can contribute with the 20 per cent to the total baryonic matter. In the case of hybrid stars the quark matter can compete with baryons; therefore the contribution to transport properties of quarks must be considered with a consistent treatment of hadron-to-quark transition. The last two research issues, superfluidity and transport properties of non nucleonic components are presently under investigation.

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ISOSPIN-DEPENDENT NUCLEAR PAIRING INTERACTION

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Abstract

The isospin dependence of the effective pairing interaction is discussed on the basis of the BCS theory of superfluid asymmetric nuclear matter. It is shown that the energy gap, calculated within the mean field approximation in the range from symmetric nuclear matter to pure neutron matter, is not linearly dependent on the isospin-asymmetry parameter due to the non linear structure of the gap equation. This result is in contrast with the recent extensions of the density-dependent effective pairing interaction applied to fit $N \neq Z$ nuclei.

BCS theory in nuclear matter

The BCS theory of superconductivity is normally extended to the nuclear pairing. In this latter case the pairing interaction is the nuclear potential itself $V(k, k')$, instead of the phonon exchange interaction.

Because of the correlations in nuclear matter the vertex corrections (screening) and the self-energy effects (medium polarization) are quite strong. But there is an indication that their effects cancel each other [1], so that the pure BCS theory seems to work quite well in nuclei.

The basic equations of BCS theory are

$$\Delta_{\tau}(k) = - \sum_{k'} \frac{V(k, k') \Delta_{\tau}(k')}{2E_{\tau}(k')}, \quad (1)$$

$$N_{\tau} = \sum_k \left(1 - \frac{\epsilon_{\tau}(k) - \mu_{\tau}}{E_{\tau}(k)}\right), \quad (2)$$

The quasiparticle energy E_{τ} (particle energy corrected by the gap Δ) is determined by the mean field

$$U_{\tau}(k) = U_{\tau, \tau} + U_{\tau, \tau'} = \sum_{k'} \langle \vec{k} \sigma \tau, \vec{k}' \sigma' \tau' | G | \vec{k} \sigma \tau, \vec{k}' \sigma' \tau' \rangle_A$$

where the effective interaction is described by the G-matrix to take into account the short range correlations. U_{τ} ($\tau=1$ for neutrons, $= -1$ for protons) is the only quantity that gives rise to the isospin effects because $U_n \neq U_p$ in asymmetric matter, regardless the Coulomb interaction.

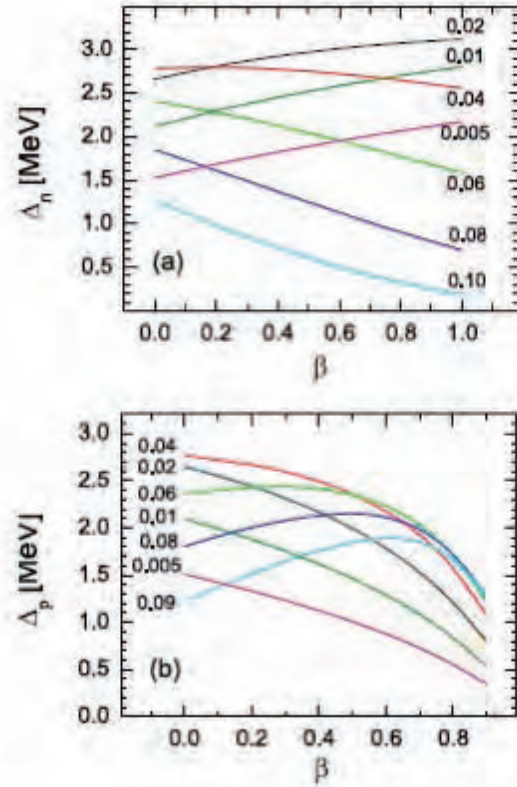


Fig.1 – Neutron (upper panel (a)) and proton (lower panel (b)) pairing gap in asymmetric nuclear matter vs. the asymmetry parameter $(N-Z)/A$ for a number of nuclear densities.

Solving the two gap equations, Eqs.(1)-(2), for the 1S_0 pairing in asymmetric nuclear matter, the pairing gaps were calculated as a function of the asymmetry parameter [2]. The numerical values are displayed in Fig.1 for a set of nuclear matter densities. The numbers attached to the curves are the corresponding densities (in units fm^{-3}).

The interaction chosen for this calculation is the Argonne AV18, which is also used to calculate the BHF potential U_{τ} . In symmetric nuclear matter $\Delta_n = \Delta_p$ because the nuclear interaction is charge independent (we neglect the Coulomb force). Increasing the density the behavior of neutron and proton gaps is different. Recalling that the density 0.02 fm^{-3} corresponds to the peak value of the gap

in neutron matter, for density less than 0.04 the β -slope is positive in the range $0 < \rho < 0.04$ and negative for range $\rho > 0.04$, when going from symmetric to pure neutron matter. The effect of the neutron mean field is very small, because it is weak, and the β -dependence is almost linear. The contrary happens for protons, but in this case the proton mean field affects the gap so much to give rise to a non linear β -dependence as shown clearly in the figure. These results give a clear indication of how to modify the effective pairing interaction to study the isospin effect in the nuclear gaps.

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Elliptic Flow at Finite Shear Viscosity in a Kinetic Approach at RHIC

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Within a covariant parton cascade, we discuss the impact of both finite shear viscosity η and freeze-out dynamics on the elliptic flow generated at RHIC. We find that the enhancement of η/s in the cross-over region of the QGP phase transition cannot be neglected in order to extract the information from the QGP phase. We also point out that the elliptic flow $v_2(p_T)$ for a fluid at $\eta/s \sim 0.1 - 0.2$ is consistent with the one needed by quark number scaling drawing a nice consistency between the nearly perfect fluid property of QGP and the coalescence process.

I. INTRODUCTION

The measure of the elliptic flow, $v_2(p_T)$, in the ultra-relativistic heavy ion collisions at the Relativistic Heavy Ion Collider (RHIC) has revealed that the so-called quark-gluon plasma (QGP) is an almost perfect fluid. However several approaches indicate that even a small finite value of the shear viscosity to entropy density ratio $\eta/s \sim 0.1 - 0.2$ affect significantly the strength of $v_2(p_T)$ [1, 2]. Hence viscous corrections to ideal hydrodynamics are indeed large and causality and stability problems present in first order relativistic Navier Stokes hydrodynamics cannot be avoided [3, 4]. Second-order Israel-Stewart approach has been developed to simulate the RHIC collision providing a first estimate of the η/s [3]. Such an approach, apart from the limitation to 2+1D simulations, has the more fundamental problem that it is based on a gradient expansion at second order that is not complete and that anyway cannot be sufficient to describe correctly the dynamics of a fluid with large η/s as the one in the hadronic phase [3, 4].

We have developed a covariant kinetic approach that is able to simulate a fluid at finite η/s by mean of a local renormalization of the cross section, $\sigma \cdot \eta/s = \langle p \rangle / 15 \rho$, similarly to [4], see Ref.[5, 6] for more details. This has the advantage to be a 3+1D approach not based on a gradient expansion that is valid also for large viscosity and for out of equilibrium momentum distribution allowing a reliable description also of the intermediate p_T range where the important properties of quark number scaling (QNS) of $v_2(p_T)$ have been observed [7].

II. IMPACT OF η/s INCREASE IN THE CROSS-OVER REGION

We focus on the $Au + Au$ collisions at $\sqrt{s} = 200$ AGeV employing standard Glauber initial conditions in r -space, a Boltzmann equilibrium distribution in momentum space for partons at $p_T < 2$ GeV

and a minijet distribution at higher p_T .

A first objective is to evaluate the importance of the increase of the η/s of the matter in the cross-over transition and in the hadronic phase [8]. This is of particular relevance because most of the work done till now to evaluate η/s has been done in the viscous hydrodynamics framework keeping the η/s constant during the entire evolution of the hadronic phase [1, 2]. As also mentioned in Ref.[3], it is desirable to take into account the evolution of the η/s inside and below the QCD phase transition. We have realized this imposing an increase of the η/s as a function of the local energy density, as shown in Fig.1. While in hydrodynamics the η/s is kept constant during the entire evolution of the system (dashed lines) in our calculation it increases when the

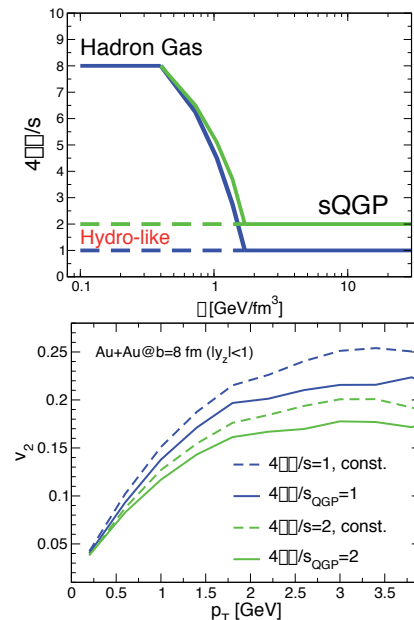


FIG. 1: Left: $4\eta/s$ vs energy density ϵ for various simulations performed; Right: Elliptic flow vs. p_T for different cases; solid lines refer to calculation with η/s increasing at $\epsilon < \epsilon_0$.

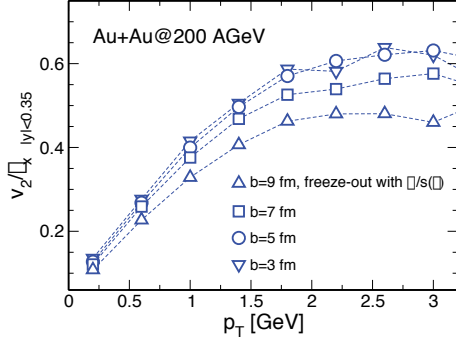


FIG. 2: The $v_2(p_T)$ over eccentricity for different impact parameters.

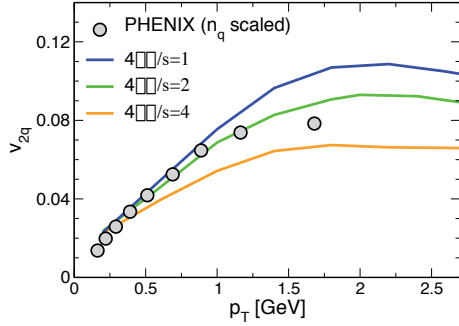


FIG. 3: Elliptic flow vs. p_T for three different value of η/s_{QGP} at $b=5\text{fm}$. Circles are data for the corresponding centrality [10] rescaled according to the n_q -scaling.

The impact of such increase on the $v_2(p_T)$ is shown on the right side of Fig.1. We see that even if most of the $v_2(p_T)$ is built up during the pure QGP phase, the cross-over region can still produce a damping of the elliptic flow. Such a finding is similar to Ref.[9], but here it is entwined in the

context of QGP finite η/s showing the relevance for its evaluation. From Fig.1 we can deduce that neglecting the expected increase of η/s across the transition can introduce a systematic error of the order of 40 – 50%.

III. SCALINGS OF v_2

An energy density dependent η/s represents also a way to realize a smooth kinetic freeze-out (f.o.) of the system. In Ref.[6], Fig.2 here, we have shown that it is indeed the f.o. mainly responsible for the observed breaking of the scaling of $v_2(p_T)$ with the initial space eccentricity ϵ_x [10, 11], at variance with ideal hydrodynamics prediction. We notice the effect of viscosity increases with p_T and is larger in the intermediate- p_T region see Fig.3. Moreover when both a suitable f.o. condition and a finite η/s are taken into account for the description of the fireball evolution, not only the breaking of the v_2/ϵ_x scaling is reproduced along with the persistent $v_2(p_T)/\langle v_2 \rangle < 1$ [11], but also the shape of $v_2(p_T)$ is consistent with the one expected from QNS [7]. In Fig.3 $v_2(p_T)$ at partonic level for different η/s is shown together with the data from PHENIX, rescaled by the number of quarks that in the QNS scenario should correspond to quark one. We can see that a $\eta/s \sim 0.15 - 0.2$ is consistent with n_q scaling. Quantitatively a comparison with experiments needs the inclusion of an equation of state with phase transition that in the context of hydrodynamics has been shown to reduce significantly the v_2 [2] and therefore it can be envisaged to shift the agreement with the data down to $\eta/s \sim 0.1$. The inclusion of a mean field dynamics with phase transition is under investigation [12].

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SYMMETRY ENERGY EFFECTS ON THE MIXED HADRON-QUARK PHASE AT HIGH BARYON DENSITY

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Abstract

The phase transition of hadronic to quark matter at high baryon and isospin density is analyzed. Relativistic mean field models are used to describe hadronic matter, and the MIT bag model is adopted for quark matter. The boundaries of the mixed phase and the related critical points for symmetric and asymmetric matter are obtained. Due to the different symmetry term in the two phases, isospin effects appear to be rather significant.

With increasing isospin asymmetry the binodal transition line of the (T, ρ_B) diagram is lowered to a region accessible through heavy ion collisions in the energy range of the new planned facilities, e.g. the FAIR/NICA projects. Some observable effects are suggested, in particular an *Isospin Distillation* mechanism with a more isospin asymmetric quark phase, to be seen in charged meson yield ratios, and an onset of quark number scaling of the meson/baryon elliptic flows.

INTRODUCTION

A very large activity, in theory as well as in experiment, is devoted to the knowledge of the symmetry energy at high densities [1]. This is of great interest for neutron star properties as well as for particle production in heavy ion collisions at intermediate energies. Here we discuss the implications on the expected hadron-quark first order phase transition at high baryon densities.

Several suggestions are already present about the possibility of interesting isospin effects on the transition to a mixed hadron-quark phase at high baryon density [2–4]. This seems to be a very appealing physics program for the new facilities, FAIR at GSI-Darmstadt [5] and NICA at JINR-Dubna [6], where heavy ion beams (even unstable, with large isospin asymmetry) will be available with good intensities in the 1-30 AGeV energy region.

The weak point of those predictions is the lack of a reliable equation of state that can describe with

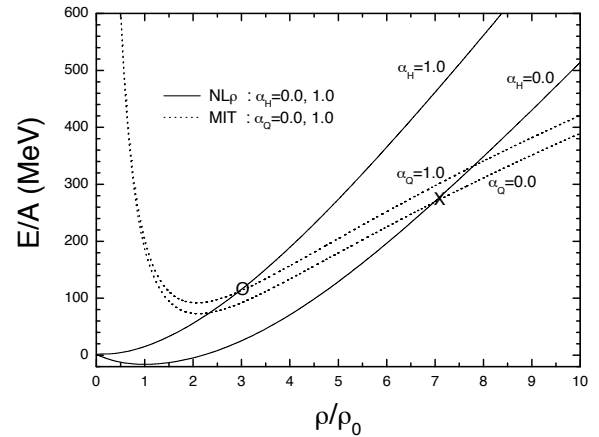


FIG. 1: Zero temperature *EoS* of Symmetric/Neutron Matter: Hadron (*NLρ*), solid lines, vs. Quark (MIT-Bag), dashed lines. $\alpha_{H,Q}$ represent the isospin asymmetry parameters respectively of the hadron, quark matter: $\alpha_{H,Q} = 0$, Symmetric Matter; $\alpha_{H,Q} = 1$, Neutron Matter.

the same confidence the two phases, hadronic and deconfined at high baryon density. On the other hand this also represents a strong theory motivation to work on more refined effective theories for a strong interacting matter. The aim of our work is just to show new results that would further stimulate the search in the field.

The main qualitative argument in favor of noticeable isospin effects on the hadron-quark transition at high density can be derived from the Fig.1, where we compare typical Equations of State (*EoS*) for Hadron (Nucleon) and Quark Matter, at zero temperature, for symmetric ($\alpha \equiv (\rho_n - \rho_p)/\rho_B \equiv -\rho_3/\rho_B = 0.0$) and neutron matter ($\alpha = 1.0$), where $\rho_{n,p}$ are the neutron/proton densities and $\rho_B = \rho_n + \rho_p$ the total baryon density [7].

In this simple, “homework”, calculation for the hadron part we use a Relativistic Mean Field (RMF) EoS ([8, 9]) with non-linear terms and an effective ρ – meson coupling for the isovector part, largely used to study isospin effects in relativistic heavy ion collisions [4, 9].

The energy density and the pressure for the quark phase are given by the MIT Bag model [12] (two-flavor case) where the bag constant (the bag pressure), taken as a rather standard value from the hadron spectra ($B = 85.7 \text{ MeV fm}^{-3}$, $B^{1/4} = 160 \text{ MeV}$, no density dependence).

The transition to the more repulsive quark matter will appear around the crossing points of the two EoS. We see that such crossing for symmetric matter ($\alpha_H = \alpha_Q = 0.0$) is located at rather high density, $\rho_B \simeq 7\rho_0$, while for pure neutron matter ($\alpha_H = \alpha_Q = 1.0$) it is moving down to about three times ρ_0 . Of course the Fig.1 represents just a simple energetic argument to support the hadron-quark transition to occur at lower baryon densities for more isospin asymmetric matter. Since the first order phase transition presents a jump in the energy, we can expect the mixed phase to start at densities even before the crossing points of the Fig.1. The lower boundary then can be predicted at relatively low baryon densities for asymmetric matter, likely reached in relativistic heavy ion collisions.

ISOSPIN EFFECTS ON THE MIXED PHASE

The structure of the mixed phase for a system with two conserved charges (baryon and isospin) is obtained by imposing the Gibbs conditions for chemical potentials and pressure and by requiring the conservation of the total baryon and isospin densities [3, 7].

Nucleon and quark chemical potentials, as well as the pressures in the two phases, are directly derived from the respective EoS.

In this way we get the *binodal* surface which gives the phase coexistence region in the (T, ρ_B, ρ_3) space. For a fixed value of the total asymmetry $\alpha_T = -\rho_3/\rho_B$ we will study the boundaries of the mixed phase region in the (T, ρ_B) plane. Since in general the charge chemical potential is related to the symmetry term of the EoS, [9], $\mu_3 = 2E_{sym}(\rho_B) \frac{\rho_3}{\rho_B}$, we expect critical and transition densities rather sensitive to the isovector channel in the two phases.

In the hadron sector we will use the Non-Linear Relativistic Mean Field models, [4, 8, 9], with different structure of the isovector part, already tested to describe the isospin dependence of collective flows and meson production for heavy ion collisions at intermediate energies, [13–15]. We will refer to these different Iso-Lagrangians as: i) *NL*, where no isovector meson is included and the symmetry

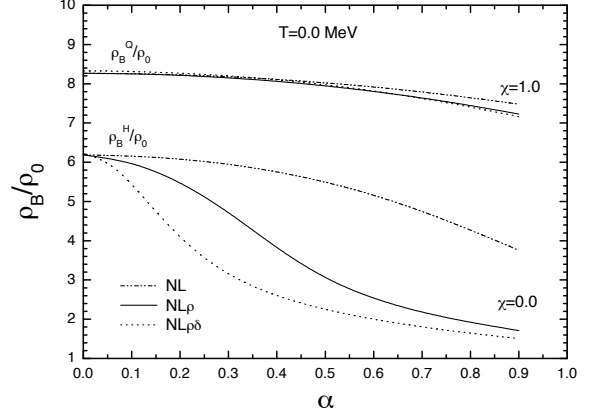


FIG. 2: Dependence on the Hadron Symmetry Energy of the Lower ($\chi = 0.0$) and Upper ($\chi = 1.0$) Boundaries of the Mixed Phase, at zero temperature, vs. the asymmetry parameter. Quark EoS: MIT bag model with $B^{1/4}=160 \text{ MeV}$.

term is only given by the kinetic Fermi contribution, ii) *NL ρ* when the interaction contribution of an isovector-vector meson is considered and finally iii) *NL $\rho\delta$* where also the contribution of an isovector-scalar meson is accounted for.

We will look at the effect on the hadron-quark transition of the different stiffness of the symmetry term at high baryon densities in the different parametrizations. As clearly shown in [8], where a rather transparent form for the density dependence of the symmetry energy in RMF approaches is discussed, the potential part of the symmetry term will be proportional to the baryon density in the *NL ρ* choice and even stiffer in the *NL $\rho\delta$* case.

We are well aware that there are several uncertainties on the stiffness of the symmetry energy at high baryon density, mainly due to the lack of suitable data, see the reviews [9, 10]. Therefore we will show also results with effective hadron interactions based on RMF models with density dependent meson-nucleon couplings (*DDRH* forces) [11], that present much softer symmetry terms at high baryon density. In this way we can directly check the “stability” of the observed isospin effects on the mixed phase.

As already mentioned, in the quark phase we use the MIT-Bag Model, where the symmetry term is only given by the Fermi contribution.

A relatively simple calculation can be performed at zero temperature. The isospin effect (asymme-

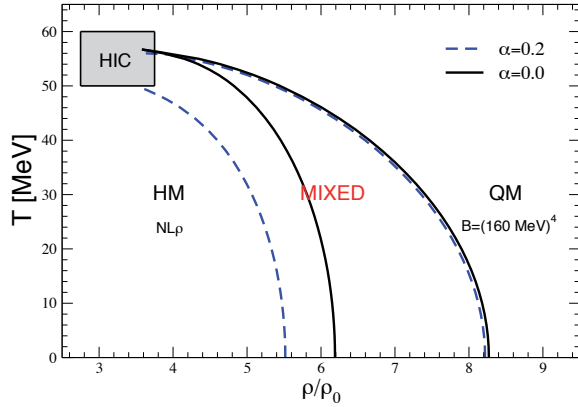


FIG. 3: Binodal surface for symmetric ($\alpha = 0.0$) and asymmetric ($\alpha = 0.2$) matter. Hadron EoS from $NL\rho$ interaction. Quark EoS: MIT bag model with $B^{1/4}=160$ MeV. The grey region corresponds to the conditions reached in Heavy Ion Collisions simulations at few AGeV beam energies, see Section 5.

try dependence) on the Lower ($\chi = 0.0$) and Upper ($\chi = 1.0$) transition densities of the Mixed Phase are shown in Fig.2 for various choices of the Hadron EoS. The effect of a larger repulsion of the symmetry energy in the hadron sector, from NL to $NL\rho$ and to $NL\rho\delta$, is clearly evident on the lower boundary with a sharp decrease of the transition density even at relatively low asymmetries.

Typical results for isospin effects on the whole binodal “surface” are presented in Fig.3 for symmetric and asymmetric matter. As expected, the lower boundary of the mixed phase is mostly affected by isospin effects. In spite of the relatively small total asymmetry, $\alpha = 0.2$, we clearly observe in Fig.3 a shift to the left of the first transition boundary, in particular at low temperature, and an indication of a relatively “earlier” Critical End Point, around ($T_c = 50-55$ MeV, $\rho_c/\rho_0 = 2.5-2.8$).

INSIDE THE MIXED PHASE OF ASYMMETRIC MATTER

From Figs.2, 3 the conclusion seems to be that for a stiffer symmetry term in a heavy-ion collision at intermediate energies during the compression stage we can have more chance to probe the mixed phase, although in a region with small weight of the quark component, see also [7].

Can we expect some signatures related to the subsequent hadronization in the following expansion?

An interesting possibility is coming from the study of the asymmetry α^Q in the quark phase. In fact since the asymmetry energy is rather different in the two phases we can expect an Isospin Distillation (or Fractionation), very similar to the one observed in the Liquid-Gas transition in dilute nuclear mat-

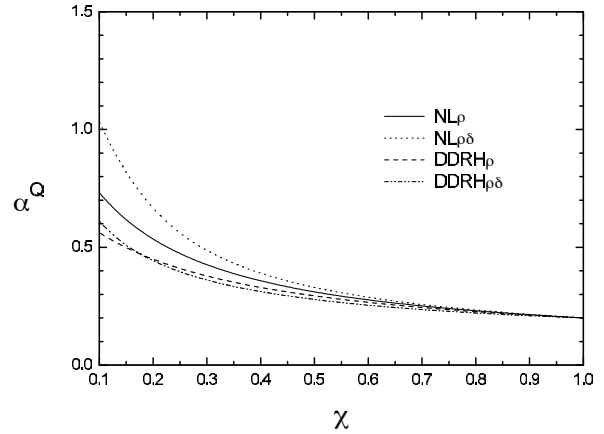


FIG. 4: Quark asymmetry in the mixed phase vs. the quark concentration for asymmetric matter with $T = 0$ and $\alpha = 0.2$. $NL\rho$ and $NL\rho\delta$ Effective Hadron Interactions are considered. The corresponding results with Density Dependent couplings are also shown. Quark EoS: MIT bag model with $B^{1/4}=160$ MeV.

ter [9, 16], this time with the larger isospin content in the higher density quark phase.

In Fig.4 we show the asymmetry α^Q in the quark phase as a function of the quark concentration χ for the case with global asymmetry $\alpha = 0.2$ (zero temperature). We see an impressive increase of the quark asymmetry when we approach the lower boundary of the mixed phase. Of course the quark asymmetry recovers the global value 0.2 at the upper boundary $\chi = 1$. A simple algebraic calculation allows to evaluate the corresponding asymmetries of the hadron phase [7].

For a 20% quark concentration we have an α^Q/α^H ratio around 5 for $NL\rho$ and around 20 for $NL\rho\delta$, more repulsive in the isovector channel. It is also interesting to compare the isospin content N/Z of the high density region expected from transport simulations without the Hadron-Quark transition and the effective N/Z of the quark phase in a 20% concentration. In the case of $Au + Au$ (initial $N/Z = 1.5$) central collisions at 1 AGeV in pure hadronic simulations we get in the high density phase a reduced $N/Z \sim 1.2 - 1.25$ (respectively with $NL\rho\delta - NL\rho$ interactions) due to the fast neutron emission [14, 15]. The corresponding isospin content of the quark phases is much larger, $N/Z = 3.0$ for $NL\rho$ and $N/Z = 5.7$ for $NL\rho\delta$. This is the *neutron trapping* effect: we would expect a signal of such large asymmetries, coupled to a larger baryon density in the quark phase, in the subsequent hadronization.

Results with a softer symmetry term at high baryon densities

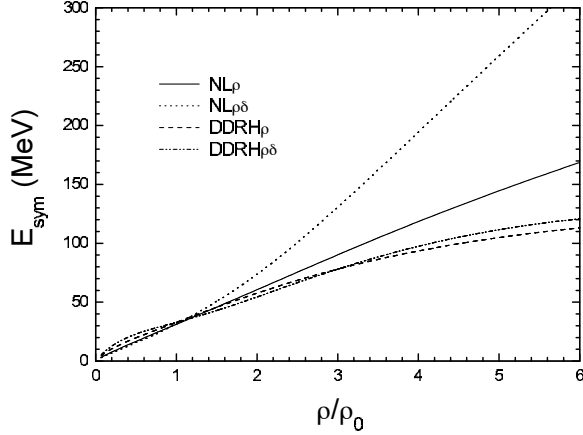


FIG. 5: Density dependence of the symmetry energy for the used RMF hadron effective models. $NL\rho$ and $NL\rho\delta$ represent the Non-Linear Effective Hadron Interactions with constant couplings. The corresponding results with Density Dependent couplings are also shown.

In order to account for the the present uncertainties on our knowledge of the symmetry term of the hadron EoS at high baryon density, see also the recent [17], we have performed a new calculation using a RMF hadron interaction which gives a much softer behavior of the symmetry energy at high densities. In this way we can check the “robustness” of the expected isospin effects on the mixed phase discussed before. We use a Density Dependent Relativistic Hadron (DDRH) field approach, where an explicit density dependence of the meson-nucleon couplings is introduced [11]. As clearly shown in Fig.5, the main difference with respect to the previously presented results is that the symmetry energy is now less repulsive at high density. This is due to the fact that, following some indications from Dirac-Brueckner calculations [18, 19], the isovector-meson couplings in the $DDRH\rho$ and $DDRH\rho\delta$ cases show an increase for the attractive δ -field and a decrease for the repulsive ρ -field.

Fig.6 shows the new shifts to the left of the lower boundaries. The new *Isospin Distillation* mechanism is presented in the $DDRH$ results added in the Fig.4 about the isospin asymmetry in the quark phase for different quark concentrations. We can conclude that isospin effects on the hadron-quark transition are still present, although with some reduction.

PERSPECTIVES AND SUGGESTED OBSERVABLES

Based on the qualitative argument of the Introduction and on more detailed calculations in a first order phase transition scheme, we have predicted

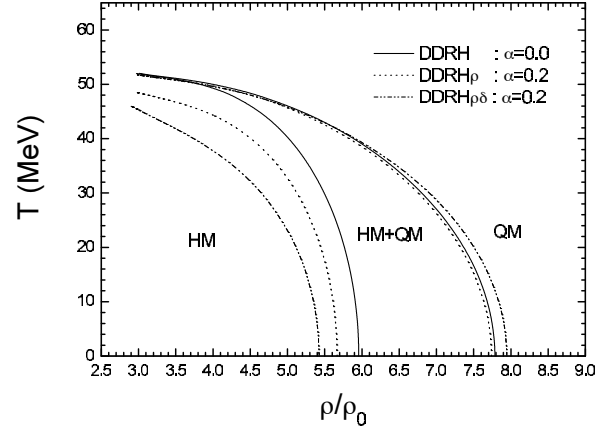


FIG. 6: Binodal surface for symmetric ($\alpha = 0.0$) and asymmetric ($\alpha = 0.2$) matter. Hadron EoS from $DDRH$ interactions. Quark EoS: MIT bag model with $B^{1/4}=160$ MeV.

rather “robust” isospin effects on the hadron-quark transition at high baryon densities..

Our results seem to indicate a specific region where the onset of the mixed phase should be mainly located: $2 < \rho_B/\rho_0 < 4$, $T \leq 50 - 60$ MeV, for realistic asymmetries $\alpha \sim 0.2 - 0.3$. A key question is if such a region of the phase space can be explored by means of Heavy-Ion-Collisions. In refs.[3, 4] it is shown that even collisions of stable nuclei at intermediate energies ($E/A \sim 1 - 2$ GeV) make available the pertinent (T, ρ_B, α) region where the phase transition is expected to occur.

Of course a relatively higher beam energy will allow to enter more deeply into the mixed phase. Such energies will however be available in the next future. In particular we notice that high intensity ^{238}U beams in this energy range would be delivered in the first stage of the FAIR facility and also at JINR-Dubna in the Nuclotron first step of the NICA project.

Which are the observable effects to look at if we enter and/or cross the mixed phase?

As already stressed, a first expectation will be the Isospin Distillation effect, a kind of *neutron trapping* in the quark phase, supported by statistical fluctuations [3] as well as by a symmetry energy difference in the two phases. In fact while in the pure hadron matter (neutron-rich) at high density we have a large neutron potential repulsion (in both $NL\rho$, $NL\rho\delta$ as well as in the corresponding $DDRH$ 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 [15], 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 [4]. 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 [20];
- (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. 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 par-

ticles, 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 $\mu_B = 0$ [21].

In conclusion the aim of this work is twofold:

- To stimulate new experiments on isospin effects in heavy ion collisions at intermediate energies (in a few $AGeV$ range) with attention to the isospin content of produced particles and to elliptic flow properties, in particular for high- p_t selections.
- To stimulate more refined models of effective Lagrangians for non-perturbative QCD, where isovector channels are consistently accounted for and/or gluon correlations, leading to diquark condensates, can induce symmetry energy effects.

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THEORETICAL STUDIES AND APPLICATIONS OF NUCLEAR REACTIONS

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Abstract

In this report we summarize some of the research also in collaboration with experimentalists. We discuss some investigations we are carrying out presently and our proposals for laser induced nuclear reactions.

QUANTUM NATURE OF A NUCLEAR PHASE TRANSITION

At finite temperatures and low densities, nuclei may undergo a phase change similar to a classical liquid-gas phase transition. Temperature is the control parameter while density and pressure are the conjugate variables. In the nucleus the difference between the proton and neutron concentrations acts as an additional order parameter, for which the symmetry chemical potential is the conjugate variable. We present experimental results which reveal the N-Z dependence of the phase transition and discuss possible implications of these observations in terms of the Landau free energy description of critical phenomena[1-2]. Within the Landau description we have shown that isoscaling could be simplified to $m=(N-Z)/A$ -scaling [3-4]. The order parameter m reflects a well known symmetry of the Nuclear Hamiltonian, which is even when we exchange N (neutrons) with Z (protons). On the same footing we might define an order parameter for pairing which should have a mixed i.e. even and odd symmetries when exchanging neutrons with protons number. The odd symmetry reflects the fact that the pairing energy changes sign for fixed A mass number from even-even to odd-odd nuclei. We expect that such a symmetry should disappear at high temperatures. These features might be relevant for the occurrence of Bose Einstein condensation in finite nuclei.

MEASURING THE TEMPERATURE OF HOT NUCLEAR FRAGMENTS

A new thermometer based on fragment momentum fluctuations is presented. This thermometer exhibited residual contamination from the collective motion of the fragments along the beam axis. For this reason, the transverse direction has been explored. Additionally, a mass dependence was observed for this thermometer. This mass dependence may be the result of the Fermi momentum of nucleons or the different properties of the fragments (binding energy, spin, etc.) which might be more sensitive to different densities and temperatures of

the exploding fragments. We expect some of these aspects to be smaller for protons (and/or neutrons); consequently, the proton transverse momentum fluctuations were used to investigate the temperature dependence of the source[13].

CONSTRAINED MOLECULAR DYNAMICS(COMD)

Microscopic calculations which take into account the Pauli principle[5] are being improved to take into account the Heisenberg principle [6]. The original CoMD approach gives in fact too many deuterons, dineutrons, diprotons etc. which we believe will be reduced by properly taking into account the Heisenberg principle. Presently, in order to reproduce the binding energies of light particles the width of the gaussians representing the nucleons wave functions are included in the total energy of the system by some authors[5]. This width is however a constant thus does not play any role in the time evolution of the light fragments which are then overproduced. We have found such a feature in microscopic models such as Antisymmetrized Molecular Dynamics (AMD) [R.Wada, private communication]. When taking effectively into account the Heisenberg principle, nucleons in light particles (d, 2n,3n,3p..) up to alpha will acquire a zero point motion which will reduce their binding energies and consequently their yields in heavy ion collisions. This might help to get a deeper understanding of pairing effects in nuclei. At the same time we are performing CoMD calculations for different systems and beam energies to study different aspects of critical behaviour in the collisions including the possibility of turbulent flow. Fractal dimension in Ca+Ca systems at different beam energies have been studied and reveal the multifractal nature of the reaction especially at a beam energy where a self similar mass distribution is found. Those mass distributions observed at different momentum scales are the same within the statistical sensitivity.

TURBULENCE IN HEAVY ION COLLISION NEAR THE FERMI ENERGY?

Sometime ago we suggested that, in a classical approximation, turbulence could occur in heavy ion collisions at relativistic energies [7]. At lower energies



we could have an onset of turbulent flow due to the reduced viscosity because of the Pauli principle which forbids many nucleon-nucleon collisions, thus reducing the viscosity. We could understand this in the Kolmogorov framework where energy is injected at the length scale L (the size of a nucleus) in the collision of the two nuclei and cannot be dissipated until the Kolmogorov length scale l_k is reached where dissipation becomes effective[7]. From dimensional analysis we can define the Reynolds number $Re=(L/l_k)^{4/3}$. If l_k is given by the minimum distance where two nucleons can collide i.e. $l_k=(s/p)^{1/2}=1.1$ fm, where $s=40$ mb is the nn-cross section and $L=10$ fm is roughly the diameter of a nucleus, we get $Re=(10/1.1)^{4/3}=19$, i.e a regime where eddies start to appear in macroscopic fluids[8]. In nuclear collisions eddies might be deformed fragments which split during the dynamical process. In the Fermi energy region, Pauli blocking effectively reduces the viscosity i.e. the effective nn cross section, thus increasing the Re numbers. Microscopic CoMD calculations performed by H.Zheng give Re of the order of 100 at 35MeV/A. Experimental data from PLF-light particles correlations using hydrodynamical scaling[9] obtained by Z.Kohley and S.Yennello's group show interesting coincidences and intermittency signal, i.e. large fluctuations. One problem with the occurrence of turbulence is the finite size of the system, however we have seen that because of the Pauli principle, the macroscopic length L and the Kolmogorov length l_k might differ of more than one order of magnitude. Furthermore, averages over ensembles are used similar to the original Kolmogorov theory of turbulent flows[8], which in part might compensate the nuclei finite sizes. Further experimental and theoretical investigations in larger systems (such as Ni+Pb) at different beam energies might confirm or reject this picture. If confirmed it would be the first evidence of turbulence in finite systems mostly due to the Fermionic nature of the particles.

SUPERHEAVY PRODUCTION.

We investigate the formation and the decay of heavy systems which are above the fission barrier. By using a microscopic simulation of constrained molecular dynamics (CoMD) on Au + Au collision, we observe that composite states stay for a very long time before decaying by fission[10]. Experimental investigations on similar systems have been performed by the J.Natowitz's group together with CoMD calculations performed by M.Barbui of the same group[11]. These results suggest a repetition of the experiment maybe at a different beam energy, to get larger statistics.

6. Symmetry Energy of Dilute Warm Nuclear Matter

The symmetry energy of nuclear matter is a fundamental ingredient in the investigation of exotic nuclei, heavy-ion collisions, and astrophysical phenomena. New data from heavy-ion collisions can be used to extract the free symmetry energy and the internal symmetry energy at subsaturation densities and temperatures below 10 MeV. Conventional theoretical

calculations of the symmetry energy based on mean-field approaches fail to give the correct low-temperature, low-density limit that is governed by correlations, in particular, by the appearance of bound states. A recently developed quantum-statistical approach that takes the formation of clusters into account predicts symmetry energies that are in very good agreement with the experimental data. A consistent description of the symmetry energy is given that joins the correct low-density limit with quasiparticle approaches valid near the saturation density[15].

NUCLEAR REACTIONS IN LASER PRODUCED PLASMAS

We discuss a method for a direct measurement of the astrophysical S-factor for neutron-less nuclear reactions induced in laser plasmas. A very preliminary experiment (LAPLAFUS) to test the concepts supporting our theoretical predictions was performed at the ENEA ABC-facility[12,14]. Up to the present the preponderance of laser induced nuclear reaction experiments have been "proof of principle experiments", meant to demonstrate that a given physical process, for instance nuclear fusion, could be observed. These initial reaction studies have revealed an underlying variation and complexity of plasma dynamics which must be understood and characterized before the full power of the technique of laser induced nuclear reactions can be utilized in both fundamental and applied science. Our group in collaboration with the group at Texas A&M University (J.Natowitz et al.) proposes to initiate a program of measurements of nuclear reactions in laser produced plasmas with the goal of bringing the understanding of the plasma interaction dynamics to the level that the measurement of fundamental nuclear cross section measurements at low temperatures, of great importance in astrophysics, can be made with confidence. In particular, the understanding and the quantitative measurement of fusion probabilities in hot and dense plasmas would contribute significantly to our understanding of stellar composition and evolution and will provide important information for development of fusion energy production. Those measurements are in preparation and will be performed at the University of Texas petawatt laboratory with the group of T. Ditmire there.

ENVIRONMENTAL PROTECTION AND RESOURCES: WHICH ENERGY FOR THE FUTURE?

We have studied different ways of producing energy. Here are our conclusions[16]:

NUCLEAR: yes to research to find more efficient ways for our power plants with little waste. Increase the efficiency from less than 1% to more than 50%, using Th resources as well.

ALTERNATIVE Energies: clean and competitive especially if equipment is home produced and installed to provide work to people. Needs sometime lots of space,

dangerous sometime (hydraulic power plants), or difficult to extract.

FUSION: surely the energy source for the future, able to provide enough for ALL mankind.

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ISTITUTO NAZIONALE DI FISICA NUCLEARE
LABORATORI NAZIONALI DEL SUD
ACTIVITY REPORT 2009

**INSTRUMENTATION
AND RELATED
TECHNIQUES**

IDENTIFICATION OF LIGHT CHARGED PARTICLES VIA DIGITAL PULSE SHAPE ACQUISITION AND RISE TIME COMPUTATION IN THE CSI(TL) DETECTORS OF CHIMERA AT GSI.

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Abstract

In the framework of the ASY-EOS experiment we have performed a test experiment at GSI using SIS and a beam of ^{238}U (73^+) at 350 AMeV on a Pb target.

The results obtained in the detection and identification of light charged particles, $Z \leq 4$, by applying digital pulse shape acquisition and digital signal processing to the pulse forms collected from CHIMERA CsI(Tl) scintillators coupled to photodiodes are presented.

INTRODUCTION

As it is well known, the time-dependence of the light output of a CsI(Tl) crystal, $L(t)$, is characterized by a combination of two components that can be described by exponential functions with different time constants, $L(t) = L_1 \exp\{-t/\tau_f\} + L_2 \exp\{-t/\tau_s\}$. L_1 and L_2 are the light amplitudes for the Fast and Slow components, with time constants $0.4 \mu\text{s} \leq \tau_f \leq 0.7 \mu\text{s}$ and $\tau_s \sim 7 \mu\text{s}$. The Fast component depends on the mass, charge and energy of the detected particle, as well as the relative intensity, while the slow component varies very slowly with particle type and energy. This dependence is the basic feature that permits particle identification by pulse shape discrimination technique.

We have investigated the applicability of Digital Pulse Shape Acquisition (DPSA) methods to a typical CHIMERA [1] detection cell in our previous work [2-4] and we have shown that high precision results can be obtained by collecting pulse-forms directly from the CHIMERA telescope preamplifiers.

The performed tests have proven that DPSA gives better results than standard analog electronics, while

reducing the complexity of the electronic chains and acquisition system.

For products punching through Silicon detectors, isotopic identification of Light Charged Particles (LCP), using a proper adaptation of the two-gate method [5] for the computation of the Fast and Slow components of the CsI(Tl) signals, has been carried out.

In the present paper we report the results obtained by applying digital signal processing, specifically by computing the CsI(Tl) signal rise time, to the pulse forms collected from CHIMERA CsI(Tl) scintillators coupled to photodiodes, at relativistic incident energies. The measurement has been carried out at GSI in the framework of the ASY-EOS experiment aimed to the study of neutron and proton elliptic flows in isospin asymmetric heavy-ion collisions in order to provide quantitative information on the symmetry term in the nuclear equation of state at supra-saturation densities.

EXPERIMENTAL SETUP

The presented tests have been performed by using DPSA to collect the full pulse form from the CsI(Tl) scintillators. The DPSA is achieved by means of high resolution fast Sampling Analog to Digital Converters (SADC). The experimental setup is based on SADC VME-boards, directly connected through the VME-PCI Bridge to a PC, used as supervisor [6], located in the controlled area, near to the detectors, and under remote control, via VNC software, of another PC, located in the acquisition room, essentially entrusted with the result visualization and optionally off-line Event Parameter reconstruction.



Hardware Architecture

In the present configuration, the digital pulse shape acquisition and on-board signal processing system is composed of:

- SADC acquisition and computation boards (Board);
- VME-PCI optical-fiber bridge (Bridge);
 - host PC (Host) used as supervisor;
 - visualization PC (Viewer) used for results visualization.

The Boards are SIS3150 VME-boards [7] (SIS3150) equipped with two ADSP-TS101S TigerSHARC Digital Signal Processors (DSPs) [8], 64 MB SDRAM memory, and two mezzanine sites each one. An SIS9300 Card [9] can be mounted on each of the mezzanine sites. Each SIS9300 provides four 14-bit, 100 MSample/s SADCs with programmable offset. Every time a trigger signal occurs, pulse shapes from all the four channels are collected. In the present tests, we used four SIS3150 boards; each one with two SADC mezzanines with a total of 8 SADC per board. We collected not only signals from the eight CsI(Tl) scintillators used, but also from Silicon detectors, used for control, and plastic scintillators, used for timing measurements.

In the present paper we fix our attention only on the CsI(Tl) signals

Software Architecture

The system we used to perform these measurements and analysis has a modular architecture, based on various programs written by us, each performing a different task. The first program runs on the DSPs in the SIS3150 boards. It is devoted to control the acquisition of the pulse-shape data from the SIS9300 CMCs boards, and to perform the on-line computation as desired. This program has been developed with Analog Devices' VisualDSP++ 4.0 [10] using the C++ language. The development of a previous version and its performance have been described in [11].

The other programs, based on the work described in [6], run on the host PC. One of them is devoted to the control of the SIS3150 boards through the VME-PCI bridge. Its task is to load the DSP software into the boards' RAM, setup the acquisition with the user-supplied parameters, and transfer the pulse shapes and the data computed on-board to the host PC, where they are saved to disk as a sequence of packets that can be read by other programs. It can work by polling continuously the boards under its control, or by waiting for an interrupt to be delivered on the VME bus.

Algorithms

The event parameters used in this work are, for each signal, the Fast and Slow components, the pulse height and risetime. These algorithms are implemented in the same way both in the DSP software and in the off-line analysis software. The first step of the computation brings to zero the baseline of the signal. The baseline part of the signal (i.e. the part sampled before the trigger event) is

fitted with a straight line that is extrapolated to all the samples and subtracted from the original signal. In this way we remove all slow variations of the acquisition chain offset.

The signal is then filtered using a customizable FIR filter. From this point the computation works on the filtered signal. We compute the maximum of the signal as the value of the maximum collected sample. This value is used as an energy parameter dependent on the amount of energy released by the particle in the scintillator, and to compute the threshold values, that will be used for evaluating the start time and the risetime of the signal, as an user-defined fraction of the maximum value. All time values are computed using a Threshold Crossing Time (TCT) algorithm, working as follows. First, the threshold value T_V is computed as a predefined fraction of the maximum value. Then we take the sample in the rising edge of the pulse whose value is nearest to the threshold value. A number of samples centered around this one is then fitted with a 3rd order polynomial $p(s)$, where s is the sample number, and we obtain a fractional s_0 threshold-crossing sample by solving the equation $p(s_0) = T_V$. The threshold-crossing sample value is converted to a time relative to the trigger applying the appropriate offset and scale factors. The risetime is computed as the difference between the crossing times of two user-defined thresholds, while the start is computed as the crossing time of the 10% threshold. With regard to the Fast and Slow parameters, in our case the signals are sampled immediately after the charge preamplifier, so we use a version of the two gate method which is very fast to compute. Each parameter is simply computed as the difference between the sample values taken at the start and stop time of the corresponding gate.

EXPERIMENTAL RESULTS

The experiment was performed at the GSI Helmholtzzentrum für Schwerionenforschung of Darmstadt (Germany) using a beam of ^{238}U (73^+) at 350 AMeV on a Pb target. This reaction produces a large variety of light particles and heavier complex fragments that were detected by the CsI(Tl) scintillators of the Chimera multidetector coupled to Hamamatsu photodiodes, type S-3204, 300 μm thick, and with an active area of $18 \times 18 \text{ mm}^2$ [12]. These photodiodes were connected to charge preamplifiers (200 mV/MeV sensitivity) and their output signals were digitized in real experimental conditions at relativistic (350 AMeV) incident energies.

The pulse forms have been first used to reconstruct the (Fast,Slow) scatter plot exploiting the fast and slow components of the decay of the emitted light output. For the two-gate method a Fast gate between 0 and 600 ns and a Slow gate between 900 ns and 6 μs have been used.

Exploiting the dependence [13] of the decay constant τ_f associated with the fast component on the ionization density for ion charges of $Z \leq 4$, $\tau_f \sim [dE/dx]^{-1} = f(E, Z, A)$, we have investigated the possibility to discriminate between charged particles using the rise time

computation, with thresholds at 30% and 70% of the pulse height.

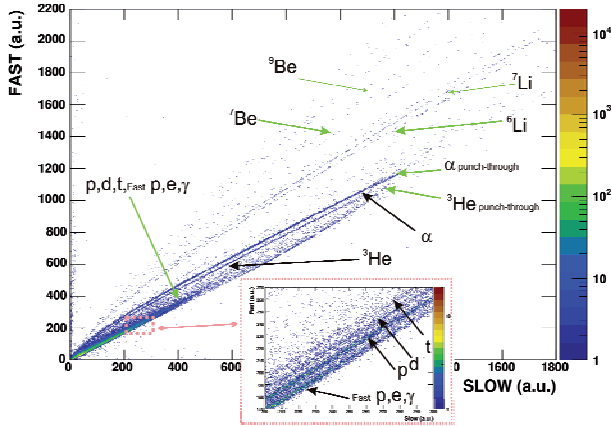


Figure 1: Fast-Slow scatter plot for the $^{238}\text{U}+\text{Pb}$ at 350 AMeV. The zoom shows the p, d, t and Fast proton, electron and γ clusters.

In Fig.1 the results obtained at GSI are reported as (Fast,Slow) scatter plot, computed using the DPSA two-gate method. In the GSI parasitic test (10^5 pps) we used a CsI(Tl) scintillator, 12 cm thick, positioned at polar angle $\theta=18^\circ$ with respect to the beam direction. When the energies of $Z=1$ and $Z=2$ isotopes exceed those corresponding to their ranges in 12 cm CsI(Tl) crystals they appear as punch-through lines as it is indicated on Fig. 1. For these punching-through particles a cusp begins to appear on the corresponding line in the (Fast,Slow) scatter plot. As their energies increase, the corresponding isotope lines display a back-bending behavior.

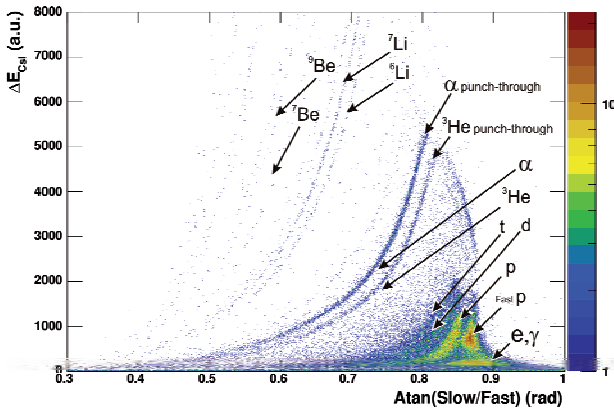


Figure 2: (E-atn(S/F)) scatter plot for the $^{238}\text{U}+\text{Pb}$ at 350 AMeV. The punch-through points for ^3He , and α 's are indicated.

A better representation of the (Fast,Slow) scatter plot data is achieved in Fig.2 where the maximum of the pulse is reported as a function of $\text{Atan}(\text{Slow}/\text{Fast})$. In this last scatter plot the punching-through energies are more prominent than in the usual (Fast,Slow) scatter plot (Fig. 1). Therefore, these clearly visible punching-through points on Fig. 2, corresponding to energies of 216 MeV and 880 MeV for protons and alpha particles,

respectively, may be used as additional energy calibration points.

In Fig. 3 the same data of Fig.1 are represented using the (E,RT) scatter plot.

From a comparison between Figs. 1 and Fig.3 the power of the (E,RT) representation clearly arises. In fact, the separation between protons and γ s (Fig.1) and between protons and fast protons (Fig.3) is very good, and the isotopic separation among $Z=1,2,3,4$ products is clear for all energies and even down to low particle energy.

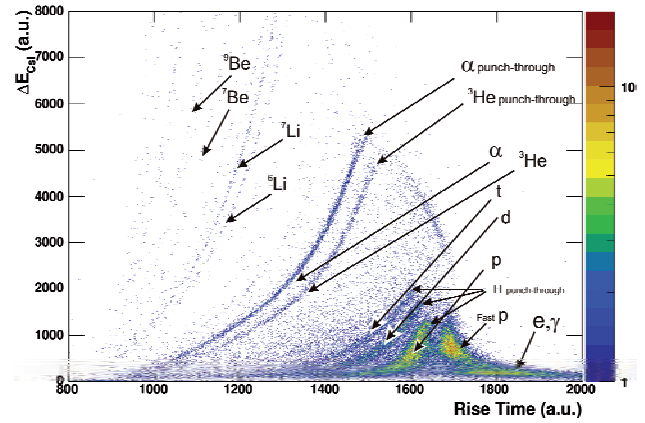


Figure 3: (E,RT) scatter plot for the $^{238}\text{U}+\text{Pb}$ at 350 AMeV. The punch-through points for p, d, t, ^3He , and α 's are indicated.

In the scatter plot the fast proton cluster is due to the high energy protons produced by the projectile fragmentation. They have enough energy to punch through the CsI(Tl) with an energy loss of ~ 120 MeV. Moreover the punching-through points for all the products are well evidenced.

The pronounced similarity of Fig.2 and Fig.3 can be explained by remarking that the fast component of the light output in the CsI(Tl) scintillator is a function of the energy, atomic number and mass number of the particle, while the slow component is lowly dependent on these quantities.

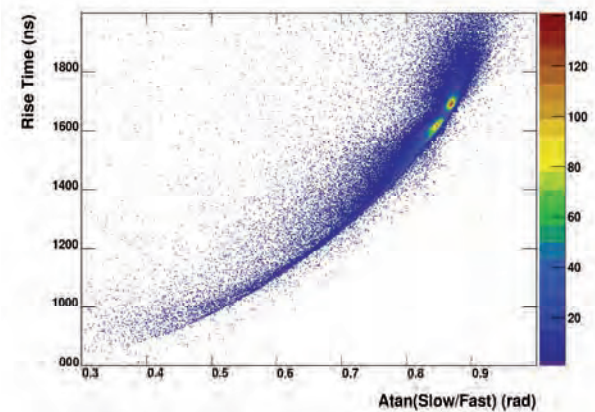


Figure 4: ($\text{Atan}(\text{Slow}/\text{Fast})$,RT) scatter plot for the same data of Figs. 4-5-6, showing a clear correlation between the two quantities.



In order to better investigate the similarity between the (E,RT) and the (E,Atan(S/F)) scatter plots, we have plotted Atan(Slow/Fast) vs. RT (Fig. 4) for the same data of Figs. 1,2,3. The obtained scatter plot shows a clear correlation between these two quantities, which explains the observed similarity.

The shown results demonstrate that it is possible to perform an efficient discrimination of LCPs in charge and mass using the CsI(Tl)+ photodiode combination and rise-time computation, instead of the Fast and Slow component computation. This is particularly the case of large dynamic ranges, typical of high energy measurements such as the one performed at 350 AMeV.

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IMPACT OF DETECTOR PARAMETERS ON LIGHT CHARGED PARTICLE AND INTERMEDIATE MASS FRAGMENTS IDENTIFICATION THROUGH PULSE-SHAPE ANALYSIS

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Abstract

We present the results of the study of the impact of the real preamplifier-detector configuration (i.e. finite bandwidth, input noise, leakage current, detector capacitance) on the measurement techniques used for the fragment identification in charge and mass in multi-detector arrays for Intermediate Energy Nuclear Physics experiments. We refer to Rise-Time vs. Energy diagram – that allows charge identification – and ToF techniques – used for the identification in mass. In this work we derived a first model able to predict the detection system performance and useful to tailor both the detector and the front-end specifications to the specific experimental case. The requirements for the optimization result to be partly conflicting – ToF technique requires fast timing signals, while pulse-shape analysis benefits from slower detector pulses.

INTRODUCTION

The design of modern multi-detector arrays for Intermediate Energy Nuclear Physics experiments has to face the problem of the improvement of the Charge and Mass Identification of Heavy and Light Charged Products. 4π detector arrays developed for the identification of mass and atomic number of the emitted fragments, such as CHIMERA [1], use detection units composed by thin silicon detectors (with thickness below 300 μm) and by thick scintillator crystals read-out by photodiodes. Processing techniques based on the pulse-shape analysis of the signals delivered by the silicon detector units are powerful tools to identify the reaction products stopping in the silicon layer. The resolution in charge and mass separation and the energy threshold achievable with a chosen pulse-shape processing technique are strictly related to the physical properties and to the topology of the detector, to the experimental setup (i.e. front-side or reverse-side mounting) as well as to the type (i.e. charge-sensing or current-sensing) and performance of the analogue front-end. The main detector parameters – the material thickness, the electric field profile facing the entrance window, the bulk doping and its uniformity – have a clear influence on the pulse shape. The detector operating temperature has an impact on the energy resolution, as it defines the detector leakage

current – one important contribution to the overall readout noise –, but also on the pulse shape through the significant dependence of carrier mobility on temperature (of the order of 1% per Kelvin).

In addition at low energies ($E/A < 20$ AMeV) it is important to correlate the kinetic energy of the fragments to the emission angle. This requirement forces towards novel detector topologies with higher segmentation degree. The requirement of a higher segmentation of the detection units has an impact on the achievable energy resolution and on the rise time of the pulses as the lower detector capacitance allows increasing the signal-noise ratio and the speed of the analogue front-end.

The CHIMERA detector uses different identification techniques for the measurement of the energy and velocity of the detected particles and for their identification in charge and/or mass [1-3] depending on the particle range. For a particle that punches through the silicon layer of the telescope the ΔE - E technique uses the signals coming from the Silicon and the CsI(Tl) detectors for charge identification of heavier ions and charge and mass identification of the lighter ones. For Light Charged Particles with $Z < 5$ stopped in the CsI(Tl) scintillator, the charge comparison method [4] allows the isotopic separation using the fast and slow component of the CsI(Tl) signals. The Time-of-Flight (ToF) technique makes use of the fact that, at fixed energy, the particle's velocity, directly proportional to the ToF, is a measure of the fragment's mass A . The ToF is measured as the time difference between the time signal coming from the silicon detector and a reference time delivered by the Super Conducting Cyclotron or a proper start detector. For particle stopping in the silicon layer the Z -discrimination is obtained through the measurement of the rise time of the signals collected from the fully depleted silicon detector. When, however, the range is small in comparison with the thickness of the detector, the measured rise times coalesce into a broad band. The Z -separation for this second ensemble of particles can be enhanced by allowing them to enter from the rear side (n-side) of the fully depleted detector. The big advantage of the Z -discrimination obtained with this technique is that it takes place in a single detector. When the technique is combined with a simultaneous time of flight measurement using a pulsed beam, complete identification of the ions

stopped in the detector is possible. One of the points of largest physical interest is the minimum energy of the reaction products that allows charge identification. Such threshold critically depends on the detector and front-end electronics properties.

In this contribution we concentrate on the fragments stopping in silicon and we want to study the impact of the detector and front-end electronics configuration on the Energy vs. RiseTime and Energy vs ToF identification techniques. The paper is organized as follows. Section 2 describes a simplified analytical model of the induced current signals in the case of the ionization profiles generated by the charged products fully stopped in the silicon layer, in an ideal detection system (i.e. no noise and bandwidth limitations). Such model has been used in Section 3 for the evaluation of the impact of detector and front-end electronics properties on the aforementioned identification techniques. Section 4 ends with the conclusions. This work was presented at the 11th European Symposium on Semiconductor Detectors held in Wildbad Kreuth, Germany from June 7 to June 11, 2009 and will be published on Nuclear Instruments and Methods in 2010.

SIMPLIFIED ANALYTICAL MODEL OF THE INDUCED CURRENT SIGNALS IN PLANAR PN DIODES

We model the planar pn detector with a 1-D approximation. We consider a pn diode with planar geometry consisting of a heavily doped p+ region (located at $z = d$ and henceforth called front-side) and of a lightly doped n substrate. A highly doped n+ region (located at $z = 0$ henceforth called reverse-side) acts as ohmic contact. The voltage V_{bias} applied to the diode is larger than the one needed to deplete the n substrate. Considering the simplest case of a pair of carriers generated at $z = z_0$, as well known [5] we can solve the motion equation for a pn diode with planar geometry and apply Ramo's theorem to derive the shape of the induced current. In order to take into account the characteristic ionization profile of each ion at a given energy, indicated with $\rho(z)$ and calculated with SRIM MonteCarlo simulator [6], we sum the single carrier expressions weighted by $\rho(z)$.

Therefore the induced current caused by the ionization profile $\rho(z)$ have the following expression:

$$i_{p,\rho}(t) = \sum_k \rho(z_k) i_p(z_k, t) \Delta z \quad (1)$$

$$i_{n,\rho}(t) = \sum_k \rho(z_k) i_n(z_k, t) \Delta z \quad (2)$$

where $i_p(z, t)$ and $i_n(z, t)$ are the single carrier induced currents:

$$i_p(t) = -q \overrightarrow{E_{w,p}} \cdot \overrightarrow{v_p(t)} = \frac{q}{d} \mu_p \left(\frac{qN_d}{\epsilon} z_0 + E_{min} \right) \left[\exp \left(\mu_p \frac{qN_d}{\epsilon} t \right) \right] \quad (3)$$

with $0 \leq t \leq t_p$ for the hole, where

$$t_p = \frac{\epsilon}{q\mu_p N_d} \ln \frac{d + E_{min} \frac{\epsilon}{qN_d}}{z_0 + E_{min} \frac{\epsilon}{qN_d}} \quad \text{and} \quad \overrightarrow{E_{w,p}} = -\frac{1}{d} \hat{z} \quad \text{is the}$$

weighting field for the p+ electrode and

$$i_n(t) = -q \overrightarrow{E_{w,n}} \cdot \overrightarrow{v_n(t)} = \frac{q}{d} \mu_n \left(\frac{qN_d}{\epsilon} z_0 + E_{min} \right) \left[\exp \left(-\mu_n \frac{qN_d}{\epsilon} t \right) \right] \quad (4)$$

with $0 \leq t \leq t_n$ for the electron, where

$$t_n = \frac{\epsilon}{q\mu_p N_d} \ln \frac{z_0 + E_{min} \frac{\epsilon}{qN_d}}{E_{min} \frac{\epsilon}{qN_d}} \quad \text{and} \quad \overrightarrow{E_{w,n}} = \frac{1}{d} \hat{z} \quad \text{is the}$$

weighting field for the n+ electrode.

Even if neglecting the important contribution of plasma effects, this simple analytical model is a precious guide for interpretation of the experimental results and for the optimization of the detector topology and operating parameters and allows the calculation of the shape of the induced signals for different ions. As an example Fig. 1a, 1b show the shape of the induced current the case of a ^{16}O ion impinging on the detector in front mounting (dashed lines) and reverse mounting (continuous lines) at two different energies – the corresponding ionization profile is shown in the inset. The gray lines represent the holes contribution, the black lines the electrons one and the bold lines the total contribution.

For both energies the current signals induced in front mounting are much shorter than in reverse mounting as expected (even close to the punching through energy), because in front mounting the signal carriers are generated closer to the high field region and the holes that are slower than the electrons have to travel for a shorter distance.

IMPACT OF THE DETECTOR AND FRONT-END ELECTRONICS CONFIGURATION ON THE ENERGY VS. RISE-TIME AND ENERGY VS. TOF IDENTIFICATION TECHNIQUES

Analysis

Fig. 2 shows the circuit equivalent of the detector and front-end electronics configuration. We have highlighted the main noise sources that are the shot noise contribution caused by the detector leakage current and the series noise of the charge preamplifier. We have neglected the preamplifier coupling capacitor that at the frequencies of interest behaves as a short circuit. We consider the case of digital pulse shape acquisition (DPSA) in which the preamplifier output pulse is directly sampled and digitized [7]. Taking into account the finite bandwidth of the preamplifier we can compute the output noise

contribution due to the equivalent series noise generator (S_v), assumed as unilateral power spectral density:

$$\overline{v_{out,ws}^2} = \frac{S_v \pi}{2\pi} \frac{1}{2(\tau_f + \tau_p)} \left(1 + \frac{\tau_D^2}{\tau_f + \tau_p} \right) \quad (5)$$

and to the equivalent current generator (S_i):

$$\overline{v_{out,wp}^2} = \frac{S_i \pi}{2\pi} \frac{R_f^2}{2(\tau_f + \tau_p)} \quad (6)$$

where τ_f is the preamplifier fall time constant, equal to $R_f C_f$, τ_p is the time constant of the charge amplifier closed-loop pole, and τ_D is a useful time constant equal to $R_f(C_f + C_{det} + C_{par})$. In the following we have assumed that the series voltage noise is dominated by the noise of the first transistor and, therefore,

$$S_v = 4kT \frac{2}{3} \frac{1}{g_m} \text{ and the white parallel noise is dominated}$$

by the detector leakage current and, therefore, $S_i = 2qI_L$.

We can model the voltage at the preamplifier output as

$$v_{out} = A \underbrace{f(t)}_{\text{signal shape}} + \underbrace{n(t)}_{\text{output noise}} \quad (7)$$

where A is the amplitude of the deterministic component of the output pulse, proportional to the fragment energy and $f(t)$ is normalized in such a way that its maximum is equal to one.

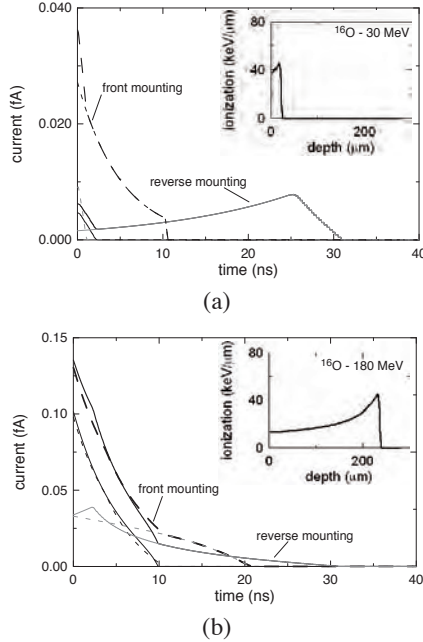


Figure 1: Shape of the induced current in the case of a ^{16}O ion impinging on the detector in front mounting (dashed lines) and reverse mounting (continuous lines) at two different energies (a) 30 MeV, (b) 180 MeV. The gray lines represent the holes contribution, the black lines the electrons one and the bold lines the total contribution. The insets show the corresponding ionization profile.

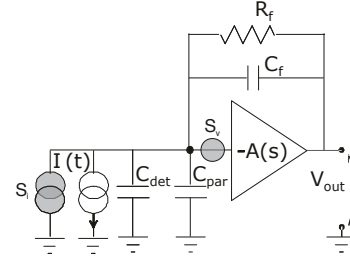


Figure 2: Circuitual equivalent of the detector and front-end electronics configuration with highlighted the main noise sources (shot noise contribution caused by the detector leakage current and series noise of the charge preamplifier).

The average output voltage is given by

$$\overline{v_{out}(t)} = \bar{A}f(t) \quad (8)$$

where we indicated with $\bar{A}$ the average amplitude of the output pulse.

We have computed the output variance for the amplitude measurement as

$$\sigma_{v_{out}}^2(t) = \sigma_A^2[f(t)]^2 + \sigma_n^2 \quad (9)$$

where σ_A^2 is the variance due to the intrinsic Fano contribution. Therefore the variance for the energy measurement on the peak (remembering that $f(t_p)=1$) is

$$\sigma_{v_{out}}^2(t_p) = \sigma_A^2 + \sigma_n^2 \quad (10)$$

The time variance of the time instant relative to the crossing of a fraction α of its amplitude is

$$\sigma_t^2|_{t_\alpha} = \frac{\sigma_{v_{out}}^2(t_\alpha)}{\left[\frac{d}{dt} v_{out}(t_\alpha) \right]^2} = \frac{\alpha^2 \sigma_A^2 + \sigma_n^2}{\bar{A}^2 \left[\frac{d}{dt} f(t_\alpha) \right]^2} \quad (11)$$

The time variance for the rise time measurement is given in a straightforward way as

$$\sigma_{RT}^2 = \sigma_t^2|_{t_{\alpha_1}} + \sigma_t^2|_{t_{\alpha_2}} \quad (12)$$

where α_1 and α_2 are the two fractions of the amplitude chosen for the rise time measurement.

Achievable performance

Fig. 3 shows the achievable resolution in the amplitude measurement, expressed in terms of FWHM, in the case of 5.5 MeV energy released in silicon as a function of the detector capacitance, according to Eq. 10. For the typical parameters of the front-end electronics and detector chosen in the analysis – we chose a detector thickness of 300 μm and a leakage current density of 3.2 nA/cm², typical for “good” detectors, and assumed for the input transistor of the preamplifier an input capacitance $C_i = 10$ pF and a transconductance, g_m , of 10 mS – the dominant contribution is the series voltage noise mainly due to the input transistor of the charge preamplifier. Therefore, any improvement of the transconductance of the input transistor translates in an overall improvement of the resolution in the energy measurement. We showed

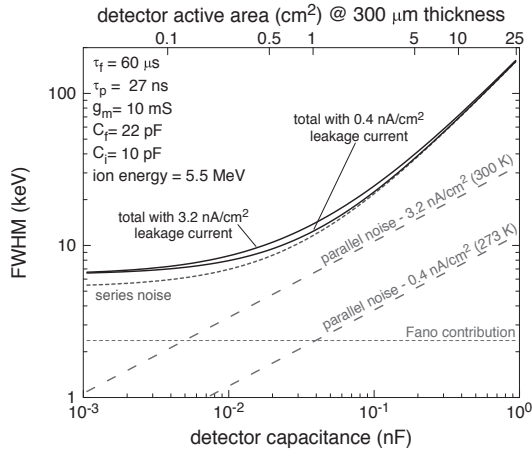


Figure 3: FWHM of the amplitude (i.e. energy) measurement as a function of the detector capacitance for typical detector and front-end electronics parameters.

also the impact of the reduction of the leakage current density – achievable by cooling the detector at about 0°C in the considered example. As it can be noticed for detector capacitances in the range 10 pF-100 pF, this has a considerable impact on the achievable resolution. Moreover it has to be noticed that the detector leakage

current tends to increase with usage due to radiation damage and leakage current densities up to 100 nA/cm² have been measured with frequently used detectors. This gives a precise indication of the opportunity of detector cooling in the case of segmented detectors that feature a detector capacitance within that range.

For what concern the achievable time resolution, given by Eq. 11, Fig. 4 shows the contour plot of the time resolution as a function of the energy deposited in the silicon layer and of the crossed fraction α of the output signal. The detector leakage current density has been assumed equal to 3.2 nA/cm². Two different detector areas has been evaluated, 1 cm², corresponding to a detector capacitance of 38 pF and a leakage current of 3.2 nA (a) and 25 cm², corresponding to a detector capacitance of 0.95 nF, and a leakage current of 81 nA (b).

CONCLUSIONS

In this work we studied the impact of the detector and front-end electronics configuration (i.e. finite bandwidth, input noise, leakage current, detector capacitance) on the identification techniques used for identification in charge and mass of the fragments stopping in the silicon layer. The rise-time vs. energy diagram allows charge identification, while ToF techniques are used for the identification in mass. The requirements for the optimization are partly conflicting – ToF technique requires fast timing signals, while pulse-shape analysis benefits from slower detector pulses. From this study we can derive a model able to predict the detection system performance and useful to tailor the detector and the front-end specification to the required experimental case.

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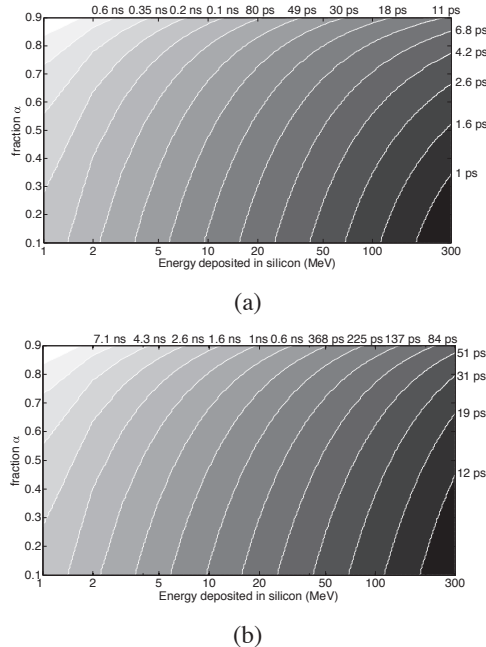


Figure 4: Contour plot of the rms time resolution as a function of the energy deposited in the silicon layer and of the crossed fraction α of the output signal. The detector leakage current density has been assumed equal 3.2 nA/cm². The detector area is 1 cm² (detector capacitance 38 pF, leakage current 3.2 nA) (a) and 25 cm² (detector capacitance 0.95 nF, leakage current 81 nA) (b).

ON SPAD DEVICES DEADTIME

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Abstract

In this work we study the signal generation process and the deadtime mechanisms of the device under a constant light regime. According to our results, it is possible to discriminate low rate signals from afterpulse and noise production and, moreover, to overcome the saturation effect due to the deadtime losses.

Starting from the G-M studies present in Literature, we have been able to evaluate the real amount of incident photon rate up to 10^7 cps using a passive quenched device with $0.97\mu\text{s}$ total deadtime.

In this way the passive quenched SPAD achieves the same performance of the active quenched one showing that relatively complex data analysis and complex device implementation are comparable solutions for constant light measurement.

INTRODUCTION

In all counting systems noise and dead time losses should be taken into account to evaluate the real amount of events from the measured ones. The dead time was widely studied in the case of the Geiger-Muller detector, used in nuclear physics [1-3].

Since many years our research group is developing a Single Photon Avalanche Diode (SPAD) matrix, suitable for time resolved single photon imaging techniques [4-6]. We have already presented the efficacy of our particular approach for imaging devices [7]. The present work has been originated from the necessity to extend the dynamic range of our imaging device.

DT is defined as the finite time after the registration of an event, before the detector is able to register another incident event. Since 1940 many works have been published about the Geiger-Müller counter DT in nuclear physics high rate applications [1]. Detailed studies identify two idealized models for DT, the paralyzable (P-DT) and the non-paralyzable (NP-DT) one. In this two simple case there are two different relations between the real counting rate 'n' and the measured one 'm', being

$$m = n \cdot \exp(-n \cdot \tau_p) \quad (1)$$

in the case of a paralyzable deadtime τ_p , and

$$m = \frac{n}{1 + n \cdot \tau_{np}} \quad (2)$$

in the case of a non paralyzable deadtime τ_{np} .

In real devices there are many sources of dead time, and they can act in series [9] or in parallel [2]. In G-M counter there are two DT sources acting in series, the first is the time duration of the signal (NP-DT τ_{np}), and the second is the recharge time needed to produce a signal with amplitude greater than the discriminator level (P-DT τ_p). The effect of this dead times combination can be described with the formula of the hybrid model [10]:

$$m = \frac{n \cdot \exp(-n \cdot \tau_p)}{1 + n \cdot \tau_{np}} \quad (3)$$

We found that this equation can be also used for SPAD detector provided that all the differences between these two devices, concerning noise, PDE and afterpulse, are taken into account.

MATERIALS

The SPAD is an avalanche diode, polarized over the breakdown voltage, working in Geiger-Müller mode [8]. When a photon is absorbed inside the depletion region of the device and creates a electron-hole couple, the overvoltage is able to generate an avalanche of charges through impact ionization. The output of this process is a macroscopic electric signal synchronized with the impinging photon. To stop the avalanche a quenching circuit is used to momentarily reduce the bias voltage below the breakdown level. We have used a passive quenching circuit in which the diode is coupled with a quenching resistor that resets to zero the overvoltage to stop the avalanche and, then, allows the recharge of the system with an exponential growth of the overvoltage until the original state is reached.

The readout of the signal is performed in a time window of $35\mu\text{s}$, with a precision of 100 ps. Many time windows, with a frequency of about 2kHz, have been acquired for statistic needs. The starting time of all signals is captured from the electronic chain and stored for analysis.

The analysis, performed with Matlab code, checks the functionality of the system, and extracts the main information, i.e. the time distribution of the incoming signals inside the acquisition time window, and the distribution of time delays between next signals.

Constant light source has been produced by a commercial LED. Wavelength is selected with a optical band filter 535nm, FWHM 20nm. Many measurements has been made with various incident photon rate, using

different gray filter, 100% (no filter), 87%, 32.2%, 9.5%, 0.9%, 0.1%, 0.01%, and modulating the LED power supply.

SPAD'S RATE DISTORTION SOURCES

Noise

In SPAD device the noise is due to the thermal generation of charge inside the depletion region of the semiconductor. It depends on the intrinsic characteristics, on the temperature, and also on the overvoltage state of the device [8]. The last dependence makes the noise production linked to the incident photons rate. During the recharge process the noise production is inhibited, so the increase of the photon count rate should increase the total duration of the dead time. As a consequence, the increase of the photon count rate should decrease the time available for the noise production and the measured noise count rate.

To check this dependence we built a special experimental setup. We used one passive quenching system connected to ten diodes in order to share the overvoltage and the recharge dead time between all diodes. We used ten different readout systems for the ten diodes, which can be assimilated to one big diode with ten spatially separated active depletion region. By illuminating only one diode, we can distinguish the signals from the lighted diode from the signals produced by the thermal generation. The result of this experiment along a Montecarlo simulation of SPAD dark count production [12] shows that we can consider that the real rate 'n' consists of the real photon rate 'p' and the real noise count rate 'd', distinguishing the noise count rate measured in dark condition 'd₀', so called dark count rate, from the real noise production in working condition 'd'.

Therefore the modified equation of the hybrid model that we considered for SPAD device is:

$$m = \frac{(p + d) \cdot \exp(-(p + d) \cdot \tau_p)}{1 + (p + d) \cdot \tau_{np}} \quad (4)$$

The parameter 'd' can be evaluated from the measurement of 'd₀' in dark condition, i.e. when photon rate 'p' is equal to zero, being

$$d_0 = \frac{d \cdot \exp(-d \cdot \tau_p)}{1 + d \cdot \tau_{np}} \quad (5)$$

In most commercial device both the dark count rate and dead time are small and there is no appreciable difference between 'd₀' and 'd'.

The variance of the dark count identifies the lower measurable value of the true incident photons rate. Because the variance is the square root of the count rate, in a device with 1kcps dark count rate the minimum true photon rate measurable is around 50cps.

SPAD deadtime configuration

In the G-M device the recharge process starts immediately after the signal end. In SPAD device the dead time extends up to the start time of the recharge

process, when the avalanche process stops [8]. For our SPAD device, using a digital oscilloscope in persistent mode, we estimate that the recharge starts after 170ns.

To understand the SPAD's behavior we must consider not only the paralyzable dead time due to the recharge process but also the variation of the Photon Detection Efficiency (PDE) and the afterpulse.

The PDE of the SPAD is proportional to the overvoltage applied to the diode [8], because the avalanche generation process depends on the overvoltage value. During the recharge process, too low overvoltage values correspond to decreased detection efficiencies. So the corresponding time interval can be considered like a non paralyzable dead time, because the lost photon doesn't restart the recharge process. The DT caused by the reduced PDE and the DT caused by the recharge process start simultaneously, after the quenching of the avalanche process.

During the period in which the two types of DT coexist the system cannot be described with two DT in parallel as in the G-M device [2], because in SPAD device the PDE varies during the recharge process and the generalized Muller equation cannot be used.

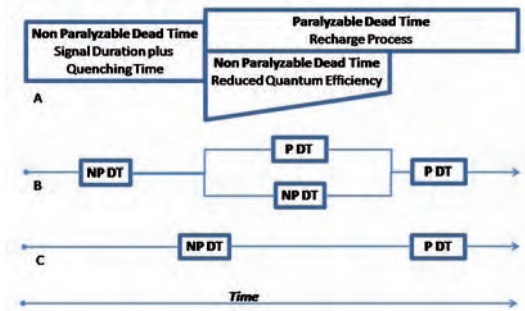


Figure 1: DT Configuration of SPAD. A) real. B) circuit schema C) simplified schema used for the dead time correction.

To solve this problem all SPAD's dead time sources must be considered. There is a NP-DT, due to the signal duration and to the avalanche quenching time (170ns), followed by two DTs in parallel, one due to the recharge process and the other due to the reduced PDE. The recharge process DT is paralyzable and much longer than the other one. The reduced PDE DT is non paralyzable and the weight of this process vary during the recharge process. Figure 1A represents the total DT configuration.

To simplify the DT configuration we have taken the variation of PDE at the extremes and assumed that the parallel circuit (Fig. 1B) can be described with a series of DT. The first NP-DT is caused by the predominance of reduced PDE process over the recharge process, and the second P-DT is caused by the quick death of reduced PDE process. Joining together the dead times of the same type we obtain a simple two DT series circuit (Fig.1C).

Afterpulse

In SPAD device the afterpulse is caused by local crystallographic defects that insert deep energy levels

inside the gap. Such levels can capture carriers during the avalanche process and release them with considerable delay. These charges can trigger the non paralyzable deadtime process or increase the output signal rate of the device.

To evaluate the photon rate dependence of this process we have mixed two photon sources, a pulsed laser and a constant light source.

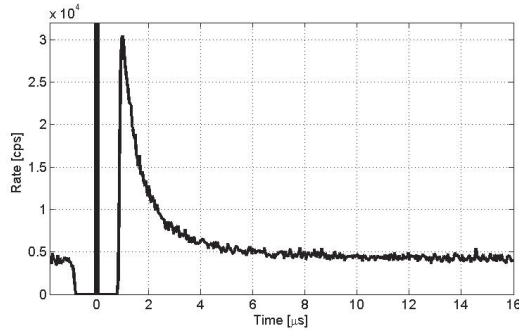


Figure 2: Measurement of afterpulse correlated with a laser pulse embed in a constant light background source.

The laser signal can be detected if previous signal is distant in time more than a DT interval. The laser generates a high and tight peak of counts, followed by a deadtime interval during which noise and constant light source cannot trigger an event (Fig. 2). After this time interval, in absence of the afterpulse, the count rate should quickly return to the previous constant value. The afterpulse causes an increase of the count rate followed by an exponential decay trend. After 6 μs the afterpulse phenomenon is completely concluded and a plateau, due to the constant signals source, follows. On increasing the rate of constant light source the total measured afterpulse linearly decreases from a 4% value in dark condition to a non measurable value at 55kcps. As a consequence the Eq. 4 should be multiply by a linear function of incident rate that represents the afterpulse modulation process. Due to the fact that the correction weight is less than 4%, this function was not deeply studied.

DEADTIME CORRECTION

The measured signal rate versus the real incident photon flux is shown in Fig. 3.

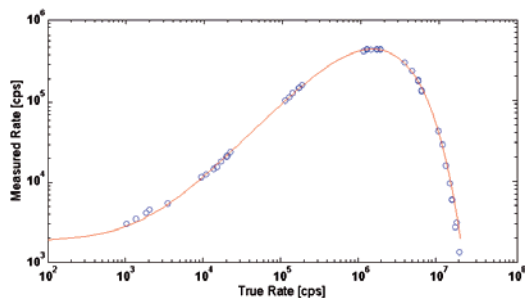


Figure 3: Relation between true and observed counting rates; circle, experimental data; line, hybrid model fitting.

We found that the proposed Eq. 4 of the hybrid model fits with good precision our experimental data along more

than four order of magnitude. The obtained dead time extension are $\tau_{np}=660\pm20ns$ and $\tau_p=310\pm10ns$.

The Fig. 3 shows that the Eq. 4 cannot be simply inverted because it is not a monotone function. In order to eliminate the ambiguity we have analyzed the Time Interval Density distribution (TID) [11]. We have measured the TID shape changes at all the true counting rates. Some of the results, approximately one per order of magnitude of the counting rate, are shown in Fig. 4. This changes eliminate the ambiguity in the inversion of Eq. 4.

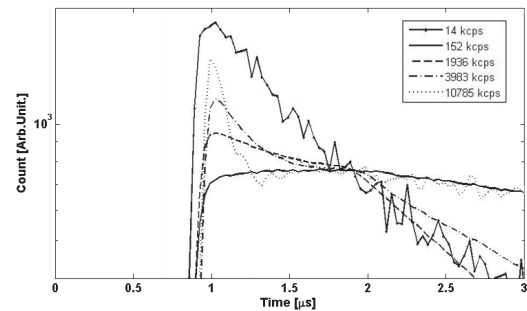


Figure 4: Time Interval Density distribution measured at various true count rates (approximately one per order of magnitude).

In order to evaluate the accordance between the measured data and the expected data, the plot of the ratio of this two quantities is reported in Fig. 5. Theoretical predictions have been calculated both using the hybrid model correction, and the simplest correction method of the dark count (d_0) subtraction.

The dispersion of experimental data, in the low count rate regime, is due to the fluctuation of SPAD device temperature and of the power supply of the light source. This fluctuation is greater than the afterpulse effect that is not considered in this circumstance.

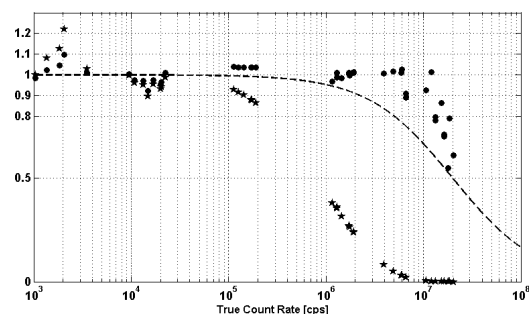


Figure 5: Calculated Counting Rate/True Counting Rate (ratio); circle, hybrid model correction; stars, dark count subtraction correction; dashed line, theoretical behavior of SPAD with 50ns of Active Quenching.

COMPARISON BETWEEN PASSIVE QUENCHING AND ACTIVE QUENCHING

To use the SPAD as counter two approaches can be followed, one is the use of passive quenched electronics with the data analysis showed in this work; the other one is the use of various active quenched electronics setup [8] to reduce the dead time of the device. Generally speaking



active quenching is a complex circuit that generates a short non paralyzable dead time which increases the count rate response of the device. To compare these two approaches, the best performance of commercial device ($\tau_{np}=50\text{ns}$) was theoretically calculated according to Eq. 2 and shown in Fig. 5. It appears that with active quenching device 10% of the signal is lost at a rate of $2.3\text{E}6$ cps while using our passive quenching device (total deadtime 970ns) with hybrid model correction the same losses is at a rate of $1\text{E}7$ cps. It is worth to note that the correction technique used for passive quenched device do not give appreciable advantage if applied to the case of active quenched device because this device shows only a non paralyzable deadtime behavior, and NP-DT response curve go rapidly to a saturation level [3]. The comparison shows that the counting performance of this two approaches is approximately the same. To choose which approach is better for a specific application we should evaluate the advantages and disadvantages of both approaches.

The active quenching strategy need the development of a dedicated circuit that increases the manufacturing complexity. This aspect, in a multiple devices configuration, involves the decreasing of the feel factor, and the development of a readout strategy able to read the huge number of signal coming out from each diode. In principle the advantage of this strategy is that the number of lost photons is very little and the correlation analysis can be done also in the nanosecond domain, but the acquisition of such big amount of data can turn into a problem and complexity of the electronics should be increased.

The characteristic of the passive quenching strategy showed in this work is the simplest electric implementation: only a resistor per diode is needed. The data correction does not require an intensive computing operation and occurs only at high rates. Moreover in the array implementation the feel factor is not limited due to the simple electronics used. The dead time losses of passive quenching strategy is negligible at low photon rate regime, while at high rate regime becomes an advantage because only a little part of the incident photons are translated into the signal that should be acquired, without overloading the external readout electronics. In any case using the showed correction technique we can evaluate the exact number of incident photons. Disadvantages of this approach are the error in the determination and in the fluctuation of the dead time parameters (τ_{np} , τ_p). However this error affects the final results with an error of few percent only at high rates

regime. Another disadvantage is that this correction technique is not able to follow rapid changes in the photon flux; to solve this problem at present we are studying how to generalize the Eqs. 1, 2, and 4 in order to take into account the transient conditions.

CONCLUSION

SPAD device is a new promising device for counting measurement. We have deeply analyzed all the device mechanism that causes distortion in counting measurement. Afterpulse and noise production have been considered to correct low rate regime measurement. Delayed recharge process and reduced PDE have been considered to design the dead time configuration of the device. Analytical equation was found for the counting response behavior of the device. The time interval density distribution was used to eliminate the ambiguity in the inversion of the response equation. With our results in the dead time analysis we extend of two order of magnitude the count rate range in which the device can be used. A comparison between active and passive quenching strategy is made, and it is clear that the development of complex electronics for active quenching device and the relatively complex data analysis shown in this paper produce similar results. The choice between the two strategies is linked to the characteristics of the particular application, taking into account the advantages and disadvantages of the two approaches.

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SIMULATING MEDEA NEUTRON DETECTION

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MEDEA is a 4π apparatus made of 180 BaF₂ detectors, arranged in a spherical geometry of 22 cm radius, carefully designed to detect gammas up to 300 MeV, protons, deuterons, tritons and alphas emitted in heavy ion reactions at intermediate energies [1]. The BaF₂ scintillator capability to detect neutrons has triggered a study of a possible modification of a few MEDEA modules for neutron detections, in order to have a better control on the reaction dynamics. Each MEDEA module is made of two separate crystals, respectively 12 cm and 8 cm long, optically coupled. The removal of the 12 cm crystal in front of the target will increase the path length, making possible some improvements in the neutron detection. A few simulations of BaF₂ crystal response to neutrons up to 18 MeV, based on GEANT4 code [2], will be reported for the standard (12cm + 8cm crystals) and modified (short) configuration (8 cm).

INTRODUCTION

In the last years, the role played by the isospin degree of freedom in nuclear reactions [3] has drawn the attention of nuclear physicists, making the neutron detection more and more appealing. Moreover, the measurements of neutron multiplicities and energy spectra can complete information given by light charged particles and gamma rays and can be very helpful in the determination of the excitation energy when hot nuclei are populated through complete and incomplete fusion reactions.

MEDEA is a detector system made of 180 BaF₂ tapered modules, arranged in a spherical geometry with a 22 cm radius, installed at LNS. Each module is made of two crystals, optically coupled, the one closer to the target being 12 cm long, while the other is 8 cm long. The BaF₂ scintillation light consists primarily of two components with decay times of about 600 ps and 620 ns. The ratio of the intensities associated with each of these components depends on the incident radiation type. Neutrons below 20 MeV undergo elastic, inelastic scattering and capture reactions in the crystal [4] and they are mainly detected in the gamma loci when fast vs total components of the signal are plotted. Then, the neutrons are separated from gammas through time of flight measurement generally

done taking the RF signal of the LNS cyclotron as a reference.

Due to their interaction mechanisms, neutrons can travel considerable distance through the matter without interacting and, once this happens, they generally don't lose all the energy in a single step. This implies that the determination of the energy can be done through the time of flight over a covered path and not from the deposited energy. The distance travelled by the neutron is known but the true path inside the detector because it can interact in any point inside the crystal. Generally an interaction point in the middle of the detector is assumed for the calculation of the energy. The direct consequence of this assumption is that the longer the crystal is the greater the uncertainty in the energy determination will be. From a different perspective, the longer the crystal is the more probable the interaction inside the detector will be. Moreover, the neutron after a first interaction could be scattered in different detectors, giving misleading information about the neutron multiplicity in the event. Therefore simulations are necessary to study the response of standard and modified detectors to neutrons in order to evaluate the advantage of changing from the long to the short configuration for a few modules. Some preliminary simulation result will be presented.

SIMULATION RESULTS

Simulations of BaF₂ crystals to neutrons have been performed using GEANT4 version 9.2 patch01. In order to evaluate the amount of cross talk, full MEDEA geometry has been implemented. The G4Trap solid has been used to reproduce the crystal shape. A single MEDEA module has been irradiated in the simulations using a monochromatic neutron source and the effect of cross talk has been evaluated. Moreover both short and long detectors have been alternatively irradiated. The neutron energies have been varied from 6 MeV up to 18 MeV in 2 MeV steps.

Figure 1 shows the deposited energy spectra for 14 MeV neutron incident energy. The black line corresponds to the deposited energy in the standard detector while the red one corresponds to the modified detector. The two peaks at about 8 MeV and 12.5 MeV are due to the end points of the energy spectra for the reactions $^{19}\text{F}(n,\alpha)^{16}\text{N}$ and $^{19}\text{F}(n,d)^{18}\text{O}$, according to their respective negative Q-

values. As easily seen, the removal of the 12cm crystal causes a reduction in neutron detection efficiency. To be more quantitative, including the experimental requirement that the interacting neutron in the crystal deposits at least 1 MeV, simulations bring out an efficiency of about 59% for the short detector relative to the long one. The value is calculated over an energy range from 6 MeV up to 18 MeV.

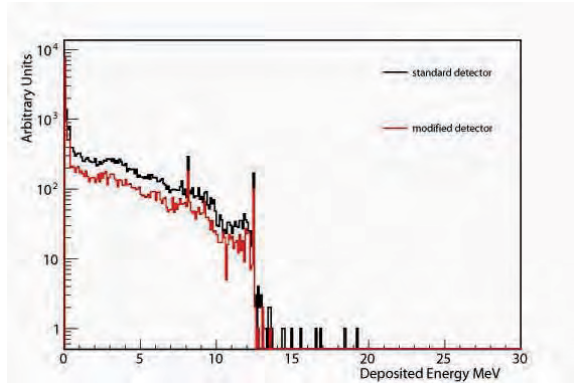


Figure 1: black line spectrum of the deposited energy obtained irradiating a standard crystal with 14 MeV neutron ; red line the same for the modified detector

In figure 2 the efficiencies for a modified (top) and standard detector (bottom) irradiated by neutrons of increasing energy from 6 MeV up to 18 MeV are reported.

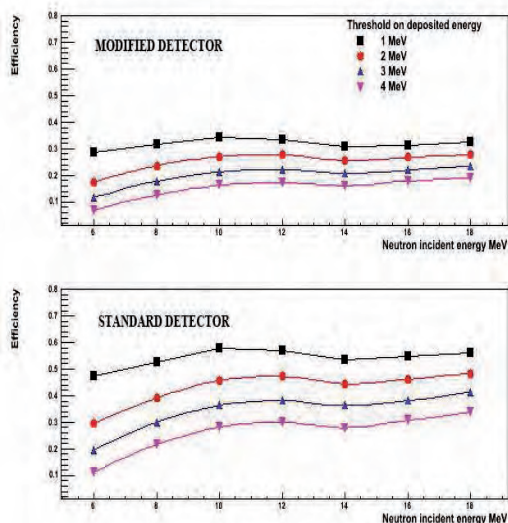


Figure 2: top figure shows efficiency to incident neutrons of energy up to 18 MeV for modified detector; the different curves describes the results for different threshold on deposited energy. Bottom figure the same for the standard detector

The different colours are referred to different thresholds of deposited energy. The behaviour of the curves in the

region around 11 MeV is ascribed to the decreasing role of the channel $^{19}\text{F}(n,n\alpha)^{15}\text{N}$ whose cross section has an important maximum at about 11 MeV (about 0.4 barns) and the opening of (n,2n) reaction channels.

However, the advantages of an increased path length and the reduced uncertainty in the determination of the interaction point, obtained shortening the crystal, strongly overcome the effect of the reduced efficiency.

The figure 3 shows the time of flight measured between the neutron generation at the centre of the apparatus and the detection of a cumulative energy greater than 1 MeV for standard (black line) and modified detector (red line) irradiated by a monochromatic source of 14 MeV neutrons.

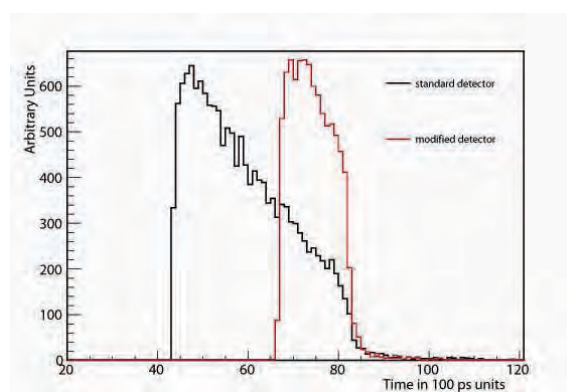


Figure 3: time spectra expressed in multiple of 100 ps for standard detector (black line) and modified one (red line). The time is measured starting from the instant when the neutron is generated until the time when the deposited energy is 1MeV

The comparison between the standard detector and the modified one is in favour of the last one. A reduced spread in the time spectrum, connected to the reduced thickness for the modified detector allows a better determination of the energy. The shifted start point for the red line reflects the longer path length.

Finally the question of the cross talk linked to the fact that the detectors are closely packed is addressed. The figure 4 shows the fold distributions derived from simulation runs of 30000 events where 14 MeV neutrons are randomly sent into a solid angle subtended by the detector. The black line is referred to the standard detector, the red line is referred to the modified one. Again, as in the time spectra, the detection of at least 1 MeV cumulative energy has been required to increment the fold spectrum. The fold 0 includes all events where the neutron is not detected or the deposited energy is below 1 MeV threshold. A quantitative indication of the goodness relative to the cross talk could be the ratio of the counts in fold1 to the counts in all folds excluding 0. The higher this value is the lower the cross talk is. A value of 0.38 has been calculated for the standard detector. The value of

0.47 calculated for the modified detector turns to this one advantage.

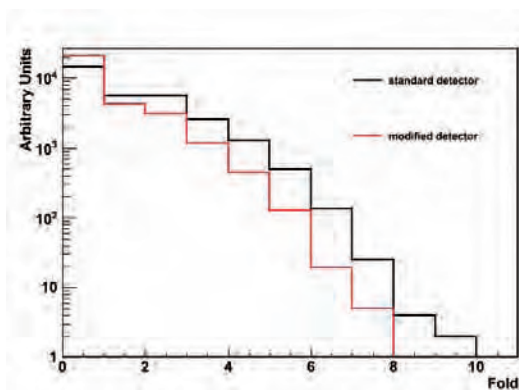


Figure 4: Fold distribution. The spectra are incremented requiring at least 1 MeV of deposited energy; red line modified detector; black line standard detector.

Obviously the requirement of a 3 MeV threshold on the deposited energy narrows the fold distribution. In this connection the figure 5 shows the fold distribution for the modified detector requiring again 1 MeV of deposited energy (red line) and 3 MeV of deposited energy (blue line).

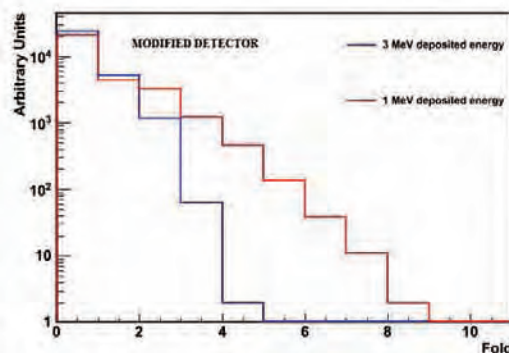


Figure 5: Fold distribution for the modified detector requiring 1 MeV of deposited energy (red line) and 3 MeV of deposited energy (blue line)

CONCLUSIONS

Simulations have been performed in order to study the neutron response for MEDEA detectors in a standard and modified configuration. First simulations seem to indicate that a detection improvement may be achieved for modified detector configuration. Notwithstanding, further simulations are needed and the preliminary study brings out the fact that is necessary to develop some strategies, including conditions on time spectra, to overcome the problem of cross talk.

We wish to thank Pablo Cirrone and Francesco Romano for fruitful discussions and suggestions concerning GEANT4 code.

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TESTS OF CHIMERA SILICON DETECTORS IN REVERSE MODE:

1) DETECTOR QUALIFICATION

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Abstract

In order to qualify the behaviour and the performance of the silicon detectors of the CHIMERA array prior to on-beam characterization with Digital Pulse Shape Acquisition of the signals coming from the preamplifiers, we performed some laboratory tests in order to assess the main detector parameters in terms of detector capacitance, depletion voltage, maximum level of overbias that can be applied, energy resolution in α -particle spectroscopy, noise parameters of the detector + charge preamplifier system.

INTRODUCTION

Prior to on-beam characterization it is crucial, especially for reverse mounting operation to experimentally assess the main detector parameters in terms of detector capacitance, depletion voltage, maximum level of overbias that can be applied, energy resolution in α -particle spectroscopy, noise parameters of the detector + charge preamplifier system.

DETECTOR QUALIFICATION

The detector used for the present tests is a CHIMERA detector pertaining to ring #6, whose picture is shown in Fig. 1. It is prototype n. 2505-5, produced by Micron [1] and features two cells of 21 cm^2 active area each, surrounded by a single guard ring. The detector nominal thickness is $299 \mu\text{m}$.

We performed a thorough detector qualification aimed to determine the main detector parameters and operating voltages. Fig. 2a shows the result of the CV measurement aimed to determine the detector depletion voltage and capacitance. It was performed with the Keithley 3321 LCZ meter at 10 kHz test frequency with 50 mV level on the P1 cell of the detector. The measured detector capacitance is 0.8 nF at the depletion voltage. Fig. 2b

shows the corresponding doping profile as a function of the detector thickness. Since for the on-beam tests it is important to study the detector performance as a function of the depletion voltage we measured the I V characteristics of the detector. Fig. 3 shows the result for the P1 cell. For over-depletion voltages up to 40 V no breakdown is observed and larger voltages have not been tested.

Each cell of the detector was coupled to a dedicated charge pre-amplifier [2] and its output signal was then fed to the ORTEC 572 spectroscopy amplifier. Spectroscopy tests were performed with a mixed nuclide α -particle source. Figs. 4 show an example of the measured spectrum on the P1 cell for illumination of the front side (a) and reverse side at $6 \mu\text{s}$ shaping time (b). The replica of the peaks at lower energy is due to the cross-talk between the two detector cells, affects about 4% of the events and fully disappear if only the cell under measurement is illuminated. Fig. 5 shows the behavior of the measured FWHM at the ^{239}Pu peak at 5.156 MeV as a function of the shaping time constant.

In order to deconvolve the white series, white parallel and $1/f$ series noise contributions, we derived the Equivalent Noise Charge (ENC) from the measured FWHM and fitted them according to the well-known

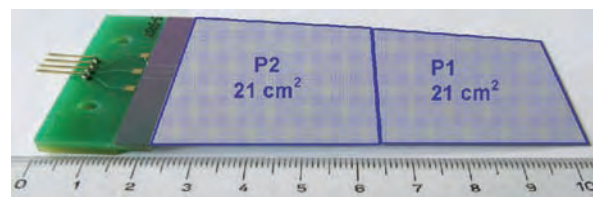
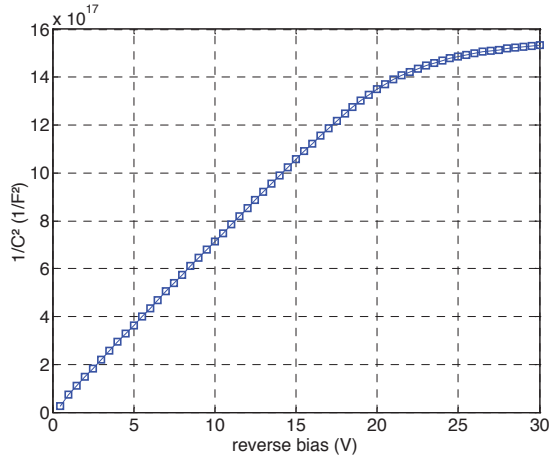
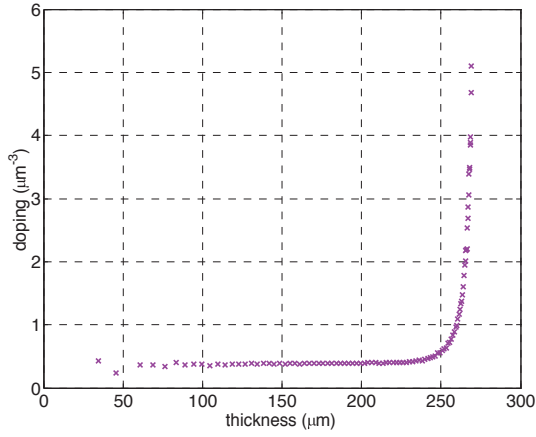


Figure 1: Photograph of the junction-side (p-side) of the detector mounted on his holder.



(a)



(b)

Figure 2: a) $1/C^2$ plot showing a depletion voltage of about 20 V. b) Doping profile extracted from the C-V measurement as a function of the detector thickness.

expression of the ENC as a function of the shaping time constant τ_{sh} [3] that we report for convenience

$$ENC^2 = A_1 \underbrace{\frac{2kT}{g_m} (C_D + C_G + C_f + C_{par})^2}_{\text{white series}} \frac{1}{\tau_{sh}} + A_2 \underbrace{\pi A_f (C_D + C_G + C_f + C_{par})^2}_{1/f \text{ series}} + A_3 \underbrace{\left(qI_G + qI_L \frac{2kT}{R_f} \right) \tau_{sh}}_{\text{white parallel}} \quad (1)$$

where A_1 , A_2 , and A_3 are the shape-dependent factors for the considered shaping amplifier, k is the Boltzmann's constant and T is the absolute temperature, C_D is the detector capacitance, C_G is the total gate capacitance of the input transistors, C_f is the feedback capacitance and

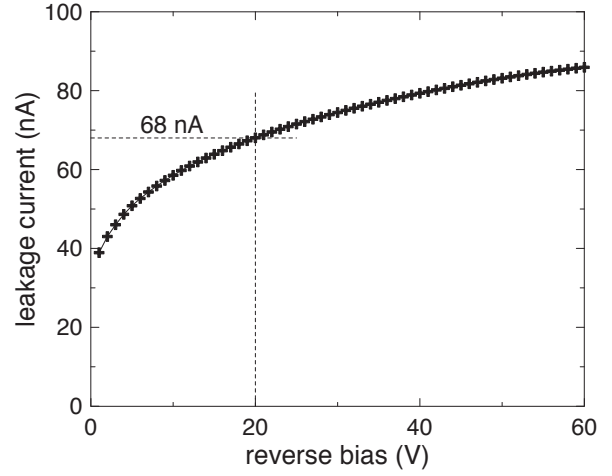
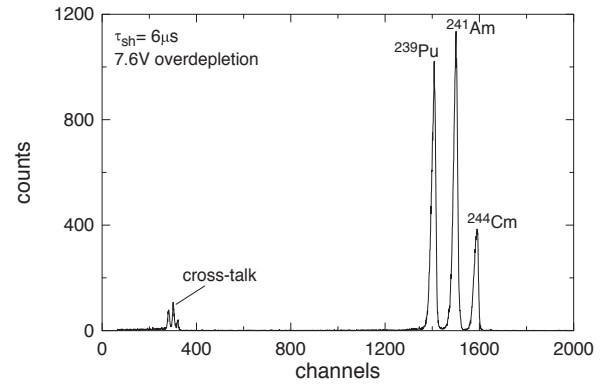


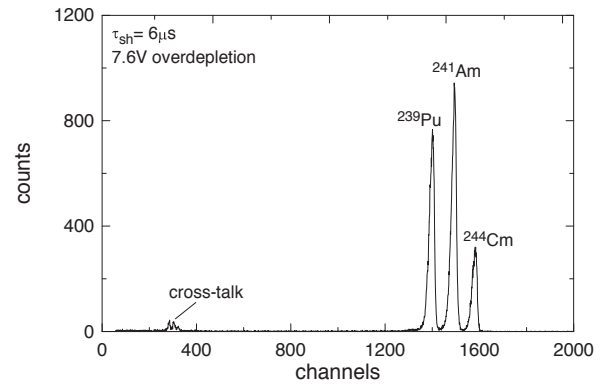
Figure 3. IV characteristic of the P1 cell of the detector.

C_{par} is the parasitic capacitance connected to the input node.

From the fitting coefficients it is possible to derive the detector leakage current, the transconductance of the input transistor and the $1/f$ series noise coefficient once



a)



b)

Figure 4: α -particle spectrum from a mixed nuclide source. a) front side illumination, b) reverse side illumination.

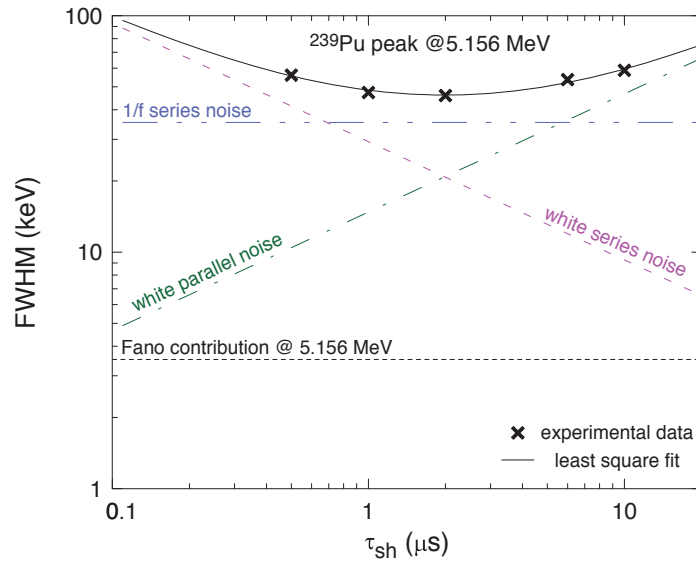


Figure 5: Measured FWHM at the ^{239}Pu peak at 5.156 MeV as a function of the shaping time constant.

assumed the detector total capacitance (0.8 nF in the present case). The derived parameters are the following: 67.8 nA leakage current, 25.6 mS input transistor transconductance, $1.1 \times 10^{-13} \text{ V}^2$ $1/f$ series noise coefficient.

The measured parameters can be inserted in the preamplifier + detector model developed to predict the detection system performance [4] for the different identification techniques

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TESTS OF CHIMERA SILICON DETECTORS IN REVERSE MODE: 2) ON BEAM MEASUREMENT

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Abstract

We are fixing our attention to the products stopping in the silicon detector that can be identified in mass by measuring the fragment Energy and Time of Flight and in charge by measuring the Energy and the Rise-Time of the preamplifier output signal. With the latter technique, one of the points of largest physical interest is the minimum energy of the reaction products that allows charge identification. To this aim we performed a measurement campaign, using the ion beam of the Superconducting Cyclotron, aimed to evaluate the performance of the CHIMERA Silicon detectors in reverse mounting.

INTRODUCTION

A large variety of techniques is available for the identification in mass and charge of the reaction products, depending on the fact that they punch through, or not, the silicon detectors. The availability of the reference signal coming from the Superconducting Cyclotron increase the number of applicable identification techniques. The use of Digital Pulse Shape Acquisition to collect the event parameters [1] allowed us to obtain more precise results than with conventional acquisition based on a full analogue readout chain.

We focus our attention on the products stopping in the silicon layer. The measure of the Energy and of the Time of Flight – (E , ToF) technique – allows velocity measurement and identifies these products in mass [2]. The measure of the pulse Rise-Time combined with the measurement of the fragment Energy – (E , RT) technique – identifies the charge of the stopped fragment [3]. One of the points of largest physical interest is the minimum energy of the reaction products that allows proper charge identification. However, for front-mounted detectors, when the detected particles have a range smaller than the detector thickness, the measured rise times coalesce into a

broad band and no identification is more possible [3]. The Z -separation for this ensemble of particles can be enhanced by allowing them to enter from the rear side (n -side) of the detector. This is due to the lower electric field in the entrance region and the lower velocity of the holes, which are mainly responsible for the signal formation. In addition the rising field profile minimizes the plasma-erosion effect near the end of the tracks where ionization density is highest. Last but not least, the current pulses become monotonically shorter when the particle range increases, since the slower holes have then generally to transverse a shorter distance [4-6]. However, it is of key importance to properly bias the detector in order to avoid any undepleted region close to the ohmic contact. The simultaneous measurement of the Time of Flight, of the Rise Time of the silicon pulse, and of the energy deposited in the silicon detector allows a complete mass and charge identification in a single detector for the fragments stopping in it.

To this aim we reverse mounted one of the CHIMERA silicon detectors and made a preliminary set of tests using the ion beam of the Superconducting Cyclotron.

DIGITAL PULSE SHAPE ACQUISITION

In order to simplify the electronic chain with respect to the conventional analogue one we applied Digital Pulse Shape Acquisition (DPSA) to collect signals from the detection cells. DPSA allows the collection of the signal pulse shape – that carries the whole information – from the preamplifier, by using a Sampling Analog to Digital Converter (SADC). So, no other electronic module is necessary. The collected pulse shapes are then digitally processed in order to obtain the physical observables.

The core of the system is the SIS3301 [7] an 8-channel digitizer/transient recorder featuring a sampling rate of up to 105 MHz for the individual channel and 14-bit



resolution. The SADCs are located in a VME crate together with the SIS3100 [8], the VME-side of the bridge module, used both as VME bus master and as monitor of the SADCs. The SIS3100 is optically connected to the SIS1100 [8], the PCI board located in the host PC. The SIS1100/3100 PCI-to-VME interface features a transfer rate of 80 MB/s. In order to reconstruct the pulse shapes and to obtain event parameters from each stream of samples, we applied several algorithms to the digitized waveforms. Moreover we used an upsampling algorithm to better estimate the start and stopping times in the *ToF* calculation.

ON-BEAM CHARACTERIZATION

The on-beam tests have been carried out at the Superconducting Cyclotron, with a 35 AMeV ^{58}Ni beam, of intensity 400 epA, bombarding a ^{112}Sn target. The detector was reverse mounted at $\theta_{\text{lab}}=14^\circ$ (6th wheel) with no collimators, and coupled to a CsI(Tl) scintillator as for front-mounted detectors. All the different identification techniques have been investigated.

$\Delta E_{Si}-E_{CsI}$ measurements in reverse mounting

Figs. 1 show the $(\Delta E_{Si}, E_{CsI})$ scatter plots – in which the side of mounting of the detector has no impact – at three levels of detector overbiasing as a benchmark of the detector performance. As expected we observe a slight worsening of the resolving power at increased overbias voltages due to the slight increase of the detector leakage current (16% for 20 V overbias and 26% for 40 V overbias).

E_{Si} –*RT* measurements in reverse mounting

Figs. 2 show the (E_{Si}, RT) [rise time (10%-90%)] scatter plot for three different levels of overbiasing. The *Z*-identification clearly appears and from Fig. 2c that shows the (E_{Si}, RT) scatter plot up to higher energies we see that it extends up to at least $Z = 19$. As expected, at increasing levels of overbiasing, the pulse rise time decreases due to the increased depletion field intensity. The energy threshold for *Z*-identification seems to slightly worsen at increasing levels of overbiasing, mainly due to the decrease of the pulse rise-times and to the slight worsening of the energy resolution.

E_{Si} –*ToF* measurements in reverse mounting

We also performed some preliminary tests to investigate the identification capabilities of the (E_{Si}, ToF) measurements with the Silicon detector in reverse mounting. One channel of the SIS3301 was used to digitize the reference signal at 23.41 MHz coming from the Superconducting Cyclotron. The signal coming from the Silicon detector provides the start signal for the *ToF* measurement while the reference signal provides the stop.

Figs. 3 show the (E_{Si}, ToF) scatter plots for three different levels of overbiasing. The energy values where

the lines are bending back correspond to the maximum energy loss of the particles in the detector as for front mounting detectors. For these high energies, the *ToF* is still measured, but as a function of the energy loss in the detector – and not of the whole particle energy –, which depends primarily on nuclear charge. As a result, at these high energies the detected fragments show separation in charge, providing an optional particle discrimination method alternatively to $(\Delta E_{Si}-E_{CsI})$. For lower energies, however, instead of the usual family of mass hyperbolas, we see a more complicated structure that can be better appreciated in Fig. 4, where we show a zoomed view of the plots shown in Fig. 3. When the detector is front-mounted, the time differences between adjacent nuclear charges due to the dependence of the pulse shape (and, hence, of the Rise-Time) on the nuclear charge are generally lower than the differences in Time of Flights of fragments featuring neighbouring masses. Therefore the larger time separation is caused by the difference in mass of the identified reaction products and the (E_{Si}, ToF) provides mass identification.

In reverse mounting, especially for the lighter fragments the dependence of the preamplifier output waveform shape on the nuclear charge causes differences in the fragment time of arrival for a given mass but for different charges comparable with the particle *ToF*, therefore a more complicated structure is formed. At energies close to penetration the higher the *Z* value, the higher the penetration energy for the same mass. We are presently making the complete analysis of the data shown in Fig. 3.

CONCLUSIONS

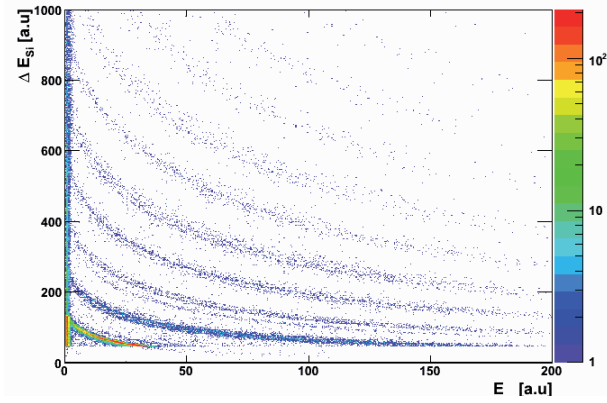
In this contribution we presented the results of the full characterization of one CHIMERA Silicon detector in reverse mode in real operating environment. Very good time (and energy) resolution were obtained albeit employing the detector in reverse mode.

The simultaneous employment of *PSD* and *ToF* methods combined with digital pulse-shape sampling opens the way for a more efficient use of silicon detectors in heavy ion nuclear reaction studies. Deeper insight is needed in the potential of joint *PSD* and *ToF* for proper discrimination of fragments stopping in the Silicon layer with respect to both mass and nuclear charge with the aim of decreasing the identification threshold.

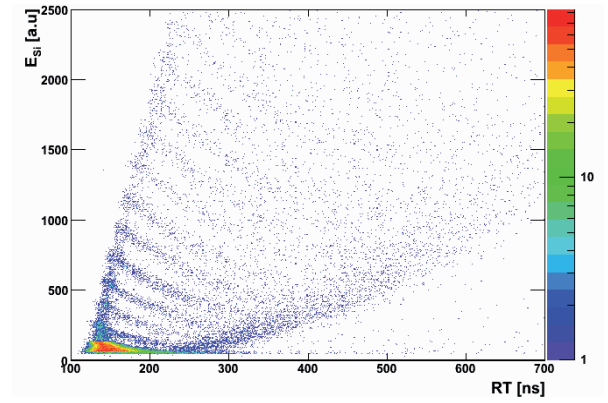
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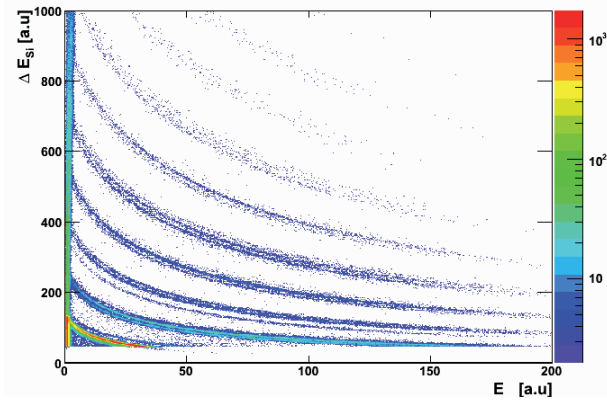
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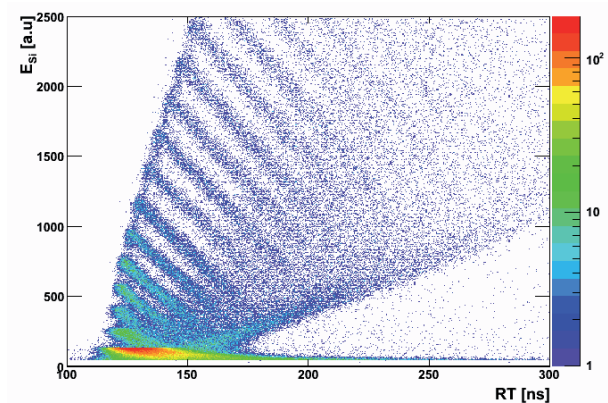
(a)



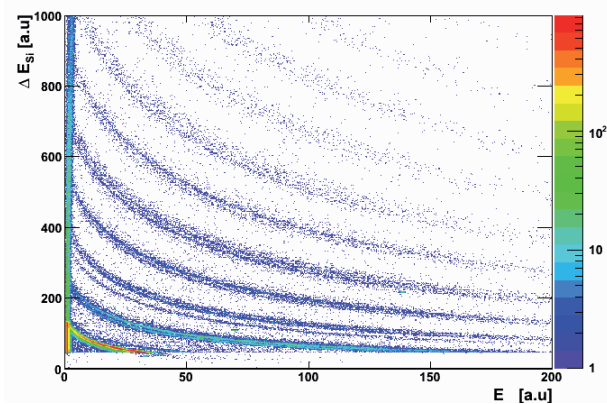
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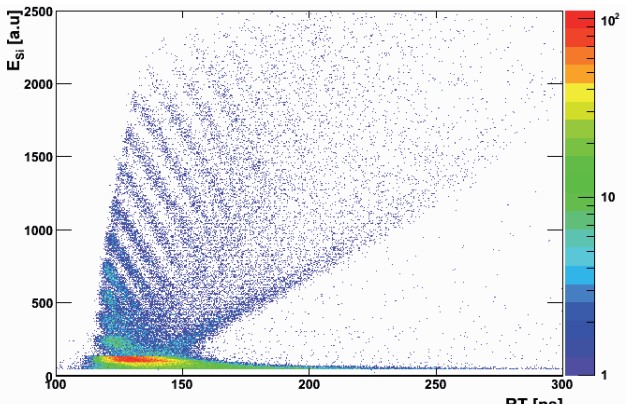
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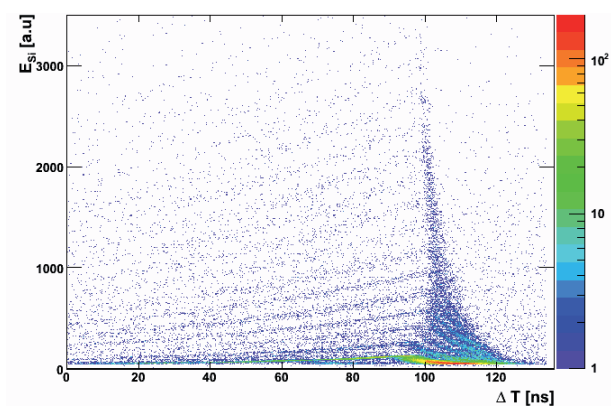
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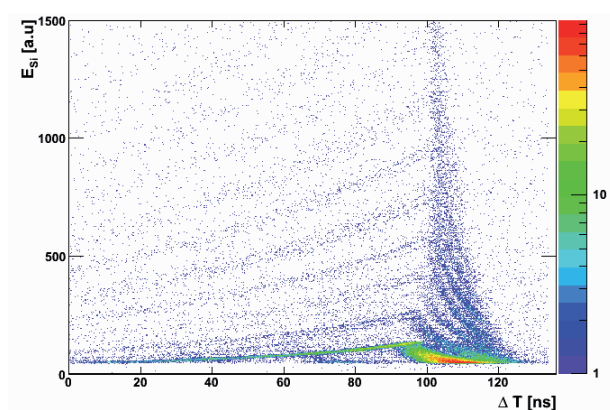
(c)

Figure 1: $(\Delta E_{Si}, E_{Csl})$ scatter plots at three levels of detector overbiasing: a) 10 V, b) 20 V, c) 30 V.

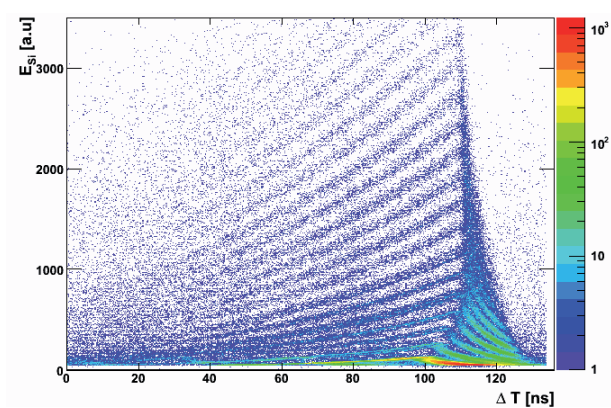
Figure 2: (E_{Si}, RT) scatter plots at three levels of detector overbiasing: a) 10 V, b) 20 V, c) 30 V.



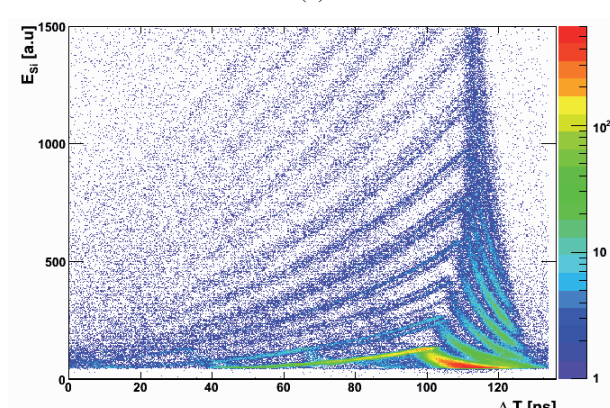
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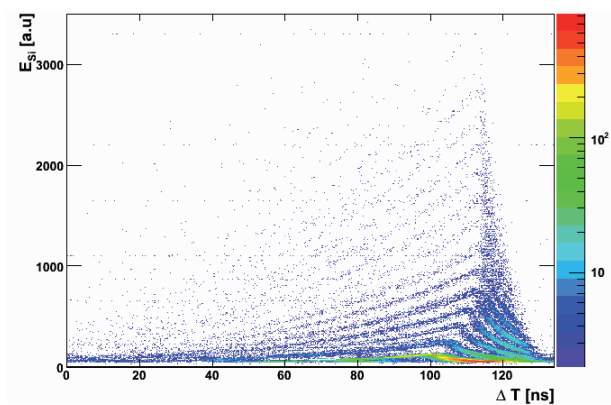
(a)



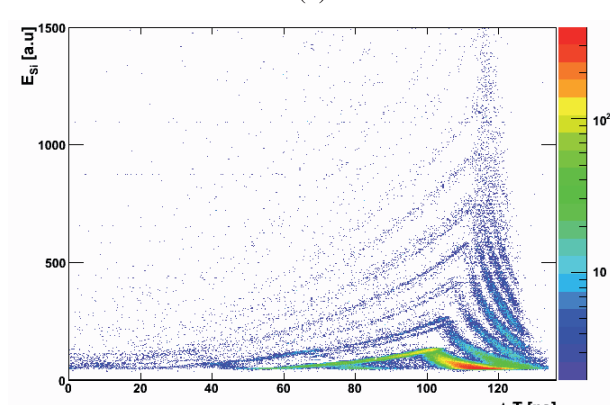
(b)



(b)



(c)



(c)

Figure 3: E_{Sr} -ToF color scatter plots for three different levels of overbiasing: a) 10 V, b) 20 V, c) 30 V.

Figure 4: Zoomed view of the 3 E_{Sr} -ToF color scatter plots shown in Fig. 8 at the same three levels of overbiasing: a) 10 V, b) 20 V, c) 30 V.

TEST OF FAZIA PROTOTYPES AT LNS

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Abstract

The response of a few silicon-silicon-CsI(Tl) and silicon-silicon telescopes with high quality detectors developed within the FAZIA collaboration [1] is tested in this work. The silicon detectors were manufactured from “random cut” wafers to avoid channeling effects and are characterized by a high dopant homogeneity. One silicon-silicon telescope was mounted on a rotating platform to compare its response in case of front and rear injection. Another silicon detector was mounted on a motorized support, sliding to angles very close to the beam ($\sim 0.5^\circ$), in order to measure the effects of radiation damage on energy resolution and PSA.

Beams of ^{84}Kr and ^{129}Xe at 35A MeV, impinging on targets of ^{nat}Ni , ^{93}Nb , ^{120}Sn and Au, produced fragments over a large range of charge, mass and energy. The aim was to explore the capabilities of various solutions exploiting the digital techniques of Pulse Shape Analysis (PSA) for the Z and A identification of stopped ions.

It has been found that PSA is able to fully discriminate the charge of stopped ions up to the maximum available Z (that of the beam, $Z=54$). The ΔE -E correlations of the first two silicon detectors can separate all the nuclides up to $Z \sim 25$ and no difference in resolution between front and rear injection is observed. The experimental data also provide some preliminary information about the effects of

radiation damage on energy resolution and PSA for high fluences of heavy ions.

INTRODUCTION

For the next generation of nuclear physics experiments it is important to optimize the isotopic resolution of reaction fragments with the lowest possible thresholds. Pulse Shape Analysis techniques coupled to digital signal processing are very useful to this aim.

In the last years the FAZIA collaboration and other groups [1,2,3] have investigated the behaviour of silicon detectors for pulse shape applications. It was found [4] that, for stopped ions, the discrimination capability with PSA strongly depends on the homogeneity of the detector resistivity and on a careful control of channeling-related effects.

Previous studies [5] of the FAZIA collaboration demonstrated the importance of using silicon detectors from wafers cut along the so called “random” directions, namely those which make the crystal appear like an amorphous material to impinging particles.

The silicon detectors of the FAZIA telescopes were built adopting such type of cut. Moreover only detectors with doping inhomogeneities of about 1% or better were used. This last selection was done with a laser-based non-

destructive method [6] developed by the collaboration, that allows building a map of the resistivity as a function of the position on the silicon.

The aim of the experiment was to test the capabilities of these well-controlled detectors for the identification of heavy ions over a large energy span.

EXPERIMENTAL DETAILS

The silicon detectors are all ion-implanted and of the nTD type, with bulk resistivity values around 3200 Ωcm . They are reverse mounted, i.e. particles enter from the low field side. In this way the risetime differences of the charge signals for different ions are maximized and this is of fundamental importance for PSA applications.

Eight different telescopes (Table 1) with their Front End Electronics (FEE) were mounted in the “Ciclope” scattering chamber of the Laboratori Nazionali del Sud (LNS Catania). They were irradiated by the reaction products of ^{129}Xe and ^{84}Kr beams accelerated at 35A MeV by the “Ciclotrone Superconduttore” (CS) impinging on targets of ^{nat}Ni , ^{93}Nb , ^{120}Sn and Au.

Table 1: Telescopes characteristics

Telescope	Silicon 1	Silicon 2	CsI(Tl) readout
Tele A	300 μm	500 μm	4 cm + PhD
Tele B	300 μm	500 μm	4 cm + PhD
Tele C (SCT)	300 μm	300 μm	4 cm
Tele D	300 μm	300 μm	4 cm + PhD
Tele E	500 μm	-	4 cm + PhD
Tele L	300 μm	-	4 cm + PhD
Tele FR	300 μm	300 μm	-
Tele RD	300 μm	-	-

Three telescopes (Tele A, B, D) consisted of three elements: a first (300 μm) silicon, a second (300 or 500 μm) silicon and a 4 cm thick CsI(Tl) scintillator with photodiode (PhD) readout. Two other telescopes (Tele E, L) consisted of a single silicon (500 μm or 300 μm thick), followed by a 4 cm CsI(Tl), read out again by a photodiode.

There was also a three-element telescope (C) of the Single Chip type (SCT) [7], namely a configuration in which the second 300 μm silicon acts at the same time as a detector and as a photodiode for the following CsI(Tl).

A silicon-silicon telescope (Tele FR) with both elements of 300 μm was mounted on a 180°-rotating platform, in order to compare its energy resolution, ΔE -E and PSA discrimination in the front- and the rear-injection configurations.

Finally, a single 300 μm silicon detector was devoted to studying the effects of radiation damage (Tele RD). It was mounted on a motorized support that could slide to angular positions very close to the beam direction ($\sim 0.5^\circ$).

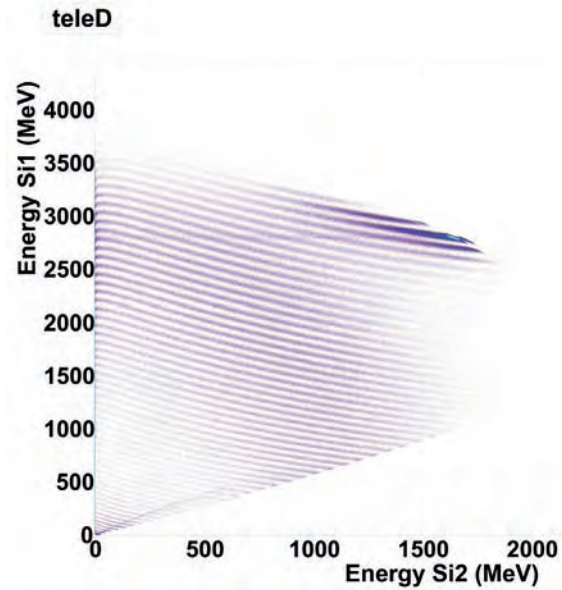


Figure 1: ΔE -E correlation for a Si(300 μm) – Si (300 μm), obtained with the ^{129}Xe beam.

By means of masks, three different small regions named “no damage”, “transmission damage” and “implantation damage” were defined for Tele RD. The first one (to be used just as a reference) is an area of the detector never exposed to a high fluence of elastically scattered ions. The “transmission damage” and the “implantation damage” regions, on the contrary, were periodically exposed to the largest fluences of elastically scattered ions: in the first case the ions had enough energy to punch through the silicon, in the second case they were degraded by an absorber, so that they were stopped inside the detector. From time to time, Tele RD was moved to larger angles with “normal” fluences, so that its performances in terms of energy resolution and PSA in the damaged areas could be compared with those of the “no damage” area, as a function of the cumulated irradiation dose.

All the 300 μm thick detectors were manufactured by FBK (Trento), while the 500 μm thick ones were from Canberra (Belgium). All the silicon wafers were cut from an nTD silicon ingot produced by TOPSIL (Denmark). All elements of the FAZIA telescopes were coupled to dedicated Front End Electronics: current and charge preamplifiers (PaCI) [8] with different gains and custom-built digitizers. The digitizers were either 125 MS/s 12bit cards (“Florence” cards [9], developed by INFN-Sezione di Firenze) or 100 MS/s 14 bit cards developed in the framework of the FAZIA collaboration. Not all the current outputs of the PaCI were exploited. In a few cases, the current signal was derived, just before sampling it, on the FEE board via an analog differentiating circuit. For those cases, just the charge output of the PACI was needed.

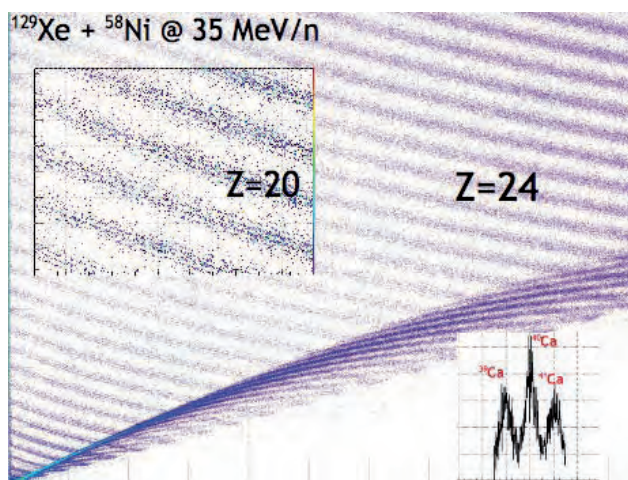


Figure 2: ΔE -E correlation for a Si(300 μ m)-Si(300 μ m), obtained with the ^{129}Xe beam. Isotopic separation is visible until $Z \sim 24$. The top inset shows a detail around the $Z=20$ lines and the bottom one the isotopic discrimination for Ca ions.

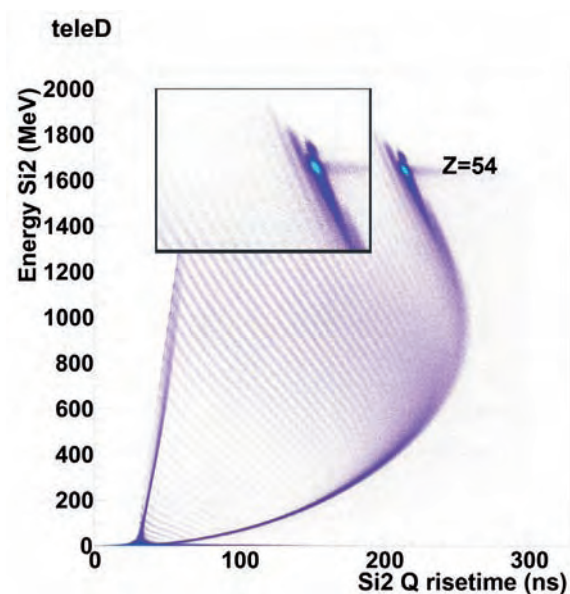


Figure 3: Identification obtained by plotting the measured energy versus the rise-time of the charge signals for ions stopped in a 300 μ m silicon detector. The inset shows a detail of the element separation around the elastically scattered ^{129}Xe beam at 35A MeV.

EXPERIMENTAL RESULTS

Ions identification with ΔE -E (Si-Si) technique

As anticipated, the used Silicon material, which strongly reduces crystal-orientation-related effects and minimizes those due to the dopant inhomogeneity, allowed us to obtain unprecedented results in the particle identification with the ΔE -E technique. An example is

presented in Figure 1, showing the ΔE -E correlation for a Si(300 μ m)-Si(300 μ m) telescope, with the ^{129}Xe beam on a ^{nat}Ni target. Clear isotopic separation is present up to $Z=23-24$, as can be seen from Figure 2, where the top inset shows the isotopic resolution around $Z=20$ and the bottom one the corresponding mass discrimination for Ca isotopes. Equally good performances have been obtained for all telescopes. We remind that this result is based not only on the selected Silicon material (doping uniformity at the 1% level) and on the special wafer cut (to avoid channelling), but also on the optimized Digital Signal Processing and on the very well performing FEE developed by the collaboration.

Ions identification via PSA in silicon

All detectors performed extremely well, as shown in the following correlations. In Figure 3, the identification obtained by plotting the energy versus the rise-time of the charge signals is shown for ions stopped in a 300 μ m Silicon detector (the high-intensity spot corresponds to elastically scattered ^{129}Xe ions of ~ 35 A MeV).

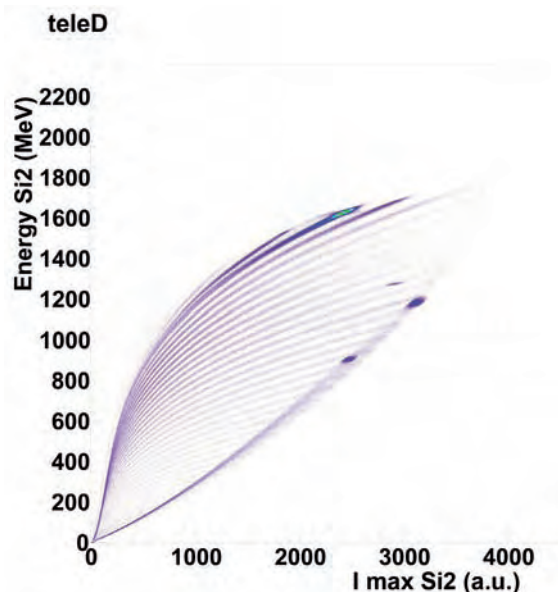


Figure 4: Identification obtained by plotting the measured energy versus the maximum of the current signals for the products of the ^{84}Kr on ^{nat}Ni reaction at 35A MeV, stopped in a 500 μ m Silicon detector.

A similar result is obtained by plotting the energy versus the maximum of the current signal [10], as displayed in Figure 4, again for the fragments from the $^{84}\text{Kr} + ^{nat}\text{Ni}$ reaction at 35A MeV. An unprecedented identification performance is obtained, with full Z separation up to the highest detected charge ($Z=54$). There is no evidence, yet, of any appreciable degradation of the Z -identification, so that full charge identification may be expected for all elements with the adopted FAZIA approach. For lower Z , mass identification was already demonstrated during an LNL-experiment [4].

The Single Chip Telescope

In the SCT, the use of digital signal processing is fundamental for disentangling the scintillation and the ionization signals. This can be done by exploiting a PSA-based method developed by the collaboration [11,12]. Once separated, the silicon and CsI(Tl) components are used to build the usual ΔE -E correlation: an example is shown in Figure 5. A good separation in Z is observed, together with a clear mass discrimination for light elements. This kind of telescope reduces the electronics needed for read out and could be employed in the future FAZIA 4π -setup for covering the most backward angles.

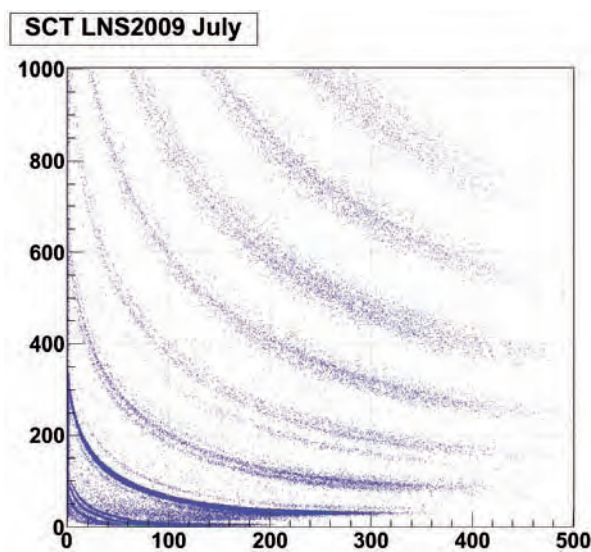


Figure 5: Digitally reconstructed (ΔE -E)-like correlation from the SCT. A good separation in Z is observable and a clear mass discrimination for the light elements.

The Radiation damage

Preliminary results on radiation damage show that for fluences of the order of 10^9 ions/cm² a significant increase of pulse-height defect and a decrease of rise-time is observed in case of implanted ions. Appreciably smaller damage is present, on the contrary, in case of punching-through ions, while practically no damage effects are visible in the area irradiated with the fluence of a “regular experiment”. Analysis of these data is still in progress.

CONCLUSIONS

In the present work the response of eight silicon-silicon-CsI(Tl) and silicon-silicon telescopes with purposely developed high quality silicon detectors has been tested. In particular the silicon detectors were manufactured with stringent requirements for what concerns doping homogeneity, thickness uniformity and crystal orientation, to avoid channeling effects. All these features are obtained by proper choice of the silicon material and cutting geometry, without significantly affecting the cost of the detectors. Custom-developed

digital electronics and original digital signal processing techniques [5,6,11] have been extensively used.

The results of the digital PSA technique for identifying stopped ions are very satisfactory: full charge separation is obtained up to the maximum observed $Z=54$. For mass identification (which was presently limited by the large dynamic-range in energy of ~ 5 GeV) a higher energy gain would have been necessary, as it was done in [4].

The ΔE -E (Si-Si) correlations allow isotopic separation up to $Z=23$ -24, not far from the physical limit imposed by the energy straggling, as suggested by simulations.

Preliminary results on the radiation damage show that an increase of the pulse-height defect and a decrease of the rise-time is observed for fluences of the order of 10^9 ions/cm², while practically no damage is found for the fluences typical of a “regular experiment”. The analysis of these aspects is still in progress.

The detectors used in this experiment, although very well performing in terms of Pulse Shape Analysis and ΔE -E discrimination, still require improvements in order to obtain also excellent timing performances. In fact the manufacturing process was not optimized for what concerns the sheet resistance of the electrodes. As a matter of fact, bench tests with a pulsed laser showed a position dependence of the time response (of the order of 1-2 ns), for both rear and front injection. Next production of silicon detectors by FBK-Trento is expected to solve this problem by a proper metallization of junction and ohmic sides. Once these detectors are available, new experimental data will be necessary to test their timing performance, with the aim of extending the present mass identification by means of the Time-of-Flight technique.

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TEST OF THE NEW LABR3:CE SCINTILLATOR

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Abstract

The properties of cylindrical 3"x3" and 3.5"x8" Lanthanum Bromide scintillation detectors have been investigated with γ rays up to 15 MeV produced via the $^{12}\text{C}(p,p'\gamma)$ reaction.

cannot be used at the optimal voltage since the signal would saturate. Results indicated that the PMT's should be used at about the 60% of the optimum voltage, and that none of the commercially available PMT's provides good linearity.

Introduction

Lanthanum Bromide scintillation detectors have been recently developed and commercialized [1]. Their physical properties are summarized in table 1 and compared with few other scintillators commonly used for γ ray detection in nuclear physics. They are characterized by a very high light yield and a very fast decay time, which implies a very good energy resolution and time response. In fact, the typical energy resolution of a LaBr3:Ce detector is 19 keV at 662 keV, and the time resolution is 300 ps. These properties make this detector very competitive. Only recently, large volumes of material, which is very hygroscopic and fragile, became available.

Table 1: Scintillator properties

Scintillator	Light Yield (ph/keV)	λ of max emission	Density (g/cm ³)	Decay time (ns)
BaF ₂ fast/slow	1800/10000	220/310	4.88	0.7/630
NaI:Tl	38000	415	3.67	230
BGO	8200	505	7.13	300
CsI(Na)	39000	420	4.51	630
LaBr3:Ce	63000	360	5.08	<30

Due to the excellent performances of the scintillating material, the properties of the associated PMT's and electronics become important. Several tests were already performed on these new detectors using Cs, Eu, PuC, and AmBe sources [2], investigating the internal activity and the properties of different PMT's as a function of voltage. Due to the high light yield, in fact, commercial PMT's

Experimental procedures and results

In order to test the linearity up to 15 MeV γ rays, we detected the γ decay from the 15.1 MeV state of ^{12}C populated via the $^{12}\text{C}(p,p'\gamma)$ reaction at $E_{\text{beam}}=20$ MeV. The beam was produced by the Tandem in LNS, with intensity of about 1 pA. Two cylindrical 3.5"x8" and one 3"x3" LaBr3:Ce from INFN Sezione di Milano and one HPGe detector from LNS were positioned on the 60° beam line. Three additional 3"x3" LaBr3:Ce detectors from ESA were also positioned (not discussed here). The 3"x3" LaBr3:Ce detector was coupled to a Hamamatsu R6233-100 PMT and a standard E1198-27 Voltage Divider (VD). One 3.5"x8 LaBr3:Ce was coupled to a Photonis XP5700 and VD202K/01 as a voltage divider while in the second a Hamamatsu R10233-100 PMT with E1198-27 was used. It is important to stress that the photocathodes of the Hamamatsu tubes are of SBA type with a minimum quantum efficiency of 38%. Signals were pre-amplified and sent to commercial spectroscopy amplifiers Ortec 672 for the 3"x3" detector, Tc244 from Tennelec and Camberra 2020 for the 3.5"x8" scintillators. The DAQ was based on VME readout which uses CAEN ADC V879 in a KMAX environment. The data have been acquired in list mode and an accurate gain matching of the data has been done during the analysis. During the measurement, the Voltage of each detector was changed 3-4 times. In this way it has been possible to measure the response of the detectors to high energy gamma rays in different working conditions for the PMTs. In order to check the stability of the PMT's, every few ours a calibration run with ^{137}Cs , ^{60}Co , and PuC sources was taken. Furthermore, at the end of the test, the detectors were calibrated using the AmBe source with Ni material, producing a 8.99 MeV gamma-ray. Figure 1 shows in the upper panel the energy spectra measured by the 3"x3" scintillator detector when 600 V Voltage was applied to

the PMT. In the lower panel, the spectrum recorded by the 3.5"x8" detector with 600 V Voltage applied is shown. The 15.1 MeV full energy peak is clearly observed and is indicated by an arrow in the figure. Also visible are the first and second escape peaks. In the plot the centroid of the full energy peak is centred at approximately 14.5 MeV instead of 15.1 MeV. This already shows a non linearity in the PMT response of the order of 4%.

Full data analysis is in progress.

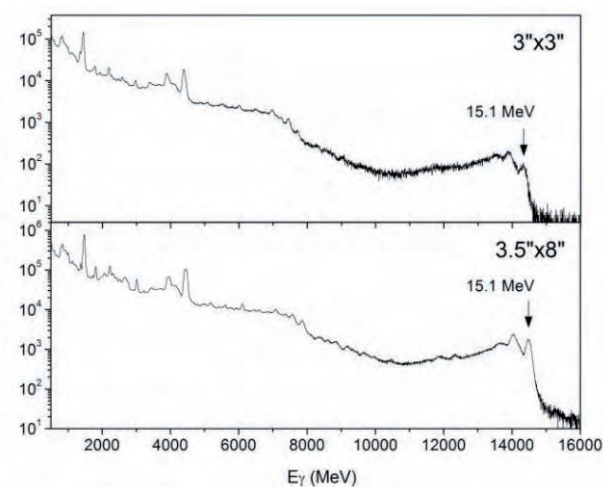


Figure 1: Energy spectra measured with the 3"x3" (upper panel) and 3.5"x8" (lower panel) LaBr3:Ce scintillator detectors. The decay γ -ray from the 15.1 MeV state in ^{12}C is indicated by an arrow. Also visible are the first and second escape peaks

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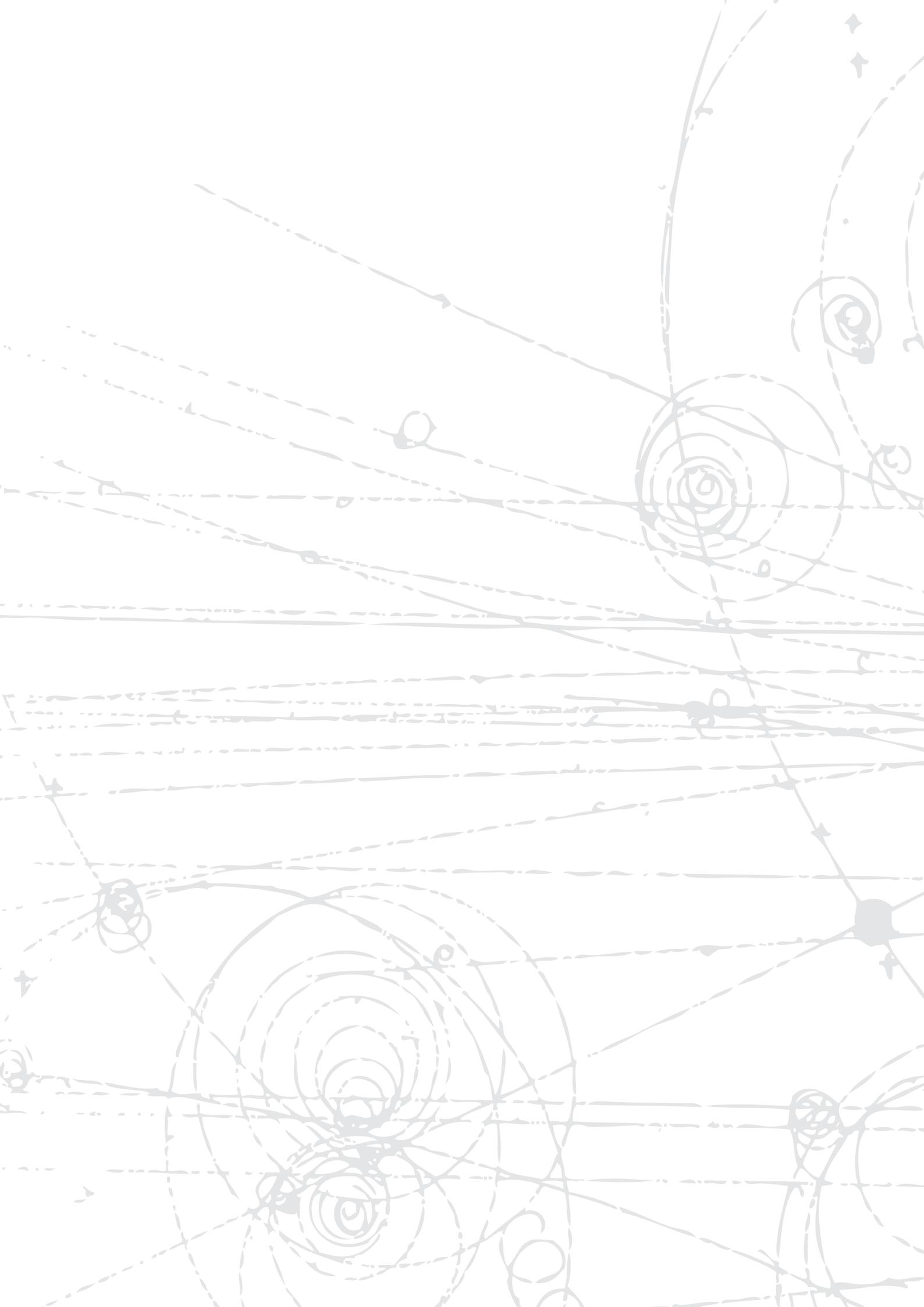
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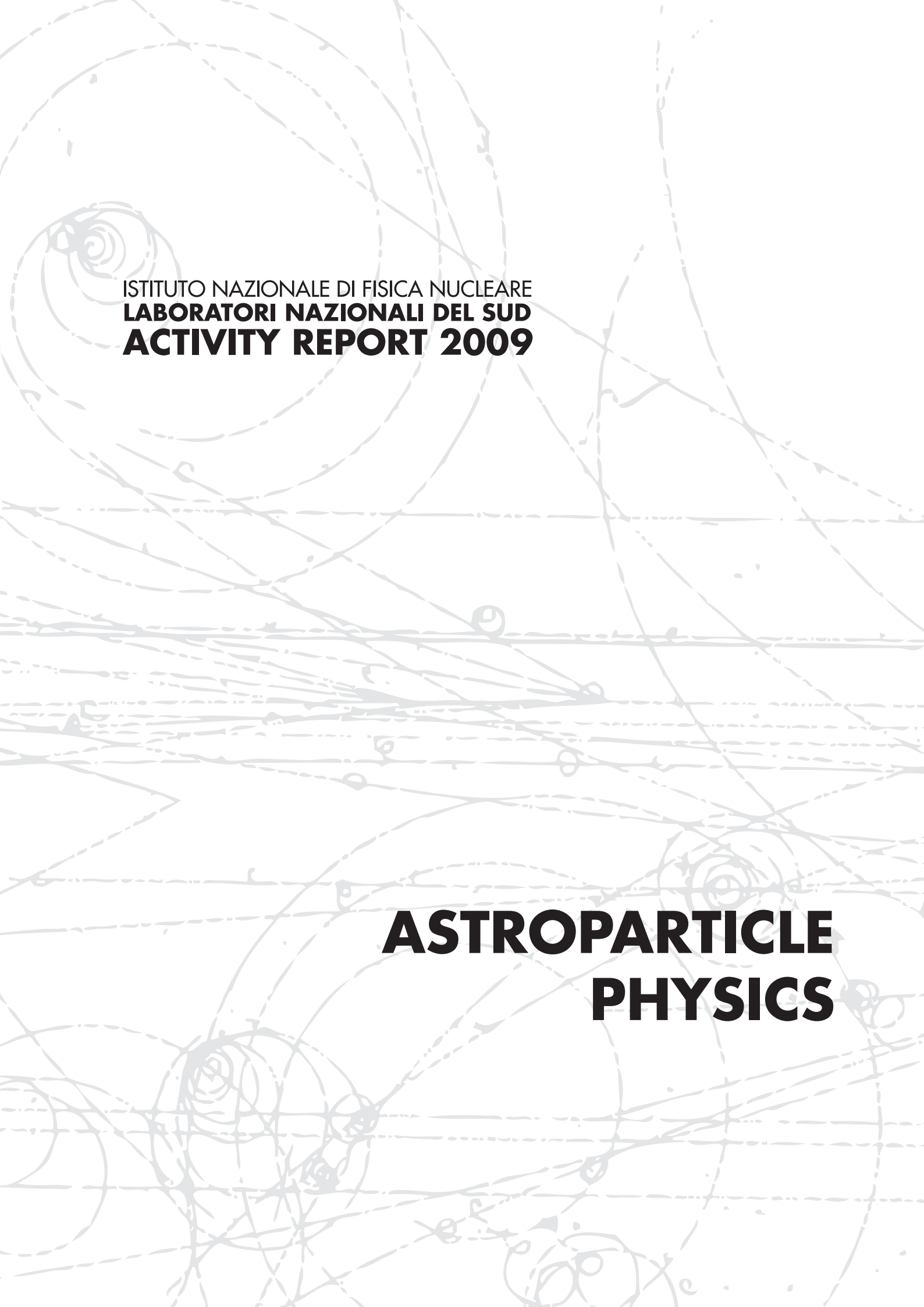
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ISTITUTO NAZIONALE DI FISICA NUCLEARE
LABORATORI NAZIONALI DEL SUD
ACTIVITY REPORT 2009

ASTROPARTICLE PHYSICS

STUDY OF THE SENSITIVITY TO POINT-LIKE NEUTRINO SOURCES FOR A FLEXIBLE-TOWER GEOMETRY FOR KM3NET

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Abstract

The KM3NeT consortium has investigated the performance of a high-energy neutrino detector by means of Monte Carlo simulations. In this work the study of the sensitivity to point-like neutrino sources as a function of the detector size and of the source declination is presented. It is shown that the detector sensitivity improves less than linearly with increasing the homogeneously instrumented volume and that the detector sky view is very large (about 3.5π).

INTRODUCTION

The detection of high energy neutrino fluxes from astrophysical sources is the main objective of an underwater or under-ice cubic-kilometer detector. Since the origin of high energy charged cosmic rays [1] is still unknown, the discovery of neutrino fluxes from galactic or extragalactic sources will shed light on the acceleration mechanisms responsible for the emission of both neutrinos and charged particles at high energies. Since neutrinos are electrically neutral and interact only weakly, they are not sensitive to magnetic fields and can traverse very dense layers of matter. These properties make them ideal messengers for discovering new sources and exploring their interior. Estimates of the neutrino fluxes from known sources indicate that a detector larger than a cubic kilometre is required. The aim of the KM3NeT consortium [2] is the construction of a research infrastructure including a cubic-kilometre-scale detector in the Mediterranean Sea. An optimisation work [3] to find the best detector geometry was done with the main focus on point-like sources in the energy range between a few TeV to about one PeV. The concepts behind the design of the detector, the technical requirements for the assembly, deployment and operation of a deep underwater detector will be reported in a Technical Design Report. In this work sensitivity studies to point-like sources for a detector based on flexible towers will be presented.

SENSITIVITY TO POINT-LIKE SOURCES: SIMULATIONS AND RESULTS

The search for a point-like neutrino source is based on statistical techniques to detect a weak neutrino signal from a cosmic source amongst the large diffuse background from atmospheric muons and neutrinos. Both are produced by the interactions of primary charged cosmic rays with the atmosphere. The atmospheric muon background, which represents a reducible background for a high energy neutrino telescope, is attenuated in intensity and energy below sea surface: it falls to zero for angles near and below the horizon, where the large slant of water and the Earth shield all the muons. For this reason the search for cosmic neutrinos is limited mainly to up-going muons. The diffuse atmospheric neutrino background is irreducible for the detection of cosmic neutrinos. Owing to the excellent angular resolution of the detector, this background can be reduced to a manageable level by performing the search in a restricted cone around the source direction.

The two main statistical approaches developed to look for steady point-like sources are binned and unbinned methods [4]. The sensitivity reported in this document has been estimated applying a binned method. Following the Feldman and Cousins approach [5], the sensitivity is the limit that can be placed on neutrino flux model from a source if no signal is detected. The average flux limit is defined as:

$$\Phi_{90} = \Phi_s \cdot MRF = \Phi_s \frac{\bar{\mu}_{90} \langle N_{bkg} \rangle}{\langle N_s \rangle}$$

where Φ_s is the normalization factor of the flux model. The sensitivity values are obtained by minimising the Model Rejection Factor (MRF) [5]. The MRF is defined as the ratio between the average upper limit μ_{90} and the average number N_s of events from the source; μ_{90} is the average upper limit of background fluctuations at 90% confidence level that would be observed in hypothetical repetitions of an experiment with a given background expectation and no true signal. By means of Monte Carlo simulations, the average number of events N_s inside a cone around a point-like source at fixed declination and

the average number of background events, N_{bkg} , are estimated. ANTARES codes [6] modified for a km^3 detector [7], including the detector geometry, the neutrino interaction, the light generation, the light propagation in water and the detector response, have been used for the simulations. A track reconstruction algorithm [8], based on a maximum likelihood estimator, developed inside the ANTARES collaboration and adapted to the km^3 geometry, has been employed to reconstruct the muon and consequently the neutrino direction.

During the KM3NeT Design Study, three combinations of technical options have been investigated and optimized in simulations studies. In this work the sensitivity to point-like sources for the geometry based on bar-structured, three-dimensional detection units (DU) will be presented. The DUs are

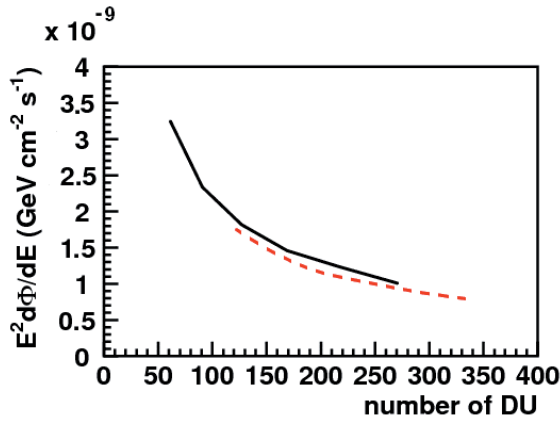


Fig. 1 - Sensitivity to an E^{-2} point-like source at a declination of -60° for one year of observation time as a function of the number of DUs for detector arranged in a homogenous set up (solid line) and in two building blocks (dashed line).

arranged with a hexagonal lay-out with a spacing of 180m. The DU consists of a sequence of 20 rigid bars, 6m long, placed orthogonally to each other with a vertical spacing of 40m. Each bar holds three couples of optical modules each one containing 8" PMTs (35% peak quantum efficiency): two couples at each bar edge with one PMT horizontal-looking and the other down-looking and a third one, located in the bar center, with the PMTs down-looking with an angle of 45° with respect to the vertical direction. In the simulation the Capo Passero optical water parameters [9], latitude and depth were used. The assumed random optical background due to the decay of ^{40}K and bioluminescence was 47 kHz per PMT.

The sensitivity to a point-like source with E^{-2} muon neutrino spectrum in the energy range from 10^2 to 10^7 GeV was evaluated for several declinations. Atmospheric neutrinos have been isotropically generated assuming the Bartol flux [10] (approximately an $E^{-3.7}$ spectrum). A prompt contribution from charm decays is also included.

The parameters that are optimized in order to get the minimum value of MRF are the size of the search cone,

the cut on the reconstruction quality parameter and a cut on the number of recorded PMT hits that is related to the neutrino energy. Only neutrinos up to 6° above the horizon were considered.

In Fig. 1 the sensitivity to a point-like source at -60° of declination (full visibility) with an E^{-2} spectrum for one year of observation time is reported as a function of the number of DUs arranged in a homogeneous setup (solid line). Sensitivities estimated for detectors made of two building blocks are also shown (dashed line). The improvement in sensitivity is not proportional to the size

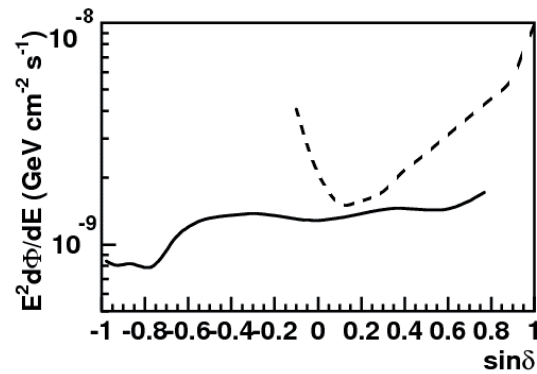


Fig. 2 – Solid line: sensitivity for a E^{-2} point-like sources for one year of observation time as a function of the source declination for a two 154 DU building blocks. Dashed line is the IceCube sensitivities [11] estimated with the unbinned method.

of the detector. For a detector of about 130 DUs a 20% increase in sensitivity requires about 30% more DUs.

Due to its location the KM3NeT neutrino telescope will observe a large fraction of the Galactic Plane, where many candidate sources are situated. In Fig. 2 (solid line) the sensitivity to a E^{-2} point-like source for one year of observation time is reported as a function of the source declination for a detector made of two 154 DU building blocks corresponding to a capital investment cost of 220M€. The result shows that the KM3NeT field of view allows for observing a large fraction of the sky (about 3.5π) including the Galactic Centre ($\sin(\delta)=-0.48$) and most of the Galactic Plane. The shape of the sensitivity curve is due to the combination of three effects: the source visibility, which is determined by the geographic location, the effect of neutrino absorption in the Earth and the detector response as a function of the zenith angle.

The KM3NeT sensitivity compared to that of IceCube [11] (dashed line) 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.

Moreover, as shown by the IceCube collaboration [4], using the unbinned method where in the probability density function a neutrino energy related component is

included, a further improvement on the KM3NeT sensitivity can be obtained.

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OPTIMISATION STUDIES FOR A DEEP SEA KM3 NEUTRINO TELESCOPE BASED ON FLEXIBLE TOWERS

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Abstract

The design and optimization of the KM3NeT telescope has been a major activity in the consortium. Some of the results for a detector design based on flexible-towers are presented.

INTRODUCTION

The KM3NeT high energy neutrino telescope [1] installed in the Mediterranean Sea will be able to observe upward-going neutrinos from about 3.5π sr of the sky and in particular the Galactic Centre and most of the Galactic plane, where HESS discovered many TeV-gamma that are very promising neutrino candidate sources. Several astrophysical sources are expected to produce high energy neutrinos spanning several orders of magnitudes in energy. The KM3NeT detector design is optimized in the energy range between 1 TeV and 1 PeV for the detection of point-like sources with a power law neutrino energy spectrum $E^{-\alpha}$ with α close to 2. In this work, we have investigated performance of a km^3 telescope made of flexible towers, i.e. a three-dimensional detection units with several photon sensors attached to horizontally extended structures (bars) at regular intervals along the structure.

SIMULATIONS OF TELESCOPE PERFORMANCE AND RESULTS

Simulations of telescope performance provide a guideline for detector design and optimization. The Monte Carlo code, developed by the ANTARES collaboration [2] and adapted to km^3 geometries [3], provides a complete simulation of incident neutrinos up to energies of 10^8 GeV, including their interactions in the medium and the propagation of the resulting secondary particles. The Bartol flux was used to simulate the contribution of the atmospheric neutrinos that represent the main source of background. In this work the performance dependence on the vertical distance between DUs and on the distance between bars is presented. Telescope performance is optimised in terms of sensitivity that represents one of the most relevant figures of merit of the detector. The sensitivity to point-like sources is estimated with the binned method according to the Feldmann and Cousin [4]

prescription that at 90% confidence level. The minimisation comes out of the optimisation of search cone size, cuts on reconstruction likelihood and on a threshold on an energy related parameter.

The results reported in the following were obtained for a telescope made of 127 flexible towers, with 20 bars per tower, 3 OM pairs per bar each containing a 8" with 35% quantum efficiency PMT.

A depth of 3500 m, an absorption length of 67 m at 440 nm was assumed and a 47 kHz uncorrelated optical background were considered.

The main advantage of the tower configuration is the three dimensional arrangement of optical modules within one DU that provides a good quality in track reconstruction, especially for tracks measured on a single detection unit due to the minimization of ambiguities in the azimuthal angle measurements. The performance dependence of a telescope based on towers on the PMT spacing in the various energy ranges was investigated [5]. In this work we report the sensitivity dependence on bar and tower distances for point-like sources with a power law spectrum $E^{-\alpha}$ with α close to 2.

In fig.1 is reported the trend of the sensitivity for point-like source sensitivity as a function of the bar distance. The reported sensitivity ratio is relative to the 30 m bar spacing. Increasing the bar distance from 30 m to 40 m and 50 m lead to an improvement of sensitivity for power law energy spectra with $\alpha=1.8, 2.0, 2.2$.

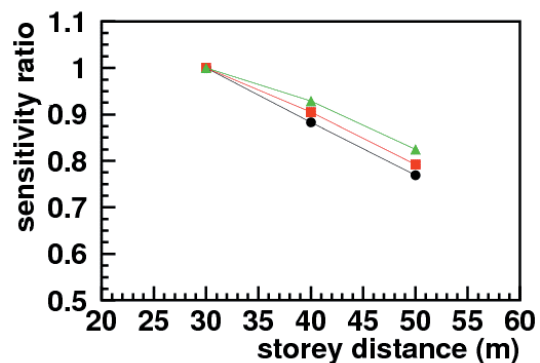


Figure 1: Point-like source sensitivity as a function of bar distance (see text). Circles $\alpha=1.8$, squares $\alpha=2.0$, triangles $\alpha=2.2$

In fig.2 is reported the sensitivity for point-like sources with energy spectra $E^{-\alpha}$ with respect to 100m tower spacing sensitivity as a function of tower distance. Sensitivity values are normalized to 100 m distance.

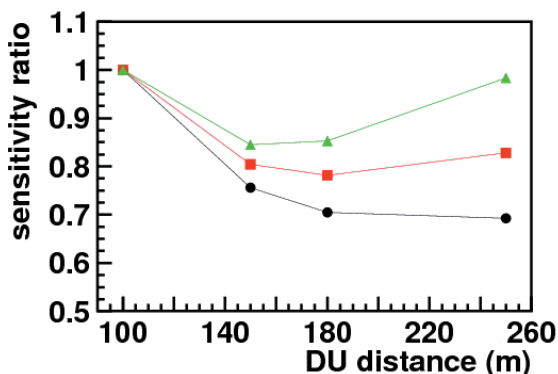


Figure 2: Point-like source sensitivity as a function of DU distance (see text). Circles $\alpha=1.8$, squares $\alpha=2.0$, triangles $\alpha=2.2$

A tower distance of about 180 m appears to be a good reference value for point source searches with spectral index close to 2.

Although the KM3NeT telescope is focused on the point-like source detection in the energy range between 1 TeV and 1 PeV, performance in other energy range are also interesting to be evaluated for a complete knowledge of telescope performance.

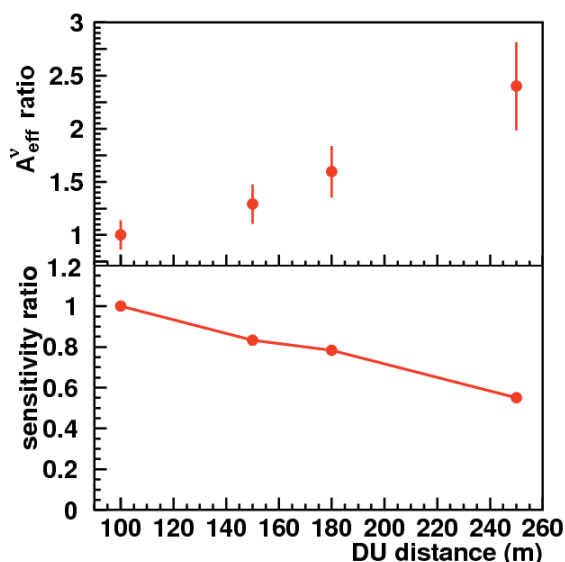


Figure 3 Top: Effective area ratio as a function of DU distance for $E > 100$ TeV neutrinos. Bottom: E^{-2} diffuse flux sensitivity as a function of DU distance.

The effect of DU distance at high energy ($E > 100$ TeV) is shown in fig. 3 where effective area for $E > 100$ TeV neutrino events and the diffuse flux sensitivity are reported. At high energy telescope performance improves with increasing DU distance.

CONCLUSIONS

The optimization of the PMT distance is strongly related to the physics case priority. A detector based on tower allows a larger spacing between detector units with respect to a string detector, thus allowing to instrument a given volume with a smaller number of detection units. A tower distance of about 180 m appears to be reasonable for point source searches with spectral index close to 2 and also provides good performance for high energy neutrinos $E > 100$ TeV. Of course increasing distance implies a reduction of the effective area in the low energy range (hundreds of GeV), that is the range of energy relevant for indirect search of Dark Matter, where dedicated studies are needed. Absolute values of point-like source sensitivity for flexible towers and its dependence on source declination is discussed in reference [6].

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KM3NET INFRASTRUCTURE

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Abstract

The KM3NeT EU-funded consortium, pursuing a cubic kilometre scale neutrino telescope in the Mediterranean Sea, is developing technical solutions for the construction of this challenging project, to be realized several kilometres below the sea level.

In this framework The NEMO Collaboration designed, developed tested and installed an infrastructure able to provide power and communication to underwater scientific equipments. The infrastructure and the latest marine operations will be described in this paper.

INTRODUCTION

The installation of the Km3net infrastructure [1], consisting of an on-shore power feeding equipment, an electro-optical cable and a Medium Voltage Converter, has been completed in November 2009. The design and construction of a NEMO tower prototype is currently under way [2].

In this paper a description of the infrastructure, the tests performed and the deployment are reported.

THE KM3NET INFRASTRUCTURE

The km3net infrastructure, installed in Portopalo di Capo Passero, consist of a shore station, a main electro-optical cable, and a Cable Termination Frame (CTF), hosting the Medium Voltage Converter (MVC) and some other ancillary devices.

In the near future a NEMO tower prototype will be built and connected to the CTF, in order to validate the proposed technologies of the project and to provide an on line monitoring of the site.

The power transmission system from shore to the detector deep-sea site is at 10kV DC with sea return [3], the anode is located on shore while the cathode off shore.

The on Shore Power Feeding Equipment (PFE), is composed by an AC/DC converter that provide 50 kW at 10 kV DC. It was realized by HEINZINGER Electronic GmbH and its main characteristics are reported in Table 1. The main electro-optical cable, has been manufactured by Alcatel Submarine Network (ASN) [4], Fig. 1. It carries a single electrical conductor, that can be operated up to 10 kV DC allowing a power transport of more than 50 kW, and 20 single mode ITU-T G655-compatible optical fibres for data transmission. The cable total length is about 96 km.

INPUT	3 phase 400 V
Power Factor	> 0.9
Output Voltage	
Negative Polarity	0 to 10 kV
Positive Polarity	0 to +1.5 kV
Regulation	< 0.1 %
Output Voltage Noise	< 1 V RMS <10 V _{pp}
Output Current	
Negative Polarity	5 Amp
Positive Polarity	1.4 Amp
Output Current Noise	< 10 mA RMS

The CTF, in order to guarantee a long term resistance against the salt water corrosion, is made of Ti gr2 welded pipes. It hosts:

- a Cable Termination Assembly, used to keep the mechanical load during the deployment and to split the optical fibres from the electrical conductor;
- a Medium Voltage Converter (MVC);
- three electro-optical wet-mateable connectors able to supply electrical power and optical communication to submarine users.

The CTF allows both to handle and deploy in a safe manner the MVC and the ancillary equipment, and to keep in a ROV friendly position the output connectors.

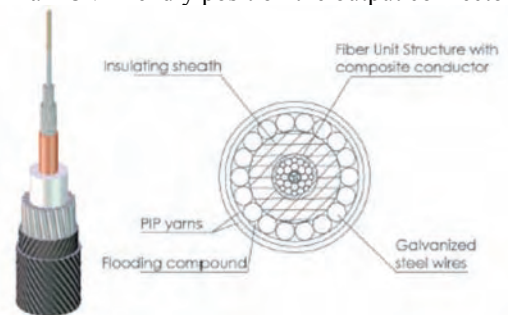


Fig. 1. Main electro-optical cable

All these elements undergone standalone tests to verify their functionality after shipment. After that, electrical and optical tests, have been performed before and after the integration of the CTF to ensure that both CTA and MVC and were operational and that the connections had been properly made, Fig. 2.

The MVC provided by ASN converts the 10 kV to an instrument-friendly 375V with 10kW capacity. The MVC is built from a number of low power sub-converters blocks arranged in a series-parallel configuration to share the load and provide redundancy.

Table 1. Power feeding equipment characteristics

The converter configuration is made of 48 power sub-converter grouped in 6 blocks (stacks), Fig. 3, arranged as matrix of 6 parallel legs with 8 sub-converters in series in each block. This arrangement allows for faults without a failure of the full converter. The estimated efficiency is greater than 85% at full load.



Fig. 2 Frame Termination Assembly ready to be deployed

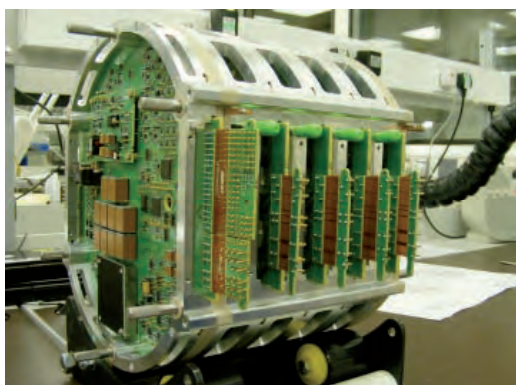


Fig. 3 Stack of a Medium Voltage Converter

The power converter is housed in a pressure vessel, Fig.4, filled with Fluorinert to facilitate the cooling and reduce voltage clearances.

The main characteristics of the NeMO MVC are shown in Table 2.

Table 2. Medium Voltage Converter characteristics

INPUT VOLTAGE	5,7 ÷ 10 kV
Output Voltage	375 V
Output current	25 A
Input shut down voltage	5,2 kV
efficiency@6kV full load	88,9%
efficiency@10kV full load	85,4%
Voltage undershoot@10kV -10% to 90% step up	40 V
Voltage overshoot@10kV -90% to 10% step down	43V
Output Ripple Voltage	1,5 Vrms @ 100 kHz

After years of design, development, assembly and testing, two units undergone the Factory Acceptance Tests in July 2009. Tests have been carried out in the last years to verify the functionality and performance of the MVC in operational working conditions. In particular some of them took place in Alcatel factory in Greenwich in August

2008 and July 2009. The aim of the tests was to verify that switching on /off all the electrical loads in a DC system with:

- a long feeding line from the 10 kV power supply to the MVC (100 km),
- long interconnecting cables of the MVC output with the electrical loads,
- distributed switching DC/DC converters as electrical loads (up to 10 kW),

the system works properly without oscillations or instability and that a big load variation doesn't cause the MVC or the loads switching off. The results of the tests were positive.



Fig. 4 Medium Voltage Converter under test

During marine operation, the main tests performed to verify the electrical and optical functionality of the system, are the following :

- *Test on board before departure* to verify the functionality of the FTA and to register electrical parameters (currents and voltages) values to be used as a reference for the following tests,
- *Test on board after main cable recovery* and connection to the FTA. Once the cable end was recovered and earthed on board, it was power up to 10 KV from the station, the dummy load was connect on each frame connector one after one. The V/I values were recorded on the Station PFE and compared to the reference ones. A laser source was connected and measured the received power on the frame connectors,
- *Test on seabed* to verify the functionality of the whole power system in its final configuration (PFE , 100 km electro-optical cable and MVC,). The Cable was powered up to 10 KV from the station, the V/I values on the station PFE were recorded and compared with the reference values measured on the deck of the ship when the MVC was powered with no load.

The equipments carried on board for test purpose were:

- 10 kV power supply
- 100 km line simulator
- 10 kW dummy load

All the test performed during the marine operation were successful.

THE KM3NET INFRASTRUCTURE DEPLOYMENT

The infrastructure's installation began in July 2007 by deploying the Main Electro Optical Cable (MEOC) between the shore station, located inside the harbour of Portopalo di Capo Passero, and the deep sea site ($36^{\circ} 17,65' \text{ N}$, $15^{\circ} 58,60' \text{ E}$; 3400 m.w.d.). The site has been chosen by the NEMO collaboration, after several years of sea campaigns and data collected, to be proposed to the km3net community for the installation of the km³ Mediterranean neutrino detector apparatus.

The deployment started by laying the cable from the shore end, and going toward the open sea final point, the length of the deployed cable was 96km. Since in 2007 the DC/DC converter was still under developing and testing, the cable's subsea end has been sealed and connected to a further length of 7 km of scrap cable, ended with a dead weight. This technique will have allowed to recover on board the cable end by grappling the scrap cable, without any damage to the MEOC.

The cable has been protected against the human activities (anchoring, trawling, etc.) both at the shore end and along his rout by using the bests standard techniques in cable laying activities. It has been protected by cast iron shells from the shore down to 20 m.w.d. and then buried down to 1000 m.w.d., both by ROV and by plough.

In the November 2009, after that the DC/DC converter has been fully qualified and installed with the other components inside the Cable Termination Frame (CTF), the final part of the infrastructure deployment began.

The CTF and all the testing equipments mentioned above have been embarked on board the Cable Ship CERTAMEN owned and operated by Elettra tlc.



Fig. 5 C/S CERTAMEN

Once on the site, the submersed end of the cable has been recovered on board the ship and has been jointed by means a Universal Joint to the cable tail coming out from the CTA.

In according with the installation procedure previously agreed between ASN and INFN, the equipments were tested and then defined ready to be deployed.

The CTF was lifted from the ship's deck and immersed in water following a safe handling procedure agreed between INFN and Elettra tlc. and tested in a previous test mission held in September 2009. During this test the CTF, hosting some dummy device to simulate the weight and the volume of the actual ones, was deployed in 700

m.w.d. and its position on the sea bed was checked by means of a Remote Operated Vehicle (ROV).



Fig. 6 the CTF on the CERTAMEN's deck

Since the CTF was designed in order to have a mechanical behaviour as much as possible similar to a cable, once immersed in the water, it was deployed following a standard cable deployment technique. The CTA was hanged by means of a grapnel and the grapnel was managed by means of the Cable Laying Engines installed on board the C/S CERTAMEN.

The frame position was constantly monitored during the deployment by means of an acoustic beacon fastened on the grapnel and interfaced with an INFN Ultra Short Base Line (USBL) installed on the ship. The USBL was set and calibrated at the beginning of the mission, giving an accuracy best of the factory specifications (0,3% of the slant range). The frame position on the sea bed is therefore known within a radius of 10m, such measure will be reduced in the near future by installing and calibrating a Long Base Line (LBL).

Once that the CTF hosting the MVC was on the sea bed, an acoustic release was activated from the surface and the grapnel was recovered on board.

CONCLUSIONS

An underwater infrastructure have been realized on the deep sea site selected by the NEMO collaboration as a candidate for the installation of the km3 neutrino telescope. The infrastructure includes a 100 km long electro-optical cable, a shore station in Portopalo di Capo Passero and the power feeding and control equipments. The infrastructure is now ready to feed an underwater application.

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DESIGN OF THE OPTICAL RAMAN AMPLIFIER FOR THE SHORE STATION OF NEMO PHASE 2

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Abstract

A distributed Raman amplifier system for the NEMO phase 2 project has been simulated. The simulation goal was to optimize the Raman pump wavelengths in order to maximize the gain in the spectral region extending between 1530 and 1563 nm, where the DWDM channels of the data transport system are allocated. The results of the simulated gain will be shown.

INTRODUCTION

The Nemo phase 2 underwater apparatus will be positioned 100 km off-shore Sicily east coast, at about 3500 m water depth [1]. An underwater electro-optical cable is already deployed together with a cable termination assembly (CTA) and medium voltage converter (MVC) supplied by Alcatel-Lucent [2]. The CTA is equipped with 3 ROV mateable connectors to connect the NEMO phase 2 detection unit. For applications like underwater neutrino detectors an optical amplifier installed on-shore is very attractive because it improves the system availability and the ease of maintenance.

DATA TRANSPORT SYSTEM

The data transport system of NEMO phase 2 is a network of passive optical components, such as ADD & DROP filters and circulators, which collects and distributes the data signals exchanged between the underwater apparatus and the shore station. The optical network can be divided into two sections: off-shore and on-shore. The off-shore section is deployed in the detection unit. For the NEMO phase 2 detection unit 18 optical channels are used to transport the data towards the shore station and a second set of 18 channels for the opposite direction (slow control and signaling).

The 36 optical channels are allocated over the standard ITU WDM grid with a frequency spacing of 100 GHz. The spectral band extending from channel 19 to 36 (from 1562.23 to 1548.51 nm) has been named A band and is dedicated to the upstream links, while the band extending from channel 38 to 55 (from 1546.92 to 1533.47 nm) has been named B band and is dedicated to the downstream links.

SYSTEM MARGIN

Preliminary calculations of the link budget of the system are needed to fix the amount of optical gain that

should be introduced in the system. In order to achieve a reliable communication the data transport layer must guarantee a signal power level at the receiver input in excess of its sensitivity.

The electrical signals modulate the optical carriers at 1Gb/s and are launched with a mean optical power of 1.7 dBmW. The receivers can achieve a bit error rate (BER) better than 10^{-9} with an optical signal to noise ratio (OSNR) of 30 dB at a rate of 1Gb/s if the power level at their input is better than -33 dBmW.

In order to measure the attenuation introduced by each component of the system a test bench has been built. For the components not available at the time of the measurements datasheets values (both typical and worst case values) have been used. Table 1 shows the results obtained with the test bench. A sample transceiver has been used to launch power in the system, and the optical power has been recorded at the output of each node.

The resulting system margin for the typical case was 3.65 dB; this value is too poor to provide an error free operation of the system throughout its operational life. A system margin of more than 10 dB is the goal to achieve to take into account not only the ageing of the components but also the maintenance of the system in case of cable breaks during the operational life of the project. This goal can be achieved using optical amplification.

RAMAN OPTICAL AMPLIFIERS

Amplifiers based on the Raman scattering effect can be deployed at the on-shore station of NEMO phase 2 offering bidirectional gain. The Raman amplifiers can be grouped into two families: discrete Raman amplifiers and the distributed Raman amplifiers (DRA). In the former family the amplification mean is a spool of fiber few km long in which the light injected by a high power laser sources (called pumps) induces the Raman scattering. In the latter family the amplification mean is the transmission fiber itself. Raman amplification is also very flexible since the designer can control the Raman pump power and wavelength to shape the bandwidth, gain and gain curve. The DRA has been chosen to implement the on-shore amplification system; this choice has also the advantage to leave the overall length of the transmission fiber unchanged.

Table 1

Summary of data obtained at the test bench. Measure points along the network and related power levels.

Measure points	Power level (d Bm)	
Transmitter emitted power	1.71	
Circulator 1	0.16	
3 dB coupler	-2.84	
Circulator 2	-3.16	
Add & Drop—PCS ^a	-4.71	
Add & Drop—APS ^b	-5.03	
Add & Drop 1–15	-6.91	
Input at shore station	-26.55	
Foreseen losses (from datasheets)	Max (d Bm)	Typ. (d Bm)
Dry mateable connector 1	-0.75	-0.3
Dry mateable connector 2	-0.75	-0.3
ROV mateable connector 2	-0.75	-0.3
ROV mateable connector 2	-0.75	-0.3
Add & Drop #8	-3.2	-1.6
Receiver input power	-32.75	-29.35
Receiver sensitivity	-33	-33
System margin (dB)	0.25	3.65

^a Power control system.

^b Acoustic positioning system.

Table 1 Summary of data obtained at the test bench. Measure points along the network and related power levels.

OPTICAL AMPLIFICATION SIMULATION

The distributed nature of the gain in a DRA compensates for the attenuation seen by the optical signals as they travel along the transmission fiber; consequently the signal to noise ratio of such amplifiers is better when compared with discrete Raman amplifiers and erbium doped fiber amplifier (EDFAs). This behaviour can be qualitatively explained considering that the power level of the signals is maintained quite above the noise level all along the transmission fiber. The simulation has been performed modelling the Add & Drop series on-shore with an ideal mux–demux, while the dense wavelength division multiplexing (DWDM) lasers have been modelled with a high level model capable of launching in the network a group of 18 channels at once. This approach aims to focus the analysis on the key elements of the amplification system that are the Raman pump and the transmission fiber while keeping the complexity of the schematics low to speed up the computation. A fully bidirectional fiber model has been used. The aim of the simulation was to quantify the Raman gain available in the A and B bands. The emitted power level for DWDM laser has been set to 1.7 dBmW, the attenuation of the transmission fiber to 0.2 dB/km and the Raman pump power level to 30 dBmW.

A preliminary simulation of a single pump configuration has been performed. Since the Raman gain curve shape depends on the Raman pump wavelength, this has been swept between 1430 and 1460 nm in a region approximately 100 nm below the C band where the contribution to the gain into C band is maximum. The simulation results show that there is no single pump configuration that maximizes the Raman gain in both A and B bands.

Therefore a second design has been simulated using two Raman pumps. Both pump levels have been set to 30 dBm. Fig. 1 shows the simulation schematics for two pumps.

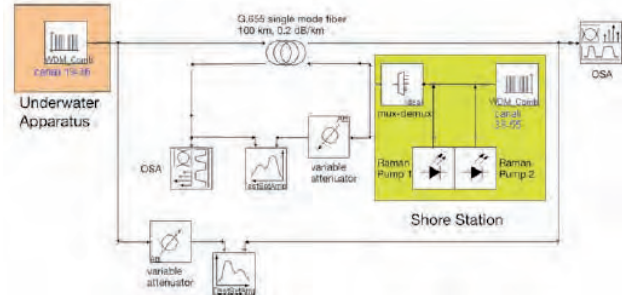


Fig. 1. Schematics of the simulated two pump Raman amplifier.

In order to find the optimum pumps wavelengths that maximizes the gain in both A and B bands the wavelengths have been swept in the range [1460, 1450 nm] for pump 1 and in the range [1430, 1425 nm] for pump 2. The simulation shows that the optimum wavelength for pump 1 is in the range [1454, 1456 nm] while for pump 2 is in the range [1426, 1428 nm]. A further simulation has been performed with pump powers as free parameters in order to find the minimum pump power to achieve a 10 dB gain in both A and B bands. It is found that the minimum pump power was 25 dBmW. Figs. 2 and 3 show the Raman gain in A and B bands for pump powers of 25 dBmW and wavelengths equal to 1427 nm for pump 1 and 1455 nm for pump 2.

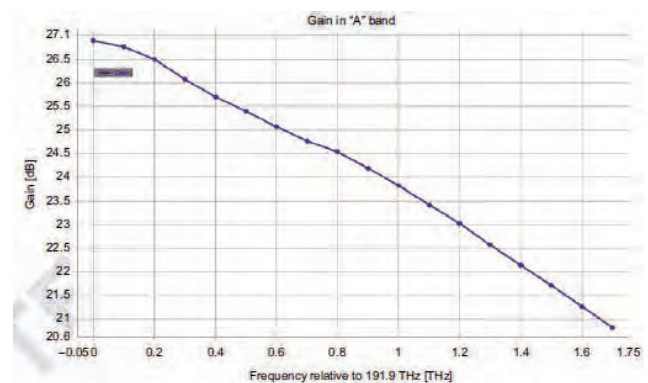


Fig. 2. Raman gain for A band in a two pump configuration.

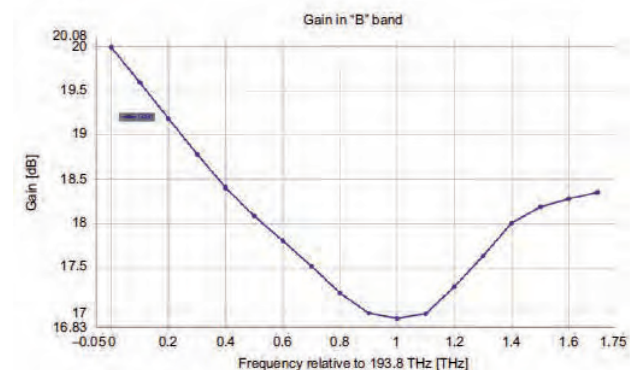


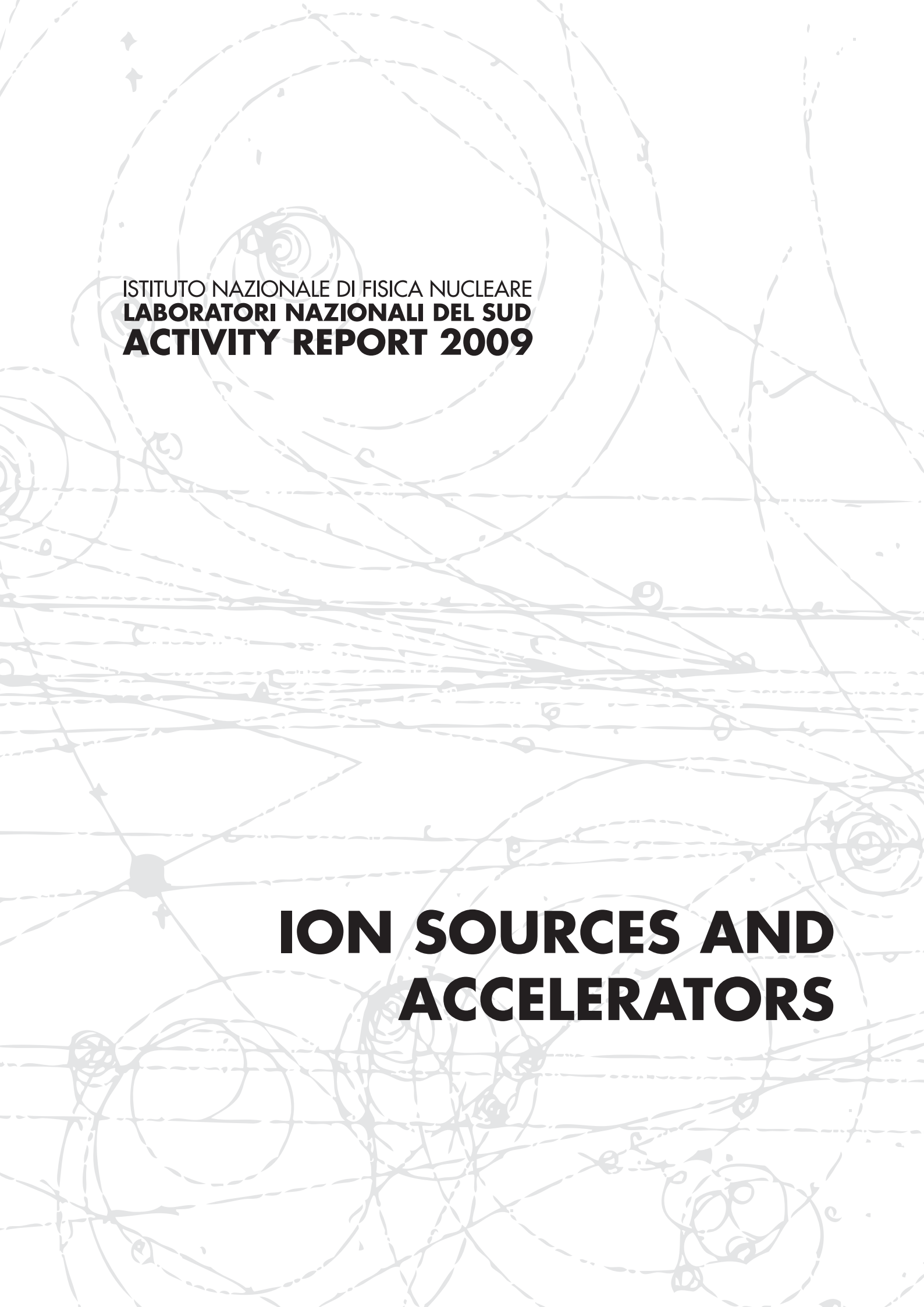
Fig. 3. Raman gain for B band in a two pump configuration.

CONCLUSIONS

A Gain in excess of 10 dBmW in both A and B bands has been demonstrated for a configuration using two Raman pumps. The gain variation in A band is 6 dB while for the B band it is less than 3 dB. This behaviour is due to the two pump configuration; a better uniformity of the gain is expected if more pumps are used.

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ISTITUTO NAZIONALE DI FISICA NUCLEARE
LABORATORI NAZIONALI DEL SUD
ACTIVITY REPORT 2009

ION SOURCES AND ACCELERATORS

LNS ACCELERATORS ACTIVITY

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Abstract

The LNS Cyclotron and Tandem activity in 2009 is described, with some details on the beam time distribution among different research activities.

1 BEAM OPERATION

In 2009, 2683 hours of Cyclotron beams and 2647 hours of Tandem beams were delivered. These amounts can be considered moderately satisfactory as compared with the previous years.

In 2009, 4 sessions of proton therapy of ocular tumors (Catana) were accomplished, using the 62 MeV proton beam from the Superconducting Cyclotron, for a total of 15 treated patients. In total the protontherapy activity took approximately 330 Cyclotron hours.

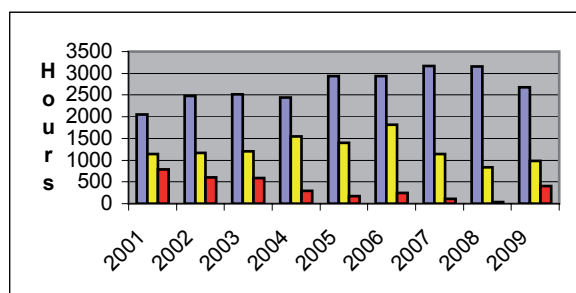


Figure 1: 2001-2009 Cyclotron beam statistics scaled to 8 months

In figures 1 and 2 the beam statistics for the years 2001 through 2009, 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 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 for most of 2009 the UPS (Uninterruptable Power System) did not work properly, therefore there was no guarantee of electricity continuity over the whole year.

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 2009 is smaller than in the previous two years, due to the correspondingly smaller demand from users.

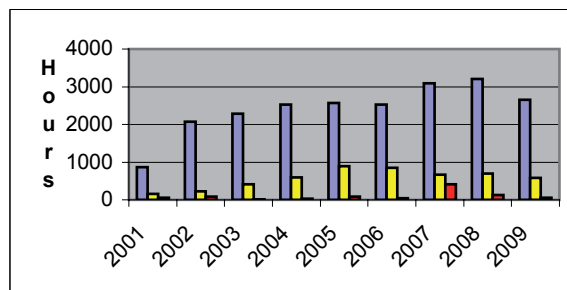


Figure 2: 2001-2009 Tandem beam statistics scaled to 8 months

Concerning the Excyt facility, during the year 2009 no beam session was performed, since efforts were dedicated to improve the safety and reliability features. In particular, the design of the front-end of the source was completely renovated, so as to allow the robot to be able to take the source from its location and move it to the shielded box few meters far from the HV platform. Moreover, some modifications were realized on the target ion source complex to improve electric contacts of the heater.

2 SUPERCONDUCTING CYCLOTRON

In 2009 Cyclotron beams were used for Nuclear Physics experiments (63%), proton-therapy (14%) and interdisciplinary experiments (23%) mainly investigating on interaction of ion beams with biological matter.

In figure 3 a plot of the experiments performed in 2008 with Cyclotron beams is presented, showing the beam time distribution (hours) among different experiments.

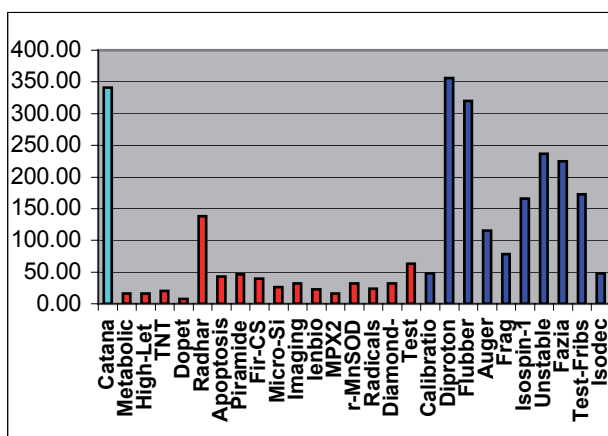
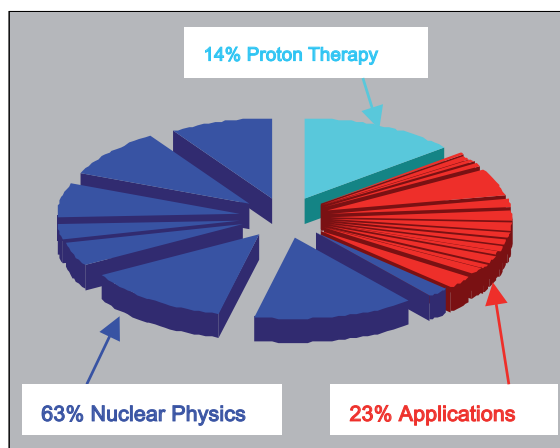


Figure 3: Cyclotron beam time distribution



In Table 1 a list of the experiments performed at the Cyclotron in 2009 is given.

Experiment	Research field
Catana	Hadrontherapy
Metabolic	Biology
High-Let	Biology
TNT	Biology
Dopet	Biology
Radhar	Rad. Hardness
Apoptosis	Biology
Piramide	Rad. hardness
Fir-CS	Superconductors
Micro-Si	Dosimetry
Imaging	Biology
Ienbio	Biology
Mpx2	Biology
r-MnSOD	Biology
Radicals	Biology
Diamond-1	Dosimetry
Test	Biology
Calibration	Nucl. Physics
Diproton	Nucl. Physics
Flubber	Nucl. Physics
Auger	Nucl. Physics
Frag	Nucl. Physics
Isospin-1	Nucl. Physics
Unstable	Nucl. Physics
Fazio	Nucl. Physics
Test-Fribs	Nucl. Physics
Isodec	Nucl. Physics

3 TANDEM

In 2009 Tandem beams were used for Nuclear Physics experiments (85%) and applicative experiments (15%). In figure 4 a plot of the experiments performed in 2009 with Tandem beams is presented, showing the beam time distribution (hours) among different experiments.

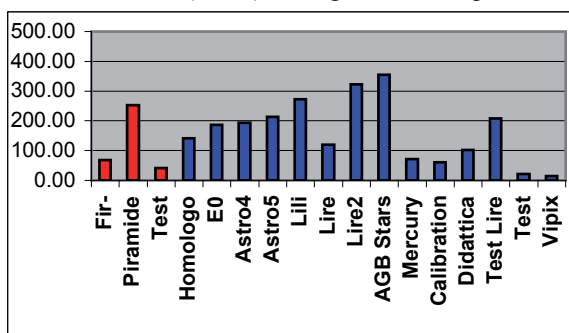
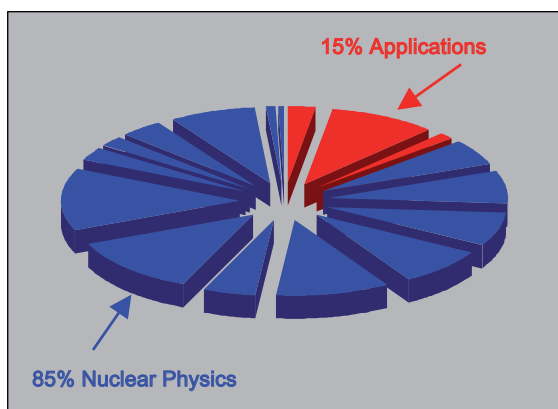


Figure 4: Tandem beam time distribution



In Table 2 a list of the experiments performed at the Tandem in 2009 is reported.

Table 2: Experiments performed in 2009 at the Tandem

Experiment	Research field
Fir-Tandem	Superconductors
Piramide	Rad. hardness
Test Landis	Cultural herit.
Homologous	Nuclear Physics
E0	Nuclear Physics
Astro4	Nuclear Physics
Astro5	Nuclear Physics
Lili	Nuclear Physics
Lire	Nuclear Physics
Lire2	Nuclear Physics
AGB Stars	Nuclear physics
Mercury	Nuclear physics
Calibration	Nuclear physics
Didattica	Nuclear physics
Test Lire	Nuclear physics
Test Magnex	Nuclear physics
Vipix	Nuclear physics



ECR ION SOURCES AND PLASMAS

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Abstract

The most difficult task in modern ECRIS physics is the beam quality improvement without huge economic and technological efforts, that can be obtainable by following two different roads: a) tailoring of the plasma electron energy distribution function through different plasma ignition methods, and b) regulation of the ion dynamics through the mediation of the electrons, directly affected by the electromagnetic field used for plasma heating. The following pages report on the most interesting results collected during the past year in these fields.

INTRODUCTION

The improvement of performances of ECR (electron cyclotron resonance) ion sources, based on the increase of either microwave frequency (it enhances the plasma density cutoff, then the output current) and mirror ratio of the magnetic trap (it confines ions for longer times in order to obtain higher charge states), is now close to saturation, limited by the reliability of the magnets and by the costs.

Experiments carried out on last generation sources have revealed that at frequencies of the order of 28 GHz (with power levels of few kW) an additional limitation comes from suprathermal electrons, with energies of the order of 1-2 MeV. These particles produce large amounts of hard X-rays, which are then partially absorbed inside the cryostat surrounding the superconducting magnets, leading to the boil-off of the liquid helium. Deterioration of the high voltage insulator was also observed. Suprathermal electrons are also useless because their ionization rate vanishes at so high energies. Their nature is still not so clear, because the current theories describing the ECR heating mechanism do not predict electron energies larger than 200-300 keV.

The HELIOS experiment was proposed in 2008 with the aim to better understand the formation mechanism of such electrons - giving some insights about their suppression in forthcoming ECRIS - while on the other hand it aimed to overcome the limitations due to costs and scaling of magnets and microwave generators by means of a better understanding of plasma heating, sustaining and beam

formation mechanisms. Experimental activities and theoretical efforts have been pursued in order to validate alternative heating methods like the frequency tuning effect, already discovered in the past years at INFN-LNS [1]. Experimental data (which put in evidence the influence of the frequency tuning effect even on the beam shape variation) and numerical simulations revealed a strong relationship between the electrons dynamics (very fast and strongly determined by the RF field) and ion dynamics (slower and unaffected by the RF field) [2, 3]. The experiments at Max Planck Institute in 2008 and 2009 about the generation of Bernstein, electrostatic waves (BW), were carried out in the HELIOS framework and aimed to the suppression of high energy particles by means of radically different heating methods: BW in fact travel in overdense plasmas without any density cutoff, and they can be efficiently absorbed at cyclotron harmonics, producing high density plasmas with low energy electrons [4]. Anyway in this report we will skip this argument because the data analysis is still in progress. A detailed report will be given in the next future.

Theoretically, our efforts were initially focused on the simulation of the electron energy distribution function (EEDF) when using the different techniques of plasma heating and for different configuration of the magnetic field profile (investigation about the hot electrons formation); the results on the beam shape variation with the frequency tuning induced us to investigate also the ion dynamics, including in our codes collisions and inner plasma electrostatic steady state structures.

EXPLANATION OF THE FREQUENCY TUNING EFFECT

The numerical simulations have confirmed that the frequency tuning effect discovered in 2005 [1] is correlated with the electromagnetic field distribution in the region closer to the ECR surface. The field pattern, which depends upon the particular electromagnetic mode excited into the chamber, regulates the rapidity of the electrons heating.

Modes with high field values over the ECR surface are the best candidate to provide strong and efficient heating of cold electrons. Results shown in [3] put in evidence for the first time the strong relationship between electron and ion dynamics, which usually are considered uncoupled because of the different timescales. Simulations revealed that the coupling mechanism is mediated by the so-called plugging effect, i.e. the additional confinement mechanism provided by the RF field [5]. Single particle simulations demonstrated that after 50 ns more than 78% of particles in the plasma chamber are effectively confined inside the ECR surface. Fluxes of escaping electrons are evident only along the chamber axis, because of the low electromagnetic field in this region. Therefore those areas in which the electrons are effectively confined by the RF field are characterized by larger densities of both electrons and ions (because of plasma quasineutrality, the diffusion fluxes of electrons and ions must equalize each other).

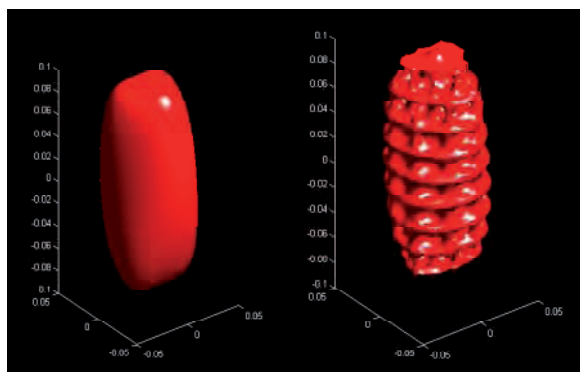


Figure 1: Smooth (left) and corrugated (right) isodensity surface of the primary plasma: the corrugation depends on the particular pattern of the electromagnetic field.

This process leads to the corrugation of the isodensity surfaces close to the ECR region, as shown in figure 1 (without the plugging effect the isodensity surfaces would be smooth). Effects of the heating dependence on the field pattern and following plugging of particles have been observed either with single particle and PIC simulations: a steady state structure of the electron density appears after few tens of ns and lasts for times longer than tens or even hundreds of μs . The inner resonance plasma (primary plasma, PP) reaches densities at least three times larger than the outer one (secondary plasma, SP). This characteristic plasma distribution influences the ion dynamics. PIC simulations, in fact, put in evidence that ions are accelerated when they cross the PP to SP boundary because of a positive potential V_{pp} existing over the resonance surface. Strongly corrugated surfaces may be generated by $TE_{n,m,r}$ or $TM_{n,m,r}$ modes with high values of the triplet of integer numbers n , m , r . In the case of a smooth potential a large fraction of ions arrive on the extraction flange, forming a marked three cusp shape; beams can be bright and mostly populated by highly charged ions. Once generated, highly charged ions are

guided by the magnetic field when traveling in the SP (neither scattering fields nor collisions exist, because the ions are accelerated up to 100-500 eV, depending on charge state): they “remember” the magnetic field near the extraction hole and the extracted beam has the characteristic three cusp shape experimentally observed in [2] (figure 2).

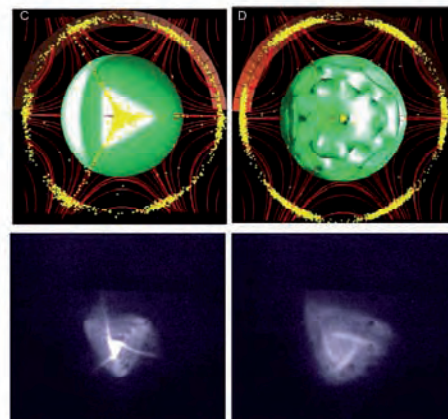


Figure 2: shape of the beam at the extraction side in the two cases (upper figures: simulations; lower figures: images from the beam viewer at GSI testbench [2]).

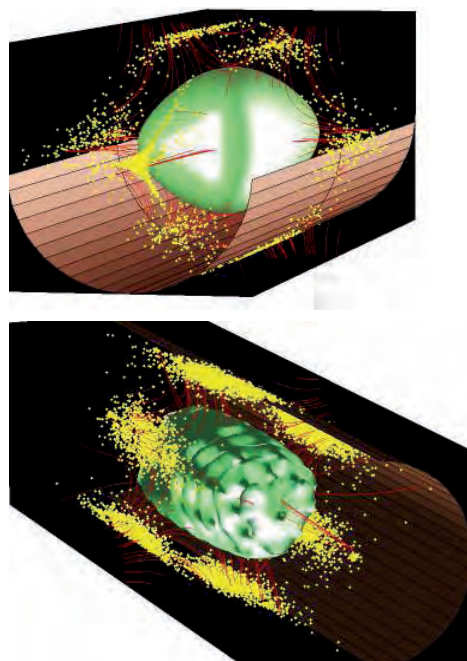


Figure 3: Ions (in yellow) impinging on the chamber walls in case of smooth (a) and strongly corrugated isodensity surfaces (b), in green.

In case of strongly corrugated isodensity surfaces we assumed V_{pp} in the 30 - 100 V range. The stronger scattering shortens the ion lifetime (especially for the highest charge states) of a factor 10: many ions collide with the chamber walls laterally, as shown in figure 3b. The beam will be characterized by low brightness and it

will be mostly populated by ions with low charge states. Between the two extreme conditions here described there are several intermediate cases, all of them depending on the particular pattern of the electromagnetic field affecting the isodensity surface corrugation, and then finally the ion scattering and the beam formation mechanism.

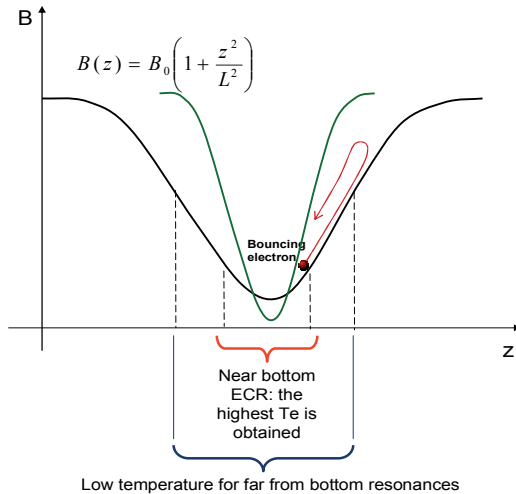


Figure 4: dependence of hot particles temperature on the shape of the mirror trap.

HOT ELECTRONS GENERATION

Single particle and PIC simulations also help to explain the origin of the high energy electrons in ECRIS, mostly generated in presence of “gentle” gradients [6]. PIC simulations revealed that the production of such high energy electrons increases for lower mirror ratios or for resonances close to the magnetic field minimum value.

In fact, the closer the resonances are to the bottom of the magnetic field trap, the higher will be the electron temperature. For resonances close to $B_{\min}$ the adiabatic invariants, which stop the electron heating, activate quite late, thus allowing the particles to diffuse in the phase space rapidly. Crucial for the overcoming of the adiabatic barrier are the wave amplitude E_0 and the l parameter, where l is the typical length of variation of the magnetic field (it roughly corresponds to the inverse of the gradient). In case of electric field amplitude of few kV/cm the electrons easily overcome the adiabatic barrier if the mirror ratio is lower than 2.5 (i.e. large l parameter).

Figure 4 summarizes the dependence of temperature and hot electron generation rate on the field profile: steep gradients and resonances far from the minimum B field are mandatory for the reduction of the number of hot particles. But even in presence of strong magnetic gradients at the resonance the hot electrons cannot be totally suppressed: according to the particular mode excited inside the cavity a small amount of these energetic particles will be produced anyway at a smaller rate in some localized areas. It can be concluded that the

magnetic field gradient is one of the two key parameters, along with the local electric field amplitude at the resonance surface.

EXPERIMENTAL RESULTS AT JYFL

The experimental results collected during 2009 reinforced the validity of the Frequency Tuning Effect (FTE). Tests have been carried out with two different sources: the ECRIS operating at Jyvaskyla University Physics Laboratory (JYFL), and the source of the CNAO, Pavia. In the latter case, a remarkable increment of the transmission along the LEBT was evident. In particular, the coupling of the CNAO source with the RFQ, during its commissioning phase, has given much better results ($T > 70\%$) with respect to the “twin” accelerator of HIT in Heidelberg. This results permits to CNAO accelerator to largely exceed the design current out of the LINAC and it is one of the most interesting results of the HELIOS activity. A similar increase of transmission by following our suggestions was observed at INFN-LNL [7]. Additional measurements were carried out at JYFL: in figure 5 the structure of the Ar^{9+} ion beam at different plasma heating frequencies is shown: a) 14.050 GHz, b) 14.090 GHz, c) 14.108 GHz. For some frequencies the strong ion scattering observed in simulations (see fig. 3) reduces and the hollow beams partially disappear. At first sight, no unequivocal explanation concerning the origin of beam structure variations can be given: they could originate from changes in inner plasma dynamics or in the beam line because of the different ion beam intensity and space charge. However, the beam intensity at the frequencies of 14.050 and 14.090 GHz was practically the same, and this indicates that changes in the beam structure are mainly due to internal plasma dynamics. The absence of hollow beams permits to improve the accelerator performances and the beam transmission increases dramatically, about a factor two.

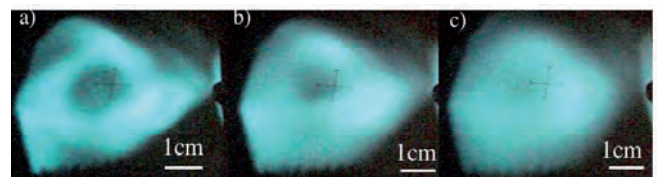


Figure 5: Beam shape variation at different frequencies at the JYFL.

EEDF VARIATION FOR DIFFERENT MAGNETIC FIELD PROFILES

Data collected with VENUS and SECAL in the last three years demonstrated that something similar to the frequency tuning effect takes place when slightly varying the magnetic field profile, and changes in the magnetic field strongly affect the temperature of the high energy component of the EEDF. The SUSI source has been used for indirect evaluations of the EEDF because of its

flexible magnetic field structure, which permits to easily change the field profile, as well as the mirror ratio. This characteristic makes SUSI the best device for studies about the magnetic field influence on plasma dynamics, especially in terms of confinement properties and electron heating rapidity. It allows to vary the magnetic gradient at the resonance region without any appreciable influence on the mirror ratio (i.e. on the confinement times of plasma particles), thus permitting to distinguish the effect of a given magnetic field profile on the confinement with respect to the effects on the electron heating rapidity. This is a crucial for the design of future sources, based not only on global scaling laws, but also on the specific and local properties of the magnetostatic field.

Data collected with SUSI have been relevant for the magnetic structure design of forthcoming projects, in particular for MISHA, a compact ECRIS designed for medical applications, to be operated around 18 GHz [8].

For these tests, Carbon has been used, without any gas mixing; X-ray spectra have been acquired by means of a Ge detector, in order to determine the distribution of electrons versus their energy, and to make comparative analysis about the different electron populations when the magnetic field changes. SUSI has been fed with microwaves at 18 GHz. The RF power was fixed at 500 W and the background pressure was fixed too. The best value of $B_{\min}$ appeared to be 0.4 T.

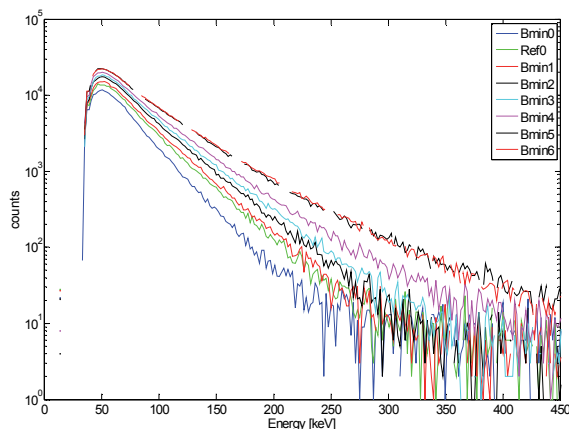


Figure 6: X-ray spectra for the different values of the minimum B field.

Figure 6 features the X-ray spectra at the different $B_{\min}$ values (keeping B_{inj} fixed at 2.5 T and B_{ext} at 1.3 T) : as expected (and already observed with VENUS two years before [6]) the production of electrons with energy above 200 keV (corresponding roughly to the adiabatic barrier) increases with $B_{\min}$. It is clear that the spectra slopes decrease with $B_{\min}$, thus meaning that a higher $B_{\min}$ enhances the plasma heating up to temperatures well above the adiabatic barrier. Similar results were also observed for the B_{ext} scaling.

Other measurements aimed to investigate how the shape of the mirror trap, once fixed the mirror ratios and the values of the axial and hexapolar fields, affects the performances.

The worse results in terms of C^{4+} extracted current were obtained when the X-ray spectrum had the less pronounced slope, i.e. the highest electron temperature. This corresponded to very small L_{ECR} . This condition may be interpreted as a large power density deposited inside a small volume plasma, which moves a large amount of electrons from the lowest to the highest levels of energy.

CONCLUSIONS AND PERSPECTIVES

The results shown in this report cover a wide spectrum of hot topics in the field of ECR ion sources; they are finalized to the optimization of the beam brightness through the investigation of the beam formation mechanism. This requires an adequate modelling from plasma ignition to the long-timescale ion dynamics, affected by the inner plasma density distribution. The results obtained in 2009 have been encouraging and experiments are in preparation, in order to complete the scope of the HELIOS experiment in 2011.

ACKNOWLEDGEMENTS

The authors acknowledge the support of the 5th National Committee of INFN (HELIOS experiment) and wish to thank the colleagues of different laboratories throughout the world, who has contributed to the results here shown, in particular P. Spaedtke, K. Tinschert, R. Long, J. Mader, T. Rossbach, H. Koivisto, V. Toivanen, O. Tarvainen, T. Ropponen, G. Machicoane, L. Sun, D. Cole, H. Laqua, M. Otte, Y. Podoba and S. Chikin.

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MISHA ION SOURCE MAGNETIC DESIGN

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Abstract

Italy is present in the field of hadron therapy either with synchrotron-based and with cyclotron-based facilities. For both types of accelerators the availability of high brightness multiply charged ion beams is essential. At the Centro Nazionale di Adroterapia Oncologica (CNAO) of Pavia, proton and carbon ion beams will be accelerated up to 400 MeV/amu by a synchrotron and the beam injection is guaranteed by two ECR ion sources built under the supervision of INFN-LNS experts. A new design for a third, more powerful ECR ion source named MISHA (Multicharged Ion Source for HAdrontherapy), has been completed recently and it will be described hereby. Other facilities, cyclotron-based, require high brightness fully stripped carbon beams and larger extraction voltages; for these facilities the MISHA source may be considered as an ideal injector.

INTRODUCTION

The MISHA ion source is a “hybrid” ECR ion source whose magnetic system is based on a compact permanent magnet hexapole able to reach up to 1.3 T radial field over the plasma chamber wall and on a set of LHe free superconducting coils for the axial plasma confinement. The frequency choice was determined by the compromise between the different requirements of a hospital facility which need high reliability operation, easy maintenance and high currents of highly charged light ion beams. The choice to use commercial TWT amplifier permits to exploit the frequency tuning effect and to fulfil the requirements above [1]. The main characteristics of the source are summarized in table 1 along with the expected performances for some relevant species.

Maximum radial field	1.3 T
Maximum axial field	2.6 T / 1.6 T
Minimum axial field	0.4 T
Operating frequency	18 GHz + 17.6 GHz (TCFH)
Operating power	500 W + 500 W
Extraction voltage	50 kV max, 40 kV operating
Chamber diameter	Ø 92 mm
LHe	Free
Body source length	580 mm
Weight	650 kg
$^3\text{He}^+$	1000 eμA
$^{12}\text{C}^{4+}$	600 eμA
$^7\text{Li}^{3+}$	250 eμA
$^{11}\text{B}^{4+}$	350 eμA
$^{18}\text{O}^{6+}$	600 eμA

Table 1: The main features of the MISHA source.

PERMANENT MAGNET HEXAPOLE

The radial magnetic field in ECR ion sources represents the key parameter, together with the operating frequency. For this reason, once it has been decided to operate at 18 GHz to reach the needed current intensity, the study of the hexapole has been carried out with the OPERA 3D code. The main idea was to use a material with high remanence field in order to achieve 1.3 T on plasma chamber wall. For this purpose the VACODYM 745 HR produced by the Vacuumschmelze company, has been the optimum choice as its main characteristics are: a remanence field of 1.44 T, a coercivity of 1.195×10^3 kA/m and the ability to maintain the magnetization even at relatively high temperature (70° max). This will permit to the magnets to “survive” to minor troubles to coupling in the plasma chamber cooling which is contained inside the hexapole. The magnetic elements are characterized from nine different directions of magnetization as shown in fig.1. The hexapole has an inner radius of 51 mm, an external radius of 110 mm and a length of 400 mm; it is able to reach a radial field slightly higher than 1.3 T at 46 mm radius for the whole plasma chamber length. However it must be taken into account that with so high magnetic field values a demagnetization of part of the permanent magnet assembly may happen when the component along the direction of magnetization of the resultant of the H_x and H_y vectors has an opposite direction with respect to the magnetization itself and a value higher than the coercivity of the material used. To avoid such effect, in these zones materials with higher coercivity have been adopted as specified in the following.

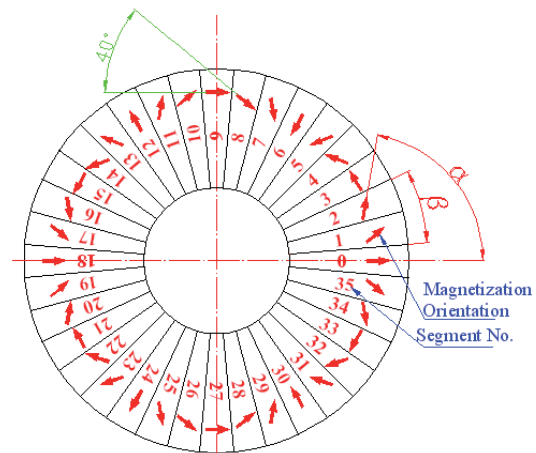


Figure 1: The hexapole structure.

AXIAL MAGNETIC FIELD

The axial magnetic field magnetic profile has been conceived on the basis of the experience gained recently with the third generation ECR source of MSU-NSCL, named SUSI, by maximizing the production of medium and high charge states. For this purpose the key parameters that needed to be controlled are: the field gradient at injection and extraction and the resonance length. To achieve such flexibility the classical system based on a set of three coils is not sufficient and the optimal solution would be a system based on five coils. For the MISHA source it has been decided to adopt a solution employing 4 LHe free superconducting coils which permit to have a good control on the above cited parameters. Figure 2 shows the magnetic field on source axis with field gradients over 21 T/m that permit to operate in the strong gradient regime even at moderate RF power (500 W – 1 kW) [2,3]. The characteristics of the solenoids are reported in table 1 and a general view of the magnetic system is given in fig.3.

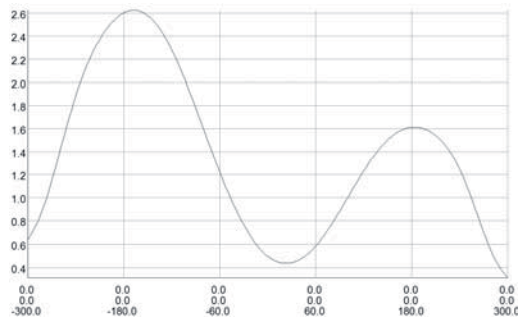


Figure 2: The magnetic field on plasma chamber axis.

Solenoid	INJ	Med1	Med2	Extr
ID [mm]	260	260	260	260
OD [mm]	340	340	340	340
Length [mm]	100	30	30	90
Current [A/mm ²]	165	-143	-143	115

Table 1: The solenoid characteristics

PM DEMAGNETIZATION

The use of superconducting magnet permits to achieve high value of axial confining field, but, the strong H_x and H_y components created off-axis have been analyzed to avoid the demagnetization of part of the structure with radial field overcoming the coercivity limit of VACODYM 745 HR. A possible solution to minimize such phenomenon is to relax the solenoid currents by using an iron plug at injection and extraction, option which has been discarded in the present design.

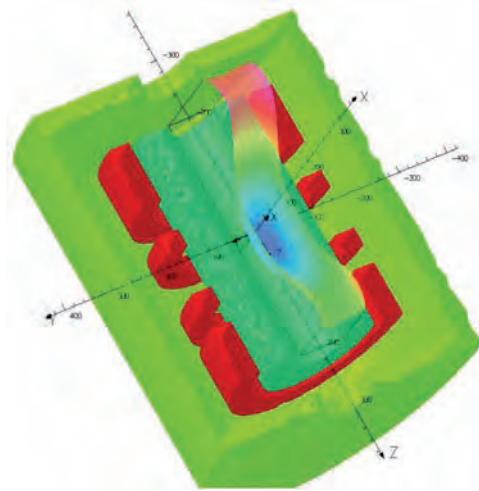


Figure 3: A 3D view of the entire magnetic system.

It is convenient to remind that the direction of H_x and H_y is dependent from the solenoid current versus, that determine also the orientation of the classical “star” on the injection and extraction flange. In order to obtain the needed orientation, the magnetic field lines must be oriented from injection to extraction. Since only the radial field component may cause demagnetization in a sector with a given radial direction of magnetization, we can neglect the z component and concentrate our analysis on x and y components. In particular a possible approach to the problem is to locate the sectors where the absolute value of the demagnetization vector is greater than the coercivity. We analyzed in these sectors the distribution of H_x e H_y , by composing them vectorially and by looking for the component along the direction of magnetization of the sector considered. Fig. 4 shows the total radial magnetic field on the hexapole and the zones where it is higher than coercivity value of VACODYM 745 HR. In particular it can be observed that the highest values are concentrated at outer radius, and at these places a permanent magnet material with coercivity higher than 2.6×10^3 kA/m is needed, while in the inner radius material with coercivity higher than 1.42×10^3 kA/m is sufficient.

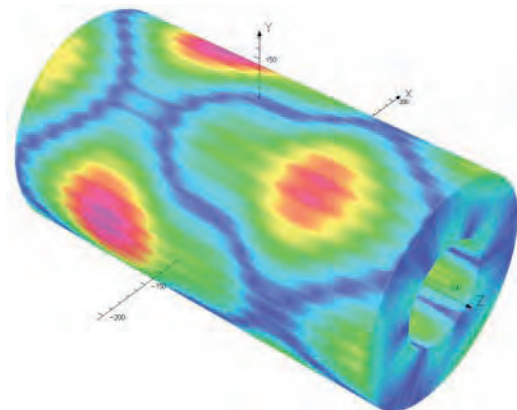


Figure 4: The resultant of H_x and H_y over the hexapole surface.

Therefore the best approach consists in dividing the hexapole in two shells:

- A inner shell with inner radius of 51 mm and external radius of 80 mm.
- A outer shell with inner radius of 80 mm and external radius of 110 mm.

The inner shell is simply analyzed. In fact the maximum field is circa 1.45×10^3 kA/m and taking into account a 20% safety margin and the characteristics of the different VACODYM material available, we need to replace in the sectors 3,9,15,21,27 e 33 the VACODYM 745 HR with the VACODYM 655 HR. The analysis of the external shell is a bit more complex: from fig. 5 it is possible to understand that the maximum radial fields are located in different sectors depending if we are considering the first half of the structure or the second half. Therefore, to have the maximum flexibility in the choice of the material, trying to keep material with high value of B_r , it is appropriate to divide this outer shell in two parts:

- The injection side: $-200 \text{ mm} \leq z \leq 0$ (the max field occurs at $z=-80$ mm and is shown in figura 5).
- The extraction side: $0 \text{ mm} \leq z \leq 200$ mm (the max field occurs at $z=100$ mm).

If we consider the injection side the maximum field is 2.5×10^3 kA/m and an adequate material to be used is the VACODYM 688TP [4] with a coercivity of 2.8×10^3 kA/m, but a B_r of only 1.14 T. In the adjacent sectors is appropriate to use material with increasing B_r , such as VACODYM 669TP and VACODYM 745HR taking care to have a margin of 20% on the coercivity.

By doing the same considerations for the extraction side of the outer hexapole shell and keeping always a margin of 20% on coercivity, the final structure of the hexapole is shown in fig. 6.

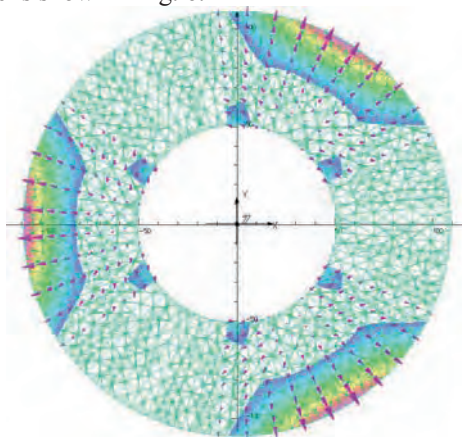


Figure 5: The zone of maximum demagnetization ($z=-80$ mm) in the injection side of the hexapole outer shell (in red and yellow).

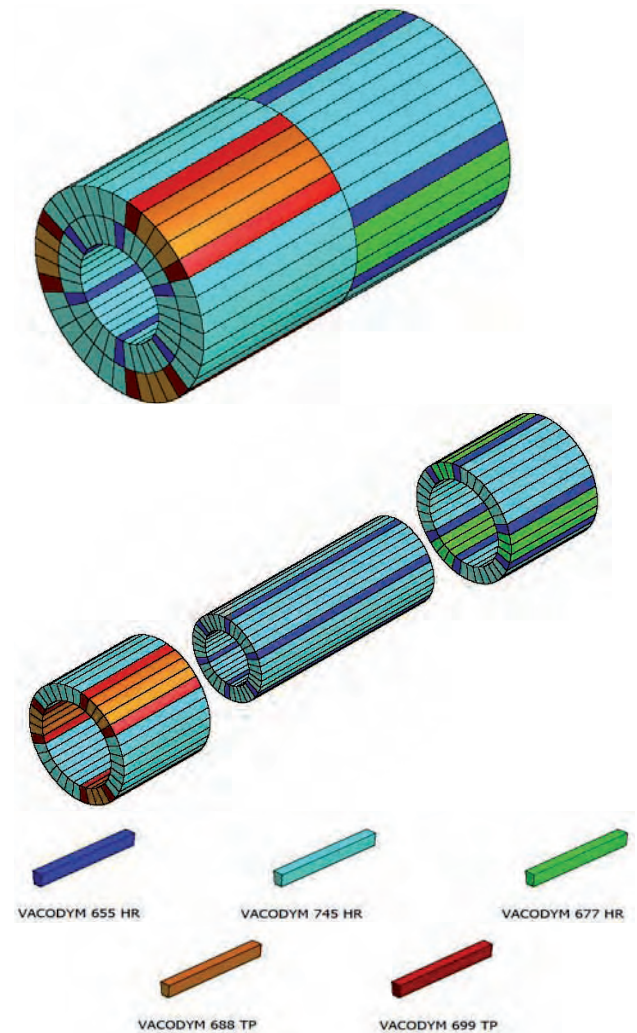


Figure 6: A 3D view of the hexapole.

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THE CANTES EXPERIMENT: A CARBON NANOTUBES BASED ELECTRON GUN TO IMPROVE THE PERFORMANCES OF ECR ION SOURCES

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Abstract

The increase of electron density in ECR ion sources assures efficient ionization of very low-gas-pressure plasma. The purpose of this experiment was the creation of a carbon nanotubes based electron gun, in order to inject electrons in the plasma core and to follow how the charge state distribution and the X-ray spectra change. The use of carbon nanotubes leads to an increase of the plasma density and to a relevant reduction of the number of high energy electrons, which are detrimental for the reliability of the modern ECRIS.

INTRODUCTION

One of the crucial issues in ECR ion sources (ECRIS) operating with B-minimum magnetic structures consists in the so-called electron starvation [1]. Although plasmas in B-min configurations are magneto-hydro-dynamically stable, electron losses may be large enough to deteriorate the source ability to generate large numbers of highly charged ions in short times. It is then necessary to supply auxiliary electrons to the magnetic trap, in order to obtain an electron density large enough for efficient ionization inside the low-gas-pressure plasma. Bias discharges are usually employed for this purpose [2], as they are able to recover a large fraction of axially escaping electrons.

Here we propose an alternative method to provide additional electrons to the plasma core, i.e. the use of carbon nanotubes (CNTs) which emit in presence of electric fields. The effect of these additional electrons is that to improve the plasma dynamics, and hereinafter the variations of the extracted charge state distribution and of

X-ray spectra will be shown. X-rays are in fact emitted by the electrons in the plasma core, as Bremsstrahlung radiation. The investigation of X-ray spectra gives some insights on the energy content of the plasma electrons, and in particular on the generation of high energy electrons (> 100 keV): they are detrimental for ECRIS not only because they have a low ionization cross section, but also because they heat the helium cryostat for the ion sources which use superconducting magnets and deteriorate the HV insulator for all the ECRIS. The damping of the mechanisms leading to strong electron heating is thus one of the crucial tasks of modern ECRIS science, because any further development of these devices depends on the ability to perfectly tailor the electron energy distribution function, maximizing the number of those particles whose energies allows effective ionization cross section (1-100 keV).

EXPERIMENTAL SET-UP

The ECR ion source named CAESAR [3] is operating at INFN-LNS laboratories as injector of the K⁻800 Superconducting Cyclotron since 2000. The main features of CAESAR are described in [3]. We just recall here that the body source consists of a water-cooled stainless steel plasma chamber, where the ionization is obtained by means of a 14 GHz RF generator. The magnetic system is composed, for the axial confinement, by two coils, independently energized, which can generate a magnetic field greater than 1.5 T. For the radial confinement a sextupole, made of Nd-Fe-B permanent magnets, is used, with maximum field of 1.1 T.



In the past, several passive techniques for the injection of secondary electrons have been tested at INFN-LNS, with the purpose to extend the plasma ion lifetime and to increase the ionization probability [4].

Active materials, like ferroelectric cathodes, have been employed because of their capability of producing high emission yields of energetic electrons [5]. However, their robustness has shown to be not sufficient for long lasting applications into ECRIS.

With this experiment, a new active technique which makes use of CNTs-based electron guns to inject electrons into the plasma has been tested. The most important components of the electron gun are the CNTs emission cathode and the anodic grid. In our set-up, two electron guns are placed on a copper support connected to the RF waveguide. A potential in the range 0-2.5 kV is then applied between the chamber and the waveguide, and the same potential is used to produce the emission field (i.e. the extraction field) between CNTs and the anodic grid.

During the test we have been able to measure the current from the bias power supply to the electron guns circuitry. The current intensity of all Kr charge states extracted from CAESAR have been monitored during the experiment and the Kr^{11+} current has been used as reference.

The carbon nanotubes based electron gun

The CNTs electron gun is essentially made of three elements: a CNTs cathode obtained on a 300 μm thick silicon substrate, a 150 μm thick mica spacer and an anodic copper grid with square cells of 350 μm side. CNTs eject electrons because of the field emission effect, i.e. quantum tunnelling, which is obtained by applying an electric field higher than 3-4 V/ μm . A field emission-scanning electron microscopy image of a typical CNTs sample is shown in Fig. 1.

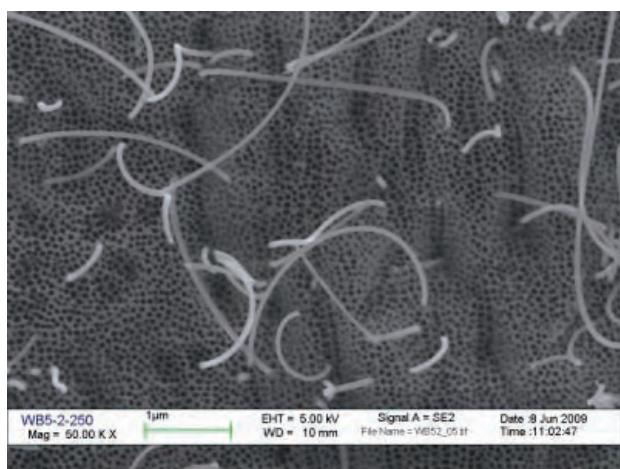


Figure 1: SEM plan-view of the surface of a typical CNTs sample.

Details on CNTs preparation and their field emission properties will be given in a separate paper [6]. Here it is worth to mention that the CNTs are obtained by means of a Catalyst-assisted Chemical Vapour Deposition (C-CVD) process at atmospheric pressure, in a quartz hot-wall furnace at 620 $^{\circ}C$, using an anodic porous alumina membrane as template. In such a process, multiwall CNTs are obtained having the same diameter of the alumina pores, i.e. 80 nm. Some of the CNTs exit the alumina surface and can reach a total length of 5-10 μm .

The gun elements are kept together by a MACOR (machinable glass ceramic) holder, on which the electrical connection is obtained by an evaporated gold track. The MACOR holder is then fixed on a copper support connected to the waveguide of the plasma chamber. The anodic grids are linked to the ground potential of the plasma chamber wall by means of copper creeping contacts. Two of such electron guns were mounted on the same copper support during the experiment (Fig. 2).



Figure 2: The copper support, holding two CNTs electron guns.

Prior to the plasma test, each CNTs sample was tested in terms of field emission, by means of a custom-designed apparatus [7]. The field emission properties of similar samples (i.e. CNTs arrays in free-standing porous alumina foils) were already tested [8] and they were found to be able to produce current densities up to 10-40 mA/cm². Emission measurements for the samples tested in CAESAR (i.e. CNTs in porous alumina on silicon), gave even better results, with current densities up to 50-100 mA/cm², as will be reported in a separate paper [6]. The emission surface in our samples was set to about 0.1 cm², by using a mica spacer with a 3 mm diameter central hole (Fig. 2).

The X-rays measurements

The measurements of X-rays emitted by the CAESAR's central plasma region have been carried out by using an HPGe detector (High Purity Germanium),

collimated through lead shielding blocks, in order to suppress secondary X-rays coming from electrons impinging on the lateral walls of the plasma chamber. The collimation hole was 1 mm^2 , i.e. smaller than the microwave port located at the injection flange of the CAESAR source. The detector is particularly suitable for the detection of X-rays in the range of tens and hundreds keV; the energy calibration was done by using an ^{152}Eu source.

RESULTS AND DISCUSSIONS

With the above described set-up, we inserted in CAESAR two CNTs electron guns and measured the axially emitted X-ray spectra for different CNTs applied voltages, as shown in Fig. 3. The detector was placed on the same axis.

We can observe that the spectrum remains unchanged when voltages are below 700 V. As we increase the CNTs applied voltage up to 800 V, the tail produced by the higher energy electrons disappeared (especially in the energy range above 200 KeV). Although the not perfect collimation of the detector cannot permit to extrapolate quantitative estimations on electron spectral temperature, it is however evident that the energy content of the hottest electron component decreases.

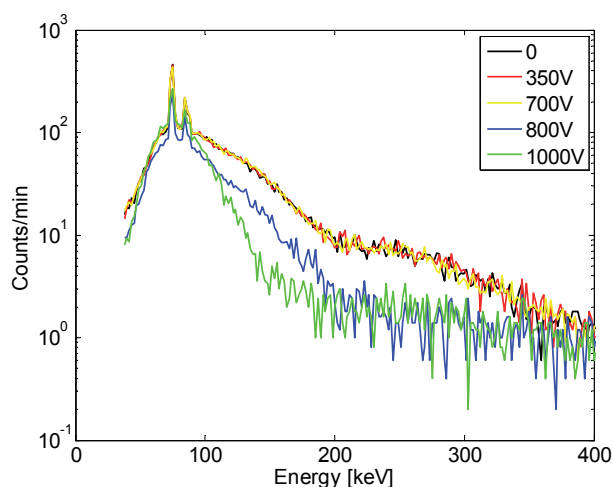


Figure 3 : Axially emitted X-ray spectra for different CNTs applied voltages, at RF power of 100 W

By increasing the CNTs applied voltage, one can observe that the Bremsstrahlung peak becomes narrower: in other words, by providing additional electrons to the plasma, the average energy per electron decreases; a larger number of electrons share the same amount of energy injected into the plasma chamber by means of the microwave (the RF power is kept constant).

As mentioned before, if we suppose that in the plasma there are thermal electrons, we can deduce the electron temperature by making a linear fit to the Bremsstrahlung spectra and calculating its slope, which is inversely

proportional to the electron temperature. From a qualitative analysis we can say that the electron temperature decreases when the CNTs applied voltage increases, or rather when the amount of electrons provided by CNTs increases.

Fig. 4 shows the trend of the extracted current of Kr^{11+} when the CNTs emission is switched on and off. The current “jump”, which takes place immediately after the electron emission from CNTs is evident, and it was obtained with 2500 V applied to the CNTs extraction grid. It is also interesting to note the afterglow-like peak when the electron gun is going to switch off. The gain of current is almost 60 % and reaches 100 % during the afterglow peak, at 35 W RF power only. Similar results were observed for larger RF power, up to 150 W.



Figure 4: Trend of the Kr^{11+} current (in μA) during the switching on-off of CNTs emission, in a time window of 30 seconds (an afterglow peak is evident at the switching off).

The use of CNTs emitted electrons provided many benefits also to the production of several charge states. Initially we focused our attention to the current increase of a single charge state (Kr^{11+}), and then we proceeded with the analysis of the entire Charge State Distribution (CSD) spectrum, at different CNTs extraction voltages.

In Fig. 5 the measurements carried out at about 100 W RF power with 0, 700 and 800 V of extraction voltage are shown. Already at 700 V the increase of Kr current when CNTs emission starts is evident. Not only the hot electrons temperature decreases with the applied voltage, but this also occurs for the warm population, i.e. for those particles responsible of the large amount of ionization process: their temperature can be estimated by looking to the CSD, whose charge state at maximum current has a ionization potential approximately equal to $1/3$ of the warm electron temperature. This temperature decrease is evident in Fig. 5: note that the CSD peak slightly shifts to lower charges states by increasing the extraction voltages on the nanotubes, i.e. by increasing the number of electrons injected into the plasma. This observation may

be misleading, because we would expect a larger average charge state due to a bigger quality factor that is given by the product between the electron density and the ion confinement time. The explanation may be found in the

local “cooling” of the plasma electrons, following the absorption of sub-keV electrons and it can be balanced by decreasing the gas pressure or by increasing the RF power.

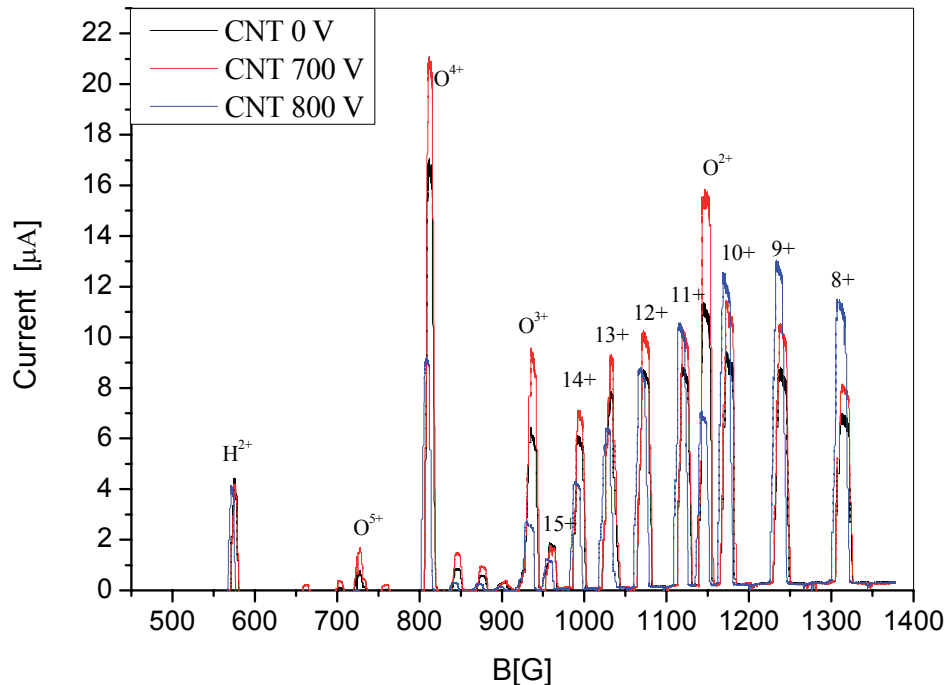


Figure 5: A charge state distribution, optimized for Kr^{11+} at about 100 W and for different CNTs applied voltage.

Measurements at low power levels (down to 30 W) revealed an even more important contribution of CNT on hot electron suppression and current enhancement. Anyway the reduction of the warm electron temperature was more evident because of the low power density deposited into the plasma.

CONCLUSIONS

We demonstrated that the CNTs-based electron gun is a powerful tool to inject electrons in ECR plasmas in order to increase the plasma density; in addition, a relevant reduction of the number of higher energy electrons has been observed. This last result is even more important, because the usage of CNTs-based electron guns may be an effective and reliable technique to further improve the modern ECRIS performances without the strong limitation of hot electrons coming out when large power and high frequencies are used.

The use of CNTs-based emitters has solved robustness problem which emerged when using ferroelectric cathodes for the same purpose. For the presented tests, their period of operation was limited to a few tens of hours. However, complementary tests with carbon nanotubes in microwave discharge plasmas have shown a good resistance in such a harsh environment.

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The upgrade of the radioactive ion beam diagnostics at LNS

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Abstract

New diagnostics for low intensity radioactive beams (EXCYT and FRIB) is going to be installed at LNS. Such upgrade will allow an accurate check of the beam parameters in real time, thus allowing the optimization of the transmission along the beam line, until to the experimental apparatus. The devices are based on nuclear particle detectors, in particular on plastic scintillators, position sensitive silicon detectors (PSSD) and scintillating optical fibres.

INTRODUCTION

At LNS-INFN we are going to install an efficient low intensity beam diagnostics, to be used with the radioactive ion beams produced with the EXCYT and FRIB facilities [1, 2]. It will allow to control in real time the main beam parameters, in particular the beam intensity and the 2-dimensional beam profiles, with sensitivity down to the single particle regime. The aim is to optimize the whole transport efficiency along the beam line, in order to maximize the intensity until to the final detector.

In fig. 1 the diagnostic devices installed along the beam line until to the Chimera detector are shown, marked by circles. In each point two different devices are placed, based on plastic scintillators and position sensitive silicon detectors (PSSD). The first is used to measure the beam intensity when its value is below 10^6 pps, that is the threshold sensitivity of the standard faraday cups. The PSSD allows to visualize the 2D transversal beam profile, in a similar way as an imaging device based on a scintillating screen and a CCD camera. The devices are installed in pair in the same cross, each one driven by means of its pneumatic actuators, in order to intercept the beam at 0° . Another device that will be installed in two points of the beam line, is a beam profiler based on a couple of scintillating fibers, that scanning the beam allows to reconstruct the 1D vertical and horizontal profiles. It has the advantage to be slightly interceptive, so that all of such devices can be used simultaneously.

BEAM COUNTING

The device used as beam intensity counter is based on a plastic scintillator BC408 ($\tau_{\text{decay}} = 2.1$ ns, $5 \times 5 \times 1$ cm³), coupled to a short PhotoMultiplier (Hamamatsu R1924A), that is placed inside the vacuum chamber and powered by an active voltage divider (Thorn EMI – PS 1807/5, $V_{\text{power}} = 6$ V) installed outside. It is used as a faraday cup for intensities below than 10^6 pps, over such a value

the linearity is lost. The detector is mounted in a steel axis fixed with a pneumatic actuator and when necessary it is moved to intercept the beam. The output of the PMT is split in two ways and sent to a discriminator for the pulse counting and to a QDC for the energy spectra acquisition. The energy spectrum is useful in particular with the FRIB beams, where several ions can be present in the beam, so that the selection of an energy window could allow more accurate measurements. Besides, in order to perform an identification of the fragments in the beam, the energy loss (ΔE) vs. time of flight (Tof) data can be acquired.

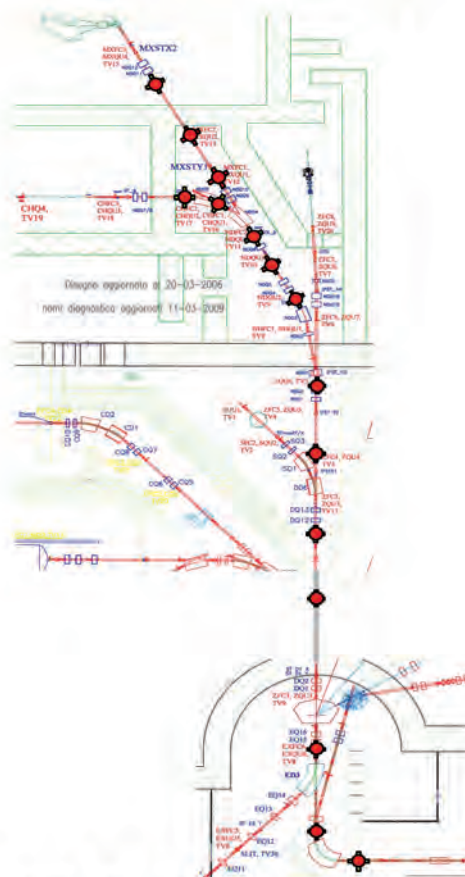


Fig. 1. Sketch of the beam line with the diagnostic points marked with the circles.

TWO DIMENSIONAL PROFILING

In order to visualize the 2-Dimensional beam profile, the low intensity of the radioactive beams ($< 10^5$ pps) does not allow to exploit the standard beam imaging devices, such as the scintillating screens. We have



therefore chosen to adopt Position Sensitive Silicon Detectors (PSSD), with a surface of $50 \times 50 \text{ mm}^2$ and thickness 500 micron (fig. 3). The anode surface is covered by a homogeneous high resistivity sheet with four signal electrodes, connected to the corners. By means of them, the total charge produced by each hitting particle is collected, that is distributed between the four electrodes as a function of the particle coordinates (x, y) [3]. Such a property allows to calculate the position of each particle event by event, so that by drawing it in real time on a X-Y plot, the transversal beam profile can be reproduced. The strong shape distortion that typically affects the response of such devices, has been corrected by means of an algorithm developed by us, that is fast enough to guarantee a real time vision of the beam profile.

We have tested such devices by exploiting an alpha radioactive source and a 2mm thick brass mask covering the detector, where a regular array of holes has allowed to set-up the correction algorithm and to measure the spatial resolution ($< 2 \text{ mm}$). We have also efficiently worked in realistic operative conditions, with beams accelerated by the Tandem and the Cyclotron, in particular with the EXCYT and FRIB beams. In fig. 4 two profiles corresponding to Lithium beams at 10 MeV and 55 MeV/A respectively (the latter is really composed on several fragments, that cross the mass separators of FRIB) are shown. The beam intensity for both is 10^3 pps . The structure of the masks is clearly visible and it is useful in order to have a spatial reference.

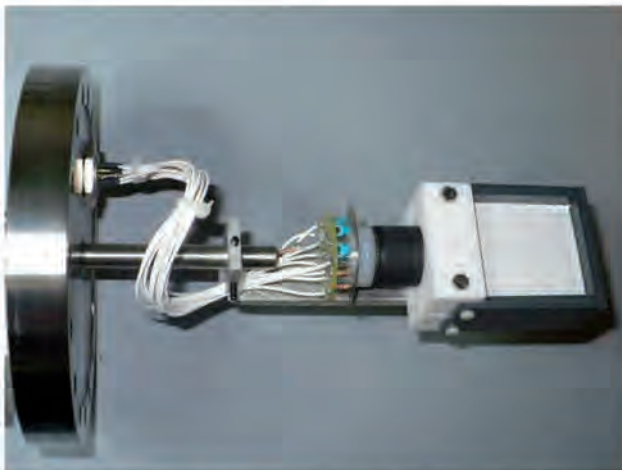


Fig. 2. Beam particle counter, based on a plastic scintillator coupled to a photomultiplier.

In order to preserve the detector by fast ageing due to radiation damage, the beam intensity must be kept below 10^4 pps .

The correct profile reconstruction, has to be guaranteed by equalizing the gain for the anode signals, during the installation of each detector. An alpha source placed in front of the detector, with a mask having a hole in the center, is used for such a purpose.

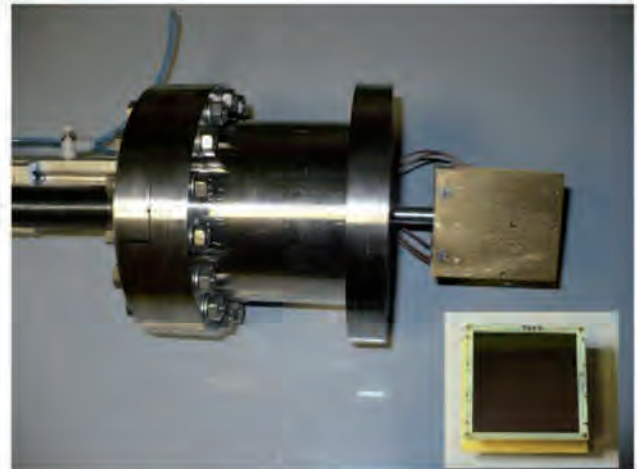


Fig. 3. PSSD mounted in a pneumatic actuator. The mask made by brass is 2mm thick.

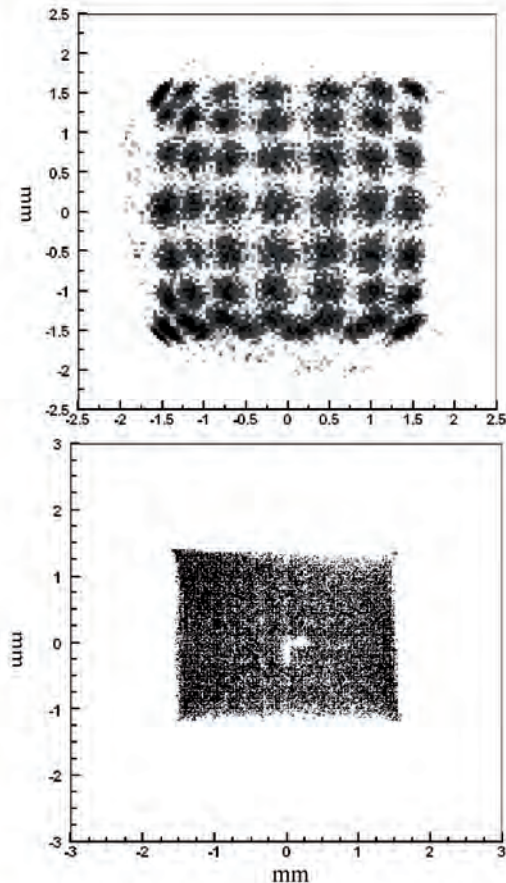


Fig. 4. Corrected beam profiles of a EXCYT (a) and a FRIB (b) beam, acquired by means of the PSSD and using two different masks.

An easy to use Graphical User Interface (GUI), gives to the accelerator crew a tool as a standard beam imaging device based on a scintillating screen and CCD camera.

ONE DIMENSIONAL PROFILING

FIBBS (Fiber Ion Beam Based Sensor) is a device based on scintillating fibres (diameter of 300 - 500 micron), that scanning the beam allow to acquire the 1D horizontal and the vertical beam profiles, with a sensitivity below 10^3 pps [4]. The profiles are acquired by plotting the intensity versus the position. Both fibre are optically coupled to a small photomultiplier (Hamamatsu H5783) biased by a Cockroft Walton power supply, that is encapsulated together with the PMT and is compatible with the vacuum regime of 10^{-7} mbar. The electronics read-out is designed in order to split the pmt output in two ways, thus to have a pulse output and an average current output, that can be acquired alternatively, as requested by the selection in the user interface. The software allows to set the parameters related to the movement of the fibres (speed and step), the gain of the pmt, the threshold level of pulse detection and the ADC gain. If the beam intensity is lower than 10^6 pps, it is convenient to make use of plastic fibres with a light decay time so fast (2.1 ns), in order to allow the particles to be counted one by one. Higher intensities can be dangerous for plastic fibres because of the radiation damage, so that glass fibres doped with terbium should be used, also if the longer decay time (3ms) does not allow to count the single particles, but only to measure the average current. During the scan of the beam, the plots corresponding to the average current or to the pulses output (depending on the setting) are continuously upgraded, in order to show both the profiles in real time. The scan velocity can be chosen as a function of the beam intensity, in order to acquire the plots with a numerical statistic that is high enough to have profiles with acceptable signal to noise ratio. In order to estimate the efficiency related to the detection of the beam particles, we have to take into account the energy released inside the core of the fibre, that depends on the atomic number of the projectile and on its energy. Unfortunately for very low energy beams the most fraction of the total energy could be lost inside the inert cladding, thus preventing their detection. Another trouble could be come from the neutron background, for which the plastic fibres are particularly sensitive. It can reduce the signal to noise ratio, making difficult the detection of very low intensity beams.

During the first sessions of the EXCYT beams, we have acquired beam profiles for several energies. In fig. 5 the profiles of a 10MeV ^8Li beam with an intensity of 10^3 pps are shown. Because of the slight interceptivity of such systems, several of them can operate simultaneously, thus allowing to check in one shot what is happening along the beam line.

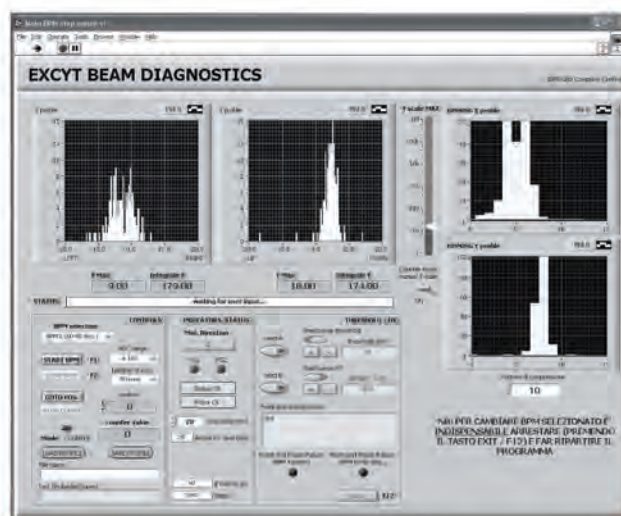


Fig. 5. Horizontal and vertical beam profiles acquired with the FIBBS device.

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UPGRADE OF MAGNEX EXPERIMENTAL EQUIPMENT

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Abstract

In this report we discuss on the status of Magnex experimental set-up and its upgrade. The automatic control of vacuum system and handling procedures have been reviewed and updated. We reviewed also the sliding seal with a new project in order to improve the whole performances.

INTRODUCTION

The current system of automatic control of vacuum consists of three groups and each of them defines a unique control in a specific part of the equipment. The first group includes the control of systems (gauges, vacuum pumps and valves) of scattering chamber and input line of the beam. The second, systems that are part of the inner chamber of the dipole spectrometer, and finally the third group includes the detector of focal plane.

Each group is fully automated, without prejudice to be used manually, allowing you to perform, in extreme security, all procedures of evacuation and return in air of various groups of the equipment. In addition it allows to secure unwanted and unexpected events [1].

During commissioning were found a number of needs and problems to be solved to ensure the functionality of the whole system. Among these, the upgrades of the control system and the electromechanical movements are required. It is also required the monitoring of the status of vacuum system through internal LNS-web.

Another pending aspect was is the implementation of sliding seal for the continuous movement of the spectrometer.

In this contribution we report the design of a new sliding seal and its link with beam line which is distant about 1.5 meters from the scattering chamber.

REMOTE CONTROL UPGRADE

The electronic system for monitoring and automatic controlling high vacuum and magnetic field is installed on a industry CPU, such as ICP-DAS I-8831. The software operating under the ANSI-C handles the automation of various stages, the security and user interface via Ethernet UDP. The handling control system is installed on the industrial CPU ICP-DAS I-7188E8.

The graphics and user interface was developed in LabVIEW 7.1 graphical environment for Windows to monitor and remotely manage, through Ethernet protocols UDP and TCP / IP, the vacuum systems, the control of the magnetic field and the handling and calibration.

The system comes with a PanelPC Axiomtek Panel 1158/822RC, Intel Pentium M 1.5GHz, TFT 15.1

"Touchscreen", for interfacing with the user in experimental hall.

The upgrade of the control system was been decided to confer a greater interactivity with the user and also to solve some problems with the handling system within the equipment. SMC Pollux drivers have been replaced with new models form stepper motor SteMoD4 with higher performance: controller configured to n. 3 independent axes, micro-stepping up to 1 / 32 pitch, parameterized trapezoidal speed profiles for each axis, position feedback for each axis.

In addition, a software (NI LabVIEW WebServer) that allows publication of graphic pages on the internal LNS-web, for monitoring the vacuum control system has been developed.

The user interface was improved for displaying the three control groups is showed in figure 1.

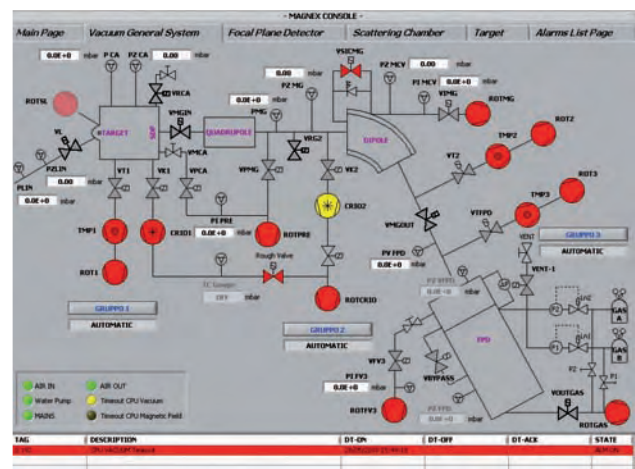


Figure 1: synoptic control system

To align targets, detectors, diaphragms, etc.. inside the scattering chamber, we realized a section of beam line removable to allow the insertion of optical instruments.

It has been redesigned and implemented a new system of handling of the Faraday-cup, to allow easier removal and the respective remote control system.

SLIDING SEAL PROJECT

In experimental nuclear physics studies, often we need a vacuum chamber that can constantly change the angle of input beam in a wide angular range while maintaining a good vacuum.

There are several mechanical solutions for the realization of a sliding seal. Based on work reported in the

literature [2] and experience of our work (double scattering experiment Fustot) the “seal strip continuous rotation” solution was chosen.

The existing scattering chamber consists of a steel body of the inner diameter of 800mm and outer diameter of 860mm, $H = 500\text{mm}$ approx.

At the center of the chamber the target is mounted with the possibility of rotation and vertical translation, and everything is fixed to the base, the center of rotation. During the rotation of the spectrometer, the target is stopped while the whole chamber rotates around the center axis.

The scattering chamber is connected to the spectrometer through a circular window on which is positioned an electro-pneumatic valve DN 200 ISO K.

The openness of the window on the scattering chamber, where the sliding seal is seated, measures 430mm of length, 50mm of height with an angle of 140 degrees.

The implementation of a sliding seal with such a wide angular range, requires a near-perfect concentricity of the outer surface of the chamber to the axis of rotation.

A number of measures were made through the installation of a system of comparable extent in which was observed a discrepancy (depending on the angle of rotation) at the most of 0.6 mm.

Moreover, the outer surface of the chamber is not suitable for direct coupling with the sliding strip.

For this reason it was necessary to devise a new structure to realize an efficient coupling with the sliding strip. This structure we call “mating shell” is designed in Anticoradal aluminum. The inside of the mating shell bring an O-ring Viton $\varnothing 12\text{mm}$ further the existing O-ring on the camera (see fig. 2).



Figure 2: Mating shell of Anticoradal aluminum

The slit on the mating shell is expected to have the same width of the slit on the camera and it will cover about 120° of rotation.

On the outside of the mating shell it is expected a placement of an O-ring Viton $\varnothing 7\text{ mm}$ placed at about 12 mm from the edge of the window to ensure a good vacuum seal with the strip.

On this O-ring will rest a stainless steel strip with a high percentage of silicon to make it harmonious. It has a

length of 3m, a height of 100mm and a thickness of 1mm (enough to maintain the air pressure on the vacuum chamber), with the edges rounded, whether above or below.

The strip will have a center hole of 30mm of diameter and it will be contained, from above and from below, by two bronze ribbons, each of them of 2mm of thickness and 20mm of height.

Two circular sectors (that will rest for 20 mm on the steel strip) made of brass, will be milled to contain two virgin Teflon ribbons, with a very low coefficient of friction, with a thickness of 4 mm and a height of 15mm. This system will help to reduce friction between the steel strip and O-ring vacuum.

The two circular sectors are fitted with a several number of grains of adjustment (1 every 5 degrees) that act directly on the Teflon ribbon, allowing you to adjust the crushing of the Teflon on the steel strip, then on the O-ring.

This registration system will allow us to find the right balance of crushing in order to keep the vacuum values in the designed range, during rotation of the spectrometer (in the order of 10-6 mbar).

To the hole on the harmonious steel strip, that as we said measure 30mm, will be rigidly coupled a steel tubular AISI 316, that will allow to combine the scattering chamber with the rest of the beam line through a flange DN 100 CF.

The steel tubular will be rigidly fixed to give stability to the system.

For this reason, we designed an iron tower support with a square base, fastened to the ground and partially filled with lead balls, to ensure a rigid fixation of the connection line-scattering chamber. The steel tubular will be fixed by an aluminum block that measures approximately $200 \times 200\text{mm}$, that will be fixed on a plane of size of $500 \times 20\text{mm}$, $s = 800\text{mm}$.

The fastening of the strips will be achieved through a special sandwich flange and against-flange (inner radius of 480 mm with O-ring seal).

Then, the system will be anchored, by a holder, to the pivot that holds the target. This will give to the system a huge mechanical stability during the rotation (see fig. 3).

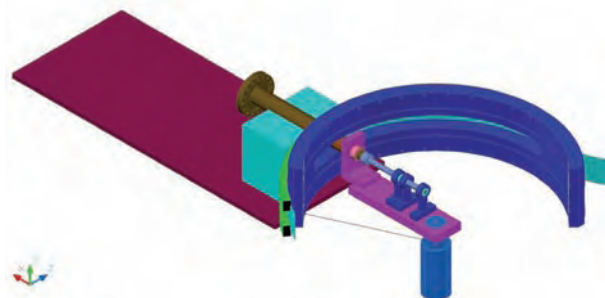


Figure 3: Internal view

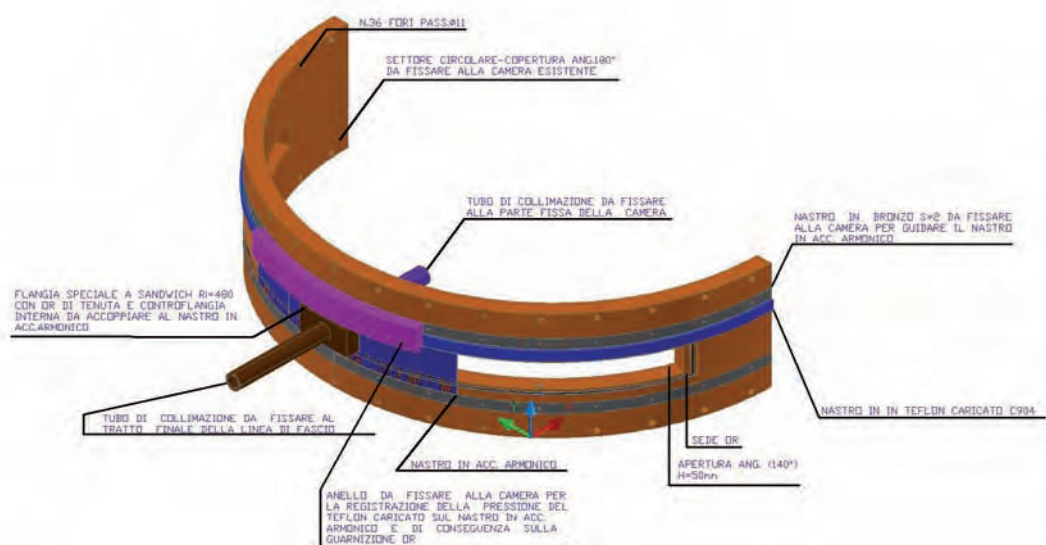


On this support is also expected the housing of a collimation system for the definition of the beam spot, realized through a stainless steel tube AISI304 of size of $\varnothing_e = 20\text{mm}$ and $\varnothing_i = 12\text{mm}$. At the head and at the tail will be two tantalum diaphragms of outside diameter of $\varnothing_e = 14\text{mm}$ and thickness of 1mm. Following the collimator will be another stainless steel tube AISI 304

A new sliding seal was also designed with its coupling to the beam line to ensure the conditions of vacuum inside the scattering chamber during the continuous rotation of the spectrometer.

The realization and implementation of the entire project is expected by summer 2010.

Special thanks to the technical staff, to the mechanical



which carries a tantalum disc, which acts as anti scattering.

In summary, the above project should ensure an easy continuous movement of Magnex spectrometer in an angular range of about 120° , maintaining the vacuum inside the chamber scattering at around 10^{-6} mbar.

CONCLUSIONS

In this report the changes made to the MAGNEX experimental equipment in 2009 have been showed. These upgrades have covered the remote control system and mechanics.

workshop, to the welding department and to the electronics department of LNS for their invaluable help and their proven professionalism.

Thanks are due to TMA and SIATEL companies for their cooperation.

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STUDIES OF ASTROPHYSICAL PLASMAS IN LABORATORY BY LASER ABLATION

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Abstract

Laser generated plasmas are employed on a wide range of physical investigations, going from matter science and nuclear physics to astrophysical studies, including laser deposition, ion acceleration and shock waves formation. We describe hereby a new experimental apparatus designed at the LNS-INFN, and installed at the DMFCI of Catania, where a Quanta System ND:Yag laser 600mJ Energy, 1064nm wavelength, 6ns pulse length operates and where the first experiments have been carried out. The new apparatus aims to the investigation of laser generated plasmas produced at different energies from several types of solid targets. These plasmas expand supersonically in vacuum, but additional investigations at intermediate pressures in presence of background gases have been performed. Our studies are mostly devoted to nuclear and astrophysical issues like shock wave production, Rayleigh Taylor instability and screening factor in nuclear fusion reactions. Preliminary results with aluminium thick targets will be reported in the following. Plasma dynamics have been investigated by means of a Faraday Cup and of a movable Langmuir Probe, through time of flight measurements performed at different distances from the laser-target interaction area. The imaging of the expansion dynamics have been obtained with a time gateable CCD camera.

INTRODUCTION

Laser generated plasmas give the opportunity to study phenomena from many fields of modern physics. In the last decades many efforts have been particularly devoted to energy science, in order to obtain plasma ignition through the ICF-Inertial Fusion Confinement according to the Nuckolls' discovery [1].

On the other hand laser plasmas can be used to study crucial astrophysical phenomena, such as shock wave formation and electron screening, that is essential for the correct calculation of the astrophysical factor. Colliding plasmas can also be employed [2, 3] for the production of jets and shock waves. They are also useful because give us the opportunity to study screening factors and fusion rates in an unexplored low energy range [4, 5].

During the assembling phase of the experimental apparatus we carried out some preliminary calculations [4] focused on single expanding plumes dynamics and on the interaction of two colliding plasmas: they featured that shocks and jets should be formed during the plumes overlapping, and that the ion and electron temperatures may be proper for remarkable studies on fusion rates at extremely low energies.

The experimental apparatus was appositely designed for the production of two colliding plasmas obtained by means of the single laser beam splitting. Anyway the first measurements were carried out on a single expanding plasma plume. The first measurements on colliding plasmas have been performed at the NCPST-National Centre of Plasma Science and Technology of Dublin in collaboration with Prof. J. Costello.

APPARATUS DESCRIPTION

The core of the experimental set-up consists in a cylindrical vacuum chamber (see fig.1) with a diameter of 250mm and 240mm of height. Four DN40 flanges are located at 90° degrees with respect to the chamber axis, while additional DN25 and DN16 form angles going from 15° to 45°.

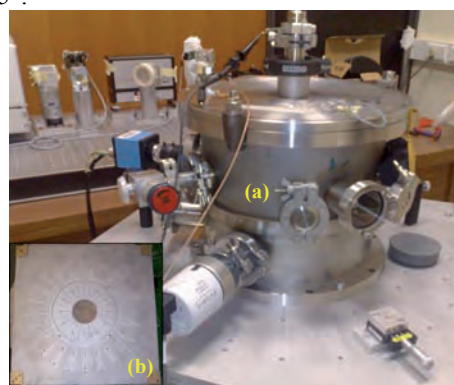


Figure 1: (a) Vacuum Chamber, (b) optical plate.

The plate where the chamber is located was designed and made at LNS and has lateral dimensions of 600mm. It is composed by four small rectangular supports located at each angle (see fig.1.b), where mirrors and beamsplitters will be placed in order to achieve the plume collision configuration. Lines of drilled threaded holes

located 15° from each other and irradiating from the plate centre served to host optical devices at fixed positions. Supports for optical devices (lenses, mirrors etc), part of diagnostics tools (like the Faraday Cup for the time of flight measurements) and other devices were designed and homemade at LNS. As mentioned above the laser used for the experiment is a Quanta System ND:Yag, with energy of maximum 600mJ, 6ns of pulse length and 1064nm of wavelength. The laser beam was focalized on the chamber with a 25mm focal length lens, obtaining spot size on the order of $200\mu\text{m}$.

DIAGNOSTIC AND SIGNAL ACQUISITION SISTEM

The Faraday cup used for time of flight measurements consists of a 10mm length Cu covering with an external diameter of 22mm and a internal diameter of 18mm. Inside the Cu disk a grafite with diameter of 18mm and 5mm thickness was placed, followed alternatively by two disks of metal and two disks of insulator both of 1mm thickness and 18mm of diameter. The cup was covered by a 12 mm length PCV cylinder, having a 24mm external diameter and a 22mm internal diameter, and placed finally in high vacuum conical flange so that the active area of the cup was 346mm^2 . The signal was collected with a BNC feedthrough. The cup was powered with a HP power supply of 30V maximum voltage and 1A of full scale current. For the determination of plasma parameters at different distances from the laser-target interaction area a movable Langmuir probe was used. It is a Hiden Analytical ESPion Advanced Langmuir Probe. 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 tip protrudes from an alumina sheath which covers the coaxial cable. A motor moves the probe with a total range of 300mm. The signal was collected with a BNC feedthrough and read out with the RC circuit showed in fig.2.b. The probe was powered with a HP power supply of 100V maximum voltage and 3A of full scale current. Both time of flight signals, coming from the Faraday cup and Langmuir probe, were collected by means of a Textronik Oscilloscope.

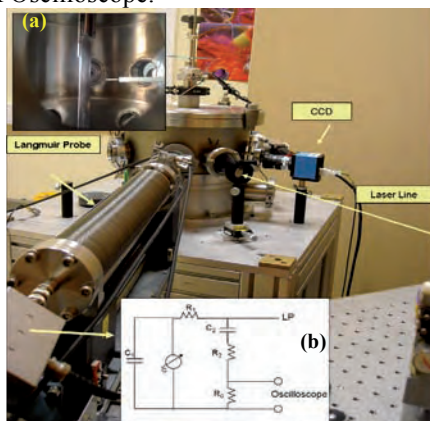


Figure 2: Experimental set-up, (a) internal view of the chamber with the Langmuir Probe close to the target, (b) RC read out.

The CCD camera used for the plasma imaging is a diagonal 8mm interline with a squarepixel array and 1.45M of effective pixels. The maximum frame rate is 1/30sec and the minimum time acquisition window is $2.3\mu\text{sec}$. It is equipped with an electronic shutter with variable charge-storage. High sensitivity and low dark current are achieved through a Hole-Accumulation-Diode. The timing of the system (see fig.3) was obtained through CAEN delay generators and LeCroy signal generators. The jitter was of 20nsec.

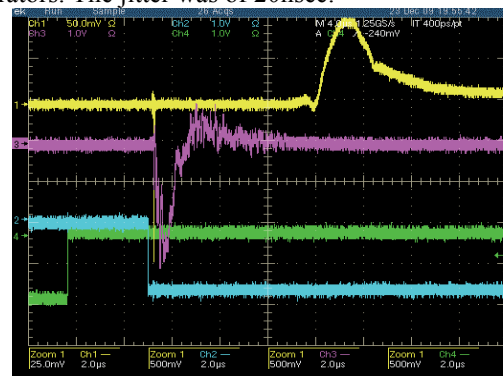


Figure 3: Timing, Laser-blue signal, CCD-green signal, Faraday-Cup-yellow signal, Langmuir Probe-violet signal

The CCD camera was triggered 2.2μsec before the laser signal so that the acquisition window of the camera was of 100nsec. The Faraday Cup and the Langmuir Probe were also triggered with the laser pulse. In fig.3, the small photopeaks of the TOF signals, that corresponds to photoemission from the detector caused by EUV emission from the initial plasma, can be observed. It comes out that the time of flight signals have a delay of 150nsec with respect to the laser pulse. For this reason we set the photopeak as the starter of the entire timing, since it was located for each laser shot at the same position, so we reduced the jitter to 1nsec.

FIRST MEASUREMENTS

In the first series of measurements the Langmuir Probe and the Faraday Cup signals were collected along with the CCD images. The geometrical configuration is shown in fig.4. The Faraday cup and the Langmuir probe were located respectively 120cm and 1.5cm away from the target, with the Langmuir Probe parallel to the target surface and perpendicular to the plume expansion direction. The Faraday Cup was biased at -30V, while the Langmuir Probe was biased from -100V to +100V 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 analysis of the I - V curves gives the plasma parameter like Electron Density, Electron Temperature and Plasma Potential [6]. All the measurements were done at an operating pressure of $4 \cdot 10^{-6}$ mbar working with fresh target at each laser shot. Raman and Pixel- α analysis [7] were used to reveal the

60cm form
- target
exact target composition: 99% of pure Al, 0.25% of Si, 0.4% Fe, 0.05% Cu, 0.05% of Mg, 0.05% of Mn and 0.07% of Zn.

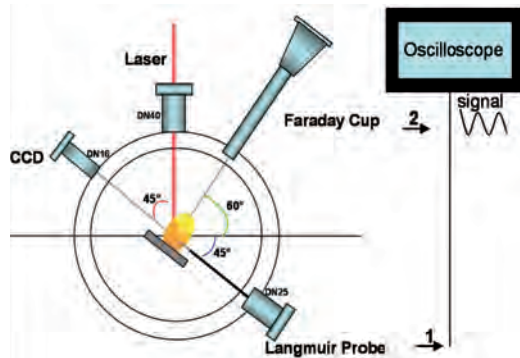


Fig.4: Geometrical configuration of the first set of measurements

In fig.5 frames of the plume are shown, for three consecutive shots on the same target surface. As we can observe from figure 6, the plume seem to be bigger for the 3th shot. This probably occurs because the laser is getting more focalized on the target surface after removing some micron of target material with the first two shots. On this purpose we also performed some measurements firing the laser on the same target surface for 50 times, to observe the evolution of the crater depth. Data analysis is in progress.

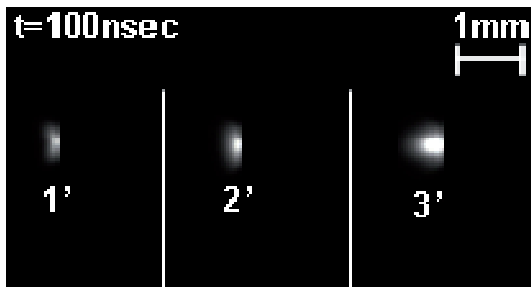


Fig.5: Plume photos for three consecutive shots on the same target surface.

In figure 6 the $I-V$ curves reconstructed at different times are shown; in this case the probe was located at 1.5cm from the target. This position was chosen to make a further comparison with the results obtained in [6] on Tantalum targets. The analysis of the $I-V$ curves is quite complex and requires a lot of time, so that it is currently in progress using a Matlab program expressly developed on purpose [6]. Anyway some preliminary results are already available: they feature electron temperatures of the order of 15eV in the first 500nsec, but rapidly decreasing down to few eV's after 1000nsec. The electron density has the same trend: it is initially of the order of $4 \cdot 10^{18} \text{ m}^{-3}$, then it decreases of one order of magnitude after 5000nsec.

In the second set of measurements the probe was located parallel the expansion direction, (the target was rotated of 15°, see fig.2). The signals were collected at

different operating pressures, going from $4 \cdot 10^{-6} \text{ mbar}$ to $6.3 \cdot 10^{-1} \text{ mbar}$.

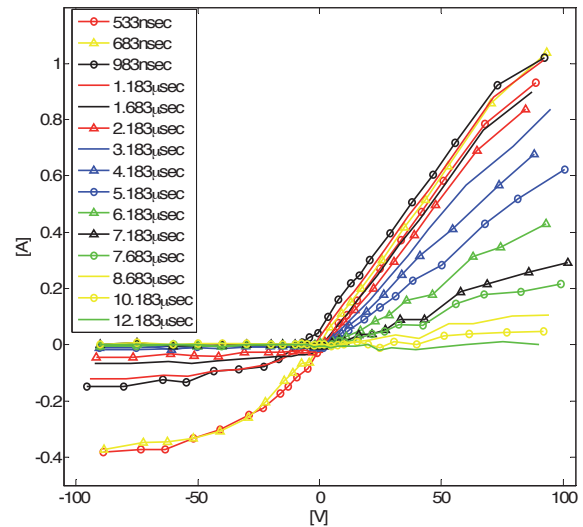


Fig.6: $I-V$ curves at different times and at 1.5cm from the target, with the probe orthogonal to the plasma flow.

The probe was placed at 2.5cm, 1.5cm and 0.5cm from the target, then reconstructing the $I-V$ curves at different operating pressures respectively of $4 \cdot 10^{-6} \text{ mbar}$ for the first and the second position, and $4 \cdot 10^{-6} \text{ mbar}$, $1 \cdot 10^{-3} \text{ mbar}$ and $1 \cdot 10^{-1} \text{ mbar}$ for the third position.

Another set of measurements were done positioning the probe at 0.2cm, 0.3cm, 0.5cm, 0.8cm, 1cm, 1.5cm, 2cm, 3cm, 5cm, 10cm and 15cm from the target at different operating pressures ($4 \cdot 10^{-6} \text{ mbar}$, $1 \cdot 10^{-3} \text{ mbar}$, $1 \cdot 10^{-2} \text{ mbar}$, $1 \cdot 10^{-1} \text{ mbar}$, 1mbar, $1 \cdot 10^1 \text{ mbar}$ $6.3 \cdot 10^1 \text{ mbar}$). In this case the probe tip was not biased, using it only as a time-of-flight detector. This study provided additional information on plume expansion dynamics and eventual inner structures, like ions multishells formation and/or electron layers [12]. In fig.7 the $I-V$ curves obtained at $4 \cdot 10^{-6} \text{ mbar}$ at 1.5cm from the target when the probe was located parallel to the plasma flow are shown. In this case at 433nsec a first plasma contribution, that was not present when the probe was placed orthogonal to the plasma flow, was observed. First preliminary analysis of that fast plasma give us an electron temperature of 5eV and an electron density of $1 \cdot 10^{17} \text{ m}^{-3}$. If we observe the $I-V$ curves for expansion times shorter than 983nsec, the ion current does not saturate, even for probe potential higher than 50V (this instead occurs for the $I-V$ curves obtained in the perpendicular configuration). At 683nsec, the $I-V$ curve of fig.7 (that because of its particular trend, we were not able to analyze it) does not show the same trend compared to the same $I-V$ curve of fig.6 that conversely, begins to saturate already at 50V. This same effect was observed from B. Doggett et al. in [10] locating a planar Langmuir Probe parallel to the plasma flow at 9.5cm from the target: the ion current did not saturate, increasing with $V^{1/2}$. They explained this behaviour with a theoretical model used also for PIII- Plasma Immersion Ion Implantation; when the Langmuir Probe is oriented

parallel to the expansion plume direction, the plasma will flow parallel to the collecting surface.

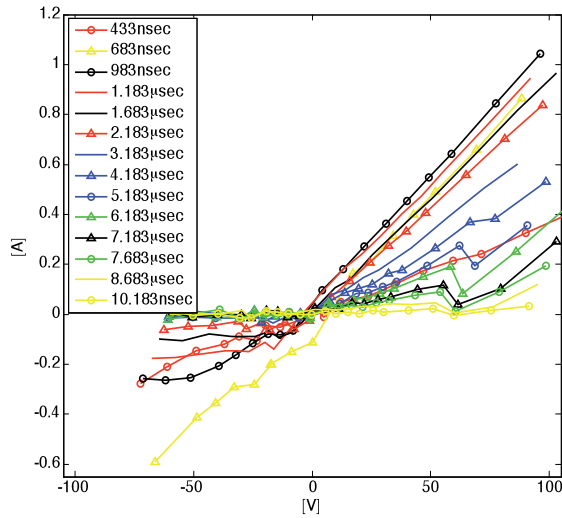


Fig.7: I - V curves at different times and at 1.5cm from the target, with the probe located parallel to the plasma flow.

If the probe is powered with a high negative voltage the electrons are repelled from the probe in a time scale on the order of the inverse electron plasma frequency, $\omega_{pe}^{-1} = [(n_e e^2)/(\epsilon_0 m_e)]^{-1/2}$, which is around 10^{-9} - 10^{-10} s. After, on a slower time scale, on the order of the inverse ion plasma frequency, $\omega_{pi}^{-1} = [(n_i e^2)/(\epsilon_0 m_i)]^{-1/2}$ (which is around 10^{-6} - 10^{-7} sec), ions are accelerated toward the detector and they fall through the ion-matrix sheath. Finally, on a still longer time scale (several $1/\omega_{pi}$), the decreasing ion density inside the sheath region due to the ion collection on the probe causes the sheath edge to expand in order to maintain the sheath potential and the ion and electron density profiles relax to establish a steady-state Child-Langmuir sheath [11]. In the case of probes oriented parallel to the plasma flow, the time taken for the Child sheath to be established can be shorter than the time taken to travel the length of the probe. Thus the current to the probe from that plasma element will vary in a rather complicated manner [10]. In addition to this effect we revealed an even more complicated structure in the first part of the signal collected by the probe at a fixed voltage. Numerical simulations based on hydrodynamic calculations demonstrate that this first part, that is where the non saturation of I - V curve is more evident, is connected with some layers characterized by alternatively electron or ion excesses, i.e. regions where the plasma quasi-neutrality has been violated by the strongly non-linear acceleration mechanism of the plasma plume. These layers freely travel in vacuum and their dynamics are uncoupled with the remaining part of the equilibrated classical plasma bulk.

Preliminary analysis of the I - V curves reported in fig.7, regarding especially the plasma bulk, show that the temperature has a value of 9eV at 983nsec decreasing to 2-3eV after 2000nsec. While the electron density is equal to $3 \cdot 10^{18} \text{m}^{-3}$ at 983nsec decreasing of one order of magnitude after 5000nsec. The electron temperature increases, as the plasma arrives to the probe and then falls

between 1000-2000nsec, in accord to the theoretical adiabatic and isentropic plasma expansion dynamical model [8].

In fig.9 the time of flight signals (without powering the probe) at 0.5cm from the target at different pressures are showed. Data show that the operating pressure significant influences the trend of the signals. Data analysis is under investigation.

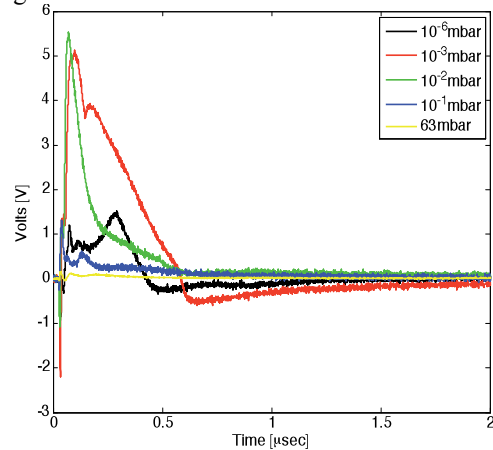


Fig.9: TOF signals at vs time 0.5cm from the target @ different pressures.

PERSPECTIVES

The data analysis is just in a preliminary phase, but these first results will be crucial for comparison with Hydrodynamic Simulations and the Anisimov model. By improving our numerical code (presented in [8]) we will be able to simulate the different time of flight signals with a *virtual probe*, distinguishing even the different charge states. Further improvement have been done in our modelling, including a more precise calculation of heat transfer from the laser energy to the plasma plume. Our final aim is to realize further experiments on nuclear astrophysics for studies that up to now have only been carried out by numerical simulations [4, 5].

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LASER GENERATED PLASMAS FOR ASTROPHYSICAL STUDIES: FUSION AND EVIDENCE OF REYLEIGH-TAYLOR INSTABILITY

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Abstract

According with the power density levels laser generated plasmas can be employed to explore several fields of modern physics, from pure research to industrial applications, including fusion for energetic purposes and astrophysical phenomena. At power densities $>10^{10}$ W/cm² lasers interacting with solid targets produce rapidly expanding plasmas with ion temperatures of several hundreds of eV, and densities around 10^{16} - 10^{18} cm⁻³. Their importance in astrophysics is constantly growing, and hereby we report some theoretical and experimental results obtained in this field at LNS during 2009 [5,8,9].

INTRODUCTION

The interest of scientific community on nuclear fusion is strongly connected with energetic issues. Anyway some unexplored energy domain persist in calculation of fusion reaction rates, especially at very low energies. We are particularly interested to these last energy domains, in which clouds of cold electrons may play a role as electron screening, thus boosting the fusion rates. At temperatures and densities that are typical of plasmas produced by beams of lasers impinging on solid targets ablation, the classical Debye screening factor becomes comparable with the one of the solar core. In plasmas the fusion rate is strongly connected with the ion temperature and density, according with the Gamow theory which takes into account the tunnel effect of the nuclear Coulomb barrier:

$$\langle \sigma v \rangle = \left(\frac{8}{\pi \mu} \right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty S(E) \exp \left[-\frac{E}{kT} - \frac{b}{E^{1/2}} \right] dE \quad (1)$$

where $E = \frac{1}{2} m_r v^2$ is the energy of the particles pair

with reduced mass and v is the velocity of the nuclei of the particles pair supposing a Maxwell Boltzmann thermal equilibrium. T is the temperature, k the Boltzmann constant and $\mu = m_r/m_p$. $\sigma(E)$ is obtained from the Gamow theory with an energy value

$$E_G = b^2 = (2\mu) \pi^2 e^4 \left(\frac{Z_1 Z_2}{h} \right)^2, \text{ where } Z_1 \text{ and } Z_2 \text{ are the}$$

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. We have considered the D-D reaction and only the first three terms of $S(E)$ have been employed.

The number of fusion reactions per unit time, for identical particles, can be written as:

$$f_{TOT} = \frac{1}{2} N \langle \sigma v \rangle \int_0^\infty \rho(t) dt \quad (2)$$

where N is the total number of particles and $\rho(t)$ is the plasma density. For energetic purposes plasmas with ion temperatures on the order of several keVs are needed, like those obtainable in tokamaks (magnetic confinement fusion) and with high intensity lasers (inertial fusion) [1]. With our energy domains, i.e. few hundreds of eV, we may cover fields of interest not only in nuclear and plasma physics, but also in astrophysics: particularly interesting is the study of fusion reactions in presence of jets and shock waves. We expect that such an unexplored field may be investigated by means of colliding plasmas: according with simulations, shocks and jets should be formed during the overlapping of the colliding plumes. They reveal also the onset of the Reyleigh-Taylor instability even in low pressure ambient gas. The RT instability is developed for about 10 nanoseconds, which is extremely fast in comparison with the necessity of thousand of nanoseconds in the case of a single plume expanding in a relatively high pressure background. The RT instability can be generated in the stagnation limit of the plume collision, as described in [9]. In fact, if two plumes are colliding in this limit, the conversion of the kinetic energy into the thermal energy ionizes further the gas and raises its local temperature. As a result we notice that the RT onset instability is enhanced in such a configuration, which also shows a jet-like structure during the collision.

We think that this type of investigation can be important in understanding the efficiency of nuclear reaction rates during the red giant phase of stellar evolution, as a significant part of the produced energy is dissipated in the low-density radiative envelope by shock waves.

NUMERICAL CALCULATIONS OF FUSION RATES

The time dependent density $\rho(t)$ of the expanding plume, which must be included into the equation (2) for the calculation of the total number of possible fusions inside the plasma plume, can be determined, at first approximation, by means of the adiabatic model proposed by Anisimov [3]:

$$\rho(x, y, z, t) = \frac{M}{I_1 XYZ} \left[1 - \frac{x^2}{X^2} - \frac{y^2}{Y^2} - \frac{z^2}{Z^2} \right]^{\frac{1}{\gamma-1}} \quad (3)$$

where M is the plume mass. The expression of I_1 is given in [3] and is also calculated numerically. This formula is a special solution obtained from S. Anisimov by solving the Euler's gas dynamical equations supposing that the plasma flow expands selfsimilarly, adiabatically and isoentropically in vacuum [3]. The front of the plume is described by the coordinates $[X(t), Y(t), Z(t)]$ at a time t and by the corresponding velocities $[\dot{X}(t), \dot{Y}(t), \dot{Z}(t)]$. Supposing an axially symmetry $X(t)=Y(t)$ the expansion can be described only by the set of coordinates $[X(t), Z(t), \dot{X}(t), \dot{Z}(t)]$ (see fig.1). $X(t)$ and $Z(t)$ are determined by the following set of adimensional expressions (each coordinate is normalized to the laser spot radius R_0):

$$\xi \frac{d\xi^2}{d\tau^2} = \eta \frac{d\eta^2}{d\tau^2} = \left(\frac{\sigma}{\xi^2 \eta} \right)^{\gamma-1} \quad (4)$$

where $\xi(t)=X(t)/R_0$, $\tau=t/t_0$, $\eta=Z(t)/R_0$ and $\sigma=Z_0/R_0$. We numerically solved equations (4) by means of a MATLAB code using the ODE45 routine based on the Runge-Kutta method; then we replaced the solutions into the 2.4 formula, thus obtaining the time-varying plasma density distribution. This model gives the best results especially at low laser energies and in the case of monoatomic targets, as long as the initial conditions are set properly [6] (in [4, 5] the simulations' results are successfully compared with Langmuir probe measurements and time of flight data).

More accurate calculations were carried out by means of the ZEUSMP2 code [7], which solves the complete set of hydrodynamic Euler equations. In this case non linear effects are taken into account and this is particularly precious when attempting to simulate the

two colliding plasmas and the possible formation of jets, shocks, etc.

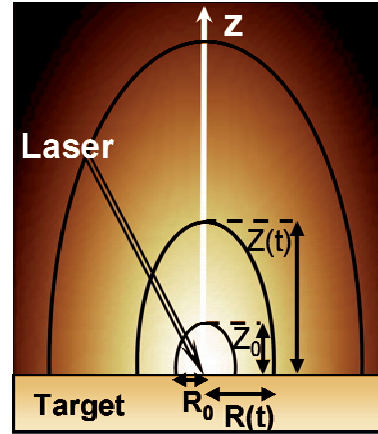


Figure 1: View of the plasma plume coming from hydrodynamical simulation and relative geometry.

Simulations performed with ZEUS revealed the onset of Reyleigh-Taylor instability, which will be discussed in the next section. Initially the plasma has been modelled like deuterium ions coming from a virtual Ti target, in order to evaluate the number of fusions for the D-D reaction after 24 hours of laser shots (10 Hz of repetition rate). The expansion dynamics was checked for 0.5 μ s, and two dimensional density maps (symmetries of the expanding plume were taken into account) were calculated every 20 ns. Reaction rates and the total number of fusions were determined by using the equations (1) and (2) at each time step, integrating the local reaction rate over the entire plasma plume volume and over the expansion time (with $t=500$ ns at maximum). Obtained results are reported in figure 2 (left). The number of fusions reported is a sum of 24 hours of laser shots at 10 Hz. Only in this way it was possible to obtain a conspicuous number of events, large enough to be higher than the background noise. The number of fusion events saturates after 100 nsec because the plasma density drastically decreases. On the basis of experimental measurements, plasma temperatures higher than 500 eV at 1 J of laser energy are unrealistic. Hence we expect that the line corresponding to 500 eV is the upper boundary of temperatures which may give us a reliable prediction of the expected number of fusions.

We calculated also the classical screening factor which may play a role in these plasmas. The calculations have been parameterized for plasmas at different temperatures and densities. It plays a non negligible role in case of electron clouds with temperatures $T_e < 10$ eV and/or densities $n_i > 10^{19}$ cm⁻³. Anyway 500 fusions may be not enough to investigate astrophysical factors and electron screening with a high enough statistics.

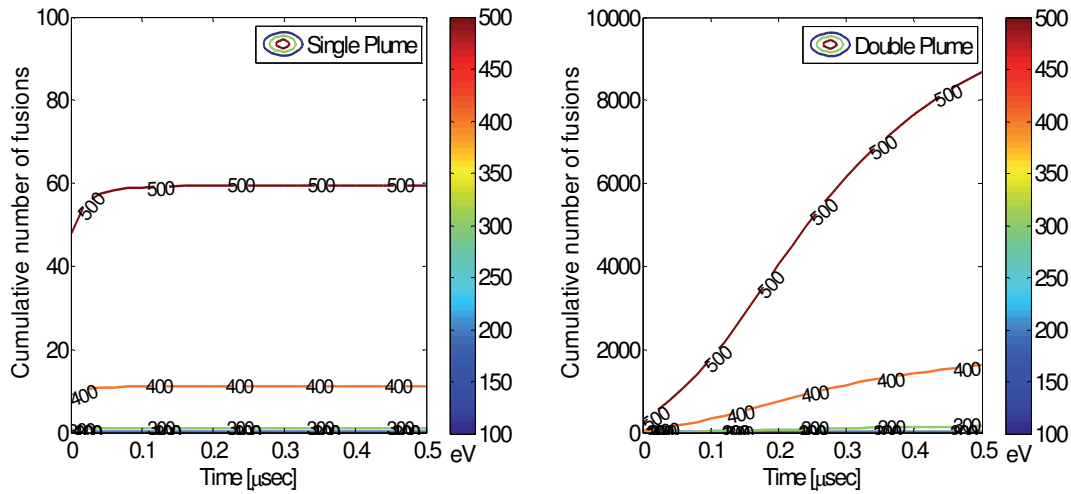


Fig. 2: (left) number of total D-D fusions vs time in case of a single plume expanding in vacuum and (right) total number of fusions in case of two colliding plasmas. In both the figures the ion temperature has been considered as a parameter in simulations.

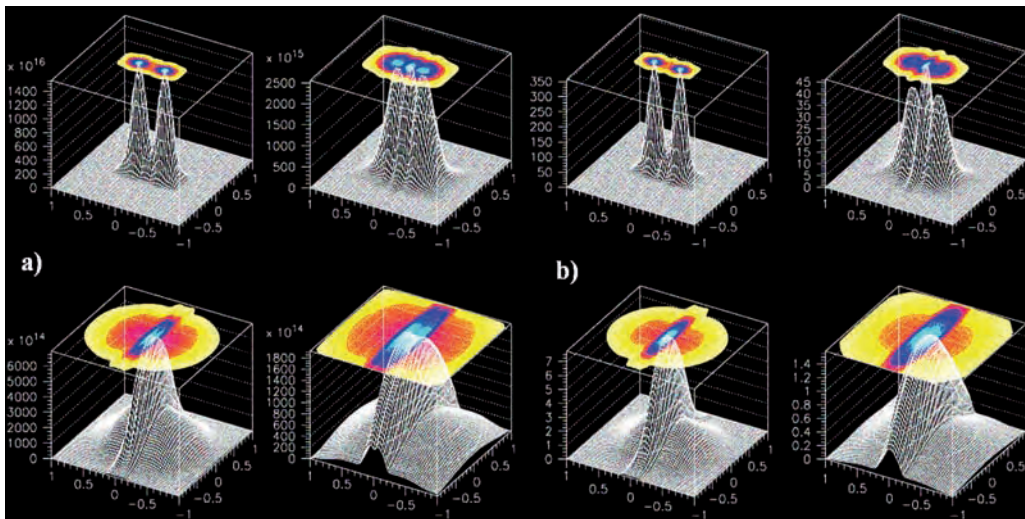


Fig. 3: Plasma density (a) and plasma temperature (b) @ 10nsec, 20nsec, 40nsec and 60nsec.

Therefore we investigated the colliding plumes, as a method that may be used to increase the plasma density without a significant increase of the electron temperature. Some preliminary simulations have been carried out, based on the ZEUS. In our simulations the two colliding plasma expand from two ideal thin CD_2 targets, located parallel at a distance of 2mm. Figures 2 (right) and 3 (a and b) reports some results. Note that when the two plasmas collide the density increases in the superposition volume up to the single plumes values. This evidence can be interpreted like a “plasma stagnation”. The temperature rises up to values slightly higher than the single plume. This means that it is possible to keep n high enough to favourite a large number of fusions for longer times. On this purpose we have calculated the fusions reaction rate considering

the time-varying plasma density of the colliding plumes. In figures 2 (right) the number of fusions versus time are reported, considering a virtual target irradiated over 24 hours at 1 Joule and 10 Hz of repetition rate, $3.3 \cdot 10^{-6}$ m of crater depth, and plasma expanding in vacuum with $\gamma = 1.4$. Also by simulations the conspicuous increase of the total, cumulated, number of fusions is evident, when using the two colliding plasmas, as a consequence of the aforementioned plasma stagnation. In case of 500 eV of plasma temperature the total number of fusions continuously increases even after 500 ns from the laser shots: more than 8000 fusions are expected at that temperature.

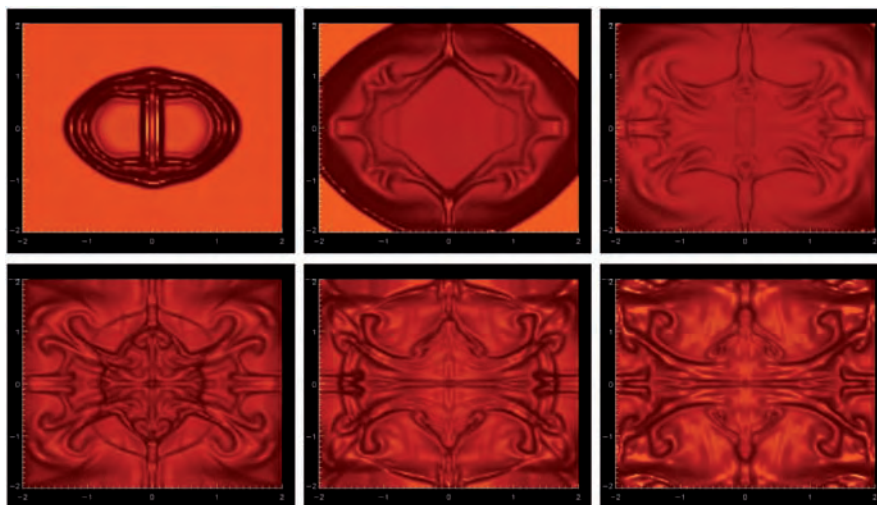


Figure 1. Rayleigh-Taylor instability patterns of colliding plumes representing density. The time evolution is 6; 20; 40; 60; 80; 100 ns.

GENERATION OF THE REYLEIGH-TAYLOR INSTABILITY

The Rayleigh-Taylor instability is associated with the interface interaction between the fluids with different density and it could be recognized usually by the perturbation structures at the contact boundary. Since this instability could appear in the plume-gas interaction of a single plume, an interesting question is whether it exhibits when two plumes colliding and if yes, how the two-plumes configuration responds to the strength of the background gas pressure. After the collision the instability growth is more likely to happen in the region of maximum acceleration. The experimental setup of Harilal et al.(8) clearly shows that only in the high-background pressure regime it is possible to observe the characteristic "fingers" of the RT instability in the intensity measurements. On the contrary, no instability is observed in the low density regime. Our numerical simulations, instead, shows that the collision of two plumes produces a shock front at the collision with a lower density region inside. Our result of two colliding plumes in low background pressure shows that it is possible to take a time interval of about a hundred of nanoseconds for the RT instability to be fully developed. The snapshots of the instability patterns of two colliding plumes are presented in Figure 4. The interacting plumes generate jet-like structure expansion, which could be seen in the earlier times.

CONCLUSIONS

Simulations of nuclear fusions in single laser shots demonstrate that using temperatures around 300-500 eV and densities on the order of 10^{18} - 10^{19} cm⁻³ the screening factor and other astrophysical reactions can be investigated. The low temperature favours the creation of very low energy electron clouds, whose

temperature is low enough to provide relatively high screening factors.

In order to increase the number of fusions in a single laser shot, a different experimental apparatus may be prepared: numerical simulations demonstrate that in case of two colliding plasma plumes the so-called plasma stagnation occurs, thus keeping the plasma density and temperature on high values for times longer than single expanding plume.

Particularly interesting is the formation of jets: the influence of such non-linearities in plasma dynamics will be carefully investigated experimentally. Other simulations demonstrate that in presence of high pressure background gases a shock wave is formed. This also will be a subject of the experimental investigation, being strongly connected with reactions in red supergiant stars.

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PRODUCTION OF INTENSE PROTON BEAMS WITH THE VERSATILE ION SOURCE (VIS)

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Abstract

The sources adapted to beam production for high power proton accelerators must obey to the request of high brightness, stability and reliability. The Versatile Ion Source (VIS) is based on permanent magnets (maximum value around 0.1 T on the chamber axis) producing an off-resonance microwave discharge at 2.45 GHz. It operates up to 75 kV without a bulky high voltage platform, producing several tens of mA of proton beams and monocharged ions. The microwave injection system and the extraction electrodes geometry have been designed in order to optimize the beam brightness. Moreover, the VIS source ensures long time operations without maintenance and high reliability in order to fulfil the requirements of the future accelerators. The main source characteristics and performances will be described, including possible options for the next developments of the project, which are relevant for future projects.

INTRODUCTION

The off-resonance microwave discharge plasma obtained by means of 2.45 GHz magnetrons is a standard tool to produce multi-mA beams of protons, deuterons and monocharged ions, and it can be easily tuned, remaining stable for several weeks without maintenance and largely fulfilling the requirement of several industrial and scientific applications like:

- Accelerator Driven Systems (TRASCO)
- Production of Neutron beams
- Production of protons and deuterons for radioactive ion beam facilities, etc.

In the past years, in the framework of the TRASCO Project [1], the microwave discharge ion source called TRIPS (TRasco Intense Proton Source) has been designed and built at INFN-LNS. Its aim was to produce with high reliability a minimum proton current of 35 mA with a rms normalized emittance lower than 0.2π mm mrad for an operating voltage of 80 kV. All the required performances have been reached with a good reliability [2]. The proton source was moved on November 2005 to INFN-LNL, where it is now in operation as a high intensity proton injector. A more compact version with permanent

magnets called VIS (Versatile Ion Source) has been designed and built at INFN-LNS. The choice of using a permanent magnet system, adopted also for the source working at CEA [3] and at other laboratories [4], permits to provide ion beams with better stability and reliability in comparison with the solenoid coils system. The VIS goals are similar to the ones of the TRIPS source but the use of permanent magnets along with a simplified extraction geometry and extraction column may permit long term operations with high reliability. The first tests have carried out in 2008 and a few tens of mA of proton current have been produced. In 2009 the optimization of all the parameters has been performed, permitting to reach a maximum current of 45 mA at 60 kV, with a good reliability and stability.

The optimization of the reliability and of the beam emittance is often conflicting with the request of larger current, and a reasonable compromise has been found, that involves the mastering of microscopic parameters, as the electron density and temperature, by means of the optimization of the gas flow and of the microwave power.

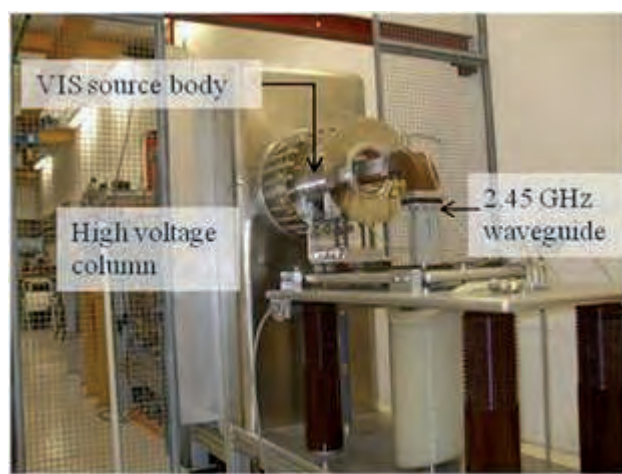


Figure 1 : A picture of the VIS source.

VIS DESCRIPTION

A picture of the VIS source is reported in figure 1. The source body 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. Due to the outer iron components the magnetic field quickly falls in the extraction region along the axis and off axis. This should minimize the stray field effects on the extracted beam as well as the Penning discharges observed in a first version of the source named PM-TRIPS [5]. The magnetic field is designed in such a way that the resonance for 2.45 GHz is obtained in two points along the plasma chamber axis. In such positions two BN disks have been placed in order to increase the plasma electron density.

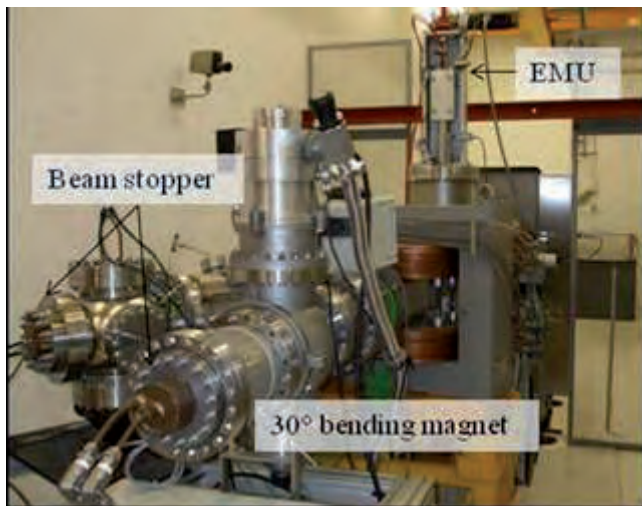


Figure 2 : A view of the VIS LEBT with the Emittance Measurement unit (EMU).

The microwave line is the result of an optimization study carried out with tools for high frequency structures simulators in order to reduce the microwave losses and to properly match to the plasma chamber. A 2.45 GHz 2 kW magnetron excites the TE_{10} dominant mode in the WR340 (86.4 mm x 43.2 mm) waveguide. An adequate matching impedance with the plasma chamber is obtained by means of an automatic tuning unit that minimizes the reflected power. A matching transformer (fig. 3) maximizes the electric field onto the axis. A dual arm directional coupler is used to measure the forward and the reflected power.

In TRIPS both the microwave line and the microwave generator are placed on the high voltage platform while in VIS the microwave generator is placed at ground potential. Then, in order to separate the high voltage region from the grounded one, a new waveguide DC-break has been designed and realized (fig. 4). It is made of aluminium sections of a WR340 waveguide insulated one each other by means of fiberglass disks. The conductive parts will be fixed to voltages gradually decreasing from 80 kV to ground voltage, still keeping

low the insertion loss, in the order of 1 dB at 2.45 GHz and slightly higher around this frequency.

The high pressure quartz window is placed before the WR284 water-cooled copper bend in order to avoid any damage due to the back-streaming plasma electrons. The performances optimization of the microwave line has been realized with HFSS [6].



Figure 3 : A photo of the matching transformer (left) coupled to the plasma chamber (right) and its inner view.



Figure 4 : A photo of the DC-break

The dimensions of the plasma chamber have been optimized for operations at 2.45 GHz, in order to have the optimum electron temperature and density at the center of the plasma chamber for a TE_{111} mode, for a resonance frequency of 2.4505148 GHz. The five electrodes extraction system used for TRIPS has been replaced with a four electrodes extractor which consists of a plasma electrode made of molybdenum at the maximum voltage (up to 75 kV), two water-cooled grounded electrodes and a 3.5 kV negatively biased screening electrode inserted between them to avoid secondary electrons due to residual gas ionisation backstreaming to the extraction area. The VIS extraction system has been optimised to operate around 40 mA and the flexibility available with a 5 electrodes system can be sacrificed without losing in terms of beam emittance.

The low energy beam transport line (LEBT) for the beam analysis consists of a focusing solenoid, a four-sector diaphragm to measure the beam misalignments, a Direct-Current Current Transformer (DCCT), a 30° bending magnet and an insulated beam stop to measure the beam current. Two turbo-molecular pumps are used to get

inside the plasma chamber along the LEBT a pressure lower than $1 \cdot 10^{-6}$ mbar, before the injection of gas and microwaves.

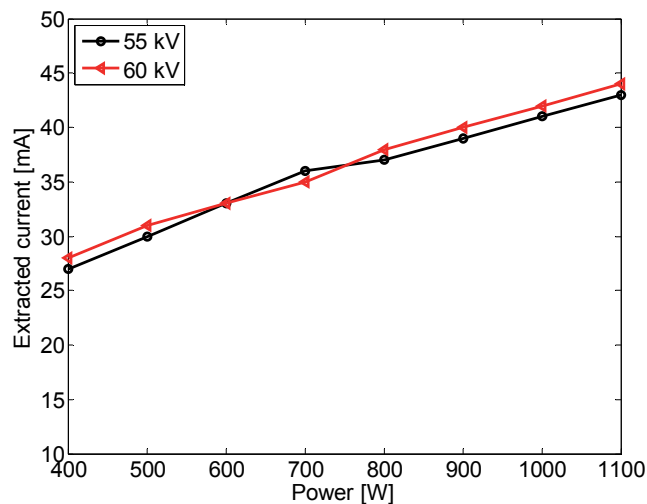


Figure 5 : Increase of the beam current with the microwave power.

VIS PERFORMANCES

VIS produced beam intensity higher than 35 mA in cw mode at 60 kV extracted voltage. To obtain such current through the 8 mm diameter aperture, power higher than 700 W were injected in the source. The H^+ fraction exceeded 80%, other species being H_2^+ .

Fig. 5 describes the increase of the beam current with the microwave power. A maximum power of 1 kW was considered for the source operation, but the plot clearly shows that larger power may be envisaged.

A complete characterization of the emittance have been carried out by means of an emittance measurement unit (EMU) provided by the CEA/Saclay SILHI group. This device allows the separate beam species analysis (H^+ , H_2^+ , etc) and the emittance measurements for the desired particle beam. It is made of three part:

- 1) the 0.2-mm-diameter tantalum sampler located in a water cooled copper block,
- 2) the permanent magnet Wien filter with adjustable electric field,
- 3) the wire for beamlet intensity measurements.

It is described in detail in ref [7]. The LEBT of the VIS source has been designed not taking in consideration the EMU, but only minor changes were needed to adapt the EMU. The emittance measurements have been carried out at different permanent magnet position, then for fixed permanent position the puller voltage, microwave power and pressure have been changed. For different experimental set-ups the beam current varies from 30 to 45 mA ($\Phi_{\text{extr}} = 8$ mm).

Fig. 6 shows the emittance measurements versus the microwave power for a permanent magnet position shifted by 8 mm from the initial position. The emittance increases with the microwave power because the beam current enhances. At 60 kV the beam emittance changes

from 0.12 to 0.17 π mm mrad. At 55 kV the beam emittance grows quickly up to 0.23 π mm mrad for power values greater than 900 W, probably because of the large outgassing of the plasma chamber. All the emittances here quoted are rms normalized one, and they have been obtained without the use of a gas flow in the LEBT, which can improve the emittance according to [8]. The high voltage has been changed from 55 to 65 kV, but then a discharge occurred and it was not possible to operate at larger power.

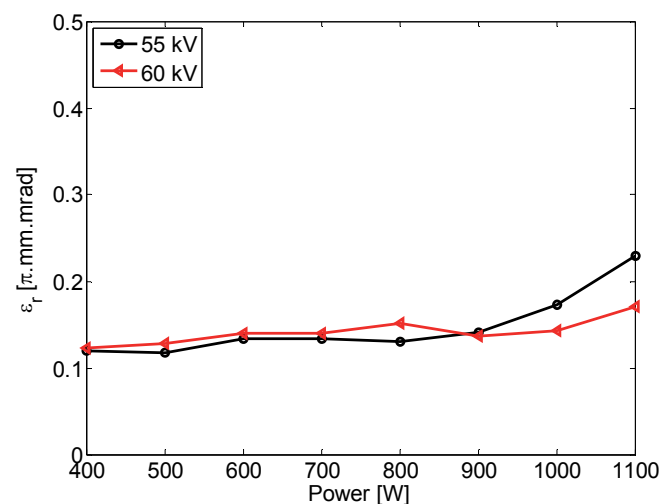


Figure 6 : Variation of beam emittance as a function of microwave power ($p_{\text{Source}} = 2.3 \cdot 10^{-5}$ mbar).

The emittance variation with respect to the permanent magnet position has been analyzed, because the ion beam intensity and ion beam emittance change as a function of the magnetic induction adjacent to the microwave window. The most important plasma parameters, like ion energies, plasma densities, electron temperature, depend substantially on magnetic field configuration. The microwaves are launched parallel to the magnetic field lines so that the ECR condition, $\omega = \omega_{ce} = eB/m$, is obtained for 2.45 GHz that is, $B_{ce} = 875$ G. Maybe the field intensity is slightly higher or lower than B_{ce} when the permanent magnet has been moved towards the microwave window. The highest divergence beam has been achieved when the permanent magnet was far 1.8 mm from the wall of the shield. Anyway in all the other configurations the emittance values have been lower than 0.2 π mm mrad, and changed only slightly with microwave power. Conversely, when we have shifted the permanent magnet towards the microwave window of six and eight mm the total extracted current decreased so if one wants to extract higher current values, it needs to apply a larger microwave power.

A typical emittance plot is shown in fig. 7, featuring minor filamentation due to the space charge effects in the first section of the LEBT. It is expected that the use of a gas flow in this section may minimize these effects with a positive influence on the emittances, while the beam transmission of the LEBT should be minimally affected.

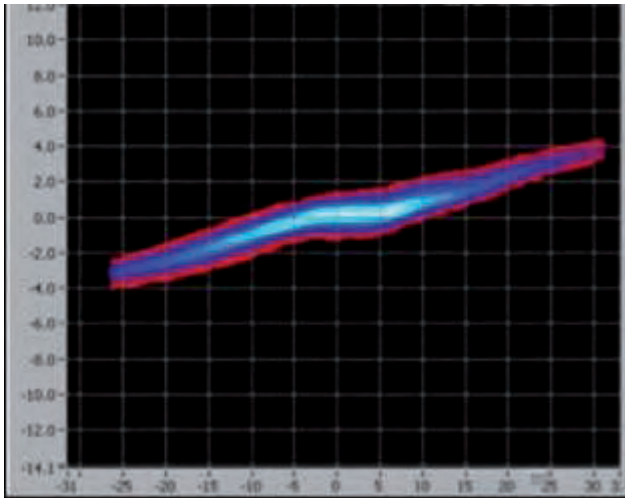


Figure 7 : A typical plot of proton beam emittance ($p=2.3 \cdot 10^{-5}$ mbar, $I_{\text{extr}}=40$ mA, $P_{\text{fiv}}=700$ W, $V=60$ kV).

The rms normalized emittance is lower than 0.2π mm mrad; these emittance values are higher than the ones measured with the TRIPS source [8] because we didn't inject a buffer gas (H_2 , N_2 , Ar or Kr) in the LEBT. The emittance growth is justified because of the lower space charge compensation.

As for the species fractions, they are plotted against the microwave power in fig. 8, featuring a proton fraction, like the beam current, which increased continuously with the microwave power from 76% to 89 % (at very large microwave power).

PERSPECTIVES OF THE VIS SOURCE

The excellent stability and reliability of the VIS source will permit to perform in 2010 a number of tests related to the possibility to increase the plasma density and finally the beam current. In particular the use of carbon nanotubes that has been successfully tested with the CAESAR source in 2009 will be adapted to the use with the VIS source, either in presence of an alumina tube inside the plasma chamber and without.

Additionally new heating schemes based on the results obtained by the HELIOS experiments will be tested, in cw mode and in pulsed mode.

This particular mode of operations will become more and

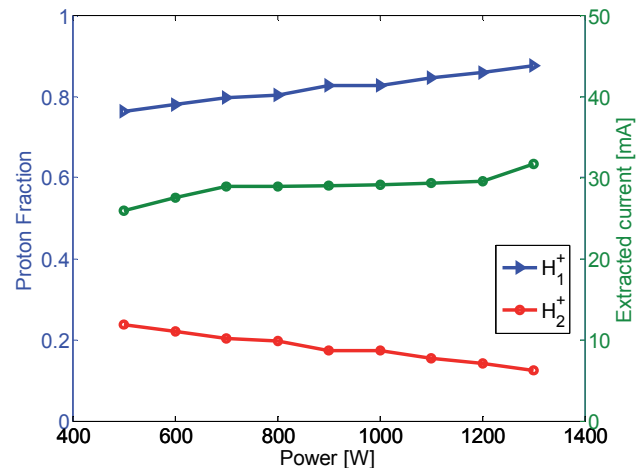


Figure 8 : Species fractions and extracted beam current vs microwave power for $P_{\text{Source}}=1.5 \cdot 10^{-5}$ mbar.

more important in the future, because of the interest of the ESS project in using VIS as a testbench along with the SILHI source at CEA, Saclay.

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PRELIMINAR STUDIES FOR THE REALISATION OF A THOMSON SPECTROMETER FOR LASER ACCELERATED CHARGED PARTICLES

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Abstract

A research project, LILIA (Laser Induced Light Ion Acceleration), has been funded at INFN (Italian Institute for Nuclear Physics) with the aim to study the mechanisms of charged particles acceleration by high power lasers. In Italy, at LNF – INFN of Frascati, a high power laser (intensity in the range 10^{20} - 10^{21} W/cm², 10 Hz repetition rate and high contrast, of the order of 10^{10} , between main pulse and pre-pulse) named FLAME will be operative within 2010. The activities related to this project, along with the FLAME peculiarities, would result in a significant synergy to improve the research on plasma ion acceleration in Italy.

In this frame our group is involved in the design and construction of a spectrometer based on the Thomson's configuration in order to diagnostic the ion ejection from the laser-generated plasma. This kind of analyzer allows to get most of information about energy, species and charge state of beams produced from a single laser shot.

The main goal is to realize a compact system which is both very practical and optimized as respect to the mass and energy resolution of particles obtained by laser-plasma interactions. The preliminary design has to be able to analyze and resolve beams of protons and ions up the total energy of 10 MeV. However, the technical choices adopted in this prototype have to be applied for the final device concerning a challenging spectrograph able to analyze beams of 150 MeV of total energy. An intensive study by means of 3D electromagnetic FEM code and beam dynamics were accomplished out and the results will be shown. The first prototype of the spectrometer is being realized and tested at LNS-INFN of Catania. After the magnetic and electric measurements the device will be calibrated as well as the detectors will be tested with proton and carbon beams delivered by the accelerators operating at LNS-INFN of Catania (Italy) within the expected energy range (5 -10 MeV) and for different charge to mass ratios ($Q=+1$ to $+6$).

INTRODUCTION

A Laser based proton acceleration systems is a promising new technology of accelerating charged particles to

energies that might become high enough for therapeutic use in radiation therapy [1] [2] [3]. Nowadays large and expensive cyclotrons or synchrotrons are used for this task. The mechanism of laser acceleration might potentially reduce the overall costs of proton therapy in cancer treatment with ionizing radiation. The long-term goal of current research is to build a laser based treatment machine that is not much bigger than a conventional photon linac. This would enable the widespread use of the superior properties of protons compared to the conventional x-rays radiation. However, much research needs to be done until a commercial laser accelerated treatment device can be build. Currently, the crucial problem is that the achievable energies are not yet high enough for the treatment of patients, but there is hope that it can be achieved soon. Another problem is the energy spectrum of the proton beam. Conventional acceleration machines produce a sharp energy with only little spread therein which gives rise to the sharp Bragg peak in the depth dose curve. Laser accelerated protons, instead, are currently not monoenergetic, showing a Boltzmann-like distribution [4].

Also the proton current should be improved because actually the maximum proton energy is reached with a stream of the order of 10^9 particles/laser-shot and an increment of about two-three order magnitude should be obtained.

Much work is in progress to produce sharper energy spectra but it is highly probable that they will never be as sharp as for conventional accelerators. The precise energy spectrum of the final beam is not known yet, but most of the experiments show exponentially decaying spectra over a wide energy range. We hope that this will change in the future and the possibility to have proton beams with a good level of monochromaticity (mandatory characteristic for clinical proton beam) will be reached.

Inside our group we are mainly working in two different directions. Exploiting the experience we achieved in the detection of the charged particle produced by the laser interaction [5] [6], we are designing and developing a Thomson spectrometer able to detect low energy charged particle produced by the laser interaction with the matter in the ambit of INFN-PLIADI and INFN-LILIA projects [7]. On the other side, making use of the power of the



Monte Carlo technique we are designing an electromagnetic selection device for the optimization of the produced proton beams (in terms of energy spread and divergency) and to study their main dosimetric characteristics. Monte Carlo simulation will also help us in the final characterization of the Thomson spectrometer.

LASER DRIVEN PROTONS FOR RADIOTHERAPY: ADVANTAGES AND MAIN DRAWBACKS

Today, the vast majority of cancer patients in radiotherapy are treated with conventional therapeutic beams consisting of high-energy electrons and photons. Although therapeutic proton beams were primarily suggested more than 60 years ago [8] and feature an intrinsically advantageous in terms of depth dose curves characteristic, even modern clinical proton facilities still require large accelerator rings and huge electromagnetic beam steering devices. Due to these circumstances, nowadays, therapeutic proton beams could not represent a serious competition to the conventional, much more practical and less expensive solutions. In the last years, laser-driven proton accelerators were proposed for therapeutic applications, as they can potentially provide handy proton sources of reasonable size and reduced costs.

For this purpose, ultrashort (i.e. femtosecond scale) laser pulses with peak intensities of the order of 10^{19} Wcm^{-2} are focused on thin hydrogenated solid foils. When incident power lasers hit the target, the strong EM laser field instantaneously ionizes atoms and creates high density plasma. The laser energy is then efficiently absorbed by heating some of the plasma electrons to relativistic energies. Subsequently, a cloud of hot electrons spreads into the target, overshoots at its edges and forms space-charge regions close to its front and back surfaces. (Note that in this work target-front as well as target-back is always defined relative to the side of laser incidence.) A variety of ions, primarily protons from hydrogenated polymers or from contaminant layers on the target surface [9] [10], are accelerated by the built-up quasi-static electric fields perpendicular to the surface of the foil in the so-called target normal sheath acceleration (TNSA). The most efficient TNSA takes place at the unperturbed rear side of the foil, where the fastest protons can be observed [10]. Peak proton energies around $E_{\text{max}} = 60 \text{ MeV}$ have been achieved so far with laser pulse intensities of the order of 10^{20} Wcm^{-2} [12].

The energy distributions follow only approximately the Boltzmann shape. The laser pulse, in fact, produces ions and the emitted yield is limited by the film thickness and laser spot. The emitted ions contain protons but also a large component of other ions, depending on the target composition. Such ions have high charge state and strong anisotropic distribution. Thus the extractable proton beam should be selected magnetically from such high ions

background. Moreover, the proton number is not high, especially if only the high energy component is considered. Thus, repetitive laser pulses on fresh thin film should be used in order to obtain a sufficient average proton current. In any case, the proton energy is not yet sufficient for therapeutic considerations and it is at the limit also for shallow tumors like eye-melanoma. However, according to particle-in-cell (PIC) simulations [13] as well as semi-analytical scaling laws [14] it seems that the new generation of petawatt laser will be able to generate protons with energies suitable for therapeutic applications ($E \leq 250 \text{ MeV}$). On the other hand, a set of drawbacks must be at moment considered in such kind of beams. The first one is related to the energy distribution of emitted particles. Different approaches, at different levels (optimization of the target, realization of magnetic devices) have been proposed to exceed this issue but a final solution has not been yet reached. Another drawback is related to the final intensities of the emitted particles that must be sufficient high to guarantee a treatment in a reasonable time interval.

DESIGN OF THE THOMSON SPECTROMETER

A group of researcher at INFN-LNS is actually involved with the design and construction of an innovative spectrometer based on the Thomson's configuration in order to diagnose the ion ejection from the laser-generated plasma, with a maximum energy of 10 AMeV . This kind of analyzer allows to get most of information about energy and species of beams produced from a single laser shot. The particles are deflected by the magnetic and electric fields, both directed perpendicularly to the trajectory of the incident beams. Therefore, while the electric field deflects the charged particle depending on the energy, the magnetic one bends these as a function of the momentum. Neglecting any fringe field effects, the amount of the deflection is given by:

$$\theta_{\text{electric}} \sim qElmv^2$$

$$\theta_{\text{magnetic}} \sim qBlmv$$

where B and E are the electric and magnetic fields, l is the length of those fields and m, q and v the particle mass, charge and velocity, respectively. If D is the distance between the electromagnetic deflector and the plane where deflected particle will be detected, (such as $D \sim l$) and supposing that the magnetic field deflects on x axis and the electric one on the y, combining the previous relations one gets the parabolas equation:

$$y = mEq l D B^2 x^2$$

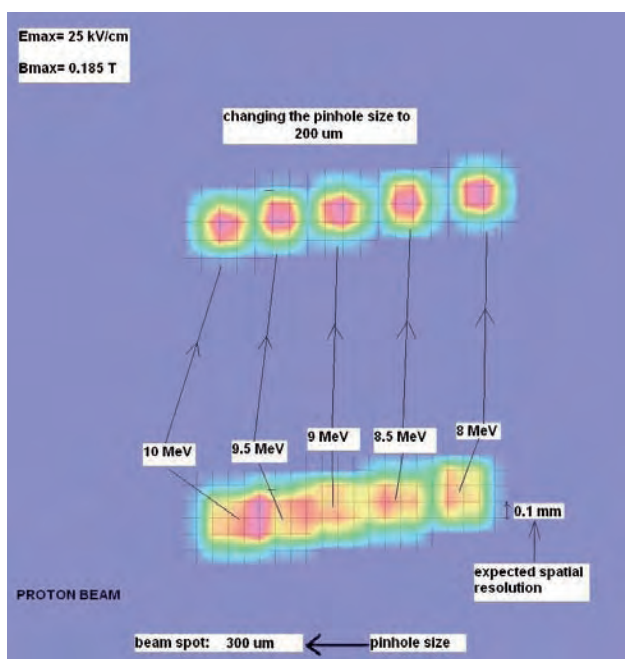


Figure 4: Simulations of different proton beam delivered through the spectrometer and intercepted on the detector plane. The beam spots at different energies are shown for two values of the pinhole size of the collimator placed upstream the magnet. The increasing of the resolving power of the spectrometer in terms of energy, is evident (upper section of the figure) decreasing the collimator aperture to 200 μm .

The electromagnetic system has been simulated by OPERA 3D and to identify the ion species with a certain charge-to-mass ratio forming a single parabola, a 3-D tracking routine for different ions and energies has been done as shown in Figures 4.

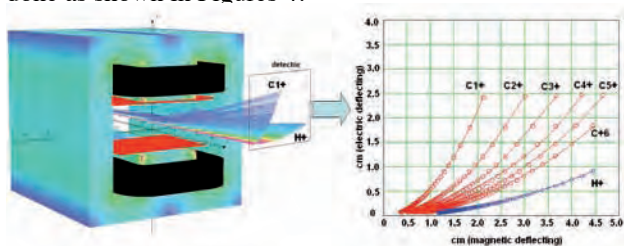


Figure 5: The simulated trajectories of proton and Carbon ion ($Q=1+$) ranging from few keV to 10 MeV, are shown in the left side. Plot of the expected traces of different Carbon ions on the detector is also shown.

The choice of the focal plane detector permitting the particles spatial localization, is a crucial issue in the design and construction of a Thomson-like spectrometer. It must be able to detect particles traversing the magnetic and electric region with a good efficiency and a sufficient spatial resolution. The efficiency is important to permit the detection of also few number of particles coming from the generated plasma. On the other hand, spatial resolution is necessary to achieve the best possible localization of the incoming ions. In fact, more precise is

in fact, the information on the particle position, more accurate results the energy resolution power of the device. This is particularly true for the highly energetic particles that are concentrated in the central region of the detector and for which spatial localization could also result not possible.

We are planning to test and use different detectors for the particle detection.

Our first choice has been directed towards the use of the GafChromic films that have been extensively used by some of the authors of this paper, for the detection of charged particle beams. The GafChromic shows many advantages in the detection of laser-generated particles: they are not sensible to the visible light (that is an important noise component in a laser-target interaction chamber), they present a good spatial resolution (of the order of 100 μm) and do not need any special development technique. On the opposite side, their use is complicated by the fact that they are off-line detectors (so it is necessary to reopen the chamber after each irradiation) and by their sensibility to the incoming particles.

GafChromic radiochromic dosimetry films are self-developing film media that have been developed for the measurement of absorbed dose and the mapping of radiation fields. They are largely exploited in the medical physics field for external radiotherapy and brachytherapy but, thanks to their interesting features, they are widely spread used also in different research fields. They consist of radiochromic microcrystalline dispersions on a thin polyester base. Its radiographic sensitivity is based on the solid-state photopolymerization of diacetylene monomer molecules. The colorless non irradiated radiochromic film responds to ionizing radiations such that its color becomes darker as the total absorbed dose increases. These media can be handled in normal room light, thereby eliminating the cost of darkroom space and of post-exposure processing. Moreover, they are light and flexible and may be cut to any shape or size desired. Individual GafChromic radiochromic dosimetry film types are available on the market and each of them is optimized for high or low energy photons as well as particle radiation. The degree of darkening is, therefore, proportional to exposure and it can be quantitatively measured with any densitometer, scanner or spectrophotometer. The net optical density is obtained after calibration procedures and by subtracting the background. GafChromic films are largely used for radiation field measurements thanks to their good spatial resolution ($< 100 \mu\text{m}$), which depends also on the system of reading used.

A characterization of different kinds of GafChromic films for the laser generated charged particle diagnostic is actually in progress in our group and results will be reported in a future paper. We are also verifying the possibility to use silicon micropixel detector to improve the spatial resolution of the Thomson spectrometer focal plane. A separate investigation is in fact, in progress, to

The particles with the same charge-to-mass ratio and different energies are deflected on a parabolic trace in the detector plane, while particles with different charge-to-mass ratio get different parabolas. The main goal is to realize a compact system which is both very practical and optimized with regard to the mass and energy resolution of particles obtained by laser-plasma interactions. The preliminary design has to be able to analyze and resolve beams of protons and ions up the total energy of 10 MeV. However, the technical solution adopted in this prototype will be applied for the final device concerning a challenging spectrograph able to analyze beams of 150 MeV of total energy.

The magnetic and electric fields range from few hundreds to about two thousand of gauss, and few hundreds of volts up to 30 kV in order to cover a wide range of possible setups of the laser-target facility. The conductors are not water cooled since they operate for few minutes at the maximum current density of 4 A/mm². To meet the compactness requirement, the magnet is 15 cm long and it is H shaped in order to provide the magnetic field as uniform as possible along the beam trajectory. The vacuum chamber is separated by the magnet system, to overcome the troubles which could occur to meet the high vacuum requirements needed for the high voltage electrodes. These are copper plates, operating at ± 25 kV placed 2 cm apart on a length of 5 cm, and placed inside the magnet gap (see Figure 2). We chose to increase the electric field value and reduce electrodes dimensions in order to deflect also particles of lower energy that mainly impact on the electrodes, degrading their performances. In order to reduce at minimum the spectrometer dimensions, we adopted the solution to locate the magnetic field in the same region of the electric one. In this configuration, the particles to analyze experience the magnetic and electrical forces at the same time and position. The main vacuum chamber can be directly connected with a separated and independent chamber where detectors can be located.

Figure 1 shows the final technical draw of the spectrometer. The left part contains the external magnetic field (gray colored) and the internal slim vacuum chamber with the electric one. The spectrometer focal plane is located 20 cm after the end of the magnetic field, inside an independent cross-shaped vacuum chamber (right side). The total length of the spectrometer is about 66 cm.

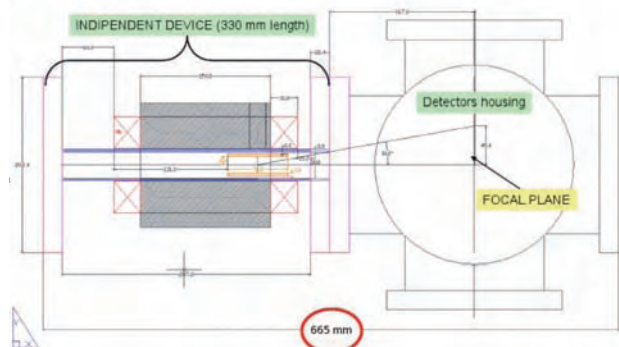


Figure1: final technical draw of spectrometer

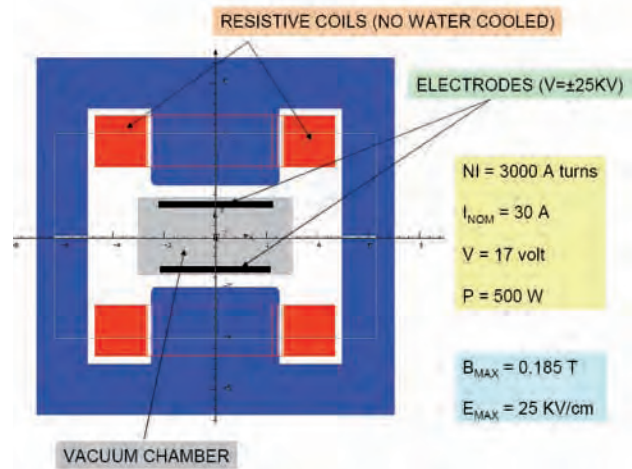


Figure 2: front view of the H magnet and positioning of the HV electrodes into the vacuum chamber. Dimensions of the reference system are in cm.

In Figure 2 a cross section of the spectrometer with its main operational characteristics, is reported. The resistive coils are represented in red while the iron in blue. The vacuum internal chamber with the electrodes is the central gray zone. Figure 3, on the other hand, shows the 3D design of the whole spectrometer.

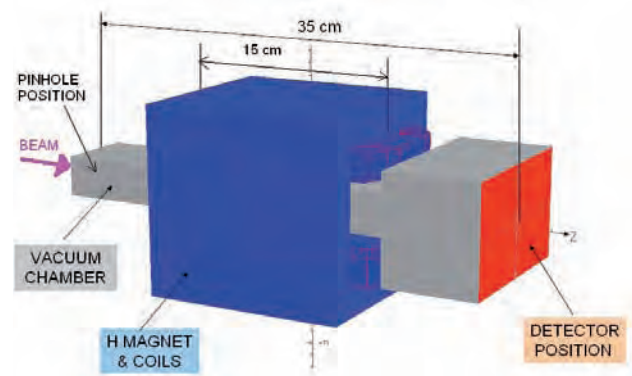


Figure 3: 3D vision of the whole spectrometer.

Studies have been done concerning the pinholes size and their effects on the performances of the spectrometer. The collimator, indeed, is placed upstream the electromagnet (35 cm from the focal plane) and it gives the angular acceptance ($\sim 10^{-4}$ msr) of the system affecting the effective spatial resolution we will measure on the detector. In order to get a good energy separation (0.5 MeV at 10 MeV) on the detector with a spatial resolution of 100 μm , it needed to set the pinhole size to 200 μm . The main difference about the energy resolution calculated by using a pinhole of 300 μm is shown in Figure 3.

verify the possibility to use a Timepix detector, at least in the central region of the focus plane, where the biggest spatial resolution is requested. The Timepix, that can reach a maximum spatial resolution of the order of 5 μm , can be used in counting mode and in Time-Over-Threshold mode. This could permit a simultaneous measure of the particles position and their detection time from which an independent energy measurement can be extracted.

The spectrometer will be calibrated as well as the detectors will be tested with proton and Carbon beams delivered by the accelerators operating at LNS-INFN of Catania (Italy) within the expected energy range (0.1-10 MeV) and for different charge to mass ratios ($Q=+1$ to $+6$).

CONCLUSIONS

Fs-terawatt lasers can be employed to irradiate hydrogenated thin target and to produce high energetic ions potentially useful for radiotherapy. Protons up to 50 MeV and Carbon ions with energy above 100 MeV have been obtained by other research groups, irradiating polyethylene thin films. At the present the ion streams are complex, because contains

protons, carbon and other species from the target composition at different charge states. Moreover the energy spectra are approximately Boltzmann shaped and the yields of some species, limited by the film thickness and laser spot, generally are below 10^{16} ions pulse⁻¹. Thus the use of proton and carbon beams extractable from the laser generated plasma need to be studied in terms of mass/charge selection by a suitable magnetic field, in terms of ion energy filtering, in order to provide a near monoenergetic ion beam, and finally in terms of repetitive laser pulses interacting with fresh thin target, in order to generate an ion beam with a near constant output current. Actually these three aspects are under investigations and, only after their improvement, the possibility to realize a radiotherapy using laser accelerated ion beam will be really possible. The Thomson parabola spectrometer represents only one of the different diagnostic techniques useful to investigate about the kind of ions, charge state and energy distributions obtainable from laser-generated plasma, permitting to reach the research goal more fastly.

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SLOW CHOPPER PROTOTYPE FOR THE SPIRAL 2PP PROJECT

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Abstract

A preliminary prototype of the slow chopper [1] for the Spiral 2 Preparatory Phase project [2] has been designed, developed and tested at INFN-LNS. The final version of the slow chopper will be placed along the beam line common to protons, deuterons and $A/Q = 3$ ions. This activity report shows the study, the hardware and the measurement results of the chopper prototype.

THE LOW ENERGY LINE

The low energy (LEBT) line of the Spiral 2 driver is designed to transport CW and high intensity beams of protons (5 mA), deuterons (5 mA) and ions (1 mA) with $A/Q = 3$ to the radiofrequency quadrupole (RFQ). The RFQ input energy is 20 keV/A and source voltages of 20, 40 and 60 kV are used for the 3 kind of particles. As shown in Figure 1, the chopper is located at the beginning of the common section just before the beam stop.

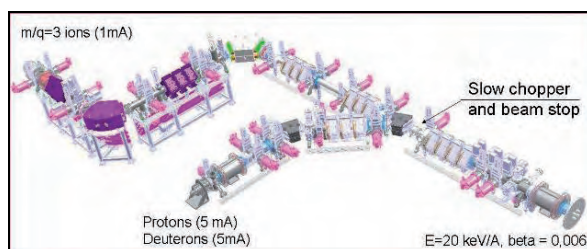


Figure 1: The injector low energy lines and the slow chopper position.

The chopper will be used to progressively increase the beam power during accelerator tuning, to rapidly remove the beam in case of failure detection, to avoid hitting the wheel spokes of rotating targets similar to the one shown in Figure 2 (FULIS or S3 experiences).

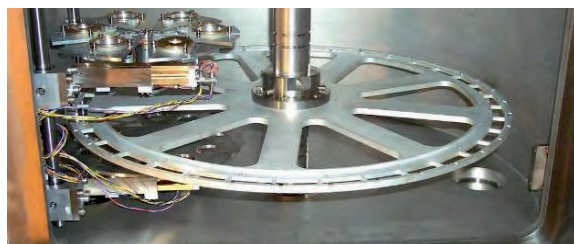


Figure 2: FULIS rotating target wheel (courtesy of C. Stodel)

CHOPPER REQUIREMENTS

The accelerator tuning is performed at quite low frequency. Due to the high beam power of 200 kW, a very large range of duty cycles will be used, starting

from very low fractions (10^{-4}). The rotating target asks for pulse repetition rates around 1 kHz. In both cases rapid transition times are required to avoid fractions of beam, neither accelerated nor deviated, to be lost through the LINAC.

The chopper voltage depends on the ion source voltage, on the distance and length of the plates and on the beam stop location. Due to the LEBT line architecture and to the current intensity, the beam transversal section at the chopper location is quite large and relevant voltages have to be applied to the electrodes to compensate their distance.

In our case, the beam section has a diameter of 76 mm, the electrode hard-edge length considered in the beam dynamics simulations is of 160 mm, the deflection at the end of the plates is of 10 mm, and a *total deviating voltage of 17 kV* has therefore to be applied. Transient times for the pulse have to be shorter than 100 ns, and an amplitude stability of a few percents is required.

High reliability and easy maintenance are also important requirements of the device.

ELECTRODE GEOMETRY

The preliminary geometry shown in Figure 3 was designed to have a flat transversal field and to produce field maps for beam dynamic simulations. It was chosen to feed the chopper with one plate positively biased and one grounded, because this solution let a easier water cooling of the ground electrode if some beam is eventually lost. The deflection plane is horizontal because the beam section is smaller on this plane than on the vertical one. In Figure 4 the simulation for the electric field is shown. To obtain the deviating field, a pulse of 9.2 kV has to be applied to the electrode, whose capacitance is around 15 pF. The pulse duty cycle defines the attenuation on the beam.

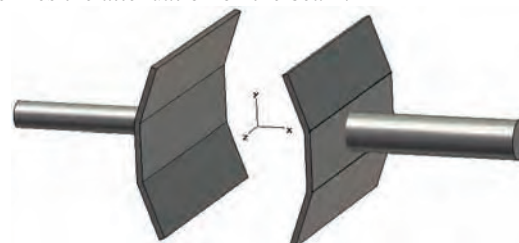


Figure 3: The electrode geometry; the plate bending angle is 20° .

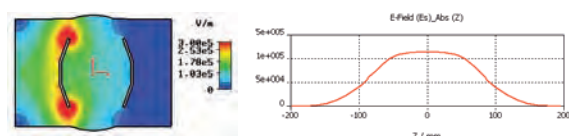


Figure 4: Electric field on the transversal plane and on the beam axis.

SLOW CHOPPER DEVELOPMENT

The development of the Spiral 2 device regards a two years period. In this first year, the power circuit, the feed-through and the assembling concept have been studied and tested on a prototype.

The design approach was strongly addressed towards reliability and decreasing of the maintenance time, both being very important issues in high power accelerators.

Electrical design

The principle scheme of the chopper is represented in Figure 5.

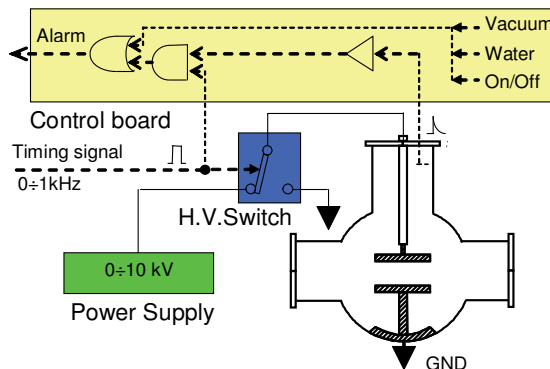


Figure 5: Principle scheme of the chopper.

A high voltage switch, alternatively connects the electrode to ground or to the high voltage power supply, following the timing signal repetition rate and the duty cycle. A high voltage sealed connector is used as feed-through. Numerical values, considered for the design, are summarized in Table 1.

Table 1: Design Parameters for the Chopper Power Circuit

Maximum voltage:	10 kV
Rise/fall time under	100 ns
Duty cycle variable from	0 to 100%
Repetition frequency	from few hertz to 1 kHz

To fit the requirements, 10 Watt, off-the-shelf devices have been selected. A standard pulse/function generator AFG310 by Tektronix is used to drive the switch, while the main components of the system are:

- Power supply MPS10P10/24 by Spellman
- Solid state switch HTS151-03-GSM by Behlke
- Vacuum feed-through SHV-20 by Caburn
- Coaxial cable HTC-50-7-2 by Draka

Figure 6 shows the scheme of the electronic cabinet. The high voltage switch, the power supply and the 1 nF buffer capacitance are visible in the rack. The solid state switch consists of two identical mosfet switching paths that form a so-called half bridge circuit configuration. Both switching paths are controlled by a common logic driver. The power supply can deliver up to 10 kV, 1 mA. The switch and the electrode are connected by a low loss coaxial cable. Great care was taken to assemble these

modules into the rack. Special attention was given for grounding and shielding all the components.

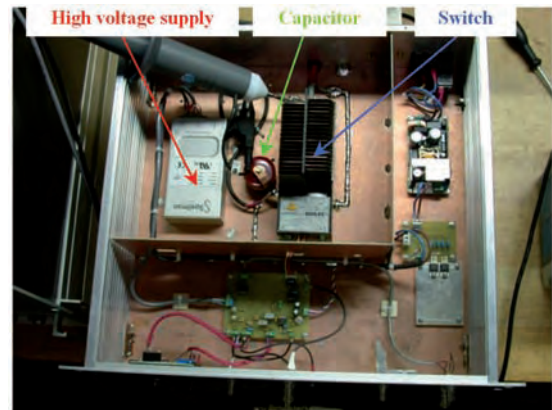


Figure 6: Scheme of the electronic cabinet.

Mechanical design

The mechanical assembling of Figure 7 was designed to test the feed-through in operating conditions and to verify the assembling concept and the plate alignment.

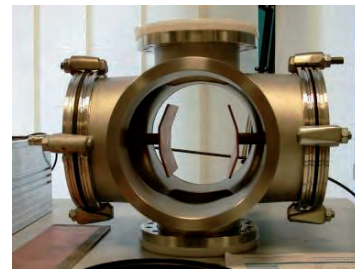


Figure 7: Cross-section of the assembled electrodes.

A standard beam line cross section with six gates was used to host the electrodes. Each electrode is constituted of a plate of 3 mm thick copper sheet supported by a copper column. They are inserted from opposite sides and each one is supported by its vacuum flange. The ground electrode is connected directly to the flange while the high voltage plate is brazed to the feed-through connector. The ceramic feed-through is a standard 20 kV single ended coaxial SHV connector. A capacitive pick-up is inserted near the feed-through to be used to check the pulse presence, but the alarm board still has to be developed.

Feed-through study

A delicate point in the chopper realization is the proper high voltage feed-through. Different solutions were taken into account. A suitable numerical study was performed on this purpose. The MDC-Caburn SHVE20-1-W weldable feedthrough was therefore employed. In Figure 8 it is shown a section of it, with the indication of the two parameters d and r . The related electrostatic simulation, for a 10 kV feed, is shown in Figure 9. In the A point the voltage assumes its maximum. In Figure 10 the values of this maximum, for different values of d and r , are given.

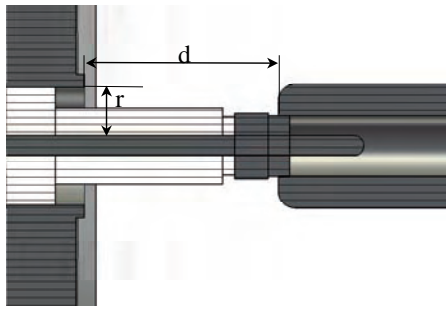


Figure 8: Section of the MDC-Caburn SHVE20-1-W feed-through.

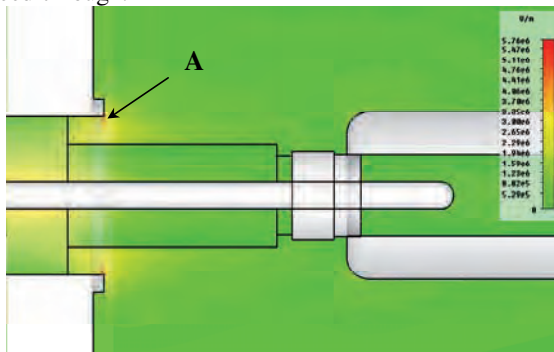


Figure 9: Electrostatic field on the section of the MDC-Caburn SHVE20-1-W feed-through.

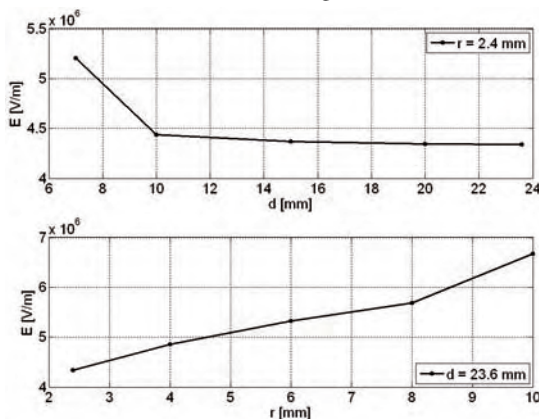


Figure 10: Field in the A point for the structure of Figure 8, for different values of the d and r parameters.

EXPERIMENTAL RESULTS

A total capacitance of about 30 pF was measured at the feed-through connector input. The cable adds some 70 pF and the data sheet gives a value of 30 pF for the switch output capacitance. With a total capacitance lower than 150 pF, the system should be able to work up to a repetition rate of 1 kHz. Anyway, the measured and stable operating range (Figure 11) was smaller, and was limited by the current of the high voltage power supply.

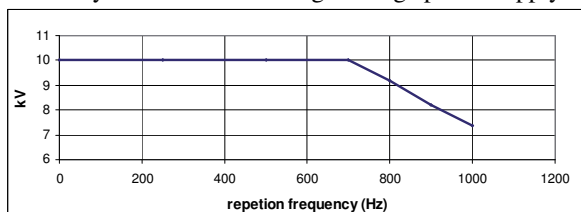


Figure 11: Measured and stable prototype operating range.

Some preliminary tests with a Spellman MPS10P20/24, 20 W power supply, were therefore performed, and the required 1 kHz repetition rate was reached. More tests about it have to be performed. Measurements of the transient times confirmed the data sheet performances: rise and fall times are around 30 ns (see Figure 12).



Figure 12: Measured rise and fall times.

Long time tests on the complete apparatus have been performed up to 10 kV, at the 50 Hz frequency, and with Duty Cycle in the range [0.01%, 99.99%] to check the circuit reliability and the stability of the pulse parameters. The amplitude stability is better than 1%, and no changes were observed in the delay between the driver and high voltage edges, which is of 160 ns as shown in Figure 13, for the 10 kV pulse at 700 Hz, and with 50% duty cycle.

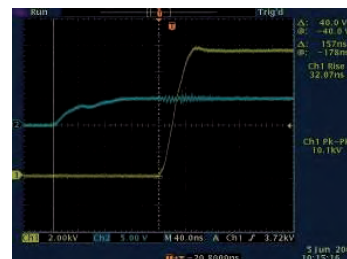


Figure 13: Pulse jitter @700 Hz, DC = 50%, 10 kV, between the driver and the measured voltage at the switch output.

CONCLUSION AND PERSPECTIVES

The pulse amplitude, jitter and transition time measured on the prototype fulfil the requirements, while a more powerful high voltage supply has been required to achieve a 1 kHz repetition rate. A complete system (electronics and electrodes) is available today for beam tests and next efforts will be dedicated to the design of the alarm control card and of the computer control interface and to the manufacture of the final mechanical ensemble to be installed on the Spiral2 injector.

ACKNOWLEDGEMENTS

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STEPS FORWARD IN THE RF CONTROL SYSTEM

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Abstract

The RF control system at Infn-Lns is being upgraded. The system maintains the same philosophy of the first 1988 version: a combination of analog and digital techniques. The analog systems still maintain the control of the amplitudes, phases and fine tunings of the RF voltages, while for the generators, interlocks, turn-on, protections and the remaining subsystems, the approach is mostly digital. A new computer-based control of the RF system is going to be fully developed. The first devices are already installed in parallel mode with the old RF computer control. At the moment, two parallel computer controls are working together. Both systems are complementary. This report shows the new computer architecture, including the new digital subsystems, developed and adopted for this new RF control system.

INTRODUCTION

The aim of RF control system is setting, checking and tuning all the wideband RF apparatus of Figure 1.

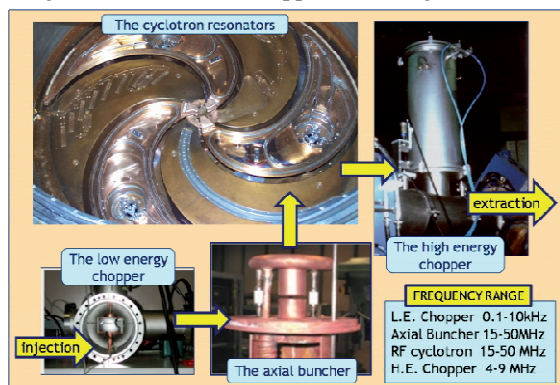


Figure 1: The RF devices along the beam line.

The arrows indicate the particles beam through the RF apparatus, from the injection to the extraction line. Table 1 summarizes the RF systems and the main technical characteristics in terms of voltage and bandwidth.

Table 1: main parameters of the RF systems

RF systems	bandwidth	Max voltage
L.E. Chopper	0.1-10 kHz	1 kV
Axial Buncher	15-50 MHz	1.5 kV
RF cyclotron	15- 50 MHz	100 kV
H.E. Chopper	4 - 9 MHz	14 kV

NEW RF CONTROL SYSTEM

The new PC-based control system is the evolution of the old one, developed more than 20 years ago [1]. This new RF control, together with the old one, manages the radiofrequency of the superconducting cyclotron, the low and high energy chopper and the axial buncher [2-3]. The general architecture block diagram of the new PC-based control system is shown in Figure 2.

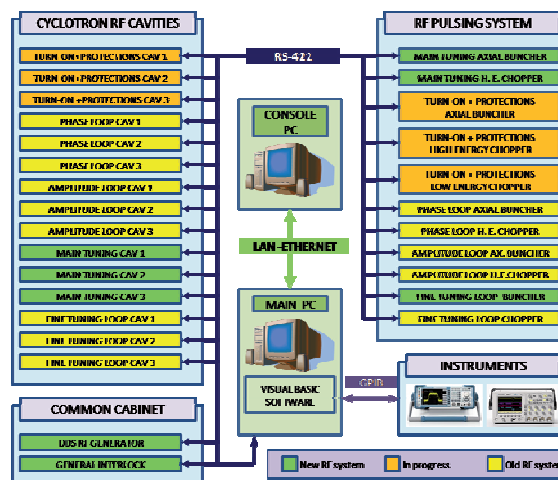


Figure 2: RF control system block diagram.

The main components are a communication bus, a couple of PC-units and the functional blocks. The RS-422 master-slave multi-drop bus allows the communication between the functional blocks and the main PC-unit. The distance, up to a hundred meters, between the PC-unit and the blocks, the full duplex characteristic and the fact it is easy to use, are the main reasons for choosing this RS-422 bus. The blocks are mostly divided into two frames, the cyclotron and pulsing system. From the hardware point of view, the cyclotron blocks are divided into three different electronic cabinets, one for each single cavity. The cyclotron control cabinets are very close to the main PC-unit while, for the pulsing system, some of the blocks are close to the related devices, along the beam line, many meters away from the same PC-unit. A couple of further blocks, only the RF generators and the general interlock at the moment, are placed in another standard cabinet.

Each specific block is a standard 19" electronic rack with a Programmable Interface Controller (PIC) on board. As regards the complexity of the specific device to be controlled, different PIC are used, including the dsPIC family; all these PIC devices are made by Microchip. If the PIC is the constant part inside each block, other components differ according to the block function. The block functions are: turn-on and protections, main tuning, fine tuning, amplitude loop, phase loop, and amplifier.

The main program, an in-house software written in Visual Basic® programming language, allows users to fully operate the blocks via a menu-driven control panel in a Windows® environment displayed on the PC-unit monitor. The same program has been diversified and developed for each single family block. Once the specific program has been uploaded on the single block, the process is worked out directly by the μ controller itself. If the PC inexplicably stops working, the system will continue to function because the PIC is used. The block can be remote controlled by the PC control panel or through a front key pad panel, placed on the rack, to operate in local mode.

The colour captions in Figure 2 show the blocks already under the new control system, the blocks under test and the blocks still under the old system. A further personal computer, connected by a LAN Ethernet, is installed in the accelerators main console like a remote PC-unit, which works in parallel mode with the main PC of the RF console. This is very useful in accelerator tuning and during the normal running of the beam. The main PC-unit parallel bus GP-IB (IEEE488) reads the RF measuring instruments.

Two separate PC-based systems, core of the old and new RF control systems, are working together at the moment. Both computers are complementary in setting, checking and controlling the RF system. The separate communication network prevents any interference or conflict. A brief description of the blocks follows.

DDS Synthesizer as RF Generator

The RF generator is a high frequency source based on the Direct Digital Synthesis technique (DDS) [4].

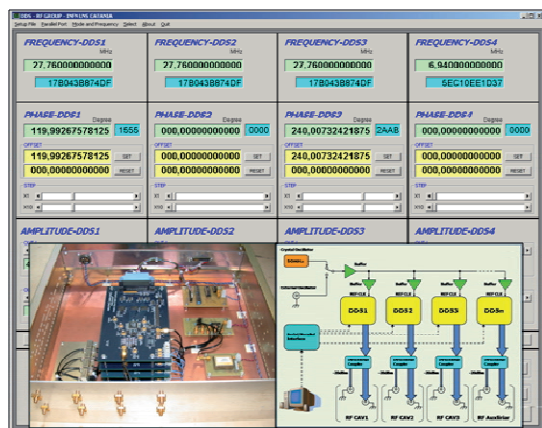


Figure 3: Control panel, rack and block diagram.

The DDS technique has been adopted to generate all the sine waves: three for the RF cavities, plus other auxiliary channels available for the axial buncher or other pulsing systems. Figure 3 shows the PC control panel, the block diagram and the electronic rack of the DDS synthesizer as RF generator. The initial amplitude and phase are set by the new PC-based control system without any phase shifters or linear attenuators. The main PC-unit is connected to the DDS devices, through the RS-422 bus. The PIC18F2585 is used in this block, while the DDS boards are based on the electronic component AD9854 by Analog Devices. The system provides a 48 bit frequency resolution together with a high stable frequency system clock of 300 MHz giving a resolution of 1 μ Hz, 0.02° in phase, 43 μ V in amplitude with a maximum frequency output of up to 120 MHz.

General Interlock

The status of the RF system in terms of vacuum level in the acceleration chamber, cooling system, environment temperatures, radiation safety, etc, is controlled by the general interlock block. The core of the system is the PIC18F4580. All the input parameters are processed and displayed on the PC control panel and on the local LCD display at the same time. Any failure from the input parameters disables the DDS RF generator, through a hardware connection, immediately. A master switch placed on the front panel of the cabinet enables or disables the RF signals. The in-house software allows users to fully operate the general interlock via a menu control panel on the PC-unit. The vacuum threshold setting and the status of the input parameters are continuously displayed. The PC-unit control panel and block diagram of the new control interlock system is shown in Figure 4.

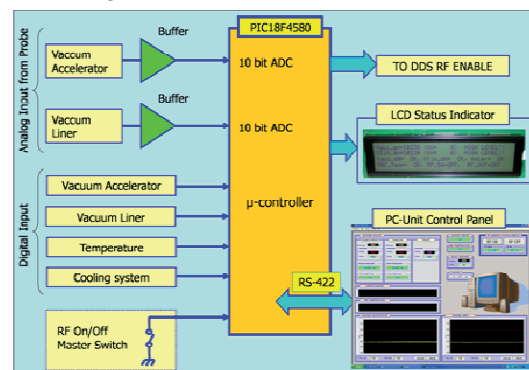


Figure 4: The control panel and the block diagram.

The Main Tuning System of the Cyclotron

The main tuning system of the superconducting cyclotron consists of six sliding shorts of three $\frac{1}{2}\lambda$ coaxial resonators. The position of the sliding shorts determines the main tuning of the RF cyclotron in the bandwidth of 15-50 MHz. The main tuning control panel sets and controls the position of the sliding shorts. The tuning resolution is 0.1 mm.

The control panel, the electronic cabinet, the mechanics and the DC motor are shown in Figure 5. This block has been renewed without any use of PIC on board. The electronic interface between the PC and the Faulhaber DC motor driver system uses a standard commercial interface.



Figure 5: The control panel, hardware and DC motors.

Axial Buncher Tuning and Matching System

The axial buncher consists of a drift tube, placed in the axial hole of the cyclotron yoke, at 0.5 meter before the electrostatic beam inflector. A matching box is placed between the drift tube and the RF amplifier. Three variable capacitors and a fixed coil inside the matching box determine the resonance and the 50 Ω matching of the buncher between 15-50 MHz. Through a PC control panel, the system sets the capacitance value of the three motorized variable capacitors until tuning and matching are achieved. The core of the system is the PIC18F2585. The tuning and matching positions are stored in a database with the relative cyclotron beam. A by-pass of the RF amplifier allows for the checking of the matching and tuning through a network analyzer, if necessary. An analog loop ensures the tuning stability after the setting and power-on. Figure 6 shows the block diagram and the hardware of the matching box.

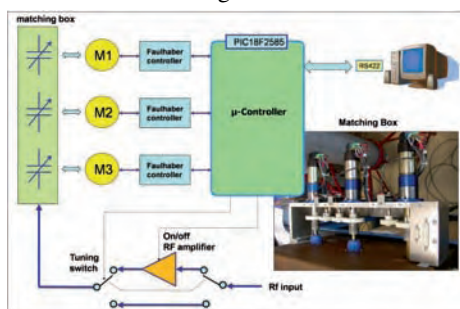


Figure 6: Tuning-matching system block diagram.

New Turn-on and Protections

The turn-on and the protections system are based on a digital μ controller of dsPIC family and an analog wide bandwidth RF amplitude modulator. The relative complex functions of this block need a dsPIC on board. The inputs, already demodulated, are the incident and reflected waves from the directional coupler, the pick-up signal from the RF field (cyclotron resonators or pulsing system) and a voltage threshold. After the low pass filter, the inputs meet a 12 bit DAC to maximize the dynamic signals. Under the multipactoring threshold, mainly in the cyclotron resonators, the protections work at very low input signal levels, while exceeding this phenomenon the input levels are very high [8]. The dsPIC analog-to-digital converters can exploit all the 12 bit of the comparators to

manage the protection and turn-on operations. The RF modulator is polarized from the PIC, through a further 12 bit DAC. The trapezoidal envelope, shown in Figure 7, allows the turn-on to feed the RF power into the cavity in one-shot, generally. An external front panel cabinet hosts the main functions and indications, such as the main alarms and turn-on/off push-buttons. The step and ramp envelope can be adjusted through the PC control panel according to the frequency. This facility is extremely useful in overtaking the resonator's multipactoring effect during the conditioning. The pulse conditioning can be set, if necessary. This kind of turn-on procedure and modulation technique is a copy of the old RF system.

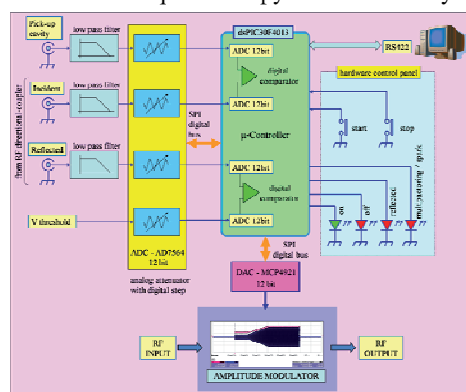


Figure 7: Turn-on and protections block diagram.

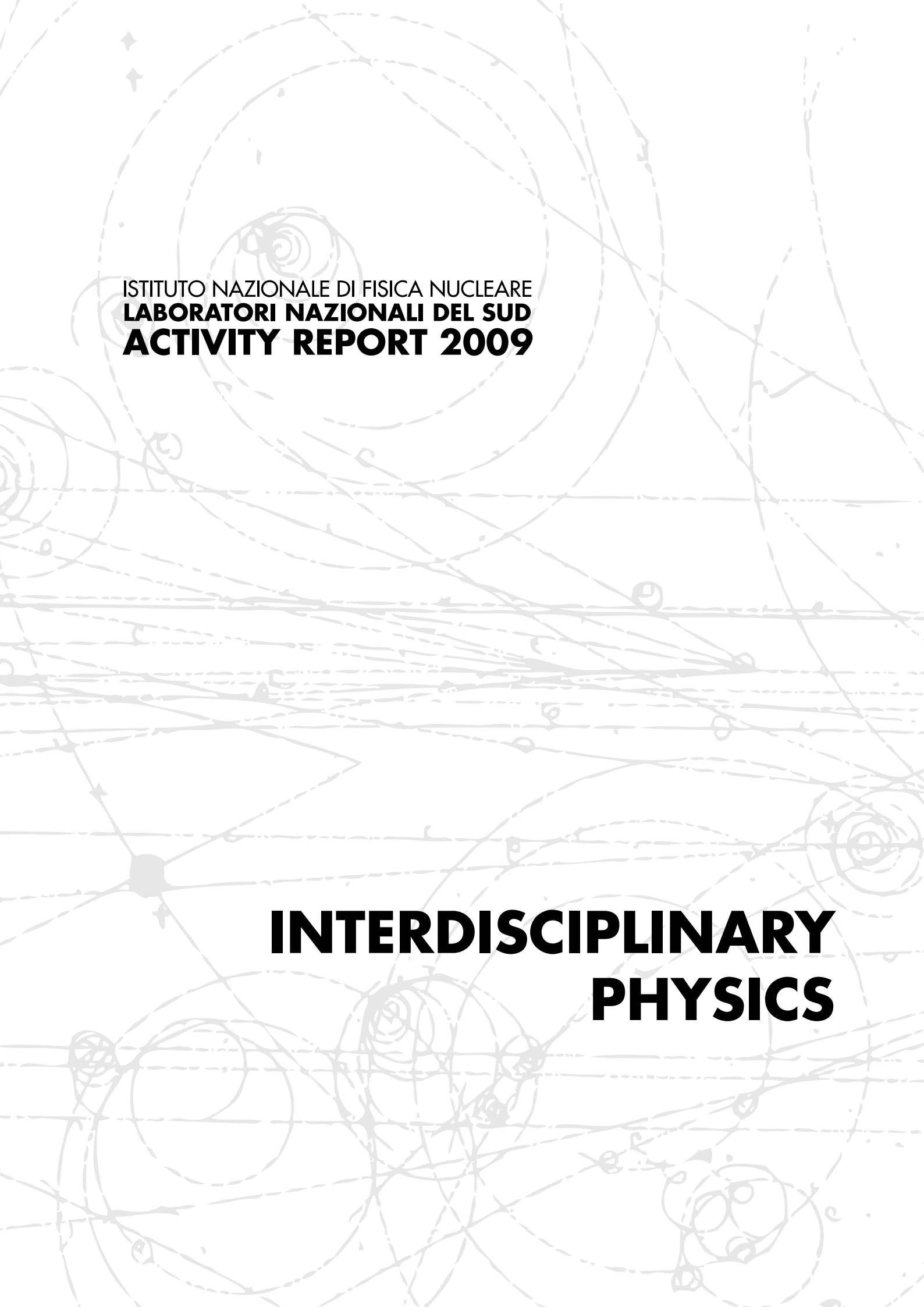
This digital upgraded version allows more freedom in setting and checking the protections and turn-on. The RS-422 bus connects block and PC-unit as usual, while the SPI digital bus is used inside the block. Some preliminary tests have been done successfully. The block diagram of Figure 7 can be a good example of the entire philosophy of the new RF control. It is mostly digital but with some analog exceptions, as the mini-circuit PAS-3, wideband modulator still used as RF switch/modulator.

FINAL REMARKS

The move from an old to new PC-based control system is in progress. The new blocks are tested during the cyclotron beam time operation. This can either be considered an advantage because the test is directly inside the accelerated beam, or a disadvantage because replacing the old blocks with the new ones cannot be synchronized always with the scheduled beam operation. The new hardware and software are developed mostly in-house. The upgrade of amplitude, phase and tuning stabilization loops, in an FPGA environment, is under study. The RF control system upgrade is in progress. In time, all the RF will be controlled by the new PC-based system.

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ISTITUTO NAZIONALE DI FISICA NUCLEARE
LABORATORI NAZIONALI DEL SUD
ACTIVITY REPORT 2009

INTERDISCIPLINARY PHYSICS

THE CATANA PROTON THERAPY FACILITY THE STATE OF ART OF CLINICAL AND DOSIMETRIC EXPERIENCE

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Abstract

After eight years of activity 206 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 battle against cancer.

INTRODUCTION

Since 2002 uveal melanomas are treated with 62 MeV proton beams at LNS-INFN in cooperation with University Hospital of Catania; the goal of proton therapy is to achieve local tumour control and retention of organ and vision; moreover, other less frequent eye diseases are treated, like choroidal haemangioma, conjunctiva melanoma 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, lens, macula and skin surface.

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 proton eye therapy.

THE PROTON BEAM LINE

The CATANA proton beam line has been entirely built at INFN-LNS and its global view is shown in Figure 1. The proton beam exits in air through 50 µm kapton window placed at about 3 meters from isocenter. Just before the exit window, under vacuum, is placed the first scattering foil made from 15 µm tantalum. The first element of the beam in air is a second tantalum foil 25 µm 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 2 shows the experimental lateral dose distribution for the 62 MeV proton beam measured with a final 25 mm diameter circular brass collimator (reference collimator). Beam data are acquired with a silicon diode in a water phantom, at the treatment depth of 12 mm, corresponding to the middle of the Spread Out Bragg Peak (SOBP).

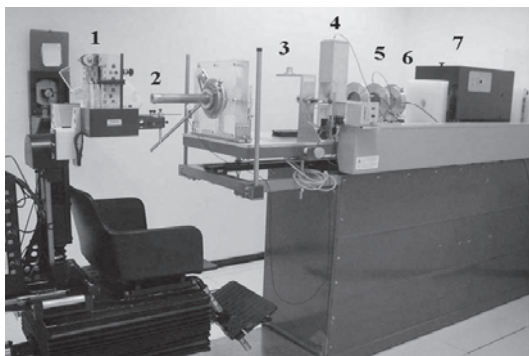


Figure 1: View of the CATANA beam line: 1. Treatment chair for patient immobilization; 2. Final collimator; 3. Positioning laser; 4. Light field simulator; 5. Monitor chambers; 6. Intermediate collimator; 7. Box for the location of modulator wheel and range shifter.

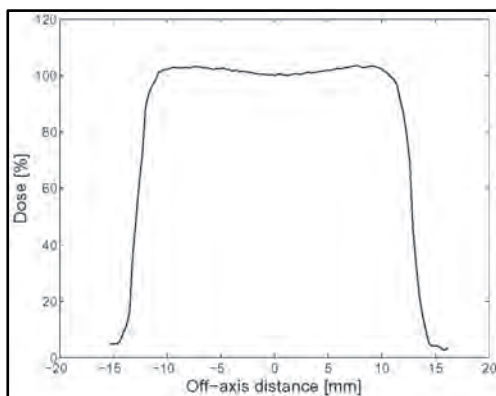


Fig. 2: Experimental lateral dose distribution for 62 MeV proton beam.

Range shifter and range modulator 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 centering. The emission light of a third laser is spread out to obtain the simulation field. A key element of the treatment line is represented by two transmission monitor ionization chambers. The aim of the chambers is, respectively, to provide the on-line control of the dose delivered to the patient and of the beam symmetry.

The last element before isocenter is the brass shaped patient collimator located 83 mm upstream of the isocenter. Finally, two Philips x-Ray tubes, with axes defined by crosshairs, are placed perpendicular and coaxial to beam line, to provide lateral and axial view of the tumor, during simulation of treatment [3].

A digital imaging acquisition system was developed to evaluate the position of four tantalum clips located around the target; two flat panel sensors, produced by Hamamatsu, are connected to the X-ray tubes.

The output images of the TPS Eyeplan are compared with the X-ray images of the tantalum clips by using a home

made software. The software automatically evaluates the correct position of the eye patient and sends the treatment coordinates to the treatment chair.

PROTON DOSIMETRY AT CATANA FACILITY

As in conventional radiotherapy, clinical proton dosimetry includes reference dosimetry, consisting in determination of the absorbed dose in 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 cm³. According to IAEA TRS 398 protocol [4], proton beam calibration is performed in a water phantom. The absorbed dose to water per monitor unit (cGy/M.U.) is measured at isocenter, for each combination of modulator and range shifter used in the clinical practice; measurement are carried out at the depth of the middle of the SOBP, using the reference 25 mm diameter circular collimator [4]. 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 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 (1×1 mm² sensitive area) [8].

Output factor is determined [4] as the ratio of small-size detector signals for the patient and reference collimators for the the same M.U. setting.

Based on experimental results on tens of collimators, we can state that the dose delivered per monitor unit decreases by less than 3% for collimator areas in the range of 490 mm² (reference collimator) to 100 mm², the latter representing the lower limit of collimator areas associated to the clinical practice.

For mono-energetic and modulated proton beams, depth-dose distributions are measured in a motorized water phantom with three fully computer-controlled stepping motors, with a scanning resolution of 0.1 mm in the Bragg peak region; 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 are measured, according to the ICRU Report N. 78, related to the clinical requirements (fig.3):

- 1) Beam range (depth of penetration) is measured by the depth of 90% distal point.
- 2) Width of the SOBP is defined as the distance of 90% dose points, proximal and distal.
- 3) Distal fall-off (DDF) amounts to the distance of 80% and 20% distal points.
- 4) Target (or treatment) length is defined as the distance between two DDF lengths ($2 \times \text{DDF}$) proximal to the distal 50% isodose level of the SOBP, and one DDF length ($1 \times \text{DDF}$) distal to the proximal 90% isodoses level of the SOBP.
- 5) Reference depth (z_{ref}) is defined at the middle of the SOBP and corresponds to the dose prescription point (ICRU point).
- 6) Beam quality (Q) is measured by the value of the residual range, defined as $R_{\text{res}} = R_p - z_{\text{ref}}$, where R_p is the depth at which the absorbed dose beyond the SOBP falls to 10%.
- 7) Longitudinal Homogeneity, defined as:

$[(D_{\text{max}} / D_{\text{min}}) \times 100] \% \text{ within the SOBP.}$

A software, entirely developed at INFN-LNS, controls the data acquisition and provides data analysis.

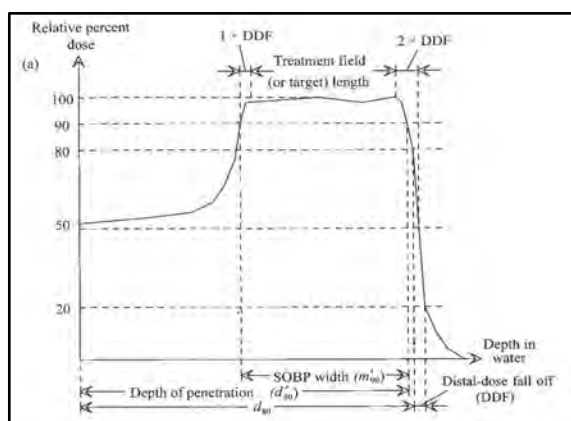


Fig. 3: Physical beam parameters related to the clinical requirements for the modulated proton beam.

Experimental depth dose profiles have been compared with a Monte Carlo simulation application, using the Geant4 toolkit, developed in LNS-INFN. Results of this comparison are extensively reported in [5].

Lateral beam profiles are characterized in terms of:

- 1) field size ($W_{50\%}$),
- 2) lateral penumbra (LP, $d_{80-20\%}$),
- 3) target (or treatment) width, defined as the distance between two LP widths ($2 \times \text{LP}$) from the 50% isodose level of the lateral profile,

4) flatness and symmetry defined as in conventional radiotherapy and evaluated in the target width.

New EBT radiochromic film [9] has been chosen as reference detector for measurement of lateral profiles; EBT film is nearly tissue equivalent [$(Z_{\text{eff}}/A) = 6.98$], with a sensitive range of 0.1 Gy to 8 Gy, providing high spatial resolution up to 100 μm .

Epson Expression 10000XL flatbed colour scanner is used to analyze EBT irradiated films; films are scanned in transmission mode in the 48 bit RGB mode (16 bit per colour) and data saved as TIFF files. The maximum of the absorption spectra is about 636 nm and therefore the red component of the image is extracted to maximize film readout.

EBT calibration is carried-out with 62 MeV mono-energetic proton beam. Several strips $3 \times 3 \text{ cm}^2$ are irradiated in a SW phantom at 1 mm depth in the entrance plateau of the Bragg curve, corresponding to a residual range of about 30 mm; films are irradiated with the reference 25 mm diameter circular collimator.

Films are irradiated at a dose rate of 15 Gy/min, corresponding to the clinical dose rate.

Calibration curve (fig. 4) is well in agreement with the corresponding curve for 6 MV photons, demonstrating water equivalence of EBT film.

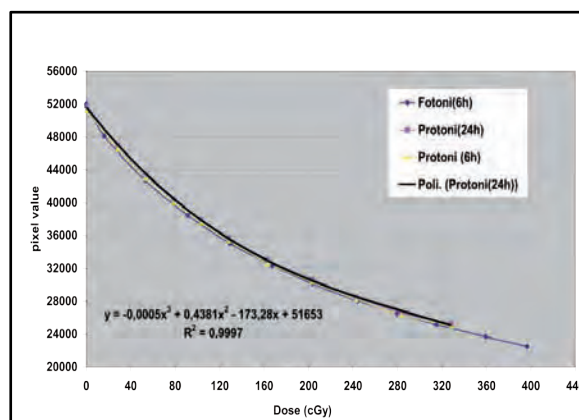


Fig. 4: Calibration curve for EBT film.

The response of EBT films was found to be energy-independent in the energy range of ocular proton therapy; as a consequence, only one calibration file is needed to evaluate films exposed at different depths.

In ocular proton therapy, EBT films are used for dosimetry verification of standard circular collimators and irregularly shaped patient collimators with very small lateral extension, down to 5 mm diameter.

Fig.5 shows the lateral profile along the central axis of the 62 MeV proton beam for the reference circular collimator of the eye proton therapy.

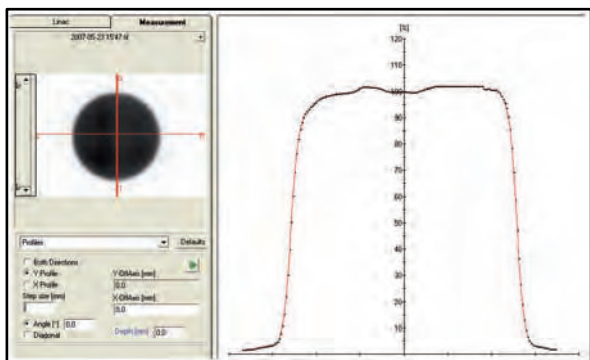


Fig. 5: Lateral profile along the central axis performed with EBT film.

Preliminary in vivo dosimetry has been carried-out on some patients with transeyelid treatment, by using microMOSFET (Best Medical Canada Ltd.). MOSFET detector calibration is performed individually for each patient, by placing the detector on a water phantom surface, with reference circular collimator. Subsequently, the output factor has been determined in order to account the patient irradiation field size. Therefore, the calibration factor is performed in order to read the delivered dose at the clinical point of interest, i.e. the middle of SOBP. The detector is placed on the patient eyelid immediately before the treatment, as show in the fig. 6 that display the detector placement on the patient eyelid during the irradiation, along with thermoplastic mask and bite block as immobilization system.

First in vivo results are promising, with a maximum difference between expected and measured doses smaller than 10%; a lot correction factors are to be determined in order to obtain agreement within 5%.

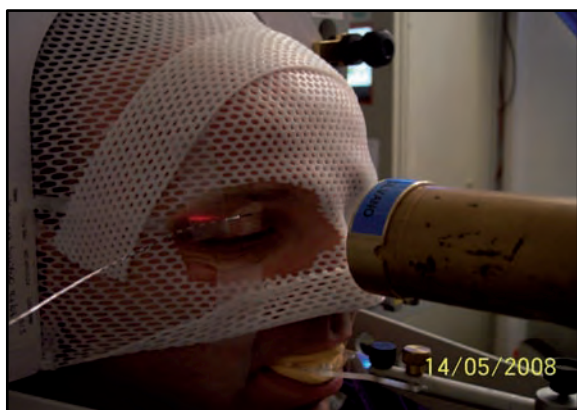


Fig. 6: In vivo dosimetry with MOSFET and patient immobilization system.

THE TREATMENT PROCEDURE

As explained before, protons allow a high dose deposition in a small deep-seated space, with precise irradiation of the target. The radiotherapist therefore needs to know the exact position of the tumor. To do that, tantalum clips are placed around the lesion on the outer sclera by the ophthalmologist, generally very close to the tumor. The surgeon also defines the tumor position and measurements, as transverse and longitudinal base diameters, elevation or height, distance to the optic disk, to the macula, to the limbus. He also makes the radiotherapist know about the eye measurements (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). The final result is the drawing of a precise fundus view model with tumor and clips locations. The ophthalmologist makes use of A-mode and B-mode ultrasound scan, retinal fluorangiography, wide-angle fundus photographs and, especially, surgical measurements to define all those parameters. He also informs the radiotherapist about the visual acuity of the effected as well as the fellow eye, the presence of exudative retinal detachment, ocular pressure and all other information he considers to be significant. A total retinal detachment or the presence of a glaucoma are contraindications to a conservative approach. Together with the diagnosis, for all patients a systemic staging is provided through a total body spiral Computed Tomography (CT) scan to exclude metastatic disease, which is, obvious ly, another contraindication. After this first phase, the patient arrives at the INFN-LNS, where the workup by the physicist and radiotherapist begins. First of all, a fixation device is made by means of a customized thermoplastic mask and bite block, with the patient in a seated position (Figure 6).

The patient is invited to gaze at a light point and two orthogonal X-ray pictures (axial and lateral) are taken. This step is repeated 3-6 times with the patient gazing at different points, depending on the tumor position in order to make the physician sure about the position of the clips. A measurement of the eyelid thickness and slope is also needed for the planning procedures. All the informations are then elaborated by means of three-dimensional therapy planning program EYEPLAN, developed at the Massachusetts General Hospital for eye tumor therapy using proton beams.

Actually, the improved version of EYEPLAN, by M. Sheen [6], is used in our facility. This software schematically displays a model of the patient's eye, including the lens, optic nerve and fovea, where the tumor is finally drawn by means of the specified measurements and position reference.

A second simulation is performed on the first day of the treatment week, with the eye in the final position to verify and to accept the treatment. If the eyelids cannot be retracted completely outside of the irradiation field, they have to be calculated in the treatment plan.

For proton therapy, the dose is prescribed (ICRU 78) as D_{RBE} [Gy (RBE)]; 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 SOBPs.

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 is between 15 and 60 sec.

CLINICAL RESULTS

Patient data

Since March 2002, 206 patients have been treated at the CATANA Eye treatment facility. A various spectrum of ocular tumors have been treated with proton beam radiotherapy in order to obtain local tumor control, to reduce the incidence of metastatic spread and to maintain the ocular globe.

The majority of the pathologies treated are uveal melanomas (91%); other ocular diseases treated are conjunctival melanoma, squamous cell carcinoma of the conjunctiva of the eyelid, conjunctival lymphoma, orbital rhabdomyosarcoma and uveal metastases from breast or lung carcinoma.

Patient were equally distributed in the males and females, and the age ranged between 14 to 84 years(mean 55.6).

Results

During the follow-up, the first data regarding local tumor control are available only after 6-8 months from the end of the treatment. To date, the results of the first follow-up at 6 months are available for 199 patients. Follow-up ranges between 6 months to eight years.

The local control is defined as a tumor shrinkage or cessation of growth at B-Mode ultrasonography, or as an increase of ultrasound reflectivity at A-Mode ultrasonography (a surrogate for tumor control). A size reduction, especially regarding the thickness of the tumor, was seen in the 75% of the patients, while the 25% maintain a stable dimensional lesion. An increased A-Mode ultrasound reflectivity was detected in almost all patients. These data clearly show a tumor control, particularly for those patients with 1 year follow-up. No major side effects requiring eye enucleation have been detected: an exsudative retinal detachment at the time of the diagnosis was seen in 40% of the patients and it remains stable in about half of them. In 30 patients a new cataract formation related to the treatment, generally at the periphery of the lens, was diagnosed. About 40% of the patients still maintain a useful visual acuity. This is obviously not always possible, especially when the tumor infiltrated directly or is located close to the optic disc or the macula [10, 11].

FUTURE DEVELOPMENTS

Physicists, medical physicists and medical doctors are continuing the improvement of the quality of the proton

treatments at INFN-LNS either from a dosimetric point of view as well as from the transport beam line control. Regarding the latter the new MOPI [7] microstrip detectors was installed as device for the control of the beam symmetry during the patient treatment. Its characterisation is actually in course.

For the next year, the CATANA facility will continue its activity and 4/5 treatment sessions per year are programmed.

CONCLUSIONS

The preliminary results show an high percentage of local tumor control, despite the limited follow-up period, 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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STUDY OF A SILICON TELESCOPE FOR SOLID STATE MICRODOSIMETRY: PRELIMINARY MEASUREMENTS AT THE THERAPEUTIC PROTON BEAM LINE OF CATANA

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Abstract

A monolithic silicon device consisting of a matrix of micrometric cylindrical diodes (about 2 μm in thickness and 9 μm in diameter) coupled to a residual energy measurement stage E (about 500 μm in thickness) was proposed and studied for assessing the quality of a therapeutic proton beam. The device was placed at different depths inside a polymethyl-methacrylate phantom and irradiated with a modulated 62 MeV proton beam at the Centro di AdroTerapia e Applicazioni Nucleari Avanzate (CATANA) of the Laboratori Nazionali del Sud (LNS, Catania, Italy) of the Istituto Nazionale di Fisica Nucleare (INFN).

At each depth, the energy imparted in the two detector stages was measured event-by-event in coincidence mode. The distributions of the energy imparted to the cylindrical diodes were corrected for tissue-equivalence by applying an optimized procedure. In order to perform a comparison with literature data measured with a cylindrical TEPC, the distributions derived with the silicon detector were corrected for shape-equivalence. The agreement with the microdosimetric spectra measured with the TEPC was satisfactory above the detection limit imposed by the electronic noise of the silicon device.

INTRODUCTION

The proposed detector is an innovative device, based on the monolithic telescope technology developed by ST-Microelectronics (Catania, Italy) [1], characterized by a ΔE stage segmented in a matrix of micrometric diodes [1]. The aim was to develop a silicon detector offering sensitive volume dimensions similar to those which can be simulated by a TEPC. The sketch of the device is shown in Fig. 1. It is constituted by a matrix of cylindrical elements, about 2 μm in thickness and 9 μm in diameter, coupled to a single E stage (500 μm in thickness). More than 7000 pixels are connected in parallel to give an effective detection area of about 0.5 mm^2 . Each segmented ΔE stage acts as a solid state microdosimeter [2,3], while the E stage gives information on the energy of the impinging proton up to about 8 MeV.

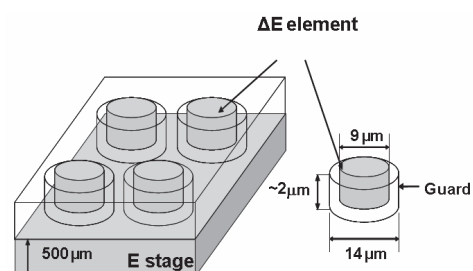


Figure 1: Sketch of the segmented telescope.

MATERIALS AND METHODS

The device was irradiated with a 62 MeV proton beam at the CATANA facility of the INFN-Laboratori Nazionali del Sud (LNS, Catania, Italy). In order to measure the beam quality at different depths, the silicon device, wrapped in a mylar foil, was placed inside a PolyMethylMethAcrylate (PMMA) bar 1×1 cm^2 in cross section. This bar was inserted in a groove made in a PMMA cube 12×12×12 cm^3 in volume. At each measurement position, an adequate number of PMMA foils (about 3 mm, 2.5 mm and 50 μm in thickness) were located in front of the detector in order reproduce the desired depth (see Fig. 2). The uncertainty of the PMMA thickness is about 0.2 mm.

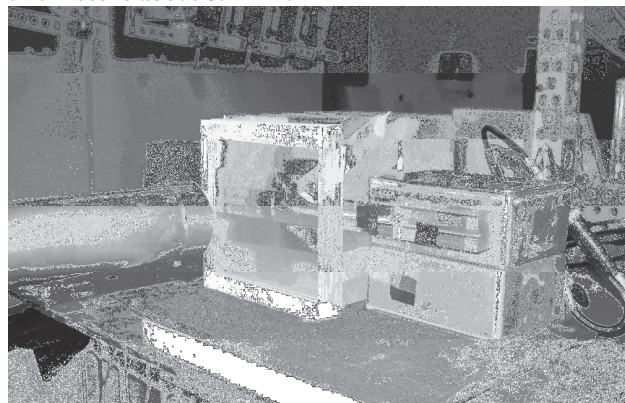


Figure 2: Experimental set-up.

Both detector stages were biased and the associated signals were amplified and shaped by using two independent electronic chains.

The pulses generated in the two stages were acquired by a custom two-channel ADC in coincidence mode, in order to maintain the time correlation.

The proton beam was attenuated by a PMMA range shifter about 4.6 mm in thickness and spread-out with a PMMA range modulator (maximum thickness of about 13.4 mm) in order to obtain the spread-out of the Bragg peak (SOBP).

It should be underlined that the irradiation set-up and the measurement points were selected in order to reproduce the experimental conditions adopted by De Nardo et al. [4] with a cylindrical TEPC. The aim was to carry out a comparison with those literature data obtained by using a reference gas microdosimeter.

Fig. 3 shows the dose profile obtained with a high-doped p-type diode [5] for the beam set-up described above. The points A-L on the curve indicate the twelve depths considered for the measurements performed with the silicon telescope.

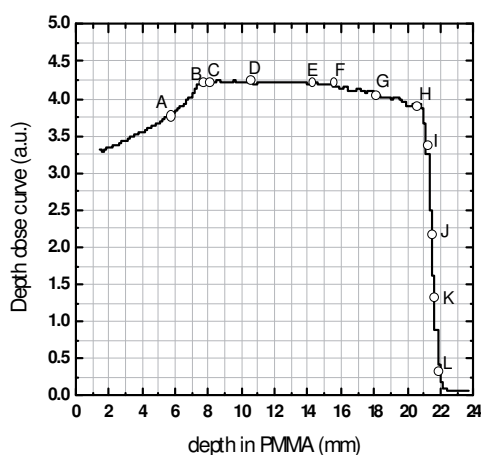


Figure 3: Depth dose profile of the 62 MeV modulated proton beam, measured with a high-doped p-type diode. The points A-L indicate the measurement positions adopted during the measurements performed with the silicon telescope. (5.7, 7.6, 8, 10.5, 14.2, 15.5, 18, 20.5, 21.2, 21.4, 21.6, 21.8 mm, respectively).

The scatter plot of the energy $E_{\Delta E}$ imparted per event in the segmented ΔE stage versus that deposited in the E stage, E_E , was acquired by the silicon device across the SOBP, at each depth shown in Fig. 3. The results obtained at a phantom depth d of about 8 mm and 21.5 mm are shown in Fig. 4 and Fig. 5, respectively. Fig. 4 is related to a shallow depth, namely the proximal part of the SOBP, where protons cross the whole silicon device (i.e. they do not stop completely in the detector, since their energy is higher than 8 MeV). The acquired low-LET events provide low energy deposition within both stages.

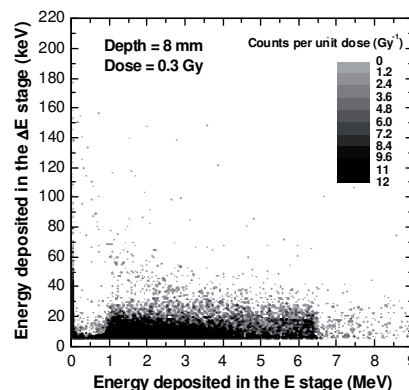


Figure 4: ΔE -E scatter plot measured with the silicon telescope across the proximal part of the SOBP (point C in Figure 3, depth=8 mm). At this depth protons cross both the ΔE and the E stage.

Fig. 5 is related to the distal part of the SOBP, where most of protons stop completely inside the E stage, thus allowing to estimate their energy of incidence E_p on the detector.

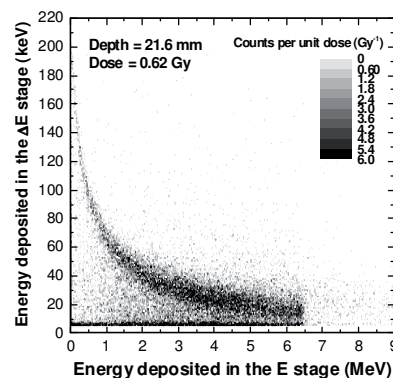


Figure 5: ΔE -E scatter plot measured with the silicon telescope across the distal part of the HSOBP (point J in Figure 3, depth=21.6 mm). At this depth protons stop inside the E stage.

In order to derive lineal energy distributions comparable to those acquired by a TEPC, the $E_{\Delta E, Si}$ spectra measured with the silicon device were corrected for i) tissue-equivalence, i.e. for obtaining distributions equivalent to those of a tissue ΔE stage, $E_{\Delta E, Tissue}$; ii) shape-equivalence, in order to take into account the different shape of the sensitive volumes (that of the TEPC and of the silicon telescope) [2]. For measurement positions from A to H (see Fig. 3), corresponding to depths d at which protons cross the E stage, the spectra of $E_{\Delta E}$ were processed by scaling $E_{\Delta E}$ with a constant factor equal to 0.574. This value was obtained by averaging the ratio $R_{Tissue/Si}(E_p)$ of stopping powers of protons in tissue and in silicon over the proton energy interval of interest, namely for E_p between 0 and 62 MeV. This is the procedure typically adopted when a single stage device is used [6]. On the other hand, for the spectra derived at

positions I – L, at which protons stop in the E stage, an optimized procedure was adopted. This procedure consists in correcting event-by-event the energy $E_{\Delta E}$ measured by the silicon device with the value $R_{\text{Tissue}/\text{Si}}(E_p)$ at the energy $E_p = E_{\Delta E} + E_E$ [2].

Some lineal energy spectra obtained with the silicon device after the corrections mentioned above are shown in figures 6a-6d (gray curve) together with those obtained by De Nardo et al. (2004) with a cylindrical TEPC (solid black curve). Those distributions correspond to measurements performed at positions B, E, H and J along the depth dose curve of figure 3. The uncertainty associated to this measurement position is about 0.2 mm. In order to properly normalize and directly compare the distributions obtained by the two systems, the lineal energy spectra measured with the TEPC were truncated at a value corresponding to the energy threshold of the silicon device ($6 \text{ keV } \mu\text{m}^{-1}$). Anyhow, figures 6a-6d illustrate also the non-normalized microdosimetric spectra measured by the TEPC (dashed black lines) in order to show the complete spectra which the silicon device should measure.

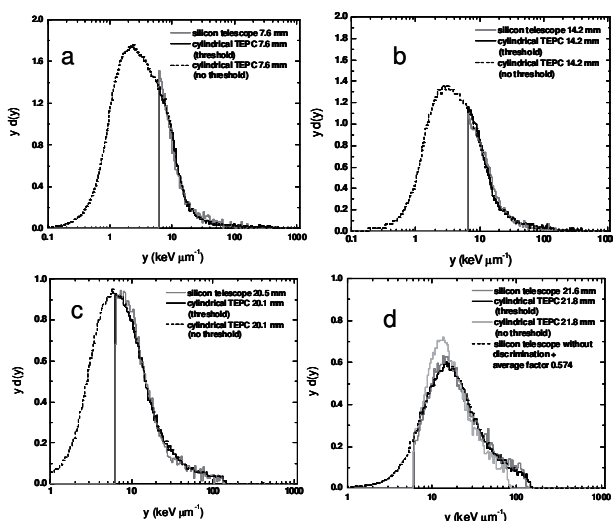


Figure 6: Comparison between the lineal energy spectra obtained with the silicon device (gray curve) and those obtained with the reference TEPC (solid black curve) truncated at a value corresponding to the energy threshold of the silicon-based system ($6 \text{ keV } \mu\text{m}^{-1}$). The non-normalized complete microdosimetric spectra measured by the TEPC are also shown (dashed black line). The measurement points are: a) B (7.6 mm); b) E (14.2 mm); c) H (20.5 mm); d) J (21.6 mm).

Figures 6a and 6b refer to shallow depths, namely to measurements corrected for tissue-equivalence with an averaged scaling factor (0.574), while figures 6c and 6d concern results obtained after the event-by-event tissue-equivalence correction. As can be observed in figure 6a – 6d, the main difference between the results derived with the two detection system is the minimum detectable energy. Lineal energy spectra measured by silicon device

are limited to a minimum value of about $6 \text{ keV } \mu\text{m}^{-1}$, which hinders to measure the low-LET events in the proximal part of the HSOBP. Anyway, the agreement between the lineal energy distributions obtained with the silicon device and those obtained with the reference cylindrical TEPC at values higher than $6 \text{ keV } \mu\text{m}^{-1}$ results to be satisfactory.

CONCLUSIONS

A silicon device based on the monolithic silicon telescope technology was proposed and tested for microdosimetry of therapeutic proton beams. The detector was irradiated with a 62 MeV modulated proton beam at different depths within a PMMA phantom at the CATANA facility of the INFN-LNS (Catania, Italy).

The measured spectra were corrected for tissue-equivalence and for shape-equivalence and the resulting lineal energy distributions were compared with literature data obtained with a cylindrical TEPC irradiated in the same experimental conditions [4].

The results of these preliminary measurements demonstrate the capability of the silicon device of measuring microdosimetric spectra of proton beams similar to those derived with a TEPC at lineal energies higher than $6 \text{ keV } \mu\text{m}^{-1}$. The work carried out highlighted the necessity of reducing the minimum detectable lineal energy in order to properly measure distribution at shallow depths within the phantom. This will be the subject of the future research for improving the performance of this silicon microdosimeter.

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THE GEANT4 MONTE CARLO TOOLKIT FOR THE DEVELOPMENT OF MEDICAL PHYSICS APPLICATIONS

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Abstract

Monte Carlo (MC) methods play a very important role in medical physics applications. In many situations, the MC approaches represent the only techniques which can be used for particular medical physics issues, like the predictions of the dose distributions using clinical proton, electron and photon beams in non homogeneous materials. In this report, we relate particular applications of MC methods in different medical physics procedures, following the experience we gained from 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 a simulation application by selecting the physical processes to be activated, is a key feature for its usage in different experimental fields. 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. The ex-

tension 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

The *Hadrontherapy* application has been firstly developed for the simulation of the CATANA proton transport beam line. Proton therapy is a precise form of radiation therapy that makes use of high energy protons in spite of the conventional, more commonly and less precise, x-ray and electron beams. The CATANA project was born many years ago for the realization of a facility for the treatment 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 about 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 collimator system. On the basis of these exigencies, we decided to realize a MC simulation, we called *Hadrontherapy*, using the GEANT4 toolkit. Each element of the passive beam line has been carefully simulated and the detector used for the depth dose distribution has been also reproduced in the application [4]. Actually, this MC application is a continuously upgraded advanced example included in the official public GEANT4 distribution, and it can be freely downloaded from the website [5]. The *Hadrontherapy* application offers great flexibility: the user can easily change geometrical configuration of the beam line, the primary proton beam characteristics and different physical models with-



out changing the code, but just calling them with simple macro commands. The use of time-dependent geometries is also a standard feature within our application, permitting the simulation of the energy modulation system. Dose released by protons can be stored in a voxelized geometry of any material and shape. For our purposes, we implemented different electromagnetic physics transport beam models, i.e. as the LowEnergy and Standard package. Moreover, we implemented different hadronic processes for protons and generic ions incident beams. An eye structure has been also simulated and dose distributions inside that can be stored, permitting isodose and X-Y profile comparisons (see the following section). The *Hadrontherapy* application has been validated against experimental data acquired by us, as reported elsewhere [6]. In Figure 1, the proton therapy beam line is shown, as it is simulated and displayed by our application.

Recently, the application has been redesigned in order to be used as a general-purpose tool with additional features [7]. Now, with simple macro commands, different geometrical configurations can be switched and chosen among the available already implemented: the CATANA proton therapy beam line (the first one implemented), the carbon ion beam line present at the 0° room of LNS, an active scanning beam line which reproduces the proton beam line present at the National Cancer Centre of Korea (thanks to the collaboration of the Korean group) and a beam line for thick target experiments present at GSI (thanks to the collaboration of the Finnish group). Moreover, routines to retrieve the stopping power values for different materials and to compute averaged LET distributions have been recently implemented. These last features are useful in order to relate the released dose to the biological damage, especially when mixed radiation fields are present.

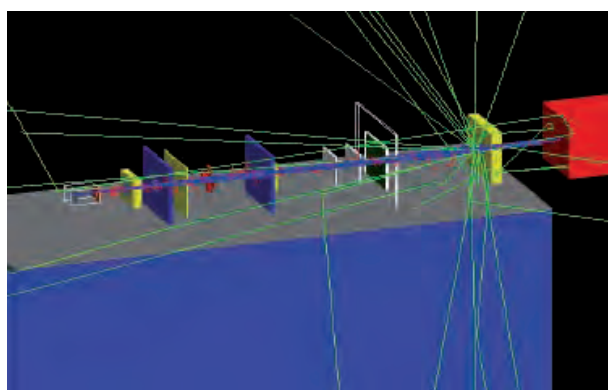


Figure 1 - Graphic view of the proton beam line simulation reproduced in the *Hadrontherapy* application.

A proton TPS commissioning and verification

Many malignant tumours are localized near normal and delicate structures, often close to radio-sensitive organs. This circumstance is also the clinical case of intraocular malignancy. The ocular pathologies are successfully treated with radiation therapy, with preservation of the eye in almost all the surviving patients. In particular, the

proton therapy offers the dosimetric advantage of a highly conformal dose region with the possibility of covering the tumour volume with an elevated accuracy, sparing the surrounding healthy tissue. The radiotherapy treatment planning process is defined as the process used to determine all features of the radiation beams used to deliver dose of radiation to a patient in order to control a cancerous tumour. Nowadays, treatment planning is performed with the assistance of a computerized Treatment Planning System (TPS), which helps the treatment planner and physician to define the target volume, determine beam directions and calculate the dose distributions. Nowadays, the most used dose distribution prediction algorithms for ocular proton therapy are based on an analytical description of the proton energy deposition. These analytical beam transport models are often inherently limited by severe approximations and simplifications. Nevertheless, these algorithms presently represent the most used techniques because they offer the clinical advantage to calculate dose distributions in a reasonable time, acceptable from a clinical point of view. Actually, EYEPLAN is the analytic standard tool in eye treatment with proton beams. To verify the correct prediction of the EYEPLAN TPS dose distributions, a validation process has been performed using the Monte Carlo toolkit GEANT4, which has allowed to simulate the geometric eye configuration. The TPS validation procedure is performed comparing the entire three-dimensional dose distributions calculated by EYEPLAN with the Monte Carlo dose distribution predictions. This comparison reveals that the TPS is not enough accurate to correctly reproduce the distal dose fall-off. Our studies demonstrate that Monte Carlo simulations are the best approach to validate an ocular proton therapy treatment planning. They are able, in fact, to predict the dose distributions for any geometry and to reveal any fails in the analytical calculations. We expect that these techniques will be used for nozzle design work, dose-per-monitor-unit predictions and, eventually, routine treatment planning. However, the results also show how Monte Carlo approach is still time consuming for routine treatment planning, even if considered the most accurate method of planned dose verification (Figure 2).

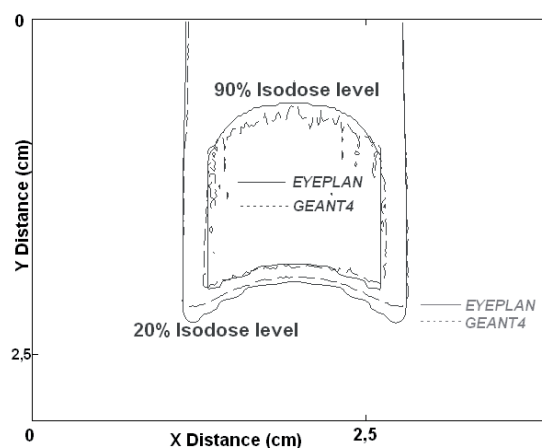


Figure 2 - Comparison between TPS and GEANT4 dose distributions.

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 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 [10]. 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, both using the Monte Carlo method as well as in experimental measurements with a first prototype of a pCT system. In our work we realized also a possible schematic example of pCT device system (Figure 5).



Figure 5 - The pCT system as simulated with GEANT4

Gamma Knife® Stereotactic Radiosurgery

Today the Stereotactic Radiosurgery with devoted machine is 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 from 201 ^{60}Co sources, focus on the isocentre (target volume), traversing a collimation system [9]. With this technique, brain disorders of different kind are treated delivering high amount of dose in a single session. The Treatment Planning System (TPS) devoted to the dose distribution computation is the Leksell 'GammaPlan', which is able to calculate the isodose curves obtained combining shots of different diameter at the isocenter (4, 8, 14, 18 mm). In order to plan the treatment in a reasonable time (considering the complexity arising from the overlapping of hundreds of gamma ray beams), the TPS has been designed including some approximations, which make the calculation faster. One of these consists on considering the patient's head only composed by water, neglecting the presence of different densities. Hence, the aim of our work has been the validation of the TPS GammaPlan using the GEANT4 toolkit. An application has been developed, which accurately reproduces all the Gamma Knife features (both geometrical and physical ones) in order to simulate with an high level of accuracy the dose deposition [10] (Figure 3).

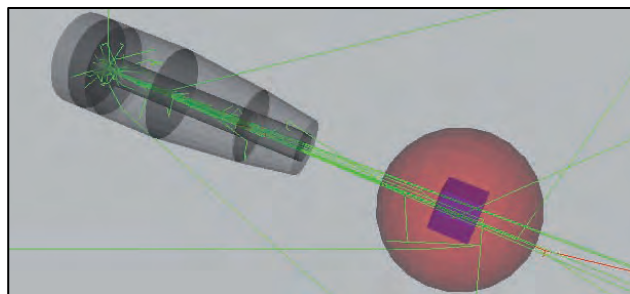


Figure 3 – Gamma Knife GEANT4 application

At first, the Monte Carlo simulation has been validated for all the available collimators in the standard configuration. Comparisons have been done between the GEANT4 dose distributions and the experimental ones, obtained by radiochromic film dosimetry measurements inside a water phantom (HS GafChromic films). In order to simplify the code, we have simulated only one source (with the correspondent collimation system) and rotated the phantom at 201 different positions, employing time-dependent geometries. In such a way we have reproduced the real configuration (sources arranged in a hemispherical shape) rotating the phantom exactly in the same angular positions where the sources are located. This procedure has been chosen because easier to implement into the code. Once the GEANT4 simulation has been validated by mean of experimental data, we have used the simulation to verify the dose distributions calculated by the TPS, firstly in standard conditions (homogeneous phantom) and then by introducing inside the phantom different den-

sity materials (inhomogeneous phantom). As regards the former configuration, results show that the TPS calculates in a correct way the dose delivered (Figure 4). As regards the case of inhomogeneous phantom, we found a discrepancy of about 4% between Monte Carlo and TPS outputs. These differences probably arise from the assumptions made in the TPS calculations. The obtained results clearly show the importance of the application of Monte Carlo methods in radiotherapy, especially in case of special techniques where the level of complexity increases, as in the case of the Stereotactic Radiosurgery.

The Gamma Knife application has been proposed and accepted by the GEANT4 international collaboration as an advanced example to be included in the future public releases of the toolkit.

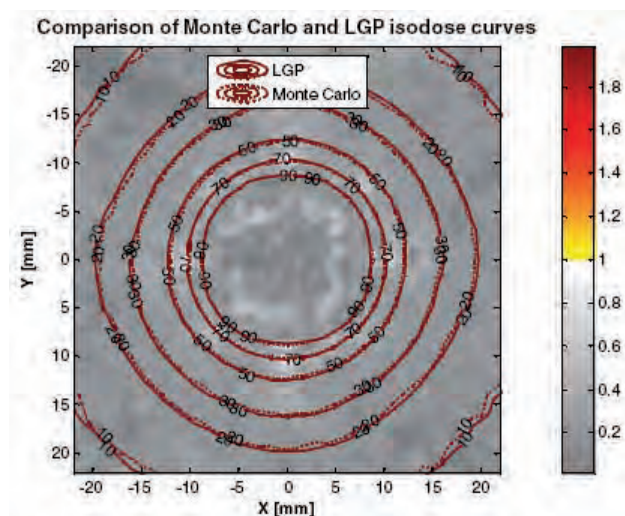


Figure 4 - Comparison of Monte Carlo and LGP isodose curves in the central plane (axial), for the 18 mm collimator. Monte Carlo voxel dimension: 1 mm; LGP voxel dimension: 1.6 mm.

Validation of GEANT4 nuclear models in the energy range of interest in hadrontherapy

As discussed in the previous sections, the use of protons sensibly enhances the ballistic precision in tumour treatments because of their high level of conformation in dose distribution, if compared to conventional radiotherapy. Protons are not the only hadrons can be used for therapeutic purposes. Indeed, heavier ions have been also investigated in the past, because of their enhanced biological effects respect to conventional radiation and also respect to protons [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 effects for healthy tissues, even if further studies are still going on about the possibility to use lighter ions [12]. Carbon ion beams treatments are actually performed in Europe and Japan, and many hadrontherapy centres for proton and carbon ion therapy have been planned [13]. Carbon ions are characterized by lower lateral scattering and range straggling, respect to protons, which is important to

achieve an enhanced level of spatial conformation to the tumour target. Moreover, they exhibit an higher biological effect, especially at the end of their path, where the Bragg peak overlaps the target region [14]. The only drawback which affects the clinical use of carbon ion beams is due to the effects of nuclear interactions, which produce projectile charged fragments. Therefore, a mixed radiation field is created, constituted by both primary and secondary particles, which have different biological effects depending on the specific isotope. It is evident that each contribution has to be considered and known with a good level of accuracy. Monte Carlo simulations are considered a suitable tool for such a kind of study, thanks to their realistic predictions in terms of physical processes and dose contributions. Of course, the accuracy of their predictions strictly depend on the reliability of the nuclear models implemented in the codes, which need to be accurately validated. An extensive validation plan has been started from our group in order to benchmark the GEANT4 nucleus-nucleus interaction models at the energy range of interest in hadrontherapy (60-400 A MeV). Unfortunately, few updated data are present in literature for carbon ions incident at this energy range. Indeed, first comparisons have been done with experimental data found in literature, regarding only neutron emission at different angles for carbon ions incident at 135 A MeV on different targets (C, Al, Cu, Pb).

In order to cover the gap of data, an experiment has been carried out at LNS-INFN of Catania, with the aim of measuring the production cross sections of charged particles for different angles and target materials [15]. Carbon ions have been accelerated by a superconducting cyclotron at 62 A MeV on thin targets of ^{197}Au , ^{12}C and CH_2 . Nuclear fragments have been detected by 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.

A wide set of comparisons have been planned in the future in order to achieve an extended validation of the nuclear models available in GEANT4. The verification of charged fragments production predicted by Monte Carlo codes represents, indeed, a crucial point for treatment planning in carbon ion therapy.

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¹H MRS CAN BE USED TO STUDY THE EFFECTS OF 62 MeV PROTON BEAMS FOR RADIOTHERAPY: COMPARISON OF TUMOR CELLS DIFFERENTLY PRONE TO APOPTOTIC DEATH

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Abstract

In the present study proton NMR spectroscopy was used to compare the effects of gamma rays and proton beam irradiation in cultured tumor cells characterized by a different radio-sensitivity, in view of possible applications in cancer affected patients.

INTRODUCTION

Proton therapy is a new modality for cancer treatment offering several advantages over conventional radiotherapy in selected tumors, such as prostate cancers and ocular tumors, due to the confinement of the high-dose area to the tumour volume and minimization of radiation damage to surrounding normal tissue [1].

To obtain the required uniform region of high dose, the proton beam is usually modulated, to create the so called "Spread-Out Bragg Peak" (SOBP).

The present work aims to exploit ¹H MR spectroscopy (¹H MRS) to study the effects of proton beams irradiation in cultured tumors cells (namely, MCF-7 from human breast carcinoma and HeLa from human cervix carcinoma), by means of identification of spectroscopic markers of radiation effects, related to cell fate, in view of possible applications in cancer treatment.

Irradiation with proton beams was performed at the first Italian proton therapy facility (INFN-LNS, Catania, Italy), optimized for the treatment of ocular tumors such as uveal melanoma.

Cells were irradiated either with the full energy proton beam, close to the Bragg peak (high Linear Energy Transfer - LET), or with the SOBP (low LET) to mimic the therapeutic conditions.

In this work, we examined lipid signals (Lip) in ¹H MRS spectra of cell samples before and after irradiation, in light of providing more information for monitoring therapeutic treatments.

EXPERIMENTAL

All cells were grown as adherent cells as described elsewhere [2]. Cells were irradiated with the proton beam at LNS with single doses of 10 Gy, in different conditions:

- a) on SOPB (depth in water 20,5 mm);
- b) close to the Bragg peak (depth in water 28 mm).

Cells were irradiated in the culturing flask taking advantage of an *ad hoc* home-designed flask holder and beam collimator (Figure 1) displacing the flasks sequentially in the (x,y) plane, perpendicular to the beam axis, by means of two step-by-step motors, with a remote control device.

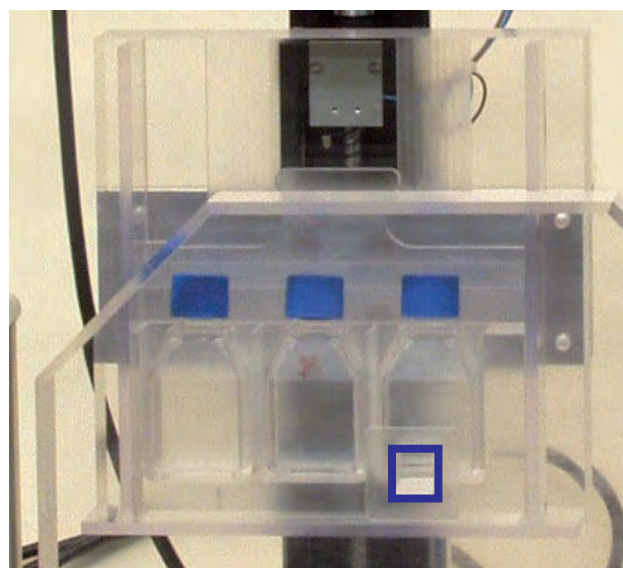


Figure 1: Proton beam collimator and flask holder. The proton beam hits the cells through the squared window (evidenced in blue).

Compliance of the dose on the flask surface was checked by means of Gafchromic® films placed on the bottom of the flask.

1D and 2D COSY ^1H NMR spectra were run at 400.14 MHz on a digital AVANCE spectrometer (Bruker, AG, Darmstadt, Germany) equipped with a 1mm microprobe. Water suppression was obtained by irradiating water signal.

RESULTS AND DISCUSSION

Fatty acid bulk methylene protons resonate at 1.28 ppm (Lip), coupled to terminal methyl protons at 0.87 ppm. The corresponding cross peak (A) is visible in 2D COSY spectra and can be also used for signal quantification. According to current models, these signals are from neutral lipids, mostly triglycerides.

Lipids were quantified in 1D spectra as ratio of methylene peak at 1.28 ppm to macromolecule methyl groups at 0.92 ppm and in 2D spectra as ratio of cross peak A to Lys at 3.00-1.70 ppm.

Differences in Lip signals were found in both cell lines with respect to controls. Figure 2a and b shows the changes measured in A/Lys ratios in HeLa and MCF 7 cells, respectively, as a function of time from irradiation.

Both cell lines are characterized by modulation of Lip signals with time, according to previous observations [2, 3].

Irradiated samples show a different behaviour, being always lower than controls in HeLa cells. In MCF-7 cells, Lip intensities were higher than controls only for the longest observation times.

The same trend was observed in the other lipid originated cross peaks and in 1D spectra (not shown). The observed variations did not seem related to the irradiation conditions, as similar effects were found in cells irradiated with full energy beam at the Bragg peak or in SOBP plateau.

HeLa cells undergo extensive apoptosis after irradiation, with apoptotic cells always > 25%, and maximum values of 60% at 44 hours post irradiation. In MCF-7 cells very little apoptosis can be observed only after 70 hours.

Regarding cell cycle analysis, HeLa cells are arrested in G2+M phases at the expenses of G1 with little changes in S phase (within inter-sample variability), while MCF-7 cells display G2+M arrest at the expenses of S phase.

A close relationship between the increase of Lip signals and the onset of apoptosis, often found by other authors [4], was therefore not confirmed by the present experiments. Cell cycle arrest modalities seem related to the observed spectral changes, according to [2].

About the observed modulations, two hypotheses can be suggested:

- 1) a perturbation due to a radiation-induced alteration of the equilibria between neutral lipid synthesis and breakdown, according to [2];
- 2) changes in lipid mobility.

Lipid mobility, in fact, strongly influences their visibility in MR spectra. Since it has been hypothesized that triglycerides may be partially present in lipid rafts. It has been suggested for a radiosensitive human squamous carcinoma cell line (SCC61) the possibility of lipid raft to coalesce to larger membrane platform [5]. This could induce changes in lipid mobility thus influencing the corresponding signal in NMR spectra.

A comparison of MR spectra of intact cell with lipids extracted as chloroform/methanol soluble molecules (such as TGs) may help in determining if one of the two hypothesis or both of them are responsible for the changes observed in NMR spectra.

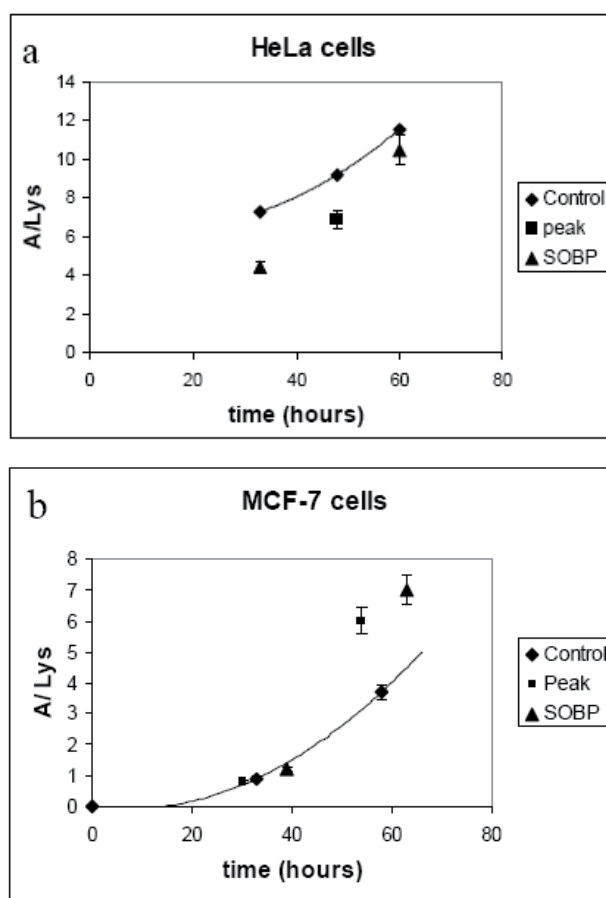


Figure 2: Ratios of A/Lys as a function of time in HeLa (a) and MCF-7 (b) cells. Fit is performed on control samples according to [2].

CONCLUSIONS

Present data show that, in proton irradiated cells, apoptosis does not correlate with the changes of Lip signals, while they may be tentatively correlated to the modalities of cell cycle arrest.

The hypothesis of radiation-induced perturbation of the equilibrium between neutral lipid synthesis and breakdown, observed in cells after gamma irradiation [2],



may hold also for proton-irradiated cells. Moreover, changes in lipid mobility could be hypothesized.

Furthermore, at present, the spectral outcome does not seem related to radiation LET.

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AN "IN-BEAM PET" PROTOTYPE FOR PROTON THERAPY: THE EXPERIMENTS ON INHOMOGENEOUS PHANTOMS

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Abstract

The DoPET (Dosimetry with a Positron Emission Tomograph) project is focused on the development and characterization of an ad-hoc, scalable, dual-head PET prototype for in-beam treatment planning verification of the proton therapy. In this note, we report the first results obtained with our current prototype, by measuring the β^+ -activation induced by 62 MeV proton beams at Catana facility (LNS, Catania, Italy) in different phantoms. Experiments were performed to evaluate the possibility to extract accurate phantom geometrical information from the activity gradients in the reconstructed PET images.

The PET prototype proved its capability in locating small structures in homogeneous phantoms with sub-millimetre accuracy and in distinguishing materials with different ^{16}O and ^{12}C content by back-mapping the phantom geometry through the separation of the isotope contributions. This could be very useful in the clinical practice as a tool to highlight anatomical or physiological organ variations among different treatment sessions and to discriminate different tissue types, thus providing feedbacks for the accuracy of dose deposition.

INTRODUCTION

Proton therapy is a treatment modality of increasing interest in clinical radiation oncology mostly because its dose distribution allows high dose conformality and a reduced integral dose compared to conventional radiation therapy based on X-rays and electrons [1]. The advantages are centred on the characteristic Bragg peak: a sharp maximum in the linear energy transfer of the projectile (LET) that, if rightly positioned, can concentrate the effect of the irradiation on the tissue in a more localized region. In this context, a meticulous planning and a careful implementation of the required treatment become crucial pre-requisites to guarantee the reliable benefits of the proton therapy, especially when the target volume is located next to critical organs and a fractioned therapy is applied.

A careful examination of uncertainty sources in the radiation process, starting from the initial treatment planning to the real patient dose delivery, has provided insights into ways in which new imaging strategies are

necessary to monitor, correct and adapt for any errors that might occur. Clinical uncertainties in the accuracy of the particle range determination are intrinsic in the use of pencil-beam-based treatment planning program. Further sources of uncertainties include random and systematic patient setup error, variations in organ physiological states, which may cause interfractional target motion and intrafractional organ motion.

A possible method to verify the geometric accuracy of the delivered dose and to ensure the high quality of the proton therapy is to use Positron Emission Tomography (PET), which takes advantage of the nuclear inelastic reactions between protons and nuclei in the tissue during irradiation, producing small amounts of short-lived β^+ -emitting isotopes, detectable by means of a positron emission scanner [2,3]. Verification of the therapy can be achieved by comparing measured PET images with the yield of the positron emitters predicted on the basis of the treatment planning system [4,5].

We are characterizing an ad hoc dual-head PET detector to enable application-optimized imaging for dose monitoring in proton therapy. The small prototype has been intended to be easy to scale-up, compact and with the resolution and sensitivity performances required for monitoring purposes at low count levels that is competitive with commercial state of art clinical PET scanner accuracy.

In this note we report the results we obtained in the attempt to evaluate the possibility of using information stored in the reconstructed PET images to resolve structures and to distinguish materials of different stoichiometry.

MATERIALS AND METHODS

The prototype architecture and the preliminary experimental results from proton activation study on homogeneous phantoms have been already reported in [8, 10]. We remind here that the PET prototype is based on two stationary planar heads, consisting of two opposing $4.5 \times 4.5 \times 1.8 \text{ cm}^3$ lutetium yttrium orthosilicate (LYSO) scintillator matrices, 21×21 pixels ($2 \times 2 \times 18 \text{ mm}^3$ pixel dimensions). A squared position sensitive photomultiplier with an external area of $5 \times 5 \text{ cm}^2$ has been used for measuring the light output. For the position encoding readout, we chose a charge division circuit based on the

Symmetric Charge Division (SCD) scheme, reducing the 64 anode signals of each photomultiplier to only 4 acquired per head [6]. The data acquisition is performed using a fast acquisition board previously developed for the small animal PET/ SPECT scanner YAP-(S)PET. The four position signals from each tube are digitized by a system composed of a peak detector plus a peak sensing ADC. The digital data from both detector heads are then transferred to a local PC server via USB connection. In all our post-irradiation measurements at CATANA, the PC server has been placed inside the treatment room, and the acquisitions have been controlled from the beam-line control room by means of a PC client via LAN connection.

We chose an iterative 3D maximum-likelihood expectation maximization algorithm (ML-EM) [9] to reconstruct the distributions of produced positron-emitters in our experiments.

EXPERIMENTAL RESULTS

The experiments on inhomogeneous phantoms

To investigate the possibility of using information stored in the reconstructed activity to back-map the phantom geometry in presence of various density values and stoichiometry, several phantoms ($5 \times 5 \times 5 \text{ cm}^3$) were realized assembling differently sized slabs of PMMA ($\text{C}_5\text{H}_8\text{O}_2$), PE (Polyethylene, C_2H_4), and other tissue equivalent materials. Phantom irradiation modalities were similar to those characterizing the first experiments presented in [8, 10]. Proton beams of 62 MeV with an initial energy spread of about 300 keV, shaped by a brass collimator with an aperture diameter of 25 mm, were delivered to the phantoms into the CATANA treatment room for eye tumours. During irradiation, all phantoms were positioned at the center of the field of view with the detector heads at a distance of 14 cm.

In Fig.1, we reported the results we obtained irradiating a phantom with PMMA and PE slabs (0.5 cm thick along the beam axis) set side by side and located between the detector heads so that the beam direction was perpendicular to the slabs.

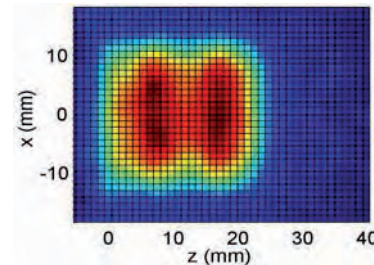
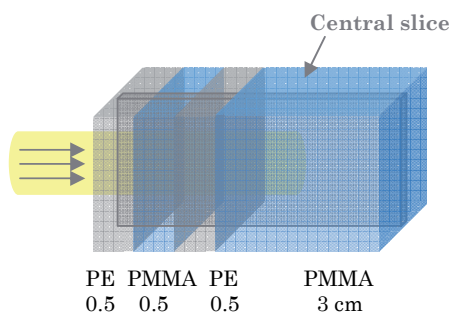


Figure 1: Phantom layout and reconstructed 2D activity distribution in the central XZ plane.

The two-dimensional positron emitter distribution in the central XZ plane shows a significant activity contrast between the two materials. In order to recover the phantom geometry by means of the gradient analysis, we tried to single out the relative amounts of isotopes produced during irradiations and to explore their contributions to the shape of the reconstructed 3D activity distributions. Separation showed how the PMMA slabs alternate with the PE slabs.

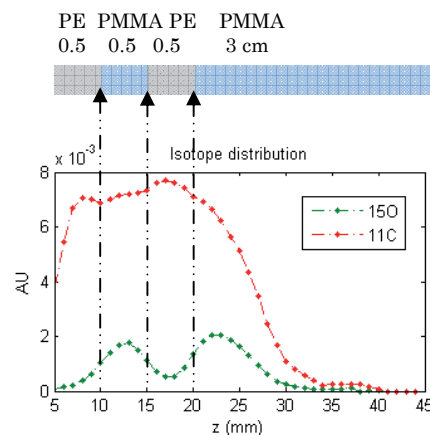


Figure 2: ^{15}O and ^{11}C isotope distributions along the beam direction.

The same considerations can be extended also to the case of the phantom with the PMMA and bone equivalent slabs arranged as shown in Fig.3. In the 2D graph, the isotope profiles along the beam line show an increased activity in the bone region since the short-lived isotope ^{38}K is detected additionally to ^{15}O , as indicated by the separation of isotope contributions displayed in the lower images.

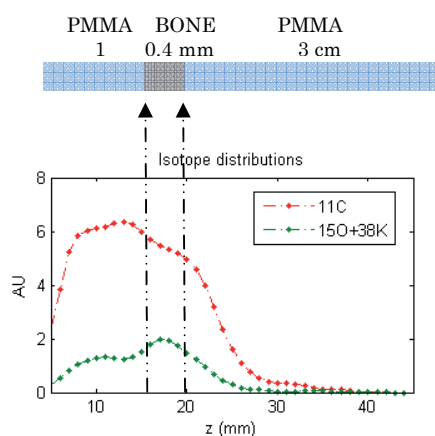


Figure 3: $^{15}\text{O}+^{38}\text{K}$ and ^{11}C isotope distributions along the beam direction in the central XZ plane of a phantom composed by PMMA and bone equivalent slabs.

CONCLUSIONS

The experiments with inhomogeneous phantoms demonstrated the sensitivity of the PET method in distinguishing material of different chemical composition.

By back mapping phantom geometries through the separation of the isotope contributions we observed how a data acquisition soon after the end of irradiation allow structures of different stoichiometry to be resolved at least qualitatively. Quantitative analyses are now under investigation and will be reported in a separated paper.

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PIXE STUDY OF DEAD SEA SCROLLS SAMPLES

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Abstract

Dead Sea Scrolls are one of the most interesting archaeological findings in the recent decades. They have been discovered in various caves on West shore of the Dead Sea (Fig. 1) and contain the most ancient copies of the Old Testament.

In recent time, a systematic investigation has been undertaken within collaboration between the INFN-LNS LANDIS laboratory of Catania (Italy) and the BAM Institute (Bundesanstalt für Materialforschung und -prüfung, WG “Analysis of Cultural Assets”) of Berlin. The aim of the research is devoted to elucidate at what extent non destructive methods, possibly carried out with portable systems, can give information on the specific provenance of the scrolls through the comparison of their chemical constituents with those (water, minerals) characterizing the Dead Sea region.

8 small fragments: 4 “Q”(Qumran) fragments from the Ronald Reed collection of the John Rylands University Library and 4 “TS” (Temple Scroll, Fig. 2) from the collection of the Shrine of the Book of the Israel Museum, have been investigated by using the portable XPIXE apparatus that makes use of a ²⁴⁴Cm source as alpha and X-ray emitter and by using a 1.3 MeV external proton beam produced by the LNS tandem accelerator. We present the experimental arrangement and the preliminary results.

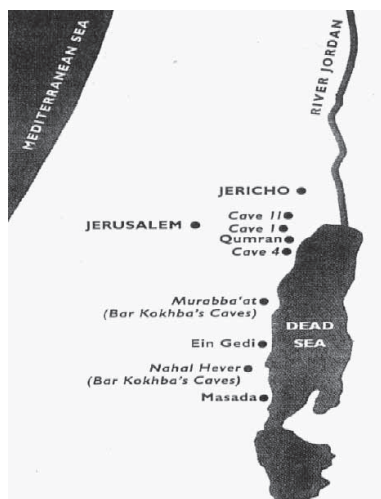


Fig. 1 – The Dead Sea Region



Fig. 2 – The Temple Scroll (11Q19)

THE SAMPLES

The analysis has been carried-out on:

- A) n. 4 samples TS2, TS4, TS5, TS7 (see Fig. 3), from the Temple Scroll, which is the longest one among the Dead Sea Scrolls and describes a Jewish temple, the sacrifices and temple practice.
 B) n. 4 Q samples: 4Q2, 4Q11b and 4Q28 coming from cave 4 of Qumran and Q9 sample of unknown origin

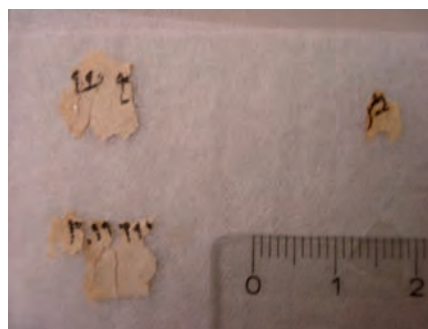


Fig. 3 – Some of the TS samples analyzed in the present work: TS4 left, upper; TS5 left, lower.

ANALYTICAL PROBLEMS AND EXPERIMENTAL METHODS

The scroll samples are generally in homogeneous. Their surface is expected to be covered by contaminants that arise from: i) the surrounding soil; ii) the residues of

restoration procedures; iii) organic residues. The body is constituted by the parchment whose matrix composition is, in general, known. The thickness of the superficial contaminant layers is of the order of few microns and the thickness of the parchment is typically of some hundred of microns. The chemical elements present in the surface and in the body are of very different atomic number: i) very light elements constituting the organic materials, ii) light elements (Na, Mg, S, Cl) of various origin, and iii) medium-high atomic number elements characterizing the body and the surfaces like Ca, Fe, Br and Sr.

The above considerations (i.e. the necessity of detecting light and medium atomic number elements present on the surface or in the body) have suggested the use, for qualitative and, whenever possible, quantitative analysis, the PIXE (Particle Induced X-ray Emission) methods and in particular the portable XPIXE which operates by emitting both alpha particles and X-rays.

XPIXE SPECTROMETER AND ANALYSIS

The XPIXE spectrometer, which makes use of an annular radioactive (^{244}Cm) source emitting both alpha particles and X-rays, has been described elsewhere [1]. It is portable and gives the possibility of detect light elements ($Z>10$) through the PIXE mechanism and the medium-heavy ones through XRF process. For this reason XPIXE is very appropriate to perform a qualitative analysis of the dead sea samples. The experimental arrangement is shown in Fig. 4.

Incoming beams (alpha particles and X-rays) induce in the samples the emission of X-rays that are detected by an SDD detector. A further collimation is achieved by limiting the incoming beam and outgoing X-rays to pass through a $\phi=10\text{mm}$ hole realized in a 3mm thick Mylar foil.

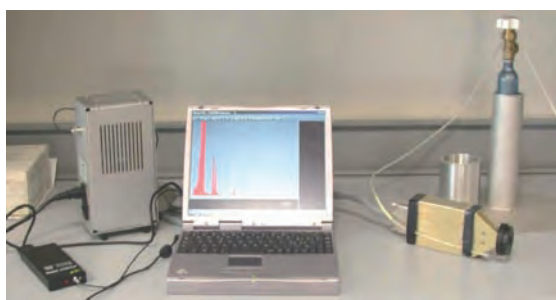


Fig. 4 – The portable XPIXE spectrometer

Typical XPIXE spectra taken on the TS and Q samples are shown in Fig. 5 - 6.

As expected, both light and medium mass number elements lines are visible, from Na to Br. As a general comment it can be observed that the data of the TS samples agree with the presence of Gypsum (S, Ca) and Alum (Al, S, K) suggested by independent measurements [2].

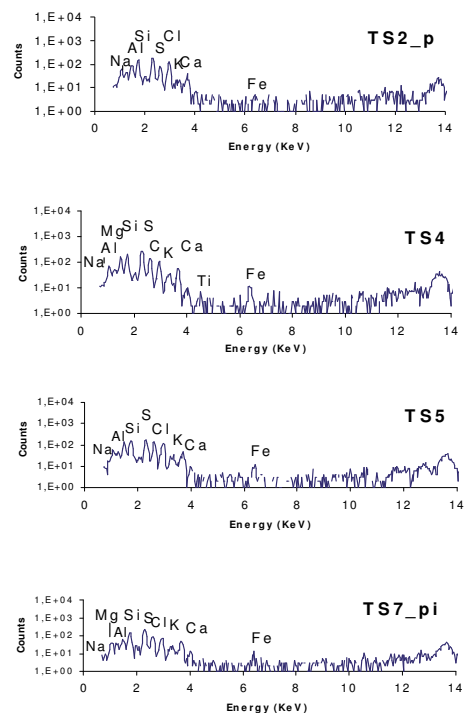


Fig. 5 – XPIXE X-ray energy spectra of the TS samples

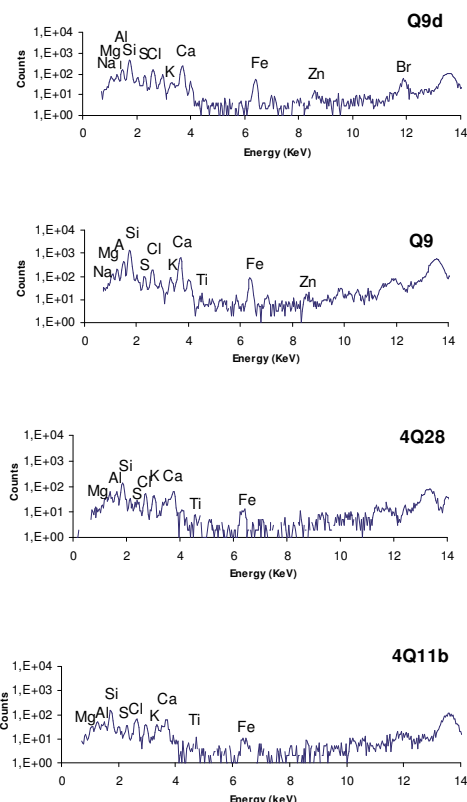


Fig. 6 – XPIXE X-ray energy spectra for the Q samples

Cl lines are clearly shown. However the sensitivity of the system do not allows the detection of Br X-rays. The Q samples show an important excitation of the Mg line; also Si, Ca and Fe are strongly excited. It is possible that these elements constitute the superficial layer of the samples. In the Q9 case the Br line is present. As before stressed, the XPIXE system cannot give separate information on the sample surface and on the body because of the above discussed arguments related to the presence of strong in homogeneities. To obtain reliable quantitative information on the composition of the samples and to increase the sensitivity we have performed accelerator based PIXE analysis.

1.3 MEV PROTON BEAM PIXE FOR THE DETERMINATION OF THE CL/BR RATIO IN TS SAMPLES

To increase the sensitivity of the system, we used as incident external beam the 1.3 MeV proton ($i = 10\text{nA}$) from the LNS tandem accelerator. The experimental arrangement is shown in Fig. 7. The fluorescence X-rays were detected by a 80 mm^2 SDD detector having 170 eV energy resolution and by a 10 mm^2 SDD detector with 140 eV energy resolution. The obtained X-ray spectra for the TS and 4Q samples are shown in Fig. 8. The X-lines of S, Cl, K, Ca are well excited. Also, at 11.9 keV the lines of Br are evident in all the spectra.

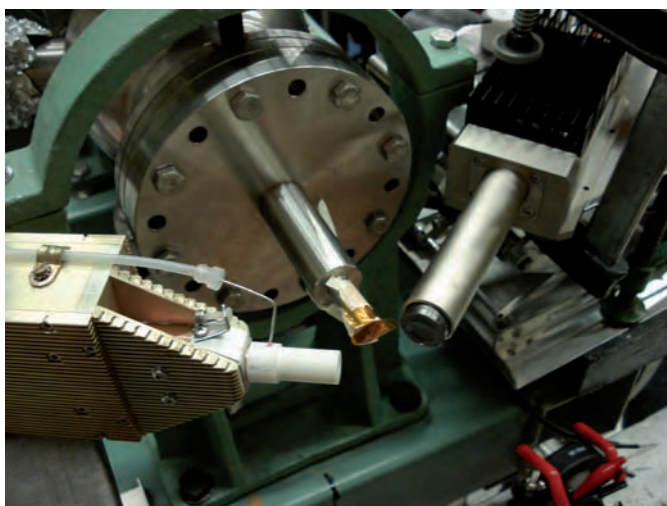


Fig. 7 - The LNS tandem external PIXE and the large area and small area detectors

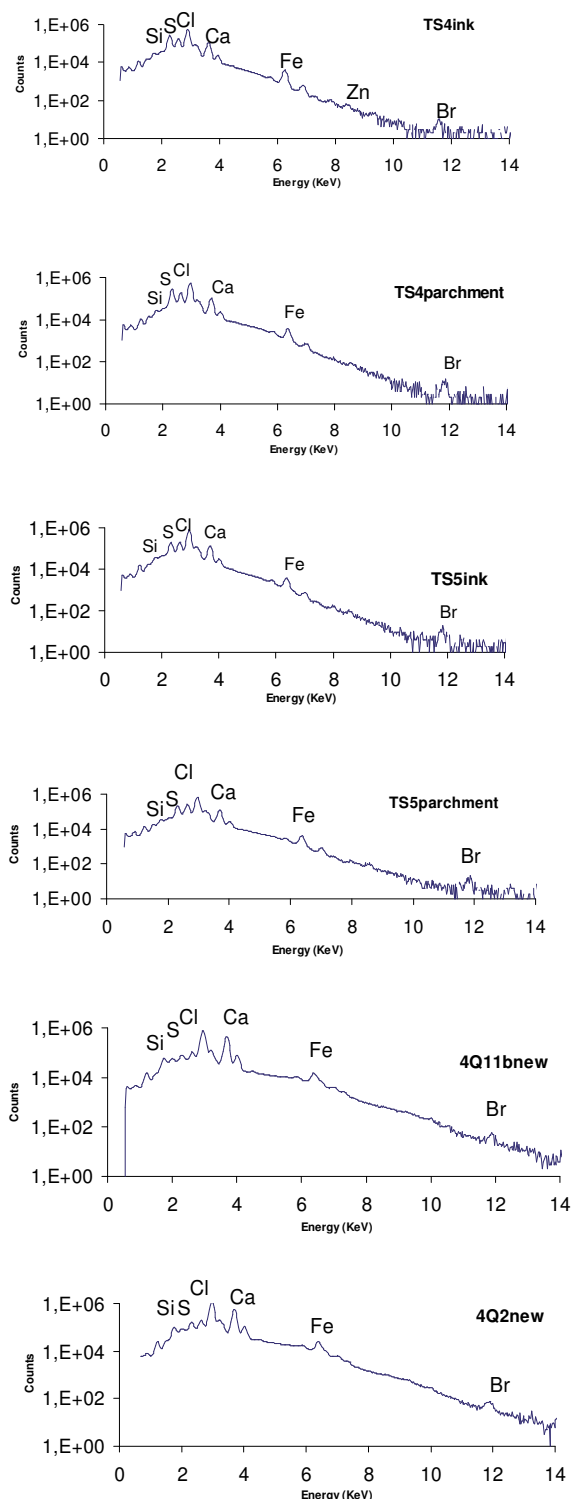


Fig. 8 – PIXE X-ray energy spectra induced by 1.3 MeV protons. Cl and Br lines are visible

CONCLUSION

Qualitative analysis. Due to the presence of both light and heavy atomic number elements, which are equally important for the dead sea samples characterization, the XPIXE system has shown to be particularly appropriate for a qualitative examination.

The TS samples exhibit high intensity peaks of Al, S, K and Ca whose presence is consistent with surface contaminations of Alum and Gypsum, as independently suggested.

The Q samples show particularly high intensity peaks due to the presence of Mg, Si, S, Ca, Fe. The most part can be attributed to a soil contamination.

In both cases Cl and Br are to be related to the salinity of the water in the region. The ratio Cl/Br could be indicative of the provenance.

Quantitative analysis. Due to the discussed inhomogeneities, a PIXE quantitative analysis cannot give reliable results: independent information on the structure of the sample are needed.

Work to obtain information on the layered structure is in progress in collaboration with the BAM Institute.

ACKNOWLEDGEMENTS

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THE EAST SICILY NODE OF THE LIDO DEMONSTRATION MISSION

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Abstract

Within the ESONET NoE, the LIDO (Listening to Deep Ocean) Demonstration Mission is carried out by ten European Research Institutes and Companies. The LIDO D.M. foresees installations in two deep sea sites: a stand-alone mooring in the Cadiz Node (offshore Portugal) and a cabled observatory in the East-Sicily Node (offshore Catania, Italy). The aim of LIDO is to demonstrate the capabilities of real-time data transmission from deep sea multidisciplinary observatories. The main topics of the mission are bioacoustics, geo-hazard and environmental monitoring.

THE LIDO DEMO-MISSION OF ESONET

ESONET, whose preparatory phase EMSO (European Multidisciplinary Seas Observatories) is in progress[1], is a European Network of Excellence of deep-sea observatories that includes 55 partners belonging to 14 countries. ESONET NoE is already providing data on key parameters of shallow and deep sea environment from several marine sites around Europe. One of the main goals of ESONET is to test and standardize technology, strategies of deployment, data sampling and data management. LIDO (Listening to the Deep Ocean environment) is an ESONET demonstration mission that proposes to establish a first nucleus of a regional network of multidisciplinary seafloor observatories contributing to the coordination of high quality research in the ESONET-EMSO, by allowing the real-time long-term monitoring of geohazards and marine ambient noise in the Mediterranean Sea and the adjacent Atlantic waters. Specific activities address the long-term monitoring of earthquakes and tsunamis and the characterisation of ambient noise, marine mammal sounds and anthropogenic sources. The objectives of the LIDO demonstration mission will be achieved through the extension of the present capabilities of the observatories working in the ESONET key-sites of Eastern Sicily (NEMO-SN1[2]) and of the Gulf of Cadiz (GEOSTAR configured for NEAREST pilot experiment) by installing new sensor equipments related to bioacoustics and geohazards, as well as by implementing international standard methods in sea operations, data acquisition and management.

LIDO - EAST SICILY

In the East Sicily (2100 m depth, 25 km off-shore the harbour of Catania) a prototype of a cabled deep-sea observatory was set up and is operational in real time since 2005: the cabled deep-sea multi-parameter station SN1[3], equipped with geophysical and environmental sensors and the cabled NEMO-OvDE station [4], equipped with 4 wideband hydrophones. The LIDO-East Sicily installation represents a further major step within ESONET/EMSO: it is a fully integrated system for multidisciplinary deep-sea science, capable to transmit and distribute data in real time to the scientific community and to the general public. LIDO-East Sicily 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, connected with the two deep sea cabled terminations named Test Site North (TSN) and Test Site South (TSS) respectively, as shown in Fig. 1.

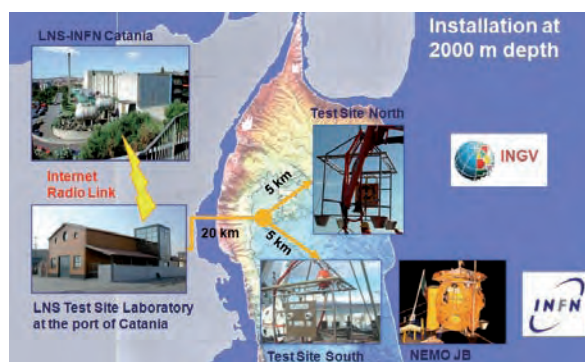


Figure 1: Scheme of the LNS-INFN Catania Test Site infrastructure, used for NEMO, SN1 and LIDO.

The whole system will be connected and powered from shore, by means of the electro-optical cable net installed at the East Sicily Site Infrastructure, and synchronised with GPS. Sensors data sampling is performed underwater and data are transmitted via optical fibre link, with optimal S/N ratio for all signals. This will also

permit real-time data acquisition, analysis and distribution on-shore. Innovative electronics for the off-shore data acquisition and transmission systems has been designed, built and tested. A dedicated computing and networking infrastructure for data acquisition, storage and distribution through the internet has been also created. The deployment and connection of the deep sea structures will be performed using the dedicated PEGASO ROV, shown in Fig.2 (owned and operated by INGV and INFN), and the MODUS Deep Sea Shuttle handling facility [3], shown in Fig. 3.



Figure 2: The PEGASO ROV (INGV-INFN)

THE LIDO TSN AND TSS STATIONS

As described before, LIDO East Sicily will be formed by two independent stations, anchored on the seabed and connected with the TSN and TSS terminations of the Catania deep-sea infrastructure cable.

The TSN station will be hosted onboard a refurbished version of the former SN1 observatory, Fig. 3.



Figure 3: Left- The SN1 Station hanged to the MODUS deep sea shuttle before the deployment (2005). Right- Mechanical structure of the LIDO TSN station.

The structure, about 1 metre height, is equipped with a cylindrical container hosting power transformation electronics (from 700 VAC, sent from shore, to low voltage for the instruments), optical fibre splitters and multiplexers, and the data acquisition electronics for a number of sensors, as listed in Table 1.

<i>Instrument</i>	<i>Model</i>	<i>Sampling rate</i>
Triaxial seismometer	Guralp CMG-1T	100 Hz
CTD and turbidity meter	Seabird 37-SM	1 sample /hour
Gravity metre	IFSI	1 Hz
Current metre	MAVS-3 Nobska	
Scalar magnetometer	Sentinel/3000	1 Hz
Vectorial magnetometer	Custom	1 Hz
Low frequency hydrophone	OAS E-2PD	100 Hz
Low frequency hydrophone	SMID 70XA405	2 kHz
Accelerometer and compass	IMU LMRK150-02-130	200 Hz
Absolute Pressure gauge	Paroscientific 8CB4000-I	0.07: 1 Hz
Differential pressure gauge	Univ. San Diego v. 6.3	100 Hz
Acoustic Doppler current metre	RDI, Workhorse Sentinel 600 kHz WHS600-I-UG149	1 profile / hour

Table 1: Geoseismic and environmental instruments onboard the LIDO TSN station.

An independent system for acoustic signals detection, equipped with four broadband hydrophones, displaced forming a tetrahedral antenna of about 1 m side, will be also installed on this frame. This system, based on the technology developed for the NEMO-OvDE station, is composed by four SMID TR-401(V)1 hydrophones [5]. The hydrophones have usable frequency response between few Hz and 70 kHz, average sensitivity of -210 ± 3 dB re 1 V/ μ Pa, and omni-directional response. Hydrophones are coupled with a 38 dB gain ultra-low-noise preamplifier, developed by SMID. Similarly to NEMO-OvDE the hydrophones signals are synchronously sampled at 24 bit, 96 kHz, using a 4 channel Sigma-Delta A/D converter Texas Instruments PCM4204 ($V_{Max}^{Input} = 2 V_{RMS}$) [6]. Data are also formatted into the AES3-EBU stereo audio standard protocol [7]. This part of the front end electronics is hosted inside a 13'' diameter glass housing (Fig. 4).

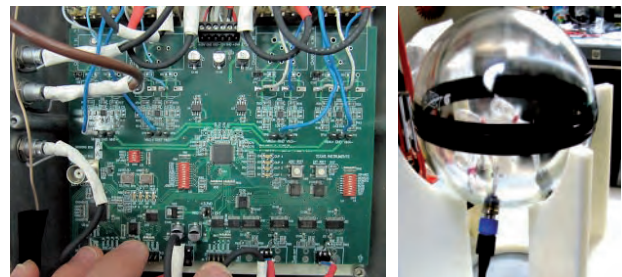


Figure 4: Left- A/D board for the LIDO TSN acoustic signal acquisition. Right- The LIDO TSN glass-housing hosting acoustic data acquisition electronics.

The two AES-3/EBU data streams, are then sent to a pair of electro-optical modems, hosted inside the cylindrical vessel, and then transmitted to shore in optical format.

The total electronics noise of the system has been measured to be about -75 dB re $1V_{RMS}$, with a spectrum shown in Fig 5. This would lead to about 80 dB dynamic range for acoustic signals in the bandwidth 4 Hz-45 kHz.



Figure 5: Electronics noise spectrum measured for a channel of the LIDO TSN acoustic data chain.

On-shore, in the LNS Lab of the Port of Catania, optical data are reconverted into electrical AES-3 standard and acquired using a professional audio DAQ board (RME – HDSP 32 [8]) installed on the PCI bus of a Personal Computer called *Acoustic Data Server* (ADS).

In the Southern termination of the Cable, the LIDO TSS station will be connected to the NEMO Test Site Junction Box [2], through an electro-optical jumper. The Junction Box will provide power supply and optical connection to shore. LIDO TSS consists of a mechanical frame (Fig. 6) holding a cylindrical pressure vessel – containing the data acquisition and transmission electronics- four SMID TR-401(V)1 hydrophones with preamplifiers and a CTD (Conductivity, Temperature, Depth) probe. The CTD will be used to recover the value of the speed of sound and to monitor environmental conditions at the site. Hydrophones signals (amplified using the same preamplifiers as in LIDO TSN) are read in pairs by two boards designed and built by the INFN in collaboration with AGE Scientific [9] (Fig. 7). Each *AcouBoard* (based on the Cirrus Logic CS5381 Sigma-Delta A/D converter [10]), samples the signals from two hydrophones at 24 bits ($V_{Max}^{Input} = 2 V_{RMS}$) and 192 kHz, and encodes it using the EBU/AES-3 standard. The digitized signals are then sent to a *Control Module* (CM) board that performs conversion from electrical into optical, embedding also the absolute GPS time into the acoustic data stream. The CM, in fact, receives the GPS time signal from shore and drives the *AcouBoards* clocks [11]. The noise spectrum of each hydrophone channel was measured (Fig. 8), the total noise power is about -70 dB re $1V_{RMS}$ over the frequency range 4 Hz ÷ 92 kHz. The latency of the whole system was also measured to be constant and equal to $170 \pm 1 \mu s$.

On shore, a twin CM board receives the optical data stream, in which are embedded data from the four hydrophones and from the CTD, and parses them. The on-shore CM distributes the hydrophones data to the ADS for further analysis and storage as described in the following.



Figure 6: Left- The NEMO Junction Box. Right- Design of the deep sea frame holding the LIDO TSS station.

A photo of the “off-shore” electronics for LIDO TSS is shown in Fig. 7: all the boards are hosted in an 80 cm-long rack fitting into the pressure vessel.

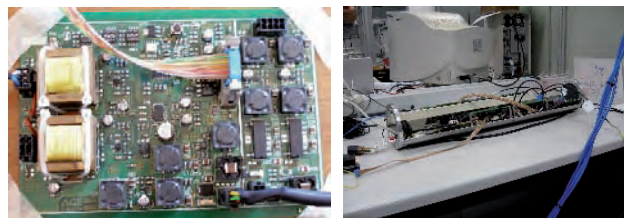


Figure 7: Left- The *AcouBoard*. Right- The rack hosting the LIDO TSS front-end and data transmission electronics.

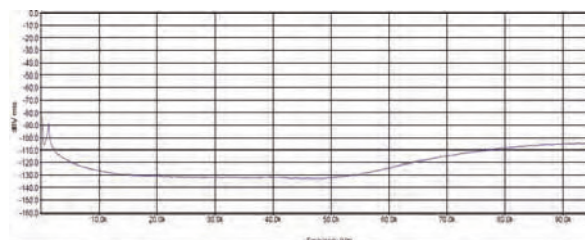


Figure 8: Electronics noise spectrum measured for a channel of the LIDO TSS acoustic data chain.

THE LIDO EAST-SICILY COMPUTING AND NETWORKING SYSTEM

All data from the two LIDO stations will be continuously transmitted from deep sea to the Catania Test Site Laboratory, through optical fibres. The data rate from the acoustic detectors is about 36 Mbps, a limited bandwidth (few kbps) is required for the geophysics and environmental sensors. The transmission to the internet of this amount of data is not possible using the available 24 Mbps radio connection between the LNS and the Site Lab. Therefore raw data must be acquired and temporary stored locally at the Test Site Lab.

The LIDO computing and networking infrastructure is sketched in Fig. 9. The ADS will receive the raw AES-3/EBU data streams from the acoustic detectors and will

re-distribute data from each hydrophone, as TCP-IP packets, through the shore Laboratory Local Area Network. Three main clients for acoustic data treatment are foreseen. One client will compress data from one TSN hydrophone in standard MP3 format, for real-time data availability over the internet. Another client will perform fast real-time analysis (noise monitoring, search for high amplitude signals, ...) and save results on a local storage unit; the third client is "circular buffer" storage unit called Raw Data Storage (RDS) that compresses raw data and copy (together with analysed data) them into a Main Data Storage (MDS) unit, located at LNS. Geophysics sensors data will be processed separately and also stored into the RDS, to be copied in the MDS.

Thanks to the fast internet access and network infrastructure available at LNS-INFN, the Institutes participating in the LIDO D.M. will access data stored in the MDS. A subset of data will be available to the general public, through web and streaming servers located at LNS.

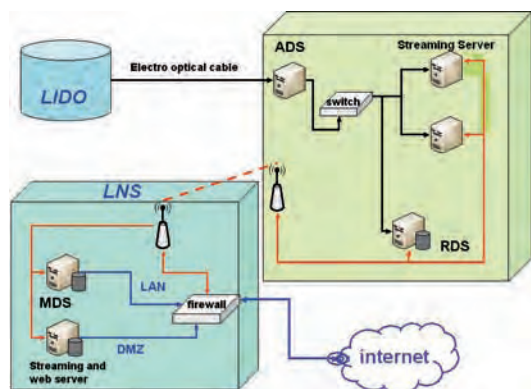


Figure 10: Networking/computing architecture for LIDO East Sicily. Data will be available on the internet, through the LNS-INFN networking and computing infrastructure.

CONCLUSIONS AND PERSPECTIVES

The LIDO Demonstration Mission Team is undergoing the integration of the two stations, that will be deployed in the East Sicily ESONET node (Catania LNS-INFN Test Site) at the end of 2010. Data will be made immediately available. An intense R&D activity was conducted to design a data acquisition system based on the "all data to shore" concept capable to provide, in addition, all data with absolute GPS time-stamp. All the components of the system were built and successfully tested to work at the site pressure (>200 bar).

LIDO East Sicily is, therefore, expected to become the first node of ESONET providing multidisciplinary data in real-time to the Earth and Sea science community and, a subset of them, to the general public for dissemination, opening a new window in the exploration and understanding of deep sea.

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AN ONLINE MONITORING SYSTEM FOR NUCLEAR WASTE STORAGE

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Abstract

The demand for on-line monitoring of short and medium term radioactive waste repositories, has led us to develop a distributed and fine-grained detection mesh. Its robustness, reliability and low cost, could open new perspectives for waste packaging and storage. The detection unit employ a new family of cheap and powerful micro sensors to be placed in shape of a fine grid around each single drum.

INTRODUCTION

The DMNR project (Detector Mesh for Nuclear Repositories) has started to develop an integrated solution for on-line monitoring of short and medium term radioactive waste, as recommended by the International Atomic Energy Agency (IAEA) [1]. The aim is to guarantee a high level of safety of the waste storage, by detecting possible leaks of radioactive material in a short time, thus reducing the risks of contamination for the operators and for the environment. A distributed mesh of low-cost detectors provides a real time 3-dimensional map of the radioactivity produced by a waste repository. When a leak occurs in a drum, it is recognized because of the increase of the local activity, so that robots or operators could be driven in case for a high accuracy inspection around the drums [2].

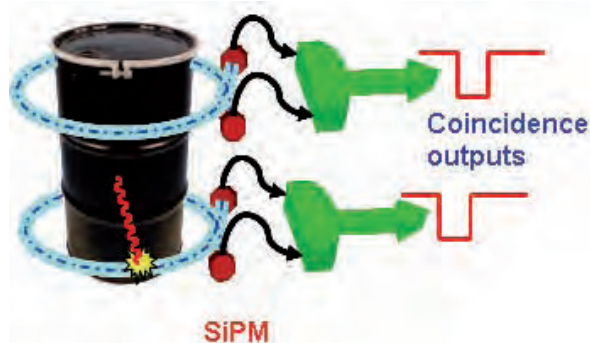


Figure 1. Grid of fibres around the drum.

The detection unit of the mesh is a scintillating fibres, arranged as a grid of sensors around each waste drum (Figure 1). At the ends of each fibre, silicon photodiodes with a very high sensitivity, known as Silicon PhotoMultipliers (SiPM), are optically coupled. The

pulses are suitably discriminated to reject the spurious, acquired by an acquisition system based on FPGA and close to the drum. Finally the collected data are sent to the main unit detection.

GEANT SIMULATION

The choice of the most appropriate detection geometry has been supported by simulations, using the Geant MonteCarlo code. It has allowed the to study the performances of a plastic scintillating fibre (polyvinyltoluene by Pol.Hi.Tec) 1.2 m long and 1 mm diameter, considering a point-like source of ^{60}Co .

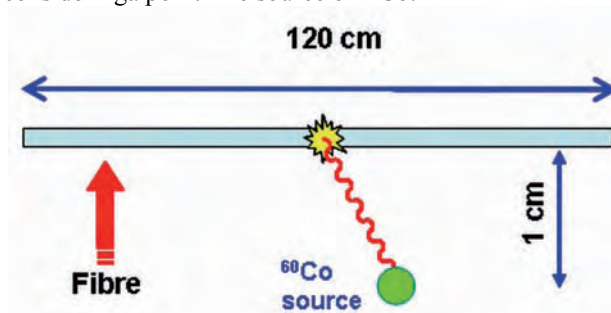


Figure 2. Basic scheme of the simulated geometry.

In our first simulation the source was placed at three distances from the center of the fibre, and we took into account only the two gamma rays produced by the ^{60}Co decay (1.17 MeV and 1.33 MeV).

We performed several runs with distances source-fibre of 0.15, 1, 10 cm, considering only those events that produce a detectable light signal at both fibre ends (i.e. in temporal coincidence). A simulated spectrum of released energy inside the fibre is shown in fig. 3; the corresponding spectrum of detected photons with a threshold of 6-photon is shown in fig. 4. The evaluated fibre efficiency, as calculated taking into account also the beta particle produced by the decay of the ^{60}Co , is shown in fig. 5. Three different distances has been considered, 1.5 mm (circle), 1 cm (diamond) and 10 cm (square).

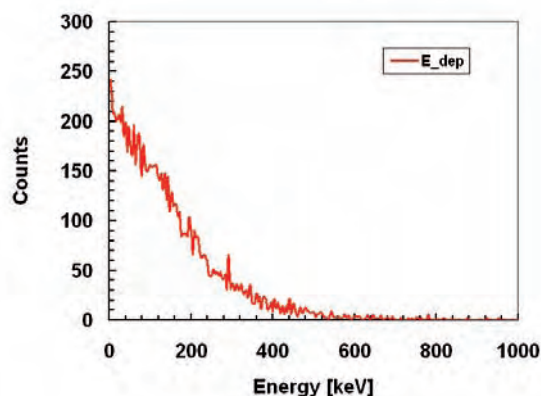


Figure 3. Energy spectrum from ^{60}Co source calculated by means of the Geant simulation.

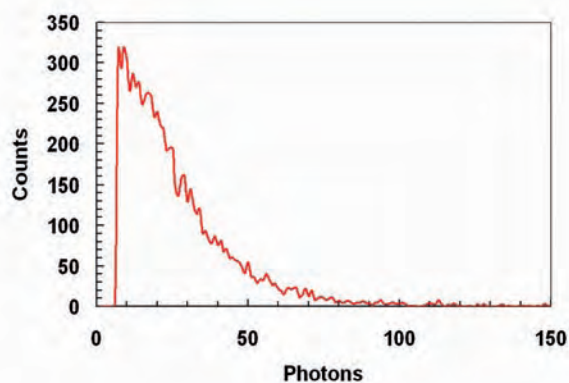


Figure 4. Example of simulated photon spectrum with a threshold of 6 photons at both fibre ends.

In a preliminary experimental test we had estimated the intrinsic efficiency of the fibres, employing a gamma source of ^{60}Co (1.17 and 1.33 MeV) and another one of ^{241}Am (59 keV). The measurements were carried out by coupling each end of the fibre with two silicon photomultiplier sensors, namely Hamamatsu MPPC S10362-11-100U, biased at 70V. We measured an efficiency of the order of 0.05-0.5%. Unfortunately these sensors are strongly affected by the presence of correlated noise, i.e. cross-talk, (see figure 6 and refs. [10] [11]), and forced us to set a high value of threshold (6 photons). In the meantime we plan to set up new measurements using better performing silicon photomultipliers biased at 30V, produced by STMicroelectronics, under more realistic conditions.

THE EXPERIMENTAL APPARATUS

The mesh of detectors has to be properly distributed, fine-grained, robust, reliable, and should be based on low-cost components. In addition, the sensors have to be operated in Geiger mode (on/off), since they are just needed to count the ionizing radiation events.

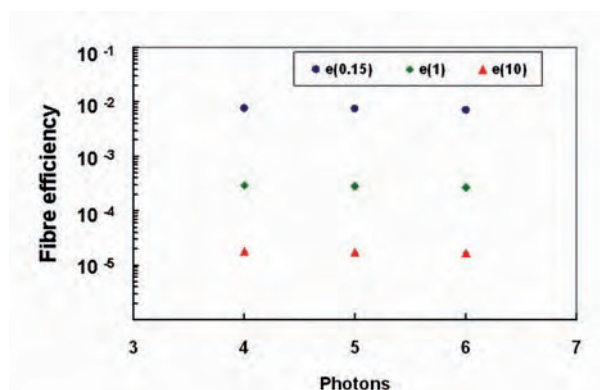


Figure 5. Simulated fibre efficiency for ^{60}Co source at three distances from the fibre center, including the contribution due to beta electrons. The errors bars lie within the symbol.

Each detector consists of a scintillating optical fibre, 1-2 m long. The plastic fibre with the scintillating core made by polyvinyl-toluene, is manufactured by Pol.Hi.Tec. Its diameter is 1 mm with 40 μm of inert cladding and attenuation length $\lambda = 3.3$ meter. Its minimum trapping efficiency for isotropic light emission is 3.4% at each fibre end, as can be easily calculated starting from the refraction index values $n_1 = 1.58$ (core) and $n_2 = 1.48$ (cladding) [5] [6] [7]. The decay time of the scintillation light, $\tau \sim 3$ ns, allows to measure activities of the order of MHz (the expected count rate is in the range $10^3 - 10^5$ /fibre/s). The scintillation spectrum lies in the blue region with a maximum around 420 nm.

From radiation hardness point of view, even though it is low for this kind of fibres, the damage will be kept low as well since the overall efficiency is low. With a reference drum containing 20 litres of waste incorporated in concrete and surrounded by a layer of mortar, with a total activity of $\sim 10^{12}$ gamma/s, the corresponding dose rate is 10 – 100 mGy/h. Under these assumptions we estimated, for a detector placed close to a drum, a life of the order of at least 100 years [3].

The fibres are arranged around each drum in longitudinal and/or ring geometry, see fig. 1. Both geometries can be adopted, as the most likely leak position has to be determined. Each fibre can intercept radiation coming out of 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 fibre itself. In order to evaluate the number of photons to be detected, we have to consider all the efficiencies, i.e. the light yield (10^4 photons/MeV), the average energy released by the gamma rays (0.1), the fraction of the light reaching the ends (roughly 3%). The detected photons should be around 20-30 per event.

Using standard photomultiplier tubes would pose issues like cost, non-ruggedness, fragility, high-voltage power supply, damage from accidental exposure to ambient light. Therefore we need a rugged photodetector to be coupled to each fibre end, with a sensitivity down to the

single photon and capable of fast timing, in order to select events in strict coincidence between the two fibre sides. When a pulse is detected on both sensors within few tens of nanoseconds, it is recognized as an ionising event, counted and recorded to compute the overall activity.

THE SiPM PHOTODETECTORS

The high sensitivity photodetector we have decided to use is the newly born SiPM (Silicon PhotoMultiplier), a promising cheap detector that is reliable and easy to handle. It is a 2-dimensional array of a Single Photon Avalanche Diode (SPAD) cells. A SPAD is a p-n junction operating in Geiger mode (on/off) at low voltage (30 to 70 Volts depending on the manufacturer) and made up in silicon planar technology. The junction is biased a little above the breakdown voltage (about 10% more of the breakdown voltage itself), and it remains inactive until a photon is absorbed in the depletion region. The outputs of all cells are connected together to form one common signal [8]. Each SPAD operates in the Geiger regime, basically producing the same pulse (rise time 0.5-5 ns) when fired by a photon or because of thermal generation. When a fast light pulse is detected by the SiPM, its output is the sum of the identical pulses produced by each fired pixel. Its sensitivity can be as low as the single photon, but such a lower limit is strongly affected by dark noise.

THE SiPM FEATURES

We have tested two SiPM models, produced respectively by Hamamatsu photonics (S10362-11-100U, commercially available) and STMicroelectronics (not yet available on the market) [9] [10]. Both feature 10x10 cells, with overall size of 1 x 1 mm² and 0.5 x 0.5 mm² respectively.

In order to characterize the device response with respect to a low level of incident light for both devices, we have used a laser source to produce fast pulses (FWHM = 50ps) in the $\lambda=650$ nm region. In fig. 6 the charge spectrum acquired by illuminating with light pulses of variable intensity [11] [12] is shown. Each one of the narrow peaks corresponds to an integer number of detected photons. Apart from the exact calculation [12], a simple look at the plots shows that the STM device has a photon resolving power about twice as large as the Hamamatsu (31 vs 17). Moreover, if we fix the laser intensity and fit the spectra with a multipeak function derived from a Poisson distribution [11], it is evident that the Hamamatsu device strongly deviates from the expected statistical behaviour, as it is heavily affected by cross-talk ($\approx 23\%$) between pixels, basically due to its design [12] [13]. This means that when one pixel fires, quite often also one or more of the neighbouring pixels will fire, following the first. This is not the case for the STM SiPM (cross-talk $< 0.5\%$).

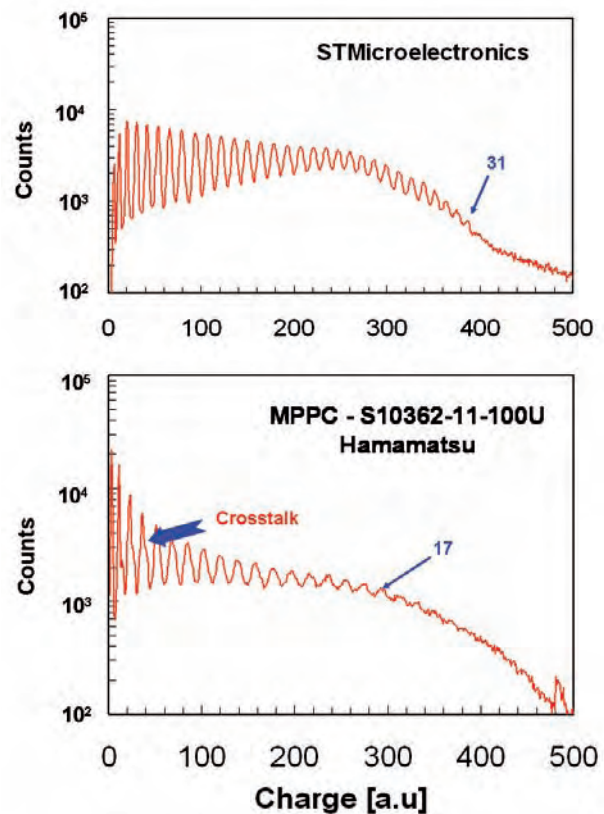


Figure 6. Charge spectrum measured with a ramp-like laser pulses. Upper plot: STMicroelectronics SiPM; lower plot: Hamamatsu MPPC. On both spectra the measured resolving power is indicated by an arrow, 31 photons of the STM sensor, and 17 photons for the Hamamatsu.

FRONT-END ELECTRONICS

The mesh of sensors needs front-end electronics and a data acquisition system, capable of handling the data produced by a high number of channels (10^3 - 10^4). Such an electronics has to be efficient, simple and cheap, in order to keep the cost of the overall system as low as possible.

Two leading edge discriminators for each fibre are thus needed, connected to a coincidence module that drives a counter, for the activity measurement related to the fibre. Data from each drum are packed and sent to an acquisition system, for proper data handling, display and storage. For every platform (4 drums), a programmable electronic board, based on an FPGA component, implements the logic circuits for coincidence, counters and data transmission protocol (fig. 7). The data transmission is twofold, via a fixed cable infrastructure and a cheap wireless network, in order to achieve a higher level of redundancy and to have the capability of monitoring the drums, even during their possible displacement. The topology of the network guarantees a high routing flexibility, in order to allow moving the platforms without any loss of data. Such a wireless network is based on the ZigBee protocol, that guarantees the desired flexibility and has a very low power

consumption. A remote control system allows to connect the platforms into a predefined grid, whereas a special purpose remotely operated robot, useful for ordinary and extraordinary operations, is currently under study.

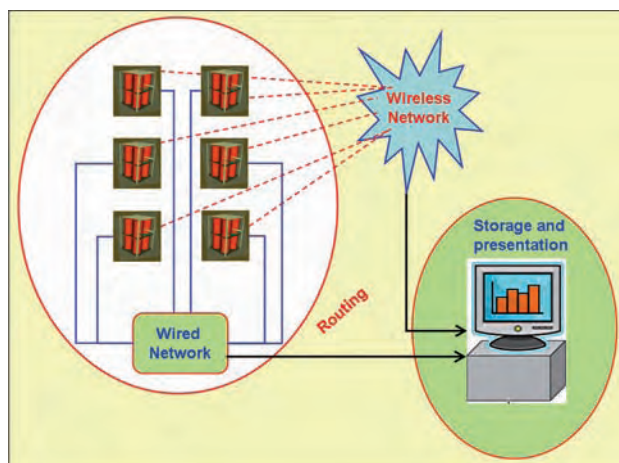


Figure 8. Overall scheme of the data acquisition, transmission, storage and presentation system.

CONCLUSIONS

The R&D activity on the possible use of on-line systems for monitoring nuclear waste storage, has shown us that the construction of a small-size complete prototype is feasible and reasonable. We plan to achieve this goal quite soon, as the single parts of the project have been proved operational.

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First results from heavy-ion beams irradiation facility at LNS-INFN

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Abstract

The possibility to induce mutations in plants by using ion irradiation at intermediate energies (not so intensely investigated up to now) has been studied in the frame of the IENBIO experiment at LNS-INFN Laboratories. A 12C beam of energy 62 MeV/A has been used to irradiate scions, cuttings and seeds at different doses. Preliminary results show that for both seeds (soya and bean) and cuttings (*Bougainvillea* and *Chrysanthemum*) the germination percentage remains about 100% also at high irradiation doses (1000 Gy and 200 Gy respectively) but a slowing in the growth (seedlings length and stem height) on increasing the doses has been observed.

Introduction

In the last decades the possibility to induce mutations in plants by using ion irradiation, which produce localized and dense ionization into cells has been demonstrated, allowing to enhance the biodiversity and clarify the underlying plant physiology [1-5]. After a preliminary contact with Dr. T. Abe, a research line in this field has been developed at LNS-INFN with the support of some Japanese researchers.

The aim of the research was:

a) to explore the potenziality of the LNS cyclotron facility in this context, studying the action of ions with intermediate energy, i.e. few tens of MeV/nucleon, not so intensely investigated up to now, in order to bring to a better understanding of the interaction mechanism and to contribute to individuate the irradiation conditions characterized by higher mutation rates;

b) to probe the possibility to identify the mutated samples inside the irradiated set using the fluorescence and the Delayed Luminescence considering that the viability of several kinds of

seeds has been successfully correlated to the DL [6,7].

As a first step an automatic set-up was entirely designed and built up at LNS [8].

The automatic irradiation system was designed in order to be used for the irradiation of different biological samples in air. A photo of the set-up is shown in fig. 1. It consists essentially of two parts: (1) a frame that can be moved in horizontal and vertical directions (x and y); (2) a sample charger that it is easily fixed at the frame.



Figure 1: Photo of the experimental set-up. In the picture, the sample charger that allows to holder the Petri dishes is shown

The frame can be moved of about 400 mm in x and y direction. Its movement is remotely controlled through a Ethernet connection by a remote computer. A shield with a collimator of 20 mm in diameter is placed in front of the frame in order to define the irradiation zone and avoid the irradiation of the other samples, assuring a beam uniformity in the irradiated region of 85%. The sample chargers are square plates

where appropriate holder are made depending on the biological samples to be studied.

Since two years the proposal of experiment "IENBIO" has been approved from the international PAC of LNS – INFN to study the influence of ion beam irradiation on the plants evolution.

Results

By using the aforesaid set-up, various plant seeds and cuttings were irradiated using a 12C beam of energy 62 MeV/A. The irradiation dose, ranging from 5 up to 1000 Gy, has been evaluated using a transmission Camera Monitor, calibrated by a Camera Markus. Once achieved a predetermined dose, the control system automatically blocked the irradiation of the sample.

The samples irradiated were seeds of different species (*Glycine max* and *Phaseolus vulgaris*) and two kind of cuttings (*Bougainvillea glabra* and *Chrysanthemum*) provided from the department of Orto Floro Arboricoltura e Tecnologie Agro-Alimentari of Catania University. In particular doses of 5, 10, 20, 30, 60 120 and 200 Gy have been used for cuttings samples, while doses of 5, 10, 25, 50, 100, 200, 300, 500 and 1000 Gy have been used for seeds samples.

Up to now we are looking for the best irradiation conditions considering that in some of our systems, due to the fact that the beam energy is not too high we aspect a non uniform dose distribution inside the system with a possible influence of the Bragg's peak. As a matter of facts some of our systems, as for instance, *Glycine max*, selected in order to study the influence of ion irradiation on DL, appears to be (see figure 2) very resistant to the ions irradiation.

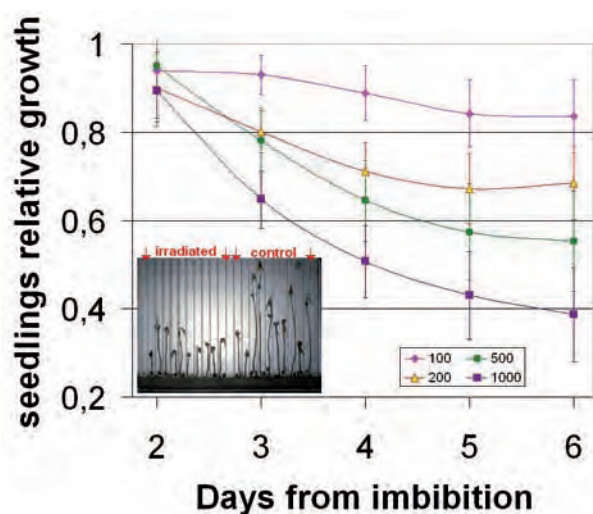


Figure 2: Comparison between *Glycine max* seedlings growth, relative to control, as a function of the days from imbibition. Different colours refer to

the various doses. It should be remarked that high dose have not affected the germination percentage of soya seeds which in all cases remain about 100%. In the inset: comparison between seedlings 4 days old. Irradiated samples have been treated with a 500 Gy dose.

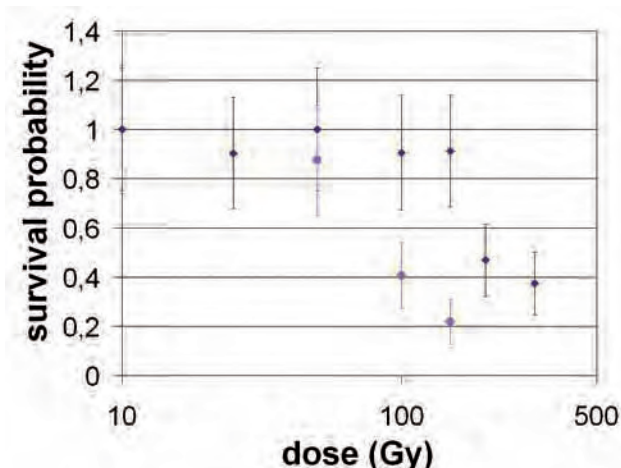


Figure 3: Effect of the Ion beam irradiation on the survival probability of *Phaseolus vulgaris*. The blue dots refer to irradiation of dry seeds, pink dots refer to irradiation of imbibed ones. old. Irradiated samples have been treated with a 500 Gy dose.



Figure 4: Comparison between the length of *Chrysanthemum* plants native (on the left and irradiated with a 60 Gy dose (on the right).

The Delayed Luminescence (DL) of these seeds has been measured before and after the beam irradiation in order to check the possibility to identify the mutated samples inside the irradiated set. Preliminary results



show that the DL changes are not simply related to the irradiation dose.

In the case of other seeds the influence of dose on the survival is much more evident. Figure 3 shows in fact that *Phaseolus vulgaris* exhibit a dependence of the survival rate from dose similar to what reported in literature.

As it regards the cuttings we have not found, up to now, changes in the shape or in the colour of the flowers.

We have only verified a decreasing of the length and of the flowering of irradiated samples. On this aspect *Chrysanthemum* appears to be less sensitive than *Bougainvillea glabra* to the irradiation dose.

CONCLUSIONS

Our results show the possibility to induce mutations in plants by using ion irradiation at intermediate energies (a ¹²C beam of energy 62 MeV/A has been used). Preliminary results show, for both the seeds and the cuttings, that the irradiation affect very few the survival percentage which remains about 100% also at relatively high irradiation doses (1000 Gy for soya seeds and 200 Gy for *Chrysanthemum* cuttings). On the other hand slowing in the growth (seedlings length and stem height) has been observed also for much lower doses.

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LOCALIZED THZ DETECTION IN YBCO SENSORS PATTERNED BY HEAVY-ION LITHOGRAPHY

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Abstract

Measurements of the photoresponse of superconducting $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ (YBCO) film devices to THz radiation are reported. The structural and electrical properties of the film were modulated in a functional way by High-Energy-Heavy-Ion (HEHI) lithography, an effective tool to locally enhance the response of the sensor to the infrared spectrum.

INTRODUCTION

Research and application of THz technology are currently focused either on high-performance sources and detectors or on low-cost and rugged devices suitable for widespread use [1]. Within this framework, high temperature superconductors emerge as good candidates for next generation superconducting bolometers.

In this report we show how $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ (YBCO) thin films, deposited on yttria stabilized zirconia (YSZ) substrate with CeO_2 buffer, can be properly exploited as THz sensors operating above the liquid nitrogen temperature if their structural and electrical properties are modulated in a functional way by High Energy Heavy Ion (HEHI) lithography [2]. It turns out that this technique is a powerful tool to enhance the overall response of the device, operating both on the YBCO thin film and on the substrate.

EXPERIMENTAL DETAILS

HEHI lithography facilities were developed at the INFN-LNS Laboratories on Linear Tandem Accelerator and on Superconducting Cyclotron Accelerator beam lines [3].

Prototype devices consisting of both nanostructured (HEHI-treated) and as-grown YBCO sensing units, for the wide-band direct detection of far infrared electromagnetic radiation, was designed and tested (Fig.1). In this experiment, we used 114 MeV Au ions and the HEHI irradiated area was extended over half of the detector surface (the prototype devices were irradiated with a fluence of $4.84 \cdot 10^{11} \text{ cm}^{-2}$).

A continuous-wave radiation was produced by a high pressure Hg arc lamp (OSRAM HBO 100W), generating a rather flat FIR spectrum (frequency below 3 THz,

wavelength larger than $100 \mu\text{m}$), that was selected by proper filtering (Fig. 2).

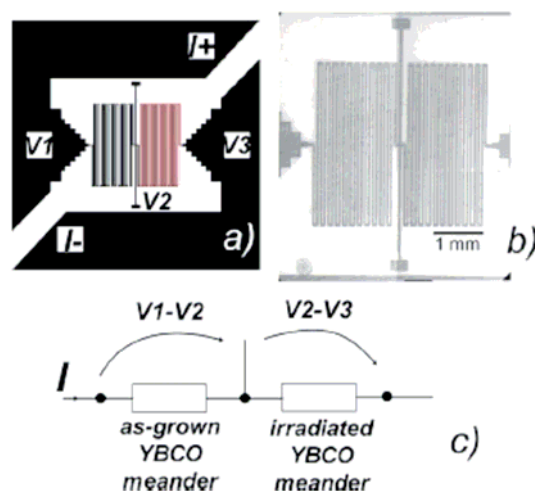


Figure 1: a) Typical device layout. b) Photograph of the sensitive area patterned in YBCO film and locally modified by HEHI (right meander, $1.62 \times 3.3 \text{ mm}^2$ area, 114 MeV ^{197}Au ions with a fluence of $4.84 \cdot 10^{11} \text{ cm}^{-2}$). c) Simplified electrical scheme of the prototype device.

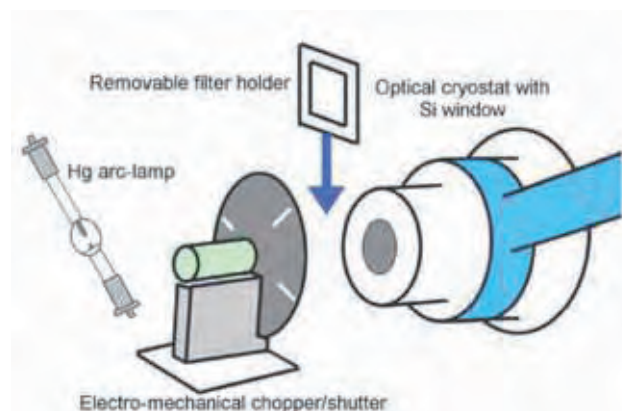


Figure 2: Scheme of the experimental set-up, composed by the infrared source (Hg arc lamp), an electro-mechanical shutter, the filter holder and the optical cryostat with Si window.

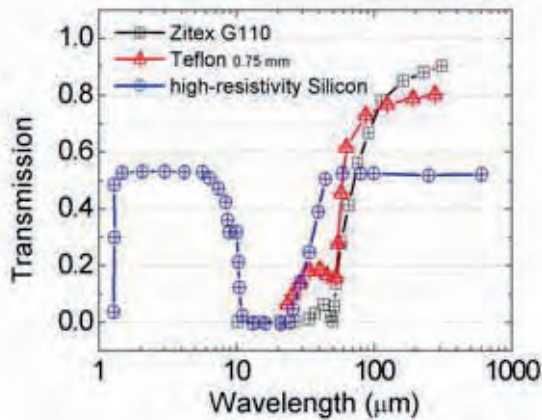


Figure 3: Transmission spectra of high-resistivity Silicon, Teflon and Zitex G110 materials in the MIR-FIR band (data taken from [4]).

In particular, we used as a window of the optical cryostat (Oxford Microstat) high-resistivity n-type Silicon that enables the transmission of the MIR-FIR component, and Teflon foil (2 mm thick) or the more efficient Zitex G110, in order to cut optical frequencies above 4 THz (passing solely the wavelength from 75 μm to 1 mm [4]) (Fig. 3).

The real-time sampling of the voltage was performed by a dual-channel Keithley Nanovoltmeter 2182 (sampling time 100ms).

RESULTS AND DISCUSSION

Resistance characterization

The superconducting transitions of the two series meanders are separately presented in Fig. 4. The bias current was kept strictly constant during the experiment and it was set between 100 μA and 10 mA (corresponding in the serpentine to an electrical current density between $8.3 \cdot 10^6$ and $8.3 \cdot 10^8 \text{ Am}^{-2}$). This value was chosen to reduce spurious heating of the device in each part and to guarantee a good S/N ratio [5]. Both the normal state and the superconducting properties of the irradiated YBCO are definitely altered by the HEHI irradiation. The increased normal state resistivity is accompanied by a reduction of the zero dissipation temperature, T_{c0} , of about 4.5K (the as-grown YBCO reaches, with this current, a zero dissipation state at $T = 87.25 \text{ K}$, see the inset of Fig. 4).

The difference between T_{c0} values of as-grown and irradiated YBCO defines the temperature region where the functional electromagnetic decoupling can be exploited [6]. Namely, in the temperature range of this phase diagram region, the electrical power dissipation due to an external electromagnetic excitation is confined into the modified areas. As for the detection of the VIS radiation [7], also in this experiment we apply a constant current bias to the whole device, at a temperature low enough such that both meanders are into a non dissipative

state. Then, the photon excitation should bring in the dissipative state only the irradiated area. The operating temperature of the sample was chosen to be around $T = 77 \text{ K}$, in order to find the compromise among several factors: minimizing the power consumption (less than 5 nW at rest), maximizing the sensitivity of the irradiated YBCO by the proximity to its dissipative state (being not too far from its T_{c0}), and, above all, working at the liquid nitrogen temperature.

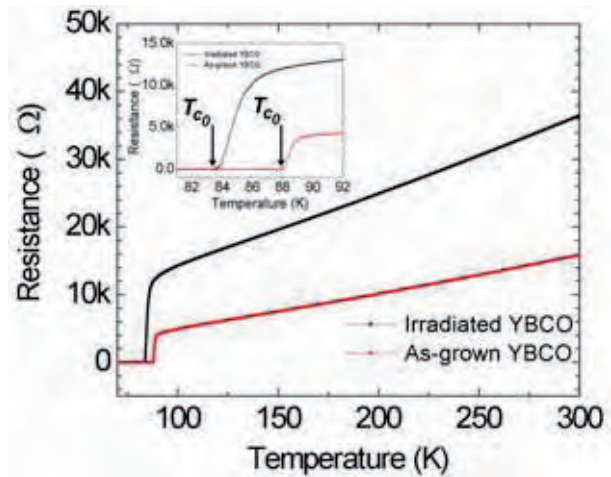


Figure 4: Resistance vs. temperature plot, simultaneously measured on both the meanders during slow cooling. The bias current was kept constant at 100 μA . As visible from the inset, the transition width of the irradiated zone is remarkably enlarged with respect to the as-grown YBCO (about 4.5K versus 0.5K).

THz detection

The voltage response of the two YBCO meanders (as-grown and irradiated one) illuminated by the infrared radiation (filtering only with Si window that produces both MIR and FIR radiation spectra) are shown in the inset of Fig. 5, while the curve of the mail panel is the sum of both signals. Results show that only the irradiated meander displays a response to the incident radiation.

The simultaneous measurement of the photoresponse, solely in the FIR spectrum (due to the efficient Zitex G110 filtering), of both irradiated and as-grown YBCO meanders demonstrates that a steady-state response to FIR signals is achieved in the irradiated region of the film alone (Fig. 6).

A quantitative estimate of the total power of the FIR radiation reaching the sample is very difficult because of the investigated frequency range [8]. Taking into account the geometry of the source, the transmission coefficient of the filters and the flat FIR emission spectrum of the source, the estimated THz radiation power is below 1 μW . Therefore, in this measurement, the correspondent responsivity is of the order of 1V/W, at least. The Noise Equivalent Power of this device sets at $1.3 \cdot 10^{-11} \text{ W Hz}^{-1/2}$ (at $T = 81.3 \text{ K}$) as estimated by means of the bolometric

model [9], taking into account the thermal conductance of the YSZ substrate ($0.015 \text{ Wcm}^{-1}\text{K}^{-1}$) [10].

Moreover, the calculated detectivity is of the order of $10^{10} \text{ Hz}^{1/2} \text{ cmW}^{-1}$. These values are comparable with those obtained by YBCO far-infrared bolometers on membranes [11], although our approach yields to a detectable response without the need of special thermal arrangement of the detecting unit.

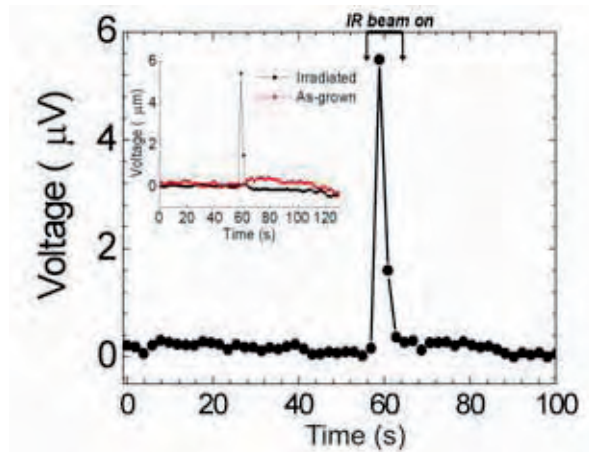


Figure 5: Real-time measurement of the photoresponse of both meanders to MIR/FIR radiation (filtering with Si window only). The bias current was 10 mA ($T=77.9 \text{ K}$). In the inset, both as-grown and irradiated signals are presented, in order to demonstrate the localization of the photoresponse in the irradiated part.

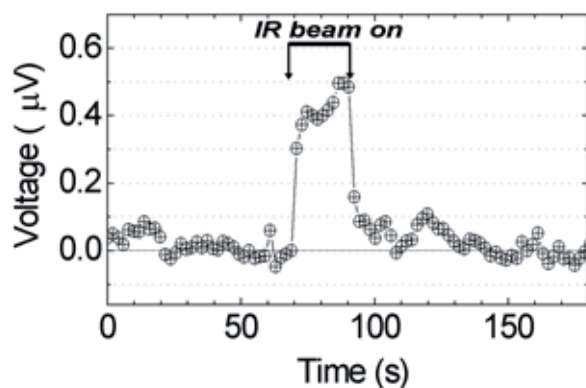


Figure 6: Real-time measurement of the photoresponse of the irradiated meander to the FIR radiation. The bias current was 10 mA ($T = 77.9 \text{ K}$). The FIR radiation can be estimated by the transmission spectra of the filters here used (Si window plus Zitex G110 sheet), to be composed by a flat spectrum below 4 THz (combined transmission $>40\%$ for wavelength larger than $75 \mu\text{m}$).

CONCLUSIONS

We conclude that patterning YBCO with Heavy Ion Lithography yields to an appreciable THz absorption that brings temporarily the irradiated meander to a dissipative state, while the as-grown material is observed to be insensitive. This allowed us designing rugged local detectors with extremely low power consumption and working above the liquid nitrogen temperature.

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BYSTANDER AND DIRECT EFFECTS INDUCED BY CARBON IONS IN AG1522 NORMAL HUMAN PRIMARY FIBROBLASTS AS REVEALED BY MICRONUCLEI INDUCTION

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Abstract

This study investigated on the ability of medium taken from cultures of AG01522 normal human primary fibroblasts irradiated with C-ions to induce a response in non irradiated AG01522 cells (the so-called medium-mediated bystander effect). The bystander response was measured as chromosomal damage observed by the micronuclei formation in binucleated cells using the cytokinesis block. The DNA damage induced also in directly C-irradiated AG01522 cells was preliminarily investigated for comparison. At this stage of the study the possibility can be suggested of a small bystander effect observable only on addition of conditioned medium taken from C-irradiated cultures 5-h after irradiation. Further experiments are needed to confirm or rule out this possibility.

INTRODUCTION

Biological effects on living organisms induced by high-LET radiation are of increasing interest for both radioprotection and radiotherapy. Assessment of health risks of ionizing radiation since long time has been based on the concept of nuclear DNA as the only critical cell target. Recently, this notion has been challenged by a range of observations at very low doses. They suggested that some factors (or signals) can be released by irradiated cells which can affect unexposed cells following high or low LET radiation (bystander effects). These factors (or signals) may reach the unexposed cells through intercellular communication via gap junctions and/or via diffusible factors transmitted through the extracellular environment. Several studies (see for example ref [1]) have shown the occurrence of such effects caused by the transfer of medium from gamma-irradiated cells (termed donor cells) to unirradiated cells (termed bystander cells). Among the factors potentially involved in the bystander effects, reactive oxygen species (ROS) and reactive nitrogen species (RNS) have been identified to play a role in the bystander response. Nitrogen oxide (NO) on one side can induce cellular damage through DNA damage while on the other side it can protect from radiation-induced damage by scavenging peroxy radicals, by inducing protective proteins or by inhibiting caspase activity [2]. Similarly, ROS are well known agents, inducing DNA damage and apoptosis; however, in

physiological conditions they are also involved in cellular signaling pathways not leading to cell death.

In this study the attention is focused on the medium-mediated bystander effects, with the overall aim to check if they can be induced by irradiation with C-ions and to get insight on the diffusible species involved. To this purpose, the medium transfer approach was used and the chosen cell end point was the micronuclei formation (related to chromosome damage) observed in binucleated cells. In order to study the involvement of ROS and RNS as early mediators of the signalling chain leading to a possible bystander effect, c-PTIO and DMSO (scavengers of ROS and NO, respectively) were used. Moreover, the dose-response for micronuclei formation was also investigated in directly irradiated cells in the absence or presence of c-PTIO and DMSO.

MATERIALS AND METHODS

Cell culture

AG1522 normal human fibroblasts were grown as monolayers in alpha-Minimum Essential Medium (α -MEM), containing 1 mM glutamine, 20% foetal calf serum, 2% Hepes buffer solution (1 M) and antibiotics (all reagents from Gibco), at 37°C in 95% air and 5% CO₂ atmosphere.

Irradiation conditions

AG01522 diploid human fibroblasts were irradiated with C-ions at the Superconducting Cyclotron radiobiology facility of the LNS-INFN. The C-ion energy at the cell entrance was about 45 MeV/u corresponding to an LET value of about 49 keV/ μ m (in water). The cells were irradiated as monolayers attached onto a T-12.5 plastic flask at room temperature, in the presence of culture medium, with doses of 0.25 and 0.5 Gy for the direct effect experiments, and 0.5 Gy for bystander effect experiments. For the latter, the medium transfer technique was used, as described previously [3]. Briefly, after irradiation the cultures were incubated for the desired time (1 or 5 h). The same incubation was applied to sham-irradiated cultures. Then, the conditioned medium from irradiated or sham-irradiated cells was transferred to the unirradiated (bystander) cells contained in slide flasks for the micronuclei induction assay. Before transfer, the

medium was filtered through a sterile systems with Teflon filters to reduce binding of proteinaceous factors. To test whether ROS and NO species are involved in radiation damage in directly irradiated or bystander cells, DMSO or c-PTIO (ROS or NO scavenger) at a final concentration of 0.5 % and 20 μM respectively, was added to the culture 1 h before irradiation. In all the experiments a dose rate of about 1 Gy min^{-1} was used. γ -rays from a ^{137}Cs irradiator (Nordion mod. 40) were used as reference radiation at the Istituto Superiore di Sanità at a dose rate of about 1 Gy min^{-1} .

Micronuclei assay

For micronuclei assay, AG1522 cells were seeded on slide flask at the density of $1.4 \times 10^4 \text{ cell/cm}^2$ about 20-24 h before irradiation. After irradiation medium was replaced by fresh MEM medium containing 1.5 $\mu\text{g/ml}$ cytochalasin B to block cytokinesis. After 72 h at 37°C , cells were fixed with cold methanol:acetic acid (4:1 v/v) for 20 minutes at -20°C . The fixation agent was then washed out and the samples were air-dried overnight. The fixed cells were stained with DAPI and scored by fluorescence microscopy.

Similar procedure was used for bystander experiments; in this case cytochalasin B was added to the conditioned medium before transfer. At least 2000 binucleated cells were scored for each sample. All cells bearing one or more micronuclei were considered as micronucleated events.

RESULTS AND DISCUSSION

Direct effect

Fig 1 shows the percentage of binucleate cells with micronuclei as a function of the dose for the three irradiation conditions: cells irradiated in the presence of medium alone, of medium with c-PTIO and of medium with DMSO.

The results suggest an almost linear responses in all cases, with a slight downwards curvature. This is consistent with the results by Shao et al [6] who observed a tendency to saturate with increasing dose for the same cell line irradiated with a 100 keV/ μm carbon beam. The same type of curvature was observed in our experiments with γ -irradiation (data not shown), which was different from the linear-quadratic response seen in other cells.

The results shown in Fig.1 give two kinds of information. 1) The bending in the dose-response implies that the effectiveness for MN induction is higher at low doses, say 0.1-0.2 Gy, than at 0.5 Gy or more. Since these low doses correspond to situations where a percentage of cell nuclei are not hit by C-ions (6% at 0.1 Gy), this higher sensitivity may indicate an extra contribution to MN induction by cells located near irradiated cells. 2) The protection factor for micronuclei induction exerted by the two scavengers at 0.25 Gy, evaluated by the best fits to the data points, is about 1.7 for both c-PTIO and DMSO; this indicates that an indirect action, mediated by ROS

and/or NO species, contributes to the chromosomal damage induced by C-ions.

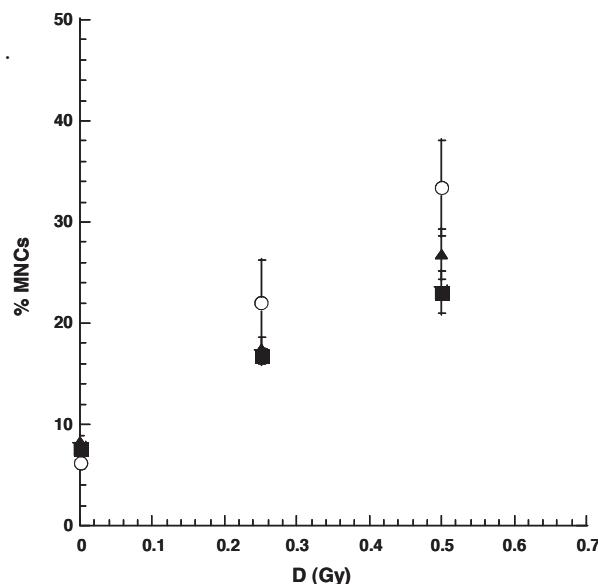


Fig.1: Micronuclei induction after irradiation with carbon ions. (○) Medium alone; (▲) Medium + DMSO; (■) Medium + c-PTIO. Data points are the means of four independent experiments without scavengers and of two independent experiment with the scavengers. The error bars are the standard errors of the mean or the semidisposition.

Bystander experiments

Fig. 2 shows the results obtained on non-irradiated (bystander) cells, incubated with medium from cells sham- or irradiated in the absence or in the presence of scavengers.

As described in the previous section, this medium was taken after 1 h or 5 h from the irradiation, so that the irradiated cells have released factors into the medium for different times. Controls have been also performed by adding the medium obtained from non-irradiated cultures after 1 or 5 h in the absence or in the presence of scavengers (sham-irradiated samples). These controls showed a certain amount of micronuclei induction that slightly increased in the presence of the scavengers, from 6-7 % without scavengers to 7-8% with c-PTIO and 9-10% with DMSO. This is likely due to a small genotoxic effect of these scavengers at the concentrations used here. Addition of 1 h-conditioned medium from irradiated cultures gave no significant differences with respect to the control. No significant differences were as well observed on cells incubated for 1 h with medium from cells irradiated in the presence of c-PTIO or DMSO. On the contrary, after addition of 5-h conditioned medium, slight differences were observed, indicating a possible bystander effect, both in the absence and in the presence of the scavengers. However, these are not firmly demonstrated on statistical bases, and seems to be related to a decrease of micronuclei percentage in the control cells rather than

to an increase in the cells that received the 5-h conditioned medium from irradiated cultures. Also, the lack of any significant change when the scavengers are present is not supporting the occurrence of a bystander effect, since it is expected that ROS and/or NO species have a role in it.

On the other hand, experiments performed at the Istituto Superiore di Sanità on the same cells irradiated with γ -rays showed a small but significant bystander effect.

Therefore, the existence of a medium-mediated bystander effect on AG01522 cells irradiated with C-ions, as revealed by micronuclei induction, should be evaluated after further experiments are performed to improve the statistics in the experimental data. Indeed, it is known that in these kind of experiments there is a quite large biological variability.

The reasons could be in the incubation times here used. Data recently obtained at the Istituto Superiore di Sanità with γ -rays on the bystander effect measured by DNA damage showed that the maximum of bystander effect is reached about 2 h after irradiation. Experiments using a different incubation time, between 1 and 5 h, could help in better identifying the presence of bystander response.

Also, it may be speculated that some specific signalling was partly or totally quenched under the conditions here used. For example, factors that transmit bystander signals could be inactivated by serum components and therefore the observation of a bystander effect could depend on the specific composition of the serum used. In effect other authors reported that the bystander effect is a complex phenomenon that may occur only in specific circumstances [4,5].

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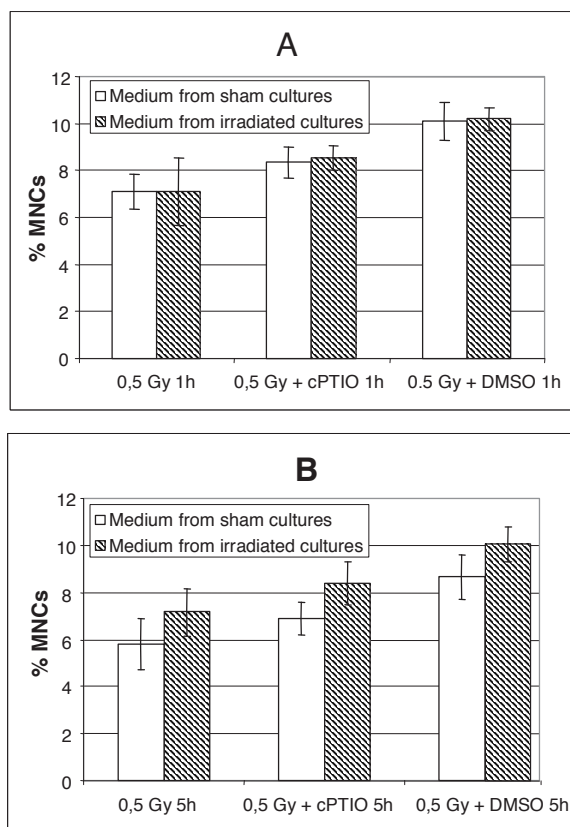


Fig.2: The medium-mediated bystander effect on AG01522 human fibroblasts, as measured by micronuclei induction, after addition of medium from cultures of the same cells irradiated with C-ions. Medium was transferred after 1 h (upper panel, A) or 5 h (lower panel, B) after irradiation. Bystander cells were assayed also in the presence of c-PTIO and DMSO to test the effect of these scavengers. Histogram bars represent the means of four independent experiments without scavengers and of two independent experiment with the scavengers.

Anyway, the data here reported indicate that there is no clear bystander effect in terms of MN induced by C-ions.

ASSEMBLING AND TEST OF A PROTON COMPUTED TOMOGRAPHY 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, we designed a proton computed radiography (pCR) prototype capable to carry out a single projection. The pCR apparatus includes a tracker (based on identical tracker modules, each including a silicon microstrip detector) to measure proton trajectory and a calorimeter (made of four YAG:Ce optically separated crystals) to measure the residual energy. Tracker modules have been extensively tested and calibrated with beta particles and protons (62 and 200MeV). Tests of the tracker coupled to the calorimeter are presently under way. Results from these experiments are presented in this contribution.

INTRODUCTION

Many projects in the field of hadrons- and light ions-therapy are being initiated worldwide, while the number of operative clinical hadron-treatment facilities is continuously growing [1,2]. One of the main advantages in using these particles to treat tumors is the possibility to tightly shape the radiation dose to the target volume, thanks to the peculiarities of the interaction on hadrons with matter. However, the spatial accuracy of proton therapy is still presently limited by the uncertainty in stopping power distribution, which is calculated from the photon attenuation coefficients measured by X-ray

tomography [3]. This uncertainty could be reduced by directly measuring stopping powers with a proton beam [4] by means of a proton tomography (pCT) apparatus. The aim of our project [5] is to design, manufacture and test a proton computed radiography (pCR) prototype for small objects analysis. Multiple images of the same object, taken at different angles (e.g. taken by using a rotating phantom), will be used to develop novel reconstruction algorithms [6], able to account for multiple Coulomb scattering and thus not entirely based on Monte Carlo simulations as in present times [7]. The entire project exploitation is necessary to conceive a final configuration for a complete pCT system.

pCT has been proposed in the seventies as an alternative to X-ray tomography to obtain high contrast images [8] with reduced delivered dose to the patient [9]. Already at that time, it appeared clear that the main problem with pCT is that protons do not move along straight lines across the medium because of multiple Coulomb scattering. Single proton tracking is a promising way to collect as much as possible information in order to circumvent this difficulty [10,11].

The pCR system presented in this study has been designed to detect protons with initial kinetic energy high enough to transverse a human trunk (in the range 250 to 270MeV) with a particle rate of ~1MHz, in order to collect data within a time of the order of 1s, suitable to clinical demands. Trajectory parameters to be measured are entrance and exit angles, entrance and exit transverse positions and residual energy. These parameters are the input data necessary to calculate the protons most likely path. As a matter of fact, it has been recently proved that a semi-analytical algorithm [12] is suitable to determine the most likely path of protons and to account for the blurring effect introducing in proton radiographic images by Coulomb scattering [13]. 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.

ARCHITECTURE

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.

TRACKER DATA ACQUISITION

Each readout ASIC consists of 32 independent channels, including a charge sensitive amplifier, a shaper and a comparator suitable to produce a digital output by comparison with a threshold V_{th} .

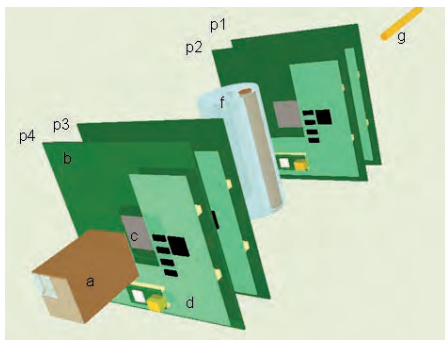


Figure 1: Sketch of the pCR system in the typical test arrangement. The Si telescope composed by the xy planes p1 to p4, the calorimeter (a) and a phantom (f) are shown. Protons emerge from beam pipe (g).

The threshold level of each front-end board can be chosen independently of the others, and a fine threshold regulation through potentiometers can be made chip by chip. Thus thresholds on a given board are:

$$V_{th}^{(j)} = 1.650V + \Delta V_{th} - V_j \quad (1)$$

where $j=1..8$ is the ASIC index, 1.650V is the quiescent level of shaper output, $(1.650V + \Delta V_{th})$ is the threshold level set on the board level and V_j is the fine regulation aimed at optimizing the performances of the j^{th} chip.

The tracker digital board carries a low-cost FPGA with high input-output capabilities (Xilinx Spartan 3AN XC3S1400AN), a static RAM memory (composed by 4 1Mbitx16 static memories) and a commercial Ethernet unit (Memec V4Fx12 mini-module). The main role of the FPGA is to sample the 256 data lines from ASIC buffers, to implement pre-processing (including zero-suppression) and to store reduced data inside the memories. Details about system architecture and tracker module are given in Refs. [14,15]. ASIC outputs are continuously sampled by the FPGA at the rate of 100MHz. The time window considered in data acquisition starts M_p clock cycles before trigger and ends M_a cycles after trigger. These values can be regulated by software. For each channel n , pulse duration $T(n)$ and delay from the beginning of the time window $D(n)$ are measured in terms of clock cycles and recorded. Presently we set: $M_p=155$, $M_a=100$ (since we are representing duration and delay with 8 bits: $M_p+M_a = 255$). Then the FPGA circuitry selects only those channels which recorded an hit ($T(n)>0$) and store the corresponding data in the block RAM.

An example of duration and delay distribution is shown in Fig.2 (data from all the 256 channels). The number of hits with a given value of duration and delay are plotted in color-scale. Note that trigger occurs with a fixed delay of 1000ns.

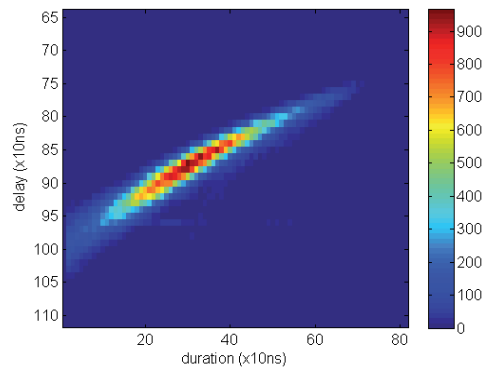


Figure 2: Delay vs duration distribution for clusters recorder using a ^{90}Sr source. Trigger occurs with a delay of 1000ns.

Almost all the hits are acquired within an interval of 250ns before the arrival of trigger, due to the delay introduced in trigger generation by calorimeter electronics. The delay spread is due to the fact that the weaker the signal, the slower the digital signal generation from front end ASIC.

Noise level can be made negligible if a proper threshold level is chosen. Fig.3 plots an example of the

behavior of the noise occupancy as a function of the threshold level ΔV_{th} .

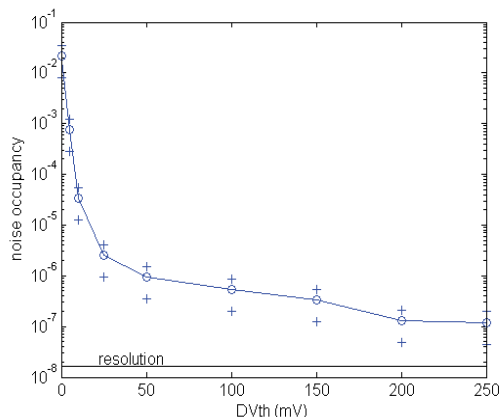


Figure 3. Noise occupancy measured for a tracker module. The resolution level of this measurement is indicated, crosses give indication of the standard deviation of each measurement.

Noise occupancy is measured by triggering the digital board with an external source without exciting the silicon sensor. Then occupancy is defined as the number of time windows with at least one active channel, divided by the number of triggers.

DETAILS ABOUT CALORIMETER READOUT

The calorimeter (a) is made by 4 YAG:Ce scintillating crystals each coupled to one photodiode. The calorimeter readout chain is shown in Fig.4. Charge preamplifiers (CSA), in their present form, are based on a scheme described in Ref. [16] and generate an output pulse with a 10 μ s decay time. The analog outputs AO1 to AO3 are directly sampled by a commercial (14 bit, 50MHz maximum sampling frequency) acquisition board, in order to measure their maxima, which are proportional to the energy released in the crystals. These signals are used also by the trigger generator board to generate the trigger (if enabled by the tracker through the Trigger_en line) and event number. Trigger generation is obtained by comparison with a software programmed threshold.

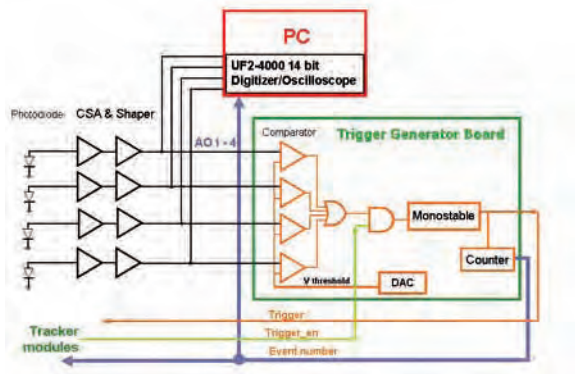


Figure 4: Scheme of calorimeter readout and trigger generation.

An example of shaper output signals is shown in Fig.5. In this case the 4 crystals were excited with 62MeV protons. Ten events are shown in the plot. Events no.1,5,7 and 8 give a signal mainly in channel 4, while events no. 2,3,6,9 and 10 generate a signal mainly in channel 2. Signal from events no. 2,4 is shared between channels 2 and 4.

CHARACTERIZATION

Both the tracker module and the calorimeter have been extensively tested with charge particles [17]. A single YAG:Ce crystal was tested with 62MeV protons at INFN-LNS (Catania, Italy) while the 4-crystal device was tested with 200MeV protons at LLMUC. The tracker module was tested with β particles from a ^{90}Sr Source at INFN Florence and 62MeV protons at INFN-LNS.

A first test of a xy plane coupled with the 4-crystals calorimeter has been carried out with 62MeV protons at INFN-LNS (with proton rates ranging from 1kHz to 50kHz) and first results are reported in the following.

Only events measured in coincidence in the two modules after a trigger from the calorimeter have been included in this analysis.

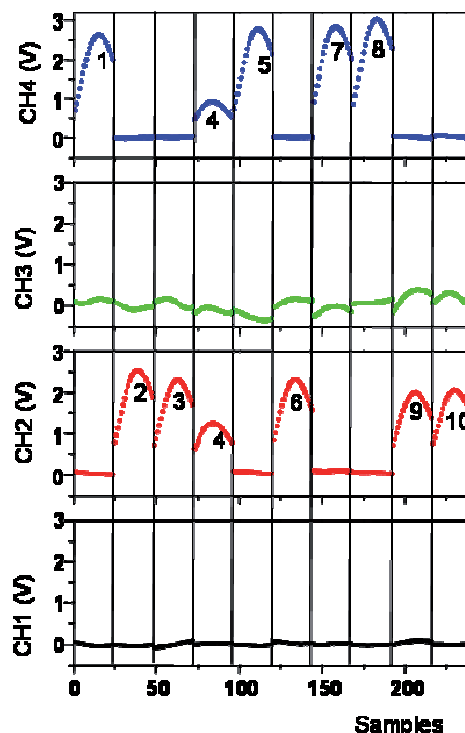


Figure 5. Analog outputs of the calorimeter shapers. The 4 calorimeter crystals were excited with 62MeV protons. Signals from 10 events are shown.

A 2D beam profile is shown in Fig.6. Here crystal III is not in the trigger, the portion of Fig.6 without events demonstrates that the tracker and calorimeter data are synchronized. The profile width is in good agreement

with the diameter of the beam collimator placed upstream the plane (5mm). Further measurements have been carried out by degrading the beam energy with an attenuator. The dependency of pulse duration T versus proton kinetic energy is shown in Fig.7 (data from both the tracker modules). As expected, if energy is reduced pulse duration increases, due to a larger charge release in silicon.

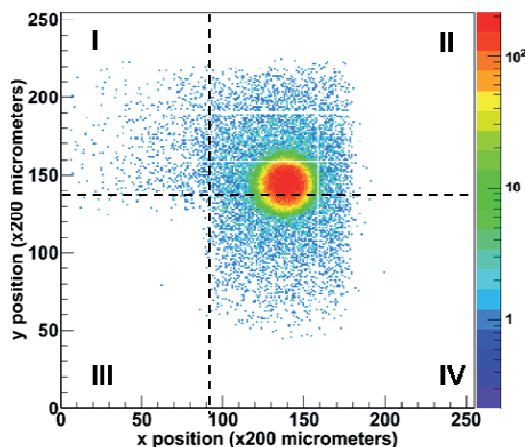


Figure 6. Number of protons crossing a given x-y position. The position is given in term of strip index (strip pitch is 200 μ m). Collimator diameter is 5.0mm. $\Delta V_{th}=200$ mV.

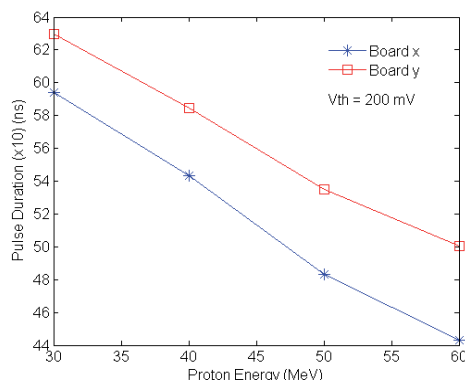


Figure 7. Duration of the digital pulse from tracker front end versus the kinetic energy of the incoming protons. The two set of data corresponds to values measured by the two tracker modules in the xy plane.

CONCLUSIONS

A system for proton radiography has been designed. It includes: i) a tracker based on Si microstrip detectors and ii) a segmented YAG:Ce calorimeter. All the components have been manufactured and tested separately with protons of various energies. A tracker xy plane has been coupled to the calorimeter and tested with 62 MeV protons at LNS. The assembling of the complete tracker (with 4 xy planes) is under way, the system will be characterized at INFN-LNS in 2010.

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ALTERATION OF P53 AND BAX/BCL-2 RATIO BY FOTEMUSTINE AND PROTON IRRADIATION

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Abstract

Deregulation of apoptosis commonly occurs in melanoma cells and could be a reason for resistance. The effectiveness of different treatments depends on their ability to activate this process. In this study the effects of combined treatments with fotemustine (FM) and proton irradiation on the regulators of apoptosis were analyzed. Sub-confluent HTB140 human melanoma cells were treated with FM (100, 250 μ M) 24 h prior to irradiation (12, 16 Gy). Cells were irradiated in the middle of the therapeutic 62 MeV proton spread out Bragg peak. Flow cytometric analysis of apoptosis and the Western blot analysis of apoptotic regulators were performed 6 or 48 h after treatments. Percent of apoptotic nuclei increased after applied treatments, reaching the level of 4 to 41 %. Induction of apoptosis was associated with p53 and Bax up regulation and Bcl-2 down regulation. The obtained results imply that analyzed treatments induce apoptosis through the activation of the mitochondrial apoptotic pathway, with better pro-apoptotic effects achieved by combined treatments.

INTRODUCTION

Investigation of melanoma is a big challenge for researchers, since the incidence of melanoma has dramatically increased over the last few decades [1]. In addition, melanoma is highly invasive radio- and chemo-resistant tumour with powerful metastatic potential. Existing clinical protocols do not provide adequate improvement for patients with melanoma metastases. The best effect in the treatment of metastatic melanoma is achieved by alkylating agents, leading to the complete remission in about 15 to 20 % of cases. Most chemotherapeutic agents achieve their action in different cancer cells through the induction of apoptosis. Low efficiency of these agents in the elimination of melanoma cells is the consequence of their inability to induce apoptosis in this tumour [2].

Tumour suppressor protein p53 has an important role in the regulation of apoptotic pathway by transcriptional activation of the pro-apoptotic members of Bcl-2 family and repression of the anti-apoptotic regulators. The members of Bcl-2 family are the key regulators of the mitochondrial apoptotic pathway. Although in the

majority of human melanoma p53 is not mutated, its modulation or reduction of transcriptional activity is detected [3].

Considering the importance that deregulation of apoptosis has in tumour progression, the use of apoptosis as a biological marker is one of the basic strategies in the formation of therapeutic approaches for treatment of various types of cancer [4].

The concept of combining therapeutic approaches in order to improve clinical efficiency, with controlled clinical toxicity of substances, is frequently applied in the recent years. Advanced understanding of molecular mechanisms of melanoma resistance can contribute to its overcoming through the activation of different target molecules [5]. According to the facts that anticancer drugs and ionizing radiation have different mechanisms of action, in this study, combined effects of FM and protons on the regulatory molecules involved in apoptosis were studied on the radio-resistant human HTB140 melanoma cells.

MATERIAL AND METHODS

Cell culture

Human HTB140 melanoma cell line was 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 HTB140 cells were exposed to FM (100, 250 μ M) (Ital farmaco S.p.A., Milano, Italy) 24 h after seeding, and irradiated with protons 24 h later. Assays were performed 6 or 48 h after irradiation. The effects of the combined treatments were compared to the corresponding single drug treatments or proton irradiation.

Irradiation conditions

Irradiation with the therapeutic 62 MeV proton beam was performed at the CATANA facility at INFN - LNS,

Italy. Delivered single doses were 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 obtained by inserting 16.3 mm thick Perspex plate (Polymethyl methacrylate - PMMA) between the final collimator and the cell monolayer. The corresponding relative dose was $99.42 \pm 0.58 \%$, with the mean energy of protons of 34.88 ± 2.15 MeV and the linear energy transfer (LET) of 4.71 ± 0.15 keV/ μ m. The mean energy and LET values were obtained by numerical simulations carried out with the GEANT4 code [6]. 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 (IAEA-TRS-398 2000) [7, 8]. All cell irradiations were carried out in air at room temperature.

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. Samples were analyzed on a FACSCalibur (Becton Dickinson, Heidelberg, Germany). The number of apoptotic cells was calculated using ModFit software (Verity Software, Becton Dickinson).

Western blot

For the Western blot analysis cells were collected, washed with PBS, lysed in lyses buffer and centrifuged at $13000 \times g$. The extracted protein samples were added in the sample buffer and subjected to denaturation, then electrophoretically separated and finally transferred onto the polyvinylidene fluoride (PVDF) membrane. The PVDF membrane was treated with phosphate buffered saline tween-20 (PBST), followed by incubation with the primary antibodies – anti-p53, anti-Bcl-2 or anti-Bax (Cell Signaling, Danvers, MA, USA). After washing with PBST, membrane was incubated with the corresponding Horseradish peroxidase (HRP, Cell Signaling) secondary antibody for 2 h and washed with PBST. Proteins were visualized with enhanced chemiluminescence (Sigma-Aldrich Chemie GmbH) and exposed to X-ray film. Densitometry of protein bands on X-ray film was performed using Image J Analysis PC 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

Flow cytometric analysis showed that the number of apoptotic nuclei increased 6 h after exposure to protons

(15 % - 25 %) or FM (5.2 – 7.3 %) as compared to untreated control. When the HTB140 cells were treated with FM and then irradiated with protons the level of apoptosis ranged from 4 to 19 % (Figure 1A).

The percentage of apoptosis significantly increased when the incubation time was extended to 48 h, especially in samples exposed to 250 μ M FM and protons, reaching from 38 to 41 % (Figure 1B).

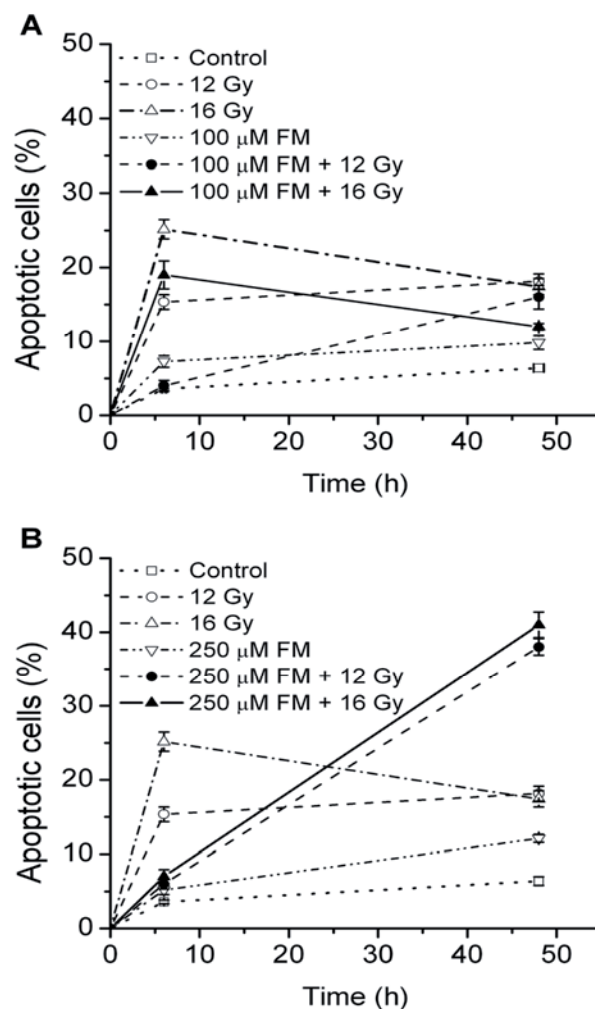


Figure 1. Percentage of apoptotic cells, evaluated by flow cytometric analysis of Annexin V/PI stained samples 6 and 48 h after treatments with protons (12, 16 Gy) and 100 μ M FM (A), as well as protons (12, 16 Gy) and 250 μ M FM (B).

To examine the molecular level of the observed induction of apoptosis, key molecules of the mitochondrial apoptotic pathway were analyzed under the described experimental conditions. This included the analysis of p53 gene and protein expression, as well as the expression of Bax and Bcl-2 regulatory proteins.

Significant increases of p53 were detected 6 h after the exposure to 16 Gy protons (12 %) and after the single treatment with 250 μ M FM (13 %) as compared to control. More enhanced increase was observed after the combined treatments (24 – 48 %).

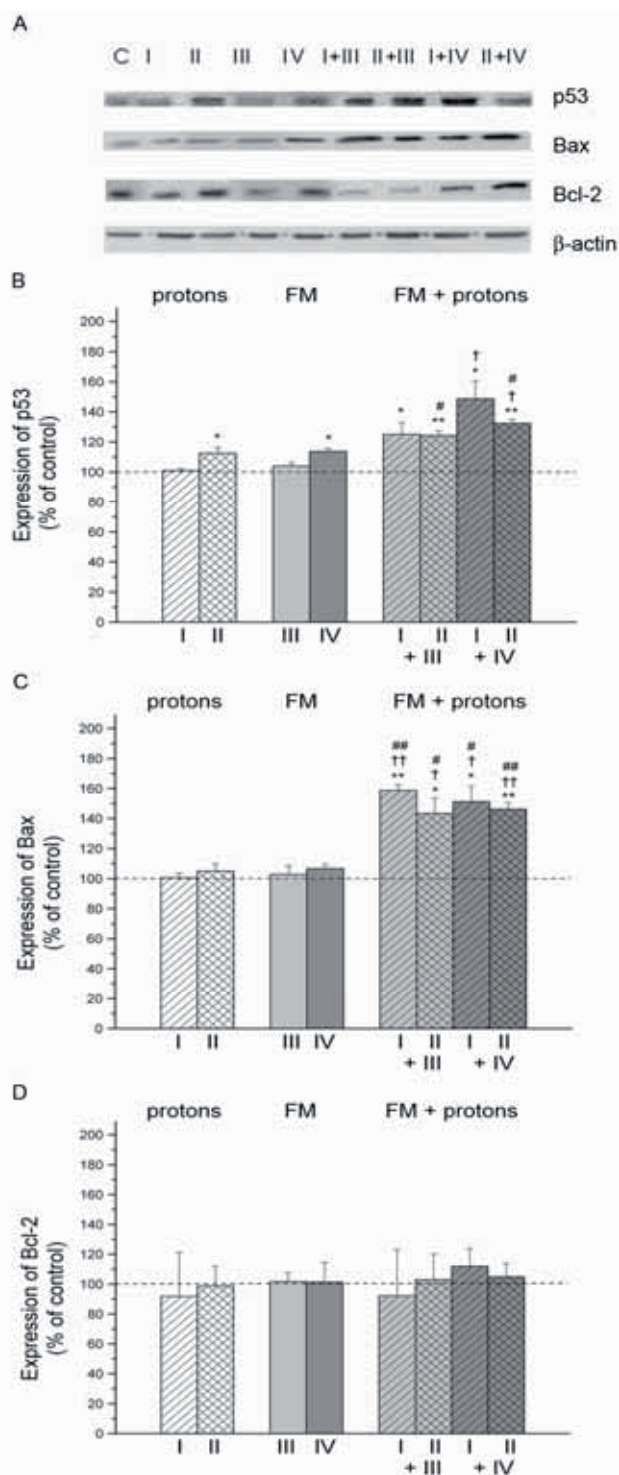


Figure 2. Western blot analysis of p53, Bax and Bcl-2 6 h after single and combined treatments with FM and protons (A). The level of p53 (B), Bax (C) and Bcl-2 (D) was normalized to β -actin and expressed as percent of control. Irradiation doses were 12 (I) and 16 Gy (II), while FM concentrations were 100 (III) and 250 μ M (IV). C – control. * - Statistical significance compared to the control; † - statistical significance compared to the radiation; # - statistical significance compared to FM. *, †, # - $0.01 < p < 0.05$; **, ††, ## - $0.001 < p < 0.01$; ***, †††, ### - $p < 0.001$.

Treatment with 250 μ M FM and 16 Gy protons additionally increased p53 expression as compared to appropriate single treatments (Figure 2A and B).

The expression of p53 was not changed 48 h after all single or combined treatments (Figure 3A and B).

The increased level of the pro-apoptotic protein Bax was detected 6 h after all combined treatments (41 – 58 %), as compared to control or to single treatments with protons or FM (Figure 2A and C). Forty eight hours after treatment, the expression of Bax increased in all analyzed samples, except in the sample exposed to 12 Gy protons. Combined treatments have shown the increase of Bax expression as compared to the appropriate single treatments (Figure 3A and C).

Furthermore, treatments with FM and protons did not induce changes in the expression of anti-apoptotic protein Bcl-2 after 6 h (Figure 2A and D), but resulted in a significant decrease of Bcl-2 expression after the incubation for 48 h, as compared to control (24 – 49 %). Better effects were achieved after combined treatments (Figure 3A and D).

DISCUSSION

Considering the significance that apoptosis has in the development of cellular chemo- and radio-resistance, in this study the effects of applied treatments were analyzed on this process. Highly radio-resistant human HTB140 melanoma cells, with SF2 values of ~ 0.93 were used [9]. Applied concentrations of FM were close to those defined as IC₅₀ values for the HTB140 melanoma cells, while the doses of 12 and 16 Gy protons were in the range of those used in therapy. Time point of 48 h after combined treatment (i.e. 72 h after FM administration) was appropriate for the analysis of FM effects [10-13].

In radio-sensitive cancer cells apoptosis usually occurs within the first 24 h after irradiation. However, for the majority of cells, apoptosis may arise after one or more cell divisions. Usually the maximal number of apoptotic cells in vitro was observed 48 h after irradiation [14]. On the basis of these data, time points of 6 and 48 h after treatment were selected for the assessment of apoptosis.

Analyzed treatments have shown different influence on the induction of apoptosis. Proton irradiation revealed better pro-apoptotic effects than FM. Similar effects were reported for PC3 prostate adenocarcinoma cells, CA301D thyroidea cancer cells and MCF7 breast adenocarcinoma cells after proton irradiation [15] and 1205Lu, 451Lu, WM35 and Sbcl2 human melanoma cells after FM treatment [16]. Combined treatments applied in this study showed time- and FM concentration- dependent pro-apoptotic effect, while the increase in radiation dose did not significantly influence the level of apoptosis. Particularly good effect was achieved when the cells were exposed to 250 μ M FM and irradiation for 48 h.

Induction of apoptosis was confirmed by the analysis of the regulatory proteins involved in this process. Transcription factor p53 is known to provoke cell cycle arrest or apoptosis in response to cellular stress, such as DNA damage induced by drugs or radiation [17].

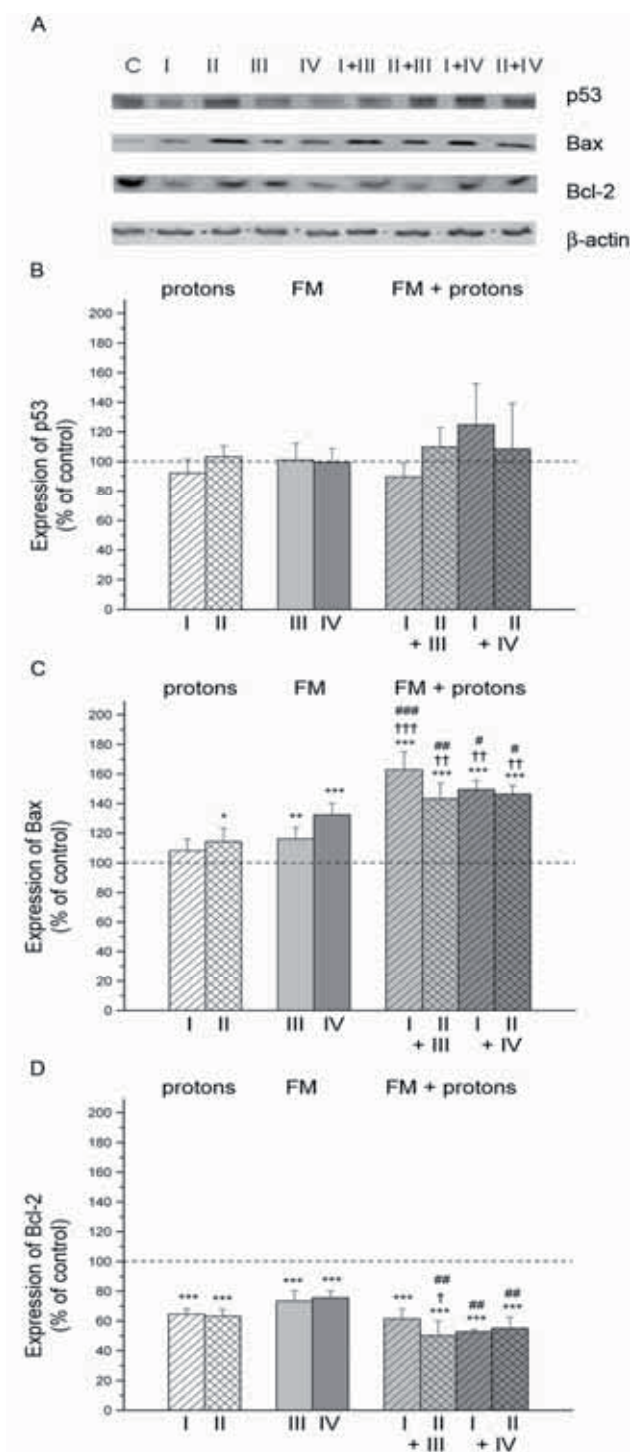


Figure 3. Western blot analysis of p53, Bax and Bcl-2 48 h after single and combined treatments with FM and protons (A). The level of p53 (B), Bax (C) and Bcl-2 (D) was normalized to β -actin and expressed as percent of control. Irradiation doses were 12 (I) and 16 Gy (II), while FM concentrations were 100 (III) and 250 μ M (IV). C – control. * - Statistical significance compared to the control; † - statistical significance compared to the radiation; # - statistical significance compared to FM. *, †, # - 0.01 < p < 0.05; **, ††, ## - 0.001 < p < 0.01; ***, †††, ### - p < 0.001.

The activation of p53 by FM and protons could affect the expression of its downstream effectors such as the Bcl-2 family of proteins, the key regulators of apoptosis [18]. In this study it was shown that the level of Bax increased at both analyzed time points, while the level of Bcl-2 decreased in the cells that were exposed to FM and protons for 48 h. This implies that the treatments that were used induced apoptosis by shifting the Bax/Bcl-2 ratio in favour of apoptosis, especially after 48 h. The obtained results suggested that FM and protons induced apoptosis through the activation of the intrinsic pathway. Significant decrease of Bcl-2 and increase of Bax in proton irradiated Lewis lung carcinoma cells (LLC), as well as hepatocellular carcinoma HepG2 cells were reported [19].

CONCLUSIONS

The obtained results indicate that combined treatments with higher concentration of FM and both doses of protons have better pro-apoptotic effect than single treatments with these agents after incubation of 48 h. Improved pro-apoptotic ability of combined vs. single treatments is also confirmed at the level of molecules involved in the mitochondrial apoptotic pathway. This was quantified by the changes of p53, as well as Bax and Bcl-2 protein expression.

ACKNOWLEDGMENTS

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APOPTOSIS OF HTB140 MELANOMA CELLS INDUCED BY CARBON IONS OF DIFFERENT LET

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Abstract

Exposure to irradiation can trigger the p53 tumor suppressor to induce cell growth arrest or apoptosis. This study was conducted in order to evaluate the ability of carbon ions to induce apoptosis. The HTB140 melanoma cells were irradiated at three positions along the Bragg curve of the 62 MeV/u ¹²C ion beams. In this way the cells were exposed to different high linear energy transfer (LET) values. The percentage of apoptotic cells was evaluated by flow-cytometry and the corresponding apoptotic indexes were calculated. The expression of apoptosis-associated proteins, p53 and Bax was estimated by Western blot analyses. A dose dependent increase of apoptosis was noticed in all irradiation positions. When moving along the Bragg curve, i.e., with the raise of LET, the level of apoptosis increased, but was somewhat attenuated for the highest LET value. The corresponding apoptotic indexes ranged from 2.45 to 7.71. Moreover, the induction of apoptosis was associated with p53 and Bax up regulation.

INTRODUCTION

Carbon ions have a unique advantage due to their physical properties and thus higher dose effect on malignant tumours compared to conventional radiotherapy. The cell mortality rate from a carbon ion beam is also greater than that from a proton beam when the same physical dose is used. The energy deposited per unit of length along the particle track, which is the linear energy transfer (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. The ratio of cell killing is expressed by the relative biological effectiveness (RBE). Commonly for most cell lines, the RBE of a carbon ion beam has been reported to be from 2 to 3, meaning that the cell killing of carbon ions is two to three times stronger than that of γ -rays [1].

Bax is the member of the Bcl-2 family that accelerates or activates apoptosis [2]. The tumour suppressor protein p53, which is the most frequently mutated gene in human cancers, plays a protective role to the genome in the response to a variety of stresses [3]. When the cells are subjected to radiation or some other stress events, p53 is

activated and its level increases. Also it provokes either cell cycle arrest or programmed cell death - apoptosis [4]. The mechanism by which p53 protein might trigger apoptotic machinery involves the pro-apoptotic regulator, Bax. In certain cell types, after the DNA damage Bax appears to be transcriptionally induced by p53 [5].

Radiobiological data for the HTB140 cells exposed to the same beam of ¹²C ions have been already reported [6].

In order to contribute to the understanding of mechanisms involved in the induction of apoptosis, the pro-apoptotic cell response to carbon ions of different, but high LET, was investigated.

MATERIAL AND METHODS

Cell Culture

The human HTB140 melanoma cells were grown in the RPMI 1640 medium supplemented with 10 % foetal calf serum, penicillin/streptomycin and L - glutamine in a humidified atmosphere of 5 % CO₂, at 37 °C (Heraeus, Hanau, Germany).

Irradiation Conditions

Cells were irradiated with the 62 MeV/u ¹²C ion beams produced by the superconducting cyclotron at INFN – LNS, in Catania. Three positions for irradiation within the Bragg curve (A, B and C) were obtained by interposing Perspex plates (Polymethyl methacrylate - PMMA) of different thickness between the final collimator and the cell monolayer. The corresponding relative doses at positions A, B and C were 73.37 ± 3.92 , 98.12 ± 2.17 and 16.68 ± 5.21 %, respectively (Figure 1) [6]. Reference dosimetry was performed by the plane-parallel PTW 34045 Markus ionization chamber calibrated according to the IAEA code of practice [7, 8]. Cells were irradiated at the single dose levels of 2, 4, 8, 12 and 16 Gy, with the average dose rate of 11.45 ± 0.31 Gy/min. For each position the corresponding LET values were obtained by numerical simulations with the GEANT4 code [9] and were 285, 465 and 765 keV/ μ m, respectively. Cell monolayers were fixed vertically in a special device for irradiation, facing the horizontal beam.

Since the range of the 62 MeV/u carbon ions is short (~ 8 mm), with a very narrow Bragg peak, the precision of

positioning of the cell samples was checked by placing GafChromic HS films (ISP Technologies, Wayne, New Jersey, U.S.A.) before and after each irradiation. Irradiations were carried out in air at room temperature.

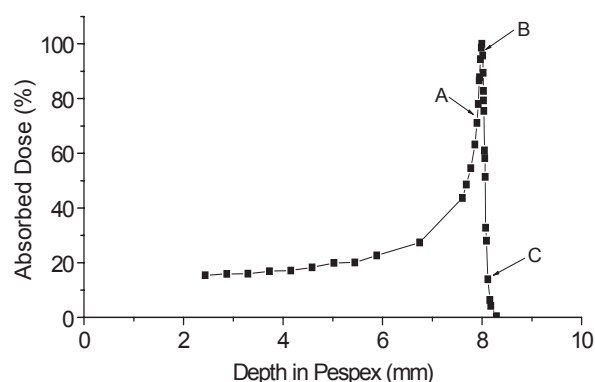


Figure 1: Depth dose distribution in Perspex of the 62 MeV/u ^{12}C ion beam produced at INFN – LNS. Arrows indicate irradiation positions.

Flow cytometric analysis

Apoptosis status was checked using propidium iodide staining (PI, Sigma-Aldrich Chemie GmbH Steinheim, Germany). PI was added to the cell samples prior to FACS analyses. 1×10^6 cells per sample were washed in PBS, counted, fixed and permeabilized with 500 μL of 70 % ice-cold ethanol, overnight at 4 $^{\circ}\text{C}$. Cells were then pelleted by centrifugation at 420 $\times g$ for 10 minutes and stained with buffer solution containing 50 $\mu\text{g/mL}$ PI and 50 $\mu\text{g/mL}$ RNase A, 30 minutes prior to the flow cytometric analyses. The percentage of apoptotic cells were calculated using the ModFit software (Verity Software, Becton Dickinson, Heidelberg, Germany).

Preparation of protein extracts

Cells were scraped off from the flask 48 h after irradiation, washed with PBS and lysed in ice-cold buffer containing 150 mM NaCl, 50 mM Tris-HCl (pH 8.0), 1 % Nonidet P-40 (NP-40), 0.1 % sodium dodecyl sulfate (SDS), 0.5 % sodium-deoxycholate, 1 mM ethylenediaminetetraacetic acid (EDTA), 1 mM ethylene glycol tetraacetic acid (EGTA), 1 mM dithiothreitol (DTT), 1 mM Na_3VO_4 , 5 $\mu\text{g/mL}$ aprotinin, 5 $\mu\text{g/mL}$ antipain, 5 $\mu\text{g/mL}$ leupeptin, 0.5 mM phenylmethanesulphonylfluoride (PMSF), and then centrifuged at 13 000 $\times g$ for 20 min at 4 $^{\circ}\text{C}$. The cell pellets were resuspended in denaturing buffer and boiled for 5 min.

Western blot detection of Bax and p53

The extracted protein samples (40 μL each) were electrophoretically separated at 150 mA for 1 h, and finally transferred onto the polyvinylidene fluoride (PVDF) membrane. Further, membrane was probed with appropriate antibodies, anti-Bax monoclonal antibody (Cell Signaling), anti-p53 monoclonal antibody (Cell

Signaling) and anti- β -actin polyclonal antibody (Sigma). β -actin was used as a loading control. The signal was developed with an enhanced chemiluminescence reagent and exposed to X-ray film. Densitometry of protein bands on X-ray film was performed using Image J Analysis PC software.

RESULTS AND DISCUSSION

Human melanoma is an extremely aggressive form of cancer with high mortality rate and rapidly growing incidence. Also, they are known as radio-resistant tumours with dissimilar response to conventional radiotherapy [10]. Therapy with heavy ion beams is more efficient in eliminating radio-resistant tumour growths than conventional radiotherapy [11].

The effects of irradiation with doses ranging from 2 to 16 Gy were followed at three positions within the Bragg curve of the 62 MeV/u ^{12}C ion beam.

Radiobiological parameters generally used to analyse and predict the success of therapeutic irradiations, were presented in an earlier study [6]. The efficiency of carbon ions to inactivate cells with respect to conventional radiation (γ -rays) was analysed through relative biological effectiveness at 2 Gy (RBE). Significant cell inactivation was observed in all analysed positions along the Bragg curve. The induction of apoptosis was investigated with the intent to better understand the way of action of irradiation with carbon ion beams.

Table 1. Dose dependent apoptosis in the HTB140 cells 48 h after irradiation with ^{12}C ions at three positions along the Bragg curve.

Irradiation position	Dose (Gy)	Apoptosis (%)	Apoptotic Index
A	0	2.23 $\pm$ 0.06	1
	2	5.46 $\pm$ 0.14	2.45
	4	9.08 $\pm$ 0.06	4.07
	8	14.2 $\pm$ 0.09	6.37
	12	13.2 $\pm$ 0.01	5.92
	16	17.2 $\pm$ 0.02	7.71
B	0	2.23 $\pm$ 0.06	1
	2	6.44 $\pm$ 0.05	2.89
	4	6.98 $\pm$ 0.11	3.13
	8	15.1 $\pm$ 0.02	6.77
	12	12.8 $\pm$ 0.08	5.74
	16	15.4 $\pm$ 0.04	6.91
C	0	2.23 $\pm$ 0.06	1
	2	8.07 $\pm$ 0.12	3.62
	4	7.22 $\pm$ 0.04	3.24
	8	11.9 $\pm$ 0.02	5.34
	12	11.1 $\pm$ 0.02	4.98
	16	6.03 $\pm$ 0.02	2.7

The percentage of apoptotic cells and corresponding apoptotic indexes of HTB140 cells were evaluated 48 h after irradiation. Obtained values are given in Table 1. In the irradiation positions A and B the dose dependant increase of the level of apoptosis was observed. The highest level of apoptosis in both positions was detected

after irradiation with 16 Gy, and was 17.2 ± 0.02 , and 15.4 ± 0.04 , respectively. In the position C, irradiation dose of 8 Gy caused the highest level of apoptosis and was 11.9 ± 0.02 .

The level of apoptosis detected in this experiment was in the range that was already reported for the same cell line exposed to protons and γ -rays [12]. These results confirm high radio-resistance of the HTB140 cells. The dose dependent increase of apoptotic cells near the Bragg peak (position A) and very close to the Bragg peak maximum (position B) could be attributed to the severe damage induced by high LET of carbon ions, leading to the induction of late apoptosis or necrosis. Slightly different values of apoptosis detected in the position at the distal fall-off part of the Bragg peak (position C), represent a kind of saturation of cell inactivation that is probably due to the over kill of cells. This conduct is in agreement with the fact that the highest efficiency of carbon ions is in the LET range of ~ 150 keV/ μ m [13, 14].

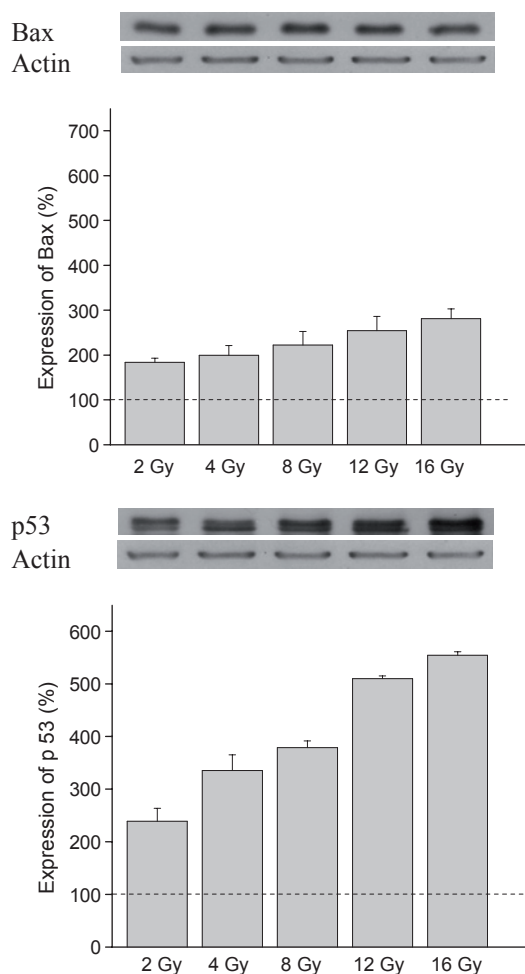


Figure 2. Western blot analysis of Bax and p53 protein 48 h after irradiation of HTB140 cells with 62 MeV/u ^{12}C ions in the position A.

Apoptotic index also showed dose dependant increase in the irradiation positions A and B. Its maximum value was 7.71 in the position A, and was obtained when the cells were irradiated with 16 Gy of ^{12}C ions.

Calculated apoptotic index 48 h after irradiation clearly show the ability of ^{12}C ion beam to provoke programmed cell death of the resistant HTB140 cells. The range of apoptosis is insignificantly different from that already reported for proton irradiation [15]. It is also concomitant with data reported for other melanoma cell lines in which apoptotic cell death was induced by the exposure to different radiation sources or drug treatments [16, 17, 18].

Western blot was used to determine the level of the expression of Bax and p53 regulators of apoptosis, 48 h after irradiation.

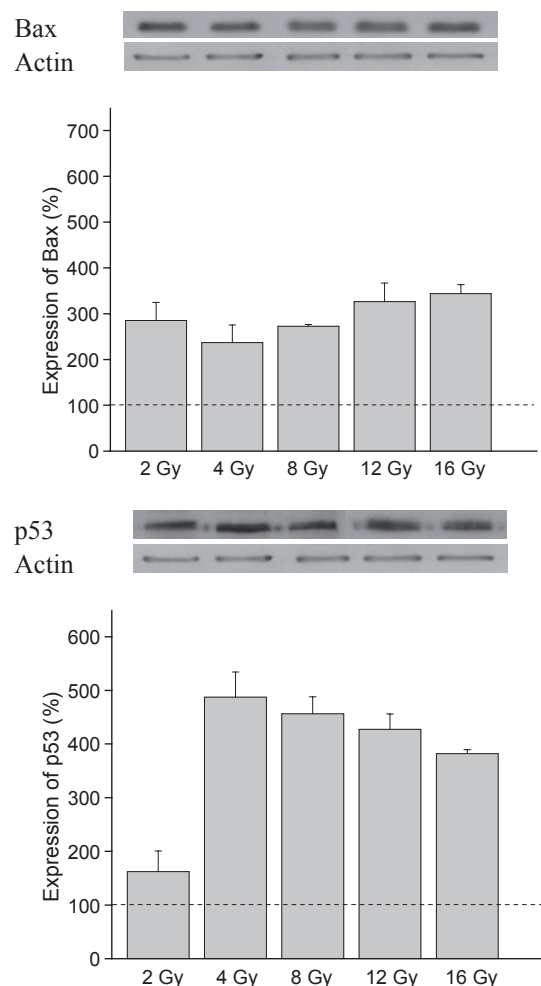


Figure 3. Western blot analysis of Bax and p53 protein 48 h after irradiation of HTB140 cells with 62 MeV/u ^{12}C ions in the position B.

Figure 2 shows the dose dependent increase of Bax in the position A (183-281%) as compared to control. In the position B, the increased level of pro-apoptotic protein Bax was also detected and ranged from 236% to 343% (Figure 3). Irradiation dose of 8 Gy in the position C

triggered the highest level of Bax expression with the value of 616% as compared to control (Figure 4).

The dose dependent increase in the expression of p53 protein was detected in the position A and C as compared to control. In the position A its range was from 238 to 554 % (Figure 2), while in the position C it was from 261 to 569 % (Figure 4). In the position B, all irradiation doses induced increase of the p53 level, from 162 to 487 %, as compared to control (Figure 4).

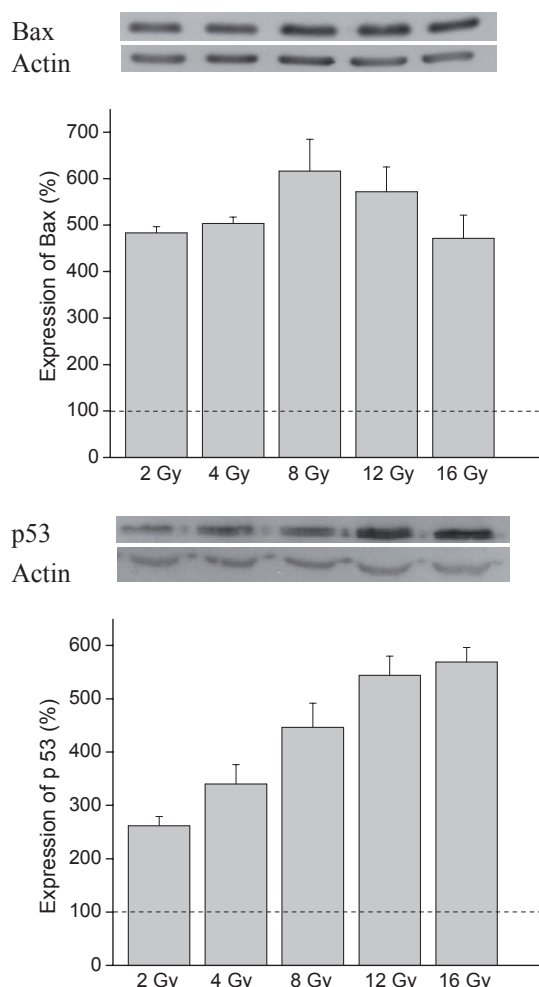


Figure 4. Western blot analysis of Bax and p53 protein 48 h after irradiation of HTB140 cells with 62 MeV/u ^{12}C ions in the position C.

An important role of Bax in the promotion of apoptosis was confirmed *in vitro* and in transgenic data [19]. It has also been shown that γ -rays induce up-regulation of Bax protein *in vivo*. Such DNA damage-induced expression of Bax is, in part, mediated by p53 [5]. Moreover, p53 mediated apoptosis protects cells from malignant conversion and negatively affects survival of already transformed cells [20].

In this study pro-apoptotic effects of carbon ion beam were confirmed by the detected changes of the Bax and p53 protein expression.

CONCLUSIONS

To better understand biological mechanisms involved in cellular response to irradiation with the high-LET ^{12}C ions, the investigation on cell inactivation and gene/protein expression level was undertaken.

The results obtained in this study point out a dose dependent increase of apoptosis in HTB140 cells after their irradiation with ^{12}C ions of various LET values. The effect increased, with the rise of LET, up to the level of the cell over kill phenomena. The induction of apoptotic cell death was associated with the increase of the expression of two regulatory proteins, p53 and Bax, involved in the mitochondrial apoptotic pathway.

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CORRELATION BETWEEN DELAYED LUMINESCENCE AND OXIDATIVE STRESS-INDUCED APOPTOSIS IN HUMAN LEUKAEMIA JURKAT T-CELLS

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Abstract

We investigate the effects of quercetin on apoptosis induced by menadione and hydrogen peroxide under treatments of different time and dosage of the flavonoid in leukemic Jurkat T-cells and provide a series of useful data regarding the optimization of the time and dosage of quercetin administration in a flavonoid-menadione combined treatment of leukemia. Our results indicate the ability of quercetin to enhance menadione-induced apoptosis in Jurkat leukemia cells even at physiological levels of 5-10 μ M. Having in view the growing interest of using delayed luminescence (DL) spectroscopy in clinical applications, a second goal of our study was to gain new insights into the biochemical mechanisms responsible for delayed luminescence of living cells. Thus, we have investigated, for the first time to our knowledge, the correlation between apoptosis, oxidative stress and delayed luminescence. Our data are consistent with 1) the involvement of Complex I of the mitochondrial respiratory chain as an important source of delayed light emission on the 10 μ s - 10 ms scale, 2) the ability of superoxide anions to quench DL on the 100 μ s - 10 ms scale, probably via inhibition of reverse electron transfer at the Fe/S centers in Complex I, and 3) the relative insensitivity of DL to intracellular $\text{OH}^\bullet$ and H_2O_2 levels.

INTRODUCTION

Menadione (vitamin K_3) is a clinically important chemotherapeutic agent used in the treatment of leukemia and other cancer types [1]. Menadione (MD) participates in redox cycling reactions catalyzed by a number of flavoenzymes [2,3], thus producing intracellularly large amounts of superoxide anion ($\text{O}_2^{\bullet-}$). Menadione reduction at Complex I of the mitochondrial respiratory chain (MRC) [2,3], which accounts for 50% of menadione metabolism [3], can readily divert the electron flow from Complex I [2] and therefore interfere with mitochondrial respiration.

Quercetin (QC) is a natural flavonoid ubiquitously occurring in fruits, vegetables and tea. This well-investigated phytochemical can display both antioxidant and pro-oxidant properties and is known to specifically inhibit cell proliferation and induce apoptosis in different cancer cell types [4-9]. Numerous studies have indicated that malignant cells are more susceptible than normal cells to quercetin cytotoxicity [4-6], and this property could be exploited to increase the efficiency of leukemia chemotherapies by employing quercetin-combined treatments. QC is able to inhibit MRC Complexes I and III [8] and participate in quinone redox cycling [5,9]. Therefore, high doses of quercetin increase cellular H_2O_2 and $\text{O}_2^{\bullet-}$ production [6,7]. For short periods of treatment, quercetin effectively decreases the cellular H_2O_2 content, whereas in long-term administration it depletes the intracellular pool of the endogenous antioxidant GSH (reduced glutathione), leading to further accumulation of reactive oxygen species (ROS) and toxic metabolites of quercetin [6-8].

Menadione, hydrogen peroxide and quercetin can activate the apoptotic program via a Ca^{2+} -dependent mitochondrial pathway, by promoting elevation of cytosolic Ca^{2+} levels, mPTP opening, collapse of the mitochondrial membrane potential ($\Delta\psi_m$) and release of cytochrome *c* from mitochondria [4,8,10,11]. Commitment to apoptosis or necrosis depends on whether the blockade of ATP production and the opening of mPTP are transitory or prolonged, respectively [11]. In Jurkat cells, menadione and H_2O_2 at low/medium concentrations preferentially induce cell death through apoptosis, whereas high concentrations promote necrosis by disrupting ATP production [8,10,11].

We have investigated, for the first time to our knowledge, the correlation between apoptosis, oxidative stress and delayed luminescence. DL (also called "delayed fluorescence") represents a very weak, long-time scale light emission following exposure to pulsed light or UV radiation. At the moment, the origin of



delayed luminescence is still a matter of debate, but there is a currently growing interest of using DL spectroscopy in clinical applications [12-15].

MATERIALS AND METHODS

Cell cultures

Human leukemia Jurkat T cell lymphoblasts were cultured in suspension in MegaCell RPMI 1640 medium supplemented with 5% fetal bovine serum, 2 mM L-glutamine, 100 units/ml penicillin and 100 µg/ml streptomycin, at 37°C in a humidified incubator with a 5% CO₂ atmosphere. We used hydrogen peroxide 30% solution and stock solutions of menadione sodium bisulphite dissolved in phosphate buffer saline (PBS), or dihydrated quercetin dissolved in dimethyl sulfoxide (DMSO). DMSO was 0.1% (v/v) in all cultures. After the treatment, cells were washed twice with PBS and resuspended in PBS (for DL samples, $\sim 40 \times 10^6$ cells/ml) or in complete medium for apoptosis assessment ($\sim 0.2 \times 10^6$ cells/ml). DL samples were analyzed immediately by DL spectroscopy. Cell density, viability and morphology were examined with a CCD camera Logitech QuickCam Pro 4000, connected to an Olympus CK30 phase contrast microscope. For cell density assessment, 25 µl- aliquots of the DL samples were diluted in PBS, stained with 0.4% trypan blue solution and ~ 1500 - 2000 cells were imaged on a Burkert haemocytometer at the time of the DL assay. Cell count evaluation was performed both during DL experiments, directly by visual inspection under the microscope, and later on, by analyzing the recorded photographs with the ImageJ software.

Flow cytometry

24 and 48 h after the treatment, samples containing 10^6 cells were fixed in 70% ethanol and frozen at -20°C. For flow-cytometer determinations, the ethanol-fixed samples were washed with PBS, incubated with a propidium iodide PI/RNase staining buffer (PHARMINGEN 550825) for 30 min. at 37°C in the dark and analyzed with a Becton Dickinson FACS Calibur flow-cytometer. For data acquisition and analysis we used the CellQuest, WinMDI 2.8 and Cylchred software. Apoptosis was evaluated as the fraction of hypodiploid cell fragments (the sub-G₀/G₁ cell fraction). The G₀/G₁, S and G₂/M cell fractions were calculated for the non-apoptotic cell population, by excluding the hypodiploid events from cell cycle analysis. For each treatment, the 24/48-h data (at least six per treatment) were used collectively to calculate the mean and the standard error of the mean (s.e.m.).

Delayed Luminescence Spectroscopy

We used an improved version of the ARETUSA set-up [16], a highly sensitive equipment able to detect single photons. The cell samples were excited by a Nitrogen Laser source (Laser Photonics LN 230C; wavelength 337 nm, pulse-width 5 ns, energy 100 ± 5 µJ/pulse). A multi-alkali photomultiplier tube (Hamamatsu R-7602-1/Q) was used as a detector for photoemission signals with

wavelengths in the range 400-800 nm, in single photon counting mode. The detected signals were acquired by a Multi-channel Scaler (Ortec MCS PCI) with a minimum dwell-time of 200 ns. DL measurements were done on at least 3 different drops from each cell sample (drop volume 15-25 µl) at room temperature ($20 \pm 1^\circ\text{C}$). PBS luminescence was subtracted from all the recordings. Photoemission was recorded between 11 µs and 10 ms after laser-excitation. DL intensity (I) was obtained as the number of photons recorded within a certain time interval divided to that time interval and to the number of living cells in the drop. The quantum yield was calculated in three time-domains of the DL emission: 11-100 µs (DL-I), 100 µs - 1 ms (DL-II) and 1-10 ms (DL-III), as the ratio between the I-integral and the energy of the laser.

Statistics

All the data presented in this paper were obtained from at least three different experiments, and are expressed as mean $\pm$ s.e.m. Statistically significant differences were determined using Student's *t*-test compared to control or between the indicated groups. A level of $p < 0.05$ was considered significant in all statistical tests.

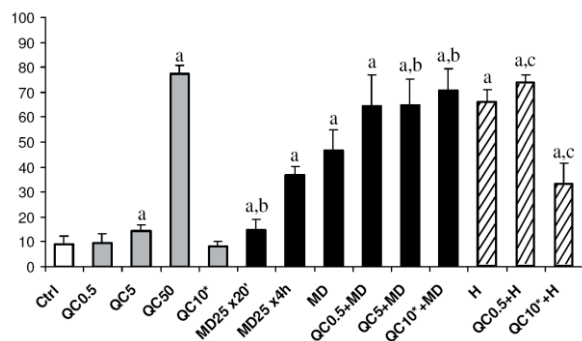
RESULTS

Flow-cytometer measurements (Fig. 1) and trypan-blue exclusion tests indicated that QC-treatment with 10 µM for 1 hour or 0.5 µM for 24 hours did not exert cytotoxic effects on Jurkat cells. QC-treatment with 5 µM for 24 h slightly increased the apoptotic rate to $14.5 \pm 2.3\%$ (vs. $9.2 \pm 3.1\%$ in control cells), whereas 24-h incubation with 50 µM QC induced apoptosis in $74.1 \pm 3.4\%$ of the cells.

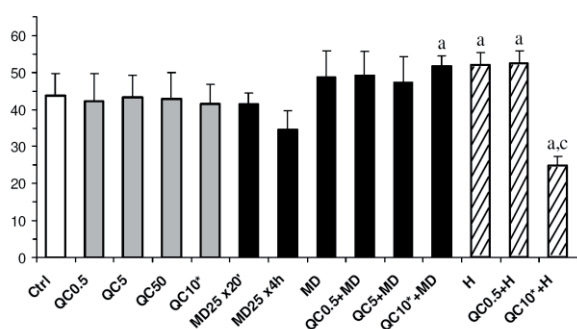
25 µM MD for 20 min. slightly increased the apoptotic cell fraction to $14.7 \pm 4.1\%$, whereas longer treatments (4 h) increased the apoptotic rate to $36.7 \pm 3.6\%$ (Fig. 1). In the latter case there was a partial blockage in the G₂/M phase of the cell cycle (G₂/M fraction $25.2 \pm 2.3\%$ vs. $16.8 \pm 3.3\%$ in control cells, $p < 0.01$), indicating the presence of DNA damage and activation of the G₂/M checkpoint (Fig. 1). Menadione at high concentration (250 µM for 20 min.) produced $46.4 \pm 8.6\%$ apoptotic cells, but did not change the cell-cycle distribution. Pre-incubation with 5 µM QC for 24 h or 10 µM QC for 1 h significantly enhanced apoptosis induced by 250 µM MD (apoptotic fractions: $64.7 \pm 10.4\%$ and $70.6 \pm 8.6\%$, respectively), suggesting an increased ROS production in combination treatments as compared with menadione alone.

Treatment with 500 µM H₂O₂ for 20 min. potently induced apoptosis in $66.0 \pm 4.9\%$ cells (Fig. 1). Pre-incubation with 0.5 µM QC for 24 h slightly increased the apoptotic cell fraction to $73.7 \pm 3.1\%$, whereas pre-exposure to 10 µM QC for 1 h protected cells from H₂O₂-induced apoptosis ($33.4 \pm 8.3\%$ apoptotic fraction). The latter effect appears to be associated with the activation of the G₂/M checkpoint (Fig. 1).

Apoptotic cells (%)



S cells (%)



G₂/M cells (%)

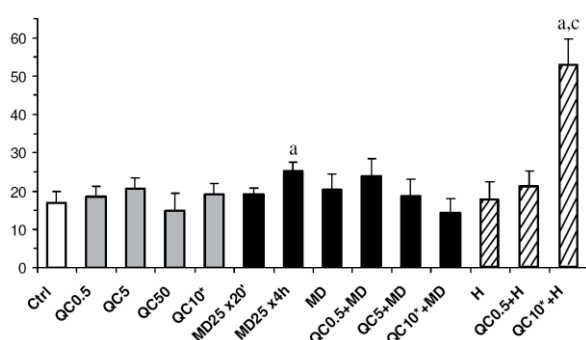


Figure 1: Apoptosis and cell-cycle distributions after treatment of Jurkat cells with 0.5, 5 or 50 μ M quercetin for 24 h (QC0.5, QC5, QC50), 10 μ M quercetin for 1 h (QC10*), menadione (MD25: 25 μ M for 20 min. or 4 h as indicated, MD: 250 μ M for 20 min.), 500 μ M H₂O₂ for 20 min. (H), or after combined treatments (quercetin pre-incubation followed by addition of 250 μ M menadione or 500 μ M H₂O₂ for 20 min.). "a" indicates significantly different from Control (Ctrl), "b"- significantly different from MD (presented for the menadione-group only, black bars), "c"-significantly different from H (presented for the H₂O₂-group only, hatched bars).

The G₂/M cell fraction at 24 h after the H₂O₂ challenge increased from $17.8 \pm 4.7\%$ (with no QC-pre-incubation) to $57.9 \pm 1.7\%$ (with QC-pre-incubation). Moreover, the G₂/M fraction decreased thereafter to $41.7 \pm 4.9\%$ at 48 h after the "QC10* + H" treatment, indicating the onset of release from the G₂/M arrest and resumption of cell proliferation.

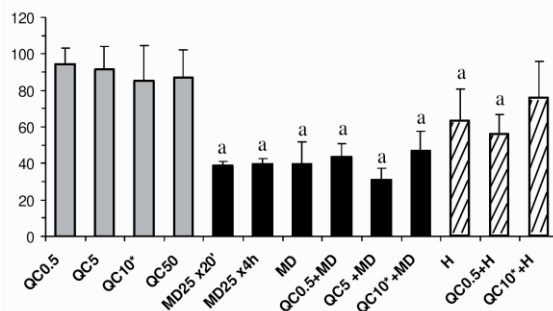
DL-I photoemission (time-scale 11-100 μ s) appeared to be relatively insensitive to quercetin but considerably reduced by menadione (Fig. 2). DL-I exhibited a

noticeable insensitivity even at high QC levels (50 μ M), in samples where 45% of the cells were in advanced stages of apoptosis (not shown), arguing against an essential role of ROS in DL-I. Menadione at concentrations ≥ 25 μ M produced a fairly even (~60%) reduction in the DL-I quantum yield, irrespective of the treatment time or the prior administration of quercetin (Fig. 2A). 500 μ M H₂O₂ produced a moderate (~35%) reduction in the DL-I quantum yield.

A

DL-I Relative quantum yield (% of control)

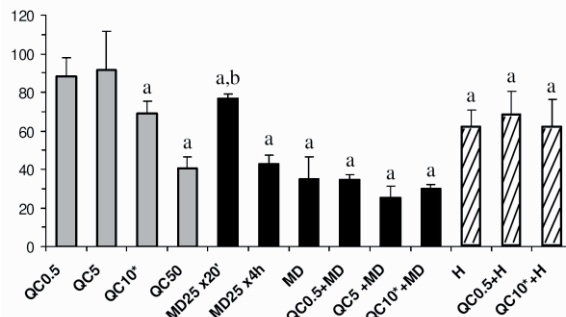
10 μ s – 100 μ s



B

DL-II Relative quantum yield (% of control)

100 μ s – 1 ms



C

DL-III Relative quantum yield (% of control)

1 ms – 10 ms

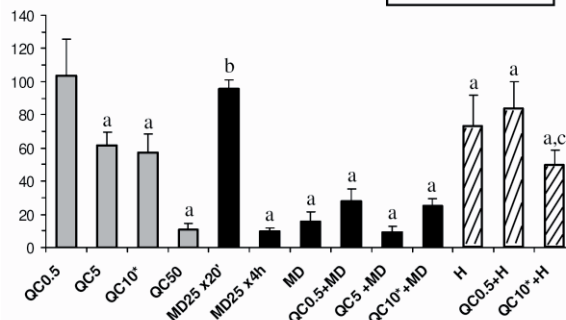


Figure 2: Relative DL-quantum yield on different time-scales (boxes) under the treatments indicated in Fig. 1. Significant differences between treatments are represented as in Fig. 1.



In our experiments, the necrotic cell fraction appeared to be low (<15% after trypan-blue staining) under all treatments, indicating that ATP production and $\Delta\psi_m$ were only transiently altered after the QC-, MD- or H_2O_2 -treatments. Taken together, our results support the hypothesis that DL-I is related to the respiratory activity of the mitochondria, and that DL-I reduction by menadione and H_2O_2 was most likely due to a temporary inhibition of forward electron transport in MRC complex I. The data obtained from MD-treated cells (Fig. 2A) suggest a ~60% contribution to DL-I of forward electron transfer in Complex I.

The regions DL-II (time-scale 100 μs - 1 ms) and DL-III (1-10 ms) were highly sensitive to both quercetin and menadione, in a dose-dependent manner (Fig. 2). There is a strong anti-correlation between the DL-II quantum yield and the apoptotic cell fraction under all treatments (Pearson correlation coefficient $r = -0.79$), suggesting that all the three drugs (MD, H_2O_2 and QC) affect DL-II by a common mechanism. For reasons detailed above, our results indicate that inhibition of forward reactions in the respiratory chain and mitochondrial depolarization participate to this effect only to a small extent. Likely candidates for explaining this behavior are the reactive oxygen species $OH^\bullet$, H_2O_2 and $O_2^{\bullet-}$, which can be produced inside the cells by all of these drugs. However, the Q10* pre-treatment, which offered consistent protection against the H_2O_2 insult, failed to restore DL-II/III emission, suggesting that DL-II/III could be correlated to the $O_2^{\bullet-}$ level rather than to the $OH^\bullet/H_2O_2$ levels. By assuming <15% contribution of forward electron transfer in Complex I, we could estimate, from maximal DL-inhibition data (Fig. 2B,C), that the contribution of the $O_2^{\bullet-}$ -sensitive states is ~55-70% to DL-II and ~70-85% to DL-III.

DISCUSSION

Our data indicate a >50% contribution of MRC Complex I to DL and the DL-quenching ability of superoxide. Spontaneous photoemission by mitochondria was associated with lipid peroxidation that occurs inside the mitochondrial membrane and produces 1O_2 [17]. We did not detect any DL increase in our experiments with varying levels of superoxide generators. Moreover, H_2O_2 appears to exert its cytotoxic effects on Jurkat cells without producing significant levels of lipid peroxides [18], and in our work the Q10*-pretreatment, which offered substantial protection against H_2O_2 and hence would prevent the lipoperoxidation effects of H_2O_2 (if any), did not ameliorate the DL reduction observed after the H_2O_2 -treatment. These findings suggest that delayed luminescence of Jurkat cells is not related appreciably to lipid peroxidation or production of singlet oxygen.

In MRC Complex I, the two electrons delivered by NADH to flavine mononucleotide (FMN) are individually transferred between eight consecutive iron-sulfur (Fe/S) clusters and eventually reach the ubiquinone. Our results support the notion that FMN can absorb UV radiation

thus producing excited singlet states that may either decay to the ground state by prompt fluorescence [19] or undergo intersystem crossing to long-lived triplet states [20] which can further relax to metastable intermediate states [20]. The long lifetime of the triplet- or metastable-state species allows a series of photochemical reactions to occur in MRC Complex I and produce secondary excitations, thus giving rise to delayed luminescence. The observed DL-II and DL-III reduction by menadione, quercetin and H_2O_2 treatments suggests inhibition by high levels of superoxide of reverse electron transfer at the two extreme Fe/S centers N1a and N2 (for DL-II, decay times ~100 μs [21]), or at the remaining centers (for DL-III, decay times ~1 ms [21]), which requires the reduced Fe/S sites to react with $O_2^{\bullet-}$ [21]. Certainly, further investigations are needed to clarify these aspects, but it is growingly clear that the use of DL spectroscopy in clinical diagnostic applications or in prospective studies of cancer treatments can offer the benefit of accuracy and rapidity of the tests.

ACKNOWLEDGEMENTS

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APOPTOSIS, CELL CYCLE AND DELAYED LUMINESCENCE OF HUMAN LEUKEMIA JURKAT T-CELLS UNDER PROTON-IRRADIATION AND OXIDATIVE STRESS CONDITIONS

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Abstract

We investigated the relation between apoptosis and delayed luminescence (DL) in human leukemia Jurkat T-cells undergoing various treatments. We used menadione, hydrogen peroxide and quercetin to induce oxidative stress conditions under different doses and treatment times. We irradiated Jurkat cells by using modulated beams of accelerated protons with energies up to 62 MeV, under a dose of 10 Gy distributed uniformly inside the cell suspension. We assessed cell proliferation, clonogenic survival and delayed luminescence of treated cells. Apoptosis and cell cycle distributions were measured by flow-cytometry. Irradiation with protons produced a modest increase in the apoptotic rate, but blocked the cell cycle at the G₂/M phase for at least 48 h after irradiation, suggesting the presence of severe DNA damage. A 34% reduction of the DL quantum yield was observed in a specific DL time interval, 1-10 ms after the laser excitation of the cell samples after 1 h from irradiation, whereas the DL quantum yield exhibited an increase of 27% in the DL time interval 0.1-1 ms in cell samples probed 24 h after irradiation. The treatments using menadione, hydrogen peroxide and quercetin as oxidant agents potently induced apoptosis of Jurkat cells in a dose-dependent manner and consistently decreased the intensity of delayed photoemission. We obtained a strong anti-correlation between apoptosis of human leukemia Jurkat cells and UV-induced delayed photoemission on a specific time interval ranging from 100 µs to 1 ms after UV-excitation of the cell samples.

INTRODUCTION

Menadione (vitamin K₃) is a clinically important chemotherapeutic agent used in the treatment of leukemia and other cancer types [1], which produces intracellularly large amounts of superoxide anion (O₂^{-•}). Quercetin (QC) and epigallocatechin gallate (EGCG) are two well-investigated natural flavonoids which are known to

specifically inhibit cell proliferation and induce apoptosis in different cancer cell types [2-4]. Menadione, hydrogen peroxide and quercetin can activate the apoptotic program via a Ca²⁺-dependent mitochondrial pathway, by promoting elevation of cytosolic Ca²⁺ levels, mPTP opening, collapse of the mitochondrial membrane potential ($\Delta\psi_m$) and release of cytochrome *c* from mitochondria [2,5-7].

The sensitivity to radiation of Jurkat cells is relatively high [8,9] and high doses (≥ 10 Gy) of radiation can induce significant apoptosis in a time- and dose-dependent manner [8,10]. Failure to eliminate cells that have been exposed to mutagenic agents by apoptosis has been associated with the development of cancer and resistance to anticancer therapy.

We have investigated the correlation between apoptosis and delayed luminescence (DL) under oxidative stress and irradiation conditions. Quantification of these aspects can help answering the question on the origin of DL, which at the moment is still a matter of debate. DL represents a very weak, long-time scale light emission following exposure to pulsed light or UV radiation. It is generally thought that DL in biological systems may arise from a variety of possible reactions and sources, such as direct emitters like flavins, carbonyl derivatives and aromatic compounds, molecular oxygen and its species, the DNA, as well as collective molecular interactions, e.g. triplet-triplet annihilation, collective hydrolysis, charge recombination within the mitochondrial/chloroplast electron transport system, or the cytoskeleton [11-15]. In this work we present direct evidence for a connection between apoptosis and DL.

MATERIALS AND METHODS

Cell cultures

Human leukemia Jurkat T cell lymphoblasts were cultured in suspension in MegaCell RPMI 1640 medium supplemented with 5% fetal bovine serum, 2 mM



L-glutamine, 100 units/ml penicillin and 100 µg/ml streptomycin, at 37°C in a humidified incubator with a 5% CO₂ atmosphere. We used hydrogen peroxide 30% solution and stock solutions of menadione sodium bisulphite dissolved in phosphate buffer saline (PBS), or dihydrated quercetin and epigallocatechin gallate dissolved in dimethyl sulfoxide (DMSO). DMSO was 0.1% (v/v) in all cultures. After the treatment, cells were washed twice with PBS and resuspended in PBS (for DL samples, $\sim 40 \times 10^6$ cells/ml) or in complete medium for apoptosis assessment ($\sim 0.2 \times 10^6$ cells/ml). DL samples were analyzed immediately by DL spectroscopy. Cell density, viability and morphology were examined with a CCD camera Logitech QuickCam Pro 4000, connected to an Olympus CK30 phase contrast microscope. For cell density assessment, 25 µl- aliquots of the DL samples were diluted in PBS, stained with 0.4% trypan blue solution and ~ 1500 - 2000 cells were imaged on a Burker haemocytometer at the time of the DL assay. Cell count evaluation was performed both during DL experiments, directly by visual inspection under the microscope, and later on, by analyzing the recorded photographs with the ImageJ software.

Irradiation conditions

Cell suspensions (7 ml) were irradiated in 50 ml-centrifuge tubes in vertical position. Clinical proton beams accelerated by the superconducting cyclotron at LNS-INFN, Catania (Italy) were used for proton-irradiation at a dose rate of 11.76 Gy/min. The proton beams were modulated to give uniform distribution of the absorbed dose in the entire cell suspension. The maximal proton energies were 62 MeV at the entrance, and 15 MeV at the exit from the cell sample. A plane-parallel advanced PTW 34045 Markus ionization chamber was adopted as a reference dosimeter. The dose measurements were performed in a water phantom, according to International Atomic Energy Agency (IAEA) TRS 398. The absorbed dose to water per monitor unit (cGy/M.U.) was measured at isocenter, at the depth corresponding to the middle of the modulated beam, with the reference circular collimator (diameter = 25 mm).

Clonogenic survival assay

After treatment, cells were harvested and plated in 96 well plates at a plating density of 4 cells/well in 100 µl of complete medium per well. After 4 weeks of incubation, the plates were inspected by microscopy and the wells containing clones with >50 cells were counted. The plating efficiency was calculated as $\ln[96/(\text{no. of negative wells})]/(\text{plating density}) \times 100$. Clonogenic survival was calculated as the ratio between the plating efficiency of treated and control cells, respectively.

Flow cytometry

24 and 48 h after the treatment, samples containing 10^6 cells were fixed in 70% ethanol and frozen at -20°C. For flow-cytometer determinations, the ethanol-fixed samples

were washed with PBS, incubated with a propidium iodide PI/RNase staining buffer (PHARMINGEN 550825) for 30 min. at 37°C in the dark and analyzed with a Becton Dickinson FACS Calibur flow-cytometer. For data acquisition and analysis we used the CellQuest, WinMDI 2.8 and Cylchred software. Apoptosis was evaluated as the fraction of hypodiploid cell fragments (the sub-G₀/G₁ cell fraction). The G₀/G₁, S and G₂/M cell fractions were calculated for the non-apoptotic cell population, by excluding the hypodiploid events from cell cycle analysis. For each treatment, the 24/48-h data were used collectively to calculate the mean and the standard error of the mean (s.e.m.).

Delayed Luminescence Spectroscopy

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RESULTS AND DISCUSSION

Irradiation with 10 Gy of protons produced a modest increase in the apoptotic rate, but blocked the cell cycle at the G₂/M phase for at least 48 h after irradiation, suggesting the presence of severe DNA damage (Fig. 1). Clonogenic survival after irradiation was below the resolution of our assay (0.12%), indicating that 10 Gy of protons induced massive necrosis in this cell system, in agreement with other reports [9,10]. Trypan blue exclusion tests confirmed high necrotic rates of 18.4% and 46.6% at 24 h and 48 h after irradiation, respectively. Delayed light emission of the living cells exhibited different characteristics when probed at 1 h or 24 h after irradiation. A 34% reduction of the DL-III relative quantum yield was observed after 1 h from irradiation, whereas the DL-II relative quantum yield exhibited an increase of 27% in cell samples probed 24 h after irradiation.

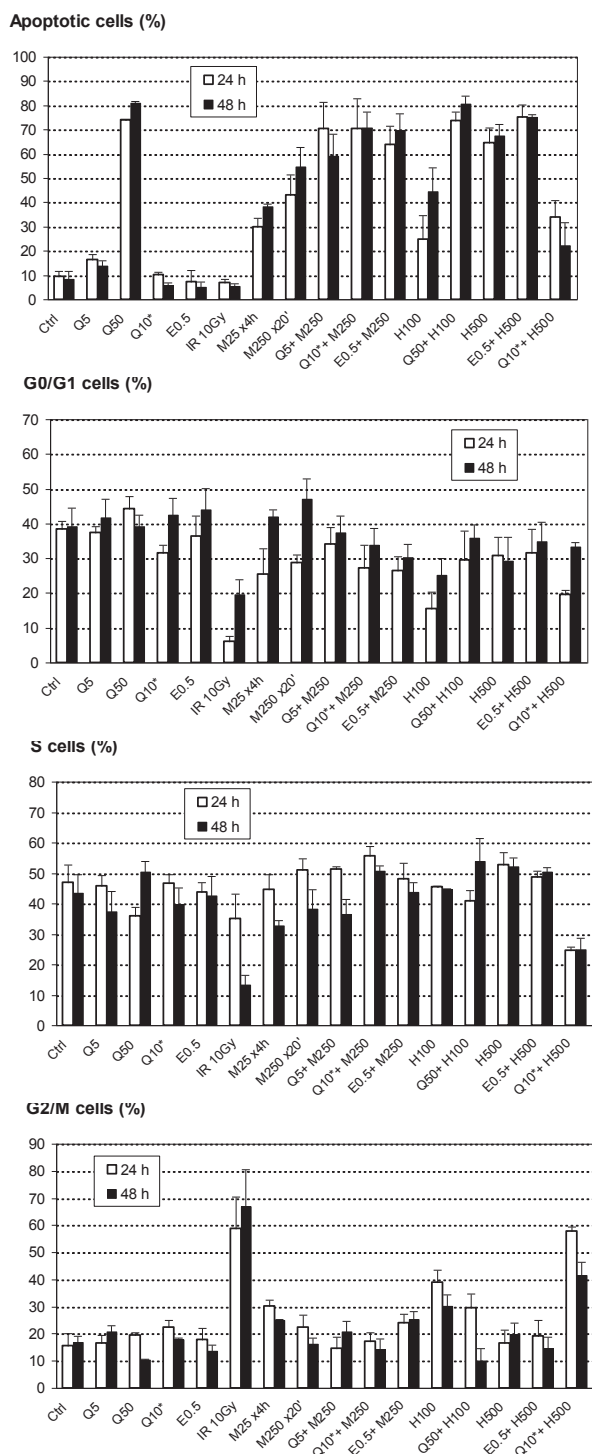


Figure 1: Apoptosis and cell-cycle distributions after treatment of Jurkat cells with 0.5, 5 or 50 μ M quercetin for 24 h (Q0.5, Q5, Q50), 10 μ M quercetin for 1 h (Q10*), 0.5 μ M EGCG for 24 h (E0.5), menadione (M25: 25 μ M for 20 min. or 4 h as indicated, M: 250 μ M for 20 min.), 100 or 500 μ M H_2O_2 for 20 min. (H100 or H500), or after combined treatments (quercetin or EGCG pre-incubation followed by addition of 250 μ M menadione or 100/500 μ M H_2O_2 for 20 min.).

QC, MD and H_2O_2 induced apoptosis in Jurkat cells in a dose- and time-dependent manner (Fig. 1). The lower dose of H_2O_2 (100 μ M for 20 min.) produced $34.8 \pm 9.9\%$ apoptotic cells and a G₂/M ratio of $34.6 \pm 4.5\%$ 24-48 h after the treatment, whereas the highest dose used (500 μ M for 20 min.) only slightly increased the S-phase cell fraction (Fig. 1). H_2O_2 can induce cell cycle arrest at G₂/M by expression of p21^{Cip1}, a cyclin-dependent kinase inhibitor [16]. It is possible that in our experiments, Jurkat cells were unable to cope with extensive oxidative damage and thus could not complete the current cell-cycle phase in less than 48 h, since damage repair following a milder stress appeared to be quite slow (as discussed above, the G₂/M blockade persisted for >48 h in both treatments with 100 μ M H_2O_2 and 500 μ M H_2O_2 + 10 μ M QC-preincubation). In addition, haemocytometer counts indicated that there was no net growth in cell cultures 24-48 h after the most severe oxidative treatments (namely "M" and "H"). Together, these results suggest that under excessive oxidative stress induced by menadione or hydrogen peroxide, Jurkat cells accumulate hardly repairable damage and therefore are stopped in all the phases of the cell cycle. Under our experimental conditions, a large part of the arrested cells initiated the apoptotic program; however, it appeared that the surviving cells eventually managed to repair the damage and continued to proliferate after >48 h from exposure (we obtained clonogenic survival $41.2 \pm 2.9\%$ for the treatment with 250 μ M MD). Finally, it is worth mentioning that trypan-blue viability tests indicated that necrosis was low (<15%) under all oxidative treatments, which is consistent with other reports [17] and with the clonogenic survival data.

At the moment, the current available data on the effects of quercetin on apoptosis induced by menadione and hydrogen peroxide in Jurkat T-cells are extremely limited. In human normal lymphocytes quercetin can produce noticeable quantities of $O_2^{\cdot-}$ and $OH^{\cdot}$ at levels ≥ 50 μ M within 30 min. of treatment [4]. After intake, quercetin and EGCG are rapidly metabolized and normal levels in the plasma remain below 10 μ M [3,18], but can increase considerably in human tissues, in particular at the inflammatory sites. In this work, a 24-hour treatment with physiological levels (0.5 - 5 μ M) of quercetin and EGCG enhanced apoptosis induced by menadione in human leukemia Jurkat T cells, whereas a short-term treatment with 10 μ M QC reduced apoptosis induced by hydrogen peroxide. In addition, preincubation with a very low level (0.5 μ M) of EGCG significantly increased the G₂/M cell fraction after the 250 μ M MD-treatment. While long-term administration of quercetin or EGCG could improve significantly the menadione-based treatment of leukemia, it is important that normal cells remain unexposed to noxious levels of the flavonoids used.

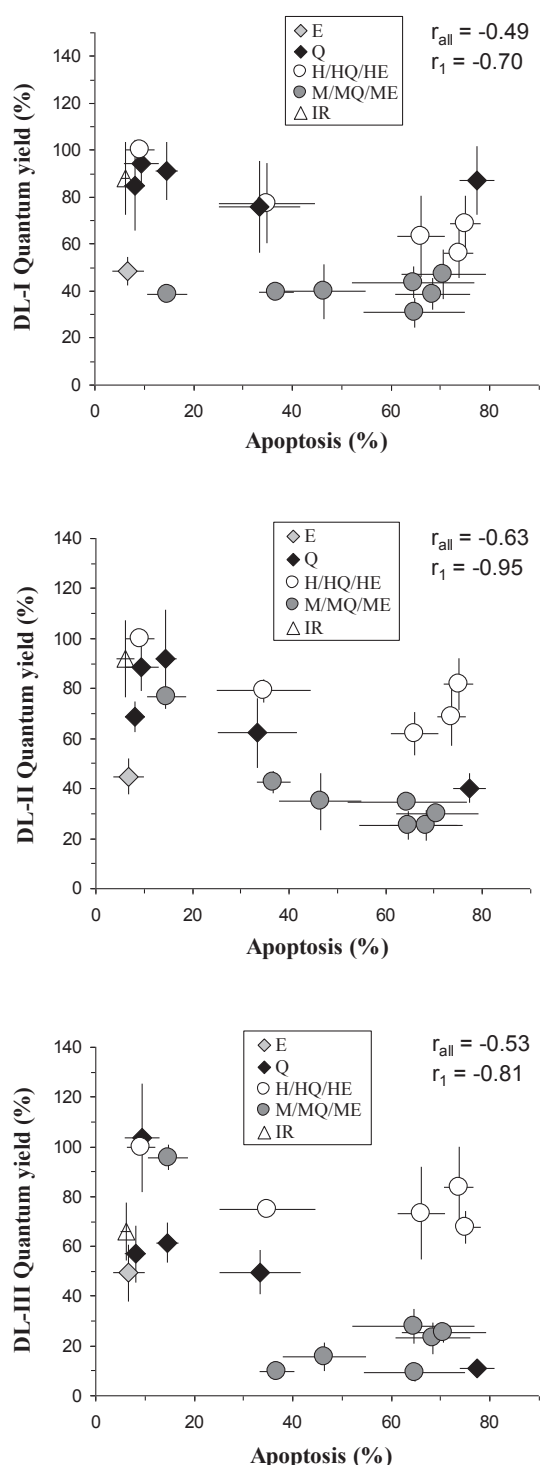


Figure 2: DL-quantum yield (relative to control) and its correlation to the apoptotic cell fraction under the treatments indicated in Fig. 1. Q, E, M/MQ/ME, H/HQ/HE and IR denote single QC- or EGCG-treatments, MD-treatments with or without QC- or EGCG-preincubation, H₂O₂-treatments with or without QC- or EGCG-preincubation, and 10 Gy proton-irradiation, respectively. The Pearson correlation coefficients are shown for all treatments (r_{all}) and for M/MQ/ME/IR treatments (r_1).

Both quercetin and menadione inhibited DL in a dose-dependent manner. Surprisingly, we found that QC and

MD at high doses exhibited virtually identical effects on DL over a wide time-interval, from 100 μ s to 10 ms after laser-excitation. Having in view the molecular interactions that are common to both chemicals, it is most likely that their similar effects on DL were caused by superoxide production and inhibition of Complex I of the mitochondrial respiratory chain.

Our studies provide new insights into the relation between the cell status and delayed luminescence. With treatments of varying time and dosage of three different pro-apoptotic agents (menadione, hydrogen peroxide and quercetin) we obtained a significant anti-correlation ($r = -0.63$) between apoptosis of human leukemia Jurkat cells and UV-induced delayed photoemission on a specific time interval ranging from 100 μ s to 1 ms after UV-excitation of the cell samples (Fig. 2). More specifically, the M/MQ/ME/IR treatments were associated with a strong anti-correlation between DL-I, DL-II and -III and apoptosis ($r_1 = -0.70$, -0.95 and -0.81 , respectively), suggesting that proton-irradiation increases the intracellular superoxide rather than the H₂O₂ level. Indeed, the effects of H₂O₂ on DL emission were relatively reduced even when very high levels of this oxidant agent were used (Fig. 2). A potential application of DL spectroscopy can thus be envisioned as a rapid and accurate method to assess the pro-apoptotic capacity of certain treatments for acute leukemia.

ACKNOWLEDGEMENTS

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PLASMA LASER ENERGETIC ION ACCELERATION & DIAGNOSTICS (PLEIADI): PROJECT UPGRADE 2010

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Abstract

The 2010 upgrade of the PLEIADI (Plasma Laser Energetic Ion Acceleration & Diagnostics) project is presented and discussed. The research activities concern the improvements of the laser ion source (LIS), of the ion extraction chamber, of the post ion acceleration system (PIAS) and of the ion diagnostics.

Ion collectors and ion energy analyzers, such as a Thomson parabola, were employed for the ion beam diagnostics of the charged particles emitted from the LIS and from the PIAS.

Multi-energetic and multi species ion beams can be accelerated from 0 to 30 kV in order to produce ion implantation in different substrates.

INTRODUCTION

PLEIADI (Plasma Laser Energetic Ion Acceleration & Diagnostics) is a INFN Project devoted to investigate on the realization of a Laser Ion Sources (LIS) and a Post-Ion Accelerated System (PIAS).

The project uses a Nd:Yag laser operating at a fundamental wavelength of 1064 nm, at intensities of the order of 10^{10} W/cm², 0.9 J pulse, 9 ns pulse duration, 0.1-30 Hz repetition rate, in order to generate non-equilibrium plasmas, in high vacuum, by interacting with solid matter. Plasma is produced with high directionality along the normal to the target surface [1]. The ion temperature of obtained plasma is of the order of 100 eV, the plasma density of the order of 10^{17} /cm³, the charge states can reach 10+ for heavy elements and the kinetic ion energies are proportional to the ion charge state and may reach about 6 keV [1]. The ion acceleration is due to the non-uniformity of the spatial charge distribution in the plasma, due to the faster electrons mobility with respect to ions, which induces formation of a high electric field directed along the normal to the irradiated target surface. The calculation of the electric field is possible by knowing the equivalent ion acceleration and the electronic temperature and density of the plasma; its value is of the order of 10 MV/cm [2].

Laser-plasma accelerated ions show “Coulomb-Boltzmann-Shifted” (CBS) distributions, which are shifted towards high energy increasing the ion charge state [3].

Thank to the high ablation yield, obtainable by focusing the laser beam on the target surface, of the order of 10^{17} atoms/pulse for fundamental wavelength ablating metals, and to the high laser repetition rate, the LIS, using the ablation of a roto-translating thick target, permits to extract a constant high current density, of the order of tens mA/cm² [4]. The low energy ions emitted from the plasma can be extracted, focused and submitted to a post-acceleration, due to an external high electric field, in order to generate a multi-energetic ion beam with more interesting energies of employment. Actually PLEIADI uses 30 kV post acceleration but a work is in progress to employ 60 kV voltage and to reach high ion dose-rates. Focalization systems, using electrical and/or magnetic deflections, can be employed in order to increase the ion current towards the acceleration axe or to increase the implantable ion rate.

The post accelerated ion beams can be employed in different scientific fields, such as the ion implantation technique, in order to modify the physical and chemical properties of different substrates, the ion sputtering processes to modify the surface morphology of different polymers, and it can be employed also to plasma diagnostic and to test different detectors dedicated to the range of radiations at low energy levels.

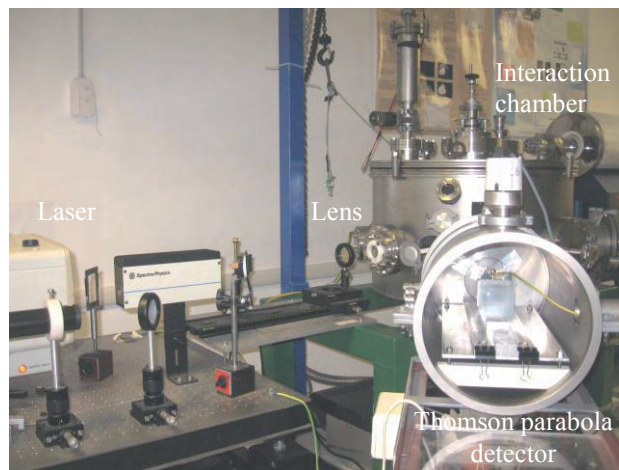


Fig. 1: Photo of the experimental set up.

EXPERIMENTAL SECTION

A Nd:Yag laser operating at 1064 nm (fundamental), 532 nm (second harmonics) and 355 nm (third harmonics) wavelength, with pulse energy from 0 to 900 mJ, with 9 ns pulse width, operating at single pulse or in repetition rate at a frequency between 0.1 and 30 Hz, is employed to be focused on solid targets placed in high vacuum (10^{-6} mbar). The minimum spot of 0.5 mm^2 permits to reach a pulse intensity of about $2 \times 10^{10} \text{ W/cm}^2$.

Different thick and thin targets can be laser irradiated in order to generate fast plasmas with supersonic expansion velocity directed along the normal to the target surface.

Light targets, such as polyethylene (CH_2), mylar ($\text{C}_{10}\text{H}_8\text{O}_4$) and Al, heavy targets such as Ta and Au, and intermediate weight targets, such as Ti, Cu and Ge, have been laser irradiated and submitted to PIAS.

The incidence angle of the laser beam was 30° and the ion diagnostic technique was placed along the normal to the target surface.

The accelerating set-up consists of a plasma expansion chamber, with a parallelepiped shape (26 cm length and 11 cm square base side) at the centre of which is placed the target (3 cm x 3 cm surface and 1-2 mm thickness).

Target and expansion chamber are connected to the same electrical potential, actually selectable from 0 and +30 kV through a high voltage power supply (Heinzinger 30 kV, 200 mA). The front base of the parallelepiped extraction chamber is opened to permit the ions exit along the longitudinal chamber axe and to reach the post acceleration electric field. Fig. 1 shows a photo of the experimental set up prepared at INFN-LNS of Catania. Fig. 2 shows the extraction chamber employed to extract the ions and to submit them to 30 kV post acceleration.

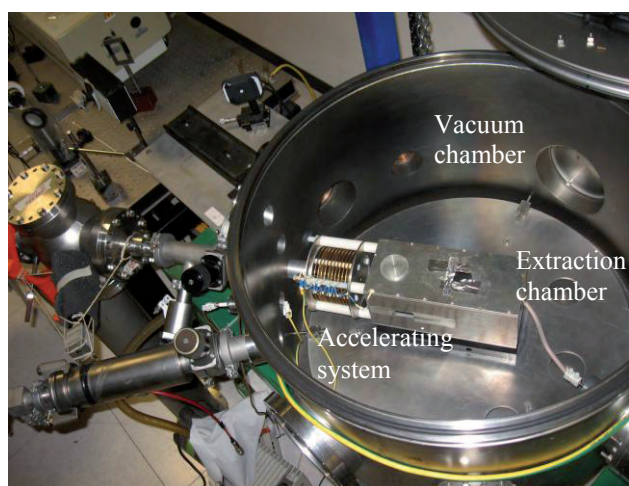


Fig. 2: Extraction chamber and acceleration system.

The extraction chamber has been realized taking in account the results of many ion simulations, performed with the Opera 3D code [5], of the ion trajectories from the laser irradiate target to the extraction chamber and from the post-acceleration system to the final detector. The simulations permit to plot the electric field and the

iso-potential lines in the extraction zone. A Monte Carlo is employed to generate randomly the ions from the plasma, with CBS distributions, at tens-hundreds eV ion plasma temperatures, within an angular distribution of about $\pm 30^\circ$. Inside the extraction chamber there is no ion acceleration and plasma expands without the influence of the external electric field. An ion collimation to 8 mm diameter transfers the ions to the post acceleration system. A focusing effect, produced in front of the extraction discs increases the extractable ion current. Fig. 3 shows a result of one simulation relative to Ti ions emitted from the target and travel towards the extraction system, the post-acceleration system and the final detector.

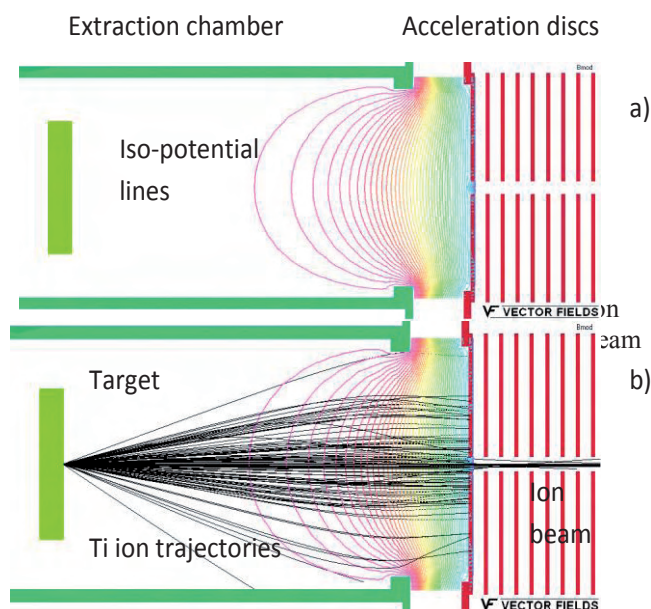


Fig. 3: Simulations of the extraction chamber (a) and of the Ti-ion acceleration section (b).

A ring ion collector (ICR) was placed along the normal to the target surface, i.e. along the direction of the maximum ion acceleration, at a target distance of 100 cm.

TOF technique was adopted by using as a start signal the one coming from a photodiode, induced by the laser shot, and as a stop signal the one coming from the ICR [6].

An electrostatic ion energy analyzer (IEA) was employed to measure the energy-to-charge ratio of the detected particles emitted from the plasma and post-accelerated along the normal direction to the target surface [6]. The IEA spectrometer uses the TOF technique at 160 cm SEM (secondary electron multiplier) detector distance from the target. A Thomson parabola was employed to analyze the produced low multi-energetic and multi-species ion beams [7]. It employs a 0.2 mm input pin-hole, 2000 Gauss magnetic field and 1 kV/cm electric field for the ion deflections, and Gaf-chromic film dosimeters were employed to record the ion parabola images on a plain orthogonally to the target normal direction [8].

The substrates ion implanted have been controlled by RBS technique by using 2.0 MeV helium beam and 170°

detection angle, at the CEDAD Laboratory of Brindisi (Italy) [9].

RESULTS AND DISCUSSION

The post ion acceleration has been applied to different ion beams, from protons up to gold and to different charged ions, from 1+ up to 10+. Sometimes the beams were constituted by different ion species, such as the proton and carbon beams coming from the polyethylene laser ablation.

The ion emitted specie, mean energy and current, and the distributions relative to the angles, energies and charge states, are monitored with the ion collector in TOF configuration. The ion energy distributions follow the CBS function and permit to measure the equivalent ion plasma temperature and energy shift.

As an example, Fig. 4 shows two typical examples of ICR (a) and IEA (b) spectra obtained ablating a Ge target and post accelerating at 30 kV the ion beam.

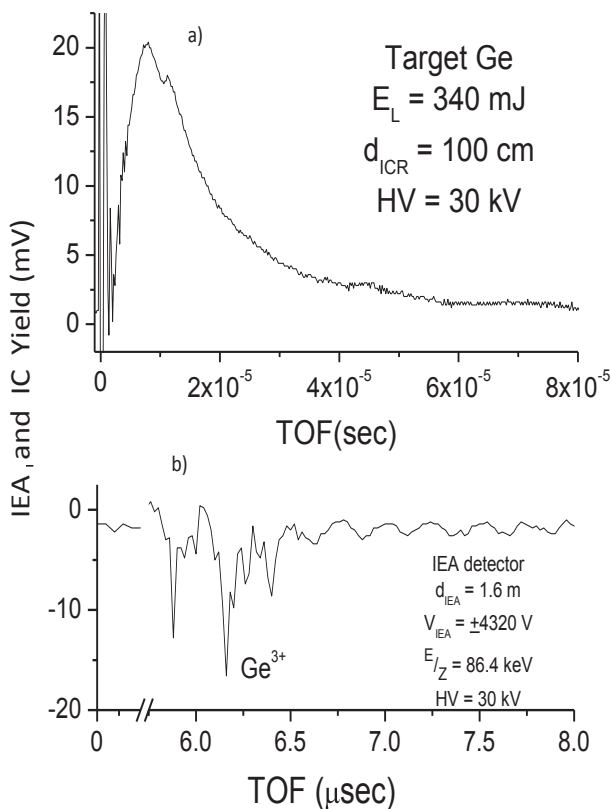


Fig. 4: Typical ICR (a) and IEA (b) spectra relative to the post-ion acceleration of Ge ions.

The IEA analysis of the post accelerated ion beams evinces the nature of the multi-energetic ions, which energy depends on their charge state multiplied by the kV acceleration voltage. Typical examples of ion energy beams are reported in Fig. 5 for the first three charge states of Ge ions. The peak energy has a resolution of the order of 2.5%. The measurements of ion extraction and post acceleration indicate that the average ion dose is of

the order of 10^9 ions/pulse. By considering that the beam area is circular with a radius of about 1 cm and that the LIS can be employed at 10 Hz repetition rate, the employing ion dose-rate is of the order of 10^9 ions/cm²s, corresponding to a current density of about 1 nA/cm².

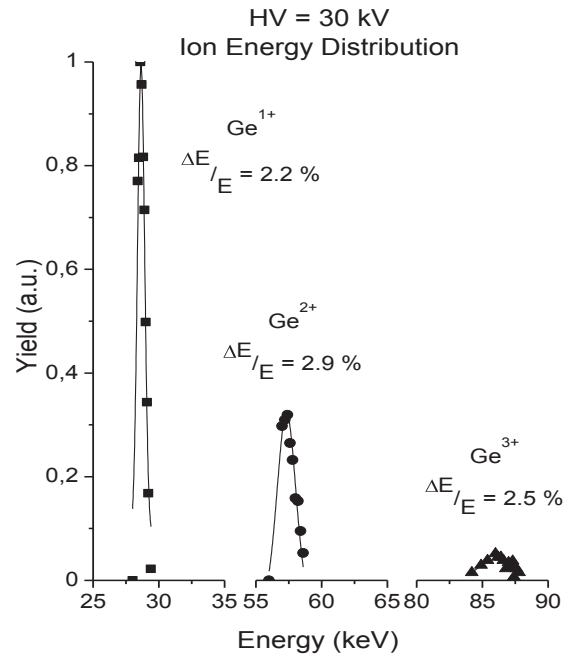


Fig. 5: IEA measurements of 30 kV post accelerated Ge ion beams.

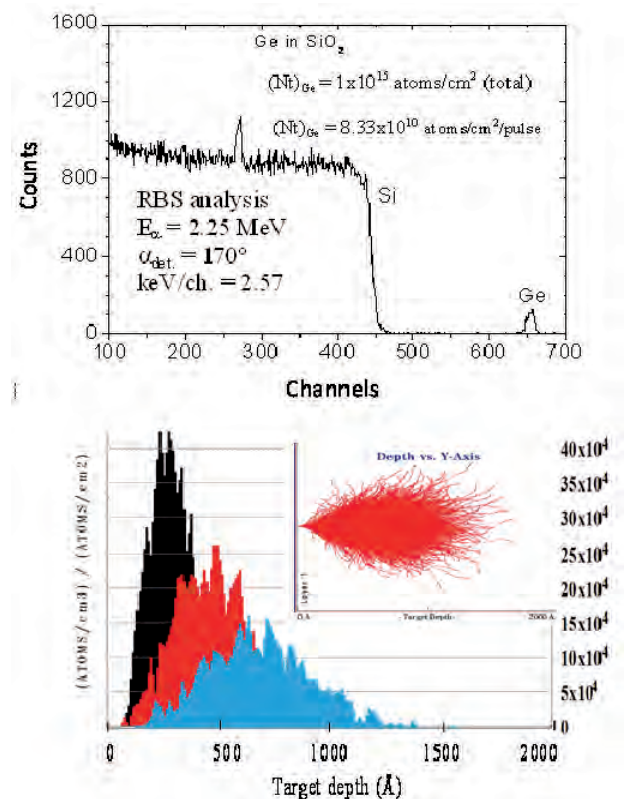


Fig. 6: Typical RBS spectrum of Ge ion implantation in Si-substrate (a) and simulations of the implanted Ge-trajectories and of the implanted specie vs. depth (b)

Ion implantation of the post-accelerated ion beams have been obtained on different light materials, such as polyethylene, Gaf-chromic films, C, Al and Si-substrates. The ion implanted substrates have been controlled by RBS technique (2.0 MeV helium beam) in order to investigate about the measurement of the effective implanted ion dose and superficial penetration depth. Fig. 6a shows a typical spectrum of Ge ion implantation on Si-substrate. The Ge ions of 30 keV, 60 keV and 90 keV are implanted in the first superficial layers, up to a maximum depth of about 120 nm.

Obtained results are in agreement with the SRIM simulations of Ziegler [10] reporting the Ge implanted trajectories in the Si-substrate, as shown in Fig. 6b, and of the triple implanted dose vs. the Si-depth.

An ion implantation of the Gaf-chromic films demonstrated that the ion beams are accompanied by a strong emission of X-rays. Such emission is due mainly to the electron bremsstrahlung in the positively charged (+ 30 kV) target and extraction chamber walls.

Fig. 7a shows a typical Ti-ion implanted Gaf-chromic film due to 100 laser pulses, corresponding to a dose of about 10^{11} ions/cm². The same photo reports a typical result of Ti-ion implantation in polyethylene surface, consisting in the induction of the roughness decrement and in the increment of the surface micro-hardness vs. the ion dose (Fig. 7b).

The ion implantation of polyethylene at energies of the order of 100 keV and doses of about 10^{13} - 10^{14} /cm², modify the electrical conductivity, the refraction index, the wetting ability, the wear, the density and the polymer composition, as reported in previous investigations [11, 12]. The ion energy deposition broken the chemical bonds and induces hydrogen degassing from the polyethylene. Thus the polymer surface becomes more and more rich in carbon content with the increment of the absorbed ion dose up to acquire, at high doses, properties similar to that of an amorphous carbon.

In conclusion the use of LIS and of PIAS permits to realize a new kind of ion implanter with low energy and relatively low current and with multi-energy beams, useful to generate ion implantation effects in polymeric substrates. The future increment of the ion energy and of the ion current will permit to apply the system to more fields of interest.

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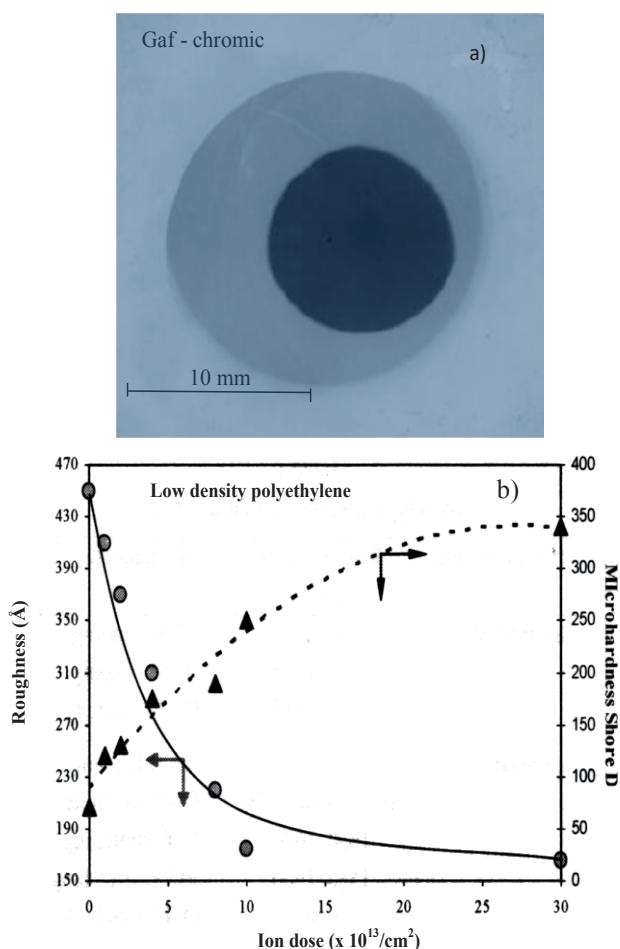


Fig. 7: Gaf-chromic films showing the post accelerated ion beam (a) and a typical results obtained by the Ti ion implantation of polyethylene (b).

WIDE DYNAMIC RANGE ACQUISITION SYSTEM FOR INNOVATIVE RADIATION

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ABSTRACT

There is particular interest to develop low noise and wide dynamic range data acquisition systems for silicon detectors in view of using the same acquisition readout electronics for a wide range of application fields like the monitoring and characterization of radiation sources or particle beams. In the framework of a research project for the qualification of COTS (Components Off The Shelf) for their use in space, research groups from INFN-Perugia, INFN-LNS and from MAPRAD have developed a fully automated, remote controllable, wide dynamic range acquisition system for silicon strip or pixelated detectors. Its design and a basic description of performance are given here.

1. DESCRIPTION OF THE ACQUISITION SYSTEM

The first generation of a multi-purpose front-end and readout system has been designed for silicon strip detectors but it is easily adaptable also to new generation of radiation sensors such as silicon photomultipliers. The current pulses generated by the sensor are sent to a low power ASIC (VA32TA2.2)[1] with a 32 channels preamplifier and fast triggering stage. The preamplifier circuitry is 32 channel low noise, low power charge sensitive preamplifier and shaper, Sample-Hold (SH) circuitry with multiplexed analog readout and calibration capabilities. Each channel of the time unit circuitry consists of one level sensitive discriminators with adjustable threshold. Only inputs with pulse amplitude above the threshold yield the trigger. The total dead time of the readout system is about 20 μ s which consists of the granularity introduced by the clock speed and additional few μ s of veto as safety margin. The dead time can be lowered almost to zero by reading the sensor on both sides and applying proper trigger algorithm on each side. This is particularly important for application where very short time delayed coincident measurements are a major concern.

The DAQ system consists of two boards, one for the p-side and one for the n-side of double sided silicon detector system. Both the boards process the analog (pre-amplification by the front-end circuitry) and digital signals after the digital conversion. The master FPGA stage (clocked at 48MHz) drives all the controls signal of the hybrid (DAC and thresholds settings) and the ADC timing synchronization. A time tag is also assigned to each triggered signal. A separate pure digital board (slave FPGA) stores the data on buffer memories and transfers to the on-board computer (Fig.1) The data from DAQ is linked to the onboard PC through a USB 2.0 interface.

Unique features of system include adjustable trigger level, the capability, on either detector sides, to use a capacitive dumping board to contain and measure the entire strip charge without saturation of front-end electronics. The power supply system is based on a TCP/IP remote controllable unit which provides the low voltage for the data acquisition system and the high voltage to deplete the sensors. A full custom LabView front-panel was developed for the online monitoring of the sensor and biasing voltages as well as for a four parameter (X, Y, Z, θ) positioning control of the detector (Fig.2). The system performance has been tested at the irradiation facility of LNS-INFN, Catania and preliminary results have been reported elsewhere [2].

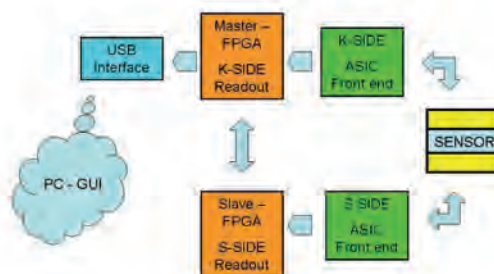


Fig.1 Block diagram of the DAQ system



Fig.2 Positioning system of the detector and DAQ electronics

2. PERFORMANCE OF THE SYSTEM

In order to evaluate the performances of the system we have used it in connection with a thick (1.5 mm thickness) double-sided silicon strip detector having 0.5 mm strip pitch (on both sides) and 3 x 3 cm² active dimensions.

We have tested the performance of such a system using cosmic rays, radioactive sources and ion beams at the Catania LNS synchrotron. Fig. 3 shows the cosmic ray signal on the junction side (top) and on the ohmic side of the detector (center). The bottom plot is the RMS noise performance on the junction side (named S) and ohmic side (named K).

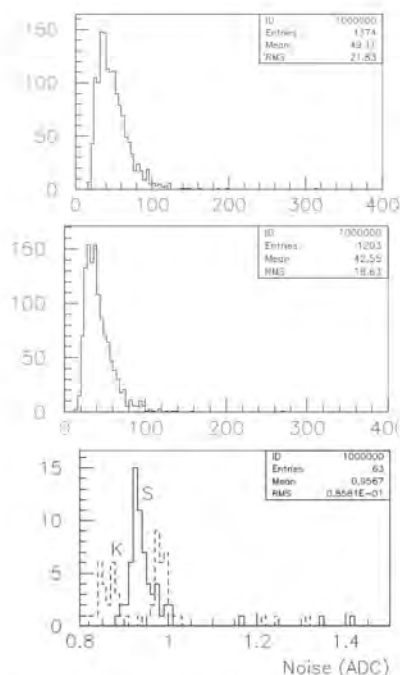


Fig.3 Cosmic ray signal measured on the junction side (top) and on the ohmic side (center) of a thick double-side silicon detector. The bottom plot shows the RMS noise on junction side (S side-continuous-line) and junction side (K side-dashed line).

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THE RADIATION ASSURANCE TEST FACILITY AT INFN-LNS CATANIA

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Abstract

This paper describes the beam monitoring system that has been developed at the Superconducting Cyclotron at INFN-LNS (Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali del Sud, Catania, Italy) in order to monitor the beam parameters such as energy, flux, beam profile, for SEE (Single Event Effects) cross-sections determination and DD (Displacement Damage) studies.

In order to have an accurate and continuous monitoring of beam parameters we have developed fully automatic dosimetry setup to be used during SEE (with heavy ions) and DD (with protons of 60 MeV/n) tests of electronic devices and systems.

The final goal of our activity is to demonstrate how operating in air, which in our experience is easier than in vacuum, is not detrimental to the accuracy on controlling the beam profile, energy and fluence delivered onto the DUT (Device Under Test) surface, even with non relativistic heavy ions.

We have exposed during the same session, two beam calibration systems, the "Reference SEU monitor" developed by ESA/ESTEC and the beam monitoring and dosimetry setup developed by our group. The results are compared and discussed here

INTRODUCTION

The LNS Superconducting Cyclotron (CS), is a compact, strong focusing three-sector machine. The pole radius is 90 cm and the magnetic field at the center ranges from 2.2 to 4.8 T. This is obtained with superconducting Nb-Ti coils cooled down to 4.2 K in an LHe bath. The expected maximum energies of the machine are of 20 MeV/amu for the heaviest ions, like $^{238}\text{U}^{38+}$, and 100 MeV/n for fully stripped light ions as given respectively by the bending limit $K_b=800$ and by the focusing limit $K_f=200$.

The measurement of beam flux and uniformity is one of the ingredients for the calculation of SEE cross-section. According to the ESA standard ESCC-25100 these measurements should be done with an accuracy of $\pm 10\%$.

The relatively high energy of the beams (for this study 20 MeV/nucleon) allows the irradiation of components in air which is used also as a degrader. The selection of the ion species we use in SEE studies is done by taking into account the easiness of beam changing operation and at the same time the necessity to cover as large a LET

interval as possible. Hence, four gaseous beams (^{20}Ne , ^{40}Ar , ^{84}Kr , ^{129}Xe) all with 20 MeV/n energy are selected.

A careful evaluation of energy loss in air end of the energy spread at DUT surface is carried out through a full Monte Carlo simulation of the test setup and comparing the results with data.

The DD studies are performed using 60 MeV/n protons instead.

BEAM MONITORING SYSTEM

At LNS we perform extraction of ion beams in air, where our flux and dosimetry setup resides; additionally we use air as a degrader in order to adjust LET values. A basic schematic of the dosimetry measurement setup is shown in. Figure 1. The upper part of the figure shows the particles getting into air from beam pipe, crossing a thin scintillator and then reaching the DUT or silicon detector surface. The air thickness between beam exit and thin scintillator is fixed while the one between thin scintillator and DUT (or Si detector) is variable (respectively, A1 and A2 in Table 1).

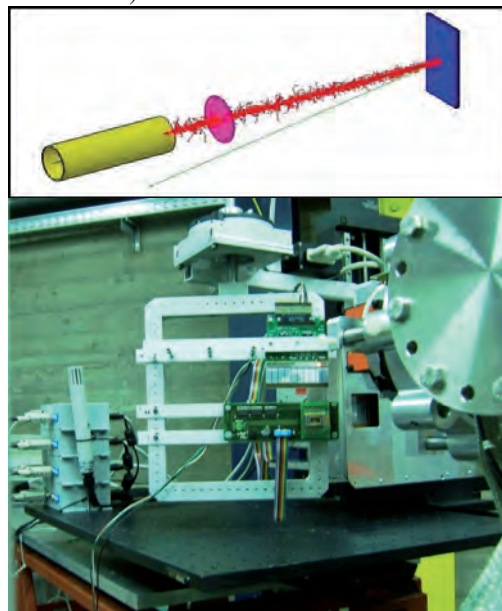


Figure 1: Upper: Geant4 simulation of setup representing, from left to right, vacuum pipe, thin scintillator and silicon detector or DUT. Lower: The beam dosimetry setup. The DS microstrip silicon detector, 3-D stage and rotator to which the DUT holder is attached are shown

Ion	E (MeV/n)	A1 (cm)	A2 (cm)	Impact Angle (°)	Scintillator Thickness (μm)	Ek Tot (MeV)	Ek at Si Surf. (MeV)	Range in Si (μm)	LET in Si (MeV/mg/cm ²)
²⁰ Ne	20	5	5	0	50	400	341	402	3,66
²⁰ Ne	20	5	30	0	50	400	259	254	4,39
⁴⁰ Ar	20	5	5	0	50	800	617	252	10,56
⁴⁰ Ar	20	5	30	0	50	800	347	105	14,26
⁸⁴ Kr	20	5	5	0	50	1680	1074	150	30,76
⁸⁴ Kr	20	5	15	0	50	1680	751	93	34,69
¹²⁹ Xe	20	5	5	0	50	2580	1473	109	57,99
¹²⁹ Xe	20	5	15	0	50	2580	923	70	56,62

Table 1: Typical set of LET(Si) values and corresponding ion species, ranges and air thicknesses

The setup consists in a thin scintillator counter (NE102A of 50 or 100 μm thickness) read by a photomultiplier just after the beam exit into air, an XYZ stage with submicron absolute position resolution. The scintillator is inserted into a metallic box with variable size beam hole to allow the adjustment of the beam size. The DUT is placed onto a supporting frame (DUT holder) which is held by a rotator fixed to the positioning stage. On the same structure close to DUT holder a double sided, 1.5 mm thick microstrip detector (500 μm readout pitch and 3x3 cm² active area) is mounted for energy, fluence and beam profile measurements. Because of its thickness the silicon detector behaves like a calorimeter to the above mentioned ion species in non relativistic regime, containing all their energy: the stopping range in silicon is, for all ions we use, at least 30 μm , in accordance to the minimum penetration depth required by the ESA standard ESCC-25100.

The dosimetry setup includes two additional important features. A laser device, which is used to measure the

distances in Z (beam) direction with 200 μm position accuracy. Such level of accuracy in measurement of the relative distances (i.e. silicon detector surface to delidded DUT surface, DUT surface to beam exit in air etc.) is important to achieve as small as possible overall systemic error on LET value in silicon. The other feature of the setup is a custom module (SELDP) built specifically to monitor the current drawn on power line of a DUT. The SELDP cuts the power supply to DUT for an adjustable time duration whenever the current drawn by DUT exceeds a preset current limit. This both protects DUT from burnout because of Single Event Latchup (SEL) effect and registers the number of SEL occurred by incrementing a counter.

The overall configuration of beam setup is given in the block diagram below. The two PCs indicated inside the red frame are located in the beam area while all the rest of the boxes are representing tasks carried out by a single laptop in the control room communicating via TCP-IP with the PCs inside the beam area.

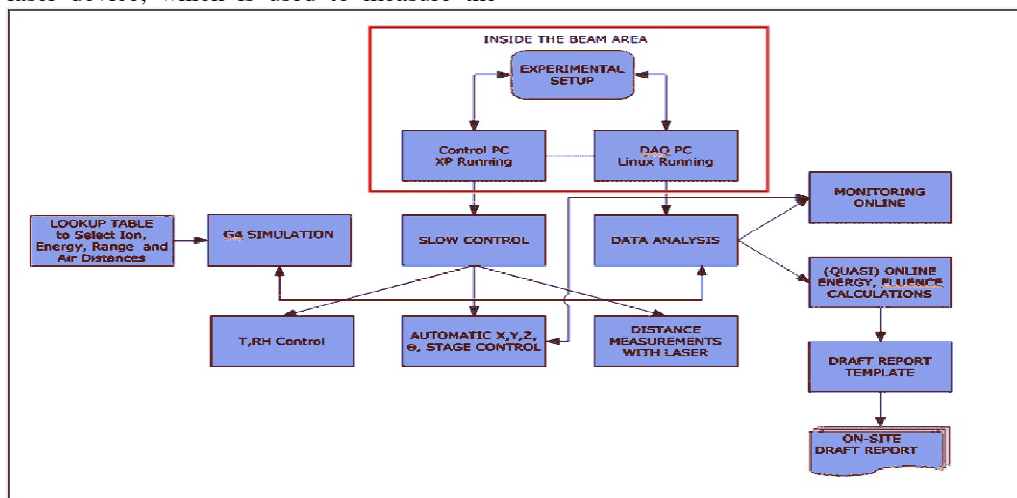


Figure 2: The configuration of DAQ and control PCs (inside the beam area) and laptop in control room. The tasks carried out by each computer are also show

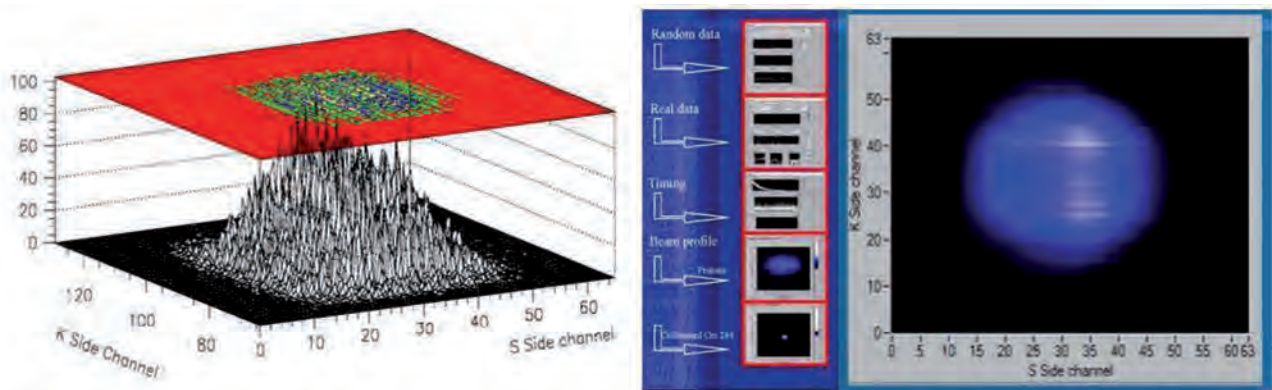


Figure 3: The online monitoring of beam parameters with silicon detector. On Left: The beam profile is shown in 3D. Each channel corresponds to 0.5 mm (strip pitch of double sided silicon detector). On Right: The beam profile reconstructed from data

PERFORMING SEE AND DD MEASUREMENTS

Prior to go to LNS for a test period, all dosimetry system including DUT mounting and performance is tested in MAPRAD laboratories (REF) onto a mock-up mechanical system of the beam setup which includes also a pulsed IR laser source. All mechanical parts necessary are produced and tested on this mock-up, as well as electronics parts which are tested under the pulsed laser beam to verify the behaviour of the entire DAQ system.

Test Procedure for SEE Studies

A full Geant4 Monte Carlo description of the setup has been done and ran for the four different ion species in use to prepare a detailed look-up table. This table includes, among others, the range and LET values achieved for each experimental configuration differing by 1 mm increments of air thickness between thin scintillator and DUT surface.

For each device to be tested, several LET values over an agreed LET range are selected and corresponding parameters are extracted from the table. A typical set of LET values and corresponding air thicknesses are listed in Table 1. The effective LET values larger than 100 MeV/mg/cm² can be obtained by altering the beam impact angle on the DUT, since $LET_{eff} = LET_{(0)} / \cos(\Theta)$.

The SEE test procedure consists in following steps;

- For each ion, we memorize on the control PC the data taking positions (see A1 and A2 distances and impact angles given in Table 1).
- Start with the beam profile on the silicon detector to get the beam shape and position with respect to DUT, so that it can be automatically moved under the beam.
- Start data acquisition by monitoring; the flux measured by thin scintillator and DUT parameters. The beam parameters (energy, profile, flux, time tag) measurement is done by moving silicon detector under the beam for short periods without stopping the run (see Figure 3). A possible alternative

procedure is to keep the silicon detector off-beam close to DUT and monitor continuously the tail of the beam. A calibration run with thin scintillator “on” and silicon detector “on/off” beam will provide normalization factors to achieve the real flux.

The steps described above, are repeated for different DUT distances (air thicknesses) or impact angles, to obtain various LET values using the same ion specie.

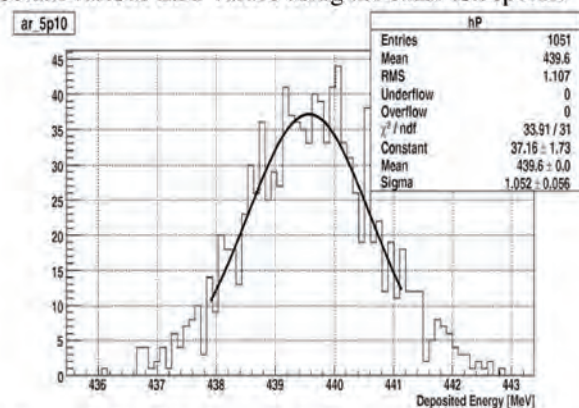


Figure 4: For ⁴⁰Ar beam at 10 cm air thickness (A2) Distribution of energy deposited in silicon simulated by Geant4.

Systematic Error Evaluation

A careful evaluation of systematic errors is necessary to estimate overall error introduced on LET and on fluence values. Definition of LET and cross section is given in Eq. 1 where ρ is silicon density.

$$LET(\text{MeV} \cdot \text{cm}^2 / \text{mg}) = \frac{dE}{dX} \cdot \frac{1}{\rho}; \quad \alpha(\text{cm}^2) = \frac{N_{SEE}}{\text{Fluence} \cdot \cos\theta}; \quad (1)$$

Systematic errors on LET values are;

- Distance (air thickness) measurements. This is done with a 200 μm accuracy laser system only once during the initial calibration phase. All other positions are relative to that point with submicron precision 4-D stage (X,Y,Z, Theta)
- Fragmentation in air. It is negligible (i.e. $<10^{-4}$ for 20 MeV/n ⁴⁰Ar after 15 cm of air) according to

- Geant4 simulation performed using “binary light ion cascade” and “Wilson abrasion” models.
- The determination of energy deposited and range in DUT by Geant4 simulation; the energy distribution from Monte Carlo has less than 3% error at FWHM (see Figure), and there is a good correlation with the charge measured by the silicon detector, which provides the possibility to convert the charge values to deposited energy. The correlation between charge collected in silicon and simulated energy for different air thicknesses for ^{40}Ar is given in Figure 1.

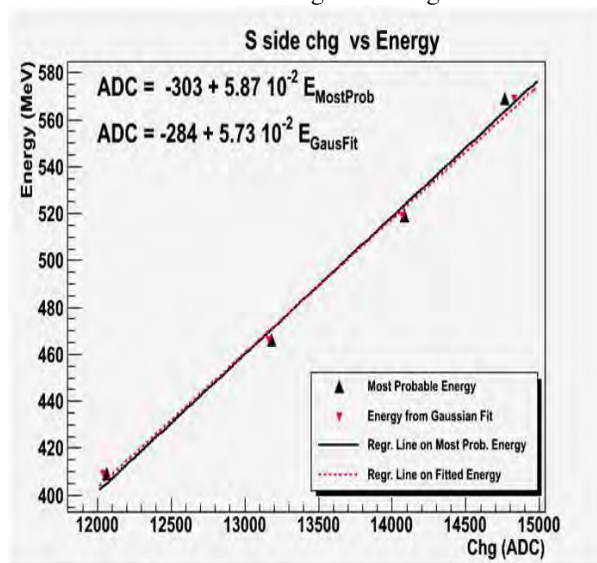


Figure 1: Correlation curves between charge deposited in silicon(ADC counts) and simulated energy release (MeV). The two data sets and curves refer to different ways to estimate energy from Monte Carlo distribution: Black triangles use the most probable value taken from energy histogram, red upside-down triangles use the mean from a gaussian fit.

- Positioning of beam spot to the center of DUT and correction of non uniformity of beam over the beam spot. Figure shows a typical beam spot and DUT dimensions. This error includes a $180\ \mu\text{m}$ contribution from the silicon detector spatial resolution, as well as a $\sim 300\ \mu\text{m}$ one from the accuracy of the DUT mounting on the holder frame; the two contributions are summed in quadrature since they are independent.

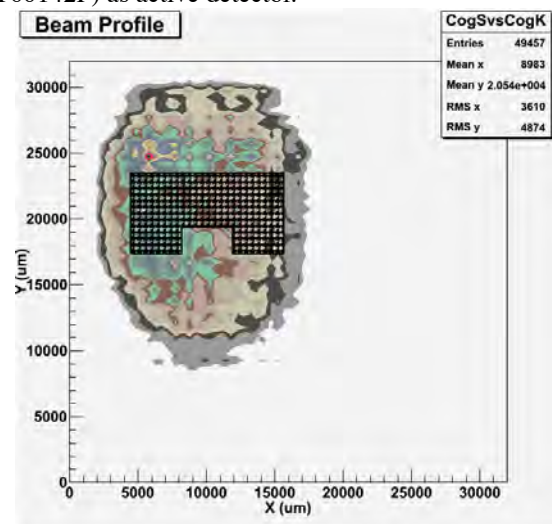
The detailed analysis of errors have shown that the overall error on determination, both of fluence and of LET, is less than 4% which is well below the upper limit (10%) required by ESCC-22500. The Table lists the overall systematic errors on LET values for different ion species at 10 cm of A2.

Ion	LET(Si) (MeV/mg/cm ²)	Error on LET(Si) (MeV/mg/cm ²)
^{20}Ne	3.7	0.1
^{40}Ar	13.1	0.2
^{84}Kr	30.6	0.7
^{129}Xe	52.9	0.8

Table 2: LET(Si) values and corresponding systematic errors for different ion species at the 10 cm of air (A2) thickness experimental configuration.

Comparison of Results with SEU Monitor

The reference SEU (Single Event Upset) monitor system [1] was developed specifically for inter-site calibrations to address the issue that in different irradiation facilities the user usually has no means of checking suspicious beams and of discovering data discrepancies on-site. In order to minimize test errors because of faulty beams a simple reference system allowing beam re-checking capabilities was necessary. The reference SEU monitor system was developed for this purpose by using a SRAM (Atmel AT60142F) as active detector.



- Figure 6: Beam spot is centred over the DUT surface. From this profile one can extract the real fluence distribution over DUT surface. The beam spot positioning accuracy is at most $400\ \mu\text{m}$.

We have used in LNS reference SEU monitor pre-calibrated with heavy-ions, protons and neutrons, provided by ESA/ESTEC to check the quality of the dosimetry systems we described above, as well as the beam quality of LNS site. After each irradiation of the SEU monitor, the user has to supply the measurements for LET and fluence from his own dosimetry system to the SEU monitor's own software, which carries out the calculation of cross section independently of the operator and adds a new data point to a comparison plot.

The results are given in Figure 6. The blue points are data points for LNS site which are in good agreement with calibration points obtained in two other irradiation facilities (HIF in Belgium and RADEF in Finland).

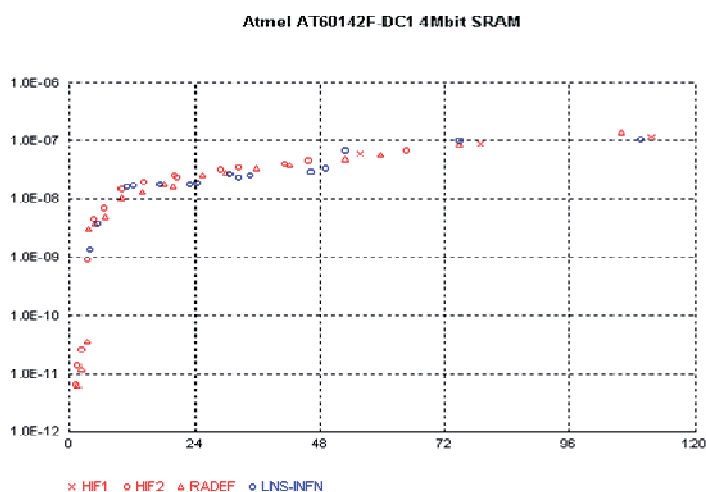


Figure 7: Comparison of cross section versus LET for the SEU monitor from different sites: the blue points are data points for LNS site, the red points are series obtained previously by ESA at other facilities (HIF in Belgium and RADEF in Finland) as calibration points. The measurements taken at LNS are in good agreement with the ESA calibration

Test Procedure for DD Studies

The displacement damage are non ionizing effects caused mostly by protons and neutrons on silicon lattice structure by dislodging or displacing the atoms from their lattice sites. The DD studies at LNS are carried out using 60 MeV protons. Here the testing procedure is simpler than that of SEE since tests are realised at a fixed A1 and A2 distances. The DUTs under proton irradiation are usually unbiased (unless otherwise is requested). The critical parameters of DUT are tested before and after irradiations. The test points are after different dose values delivered to the DUT, which are calculated as:

$$\text{Dose (rad(Si))} = \text{LET (SiO}_2\text{)} * \text{Fluence} * 1.610^{-5} \quad (2)$$

In this kind of test, the main problem is that test equipment materials, do activate after prolonged exposition to the proton beam. For this reason we designed the supporting frame so that only the DUT and a minimal amount of test board is directly under the beam, in order to reduce activations as much as possible. To avoid putting the silicon detector under the beam for long times, it is possible to use it to monitor the intensity of the beam tails after an initial intercalibration phase with a gas chamber put in front of the beam outlet; the chamber can then be removed during actual DUT irradiation. The electrical connections of the DUT's pins to power supply,

bias line and measurement apparatus must be designed so that it is possible to (dis)connect them remotely to avoid getting close to a possibly activated DUT.

CONCLUSIONS

In Europe there is a limited number of accelerator sites whose delivered ion beams fulfil the requirements of ESCC standards for SEE testings. We have developed a fully automatic dosimetry system to demonstrate the validity of beam characteristics of LNS sites for SEE and DD tests as well as to accurately measure the parameters relevant to perform detailed SEE and DD studies. With energies available at LNS and with four selected gaseous beams it is possible to perform SEE studies from few up to 110 MeV/mg/cm² of LET.

The beam changing time is relatively short (few hours) and beam size and fluence are stable in time. Furthermore, the presence of air gives possibility to reach "fine-tuned" LET values by adjusting the air thickness accordingly. Last but not least, operating the setup in air has its obvious advantages of reducing setup time and complexity.

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- [1] R. Harboe-Sorensen, F.-X. Guerre and A. Roseng, Design, Testing and Calibration of a "Reference SEU Monitor" System. Proceedings of RADECS 2005.

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De Bonis Giulia	Italy	Barbarino Giancarlo	Italy
Circella Marco	Italy	Barbarito Elio	Italy
Spurio Maurizio	Italy	Margiotta Annarita	Italy
Chiarusi Tommaso	Italy	Smerzi Augusto	Italy
Rivet Marie France	France	Brink David	England
Napolitani Paolo	France	Wei Zuo	China
Matera Francesco	Italy	Bou Cabo Manuel	Spain
Capel Pierre	Belgium	Menegon Oshima M	Brasil
Pleskac Radek	Germany	Rodrigues Marcia RD	Brasil
Shvedov Leonid	Ukraine	Sura Jozef	Poland
Verboncoeur John	Usa	Zhanov Akram	Russia
Zhao Enguang	China	Zhou Shangui	China
Hang Janlong	China	Acquaviva Grazia	Italy
Aliotta Marialuisa	UK	Balabanski Lukanov	Bulgaria
Bardelli Luigi	Italy	Barlini Sandro	Italy
Benitez Sanchez Miguel	Spain	Bini Maurizio	Italy
Casini Giovanni	Italy	Ciaranfi Roberto	Italy
Cirio Roberto	Italy	Ciulla Elena	Italy
Degerlier Meltem	Italy	Del Carmine Piero	Italy
Di Franco Ivana	Italy	Donetti Marco	Italy
Emanuele Umberto	Italy	Galichet Emmanuelle	France
Giordanengo Simona	Italy	Grassi Laura	Italy
Guazzoni Paolo	Italy	Gueli Anna Maria	Italy
La Monica Viviana	Italy	Lo Bianco Giovanni	Italy
Lo Faro Giuseppe	Italy	Malannino Daniela	Italy
Manzelli Luca	Italy	Marchetto Flavio	Italy
Mezzetti Enrica	Italy	Minetti Bruno	Italy
Nicolosi Dario	Italy	Olmi Alessandro	Italy
Ott Johannes	Italy	Owens Alan	NL
Pagano Angelo	Italy	Papa Massimo	Italy
Pasquali Gabriele	Italy	Petta Catia	Italy
Piantelli Silvia	Italy	Pirrone Sara	Italy
Poggi Giacomo	Italy	Politi Giacomo	Italy
Potenza Renato	Italy	Privitera Sonia	Italy
Pulvirenti Manuela	Italy	Quarati Francesco	Italy
Randazzo Nunzio	Italy	Ricupero Simone	Italy
Rosato Elio	Italy	Russo Valerio	Italy
Sambi Sara		Sanfilippo Marisa	Italy
Sipala Valeria	Italy	Spatola Corrado	Italy
Sperduto Maria Leda	Italy	Stefanini Andrea	Italy
Tobia Gianpaolo	Italy	Tricomi Alessia	Italy
Trifirò Antonio	Italy	Tuvè Cristina	Italy

Valastro Lucia
Zanini Alba
Colonna Nicola

Italy
Italy
Italy

Verde Giuseppe
Zdenek Hons

Italy
Czech rep.

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Russotto P, De Filippo E, Pagano A, Piasecki E, Amorini F, Anzalone A, Auditore L, Baran V, Berceanu I, Blicharska J, Borderie B, Bougault R, Bruno M, Brzychczyk J, Cardella G, Cavallaro S, Chatterjee M B, Chbihi A, Colonna M, D'agostino M, Dayras R, Di Toro M, Frankland J, Galichet E, Gawlikowicz W, Geraci E, Giustolisi F, Grzeszczuk A, Guazzoni P, Guinet D, Kowalski S, La Guidara E, Lanzalone G, Lanzano' G, Le Neindre N, Maiolino C, Majka Z, Papa M, Petrovici M, Pirrone S, Planeta R, Politi G, Pop A, Porto F, Rivet M F, Rosato E, F Rizzo, Schmidt K, Siwek-Wilczynska K, Skwira-Chalot I, Sochocka A, Swiderski L, Trifiro' A, Trimarchi M, Vigilante M, Wieleczko J P, Wilczynski J, Zetta L, Zipper W

Isospin effects in projectile-like dynamical fission for $^{112,124}\text{Sn} + ^{58,64}\text{Ni}$ reactions at 35 A MeV

AIP Conference Proceedings - American Institute of Physics, 1175, 389-392

Van Hees H, Mannarelli M, Greco V, Rapp R

"T-matrix approach to heavy quark diffusion in the QGP"

European Physical Journal C, 61, 799-806, 2009

Sudol M, Agakishiev G, Agodi C, Balanda A, Bellia G, Belver D, Belyaev A, Bielcik J, Blanco A, Bortolotti A, Boyard JL, Braun-Munzinger P, Cabanelas P, Chernenko S, Christ T, Coniglione R, Destefanis M, Diaz J, Dohrmann F, Duran I, Dybczak A, Eberl T, Fabbietti L, Fateev O, Ferreira-Marques R, Finocchiaro P, Fonte P, Friese J, Froehlich I, Galatyuk T, Garzon JA, Gernhaeuser R, Gil A, Gilardi C, Golubeva M, Gonzalez-Diaz D, Grosse E, Guber F, Heilmann M, Heinz T, Hennino T, Holzmann R, Ierusalimov A, Iori I, Ivashkin A, Jurkovic M, Kaempfer B, Kanaki K, Karavicheva T, Kirschner D, Koenig I, Koenig W, Kolb BW, Kotte R, Kozuch A, Krasa A, Krize F, Kruecken R, Kuehn W, Kugler A, Kurepin A, Lamas-Valverde J, Lang S, Lange JS, Lapidus K, Lopes L, Lorenz M, Maier L, Maiolino C, Mangiarotti A, Marin J, Markert J, Metag V, Michalska B, Michel J, Moriniere E, Mousa J, Muench M, Muentz C, Naumann L, Novotny R, Otwinowski J, Pachmayer YC, Palka M, Parpottas Y, Pechenov V, Pechenova O, Perez Cavalcanti T, Piattelli P, Pietraszko J, Pospisil V, Przygoda W, Ramstein B, Reshetin A, Roy-Stephan M, Rustamov A, Sadovsky A, Sailer B, Salabura P, Sapienza P, Schmah A, Schroeder C, Schwab E, Simon R, Sobolev YG, Spataro S, Spruck B, Stroebele H, Stroth J, Sturm C, Tarantola A, Teilab K, Tlusty P, Traxler M, Trebacz R, Tsertos H, Wagner V, Weber M, Wisniewski M, Wojcik T, Wuestenfeld J, Yurevich S, Zanevsky Y, Zhou P, Zumbach P

"Measurement of low-mass $e + e -$ Pair production in 1 and 2 A GeV C-C collision with HADES"

European Physical Journal C, 62, 81-84, 2009

Di Toro M

"Isospin effects on particle production, flows and phase transitions at high baryon density"

Eur.Sci. Foundation Workshop on High Density Symmetry Energy, 10 October 2009

Zagreb, Croazia

Di Toro M

"Isospin Physics and Heavy Ion Collisions"

Graduate School of the Chinese Academy of Science 17 June 2009, Beijing, China

Amorini F, Anzalone A, Boiano C, Cardella G, Castoldi A, Cavallaro S, De Filippo E, Geraci E, Grassi L, Guazzoni C, Guazzoni P, La Guidara E, Lombardo I, Moser S, Pagano A, Pirrone S, Politi G, Porto F, Riccio F, Rizzo F, Russotto P, Zetta L

"Preliminary tests of CHIMERA silicon detectors in reverse mode"

IEEE Nuclear Science Symposium Conference Records, IEEE, 2115-2120, 23 – 31 October 2009, Orlando, Florida

Mezzetti E, Laviano F, Gerbaldo R, Ghigo G, Gozzelino L, Lopardo G, Minetti B, Rovelli A

"Localized photoresponse of YBCO films patterned by heavy-ion lithography"

IEEE Transactions on Applied Superconductivity, 19, 753-756, 2009

Aloisio A, Ameli F, Giordano R, Giovanetti G, Izzo V

"Performance study of a DWDM link with real-time characteristics"

16th IEEE-NPSS Real Time Conference - Conference Record, 214-219, 2009

Di Toro M

"Nuclear matter at high baryon and isospin density: a great challenge"

IHEP Theory Seminar 16-06-2009 - Ihep Beijing, China

Greco V

"Probing the symmetry energy at high baryon density with heavy ion collisions"

IWND09, 22 August 2009, Shanghai China

Colonna M

"Isospin effects and sensitive observables in the Fermi energy domain"

IWM09, 04 November 2009, Catania, Italy

Sun B, Knoebel R, Litvinov YuA, Nakajima S, Geissel H, Meng J, Beckert K, Bosch F, Boutin D, Brandau C, Chen L, Cullen IJ, Dimopoulou C, Fabian B, Hausmann M, Klepper O, Kozhuharov C, Kurcewicz J, Litvinov SA, Mazzocco M, Montes F, Muenzenberg G, Musumarra A, Nociforo C, Nolden F, Ohtsubo T, Ozawa A, Patyk Z, Plass WR, Scheidenberger C, Steck M, Suzuki T, Walker PM, Weick H, Winckler N, Winkler M, Yamaguchi T

"Large-scale mass measurements of short-lived nuclides with the isochronous mass spectrometry at GSI"

International Journal of Modern Physics E, 18, 346-351, 2009

Zetta L, Guazzoni P, Cavallaro M, Faestermann T, Graw G, Hertenberger R, Wirth HF

¹¹⁷In and ¹¹⁸Sn homologous state identification via the ¹²⁰Sn(pvec,α)¹¹⁷In and ¹²¹Sn(pvec,α)¹¹⁸In reactions

Jaskola Proceedings of the Conference "SPIN PHYSICS: 18th International Spin Physics Symposium", 6-11 October 2008, Charlottesville, Virginia, published in AIP Conf. Proc.

1149, 703-706, 2009

Torrisi L, Foti G, Giuffrida L, Puglisi D, Wolowski J, Badziak J, Parys P, Rosinski M, Margarone D, Krasa, J Velyhan A, Ullschmied U

"Single crystal silicon carbide detector of emitted ions and soft X rays from power laser-generated plasmas"

Journal of Applied Physics, 105, 2009

Di Toro M

"Probing the density dependence of symmetry energy with HIC" (2 Lectures)

KITPC-ITP workshop on "Relativistic Many-Body Problems for Heavy and Super-Heavy Nuclei" 07 June 2009 Kitpc Beijing, China

Greco V

"The effect of quark coalescence on conical signals"

Knoxville Quark Matter 2009, 29 March 2009, USA

Scordino A, Grasso R, Gulino M, Lanzano L, Musumeci F, Privitera G, Tedesco M, Triglia A, Brizhik L

"Hydration effects on photophysical properties of collagen"

NATO Science for Peace and Security Series A: Chemistry and Biology, 359-383, 2009

Di Toro M

"Isospin effects on phase transitions of hadronic to quark matter"

NICA-Round Table Workshop 08 September 2009 Jinr-Dubna, Russia

Di Toro M

"Probing the nuclear matter at high baryon and isospin density with heavy ion collisions"

Nuclear Reactions on Nucleons and Nuclei 03 October 2009, Messina, Italy

Balanda A, Belver D, Belyaev AV, Blanco A, Boehmer M, Boyard JL, Braun-Munzinger P, Cabanelas P, Castro E, Chernenko S, Diaz J, Dybczak A, Epple E, Fabbietti L, Fateev OV, Finocchiaro P, Fonte P, Friese J, Froehlich I, Galatyuk T, Garzon JA, Gernhaeuser R, Gil A, Golubeva M, Gonzalez-Diaz D, Guber F, Hennino T, Holzmann R, Huck P, Ierusalimov AP, Iori I, Ivashkin A, Jurkovic M, Kaempfer B, Karavicheva T, Koenig I, Koenig W, Kolb BW, Kopp A, Kotte R, Kozuch A, Krasa A, Krizek F, Kruecken R, Kuehn W, Kugler A, Kurepin A, Kaehlitz PK, Lamas-Valverde J, Lang S, Lange JS, Lapidus K, Liu T, Lopes L, Lorenz M, Maier L, Mangiarotti A, Markert J, Metag V, Michalska B, Michel J, Moriniere E, Mousa J, Muentz C, Naumann L, Pachmayer YC, Palka M, Parpottas Y, Pechenov V, Pietraszko J, Przygoda W, Ramstein B, Reshetin A, Roskoss J, Rustamov A, Sadosky A, Salabura P, Schmah A, Siebenson J, Simon R, Sobolev YuG, Spruck B, Stroebele H, Stroth J, Sturm C, Sudol M, Tarantola A, Teilab K, Tlusty P, Traxler M, Trebacz R, Tsertos H, Veretenkin I, Wagner V, Weber M, Wisniowski M, Wuestenfeld J, Yurevich S, Zanevsky YV

The HADES Collaboration

Nuclear Physics A, A830, 2009

Colonna M

"Dynamical phase trajectories in baryon and isospin density spaces"

Nucleus-Nucleus Collisions 2009, 16 August 2009, Beijing, China

Greco V

"Elliptic Flow at Finite Shear Viscosity in a Kinetic Approach at RHIC"

Nucleus-nucleus collisions 2009, 16 August 2009, Beijing China

Picciotto A, Pucker G, Lui A, Torrisi L, Margarone D, Bellutti P

"Surface plasmon resonance analysis of Ag nanoparticles generated by pulsed laser ablation"

Proceedings of SPIE - The International Society for Optical Engineering, 7366, 2009

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

Proceedings of the "12th International Conference on Nuclear Reaction Mechanisms", 15-19 June 2009, Varenna, Italy,

Cappuzzello F, Cavallaro M, Cunsolo A, Foti A, Orrigo SEA, Rodrigues MRD, Carbone D, Schillaci M, Borello-Lewin T

States of ^{15}C via the $(^{18}\text{O}, ^{16}\text{O})$ reaction

Proceedings of the "12th International Conference on Nuclear Reaction Mechanisms", 15-19 June 2009, Varenna, Italy

Cavallaro M, Cappuzzello F, Cunsolo A, Foti A, Carbone D

The MAGNEX large acceptance spectrometer

Proceedings of the "5th European Summer School on Experimental Nuclear Astrophysics", S. Tecla, Italy, 20-27 September 2009

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

Proceedings of the "EXON2009: International Symposium on Exotic Nuclei", Sochi, Russia, 28 September-02 October 2009

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

Proceedings of the "EXON2009: International Symposium on Exotic Nuclei", Sochi, Russia, 28 September-02 October 2009

Cunsolo A, Cappuzzello F, Cavallaro M, Foti A, Orrigo SEA, Rodrigues MRD, Borello-Lewin T, Petrascu H, Carbone D

First results and planned experiments with the INFN-LNS ray-tracing magnetic spectrometer MAGNEX

Proceedings of the "XXXII Reuniao de Trabalho sobre Fisica Nuclear no Brasil", Aguas de Lindoia, Sao Paulo, Brazil, 7-12 September 2009

Di Toro M

"Relativistic transport equations and phenomenology of heavy ion collisions at high energies" (4 lectures)

School on Theoretical Nuclear Physics, "R. Anni", IV Course, 01-06-2009, Otranto, Italy

Di Toro M

"the symmetry energy in nuclear physics"

Peking University Theory Seminar 19-06-2009, Beijing, China

Almaviva S, Bellini V, Caridi F, Costa S, Mammoliti F, Margarone D, Marinelli M, Dilani E, Potenza R, Prestopino G, Sutura C, Torrisi L, Tucciarone A, Tuve C, Verona C, Verona-Rinati G

"Thin-film CVD single-crystal diamonds for high-energy ion beam detection",

Radiation Effects and Defects in Solids, 164. 363-368, 2009

Rizzo F, Cirrone GP, Cuttone G, Esposito A, Garraffo S, Pappalardo G, Pappalardo L, Romano FP, Russo S

Non-destructive determination of the silver content in Roman coins dated to 308-311 A.D. by combined use of the PIXE-alpha, XRF and DPAA techniques

TechnArt2009 Non-destructive and Microanalytical Techniques in Art and Cultural Heritage, 27-30 April 2009, Athens, Greece

Caruso A, Consoli F, Spartà A, Longhitano A, Xia Le

New pc-based control for RF system at INFN – LNS

The 12th International Conference on Accelerator and Large Experimental Physics Control System, ICALEPCS 12 -16 October 2009, Kobe, Japan

Pappalardo G

Il Laboratorio LANDIS (INFN/CNR) e le analisi non distruttive sulle monete di Misurata

Workshop "Il grande tesoro di Misurata – Stato degli studi e prospettive future", CNR, 7 July 2009, Roma, Italy

Rizzo F

Il metodo DPAA dei LNS per l'analisi del bulk delle monete

Workshop "Il grande tesoro di Misurata – Stato degli studi e prospettive future", CNR, 7 July 2009, Roma, Italy

Romano FP

Lo spettrometro portatile BSC-XRF dei LNS per le analisi del substrato (China di micron) dei nummi

Workshop "Il grande tesoro di Misurata – Stato degli studi e prospettive future", CNR, 7 July 2009, Roma, Italy

Romano FP, Garraffo S, Pappalardo G, Pappalardo L, Rizzo F

Analisi in-situ di elementi in traccia nei folles romani del Tesoro di Misurata (Libia) mediante l'impiego della tecnica BSC-XRF (Beam Stability Controlled – XRF) del laboratorio LANDIS di Catania

XCIV Congresso Nazionale della Società Italiana di Fisica, 28 September – 3 October 2009, Bari, Italy

Gammino S, Celona L, Ciavola G, Gambino N, Lanzalone G, Maimone F, Mascali D, Miracoli R, Samperi F, Torrisi L, Tudisco S, Tumino A

A plasma reactor for environmental applications

XIX Congresso AIV, 19-21 May 2009, Senigallia, Italy

Rodrigues MRD, Borello-Lewin T, Horodinsky-Matsushigue LB, Cunsolo A, Cappuzzello F, Duarte JLM, Rodrigues CL, Souza MA, Miyake H, Ukita GM

(⁶Li,d) experiments on light mass nuclei at IFUSP Pelletron-Split-Pole facility

XXXII Reunião de Trabalho sobre Física Nuclear no Brasil, 7-11 September 2009 Águas de Lindóia, Brasil

Torresi Domenico

Inverse kinematics resonant scattering on thick target with exct beams

Final EURISOL Design study Town Meeting, 30 March – 01 April 2009, Pisa, Italy

Scuderi Valentina

Study of reaction mechanisms for ^{9,10,11}Be + ⁶⁴Zn systems around the Coulomb barrier

Final EURISOL Design Study Town Meeting, 30 March – 01 April 2009, Pisa, Italy

Musumarra Agatino

Electron screening effects on alpha-decay

Nuclear structure and Dynamics, 04 – 08 May 2009, Dubrovnik, Croazia

Di Pietro Alessia Francesca

Structure effects in collision induced by weakly bound stable and radioactive nuclei

Nuclear Structure and Dynamics, 04 – 08 May 2009, Dubrovnik, Croazia

Scuderi Valentina

Study of reaction mechanisms for $^{9,10,11}\text{Be} + ^{64}\text{Zn}$ systems around the Coulomb barrier

La Rabida International Scientific Meeting on Nuclear Physics, 04 – 10 July 2009, La Rabida, Spagna

Di Pietro Alessia Francesca

Structure effects in collision induced by weakly bound radioactive and stable nuclei

The 10th International Conference on Nucleus-Nucleus Collisione, 16 – 21 August 2009, Beijing, China

Di Pietro Alessia Francesca

Structure effects in collisions induced by halo and loosely bound nuclei

XVIII International School on Nuclear Physics, Neutron Physics and Applications, 21 – 27 September 2009, Varna, Bulgaria

Scuderi Valentina

Structure effects in collisions induced by halo and weakly bound nuclei around the coulomb barrier

Nuclear reactions on Nucleons and Nuclei 2009, 05 – 09 October 2009 Messina, Italy

Maiolino Concettina

Simulation of MEDEA response to neutrone

14th Geant4 Users and Collaboration Workshop, INFN - LNS, 15-22 October 2009 Catania, Italy

Musumarra Agatino

Measuring total reaction cross-sections at energies near the Coulomb barrier by active target method

Direct reactions with Exotic Beams, 16 – 19 December 2009 Tallahassee, USA

Pellegriti Maria Grazia

^{19}Na single-particle levels investigated by ^{18}Ne elastic and inelastic scattering on $(\text{CH}_2)_n$ target

Direct reactions with Exotic Beams, 16 – 19 December 2009 Tallahassee, USA

Figuera Pierpaolo

Study of the collisions $^{9,10,11}\text{Be} + ^{64}\text{Zn}$ near the Coulomb barrier

Direct reactions with Exotic Beams, 16 – 19 December 2009 Tallahassee, USA

Pizzone RG

The effect of distortion in light nuclei

Nuclear Structure and Dynamics, 4 – 8 May 2009, Dubrovnik, Croazia

Pizzone RG

Trojan Horse Method: a useful tool for electron screening investigation

Nucleus Nucleus Conference, 16 – 21 August 2009, Beijing, China

Pizzone RG

Trojan Horse Method and the application to fusion reactors

Physcon 2009, Catania, Italy, 1 – 4 September 2009

Pizzone RG

The trojan horse method as a tool for studying electron screening effect

Nuclear Physics in Astrophysics Conference, 8 – 12 June 2009, Frascati, Roma, Italy

Riccobene G

Underwater/ice neutrino telescopes

International School of Physics "Enrico Fermi" - COURSE CLXXV - RADIATION AND PARTICLE DETECTORS, 20-25 July 2009, Varenna, Italy

Capone A, Aiello S, Aloisio A, Ameli F, Amore I, Anghinolfi M, Anzalone A, Barbarino G, Barbarito E, Battaglieri M, Bazzotti M, Bellotti R, Bersani A, Beverini N, Biagi S, Bonori M, Bouhdaef B, Brescia M, Cacopardo G, Cali C, Caponetto L, Carminati G, Cassano B, Castorina E, Ceres A, Chiarusi T, Circella M, Cocimano R, Coniglione R, Cordelli M, Costa M, D'Amico A, D'Amato C, D'Amato V, De Bonis G, De Rosa G, De Ruvo G, De Vita R, Distefano C, Falchini E, Flaminio V, Fratini K, Gabrielli A, Galeotti S, Gandolfi E, Giacomelli G, Giorgi F, Giovanetti G, Grimaldi A, Grmek A, Habel R, Leonora E, Lonardo A, Longo G, Lo Presti D, Lucarelli F, Maccione L, Margiotto A, Marinelli A, Martini A, Masullo R, Maugeri F, Megna R, Migneco E, Minutoli S, Mongelli M, Morganti M, Musico P, Musumeci M, Nicolau CA, Orlando A, Osipenko M, Osteria G, Papaleo R, Pappalardo V, Petta C, Piattelli P, Piombo D, Raffaelli F, Raia G, Randazzo N, Reito S, Ricco G, Riccobene G, Ripani M, Rovelli A, Ruppi M, Russo GV, Russo S, Sapienza P, Sedita M, Shirokov E, Simeone F, Sipala V, Sollima C, Speciale F, Spurio M, Stefani F, Taiuti M, Terreni G, Trasatti L, Urso S, Valente V, Vecchi M, Vicini P, Wischniewski R

Recent results and perspectives of the NEMO project

VLVnT Workshop, 22-24 April 2008, Toulon, France – NIM A602, 47-53, 2009

Cocimano R for the KM3NeT collaboration.

A comparison of AC and DC power feeding systems based on the NEMO experiences

VLVnT Workshop, 22-24 April 2008, Toulon, France – NIM A602, 171, 2009

Leonora E on behalf on NEMO collaboration

Characterization of two prototypes for a new large area four anode photomultiplier

VLVnT Workshop, 22-24 April 2008, Toulon, France – NIM A602, 217, 2009

Amore I for the NEMO collaboration

First results from the NEMO Phase-1 experiment

VLVnT Workshop, 22-24 April 2008, Toulon, France – NIM A602, 68, 2009

Bersani A

Instrumentation of a new direction sensitive segmented optical module

VLVnT Workshop, 22-24 April 2008, Toulon, France – NIM A602, 213, 2009

Ameli F for the KM3NeT collaboration.

KM3NeT: A proposal design for a detection unit data transmission system based on copper backbone

VLVnT Workshop, 22-24 April 2008, Toulon, France – NIM A602, 159, 2009

Coniglione R, Distefano C, Migneco E, Sapienza P for the KM3NeT collaboration

KM3NeT: Optimization studies for a cubic kilometer neutrino detector

VLVnT Workshop, 22-24 April 2008, Toulon, France – NIM A602, 98, 2009

Sapienza P, Coniglione R, Distefano C, Migneco E for the KM3NeT collaboration

KM3NeT: Study of the angular acceptance for a high energy neutrino telescope in the Mediterranean sea

VLVnT Workshop, 22-24 April 2008, Toulon, France – NIM A602, 101, 2009

Lo Presti D, Caponetto L, Randazzo N

Low power multi-dynamics front-end architecture for the optical module of a neutrino underwater telescope

VLVnT Workshop, 22-24 April 2008, Toulon, France – NIM A602, 126, 2009

Megna R

Monte Carlo simulation studies of the timing calibration accuracy required by the NEMO underwater neutrino telescope

VLVnT Workshop, 22-24 April 2008, Toulon, France – NIM A602, 80, 2009

Orlando A. for the NEMO collaboration

On line monitoring of the power control and engineering parameters systems of the NEMO phase-2 tower

VLVnT Workshop, 22-24 April 2008, Toulon, France – NIM A602, 180, 2009

Russo S

Qualification tests and readout electronics reliability analysis for the deep sea Underwater telescope NEMO

VLVnT Workshop, 22-24 April 2008, Toulon, France – NIM A602, 137, 2009

Piombo D, for the ANTARES and NEMO collaborations

The sector of the ANTARES line to be deployed in the NEMO site

VLVnT Workshop, 22-24 April 2008, Toulon, France – NIM A602, 168, 2009

Toscano S, Ardid M, Bou-Cabo M, Circella M, Hernandez-Rey JJ, Perkin J, Schuller JP, Thompson LF

Time calibration and positioning for KM3NeT

VLVnT Workshop, 22-24 April 2008, Toulon, France – NIM A602, 183, 2009

Circella M, for the NEMO collaboration

Time calibration of the Neutrino Mediterranean Observatory (NEMO)

VLVnT Workshop, 22-24 April 2008, Toulon, France – NIM A602, 187, 2009

Circella M, for the ANTARES collaboration

The Construction of ANTARES, the first undersea neutrino telescope

VLVnT Workshop, 22-24 April 2008, Toulon, France – NIM A602, 1, 2009

Giovannetti G, for the NEMO collaboration

New electronics architecture in NEMO phase-2.

VLVnT Workshop, 22-24 April 2008, Toulon, France – NIM A602, 133, 2009

D'Amico A, for the NEMO collaboration

The electro-optical cabling system for the NEMO phase-2 tower

VLVnT Workshop, 22-24 April 2008, Toulon, France – NIM A602, 164, 2009

Sapienza P, for the KM3NeT collaboration

KM3NeT: a cubic-kilometer scale deep sea neutrino telescope in the Mediterranean sea.

NNN09 - Workshop on next generation nucleon decay and neutrino detectors, 8-10 October 2009, Estes Park, Colorado, USA

Riccobene G

The ESONeT East Sicily Node

ESONeT 05 - 07 October 2009 - IGP, Paris, France

DEGREES THESES

Student: Barbagallo Massimo

"Studio di fattibilità di un rivelatore compatto per neutroni termici"

Tutor: Bellia G, Finocchiaro P, Cosentino L

Student: Candiano Giuliana

"Ricostruzione tomografica di una immagine con protoni attraverso simulazione Montecarlo"

Tutors: Cirrone GAP, Cuttone G, Lo Nigro S

Student: Carbone Diana

"Studio della reazione $^{13}\text{C}(^{18}\text{O}, ^{16}\text{O})^{15}\text{C}$ a 84 MeV con MAGNEX"

Tutors: Cunsolo A, Cappuzzello F

Student: Febbraro Vincenzo

"Rivelazione di gamma per il monitoraggio di scorie radioattive"

Tutor: Bellini V, Finocchiaro P, Capogni M

Student: Greco Giuseppe

"Caratterizzazione di dispositivi fotomoltiplicatori al silicio per applicazioni di monitoraggio di radiazioni"

Tutor: Russo GV, Finocchiaro P, Pappalardo A

Student: Minniti Triestino

"Produzione di Ioni da Plasma Laser per studi di reazioni nucleari D-D"

Tutor: Torrisi L

Student: Rizzo Carmelo

"Effetto di isospin su meccanismi dissipativi in collisioni fra ioni pesanti alle Energie di Fermi"

Tutors: Colonna M, Di Toro M

Student: Scardina Francesco

"Dinamica del QGP: soppressione di jet adronici e flussi collettivi"

Tutors: Di Toro M, Greco V

Student: Schillaci Maria

"Ricerca della strength di Gamow-Teller nella $^{28}\text{Si}(^7\text{Li}, ^7\text{Be})^{28}\text{Al}$ con MAGNEX e la tecnica di ricostruzione delle traiettorie"

Tutors: Cunsolo A, Cappuzzello F

Student: Spartà Roberta

"Studio dei canali di reazione $^2\text{H}(d,p)^3\text{H}$ e $^2\text{H}(d,n)^3\text{He}$ ad energie di interesse astrofisico attraverso il Metodo del Cavallo di Troia"

Tutors: Spitaleri C, Pizzone RG

Student: Trovato Agata

"Ottimizzazione delle prestazioni del telescopio per neutrini KM3NET"

Tutors: Migneco E, Coniglione R, Sapienza P

Student: Viola Salvatore

"Realizzazione e test di un sistema di posizionamento acustico innovativo per il telescopio Km3"

Tutors: Migneco E, Riccobene G

PH.D. THESES

Student: Cavallaro Manuela

"First Application of the MAGNEX spectrometer: investigation of the $^{19}\text{F}(^7\text{Li}, ^7\text{Be})^{19}\text{O}$ reaction at 52.2 MeV"

Tutors: Cunsolo A, Cappuzzello F

Student: Plumari Salvatore

"Dinamica partonica in presenza di campi effettivi autoconsistenti"

Tutors: Di Toro M, Greco V

SEMINARS

The following seminars were presented at LNS this year

18-Feb-2009

F. Cappuzzello

MAGNEX: primi risultati e prospettive

23-Feb-2009

D. Mascali

A new approach to the study of the ECR heating and particle dynamics in the plasma of ECR Ion Sources

25-Feb-2009

B. Irgaziev

Use of Mathematica

6-Mar-2009

P. Finocchiario

New LNS website

12-Mar-2009

R. Calabrese

Intrappolamento di atomi di Francio per test di simmetrie fondamentali

18-Mar-2009

I. Rabin

Archaeometry of Dead Sea Scrolls

18-Mar-2009

M. Bicchieri

Spectroscopic analysis of jewish parchments

23-Mar-2009

L. Calabretta

Informal meeting on FRIBs update

11-May-2009

D. Pereira

Nuclear rainbow scattering in heavy ion systems

19-May-2009

G. Cuttone

Misure di frammentazione per adroterapia...

22-Jun-2009

T. Borello Lewin

($6\text{Li}, d$) experiments on odd light

16-Jul-2009

C. Mazzocchi

Astrofisica nucleare

23-Jul-2009

P. Capel

Theoretical description of breakup reactions o

31-Jul-2009

J. Verboncoer

Overview of the Particle-in-Cell Simulation

31-Jul-2009

J. Verboncoeur

A PIC-MCC Model of a Sputtering Magnetron

31-Jul-2009

J. Verboncoeur

XOOPIC tutorial

12-Oct-2009

J. Harasimowicz

Beam instrumentation development development at the QUASAR group, University of Liverpool

13-Nov-2009

I. Padròn Diaz

Experimental progress on reaction

14-Dec-2009

G. Riccobene, F. Del Tevere, F. Ferrera, G. Barbagallo, VR. Potenza

Nuove infrastrutture e servizi di rete ai LNS

18-Dec-2009

X. Michalet

New detectors for single-molecule fluorescence spectroscopy and imaging

EVENTS

- | | |
|--|--|
| <i>February 11</i>
Olimpiadi della Fisica | <i>September 18 – 19</i>
Workshop in honor of the 70th birthday of Massimo Di Toro |
| <i>March 23</i>
Informal Meeting on FRIBs update | <i>September 20 – 27</i>
5th European Summer School on Nuclear Astrophysics |
| <i>April 3</i>
Emilio Migneco's 70th birthday | <i>October 10</i>
Open Day ASPERA |
| <i>April 6 – 16</i>
XIX Settimana della Cultura Scientifica e Tecnologica | <i>October 12 – 14</i>
Utilizzo del codice GEANT4 in campo medico LNS |
| <i>May 11</i>
Fisica in Barca | <i>October 15 – 22</i>
14th Geant4 Users and Collaboration Workshop |
| <i>June 8 – 12</i>
Technical Meeting on Heavy Charged Particle Interaction data for radiotherapy | <i>November 4 – 7</i>
IWM2009 International Workshop on Multifragmentation |
| <i>June 18 – 20</i>
PPLA 4th Workshop Plasma Production by Laser Ablation | <i>November 27</i>
Caffè Incontro con gli Studenti di Fisica ai LNS |
| <i>June 30</i>
Meeting gruppo III LNS | <i>November 30 – December 2</i>
Spes – Excyt incontro tecnico |
| <i>July 1</i>
Meeting gruppo V LNS | <i>December 4</i>
Caffè Incontro con gli Studenti di Fisica ai LNS |
| <i>July 8 – 9</i>
LNS Scientific Committee | <i>December 9 – 11</i>
The First EURISOL UG topical meeting |
| <i>July 10</i>
LNS User Meeting | |
| <i>September 14 – 18</i>
INFN CNS V Annual Meeting | |

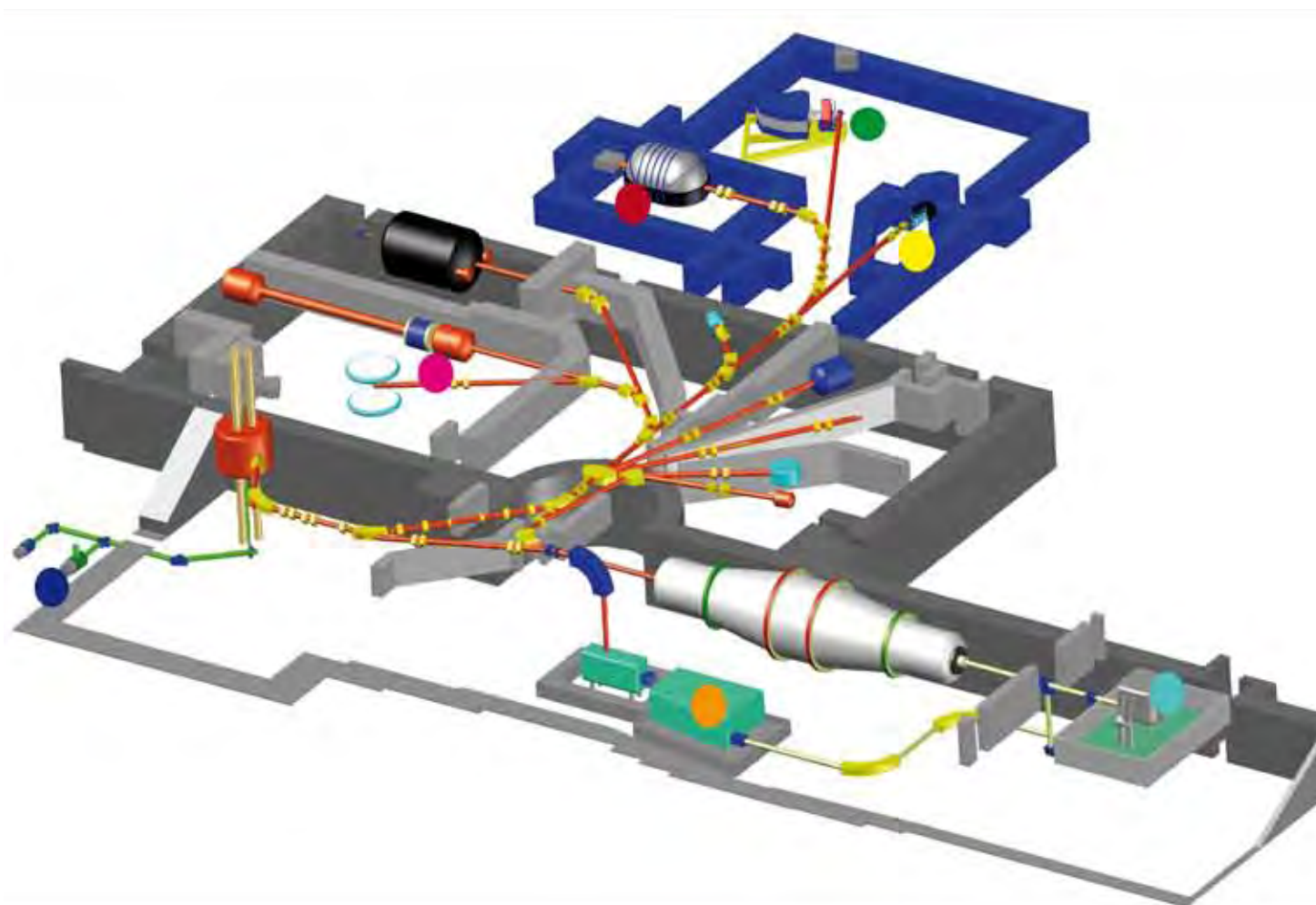
**ISTITUTO NAZIONALE DI FISICA NUCLEARE
LABORATORI NAZIONALI DEL SUD
ACTIVITY REPORT 2009**

**LNS
EXPERIMENTAL
HALLS**

PHOTO BY DOMENICO SANTONOCITO



PHOTO BY GIACOMO LEONE





**ISTITUTO NAZIONALE DI FISICA NUCLEARE
LABORATORI NAZIONALI DEL SUD
ACTIVITY REPORT 2009**

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ADRIATICA sosta nel Porto di Catania
lunedì 11 maggio
 (molo di levante - visite ore 10 - 19)

Seminari su: radiazioni cosmiche, neutrini extrasolari, acustica sottomarina, astronomia, meteorologia, fisica dei fluidi, navigazione, tecnologia energetica per l'ambiente.

Con l'Infn si salpa alla scoperta della fisica che serve per andar per mare!

Navigare con la relatività, i raggi cosmici, la radio, il Sole

Fisica in barca 2009

L'Istituto Nazionale di Fisica Nucleare (Infn) è uno dei punti di eccellenza della ricerca scientifica italiana. L'ente si occupa di ricerca di base nell'ambito della fisica nucleare, delle particelle elementari e delle astroparticelle, oltre che delle applicazioni tecnologiche che derivano da questa attività.

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 INFN - Sezione Catania
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 info@infn.it

INFN Istituto Nazionale di Fisica Nucleare

con il contributo di





The first EURISOL UG topical meeting



INVITED SPEAKERS

Torick Blumensfeld (ICRN-ISOLDE)
The future of EURISOL and open discussion

Angela Bracco (INFN and University of Milano)
The Pygmy Dipole Resonance in the neutron rich nucleus ^{68}Ni

Kostantze Boretzky (GSI - Darmstadt)
Dipole strength in neutron rich Ni and Sn isotopes

Luciano Calabretta (INFN-LNS)
Introducing the LNS facilities

Bradley Chad (The University of Manchester, UK)
Optical techniques for π -process nuclei

Silvio Cherubini (University of Catania and INFN-LNS)
Nuclear Astrophysics research in Catania

Gianluca Colo (INFN and University of Milano)
Single-particle and collective strength in neutron-rich nuclei using non-relativistic effective forces

Maria Colonna (INFN-LNS Catania)
Testing the low density behavior of neutron-rich systems

Jon Dirken (IKS - KU Leuven)
Cosmological evolution of ^{73}Ge with MINIBALL at REX-ISOLDE

Jacek Dobaczewski (University of Warsaw/University of Jyväskylä)
New ideas in the nuclear energy density functional approach

Angela Gargano (INFN, Sez. di Napoli)
Neutron-rich nuclei around Closed Shells: Nuclear Forces and Shell Structure

Stéphane Goriely (Institut d'Astronomie et d'Astrophysique - Université Libre de Bruxelles)
The π -process: a longstanding mystery with still many nuclear and astrophysics pending questions

Magdalena Gorska (GSI - Darmstadt)
Structure of heavy Cd and In isotopes up to N=82

Alexander Herlert (ISOLDE-CERN)
Mass measurements on neutron rich nuclei at ISOLTRAP: Present status and future perspectives

Ari Jokinen (University of Jyväskylä)
Exploring structure of neutron rich nuclei by direct mass measurements

Thorsten Kroell (Institut fuer Kernphysik, Technische Universität Darmstadt)
Cosmological evolution of neutron rich nuclei around ^{132}Sn at REX-ISOLDE

Marco La Cognata (INFN-LNL)
Solving the large discrepancy between inclusive and exclusive measurements of the $^{132}\text{Sn} + \alpha \rightarrow ^{136}\text{Te} + n$ reaction cross section at astrophysical energies

Edoardo G. Lanza (INFN Sezione di Catania)
On the nature of the Pygmy Resonances

Gabriel Martinez Pineda (GSI - Darmstadt)
The role of nuclear physics π -process nucleosynthesis

Steven Pain (University of the West of Scotland, UK)
Neutron transfer measurements around the doubly magic ^{132}Sn

Rene Rofarth (GSI - Darmstadt)
Experiments close to stability contributing to our understanding of the π -process

Gary Simpson (IPSC, Grenoble)
Current status of gamma-ray spectroscopy data in the ^{132}Sn region

Olivier Sorlin (GANIL)
Experimental studies on the π -process at SPIRAL2

Dimitry Testov (INFN, JINR)
Delayed multiple neutron emission from photo-fusion fragments

Calin Ur (INFN-LNL and University of Padova)
Study of neutron-rich nuclei with FRISMA-CLARA: Future perspectives with EURISOL

David Verney (IPN Orsay)
Structure of nuclei "North and Northeast of ^{78}Ni ": Contribution from beta-decay

SCIENTIFIC COMMITTEE

Dieter Ackermann
Bertram Blank
Torick Blumensfeld
Angela Bracco
Peter Butler
Giampaolo De Angelis
Ari Jokinen
Marcello Lattuada
Marek Lewinowicz
Matti Lindqvist
Witold Nazarewicz
Angelo Pagano
Robert Page
Berta Rubio
Claudia Spitaleri
Michael Thoennessen

LOCAL COMMITTEE

Giuseppe Agnello
Elena Geraci
Maria Grazia Pellegrini
Gianluca Pizzone
Virginia Palazzo
Giuseppe Verde

Laboratori Nazionali del Sud - Catania, Italy

9 - 11 December 2009



4th Workshop "Plasma Production by Laser Ablation"
(PPLA 2009)
June 18-20, 2009 MESSINA, Italy







PPLA-09



Organized by
Istituto Nazionale di Fisica Nucleare - I.N.S.
and Section of Catania
University of Messina
and
University of Lecce

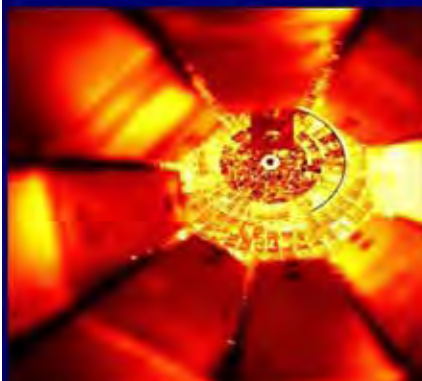
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IWM2009



International Workshop on Multifragmentation and related topics
4th - 7th November 2009, Catania, Italy



Main Topics

- Multifragmentation
- Properties and phases of nuclear matter
- Isospin & symmetry energy
- Dynamics of heavy-ion collisions
- Correlation techniques and characterization of emitting sources
- Future detectors and facilities

CHIMERA and INDRA Collaborations

Scientific Committee

CARDELLA Giuseppe	INFN Sezione di Catania, Italy
DI TORO Massimo	INFN - LNS & Univ. of Catania, Italy
FRANKLAND John	GANIL, Coen, France
LAUTESSE Philippe	LPC Caen, France
LUKASIK Jerzy	IFJ-PAN Kraków, Poland
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RIVET Marie-France	IPN Orsay, France
RIZZO Francesca	INFN - LNS & Univ. of Catania, Italy
VERDE Giuseppe	INFN Sezione di Catania, Italy

Local Organization

AGNELLO Gaetano	INFN, LNS - Italy
LANZALONE Gaetano	INFN, LNS and Univ. of Enna - Italy
MAGRÌ Anna Linda	INFN, Sezione di Catania - Italy
RUSSOTTO Paolo	INFN, LNS and Univ. of Catania - Italy



<http://www.ct.infn.it/iwm2009> email iwm2009@ct.infn.it
Contact person Sara Pirrone, INFN-Sezione di Catania, Sara.Pirrone@ct.infn.it



Commissione Nazionale Scientifica V

Catania, 14-18 Settembre 2009

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14th Geant4 Collaboration and Users' Workshop

Laboratori Nazionali del Sud
Istituto Nazionale di Fisica Nucleare
Catania, Italy

Geant4

15 - 22 October 2009

www.lns.infn.it/geant4/geant4ws2009/

Local committee

G. Agnello
INFN-LNS
B. Caccia
INFN-ISS
G. A.P. Cirrone
INFN-LNS
G. Cuttone
INFN-LNS
F. Di Rosa
INFN-LNS
L. Pandola
INFN-LNGS
F. Marchetto
INFN Section of Turin
F. Romano
INFN-LNS and Catania
University
M.G. Sabini
A.O. Cannizzaro and INFN
A. Solano
INFN Section of Turin



Program:

Users' Session
15 - 17 October

Collaboration Session
(Geant4 members only)
19 - 22 October

Important dates:

Abstract submission
(for Users' Session only)
1 May - 30 September

Registration
and accommodation
1 May - 30 September

Social dinner
17 October

Excursion
18 October



TOPICS

- HEP simulations
- Nuclear physics
- Medical physics
- Space physics
- Radiobiology

Users' Conference consists of presentations
by Geant4 users and status reports by Geant4
developers.

The collaboration workshop is closed to the
collaboration members.

Geant4 (Geometry And Tracking) is a toolkit
for the simulation of particle tracking and
interaction with the matter. Its area of
application includes high energy, nuclear and
accelerator physics, as well as studies in
medical and space science.



**1^o Caffè - Incontro con gli studenti ai Laboratori Nazionali del Sud per
la presentazione di argomenti per lo svolgimento di tesi di laurea**

Venerdì 27 Novembre 2009 - Aula Rizzuto LNS

15:00 Introduzione Direttore dei LNS
Experimental Nuclear Physics
15:20 Angelo Cusolo
15:30 Giuseppe Cardella
15:40 Alessia Di Pietro
Accelerator Physics
15:50 Luciano Calabretta
16:00 Santo Gammino
Astroparticle Physics &
Nuclear Astrophysics
16:10 Claudio Spitaleri
16:20 Gianluca Pizzone
16:30 Paolo Piattelli
discussione e chiarimenti
16:50 Caffè e incontro con i relatori

Venerdì 04 Dicembre 2009 - Aula Rizzuto LNS

15:00 Introduzione Direttore dei LNS
Technology & Multidisciplinary
15:20 Giacomo Cuttone
15:30 Paolo Finocchiaro
15:40 Franco Musumeci
15:50 Giorgio Riccobene
16:00 Ninni Rizzo
16:10 Lorenzo Torrisi
Theoretical Nuclear Physics
16:20 Maria Colonna
16:30 Umberto Lombardo
discussione e chiarimenti
16:50 Caffè e incontro con i relatori

www.lns.infn.it - Servizio di Informazione Scientifica tel 095/542301(296) - sis@lns.infn.it

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Workshop in honor of the 70th birthday of Massimo Di Toro

Open Day ASPERA INFN-LNS

Astroparticle physics
the European week

10-17 October 2009

Le Stelle viste dai regni
di Vulcano e di Nettuno





Workshop in honor of the 70th birthday of Emilio Migneco

