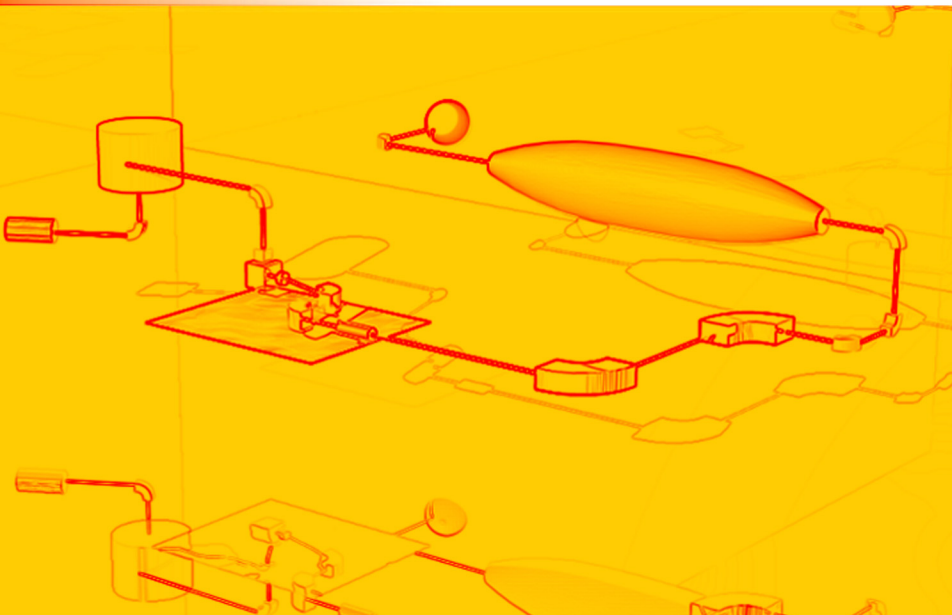


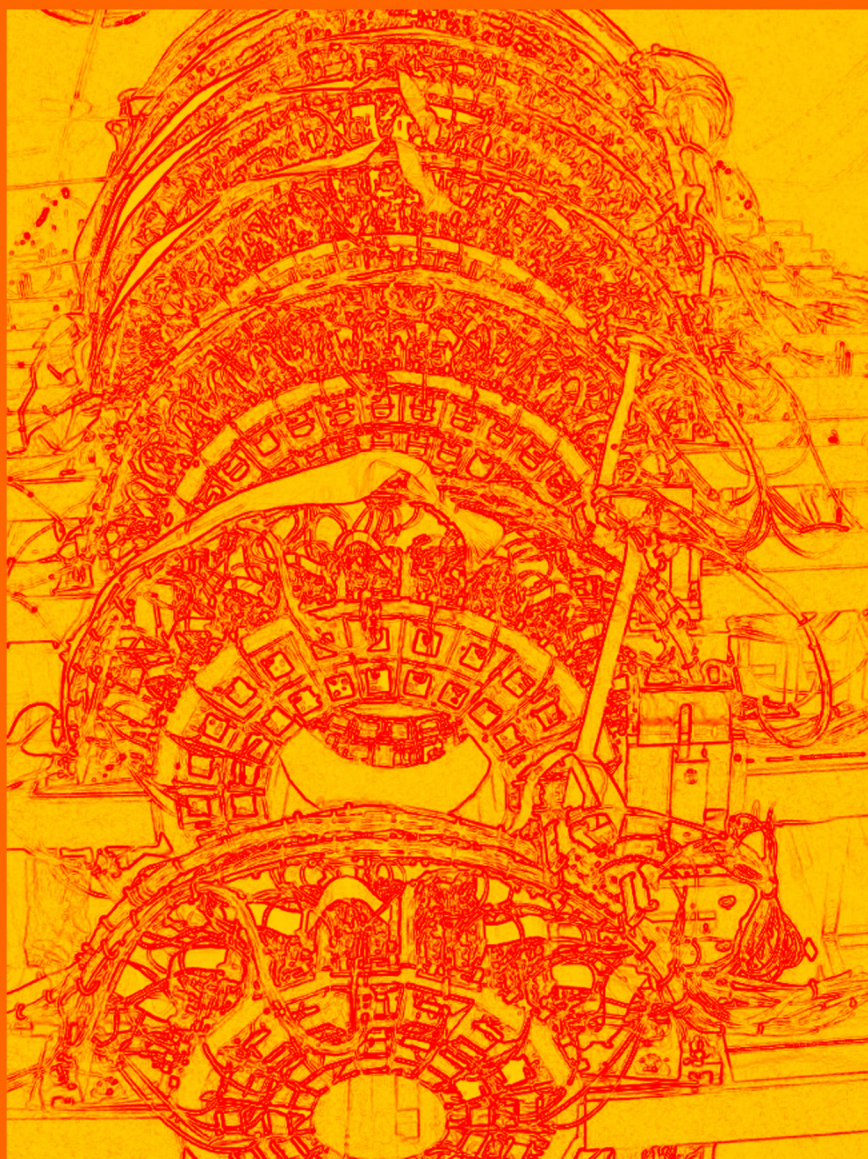
ACTIVITY REPORT 2001



LNS

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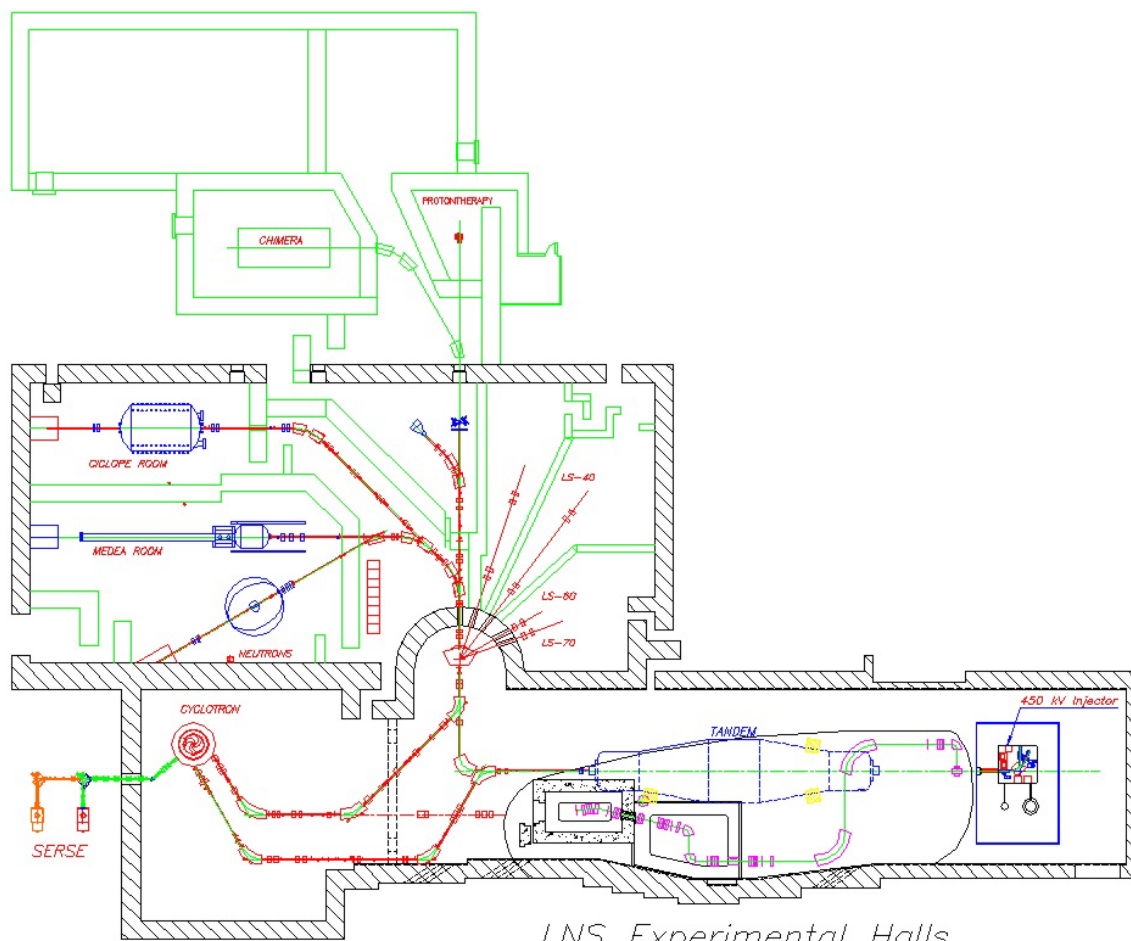
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LNS Activity Report 2001

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Artistical view of the 4π multidetector CHIMERA and the EXCYT project by P. Finocchiaro



LNS Experimental Halls

Foreword

The year 2001 has been characterized by an intense activity of the two accelerators resulting in a large number of experiments performed with them as well as in a relevant widening of beams developed and delivered to the users. This was partly due to the full operation of the new by-pass beam line that allowed for contemporary experiments with the two machines. In addition the improvements achieved with the design and construction of new electrostatic deflectors, thanks to joint efforts of the physicists and the technical staff working around the Cyclotron, brought a higher degree of reliability in the operation of this accelerator.

Experiments concerning the study of nuclear structure, reaction mechanisms and nuclear astrophysics at tandem as well as experiments on reaction dynamics and on the behaviour of nuclear matter at intermediate energy, using the Superconducting Cyclotron beams, were successfully performed both by LNS and external research groups. Interesting results in all these fields have been deduced from the completion of the analysis of data taken in the previous years.

At the same time big efforts have been devoted to improve the characteristics of the existing detection devices, like CHIMERA and TRASMA, and to complete the design and begin the realization of forthcoming installations, like MAGNEX.

Continuous support to the experimental activity has been provided by the work of the theoretical group on properties of nuclear matter and nuclear dynamics.

Strong activity has also characterized the technological research on different aspects of the Cyclotron, like the mentioned deflectors, the ion sources and the chopper and axial buncher systems. Studies have also been undertaken with the aim of improving the power of beams delivered by the Cyclotron, an important step specially in view of its use as driver of the forthcoming RIB facility EXCYT.

As regards the exploitation of nuclear tools in multidisciplinary researches, the accelerators were widely used, for instance, in studies concerning the enhancement of superconductive properties of materials induced by ion irradiation and the development of new techniques like ion beam micrometric lithography.

In this framework it is also to be mentioned that all the preliminary studies concerning the CATANA project were completed and the set up was fully installed: at the end of the year the proton therapy facility was ready to start patient treatment, opening the gate of LNS to an activity of deep social impact.

The PIXE-Alpha portable system developed in the framework of the LANDIS laboratory for in situ analysis of samples was improved and widely used in the investigation of objects of archaeological interest.

In the frame of the NEMO project aimed at the construction of a high energy neutrino telescope, a campaign was conducted to measure the optical properties of the deep water in Lake Baikal (Siberia). The results are compatible with those previously reported by the BAIKAL Collaboration and confirm the reliability of the used measurements technique.

Prof. Emilio Migneco
LNS Director

Foreword

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Scientific Guests

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Graduate and Undergraduate Students

Journal Publications

Conference Publications

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Proton-induced lithium destruction cross section and its astrophysical implications

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Abstract. The primordial nucleosynthesis offers a powerful tool to retrieve information on the baryon density of the Universe. In this context lithium isotopes play a crucial role and in particular it is underlined how important the bare nucleus cross section for the ${}^7\text{Li}(p, \alpha){}^4\text{He}$ reaction is. Recent application of the Trojan Horse Method led to an indirect measurement of that cross section. In the present paper its astrophysical implications are examined in the case of the Solar lithium problem and of the primordial nucleosynthesis.

Key words. Nuclear reactions, nucleosynthesis, abundances, Sun: abundances, cosmological parameters

1. Introduction

Big Bang nucleosynthesis has emerged as one of the tests of the Big Bang Model, together with the Hubble expansion and the cosmic microwave background radiation. Among them, Big Bang nucleosynthesis probes the Universe to the earliest times, from a fraction of a second to hundreds of seconds.

According to the Standard Big Bang model (Malaney & Mathews 1993) for $T \leq 10^9$ K it is possible the formation of light nuclei (up to $A \leq 7$) from protons and neutrons. Consistent amounts of these primordially synthesized elements should be found nowadays in the appropriate astrophysical contexts. The Standard Big Bang model has the very powerful feature that prediction for light elements’ production (${}^2\text{H}$, ${}^4\text{He}$, ${}^7\text{Li}$) is primarily dependent only on one free parameter, the baryon-to-photon ratio η (which is connected to the baryon density of the Universe, Ω_b). Starting from this, the measured primordial abundances can be fitted up to 10 orders of magnitudes (Schramm & Turner 1998).

In this way a comparison between theoretically calculated yields and observed primordial abundances of such elements can be performed in order to test the SBBN. Moreover it is possible (Copi et al. 1995) to infer hints on the relevant cosmological parameter η and therefore on Ω .

This procedure has some uncertainties; although many of them have been reduced thanks to recent improvements (for instance the uncertainty on τ_n , neutron decay period) some still remain important:

- errors on observed primordial abundances;
- uncertainty on the Hubble parameter;
- errors on reaction cross section at astrophysical energies.

Up to now, a lot has been done in all these fields, but a definitive solution is still far away from being found.

Among these “primordial” isotopes, lithium has been studied both observationally and theoretically in the last decades (Michaud & Charbonneau 1991). In particular the key role of the reaction ${}^7\text{Li}(p, \alpha){}^4\text{He}$ must be acknowledged for both the primordial nucleosynthesis and the lithium destruction in stellar environment. The indetermination on this cross section is one of the main sources of uncertainty in these fields (Vangioni-Flam et al. 2000), even if great efforts have been devoted to reduce it.

Experimental measurements of this cross section have been performed (Rolfs & Kavanagh 1986), (Engstler et al. 1992) and, as it usually happens for charged-particle induced reactions, the main difficulty arises from the presence of the Coulomb Barrier (whose height is E_C). This greatly reduces the cross section $\sigma(E)$ at low energies ($E \ll E_C$), leading to a low-energy

limit of experimental measurements, which is typically much larger than the energy relevant for astrophysical application, E_0 (Rolfs & Rodney 1988). In such cases, an extrapolation of high energy data is usually performed via the definition of the astrophysical $S(E)$ -factor

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

with $\eta = Z_1 Z_2 e^2 / \hbar v$ the Sommerfeld parameter. Of course, this extrapolation “into the unknown” may introduce a large uncertainty in $\sigma(E_0)$.

Moreover, measurements at ultra-low energies suffer from the complication due to the effects of electron screening (Assenbaum et al. 1987). This leads to an exponential increase of $\sigma(E)$ (or equivalently of $S(E)$) with decreasing energy with respect to the case of bare nuclides. It should be pointed out that, in the astrophysical environments, the cross section under plasma conditions $\sigma_{pl}(E)$ is related to the bare cross section $\sigma(E)$ by a similar enhancement factor which depends on detailed properties of the plasma, such as the Debye-Hückel radius. So what is needed for astrophysical calculations is the bare nucleus cross section which must be inferred from the directly measured one by means of theoretical extrapolation. This has been done in (Engstler et al. 1992) for the ${}^7\text{Li}(p, \alpha){}^4\text{He}$ reaction giving an extrapolated value $S(E=0)=58 \text{ keV}\cdot\text{b}$.

2. The method and experimental results

The Trojan Horse Method (THM) is a useful tool for measuring the bare nucleus reaction cross section without any extrapolation and allows to overcome the Coulomb Barrier and the electron screening effect. The method is extensively discussed in (Baur 1986) and (Spitaleri et al. 1999), so here we will briefly review its main features.

The THM is based on a quasi-free break-up process and allows to extract the cross section of a two-body reaction (of astrophysical interest)

$$a + x \rightarrow c + C$$

from a suitable three body one

$$a + A \rightarrow c + C + s.$$

In this notation the particle A , the “Trojan Horse”, which can be either the projectile or the target nucleus, has a high probability to be clustered into x and s , i.e. $A = x \oplus s$. Particle x acts as a participant to the two body reaction, while s keeps the role of spectator. If the energy in the entrance channel is higher than the Coulomb barrier, then the interaction between x and a occurs directly in the nuclear interaction zone, thus by-passing the Coulomb barrier and the electron screening effect.

An improved theoretical formalism, based on a Distorted Wave Born Approximation (DWBA) (Typel & Wolter 2000) allows the extraction of the energy trend for the bare nucleus astrophysical factor whose absolute normalization must be performed via a comparison with direct data at energies above the

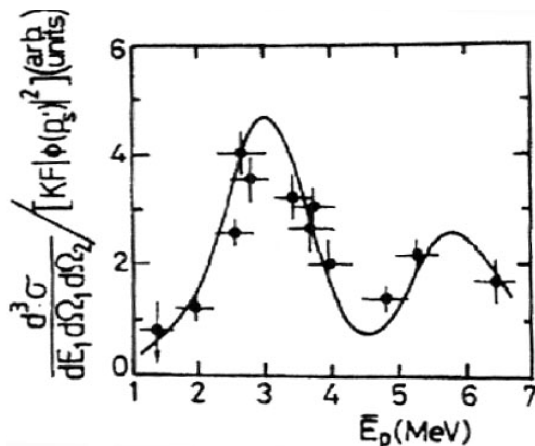


Fig. 1. Comparison between the indirect data (full dots) and direct data (solid line) for the ${}^7\text{Li}(p, \alpha){}^4\text{He}$ reaction (Zadro et al. 1989) at energies above the Coulomb Barrier.

Coulomb barrier, where the THM and the direct results should be equivalent.

The method has been applied to measure the bare nucleus astrophysical $S(E)$ -factor of two important lithium depleting reactions, the ${}^6\text{Li}(d, \alpha){}^4\text{He}$ (Spitaleri et al. 2001) and the ${}^7\text{Li}(p, \alpha){}^4\text{He}$ (Lattuada et al. 2001), and hence the electron screening potential for both reactions.

The reaction ${}^7\text{Li}(p, \alpha){}^4\text{He}$ has been studied via the three-body reaction ${}^7\text{Li}(d, \alpha\alpha){}^4\text{He}$ at the Laboratori Nazionali del Sud, Catania. In this case the Trojan Horse particle was the deuteron, carrying inside the “participant” proton. A first run of the experiment was performed at relative energies between ${}^7\text{Li}$ and p higher than the relative Coulomb barrier (validity test). The results are taken from (Zadro et al. 1989) and are shown in figure 1. A fair agreement is achieved and both resonances associated with the ${}^8\text{Be}$ compound nucleus are correctly reproduced. The next step was to extract data at energies lower than the Coulomb Barrier. This has been performed in the energy range $E_{cm} = 0 \div 0.4 \text{ MeV}$ in two different experimental runs. A more complete description is reported in (Calvi et al. 1997) and (Lattuada et al. 2001), respectively.

Here we report only the final results and we refer to those papers for an exhaustive discussion about the experiments and data-analysis; the bare astrophysical $S(E)$ -factor is plotted in figure 2 and it is compared with the direct data obtained in (Engstler et al. 1992). A second-order polynomial fit to the indirect data (Lattuada et al. 2001) gives $S(E=0)=55 \pm 3 \text{ keV}\cdot\text{b}$, in agreement with theoretical predictions (Aliotta et al. 2000). It has to be remarked how this result is only slightly different from what is obtained in the direct measurements (Engstler et al. 1992).

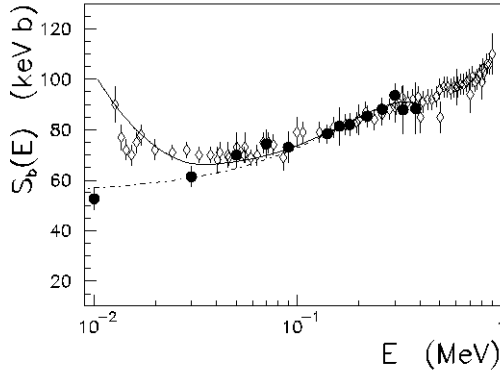


Fig. 2. The bare astrophysical $S(E)$ -factor for the ${}^7\text{Li}(p, \alpha){}^4\text{He}$ compared with direct data. The fit performed to obtain the electron screening contribution is also shown as a solid line (taken from (Lattuada et al. 2001)).

3. Astrophysical applications

In this paper we focus our attention on the astrophysical impact of the measurement of the ${}^7\text{Li}(p, \alpha){}^4\text{He}$ bare nucleus cross section. It has to be stressed that it has been obtained in this case without any extrapolation by applying the THM. So it seems worthwhile to apply these results to the solar lithium problem and primordial nucleosynthesis.

3.1. The Solar lithium problem

In different astrophysical objects many attempts of modeling lithium abundance time-evolution were carried on. The best studied case is the Solar one.

The present lithium abundance on solar surface corresponds to a mass fraction of $\approx 7.0 \times 10^{-11}$ (Grevesse & Sauval 1998); this value has to be compared with the meteoritic value of $\approx 9.9 \times 10^{-9}$ (Anders & Grevesse 1989). Since at the beginning of the solar system the proto-solar nebula is assumed to be homogeneous, the Sun has clearly depleted lithium for a factor 140.

We have investigated the impact of our measurement of the bare nucleus cross section for the ${}^7\text{Li}(p, \alpha){}^4\text{He}$ reaction on the lithium abundance on solar surface. This has been done by using the FRANEC code, which is extensively discussed in (Ciaccio et al. 1997). It was applied to calculate a solar model which includes the light elements' diffusion; in particular the lithium surface abundance at present time ($t_{\odot} = 4.6 \times 10^9$ years) was calculated taking into account both Pre-Main Sequence and Main Sequence lithium depletion. Our Standard Solar Model (SSM) reproduces at the solar age the observed luminosity, radius and Z/X ratio and the helioseismic observables (Ciaccio et al. 1997) (see e.g. Bahcall, Pinsonneault & Basu 2001 for more details on SSMs). We adopted the OPAL opacity (Rogers & Iglesias 1995) and equation of state

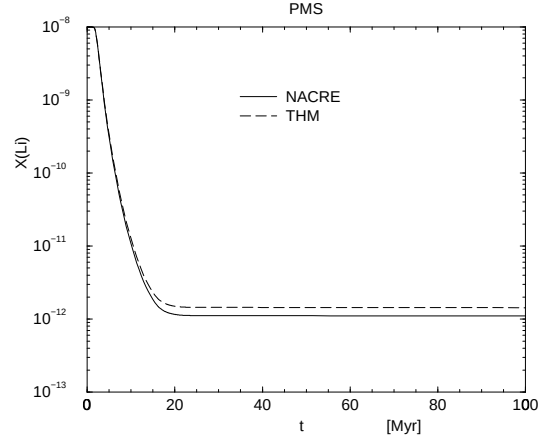


Fig. 3. Time-evolution of the lithium surface abundance (mass fraction) during the PMS phase for the Sun. The solid line represents a calculation performed using the FRANEC code with the rate for the ${}^7\text{Li}(p, \alpha){}^4\text{He}$ taken from (Angulo et al. 1999). The dashed line represents the same model calculation with the cross section extracted in (Lattuada et al. 2001).

(Rogers & Iglesias 1996), and the mixing length parameter $\alpha = 1.9$; the initial helium abundance is $Y = 0.269$ and the metallicity $Z = 0.0198$.

Since the evolution of lithium abundance will be described from the PMS phase, we took as initial value of lithium abundance the meteoritic value, 9.9×10^{-9} .

Two different calculations have been performed using the FRANEC code: in the first case, we adopted the cross section of the ${}^7\text{Li}(p, \alpha){}^4\text{He}$ directly measured in (Engstler et al. 1992) and used for the NACRE (Angulo et al. 1999) compilation. The second calculation was performed by assuming as cross section the THM one reported in (Lattuada et al. 2001). As it was expected the difference is quite small and is around 5 %. In figure 3 we report the trend of lithium abundance versus stellar age (expressed in units of 10^6 years) for the Sun during the PMS phase. The solid line represents the calculation performed using the rate of the ${}^7\text{Li} + p \rightarrow \alpha + \alpha$ extracted from the NACRE compilation while the dashed one represents the result for the THM measurement of the cross section.

In the MS phase the lithium abundance decreases, mainly due to microscopic diffusion, as sketched in figure 4; again the solid line represents the calculation performed using the rate reported in the NACRE compilation (Angulo et al. 1999) while the dashed one represents that obtained by using the THM cross section. It was assumed the same α , metallicity, primordial helium and physical inputs for both phases. The discrepancy in the lithium abundance between the two calculations, is around 5 %.

Thus the present measurement of the ${}^7\text{Li}(p, \alpha){}^4\text{He}$ $S(0)$ -factor doesn't change significantly the superficial lithium abundance for the present Sun, with respect to the NACRE compilation as expected because of the small discrepancy between the two rates.

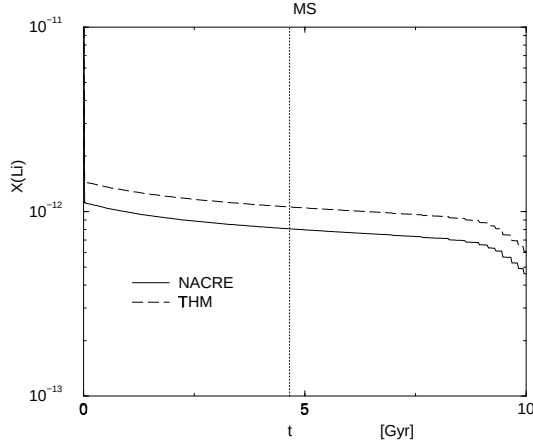


Fig. 4. Time-evolution of the lithium surface abundance during the MS phase for the Sun. The solid line represents a calculation performed with the rate for the ${}^7\text{Li}(p,\alpha){}^4\text{He}$ taken from (Angulo et al. 1999). The dashed line represents the same model calculation with the cross section extracted in (Lattuada et al. 2001). The vertical dotted line marks the present age of the Sun.

So, as expected, the “Lithium problem” for the Sun as well as for the population I and II (and hence the time evolution of the lithium abundance) is not solved even applying the THM and the observed lithium surface abundance is not reproduced by the model. Other mechanisms and uncertainties should be taken into account in order to solve the “Lithium problem” such as the efficiency of convection in the external envelope of stars, non standard mixings, rotation, uncertainties on opacity and equation of state (see e.g. Swenson et al. 1994, Morel et al. 1997, Brun, Turck-Chieze & Zahn 1999, Imperio, Castellani & Degl’Innocenti 2001). A better evaluation of the role and relative weight of each one of these mechanisms will provide more reliable bases to the astrophysical models.

3.2. The primordial nucleosynthesis

The ${}^7\text{Li}(p,\alpha){}^4\text{He}$ reaction is one of the main channel of lithium destruction also in the Big Bang nucleosynthesis (BBN) network (Schramm & Turner 1998); its rate influences the calculated abundance of primordial nucleosynthesis. The bare nucleus cross section, measured via the THM in (Lattuada et al. 2001), has been applied to the BBN in order to investigate the sensitivity of the calculated lithium abundance with respect to the variation of the adopted cross section. As a simple approach we have used the program described in (Fiorentini et al. 1998) and in (Lisi et al. 1999). In this calculation we assumed a number of neutrino species $N_\nu=3$.

In figure 5 the predicted lithium abundance, by number, after BBN is reported as a function of

$$x = \log \eta + 10$$

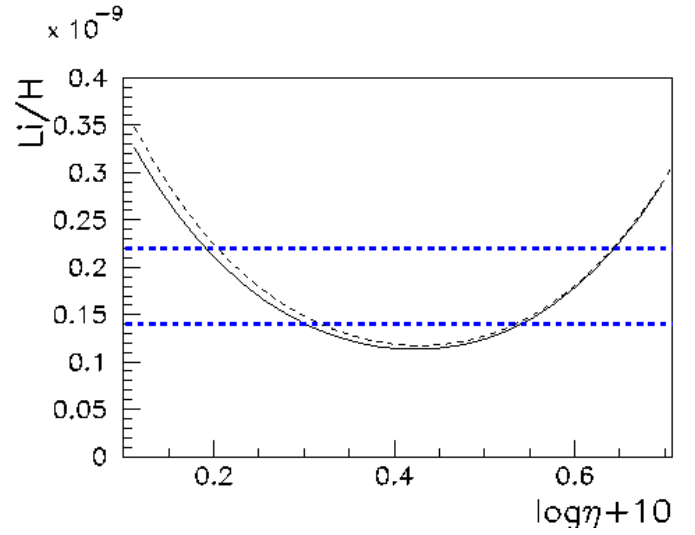


Fig. 5. Theoretical prediction of the Li abundance vs. the baryon to photon ratio, η . Solid line represents the model with ${}^7\text{Li}(p,\alpha){}^4\text{He}$ reaction rate adopted in (Smith et al. 1993) while dashed line the rate obtained from (Lattuada et al. 2001). Thick dashed lines represents the observed “primordial abundance” according to (Vangioni-Flam et al. 2000).

for two different choices of ${}^7\text{Li}(p,\alpha){}^4\text{He}$ cross section. The solid line represents the calculation with the rate reported in (Smith et al. 1993) while the dashed one adopts the cross section measured in (Lattuada et al. 2001). At very low η the discrepancy between the two models is around 5 %, and progressively reduces for higher η , as expected.

The comparison with observed primordial lithium abundance (for this value we adopted the same of (Vangioni-Flam et al. 2000)) gives the following constraints on η (for the THM value of the ${}^7\text{Li}(p,\alpha){}^4\text{He}$ cross section):

$$1.7 < \eta_{10} < 2.7 \quad (2)$$

$$3.4 < \eta_{10} < 4.5 \quad (3)$$

with $\eta_{10} = \eta \times 10^{-10}$ and considering only the mean value of the calculated abundance. This is substantially in agreement with recent and more accurate calculation (Vangioni-Flam et al. 2000).

These constraints on the η parameter can be expressed in terms of the baryonic adimensional density according to the relation:

$$\Omega_B = \frac{\rho_B}{\rho_c} = 0.00366 \cdot \eta_{10} \cdot h^{-2} \quad (4)$$

where ρ_B is the baryonic density, ρ_c is the critical density, $h = H_0/100$ with H_0 the Hubble parameter. our constraints on η the following limits on the baryon density are obtained

$$0.015 < \Omega_B < 0.019 \quad (5)$$

$$0.029 < \Omega_B < 0.039 \quad (6)$$

assuming $h=0.65$.

These results are in fair agreement with the values reported on (Vangioni-Flam et al. 2000).

4. Conclusions

The application of the recent determination of the ${}^7\text{Li}(p, \alpha){}^4\text{He}$ bare nucleus cross section, via the Trojan Horse Method has produced results, in the field of Solar lithium problem and primordial nucleosynthesis, which agree within 5% with the ones based on present compilations of nuclear reaction rates. Our aim is to study via the same method other reactions of great astrophysical interest, such as the ${}^6\text{Li}(p, \alpha){}^3\text{He}$, whose analysis is in progress.

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The Trojan-horse Method applied to the ${}^6\text{Li}(p,\alpha){}^3\text{He}$ Reaction

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Abstract

The ${}^6\text{Li}(p,\alpha){}^3\text{He}$ reaction has been studied in the energy range from 2.5 MeV down to astrophysical energies by means of the Trojan-Horse Method applied to the three-body $d({}^6\text{Li},\alpha){}^3\text{He}n$ reaction. Coincidence spectra measured in a kinematically complete experiment show the presence of the quasi-free ${}^6\text{Li}-p$ process. The excitation function of the quasi-free cross section for small neutron momenta (≤ 30 MeV/c) was compared with that extracted using the free reaction cross section, after correcting the quasi-free data for the s and p wave penetration functions.

1 INTRODUCTION

In recent years the Trojan-horse Method (THM) has been successfully applied to study several astrophysically relevant two-body reactions by using appropriate three-body break-up reactions [1-4]. The method has proved to be particularly suitable for acquiring information on charged-particle induced cross-sections at astrophysical energies, since it allows to overcome the Coulomb-barrier of the two-body entrance channel. Briefly describing the method, a projectile a strikes a target nucleus A , whose wave function has a large amplitude for a s - b cluster configuration. Under appropriate kinematical conditions, the particle a interacts only with the part b of the target nucleus A , while the other part s behaves as a spectator to the process $a+b(+s) \rightarrow c+d(+s)$. In order to completely determine the kinematic properties of the spectator s , the other two particles have to be detected and identified and their energies and angles measured. Since the bombarding energy is chosen to be above the Coulomb barrier in the incident channel for the $a+A \rightarrow c+d+s$, the particle b can be brought into the nuclear interaction region to induce the $a+b \rightarrow c+d$ reaction. Moreover, if the beam energy is settled on to be compensated for the $b+s$ binding energy and for the Fermi motion of b inside A , the two-body reaction can take place at very low a - b relative energy, e.g. in the region of

astrophysical relevance. The deduced reaction cross-section $\sigma^N(E)$ represents the nuclear part alone, the Coulomb barrier being already overcome in the entrance channel. In order to compare the two sets of data it is necessary to correct the $\sigma^N(E)$ for the penetration function through the Coulomb barrier. Thus its energy dependence should be identical to that derived by the direct measurements, except at low energies where their behaviour should differ due to the effects of the electron screening on the direct cross-section. The absolute scale for the cross section is obtained by normalization to the direct data at energies where the effects of the electron screening on the direct data are still negligible. These considerations are of course valid for the corresponding S -factors. Then, going at low energy, the THM allows to obtain an estimate of the screening potential U_e , by comparing the behaviour of the bare nucleus S -factor, with the direct “screened” one.

2 THE EXPERIMENT

Within an experimental program aimed to study relevant reactions destroying Li isotopes in stellar environments, we have performed the study of the ${}^6\text{Li}+p \rightarrow \alpha+{}^3\text{He}$ reaction applying the THM to the three-body ${}^6\text{Li}+d \rightarrow \alpha+{}^3\text{He}+n$ break-up reaction. The $d({}^6\text{Li},\alpha){}^3\text{He}n$ experiment

was carried out with the SMP Tandem van de Graaff accelerator at the Laboratori Nazionali del Sud in Catania. A $200 \mu\text{g}/\text{cm}^2$ CD_2 target was bombarded with a 25 MeV ^6Li beam, with a spot size on target of about 1 mm diameter. The experimental set-up consisted of two ΔE -E telescopes with 20μ silicon detectors as ΔE - and 1000μ Position Sensitive Detectors (PSD) as E-detector. The two telescopes, called T1 and T2 in the following, were placed on opposite sides of the beam direction covering the laboratory angles 14.5° to 24° and 28.3° to 37.7° respectively, with equal solid angles of 12.5 msr. These ranges have been chosen in order to fulfil the quasi-free break-up condition $p_n = 0$ MeV/c, once α and ^3He are detected and identified in T1 and T2 respectively. The trigger for the event acquisition was given by the coincidence between the two fired telescopes. Energy and position signals for the detected particles were processed by standard electronics together with the delay between the time signals for each coincident event, and sent to the acquisition system for the on-line monitoring of the experiment and the data storage on magnetic tape for the off-line analysis.

3 DATA ANALYSIS

The energy and position calibration of ΔE -detectors and PSDs was performed using data acquired in preliminary runs of the $^{12}\text{C}(^6\text{Li},\alpha)^{14}\text{N}$ reaction at several beam energies. In order to fully identify the channel of interest, and to focus on the kinematic conditions where the quasi-free process should be dominant, α and ^3He loci have been selected in the ΔE -E matrices of the T1 and T2 telescopes respectively.

The kinematics were reconstructed under the assumption of a neutron as third particle, leading to the Q-value spectrum reported in fig.1. The spectrum shows a sharp peak centred just below 2 MeV which corresponds to the channel of interest $^3\text{He}+\alpha+n$, whose calculated Q-value is 1.79 MeV. The corresponding locus of the events in the $E_{^3\text{He}}$ vs E_α plane is reported in fig.2.

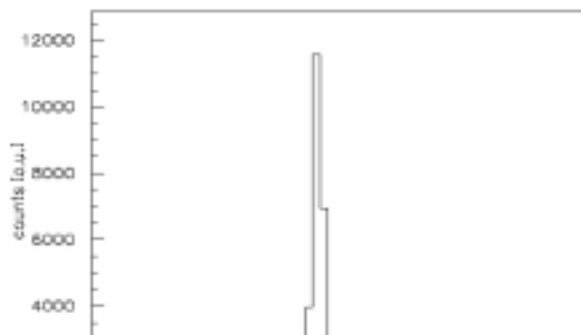
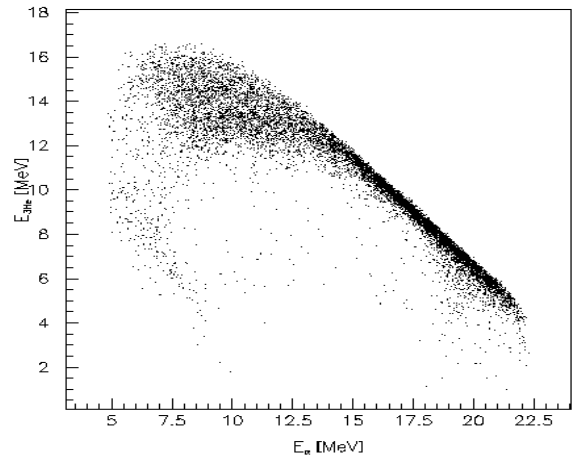


Figure 1: Q-value spectrum deduced from α - ^3He coincidences. Kinematics has been reconstructed under the assumption of mass 1 for the undetected particle.



In order to check the presence of the quasi-free contribution, coincidence spectra have been projected on the $E_{^3\text{He}}$ (E_α) axis for a fixed angle of one of the two particles, $\theta_{^3\text{He}}$ (θ_α) and for different angles of the other detector. Once selected the quasi-free coincidence yields, the experimental momentum distribution for the neutron was obtained and compared with the theoretical one given in terms of the Hulthen function [1] (fig.3) within the region of low momenta. A fair agreement shows-up, supporting (proving) the dominance of the quasi-free mechanism in this region approaching zero neutron momentum.

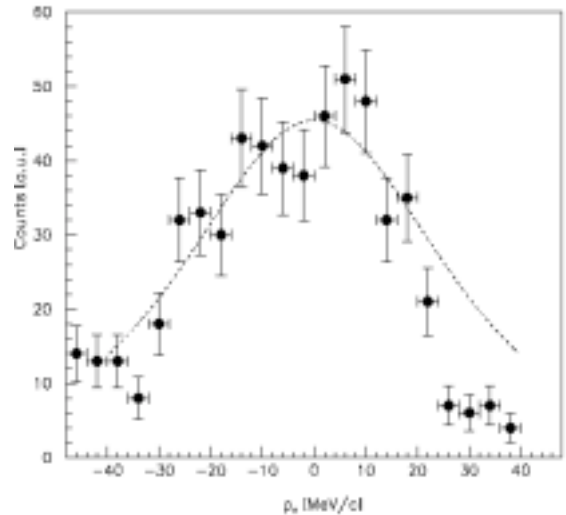


Figure 3: Experimental momentum distribution for the spectator neutron (full circles), compared with the corresponding theoretical behaviour (dashed line).

The coincidence yield is reported in fig.4 (full circles) as a function of the p - ${}^6\text{Li}$ relative energy for neutron momentum ranging from -30 to 30 MeV/c. A wide energy range is populated going from 2.5 MeV down to the lowest point at 40 keV. A fit to the experimental behavior was made applying the DWBA approach developed in ref. [5]. A cut-off radius of 3.5 fm was assumed. The calculation fully accounts for the Coulomb effects and allows to obtain a definite relation between on-shell and off-shell two-body cross-sections. In the present case, the calculated three-body cross section contains the contribution of two partial waves, $l=0$ due to the non resonant part of the two-body cross-section, and $l=1$ which accounts for the presence of a $5/2^-$ resonance associated with the 7.2 MeV state of ${}^7\text{Be}$ in the two-body channel [6]. Fig.4 shows both the separate $l=0$ and $l=1$ contribution (dotted and dashed lines respectively) and their incoherent sum (full line). The fit reproduces quite well the experimental behavior. Next step will be to improve the calculation introducing the interference between the two $l=0$ and $l=1$

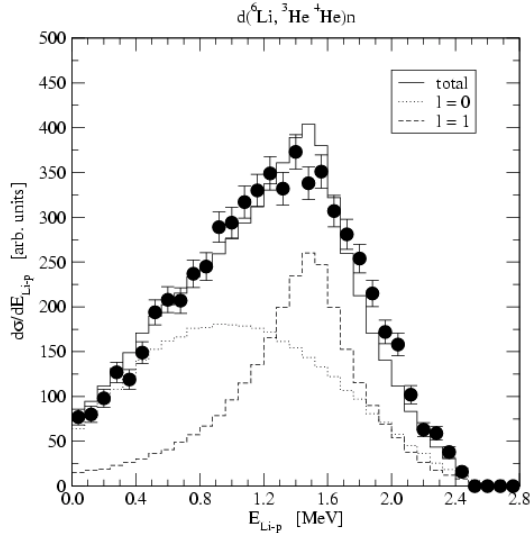


Figure 4: Coincidence yield projected on the p - ${}^6\text{Li}$ relative energy axis (full circles). Superimposed to the data is the calculated three-body cross section (full line), as explained in the text. Dashed and dotted lines represent the separate calculated contributions of the $l=0$ and $l=1$ angular distributions respectively.

angular distributions. Once the fit is optimized, we can proceed to extract from the indirect data the on-shell two-body cross section. This quantity is obtained simply dividing the experimental data of fig.4 by the result of the calculation performed assuming a constant two-body cross-section. Then, from the comparison between the two astrophysical S-factors at low energy, it should be possible to deduce an estimate of the screening potential.

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2 THE EXPERIMENT

Within an experimental program aimed to study relevant reactions destroying Li isotopes in stellar environments, we have performed the study of the ${}^6\text{Li}+p \rightarrow \alpha+{}^3\text{He}$ reaction applying the THM to the three-body ${}^6\text{Li}+d \rightarrow \alpha+{}^3\text{He}+n$ break-up reaction. The $d({}^6\text{Li},\alpha){}^3\text{He}n$ experiment

was carried out with the SMP Tandem van de Graaff accelerator at the Laboratori Nazionali del Sud in Catania. A $200 \mu\text{g}/\text{cm}^2$ CD_2 target was bombarded with a 25 MeV ^6Li beam, with a spot size on target of about 1 mm diameter. The experimental set-up consisted of two ΔE -E telescopes with 20μ silicon detectors as ΔE - and 1000μ Position Sensitive Detectors (PSD) as E-detector. The two telescopes, called T1 and T2 in the following, were placed on opposite sides of the beam direction covering the laboratory angles 14.5° to 24° and 28.3° to 37.7° respectively, with equal solid angles of 12.5 msr. These ranges have been chosen in order to fulfil the quasi-free break-up condition $p_n = 0$ MeV/c, once α and ^3He are detected and identified in T1 and T2 respectively. The trigger for the event acquisition was given by the coincidence between the two fired telescopes. Energy and position signals for the detected particles were processed by standard electronics together with the delay between the time signals for each coincident event, and sent to the acquisition system for the on-line monitoring of the experiment and the data storage on magnetic tape for the off-line analysis.

3 DATA ANALYSIS

The energy and position calibration of ΔE -detectors and PSDs was performed using data acquired in preliminary runs of the $^{12}\text{C}(^6\text{Li},\alpha)^{14}\text{N}$ reaction at several beam energies. In order to fully identify the channel of interest, and to focus on the kinematic conditions where the quasi-free process should be dominant, α and ^3He loci have been selected in the ΔE -E matrices of the T1 and T2 telescopes respectively.

The kinematics were reconstructed under the assumption of a neutron as third particle, leading to the Q-value spectrum reported in fig.1. The spectrum shows a sharp peak centred just below 2 MeV which corresponds to the channel of interest $^3\text{He}+\alpha+n$, whose calculated Q-value is 1.79 MeV. The corresponding locus of the events in the $E_{^3\text{He}}$ vs E_α plane is reported in fig.2.

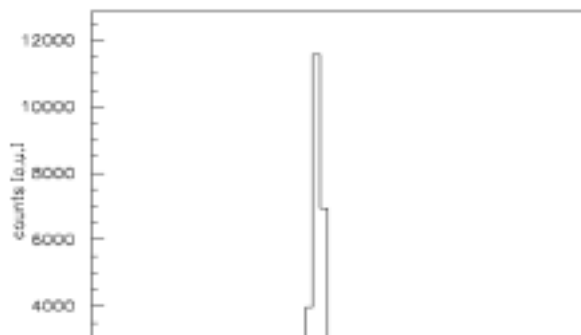
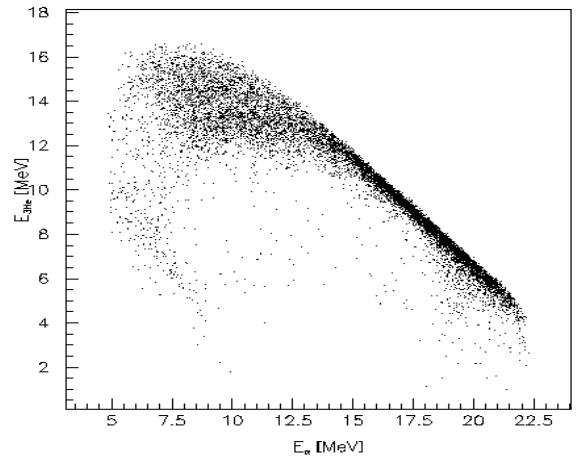


Figure 1: Q-value spectrum deduced from α - ^3He coincidences. Kinematics has been reconstructed under the assumption of mass 1 for the undetected particle.



In order to check the presence of the quasi-free contribution, coincidence spectra have been projected on the $E_{^3\text{He}}(E_\alpha)$ axis for a fixed angle of one of the two particles, $\theta_{^3\text{He}}(\theta_\alpha)$ and for different angles of the other detector. Once selected the quasi-free coincidence yields, the experimental momentum distribution for the neutron was obtained and compared with the theoretical one given in terms of the Hulthen function [1] (fig.3) within the region of low momenta. A fair agreement shows-up, supporting (proving) the dominance of the quasi-free mechanism in this region approaching zero neutron momentum.

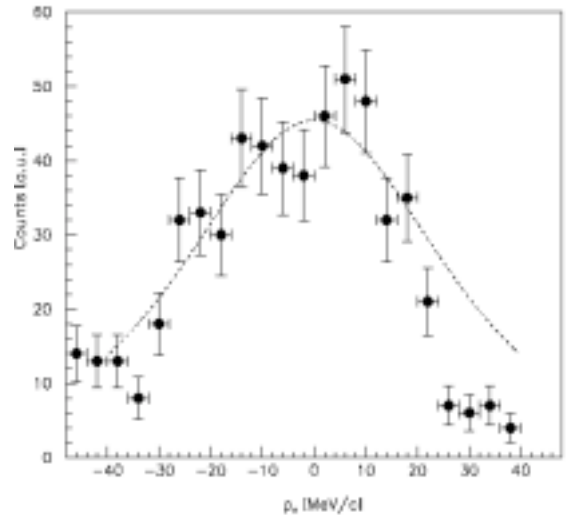


Figure 3: Experimental momentum distribution for the spectator neutron (full circles), compared with the corresponding theoretical behaviour (dashed line).

The coincidence yield is reported in fig.4 (full circles) as a function of the $p\text{-}^6\text{Li}$ relative energy for neutron momentum ranging from -30 to 30 MeV/c. A wide energy range is populated going from 2.5 MeV down to the lowest point at 40 keV. A fit to the experimental behavior was made applying the DWBA approach developed in ref. [5]. A cut-off radius of 3.5 fm was assumed. The calculation fully accounts for the Coulomb effects and allows to obtain a definite relation between on-shell and off-shell two-body cross-sections. In the present case, the calculated three-body cross section contains the contribution of two partial waves, $l=0$ due to the non resonant part of the two-body cross-section, and $l=1$ which accounts for the presence of a $5/2^-$ resonance associated with the 7.2 MeV state of ^7Be in the two-body channel [6]. Fig.4 shows both the separate $l=0$ and $l=1$ contribution (dotted and dashed lines respectively) and their incoherent sum (full line). The fit reproduces quite well the experimental behavior. Next step will be to improve the calculation introducing the interference between the two $l=0$ and $l=1$

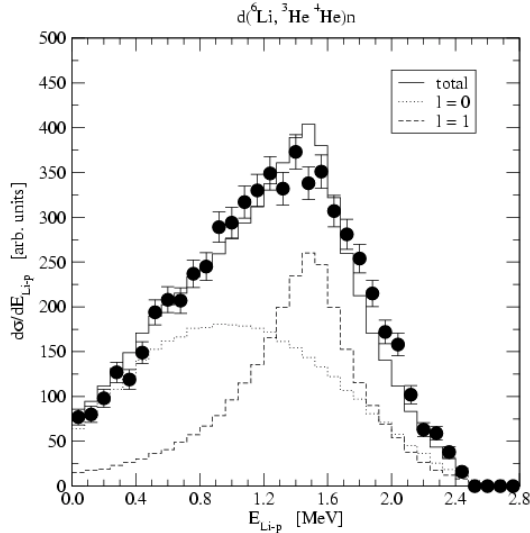


Figure 4: Coincidence yield projected on the $p\text{-}^6\text{Li}$ relative energy axis (full circles). Superimposed to the data is the calculated three-body cross section (full line), as explained in the text. Dashed and dotted lines represent the separate calculated contributions of the $l=0$ and $l=1$ angular distributions respectively.

angular distributions. Once the fit is optimized, we can proceed to extract from the indirect data the on-shell two-body cross section. This quantity is obtained simply dividing the experimental data of fig.4 by the result of the calculation performed assuming a constant two-body cross-section. Then, from the comparison between the two astrophysical S-factors at low energy, it should be possible to deduce an estimate of the screening potential.

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Proton-proton quasi-free scattering at low energies

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The ${}^2\text{H}(p, pp)n$ reaction has been recently investigated at Laboratori Nazionali del Sud, INFN, Catania at a proton beam energy of 6 MeV. Proton-proton coincidences from two position sensitive detectors (PSD), centered at symmetrical angles (20°) with respect to the beam direction, have been acquired. The experimental data have been compared with a Plane Wave Impulse Approximation calculation. In the framework of the Trojan Horse Method, new hints on the proton-proton interaction within a three-body reaction can be drawn.

I. INTRODUCTION

The $p + d \rightarrow p + p + n$ reaction has been widely studied both experimentally [1, 2] and theoretically [3, 4]. One of the reasons is that a deuteron can be used as a neutron (proton) target due to its small binding energy. It also represents, together with the $n + d \rightarrow n + n + p$, the simplest three-body reaction that can be studied.

The quasi-free scattering is one of the possible breakup mechanisms. The three-body cross section, in Plane Wave Impulse Approximation, is expressed as a product of the phase space, the momentum distribution of the spectator inside the deuteron and the two body cross section:

$$\frac{d^3\sigma}{d\omega_1 d\omega_2 dE_1} = \frac{4(2)^{1/2}}{\pi^2} \frac{1}{E_o^{1/2}} \cdot \frac{E_2 E_1^{1/2}}{2E_2^{1/2} - E_o^{1/2} \cos\theta_2 + E_1 \cos(\theta_1 - \theta_2)} \cdot \frac{E_\alpha^{1/2} E_\beta^{1/2} (E_\alpha^{1/2} + E_\beta^{1/2})^3}{(E_\alpha + 2E_3)^2 (E_\beta + 2E_3)^2} \cdot \left. \frac{d\sigma}{d\omega}(\theta_{12}, E_{12}) \right|_{free}^{cm} \quad (1)$$

where E_o is the proton bombarding energy; E_1, E_2, θ_1 and θ_2 are the energies and the angles of the detected protons; $E_\alpha = 2.225$ MeV and $E_\beta = 59.8$ MeV are the Hulthén function parameters; θ_{12}, E_{12} are the angle and the energy in the c.m. system of the two detected protons in the exit channel. The p-p cross section trend is very similar to the p-n or n-n ($\approx 1/v$) except at low proton energies (≈ 382.43 keV) where it shows a deep minimum due to the interference between the nuclear and the Coulomb part of the interaction[5].

The Trojan Horse Method, THM, originally introduced by [6], is based on the quasi-free mechanism and has been applied to study some astrophysically relevant reactions [7–12]. A formulation of the THM in the framework of direct reaction theory is given in reference [13]. This indirect method allows to overcome the problem of low cross

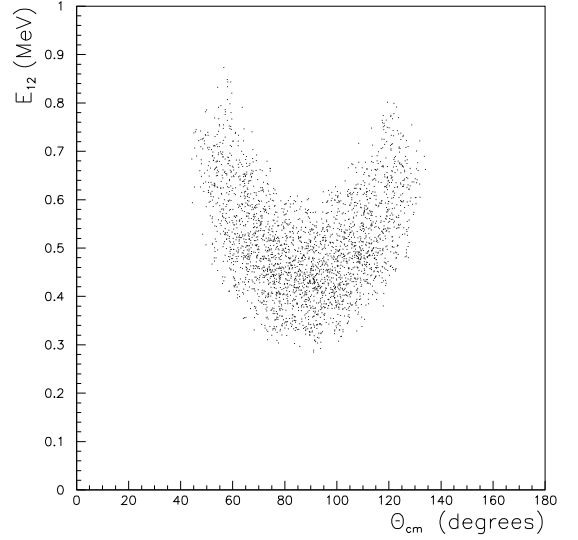


FIG. 1: Proton-proton relative energy E_{12} as a function of the center-of-mass angle θ_{cm} . The matrix is symmetric with respect to 90° because of the symmetric detection angles.

section at energies under the Coulomb barrier. In this context the two-body reaction cross section is related to an appropriate three-body one. If the bombarding energy is chosen higher than the Coulomb barrier in the entrance channel of the three-body reaction, the two-body interaction can take place inside the nuclear field (see [8] for details). It is important to underline that the extracted two-body cross section is the nuclear part, the Coulomb barrier being already overcome in the entrance channel [8]. In this framework, one can assume that the extracted two body cross section is Coulomb suppression free.

The $p + d \rightarrow p + p + n$ reaction represents the simplest case where one can observe the extracted two-body

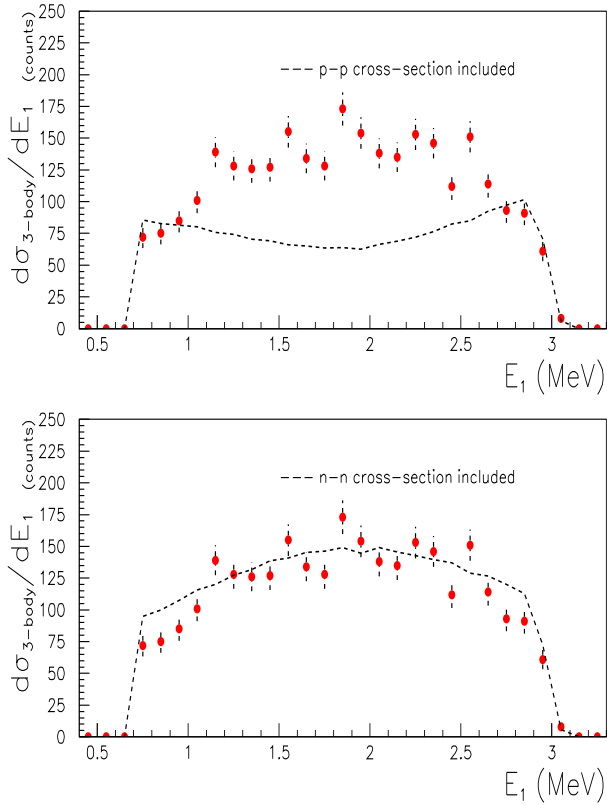


FIG. 2: Experimental spectra (dots) and Monte Carlo simulation (dashed line) as a function of one of the two detected proton energies E_1 . The p-p cross section (upper picture) or the n-n one (lower picture) have been respectively included in the simulation.

cross section energy trend. In order to investigate this behaviour, a new experiment has been performed to study the $^2H(p,pp)n$ reaction at proton-proton relative energies in the region of the deep minimum.

II. EXPERIMENTAL SET-UP

A kinematically complete experiment has been carried out at the Laboratori Nazionali del Sud, INFN, Catania. The 15 MV Tandem Van de Graff provided a 6 MeV proton beam. The current was about $1 \div 2$ nA and the target consisted of a deuterated polyethilen film, $178 \mu\text{g}/\text{cm}^2$ thick. Proton-proton coincidence have been detected by a couple of Position Sensitive Detectors, PSD, placed at about symmetrical angles with respect to the beam direction: $16.2^\circ < \theta_{p1} < 24^\circ$ and $15.6^\circ < \theta_{p2} < 23.4^\circ$. The energy threshold for the two protons has been 0.7 MeV while the energy and angular resolution of the PSD's have been 100 keV and 0.1° respectively. A cut in the TAC spectra has been done together with a selection of the p-

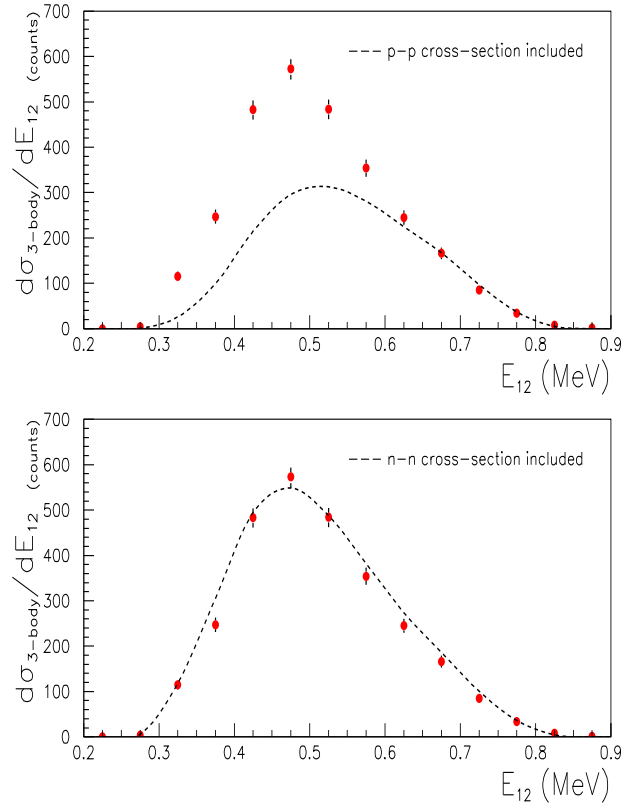


FIG. 3: Experimental spectra (dots) and Monte Carlo simulation (dashed line) as a function of the proton-proton relative energy E_{12} . The p-p cross section (upper picture) or the n-n one (lower picture) have been respectively included in the simulation.

p kinematical locus. The proton-proton relative energy versus the proton-proton center-of-mass angle is shown in Fig.1. The investigated relative energy range is $0.3 \div 0.8$ MeV.

III. THE SPECTATOR MODEL

The experimental spectra have been compared with a Monte Carlo simulation performed by using the Plane Wave Impulse Approximation (see Eq. 1). The phase space has been modulated by the neutron momentum distribution inside the deuteron (Hulthén function) and the obtained results weighted by the proton-proton cross section.

A standard expression [14] for the proton-proton cross section has been used. The $l=0$ phase shift is calculated in the Jackson and Blatt formalism [15] by using the Foldy et al. parameters [16]: $-R/a = 3.704$ and $r_o = 2.7610 \cdot 10^{-13} \text{cm}$ where a is the scattering length, r_o is the effective range and R is equal to $\frac{\hbar^2}{me^2}$.

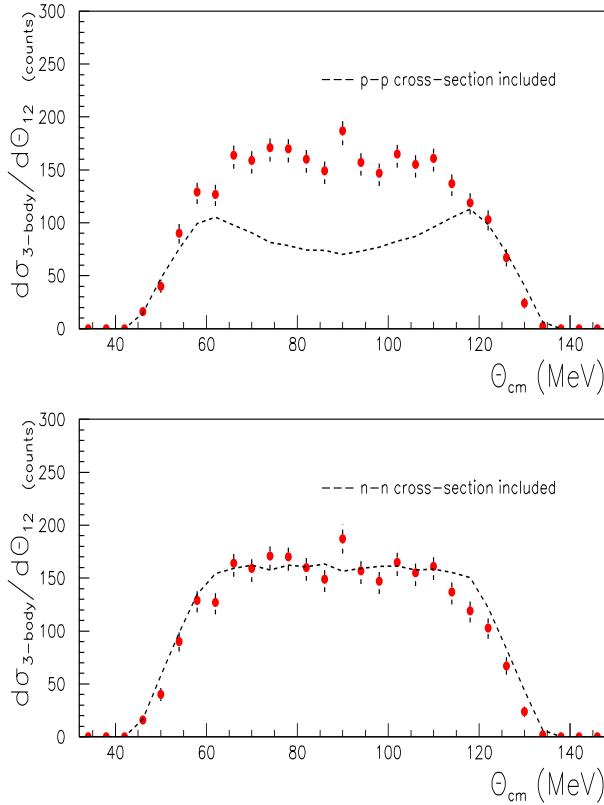


FIG. 4: Experimental spectra (dots) and Monte Carlo simulation (dashed line) as a function of the proton-proton center-of-mass angle θ_{12} . The p-p cross section (upper picture) or the n-n one (lower picture) have been respectively included in the simulation.

Data compared with the calculation are shown as a function of the detected proton energy in Fig. 2 (upper picture). The calculation does not fit the data well. This is in contradiction with the comparison between data and calculation from [2]. If we compare our kinematical conditions to those in ref. [2] we cover different angular ranges. They detect the two protons at two symmetrical angles (30°) while we are covering about ten degrees at around 20° . This allows us to investigate a range of very low relative energy but forces us to use a part of the proton-proton cross section that is sensitive to the Coulomb interaction. The fact that our calculation does not fit data could imply that by using the three-body we are going to suppress the Coulomb part of the interaction.

Under the assumption that the Coulomb part is suppressed, another calculation has been done replacing the proton-proton cross section with the neutron-neutron one (see Fig. 2, lower picture). Now only the nuclear part of the interaction is taken into account in the calculation and the agreement is fairly good. A comparison of the two calculated cross sections with the data is done also as

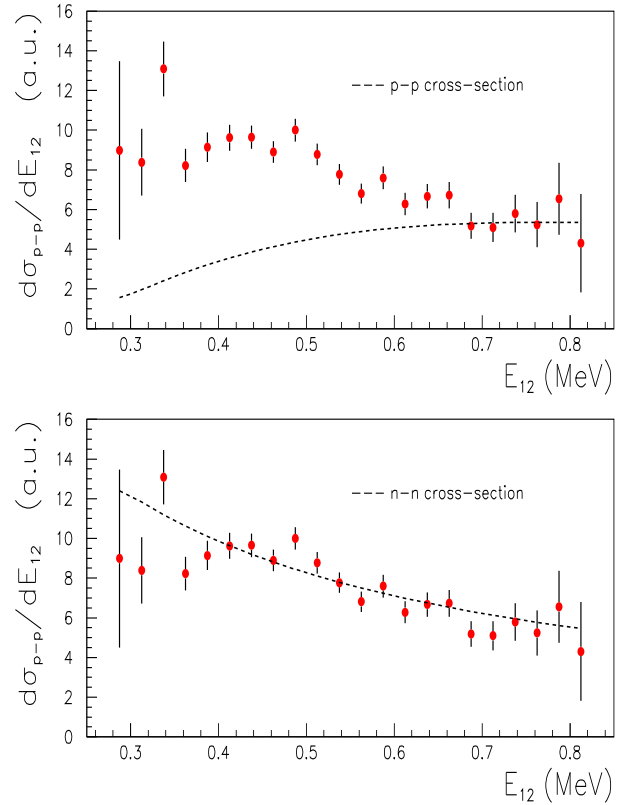


FIG. 5: Extracted two body cross section (dots) compared with the p-p cross section (dashed line, upper picture) and with the n-n cross section (dashed line, lower picture). The p-p and the n-n cross section are expressed as a function of the relative energy. For each energy, the contribution of the different c.m. angle is summed up (see Fig. 1).

a function of the proton-proton relative energy and the center-of-mass angle (see Fig.3 and Fig.4). The calculated cross section is normalized to experimental counts under the hypothesis that at higher energies the calculation with the p-p parametrization must fit the data well.

IV. THE EXTRACTED TWO BODY CROSS SECTION

Since we have used eq.1 to express the three-body cross section, it is possible to extract the two-body cross section simply dividing the measured three-body by the phase space and the momentum distribution of the neutron inside the deuteron. The obtained cross section is shown as a function of the proton-proton relative energy. For each energy the contribution of different c.m. angle is summed up (see Fig.1). In these two different plots, the same experimental data are compared with the p-p cross section and the n-n one in the same phase space.

Again here the agreement between data and n-n cross section is fairly good.

V. CONCLUSIONS

These preliminary results represents an important starting-point. The behaviour of the extracted cross section (Fig.5) shows that the Coulomb interaction is somehow suppressed. A detailed analysis from a microscopic point of view or in the framework of direct reactions is

however necessary.

VI. ACKNOWLEDGEMENTS

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MOLECULAR STATES OF LIGHT NEUTRON RICH NUCLEI

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Abstract

The measurement of $^{18}\text{O} + ^9\text{Be}$ reaction was performed detecting coincidences between Helium isotopes produced in the decay of excited neutron-rich Be and C isotopes, with the aim of studying the predicted rotational bands associated with chain configurations made of sequences of α -particles and valence neutrons.

1 INTRODUCTION

In analogy with the case of the H_2 molecule, where the binding of the two protons is realized by the exchange of the valence electrons, the nucleus ^9Be has been described as a two center molecule where the two alpha particles are bound by a valence neutron [1]. It supplies the needed binding energy to the 2α system which is otherwise unstable due to the properties of the alpha-alpha potential. So the ^9Be ground state has been seen as a α -n- α structure and a rotational band of states with the same structure has been built on it.

The description has been recently extended to heavier Beryllium isotopes [1]. The spectroscopy of ^9Be is rather well known and comparison of the calculated bands with states observed in transfer reactions has fairly confirmed the predictions. Our recent experimental results on the $^6\text{Li}(^6\text{He}, ^{10}\text{Be})^2\text{H}$ reaction indicate that some states of ^{10}Be at high excitation energy have this structure. Theoretical calculations using the antisymmetrized molecular dynamics [5] as well as the molecular orbit model [6] support these findings.

In the case of ^{12}Be the two center description leads to metastable states for large deformation (large distance between the two centers).

Chain states made of α -2n-2n- α may then be expected starting from the excitation energies

close to the threshold for decay into the ^4He - ^8He or ^6He - ^6He channels $E_{\text{th}} = 8.95$ and 10.11 MeV respectively.

By using alpha particles and valence neutrons as building blocks, also neutron-rich Carbon isotopes have been described in terms of nuclear polymers. Starting from the 0_2^+ state of ^{12}C whose description in terms of three loosely bound alpha particles is widely accepted, and adding valence neutrons, chain states made of sequences of alpha's and neutrons have been constructed for ^{14}C and ^{16}C . Decay of these metastable states into shorter chains like $^{10}\text{Be}^*$ and $^{12}\text{Be}^*$ in the states having similar structural characteristics, or into lightest constituents like ^4He and ^6He has been predicted [2].

Earlier experiments [2] on ^{12}Be spectroscopy indicated possible existence of states whose structure was supposed to be of molecular type, even if the lack of information on the spins prevented any definite conclusion on their nature. A recent experiment [3] reports on observation of $4^+ 6^+ 8^+$ states of ^{12}Be presumably belonging to the same molecular band, obtained by fragmentation of a ^{12}Be beam on Carbon and Hydrogen targets at GANIL.

The lowest spin states of such band fall under the excitation energy threshold of the experiment and the bandhead position inferred by the measured $E^* \text{ vs } J$ trend is higher than the predicted one by a factor two.

In principle radioactive beams should be the natural choice for the study of such neutron-rich systems. A serious drawback of such choice could be the low intensity of radioactive beams, which may represent a serious obstacle to the measurement of angular correlations needed for the spin assignment. Thus the ^{12}Be molecular states were studied by the interaction of a stable ^{18}O beam with a ^9Be target.

With the same entrance channel we can also reach other final states still involving neutron-rich isotopes of light nuclei. For example we expect indications of formation of $^{14}\text{C}^*$ and $^{16}\text{C}^*$ in the same reaction. Two different polymeric configurations are expected in $^{14}\text{C}^*$ the so called Y -configuration (α -2n- α - α) and X -configuration (α -n- α -n- α) for which different sequences of states are predicted, due to the different role of valence neutrons.

The bandhead of the ^{16}C states associated with polymeric shapes is instead predicted well below the thresholds for decay into channels with the same structure and thus should have small widths for particle decay.

2 THE EXPERIMENT

The experiment was performed by bombarding a ^9Be target with a beam of ^{18}O at the energy of 15 A*MeV. The beam energy was chosen in such a way that the energy thresholds due to the first ΔE stage of the detectors do not affect relevantly the detection efficiency.

The particles emitted by the deexcitation of ^{12}Be were detected in coincidence and identified by 96 triple telescopes from the detection system HODO-CT. Each telescope consists of two Silicon ΔE stages (50 μm and 300 μm) backed by one 6 cm-thick CsI detector.

They were assembled in a symmetric configuration in order to cover the in-plane range of 6° to 48° on both sides of the beam direction. With such geometry ^6He - ^6He pairs with relative energy up to 35 MeV can be detected. Almost the same relative energy range is covered by detection of ^4He - ^8He pairs.

Data analysis is in the stage of calibrations. Single spectra of 46 MeV ^7Li beam on ^9Be and ^{197}Au targets had been measured in preliminary runs of the experiment and are now used for energy calibration of detectors.

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EXPLORING THE STRUCTURE OF ^{15}C BY MANY BODY APPROACH

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Abstract

The results of Dynamical Core Polarization (DCP) calculations of the $s_{1/2}$ and $d_{5/2}$ response functions of ^{15}C nucleus are presented and discussed.

1 INTRODUCTION

Among the challenges of modern nuclear physics that of the description of the structure of nuclei far from the line of β -stability is very enchanting. For light neutron-rich nuclei, the unusual combination of high charge asymmetry, weak binding energy and proximity of the particle continuum may lead to the less effective confinement of the outermost neutrons. An example is given by *halo* nuclei [1]. In particular, one-neutron halo nuclei are the main candidates suited to study the interaction between the weak bound nucleon and the core nucleus. Experimental evidences [2,3] and theoretical studies [4,5] show as Dynamical Core Polarization (DCP) effects, well established in stable even-odd nuclei [6], become particularly important approaching the drip lines because the even-mass core itself can be already far from stability.

The ^{15}C nucleus represents, as weakly bound system ($S_n=1.218$ MeV), an interesting intermediate case between the well-bound $^{12,13,14}\text{C}$ nuclei and the exotic ^{19}C . The longitudinal momentum distribution of the ^{14}C fragments measured in one-neutron removal reactions is much narrower than that of ^{17}C [7], indicating strong spatial delocalization of the valence neutron. The removal of an s-wave neutron leads to production of the core fragments in 0^+ ground state, while the removal of a p-wave neutron leads to production of core fragments in 1^- and 0^- excited states [8]. Moreover, the one-neutron removal cross section σ_{-1n} measured at intermediate energies for ^{15}C exhibits an enhanced value in comparison to that of closer isotopes [9]. On the other hand, it is not properly

recognized as a halo nucleus because its matter radius does not show a considerable deviation from systematic increase with mass number [10].

The ground state spin-parity of ^{15}C is $J^\pi=1/2^+$ [11]. Shell model calculations using WBP interaction reproduce the inversion between $0d_{5/2}$ and $1s_{1/2}$ orbitals [12]. Relativistic Mean Field (RMF) calculations on carbon isotope chain predict an increasing deformation with a maximum for ^{18}C [13]. In Ref. [14] the quadrupole polarizability predicted for carbon isotopes has a maximum around $^{16,18}\text{C}$. Instead the dipole polarizability changes less, the 10% only over the $^{10-22}\text{C}$ isotopic chain.

When a configuration with three neutrons coupled to an hard core of 3α particle is taken into account for ^{15}C isotope, at low excitation energy an important part of the phase space is represented by the coupling of two neutrons with the hard core and the consequent formation of ^{14}C core plus one unpaired neutron. Under these conditions the high polarizability of the soft core together with the low binding of the external neutron make possible the independent excitation of the core and single neutron degrees of freedom. Phenomenologically, one observes in the energy spectrum bound states embedded in the continuum (BSEC) connected with DCP well beyond the neutron emission threshold, resulting for the pure excitation of the core states [15]. Similar effects have been noticed in the ^{11}Be [3] and are under study for the ^7He , both presenting a structure with 3 neutron coupled with an integer number of α particle.

Here, a microscopic nuclear structure model has been employed for including DCP effects in

^{15}C nuclear system, using a QRPA approach for the ^{14}C core.

2 DCP MODEL

Single particle configurations with respect to a vibrating core nucleus were investigated first by Bohr and Mottelson in a quasiparticle-core coupling (QPC) model [16], where core excitations are described through the collective model. In the microscopic version of the QPC-model [17, 18, 19, 20] the core excited part of the odd-mass system wave function is described by one-quasiparticle (1qp) states coupled to vibrational one-particle-one-hole (i.e. two-quasiparticle (2qp)) excitations of the even-mass core nucleus. Theoretically, these effects are taken into account by first describing core polarizations microscopically for single particle and hole configurations relative to a mean-field ground state. As a consequence of such many body effects the single particle strength is distributed over many eigenstates of the odd-mass nucleus. The basic idea of such approaches is to approximate the single particle component by the corresponding unperturbed shell model wave function. This means equally to approximate the mass operator by its diagonal parts only.

Since our interest is to describe ^{15}C strength distribution in a large excitation energy range, it is fundamental to take into account also the non diagonal-parts of the self-energy. An original method [20] to do that is by expanding the single particle component into a set of unperturbed wave function of fixed orbital and total angular momentum (l, j) but different radial quantum number n . The formalism used is the QRPA one. The ground state of the even-even nucleus is supposed to be known and becomes the vacuum state $|0\rangle$ for the quasiparticles operators ($\alpha^\dagger, \alpha$) [21], and its excitations are considered as QRPA-phonons.

In order to account for core excitations effects, the wave functions of the odd-mass system become the superposition of two contributions related to 1qp and 3qp excitations, respectively, as

with total spin j and $\lambda = (E_j, \pi)$, excitation energy E_j and parity π .

The first term of the (1) is the superimposition of wave functions which differ only in radial quantum number n ('major shell mixing'). The second term corresponds to the core excited component with a 1qp j' and 2qp core excitations

J_c coupled to total angular momentum j . The 3qp states are due to elementary excitations where the energies are given by the sum of the unperturbed core and single particles ones. The two contributions are schematized in the Fig. 1.

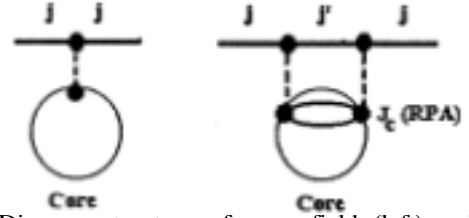


Fig. 1. Diagram structure of mean-field (left) and core polarization interactions (right) of a nucleon in a single particle state j .

The effective hamiltonian of the odd-mass system $H = H_0 + V_{13}$ is separated into a part H_0 which is diagonal in the 1qp states and QRPA states and a residual interaction V_{13} which couples 1qp and 3qp configurations. The main feature is the derivation of an effective Schroedinger equation for the single particle coupled to core-excited configurations, leading to an energy dependent contribution in the single particle self-energy operator. The single particle motion is treated in a complete way by taking into account 'off shell' scattering processes between states from static mean-field. Such extension of the usual QPC approach accounts in a better way for the non-locality of the mass operator in the coordinate space. Moreover, the model allows a consistent description of transfer form factors and strength distributions that is difficult to achieve in other different approaches.

2 DCP RESULTS ON ^{15}C

Single particle energies and wave functions have been calculated in Wood-Saxon potentials with fixed geometry whose depth was fitted to reproduced Hartree-Fock-Bogolyubov energies in ^{14}C . The single particle continuum has been discretized up to 100 MeV excitation energy by enclosing the system in a spherical cavity having radius $R = 40$ fm.

The quasiparticle energies E_{ij} and the

$$|jm, \lambda\rangle = \sum_n z_{nlj}(\lambda) |nlj\rangle + \sum_{j' J_c} z_{j' J_c}(\lambda) |j' J_c j\rangle \quad (1)$$

occupation amplitudes $|v_{nlj}|^2$ have been obtained for ^{14}C from BCS calculation with pairing interaction parameters $G_p = 17.5$ MeV/A and $G_n = 12.5$ MeV/A for proton and neutron,

respectively. Unperturbed 2qp states up to 100 MeV have been used in order to describe the ^{14}C spectrum up to 40 MeV excitation energy. A one-body field, $\delta U_c = \sum_i N_i(c) \delta U_i$ with δU_i

depending on the orbital, spin, isospin and total angular momentum transfer of the 2qp pair but independent of the QRPA eigenstates has been considered.

The strength functions have been calculated for different multipolarities with $J \leq 4^\pm$ [22]. The residual particle-hole interaction has been derived from the M3Y-G matrix interaction [23]. The exchange contributions to the all matrix elements were calculated by an effective density dependent zero-range interaction, which is derived by a local density approximation to the exchange part of the particle-hole scattering amplitude in infinite nuclear matter. The procedure is similar to the DME method of Negele [24]. The strength in the different spin-isospin channels has been adjusted so that Landau-Migdal parameters in nuclear matter are reproduced. The one-quasiparticle component has been expanded into contributions from major shells covering an energy range of about 18 MeV. In the core-excited components of Eq. (1), QRPA excitations with $E_x \leq 25\text{MeV}$ are included, covering completely the three-quasiparticle spectrum. The high-lying core excitations enter *off-the-energy-shell* into the mass operator of low-lying excitations in the odd system. Therefore they do not contribute directly to the fragmentation of low-energy strength but determine the position of the eigenvalues (level ordering and spacing). In such a description the energy reached by the core can be also very high and the quantum number n is not good anymore. In core excitation processes the final states could be very different from the initial ones providing that a sufficiently large amount of linear momentum is transferred.

The results obtained in the 1qp energy scale respect to the ^{14}C are shown in Fig.2 for $s_{1/2}$ and $d_{5/2}$ single particle strength distributions, taking into account the coupling to 1^- and 2^+ core states. The $2s_{1/2}$ is lower in energy than the $1d_{5/2}$. The energy difference between the ground state and the first excited state is around 100 keV. The contribution due to the selected DCP phase space is around 200 keV. The observed energy difference of 740 keV is not exactly obtained. This may be due to the not complete treatment of the core excitation. Calculations with more extended configurations are then necessary to understand this point.

Strong fragmentation of the strength is present in both cases starting from about 7 MeV above the main structures (the first excited states of the ^{14}C is at 6.09).

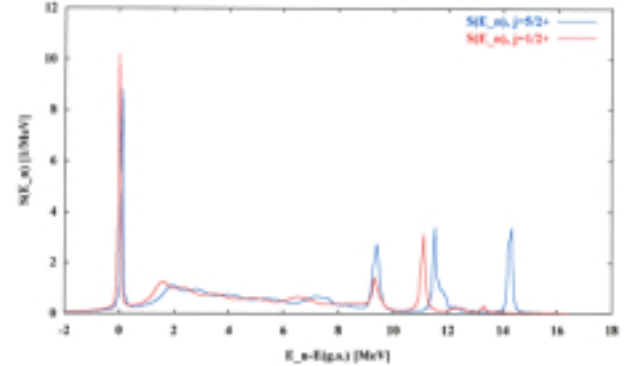


Fig. 2. Response function of ^{15}C for $1/2^+$ (red line) and $5/2^+$ (blue line) strength for 1^- and 2^+ states of the core. The energy scale corresponds to excitation energy of the ^{15}C nucleus.

The comparison with the excitation energy spectra measured via the $^{15}\text{N}(^7\text{Be}, ^7\text{Li})^{15}\text{C}$ charge exchange reaction at 57 MeV [15,25,26] indicates that the observed narrow structure at 8.5 MeV, which cannot be justified within a single particle model [15], can be explained within the here presented DCP framework.

4 CONCLUSIONS

Some results of the DCP calculations obtained for ^{15}C nucleus have been presented. The low energy spectrum is qualitatively well reproduced. The inversion of $s_{1/2}$ and $d_{5/2}$ orbitals for the ground state is obtained. The $s_{1/2}$ and $d_{5/2}$ strength distributions have been calculated up to 16 MeV excitation energy. As main result, strong fragmentation of the strength has been obtained between 9 and 15 MeV excitation energy, both for $s_{1/2}$ and $d_{5/2}$. Narrow resonances well beyond the neutron emission threshold appear when the coupling of the unpaired neutron to the 1^- and 2^+ excited states of the ^{14}C is considered. In particular, the model predicts well the presence of a narrow resonance centered at 8.5 MeV observed experimentally via the $^{15}\text{N}(^7\text{Li}, ^7\text{Be})^{15}\text{C}$ charge exchange reaction at 57 MeV bombarding energy, thus offering new perspective in the interpretation of the spectroscopy of neutron-rich nuclei.

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REVERSE EXPERIMENT AT LNS

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Abstract

The REVERSE experiment has been carried on the period September 1999 – May 2000, at the LNS in Catania, with the forward part of the 4π multidetector CHIMERA. This part of the device consists 688 Si-CsI (Tl) telescopes arranged in nine ring and has been used to study the inverse reactions $^{112,124}\text{Sn} + ^{58,64}\text{Ni}$, ^{27}Al , at E_{beam} 35 MeV/A. Much care was devoted in calibrating the detectors in energy, charge and mass for the proper identification of light heavy nuclei and charged particles was obtained. The first physical results are presented.

1.INTRODUCTION

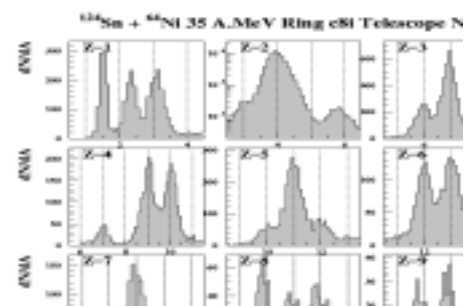
REVERSE is the first experiment proposed with the 4π multidetector CHIMERA.

The experiment has been approved by INFN with three main items named ISOSPIN, CLUSTER and FISSION, that are briefly reported in the following.

a) ISOSPIN proposes the investigation of the systems $^{112}\text{Sn} + ^{58}\text{Ni}$ (neutron poor) and $^{124}\text{Sn} + ^{64}\text{Ni}$ (neutron rich) at 35 A.MeV. The aim is to study the influence of the isospin degree of freedom in the multifragmentation with particular

emphasis to the mid rapidity source, (neck), formed in semi-peripheral reactions.

b) CLUSTER suggests the study of the IMF production in central collisions as a function of total charge and excitation energy of the composite system for the reactions $^{124}\text{Sn} + ^{64}\text{Ni}$, ^{27}Al at 25 and 35 A.MeV. The aim is to

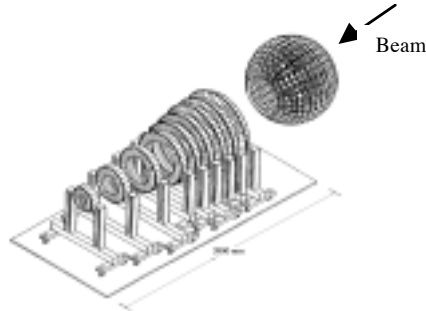


disentangle between statistical and dynamical effects in the region of subthreshold multifragmentation.

c) FISSION intends to study the reactions $^{238}\text{U} + ^{58}\text{Ni}$, ^{197}Au at 18 A.MeV, in order to distinguish between dynamical and statistical properties of fission decay channel in semi-peripheral heavy-ion collisions.

2. EXPERIMENTAL SYSTEM AND METHODS

The 4π array CHIMERA [1], presently being set up at LNS in Catania consists of 1192 ΔE -E time of flight (TOF) telescopes covering 94% of the 4π solid angle in the angular range between 1° and 176° , arranged in 35 rings in a cylindrical geometry along the beam axis. The first ring (1°) and the last one (176°) are placed at 3.5m and 0.4m respectively from the target; so, the total length of the device is about 4m (Fig. 1). Each telescope consists of a two-pad planar silicon detector (300 μm) followed by a CsI(Tl) scintillator with thickness ranging from 3cm (backward angles) to 12 cm (forward angles).



The main characteristics of the detector are a systematic measurements of the TOF, allowing for velocity determination, a low energy threshold (about 0.5 A.MeV) for fragments detection[2]

In order to identify the charged reactions products, three different techniques are used:

a) the ΔE -E technique, allowing for charge identification from light charged particles up to the heaviest ones. With this method an isotopic separation for light ions with $Z < 9$ was also recently achieved [3]. An example of such identification is shown in Fig.2.

Fig 2 Isotopic yield distribution in the REVERSE experiment

b) the ΔE and TOF technique allows for both mass identification of slow particles stopped in

the Si detector [4] and for velocity measurements. The complete analysis of these calibration procedures is going on for the data collected in the REVERSE experiment.

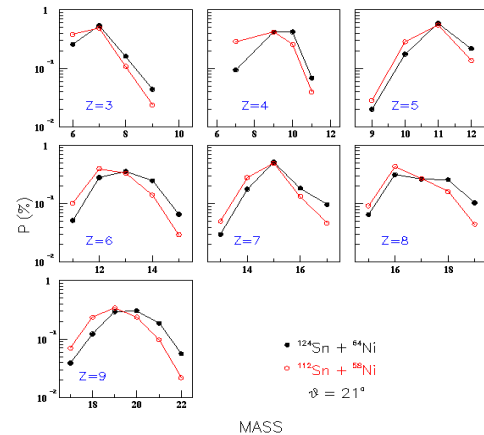
c) the pulse shape discrimination technique for isotopic separation of energetic particles with $Z \leq 4$ stopped in the CsI(Tl) scintillator. A detailed description of the method was given in Ref. [5]

3. RESULTS

On April 2000 the first physical campaign was started by using the forward part of the detector, consisting in nine wheels of telescopes, covering an angular range from 1° to 30° . The nuclear systems $^{124}\text{Sn} + ^{64}\text{Ni}$, $^{112}\text{Sn} + ^{58}\text{Ni}$, $^{124}\text{Sn} + ^{27}\text{Al}$ at 35 A.MeV, were investigated in reverse

Fig.3 the relative abundances of isotopes for element from $Z=3$ to $Z=9$, as a function of the mass number kinematics, with the aim to study isospin effects in nuclear collisions.

The preliminary comparison between ^{124}Sn and ^{112}Sn induced reactions in the ISOSPIN experiment has clearly evidenced isospin effects in the isotopic yield distribution,[6,7], for the two systems $^{112}\text{Sn} + ^{58}\text{Ni}$ and $^{124}\text{Sn} + ^{64}\text{Ni}$, at $E_{\text{beam}} = 35 \text{ MeV/A}$. In fig.3 are reported the relative abundances of isotopes for element from $Z=3$ to $Z=9$, as a function of the mass number.



A memory effect of the isospin entrance channel is clearly seen. Neutron rich system favours the production of neutron rich isotopes.

Besides, in fig.4 the average ratio of neutron number over atomic number, $\langle N \rangle / Z$ of the fragments is plotted as a function of Z for the two systems.

The dashed line is the corresponding value of the stability line (as evaluated by the natural abundance).

The $\langle N \rangle / Z$ value for the neutron rich system is systematically larger than the neutron poor one. For $5 \leq Z \leq 8$ the two systems show a $\langle N \rangle / Z$ value well above the stability line, while for light fragments ($Z < 5$) the ratios are close to the stability line with a clear tendency of the

Fig.4 $\langle N \rangle / Z$ of the function of Z fragments is plotted as a for the two systems.

neutron poor system to produce fragments with $\langle N \rangle / Z$ below the stability line.

In Fig.5 the charge distribution is plotted for the three systems $^{124}\text{Sn} + ^{64}\text{Ni}$, $^{112}\text{Sn} + ^{58}\text{Ni}$, $^{124}\text{Sn} + ^{27}\text{Al}$ at 35 A.MeV.

The similarity between Sn induced reactions on Ni targets (equal center of mass energy $\approx 7.5\text{A.MeV}$) is impressive for $Z < 50$. The strong difference for atomic number close to $Z=50$ (atomic number of the projectile) was due to the different first level trigger conditions (multiplicity > 2 in reaction $^{112}\text{Sn} + ^{58}\text{Ni}$ and multiplicity > 3 in reaction $^{124}\text{Sn} + ^{64}\text{Ni}$).

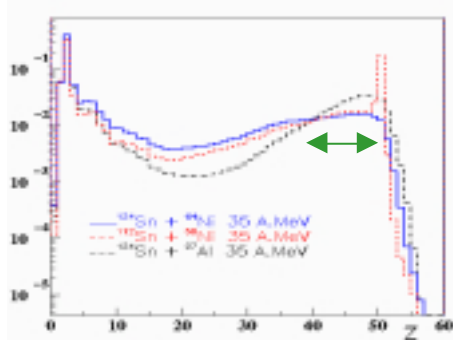
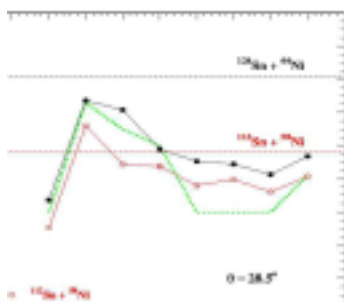


Fig.5 : Charge distribution for the three systems investigated in the

So, we proved that, by adopting the highest trigger multiplicity in some runs, essentially binary useful in order to control the dead time of the acquisition data and pile-up distortions.



In contrast, strong differences are clearly evidenced for the $^{124}\text{Sn} + ^{27}\text{Al}$ system both in the region $Z \approx 50$ (horizontal arrow) and in the region $Z \approx 15-30$ as a consequence of the reduced Coulomb interaction in the entrance channel and the lower center of mass energy ($\approx 4.5\text{A.MeV}$). In this case the composite system is well below the limiting temperature [8] and the reaction scenario is dominated by the one body dissipation and incomplete fusion reactions.

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ENERGETIC PROTON EMISSION: A TEST BENCH FOR NUCLEAR DYNAMICS AROUND THE FERMI ENERGY

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Abstract

Energetic proton emission was investigated with MEDEA and MULTICS apparatus. A detailed comparison with dynamical calculations shows that the bulk of data is well reproduced by BNV calculations. The data analysis as a function of the impact parameter has put in evidence that a momentum dependent interaction is needed to describe the energetic proton emission in central collisions.

1 INTRODUCTION

Heavy ion collisions at energy between 20 AMeV and 2 AGeV allow to explore the behaviour of the nuclear matter in condition of densities and temperatures far away from stability. In spite of many problems to cope with, many progresses have been done both from the experimental and theoretical side in the investigation of the equation of state (EOS) of nuclear matter. In particular, since the relevant parameters of the EOS are not directly accessible experimentally, the feedback between theoretical models and experimental observables is crucial. Moreover, since the dynamics the system evolves from the high density and temperature phase to the expansion and de-excitation phase very rapidly, the search for specific probes of the various stages of the reaction has been very intense in the last years. Thanks to the big developments in the detection systems, recent data allow an accurate comparison between calculations and experiments aiming to constrain basic ingredients of the models such as mean field interaction, nucleon-nucleon cross section, compressibility and so on. Moreover, the possible interplay between various effects has to be considered. The crosscheck between several

probes which exhibit different sensitivities to key ingredients seem the only feasible way to build a coherent picture.

In this contribution, we report our results concerning the energetic proton emission in the reaction $^{58}\text{Ni} + ^{58}\text{Ni}$ 30 AMeV which put constraints on nuclear dynamics at pre-equilibrium. In particular, the sensitivity to momentum dependent interactions (MDI) has been investigated.

2 EXPERIMENTAL PROCEDURES AND RESULTS

The experiment was performed at Laboratori Nazionali del Sud with the MEDEA [1] and MULTICS [2] apparatus.

A ^{58}Ni beam at 30 AMeV was delivered by the Superconductive Cyclotron system to bombard a ^{58}Ni target 2 mg/cm² thick. Energetic protons were detected in coincidence with photons, light charged particles ($Z=1,2$) and intermediate and heavy fragments on an event by event basis, thus allowing a rather complete description of the reaction dynamics as well as an estimate of impact parameter.

Proton spectra at different laboratory angles ($30^\circ \leq \theta \leq 165^\circ$) were measured. Following the standard moving source analysis we have parametrized the proton yield as a superposition of protons emitted from a projectile-like source, a target-like source and an intermediate velocity source. The intermediate velocity source exhibits a velocity close to the half beam velocity, corresponding to the average nucleon-nucleon (NN) velocity, and a high inverse slope parameter, reflecting the coupling between the beam velocity and the Fermi velocity [3]. This source accounts for the high energy proton emission at large polar angles and is interpreted in terms of pre-equilibrium emission due to quasi-free NN collisions occurring in the interaction zone.

Experimental and calculated proton spectra with a

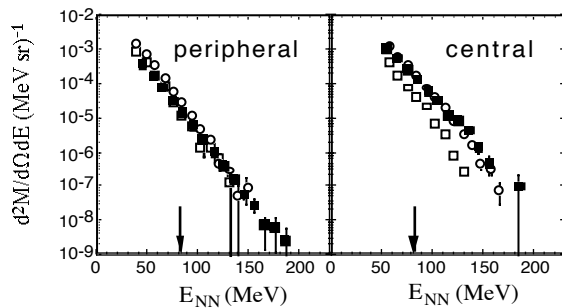


Fig. 1 – Proton energy multiplicity spectra in the NN reference frame for peripheral (left) and central (right) collisions. Data (full squares), BNV with local Skyrme interaction (open squares) and with momentum dependent interaction (open circles) are reported. The arrows represent the kinematical limit.

Boltzmann-Nordheim-Vlasov (BNV) code, which solves the transport equation in the frame of mean field and two body dynamics, are reported in fig.1 for peripheral and central events. The arrows indicate the kinematical limit expected in the hypothesis of first chance NN collisions and sharp momentum distribution.

Two different potentials were implemented in the BNV code: one using a local Skyrme interaction for the mean field (open squares of fig.1) and another using a Gale-Bertsh-Das Gupta momentum dependent Skyrme interaction (open circles of fig.1) [4]. A soft EOS has been used in both cases ($K=200$). For peripheral events both calculations provide a reasonable

description of data, while remarkable differences are observed for central events. Indeed in this case, the calculated proton spectrum overshoots the data at high energy. The inverse slope parameter is too high while the momentum dependence is too weak. The data (at least absolute values) should be slightly reduced since in this kind of calculation only free nucleons are emitted while in the reaction also complex particles are emitted and observed experimentally [5]. The extremely energetic proton production ($E_p > 130$ MeV) has been investigated in detail in this reaction [6], and the failure of BNV at the highest energies claims for the inclusion of mechanisms beyond the one and two body dynamics such as cooperative effects. This problem, which definitely deserves further investigation, will be not be discussed in the following.

A more detailed analysis has been performed to study the behavior of inverse slope parameters and proton multiplicities as a function of the impact parameter. Experimental and calculated inverse slope parameters of proton spectra ($E_p > 60$ MeV) as a function of the impact parameter are reported in fig.2 and show a good agreement with momentum dependent BNV calculations since both values and trend of data are well reproduced. Calculations with a local Skyrme potential exhibit an inverse slope parameter smaller than the data one for the most central collisions.

In fig.3 the average proton multiplicity for energy close to the kinematical limit ($60 < E_p < 80$ MeV) is reported as a function of the number of nucleons participating, A_{part} .

Fig. 3 – Proton multiplicity versus A_{part} . Experimental values (full squares), MDI BNV calculations (open circles) and local Skyrme interaction (open squares) are reported. BNV calculations are scaled by a factor 0.6.

The BNV calculations, filtered with the experimental apparatus, are also reported in fig.3 (MDI open circles and local Skyrme open squares). Calculations have been scaled by a factor 0.6 to allow a better comparison with the data. This scaling is consistent with the yield reduction needed to account for complex particle emission. Within this assumption, a very good agreement with the data is observed in fig.3 for the momentum dependent calculations while the

local Skyrme is able to describe data only for peripheral collisions (small A_{part}). To better isolate the effect of the MD interaction on the proton production, we have also performed a calculation with a local Skyrme and a stiff EOS ($K=380$).

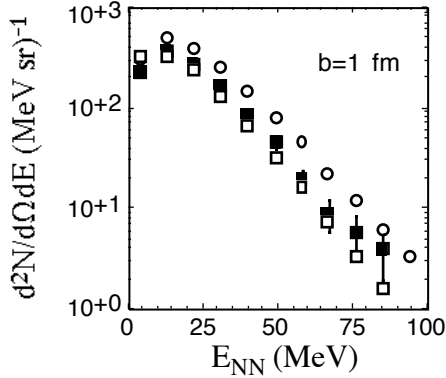


Fig 4 – Calculated proton energy spectra for momentum dependent Skyrme interaction (open circles), local Skyrme with $K=200$ (open squares) and local Skyrme with $K=380$ (full squares)

Indeed, it has been argued that some of the MDI effects could be reproduced by a stiff EOS. Calculated proton spectra are reported in fig. 4 for MDI interaction (open circles), for local interaction with soft EOS (open squares) and for local interaction with stiff EOS (full squares) for $b=1$ fm. The proton spectrum calculated with the stiff EOS looks very similar to the soft one with local Skyrme but with a slightly larger yield indicating that pre-equilibrium proton emission is not much sensitive to the nuclear compressibility.

In conclusions, the different trends observed in calculations seem to be due to the repulsive nature of momentum dependent interactions. Indeed, since MD interactions lead to a less attractive mean field, although the average number of collisions is smaller than in the local case, we observe a larger fraction of escaping particles. For the same reason the emitted particles are more energetic in the case of MD interaction. Of course, energetic proton production is also sensitive to the nucleon-nucleon cross section σ_{NN} [8] and the possibility to extract information on in medium effects should be investigated. However, flow data

estimate a σ_{NN} reduction factor $\alpha = 0.2-0.3$ depending on the system [9].

3 CONCLUSIONS

Energetic proton emission has been investigated in detail in the $^{58}\text{Ni} + ^{58}\text{Ni}$ 30 AMeV reaction. The bulk of data is well reproduced by BNV calculations with a momentum dependent interaction. Calculations with MD exhibit remarkable differences compared with the local Skyrme ones which underestimate both yield and slope of the proton spectra especially for central collisions. These results confirm the need for a momentum dependent interaction as already indicated by experimental data on flow [10] also at energy as low as 30 AMeV. Our experimental results show that energetic proton emission, which is governed by the interplay of mean field and of nucleon-nucleon cross section, provide constraints on nuclear dynamics at pre-equilibrium. Moreover, since energetic particle emission occurs in the first stage of the reaction ($t < 100$ fm/c at these incident energies), the amount of emitted mass and energy is relevant for a more reliable definition of the features of the system and its subsequent evolution.

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Possibility to deduce the emission time sequence of neutrons and protons from the neutron-proton correlation function

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Abstract

Experimental information has been derived from the neutron-proton correlation function in order to deduce the time sequence of neutrons and protons emitted at 45° in the $E/A = 45$ MeV $^{58}\text{Ni} + ^{27}\text{Al}$ reaction.

1 INTRODUCTION

Two-nucleon correlation functions are normally utilized to extract information on the size of the emitting source and on the time duration of the emission. The combined information from singles n and p spectra, pp , nn and np correlation functions is very powerful for setting constraints on reaction models [1]. Furthermore, when correlations of non identical particles are considered, additional model-independent information on the emission chronology of the particles can be obtained.

The sensitivity of the correlation function to the asymmetry of the distribution of the relative space-time coordinates of the particle emission points can be used to determine the differences in the mean emission times of any kind of interacting, non-identical particle pairs [2]. This effect has been discussed theoretically for pd , np [2], πp [3] and K^+K^- [4] and studied experimentally to deduce the emission time

sequence of p and d in the $E/A = 50$ MeV $\text{Xe} + \text{Sn}$ reaction [5] and of p , d , t , ^3He and α particles in central $E/A = 400$ MeV $\text{Ru} + \text{Zr}$ collisions [6].

In this contribution we report on the first experimental evidence that the emission chronology of neutrons and protons can be deduced from the neutron-proton (np) correlation function. These data come from the $E/A = 45$ MeV $^{58}\text{Ni} + ^{27}\text{Al}$ reaction [1,7]. After a short discussion about the possibility to obtain chronology information, indications on the emission sequence are derived from the experimental np correlation function gated on the parallel velocity and on the total momentum of the nucleon pair.

2 EMISSION CHRONOLOGY

The possibility to access information from the np correlation function on the particle emission time sequence is connected to the different

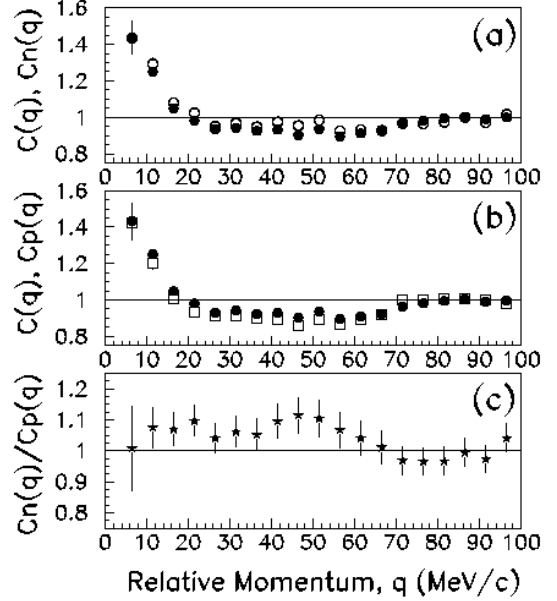
strength of the nuclear final state interaction experienced by different pairs. Namely, from a merely classical viewpoint, if there are pairs for which the average distance between the two particles (when they start to interact) is smaller, these pairs experience a stronger interaction and exhibit an enhanced correlation (or anti correlation) strength, as compared to those pairs for which the average particle distance is larger. Note that an average time difference in the emission times of the two particles implies a difference in the average distance for pairs $E_n > E_p$ and $E_n < E_p$.

Model calculations [2,8] do predict that when a time delay in the emission of the two particles is introduced, the interaction is enhanced for those pairs for which the average distance is smaller. This effect can be studied by comparing the correlation function $C_n(q)$, gated on pairs $E_n > E_p$, with the correlation function $C_p(q)$, gated on pairs $E_n < E_p$. If the proton is emitted earlier (later) than the neutron, the ratio C_n/C_p will show a peak (dip) in the region of q where there is a correlation, a dip (peak) where there is an anticorrelation, and will approach unity both for q approaching 0 (since the energy difference of the two emitted particles is negligible) and q approaching infinity (since modifications of the two-particle phase space density arising from final state interactions are negligible). The exact location of the peak and dip in the ratio depends on the source model and on the parameter set (as does of course the correlation function itself [2,8]).

3 EXPERIMENTAL RESULTS

The experimental np correlation function from the $E/A = 45$ MeV $^{58}\text{Ni} + ^{27}\text{Al}$ reaction, obtained with a proton detection array placed at 45° and a neutron setup of liquid scintillators placed at 25° , 45° and 90° , was presented in Ref. [1] and is shown by the solid dots in Figs. 1a, 1b. Kinetic energy thresholds of 2-50 MeV for neutrons and 6-50 MeV for protons are applied to the data. The normalization is defined in the region $q = 80$ -120 MeV/c. $C(q)$ shows a clear correlation

for $q < 20$ MeV/c and a very small



anticorrelation for $20 < q < 70$ MeV/c.

In order to study the n - p emission chronology, the correlation function $C_n(q)$, gated on pairs $E_n > E_p$, and $C_p(q)$, gated on pairs $E_n < E_p$, are presented in Fig. 1 together with the ratio C_n/C_p . Fig.1 Experimental ungated np correlation function $C(q)$, from the $E/A = 45$ MeV $^{58}\text{Ni} + ^{27}\text{Al}$ reaction, (solid dots in panels (a)(b)) compared to: Panel (a), open circles: $C_n(q)$, constructed from pairs of type $E_n > E_p$. Panel (b), open squares: $C_p(q)$, constructed from pairs of type $E_n < E_p$. The ratio C_n/C_p is shown in panel (c).

E_n and E_p are calculated in the reference frame of a source moving with a velocity of $0.16c$ [7]. A single normalization constant, calculated from the ungated correlation function, is utilized for both energy-gated correlation functions $C_n(q)$ and $C_p(q)$. The data show a small experimental signal. $C_n(q)$ is slightly enhanced with respect to $C(q)$ for all values of $q < 60$ MeV/c (Fig.1a). Correspondingly $C_p(q)$ is suppressed in the same q -region (Fig.1b). The ratio C_n/C_p is above unity for $q < 70$ MeV/c (Fig.1c).

As discussed above, the enhancement of $C_n(q)$ where $C(q)$ has a correlation ($q < 20$ MeV/c) might indicate that for those pairs that contribute to the region $q < 20$ MeV/c protons are on average emitted earlier than neutrons. The enhancement of $C_n(q)$ in the region $20 < q < 60$ MeV/c might instead indicate the

opposite emission time sequence as $C(q)$ has an anticorrelation there. However, one should keep in mind that the inclusive correlation function reflects a convolution of different sources and origins of emission thus it is not reasonable to expect that the information from the inclusive data should provide us with a well defined and unique np emission time sequence.

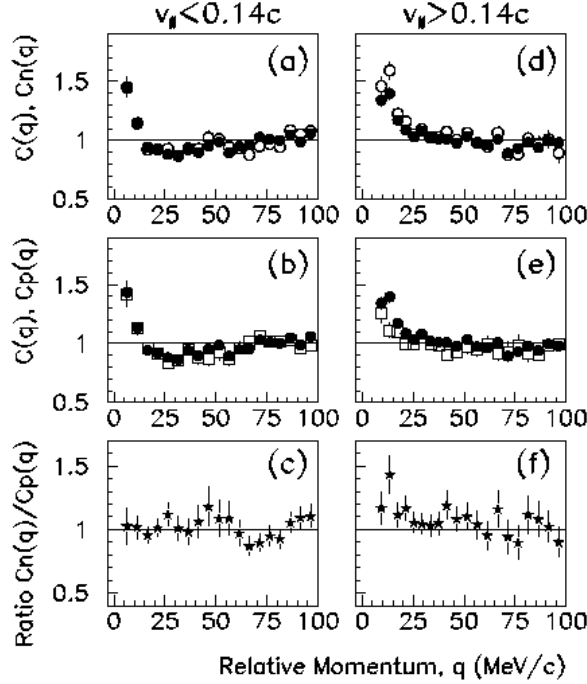


Fig.2 The same as in Fig.1, for low- $v_{\text{parallel}} (< 0.14c)$ np pairs (panels (a)(b)(c)) and for high- $v_{\text{parallel}} (> 0.14c)$ np pairs (panels (d)(e)(f)).

In order to disentangle the different effects and minimize such averaging, various kinds of gates can be applied to the inclusive data. Fig. 2 illustrates how the results of Fig. 1 are modified when cuts on the parallel velocity of the particles are applied. The effects of these cuts, that are defined on the basis of BUU calculations [9] and of the available statistics, are to enhance (suppress) the quasi-projectile source by selecting nucleons with large (small) values of the parallel velocity. Figs. 2a, 2b, 2c correspond to a low- v_{parallel} gate and Figs. 2d, 2e, 2f to a high- v_{parallel} gate. One can notice that the behavior of the correlation functions and of C_n/C_p ratio is quite different for the two different event selections. Projectile-like events (i.e.

high- v_{parallel} selection) exhibit an enhanced correlation function strength and an enhanced C_n/C_p ratio in correspondence to the correlation ($q < 25$ MeV/c). Target-like events (i.e. low- v_{parallel} selection) exhibit a slight suppression in the correlation function strength ($q < 20$ MeV/c), a weak anticorrelation for $q = 20-50$ MeV/c and a C_n/C_p ratio quite close to unity in the correlation region.

Gating on the momentum (or energy) of the particle pair in the source system is particularly useful to investigate the time-scale of the emission and to study the interplay between dynamical and statistical effects in particle emission. The np correlation function gated on high- P_{tot} pairs has already been presented in Ref.[1]. An enhancement in the correlation function strength was observed indicating a smaller space time extent of the preequilibrium source of emission [1]. Fig. 3 presents total-momentum-gated correlation functions. A low- P_{tot} gate is applied to all results shown in Figs. 3a, 3b, 3c and a high- P_{tot} gate in Figs. 3d, 3e, 3f.

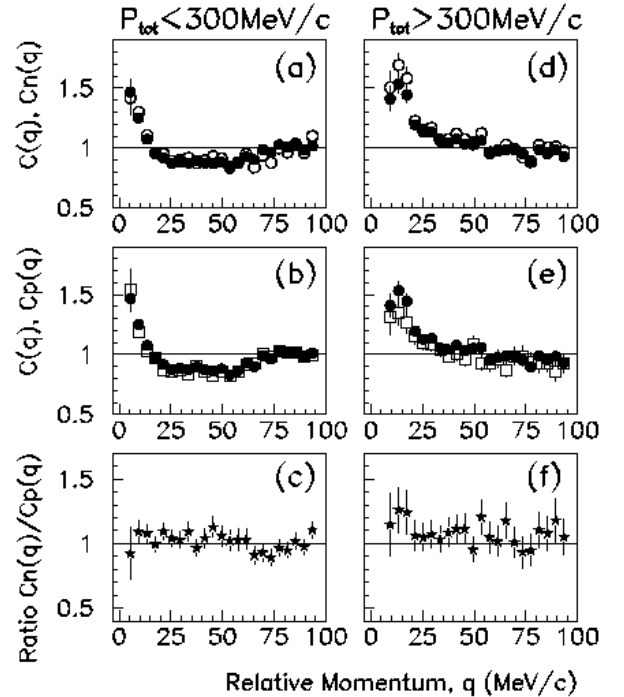


Fig.3 The same as in Fig.1, for low- $P_{\text{tot}} (< 300 \text{ MeV/c})$ np pairs (panels (a)(b)(c)) and for high- $P_{\text{tot}} (> 300 \text{ MeV/c})$ np pairs (panels (d)(e)(f)). P_{tot} is calculated in the ref. frame of a source moving with $v_{\text{source}} = 0.16c$.

The effects of the gates on the correlation functions and on the C_n/C_p ratio are similar to those observed in Fig.2. High-total-momentum selected events exhibit an enhanced correlation function strength and an enhanced C_n/C_p ratio in correspondence to the correlation ($q > 25 \text{ MeV/c}$). Low-total-momentum selected events exhibit a slight suppression in the correlation function strength ($q < 20 \text{ MeV/c}$), a weak anticorrelation in the intermediate q -region and a C_n/C_p ratio that does not appreciably deviate from unity at any values of q . The enhancement of the C_n/C_p ratio in the low- q region, observed in Figs. 2F and 3f, could be interpreted as an indication that for those np pairs, protons are on the average emitted earlier than neutrons.

4 CONCLUSIONS

The experimental results from differently gated correlation functions support the interpretation that in high-parallel-velocity and high-total-momentum selected events, which enhance projectile-like and/or intermediate velocity sources, the proton is on average emitted earlier than the neutron. The result of a shorter average emission time for protons seems to corroborate our previous findings from nn and pp data compared to a two-component statistical model [1]. However, the calculation of the C_n/C_p ratio with the two-source model parameters used in Ref. [1] yields a negligible effect as compared to the experimental data. The model of [1] neglects any residual interaction between the emitted particles and the reaction zone. In particular, the Coulomb interaction between the proton and the emitting source -which could increase the average distance between the two particles if the proton is emitted first- has not been taken into account [1]. Alternative explanations might be found in reaction mechanisms that are neglected in our calculations, such as delayed feeding from the decay of excited primary fragments.

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TEMPERATURE AND DENSITY DETERMINATION IN HEAVY ION REACTIONS AT INTERMEDIATE ENERGIES

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Abstract

The preliminary results of the Fiasco-Temperature experiment, performed at LNS in 2001, are reported. A wide range of incident energies, projectile and target masses has been investigated with the FIASCO and the HODO-CT detection arrays. This experimental setup allowed simultaneous measurements of excitation energies, temperatures and densities of the fragmenting systems. The preliminary data show that, at the explored incident energies, the deep-inelastic process produces a *quasi*-projectile and a *quasi*-target at such extreme values of density and temperature to cause their multifragmentation. For the same data set, a calorimetric study has been performed and the nuclear caloric curve has been extracted: the trend confirms the plateau-like behavior of the nuclear caloric curve and the mass dependence of the corresponding limiting temperature.

1 INTRODUCTION

The search for the liquid-gas phase transition in nuclear matter is one of the most intriguing questions of heavy ion reaction studies.

The similarity of the nuclear caloric curve of the projectile spectator in $^{197}\text{Au}+^{197}\text{Au}$ reaction at 600 A MeV [1] to the first-order liquid-gas phase transition in macroscopic systems has initiated a widespread activity, both theoretical and experimental. One of the goals of the present work was to study the excitation energy-temperature correlation, measuring both quantities for a variety of systems in the 17-40 A MeV incident energy range. At the same time, particle-particle correlation measurements allowed the source spatial distribution determination and, consequently, density measurements.

2 EXPERIMENTAL SETUP

The experiment was performed in 2001 at the LNS. A wide range of projectile (^{93}Nb , ^{116}Sn , ^{120}Sn), target (^{58}Ni , ^{93}Nb , ^{116}Sn , ^{124}Sn , ^{197}Au) and incident energies (between 17 and 40

A MeV) was explored. A view of the experimental setup is shown in Fig.1. A high granularity hodoscope (HODO-CT) was used to identify excited particle-unstable resonances in light fragments from the correlated detection of their decay products and to simultaneously

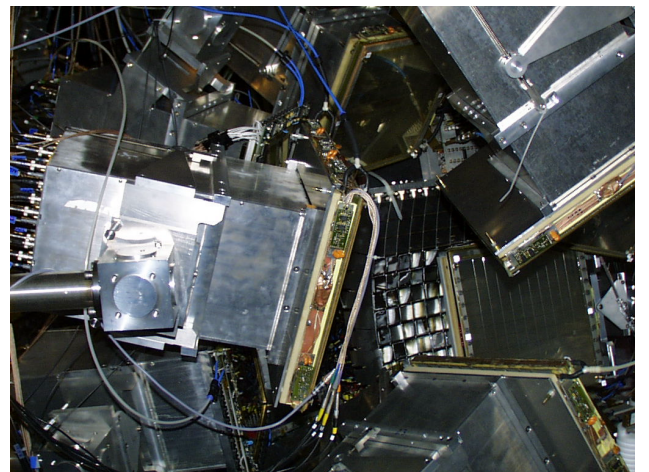


Fig.1: Experimental setup used in the FIASCO-Temperature Experiment at LNS.

measure the yields of isotopically resolved

fragments. It was set up at a distance of 0.6 m from the target and consisted of 96 three-folds telescopes: 50 μm + 300 μm Silicon detectors 3 $\times$ 3cm² active area, followed by a 6 cm long CsI(Tl). It covered the angular range $\theta_{\text{lab}} = 25^\circ \div 55^\circ$. The multidetector FIASCO [2] allowed the direct determination, event-by-event, of the excitation energy deposited in the fragmenting system. It includes 24 position sensitive gas detectors (PPAD) for the determination of the velocity vectors of heavy fragments ($A > 20$), 96 silicon telescopes for the measurement of the PLF secondary quantities (energy and charge) and 158 phoswich telescopes for the identification of light charged particles and intermediate mass fragments and for the measurement of their time of flight.

3 REACTION CHARACTERISATION

The determination, event-by-event, of the excitation energy has been performed through the Kinematic Coincidence Method [3]: each event has been reconstructed cinematically from the measured velocity vectors of the heavy fragments emitted from the *quasi*-projectile and the *quasi*-target and detected by FIASCO.

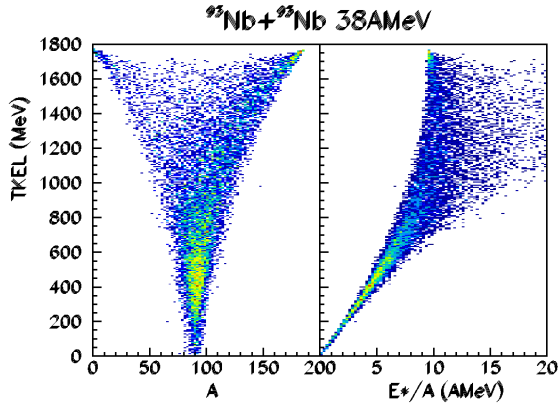


Fig.2: Diffusion plot (left panel) and correlation between the TKEL and the excitation energy (right plot) for $^{93}\text{Nb}+^{93}\text{Nb}$ at 38AMeV.

From the analysis of the diffusion plots (fig. 2) the binary character of the main reaction mechanism is evident. This finding allows a clean determination of the system mass and of the corresponding primary deposited energy. The data have been sorted in bin of TKEL

(Total Kinetic Energy Loss): this latter quantity is proportional to the excitation energy deposited into the systems (fig.2- right panel) and to the centrality of the reaction. Due to the reduced solid angle coverage of the HODO-CT, as shown by the rapidity plots of fig.3, the analysis has been focused to the determination of the calorimetric and spatial characteristics of the *quasi*-target formed in deep inelastic

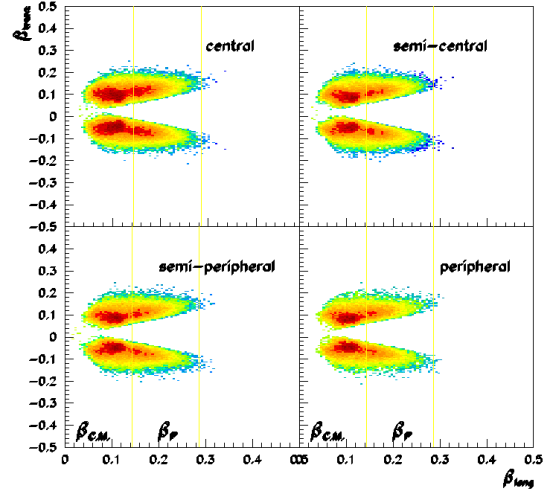


Fig.3: Rapidity plot for the $^{93}\text{Nb}+^{116}\text{Sn}$ at 38AMeV reaction for IMF detected by the hodoscope.

processes and, in the most central collisions, of the composite system formed in fully damped collisions or by complete or incomplete fusion.

4 CALORIMETRIC ANALYSIS

The coincidence spectra, as a function of the relative momentum of the two coincident particles, exhibit peaks due to the resonant decay superimposed to the background of coincident but uncorrelated particle emission. Correlation functions are extracted by dividing the coincidence yields by uncorrelated yields obtained from event mixing.

The efficiency matrix of the acceptance of the HODO-CT for particular resonance decay was evaluated by using a Monte-Carlo simulation [4]. From the acceptance corrected yields the nuclear temperatures (emission temperature) can be calculated assuming that the states of the decaying fragments are populated according to the Boltzmann law. On the other hand we extract temperatures from the double ratios of

isotope yields [5]. Energy spectra of the individually resolved isotopes are reproduced by using a standard two moving sources fit procedure. The $(^3\text{He}/^4\text{He})/(^6\text{Li}/^7\text{Li})$ double yield ratios are deduced from the integrated cross sections.

The measured values of $T_{\text{He-Li}}$ are reported in Fig. 4 as a function of the TKEL bin.

In order to crosscheck and calibrate the isotope temperatures, they are also compared with temperatures deduced from the relative population of states in ^5Li : we have obtained a very good agreement between the two thermometers over the TKEL range explored.

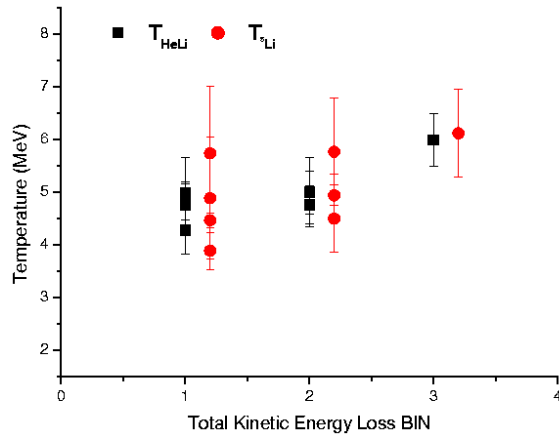


Fig.4: Isotope and emission temperatures cross - comparison as a function of the Total Kinetic Energy Loss bin for the $^{93}\text{Nb}+^{93}\text{Nb}$ reactions.

Once the excitation energy deposited in the system was evaluated from the measured TKEL (figure 2, right panel), correlating the former with the isotopic temperature, the nuclear caloric curve was constructed and compared with the ALADiN one [1]: the comparison, shown in figure 5, confirm the *plateau-like* behaviour of the nuclear caloric curve over the 2÷10 AMeV excitation energy range, already interpreted as a strong evidence of a first order liquid-gas phase transition in nuclear matter.

Recently, it has been shown that the mass of the fragmenting system has also an influence on the observed shape of the caloric curve: in particular, the temperature of the observed plateau decreases with increasing the mass of the fragmenting system [6]. The wide range of masses explored in this experiment, allowed us to perform the same analysis on our data. The

obtained limiting temperature (Fig. 6) confirm the monotonous decreasing of the temperature with increasing system mass.

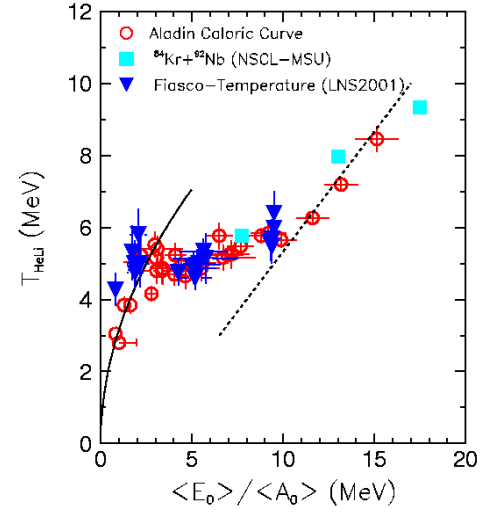


Fig.5: Nuclear caloric curve for the analyzed reactions and comparison with the ALADiN [1] one.

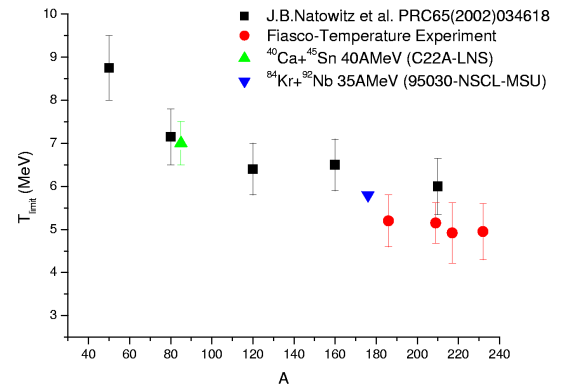


Fig.6: Limiting Temperature as a function of the system mass.

4. DENSITY MEASUREMENT

Particle-particle correlation technique was applied to the same data, sorted into bins of TKEL.

The analysis of the p-p correlation functions was performed within the Koonin-Pratt formalism [7] and by applying the source imaging technique [8], thus allowing a direct cross-comparison between the two different methods. Radii were deduced in the limit of zero-lifetime for the source. The similarity of the longitudinal and transverse pp correlation functions corroborates the assumed time

independence [9] for all the TKEL bins except the most central ones, where the differences between these two correlation functions indicate a strong contribution of different emission times.

For the p- α and d- α correlations analysis the numerical results of Boal and Shillcock were used [10]. The extracted radii values are reported in fig. 7 for a system mass around 93.

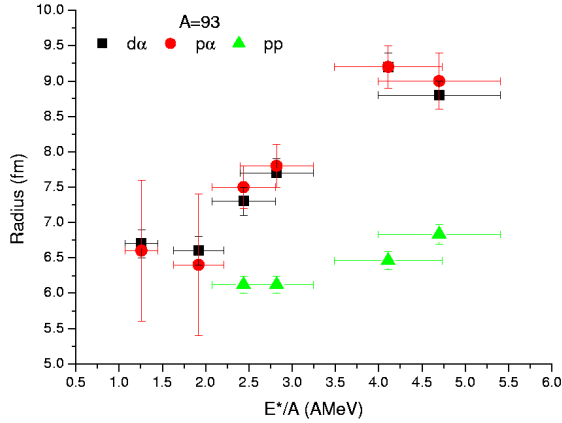


Fig.7: Radii extracted from the pp,p α and d α correlation functions as a function of the excitation energy for system masses around 93.

As clearly visible, the source dimensions increase with increasing excitation energy indicating an expansion of the system. It should be noted that the values deduced from the p α and d α correlation functions agree within the error bars and are always greater than the values extracted from the pp. How this difference, already found in previous analysis, can be connected to an emission time ordering is, presently, still under investigation.

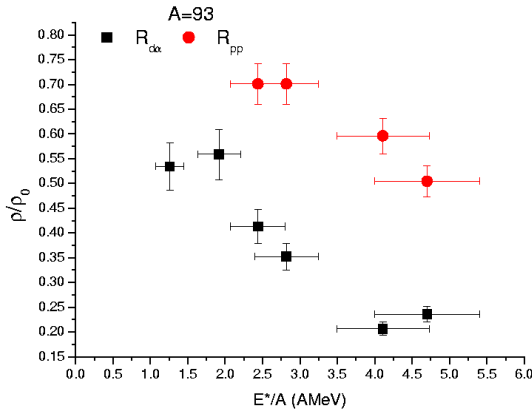


Fig.8: Extracted densities as a function of the excitation energy for system masses around 93.

Densities in fig.8 were calculated by dividing the *quasi*-target mass, as indirectly measured by the FIASCO detector, by the source volume. It should be noted that density values around $\rho/\rho_0 \approx 0.25$ indicate a strong expansion of the system, which, for these events, seems to be referable to a *quasi*-target.

5. CONCLUDING REMARKS

The preliminary results here presented refer to excitation energy, temperature and density measurements of *quasi*-target nuclei, formed in deep inelastic reactions in the 17-40 AMeV incident energy range. The binary character of the reaction, clearly shown by the diffusion plots, allowed an unambiguous determination of the excitation energy deposited into the system up to around 8-9 AMeV. The calorimetric analysis for these highly excited systems, confirms the plateau-like behavior of the caloric curve indicating a first-order phase transition in nuclear matter. In particular, the limiting temperature decreases with increasing system mass. The low densities reached by the system, increasing the excitation energy, indicate that both partners of the deep inelastic channel reach extreme conditions before their decay. That one of the decay channels, as suggested in ref.[11], could be their multifragmentation, seems an hypothesis supported by the present data.

The authors acknowledge the FIASCO group for providing the calibrated data of the FIASCO detector by the KCM method.

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FRIBS: Radioactive Ion Beams at LNS by Projectile Fragmentation

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Abstract

Preliminary results on radioactive ion beams produced at LNS by projectile fragmentation at intermediate energies are presented. $^{12}\text{C} + ^9\text{Be}$ (500 μm) at 62 AMeV and $^{40}\text{Ar} + ^9\text{Be}$ (500 μm) and $^{58}\text{Ni} + ^{27}\text{Al}$ (100 μm) both at 40 AMeV reactions were studied. Two similar detector arrays were placed at the final focus of the magnetic fragment separator and at the entrance of the Ciclope scattering chamber to measure production and transmission yields. Several isotopes were identified and their rates were measured and compared with LISE predictions. The easy ion identification and their rates open the possibility of using such ions as tagged beams for nuclear reactions and/or spectroscopy studies.

1 INTRODUCTION

The possibility of producing radioactive ion beams (RIB) has become nowadays a reality in several laboratories [1]: GSI, GANIL, NSCL-MSU, RIKEN, and JINR Dubna produce relativistic and intermediate energy RIB by projectile fragmentation (the so called IN-FLIGHT method) ; Louvain-le Neuve ,SPIRAL-GANIL, ISOLDE-CERN, TRIUMF-Vancouver, ORNL Oak Ridge and ANL Argonne produce low energy RIB by the so called ISOL method. New projects are at present under development: RIA (USA), E-arena (JHF) (Japan), EURISOL (Europe) based on both techniques. At the LNS two projects were started some years ago, EXCYT [2] (ISOL based) and ETNA [3] (IN-FLIGHT). While the first one is still under construction, recently, a modified version of the ETNA fragment separator has become available and, therefore, we tested the possibility of producing tagged radioactive beams at intensities useful for experiments.

2 THE FRAGMENT SEPARATOR

Fig.1 shows a drawing of the present Fragment Separator and Table 1 summarizes a comparison with presently operating similar devices. It consists of two 45° bending magnets D_1 and D_2 , three quadrupole triplets Q_1 - Q_3 , Q_4 - Q_6 and Q_7 - Q_9 , two sextupole correctors S_4 and S_9 near quadrupoles Q_4 and Q_9 . There are two slits at the intermediate and achromatic foci and a beam stopper after the bend D_1 . A degrader foil could be installed at the intermediate focus, however was not used in the present experiment. Larger solid angle and momentum acceptance will be achieved by replacing the present quadrupoles with larger ones (FRIBs in Table1).

The production targets were set in a rotating holder and, self supported targets of ^9Be and ^{27}Al 500 and 100 μm thick respectively, were used. The dipoles current was scaled accordingly to the Bp values, calculated in the code LISE [4], self-consistently with respect to

the values measured for the transmission of the primary beam.

Table 1: Fragment Separators Main Parameters.

	$\Delta\Omega$ (msr)	$\Delta P/P$ (%)	R_p	MaxBp (Tm)	Length (m)
FRIBs	4.0	+/- 1.1	800-1500	4.0	23
Present	1.1	+/-0.65	1000	2.7	23
GANIL	1.0	+/-2.5	800	3.2	18
GSI	0.7- 2.5	+/-1	240-1500	9-18	74
RIKEN	5.0	+/-3	1500	5.76	21
NSCL	0.8- 8	+/-1.5	700-1500	5.4	22
JINR	6.4	+/-1	4360	4.5	14.5

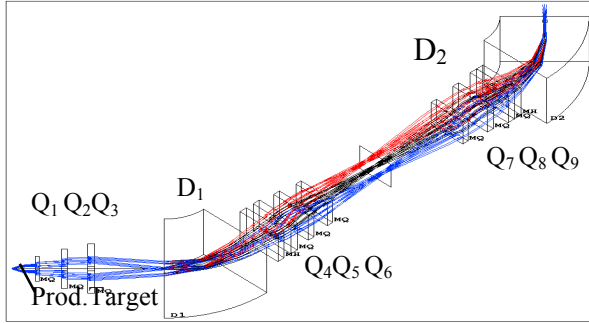


Fig.1:LNS Fragment Separator layout.

3 THE DETECTOR ARRAY

Two similar detector arrays were installed: one at the final focus of the fragment separator and the other at the entrance of the Ciclope scattering chamber (see fig.s 2 and 3). They consist of:

- PPAC (4x 4 cm² active area, 40x40 wires , operated at 500 Volts and at 4 mbar of eptane between windows of Mylar 0.8 mg/cm² thick)
- Silicon detector 300 μ m thick and 3x3cm² active area (5x5 cm² in the Ciclope setup).
- Plastic scintillator 0.5 mm thick and 2.5x2.5 cm² active area (CsI scintillator 8 cm long, 5x5 cm² in the Ciclope setup).

The silicon detectors were calibrated in energy both with a three peaks alpha source and with the primary beam, as shown in fig.4.

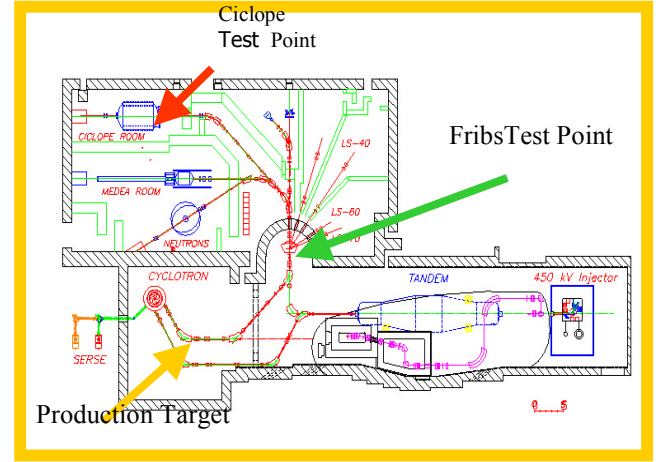


Fig.2: Location of the detectors.

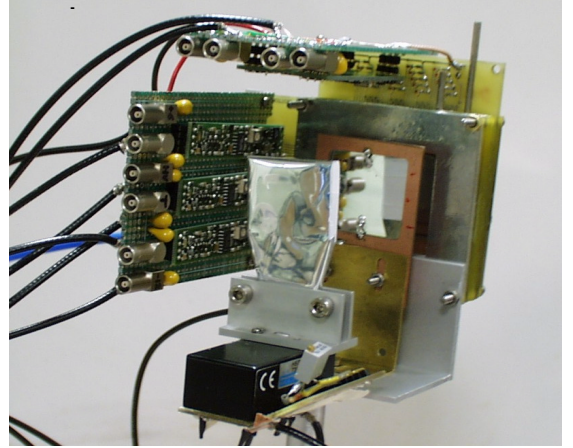


Fig. 3: Detector array at the final focus of the fragment separator.

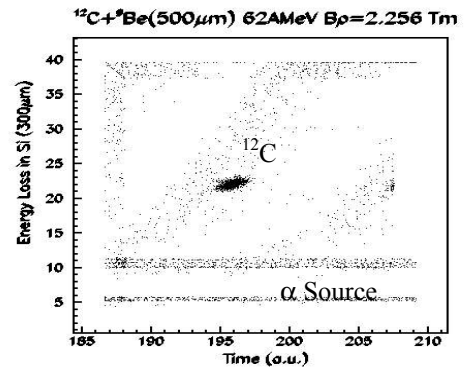


Fig4: Energy Calibration by ¹²C primary beam and three peaks alpha source.

This detector's combination allows the measurement of energy, charge and position of all the products but, for tagging an ion that can be used as a beam, only thin detectors must be used. Therefore we checked the possibility of identifying the products, event-by-event, by coupling the ΔE information from the silicon detector with the time of flight of the ion measured by the same detector with respect to the RF signal from the accelerator. Time resolution was of the order of 1.2 nsec.

4. RESULTS

Three different combinations of projectile and target were used: $^{12}\text{C} + ^9\text{Be}$ (500 μm) at 62 AMeV and $^{40}\text{Ar} + ^9\text{Be}$ (500 μm) and $^{58}\text{Ni} + ^{27}\text{Al}$ (100 μm) both at 40 AMeV. Current intensities were typically set in the 100 epA range. Fig.5 shows the energy loss in the silicon detector versus the time of flight of the products detected in the three reactions.

Fig.6 shows energy loss versus residual energy in the thick detector for the ^{40}Ar and ^{58}Ni induced reactions.

Several isotopes were well identified both in the ΔE -E plot and in the ΔE -ToF, allowing an event-by-event tagging of the produced ion. Position diagnostic was achieved by the PPAC information. Beam spots of 9x21 mm² were measured at the Ciclope entrance, but no focusing was attempted (Fig 7).

Measured yields were in good agreement with LISE calculations and they are reported, for the most populated isotopes, in Table 2. Moreover a transmission of about 70% along the beam line up to the Ciclope scattering chamber was measured without any optical optimization (Fig.8).

Rates between 10 and 100 ions/sec have been measured for the most produced ions at 100 epA of primary beam current.

Therefore, increasing the beam currents up to 100 enA and with the new quadrupoles in the fragment separator which will increase the total acceptance by a factor 10, rates of the order of $10^5 - 10^6$ ions/sec can be achieved.

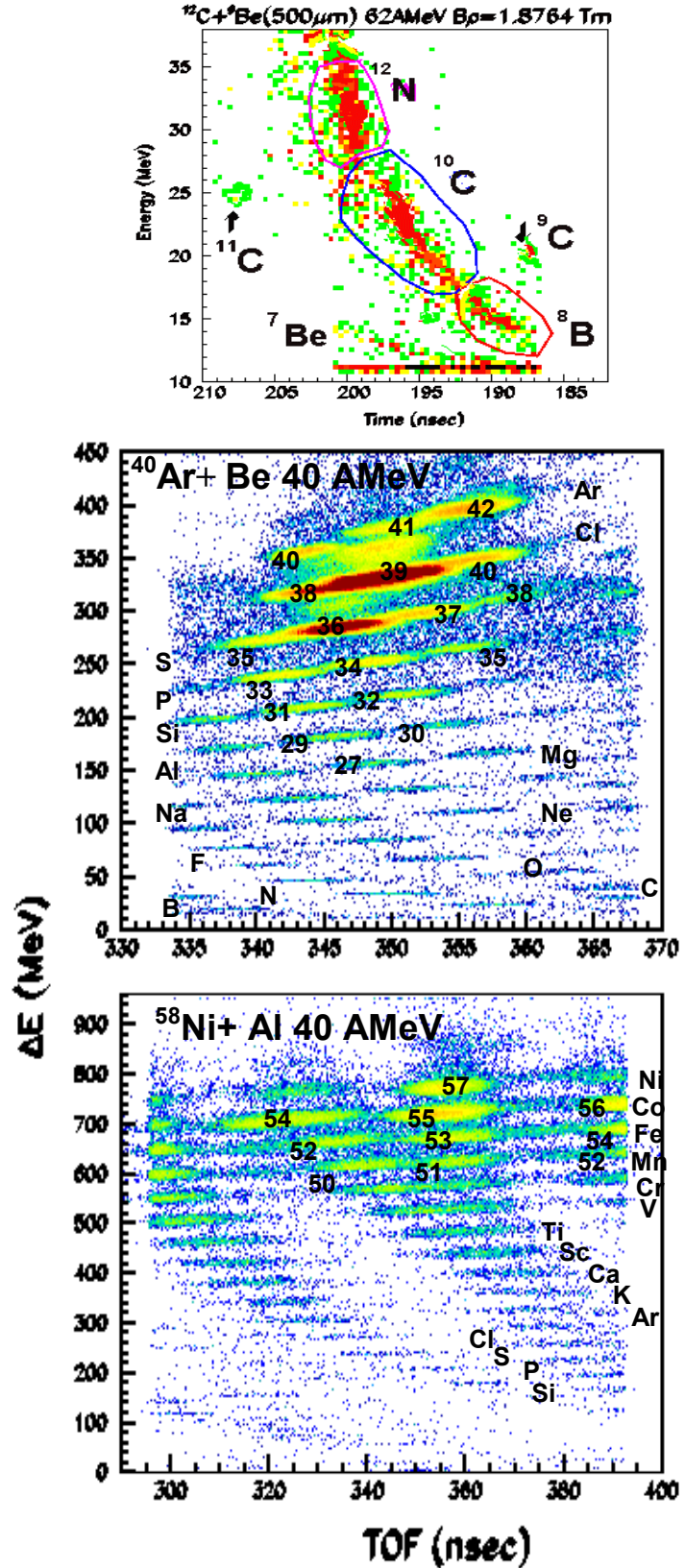


Fig.5: Energy loss in the silicon detector versus ToF.

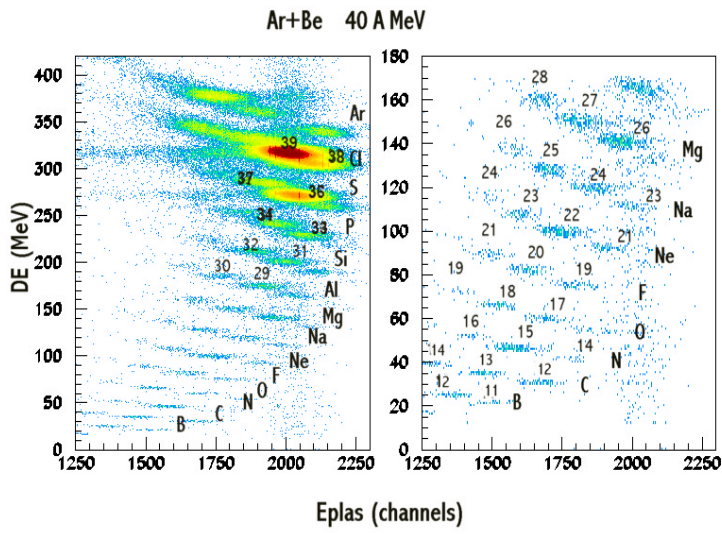


Fig.6: Energy loss versus residual energy in the ^{40}Ar and ^{58}Ni induced reactions.

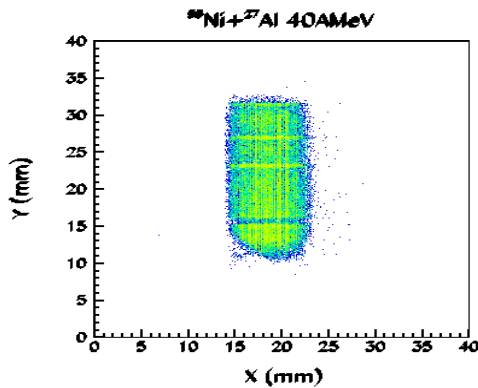


Fig.7: PPAC X-Y position in $^{58}\text{Ni} + ^{27}\text{Al}$ reaction measured in Ciclope.

5. CONCLUDING REMARKS

The preliminary results here presented refer to an experiment intended to identify event-by-event radioactive ions produced in the projectile

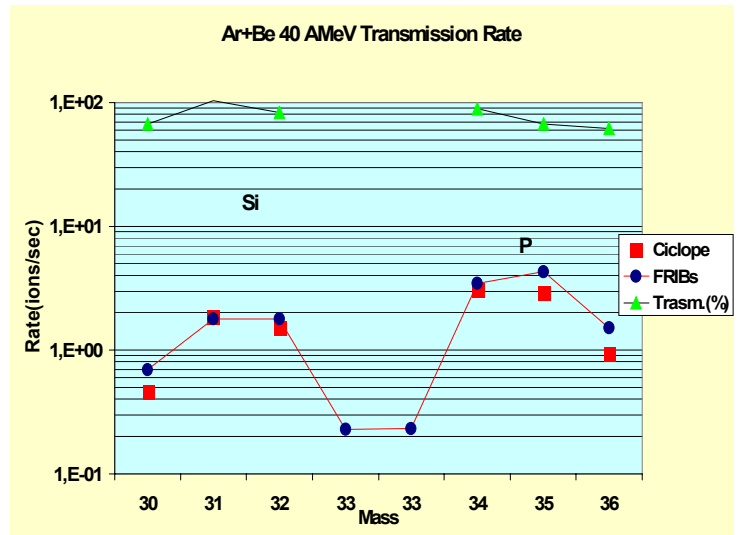


Fig.8: Rates measured at the FRS exit and at the Ciclope entrance in the $^{40}\text{Ar} + ^9\text{Be}$ reaction for $I=100$ epA.

fragmentation. ^{12}C , ^{40}Ar and ^{58}Ni beams were used on light targets.

Very good identification of the products was achieved and production rates were in good agreement with the LISE code estimated ones.

Table 2: Rates of Produced Isotopes for $I_{\text{Beam}}=100$ epA.

C+Be	Ions/sec	Ar+Be	Ions/sec	Ni+Al	Ions/sec
^{12}N	61.2	^{39}Cl	9.3	^{55}Co	1.6
^{10}C	29.0	^{36}S	5.8	^{54}Fe	0.9
^8B	8.8	^{34}P	3.1	^{52}Mn	0.6

Transmission through the beam line was of the order of 70%. The present results show the possibility of producing at the LNS Radioactive Ion Beams at rates of $10^5 - 10^6$ ions/sec that can be used as tagged beams for nuclear reactions or spectroscopy studies.

The authors acknowledge the enthusiastic support from the accelerator staff, and G.Casini, S.Piantelli, G.Immè and the Chimera Group for their help in detectors construction and in the data acquisition setup.

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WEB Site: <http://www.ganil.fr/LISE/prog.html>.

Dependence of fast electrons production from interaction of swift heavy ions with solid thin targets on beam and target atomic number

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Electron emission induced by swift heavy ions on solid targets offers the possibility to probe the theoretical description of ionization processes. Furthermore, effects related to ejection of electrons have important applications in material science and radiation medicine where the knowledge of the intense spatial ionization produced by energetic incident ions in inert or biological matter is essential [1]. In the field of intermediate heavy ions energy range between 20 and 100 A.MeV, in which few studies exist [2-3], we have performed a series of experiments (at LNS and GANIL laboratories) with the ARGOS multidetector, based on use of time-of-flight techniques and scintillators allowing the measurements of velocity spectra and absolute cross sections for angular distributions for the ejected electrons, thus permitting a careful comparison of data with theoretical descriptions of the ionization and transport theories of electrons in solids [4].

In the most recent experiment at LNS (November 2001), we used three different beams, delivered by the Superconducting Cyclotron, 36^{+197}Au , 14^{+58}Ni and 3^{+12}C at the same energy of ~ 23 A.MeV to bombard ^{12}C , ^{27}Al , ^{58}Ni , $^{\text{nat}}\text{Ag}$, ^{197}Au and ^{209}Bi targets of almost the same $90\text{ }\mu\text{g}/\text{cm}^2$ thickness, placed in the CICLOPE scattering chamber. In the experiment 32 phoswich scintillators of the ARGOS multidetector were located in the horizontal plane passing through the target, covering the angular range from 3° to 175° at increasing distance from the target up to 426 cm in the forward direction. A ring of 12 detectors was also positioned at 400 cm from the target

at about 1.5° . Electrons were identified by combining shape discrimination of the photomultiplier signals (“fast” and “slow” components of the detectors) with time-of-flight (TOF); their velocity was determined by the TOF measurement triggered by the CS radiofrequency. Absolute velocity calibration was obtained exploiting the prompt target X-rays or γ -ray peak from nuclear reactions in the target. The overall time resolution was about 1 ns. Electronic threshold was about 8 cm/ns corresponding to electrons of about 20 keV.

In the forward direction electrons are mainly produced by two reaction mechanisms: a binary encounter (BE) between the incident ion and an atomic electron produces electrons with a maximum velocity of almost twice the projectile velocity. Also, target electrons may be captured or projectile electrons may be lost into low lying projectile centered continuum states. These so-called convoy electrons (CE) travel with a velocity close to that of the projectile and lead to a cusp shaped peak in the electron velocity spectra. Electrons with velocity higher than the one corresponding to binary encounter have also been observed and explained as due to multiple scattering within the target-projectile system [2-3,5-6]. The main goal of this experiment is to study the production mechanism of the ejected electrons as a function of beam and target atomic number combinations, in particular extending this study also to electrons ejected in the backward direction where transport effects in the atomic medium of the target become important.

Fig. 1, in which the fast component signal is reported as a function of time-of-flight, gives an example of many of the above described electron emission features for the two reactions $^{197}\text{Au} + ^{197}\text{Au}$ (Fig 1a) and $^{12}\text{C} + ^{12}\text{C}$ both at about 23 A.MeV incident energy:

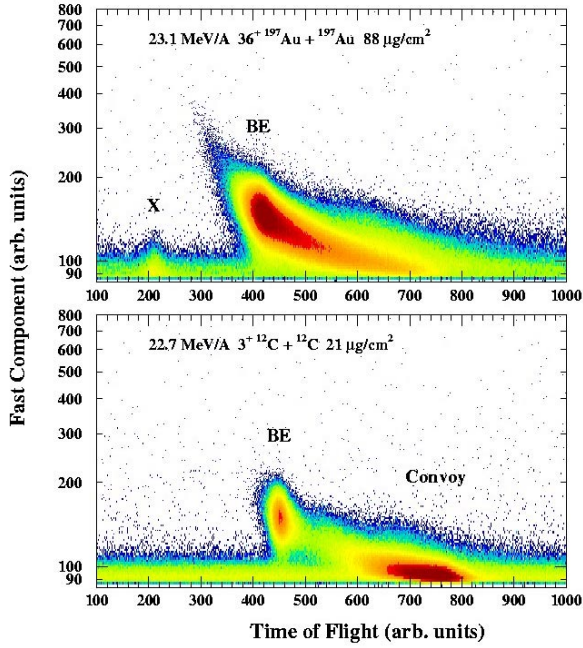


Fig. 1: Fast component – Time-of-Flight plot for electrons ejected at $\theta_{\text{LAB}} = 5^\circ$ in the reaction induced by 23 A.MeV $36^+ ^{197}\text{Au}$ on a Au target ($88 \mu\text{g}/\text{cm}^2$) a), and by 22.7 A.MeV $3^+ ^{12}\text{C}$ on a thin carbon ($21 \mu\text{g}/\text{cm}^2$) target b). The position of prompt X-rays, binary encounter (BE) and convoy electron is indicated. The particle velocity increases in the opposite sense with respect to the one of Time-of-Flight.

The convoy component is mainly observed with lighter beam and target atomic number at the limit of electronic threshold. The BE component is clearly seen in the figure. The broadening of the BE peak in the Au+Au reaction is mainly due to electrons transport through the target whose effect increases with the target thickness and atomic number. The Au+Au reaction evidences also a tail at higher velocity well beyond the BE centroid peak.

Fig. 2 shows the double differential cross section for electrons detected at 5° as a function of the electron velocity for the reactions induced by ^{197}Au on several targets with about the same thickness. The cross section is here normalized to

the number of electrons per unit area [7]. In fact BE yields are roughly proportional to the number of electrons “seen” by the projectile on its way through the target.

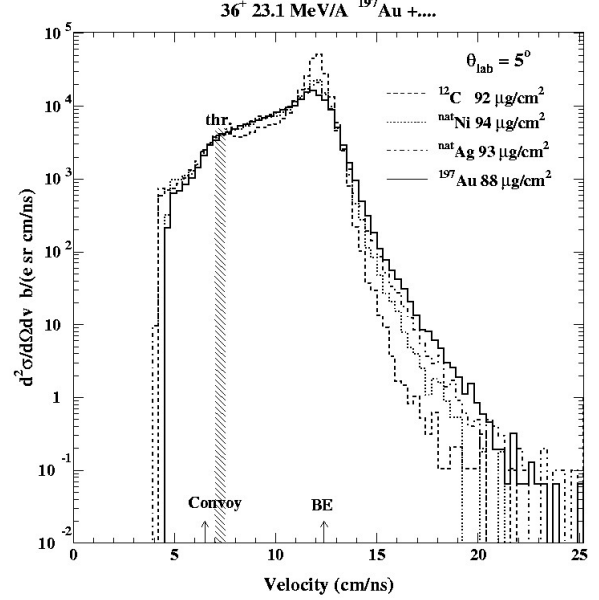


Fig. 2: Double differential cross-section for electrons detected at 5° in reactions induced by 23 A.MeV $36^+ ^{197}\text{Au}$ on different targets. The cross-section is normalized to the total number of target electrons. The electron detection threshold is indicated by the hashed area. Arrows indicates expected values for convoy and BE electron velocities.

The spectra in Fig. 2 show also an extended tail in the high velocity part of the BE peak. A clear dependence of the energetic tail upon the target atomic number is seen in the figure. A possible mechanism to explain the production of these energetic electrons can reside in a multiple collision scattering of electrons between projectile and target. In this mechanism a part of the BE electrons are scattered back in the interaction with the target and have a certain probability to collide again with the incoming projectile. Data collected in our experiment will permit to study in detail this interesting process as a function of the target and projectile atomic number.

An important fraction of electrons produced in the interaction with the target are deviated at backward angles. Fig. 3 shows double differential cross section for electrons detected at 175° in the reaction induced by ^{197}Au on various targets. The

spectra present an almost exponential tail and are affected in a significant way by threshold effects.

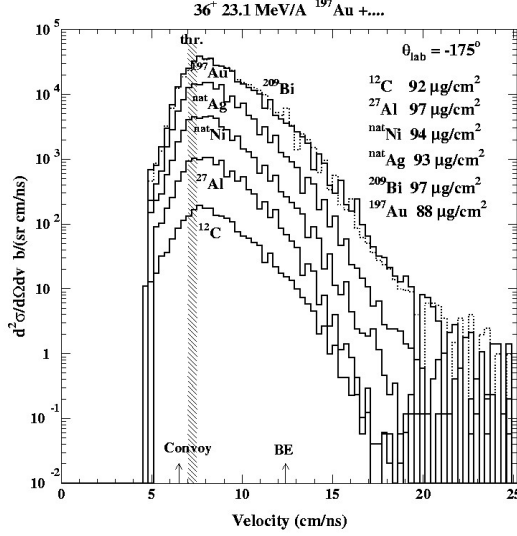


Fig. 3: Double differential cross-section for electrons detected at 175° in reactions induced by 23 A.MeV $36^+ {}^{197}\text{Au}$ on different targets.

The figure shows also the dependence of the production yield for backscattered electrons from the atomic number of the scattering center: in fact an increase of the cross section with target atomic number is clearly observed.

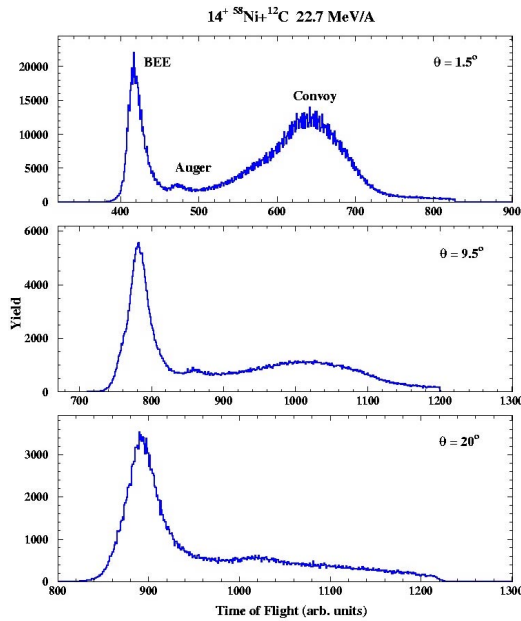


Fig. 4: Electron Time-of-Flight for the reaction induced by 22.7 A.MeV $14^+ {}^{58}\text{Ni}$ beam on a $21 \mu\text{g}/\text{cm}^2$ carbon target at three different laboratory angles.

Finally electrons with velocity intermediate between the beam velocity and BE velocity can be observed. Generally they are due to electron transport effects in the target [7] so their cross section production increases with target thickness and/or target atomic number. Another source of intermediate velocity electrons can be the emission of Auger electrons [8] that could be the origin of the peak observed at the top of Fig. 4 for the reaction $14^+ {}^{58}\text{Ni}$ (22.7 A.MeV) + ${}^{12}\text{C}$. The Auger process is in competition with radiative X-rays emission (with higher probability for low atomic number atoms) and produces electrons of well defined energy. Auger electrons produced in the rest frame of the projectile will have in the laboratory frame a velocity given by the composition of the projectile velocity and Auger electron velocity. In the case of a ${}^{58}\text{Ni}$ excited atom an Auger transition should produce electrons with a velocity of 4.6 cm/ns. From experimental data taken at forward angles, where the intermediate peak can be easily selected, we have evaluated for this peak, in the rest frame of the projectile, a velocity of about 4.0 cm/ns, very close to the predicted value.

We have presented preliminary results of a recent experiment at LNS in which the dependence on beam and target atomic number of fast electron emission has been studied using a large projectile-target combination at beam energy of 23 A.MeV. Absolute production cross-sections can be measured allowing cogent comparison with atomic ionization and transport theories. In the forward direction electron emission is dominated by convoy and binary encounter components, but velocity spectra present a complex behaviour and a strong dependence on beam-target combination. The velocity spectra exhibit, mainly at forward angles, an energetic tail that can be explained by a multi-scattering mechanism. In reactions induced by ${}^{58}\text{Ni}$ beam on thin targets we have evidenced an intermediate velocity component that could be interpreted as due to in-flight deexcitation of excited projectiles by Auger electron emission. But this interesting problematic requires more detailed further analysis.

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Spin-polarized states of nuclear matter

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The equations of state of spin-polarized nuclear matter and pure neutron matter are studied in the framework of the Brueckner-Hartree-Fock theory including a three-body force. The energy per nucleon $E_A(\delta)$ calculated in the full range of spin polarization $\delta = \frac{\rho_{\uparrow} - \rho_{\downarrow}}{\rho}$ for symmetric nuclear matter and pure neutron matter fulfills a parabolic law. In both cases the spin-symmetry energy is calculated as a function of the baryonic density along with the related quantities such as the magnetic susceptibility and the Landau parameter G_0 . The main effect of the three-body force is to strongly reduce the degenerate Fermi gas magnetic susceptibility even more than the value with only two body force. The EOS is monotonically increasing with the density for all spin-aligned configurations studied here so that no any signature is found for a spontaneous transition to a ferromagnetic state.

I. INTRODUCTION

Studies of spin-polarized nuclear and neutron matter have been mainly focussed on the possible onset of a ferromagnetic transition in the neutron star core. This transition could explain in fact the high intensity magnetic fields (10^{12} gauss) estimated from the timing observations in pulsars and magnetars (for a review see Ref. [1]). Besides this exciting issue the motivation for such studies can be based on a more general context of nuclear physics.

First of all, from the change of the energy per nucleon with the spin polarization one may extract a theoretical prediction for the spin symmetry energy, whose empirical value is so far quite uncertain. The nuclear matter instability against spin fluctuations is driven by the Landau parameter G_0 which is determined from the spin-symmetry energy. The value of this parameter is still a largely controversial topic and no agreement exists among the different approaches to the theory of nuclear matter [2]. Experimental information could come from spin giant resonances, which have not yet been clearly observed. Information could also come from heavy-ion collisions as soon as polarized heavy targets become available. Extending the calculation to spin-polarized asymmetric nuclear matter one may also have access to the Landau parameter G'_0 , which is related to spin-isospin density fluctuation. In this case a constraint is provided by the Gamow-Teller giant resonances.

The second issue related to the study of spin-aligned states of nuclear matter is the propagation of neutrinos in neutron stars. It has been shown that the neutrino mean free path is strongly affected by the magnetic susceptibility. The latter is sizeably suppressed by the strong correlations in nuclear matter and, as a consequence, the mean free path might change sizeably and, eventually drop to zero in the presence of a ferromagnetic transition [3, 4].

There is a guess that the ferromagnetic transition could be a relativistic effect due to π -exchange and in fact all

calculations, based on the relativistic mean field approach, predict this transition to occur in dense matter [5, 6]. On the other hand, non-relativistic approaches [7–10] do not support such a transition except Hartree-Fock calculations with phenomenological Skyrme-like forces (for a review see Ref. [4]). This aspect cannot be disconnected from the problem of the in-medium nucleon-nucleon (NN) force, which is poorly known in dense matter due to the lacking of empirical constraints far above the saturation density. However important relativistic effects can be incorporated into the effective interaction via the three-body force associated with a virtual nucleon-antinucleon excitation [11]. Moreover non-relativistic calculations including only two-body forces miss the empirical saturation point of nuclear matter [12]. So it seems worthwhile to investigate the spin-aligned states of nuclear and neutron matter in the non-relativistic Brueckner theory with three-body forces. They contain not only the above mentioned relativistic contributions but also nucleonic excitations which decisively enhance the agreement between theoretical and empirical saturation density [13].

II. FORMALISM

The spin and isospin asymmetric nuclear matter (ANM) consists of spin-up neutrons ($n \uparrow$), spin-down neutrons ($n \downarrow$), spin-up protons ($p \uparrow$) and spin-down protons ($p \downarrow$) in different density states: $\rho_{n\uparrow}$, $\rho_{n\downarrow}$, $\rho_{p\uparrow}$, and $\rho_{p\downarrow}$, respectively. Therefore four parameters are required to specify a given configuration of spin and isospin ANM. The Fermi momenta of the four components are generally different from each other, and related to their respective densities by the following relation:

$$\rho_{\lambda} = \frac{1}{6\pi^2} (k_F^{\lambda})^3$$

where λ denotes the z -components of isospin and spin, i.e., $\lambda = (\tau_z, \sigma_z)$. Instead of ρ_{λ} , one can use the following

four parameters to identify a given spin and isospin state,

$$\beta = \frac{\rho_n - \rho_p}{\rho}, \quad \delta_n = \frac{\rho_{n\uparrow} - \rho_{n\downarrow}}{\rho_n}, \quad \delta_p = \frac{\rho_{p\uparrow} - \rho_{p\downarrow}}{\rho_p},$$

where ρ , ρ_n , and ρ_p are total density, neutron density and proton density, respectively. The ratio β is the isospin asymmetry parameter and δ_n and δ_p are the spin asymmetry parameters for neutrons and protons, respectively.

The starting point of the Brueckner-Bethe-Goldstone (BBG) approach is the reaction G -matrix. The G -matrix incorporates strong short-range correlations in nuclear medium by means of the infinite ladder diagram summation of the bare NN interaction. It satisfies the Bethe-Goldstone equation. The latter can be expressed for the spin-isospin ANM in the total angular-momentum basis as follows,

$$G_{LL'}^{TSJ, \lambda\lambda'}(\omega, P; q, q'; \rho, \beta, \delta_n, \delta_p) = v_{LL'}^{TSJ}(q, q') + \frac{2}{\pi} \sum_{L''} \int q''^2 dq'' v_{LL''}^{TSJ}(q, q'') \\ \times \frac{\langle Q^{\lambda\lambda'}(q'', P) \rangle}{\omega - e_{12}^{\lambda\lambda'}(q'', P) + i\eta} G_{L''L'}^{TSJ, \lambda, \lambda'}(\omega, P; q'', q'; \rho, \beta, \delta_n, \delta_p)$$

where $v_{LL'}^{TSJ}(q, q')$ are the partial wave components of the NN interaction, $\vec{P} = \vec{k}_1 + \vec{k}_2 = \vec{k}'_1 + \vec{k}'_2$ is the total momentum, $\vec{q} = \frac{\vec{k}_1 - \vec{k}_2}{2}$ and $\vec{q}' = \frac{\vec{k}'_1 - \vec{k}'_2}{2}$ the relative momenta of the two particles in their initial state and final state, respectively. The Pauli operator $Q^{\lambda\lambda'}(\vec{q}'', \vec{P})$ and the energy denominator $e_{12}^{\lambda\lambda'}(\vec{q}'', \vec{P}) = \epsilon^\lambda(k''_1) + \epsilon^{\lambda'}(k''_2)$ have been angle averaged in order to remove the coupling between different channels $\alpha = \{JST\}$. It is worth noticing that the different components of the G -matrix differ in general from each other due to the dependence of the Pauli operator and energy denominator on the spin-isospin configuration (λ, λ') . The single particle energy is given by $\epsilon^\lambda(k) = \hbar^2 k^2 / 2m + U^\lambda(k)$. The continuous choice for the auxiliary potential $U^\lambda(k)$ is adopted in the present calculations since, on the one hand, it has been shown to provide a much faster convergence of the

hole-line expansion than the gap choice [15], on the other hand, it describes physically the single-particle potential felt by a nucleon in nuclear medium. In the continuous choice, $U^\lambda(k)$ is the real part of the on-shell mass operator, i.e.,

$$U^\lambda(k) = Re \sum_{\vec{k}', \lambda'} n^{\lambda'}(k') \langle \vec{k}\lambda, \vec{k}'\lambda' | G[\omega] \\ = \epsilon^\lambda(k) + \epsilon^{\lambda'}(k'), P | \vec{k}\lambda, \vec{k}'\lambda' \rangle_A,$$

where the subscript A denotes antisymmetrization. For spin and isospin ANM, it is convenient to split it into two contributions as

$$U^\lambda = U^{\lambda\lambda} + U^{\lambda\lambda'}, \quad (\lambda' \neq \lambda).$$

Each individual contribution is calculated by casting it into the partial wave expansion,

$$U^{\sigma_z \tau_z, \sigma'_z \tau'_z}(k) = \int_0^{k_F^{\sigma'_z \tau'_z}} d^3 k' \sum_{TSJ} \sum_{LL'} \sum_{S_z T_z} i^{L-L'} \left[C\left(\frac{1}{2}\sigma_z \frac{1}{2}\sigma'_z | SS_z\right) \right]^2 \left[C\left(\frac{1}{2}\tau_z \frac{1}{2}\tau'_z | TT_z\right) \right]^2 \\ \times \sum_{M_L} C(L' M_L SS_z | J M_L + S_z) C(L M_L SS_z | J M_L + S_z) Y_{L' M_L}^*(\hat{q}) Y_{L M_L}(\hat{q}) \\ \times 2G_{LL'}^{TSJ, \lambda\lambda'}(\omega, P, q, q; \rho, \beta, \delta_n, \delta_p).$$

The summation over partial wave states is physically constrained by the selection rule $S + T + L = \text{odd}$ due to the Pauli principle and consequently the antisymmetrization of the G -matrix simply implies multiplication by a factor of 2 for the allowed partial wave channels. For spin symmetric case ($\delta_n = \delta_p = 0$), a spin-up neutron (proton) has the same Fermi momentum as a spin-down

neutron (proton) and thus the single-particle potential felt by a nucleon does not depend on the direction of its spin. The summation on the spins of the two particles in the final state and the average of that in the initial state remove the non-diagonal contributions in angular-momentum from the single-particle potential. One easily finds

$$U^{\tau_z \tau'_z}(k) = \frac{1}{2} \sum_{\sigma_z \sigma'_z} U^{\sigma_z \tau_z, \sigma'_z \tau'_z}(k) = \frac{1}{2} \int_0^{k_F^{\tau'_z}} d^3 k' \sum_{TSJL} \sum_{T_z} \left[C\left(\frac{1}{2} \tau_z \frac{1}{2} \tau'_z | TT_z\right) \right]^2 \frac{2J+1}{4\pi} 2G_{LL}^{TSJ, \tau_z \tau'_z}(\omega, P, q, q; \rho, \beta).$$

For spin-asymmetric but isospin-symmetric nuclear matter, we have $\beta = 0$ and $\delta_n = \delta_p = \frac{\rho_\uparrow - \rho_\downarrow}{\rho} = \delta$. In this

case, the single particle potential becomes,

$$U^{\sigma_z, \sigma'_z} = \int_0^{k_F^{\sigma'_z}} d^3 k' \sum_{TSJ} \frac{2T+1}{2} \sum_{LL'} \sum_{S_z} i^{L-L'} \left[C\left(\frac{1}{2} \sigma_z \frac{1}{2} \sigma'_z | SS_z\right) \right]^2 2G_{LL'}^{TSJ, \sigma_z \sigma'_z}(\omega, q, q; \rho, \delta) \\ \times \sum_{M_L} C(L' M_L SS_z | J M_L + S_z) C(L M_L SS_z | J M_L + S_z) Y_{L' M_L}^*(\hat{q}) Y_{L M_L}(\hat{q}).$$

The present calculations will mainly consider this spin-polarized nuclear matter as well as the spin polarized neutron matter.

III. RESULTS AND CONCLUSIONS

We performed some calculations within the BHF self-consistent approach above described. The Argonne V_{18} force is adopted as bare two-body interaction. This has been implemented by a microscopic three-body force, which is described in detail in Ref. [16] together with the average procedure to transform it into an effective two body force. In Fig. 1 the energy shift per nucleon $E_A(\delta, \rho) - E_A(0, \rho)$ in symmetric nuclear matter is reported as a function of the square of spin polarization δ^2 for a set of densities. Due to the linear dependence on δ^2 , also reported in Refs. [9, 10] one can write:

$$E_A(\delta, \rho) = E_A(0, \rho) + \mathcal{E}_{sym}(\rho) \delta^2,$$

i.e. the spin dependence of the energy per nucleon can be simply expressed in terms of spin-symmetry energy

$$\mathcal{E}_{sym}(\rho) = \frac{1}{2} \frac{\partial^2 E_A(\delta, \rho)}{\partial \delta^2}$$

in the density range here considered.

The δ^2 -law is mainly due to the BHF approximation (two-hole line terms only). The same behavior is in fact exhibited by the energy vs. isospin either [14]. The effects of three-hole line terms are rather small when adopting the continuous choice for the auxiliary potential [15]; this choice is also adopted for the present calculations. The slope of the energy shift is monotonically increasing with density so that no signature for a ferromagnetic phase transition in symmetric nuclear matter is expected.

The effect of three-body force is to enhance this slope for densities above the saturation point. This effect is more clearly shown in the plot of $\mathcal{E}_{sym}$ vs. density in Fig. 1.

The magnetic susceptibility has been also calculated from the spin-symmetry energy

$$\chi = \frac{\bar{\mu}^2 \rho}{2\mathcal{E}_{sym}},$$

where $\bar{\mu}$ is the average of neutron and proton magnetic moments (in neutron matter $\bar{\mu}$ is the exact neutron magnetic moment). Usually one calculates the ratio of χ to χ_F , χ_F being the magnetic susceptibility for a degenerate free Fermi gas. The effect of strong correlations in nuclear matter due to the two-body force is a reduction of χ with respect to χ_F . This reduction increases with density up to a factor of 0.3 at $\rho = 0.8 fm^{-3}$. The above result is common to most Bruckner calculations [8–11]. More pronounced is the quenching due to three-body force. Fig. 2 also shows the Landau parameter G_0 describing the spin density fluctuations in the effective interaction. G_0 is simply related to the spin-symmetry energy or, equally, to the magnetic susceptibility by the relation

$$\frac{\chi}{\chi_F} = \frac{m^*}{1 + G_0}$$

where m^* is the effective mass. A magnetic instability would require $G_0 < -1$ which is analogous to the condition $F_0 < -1$ for the mechanical instability giving rise to the liquid-vapour phase transition. But, the value of G_0 vs. density from the BHF calculations is always positive and monotonically increasing up to the highest density. The three-body force pushes up the curve of χ . This result is in strong disagreement with the prediction with Skyrme forces. This is not a complete surprise since Skyrme forces are only well suited in the proximity of the empirical saturation point. Astonishing is the

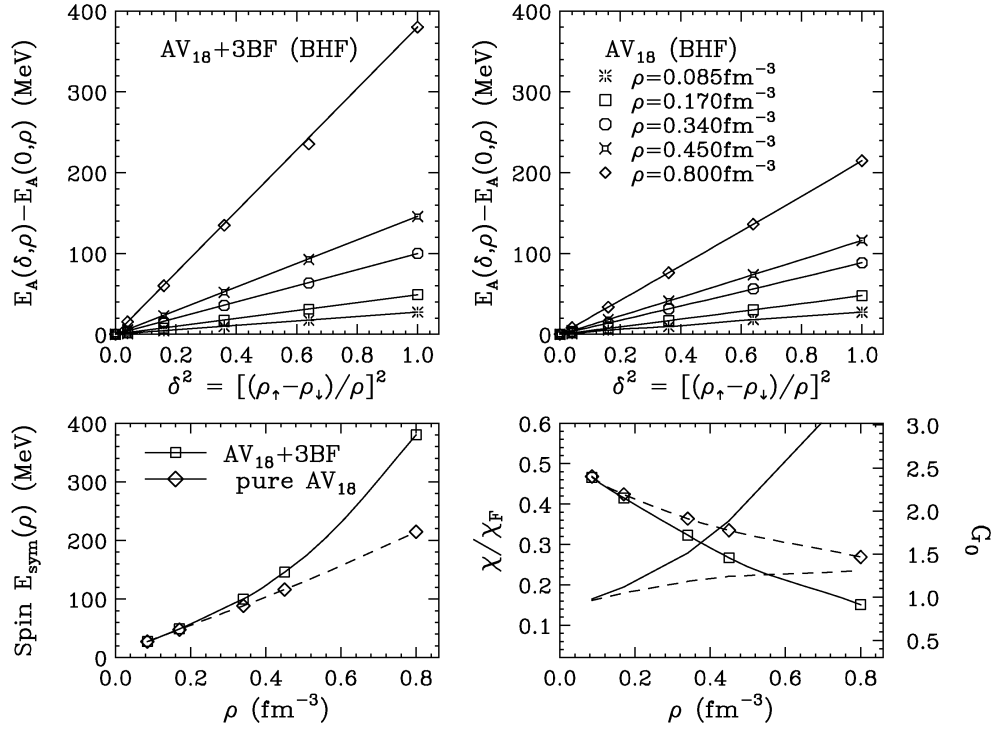


FIG. 1: Upper windows: The EOS of spin-asymmetric nuclear matter as a function of spin-asymmetry at five values of density, predicted by Brueckner Hartree-Fock calculations adopting pure AV_{18} two-body force (right-upper window) and AV_{18} plus the TBF(left-upper window). Right-Lower window: density dependence of spin-symmetry energy for both cases with the TBF (solid curve) and without the TBF(dash curve). Left-lower window: Magnetic susceptibility χ/χ_0 (curves with symbol) and Landau parameter G_0 (curves without symbol) as functions of density.

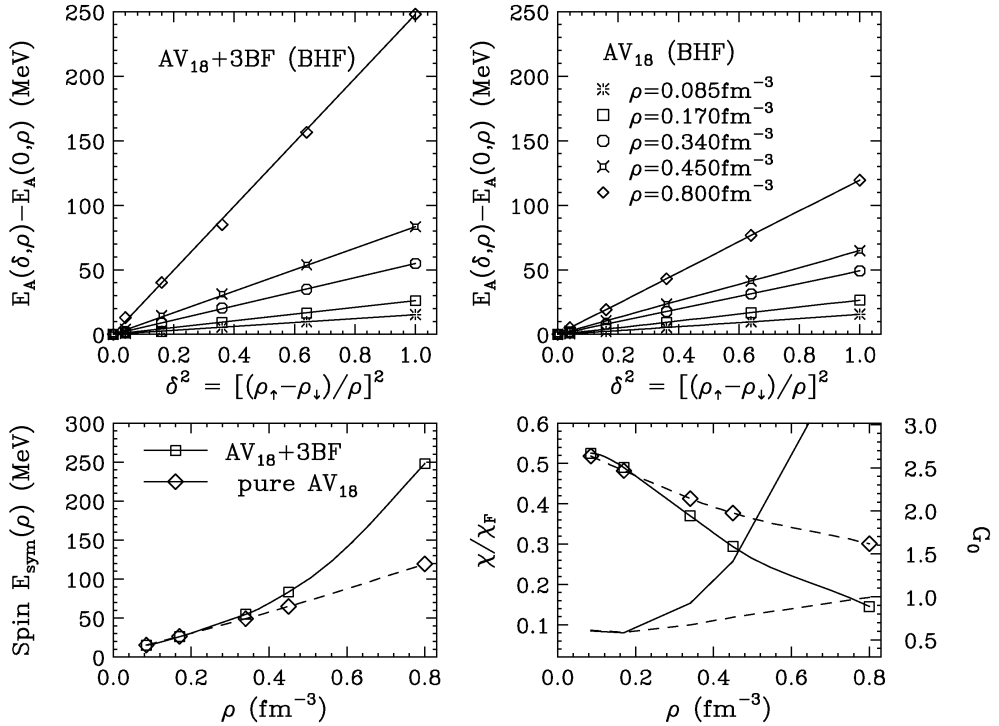


FIG. 2: The same as Fig.1 for spin-polarized neutron matter.

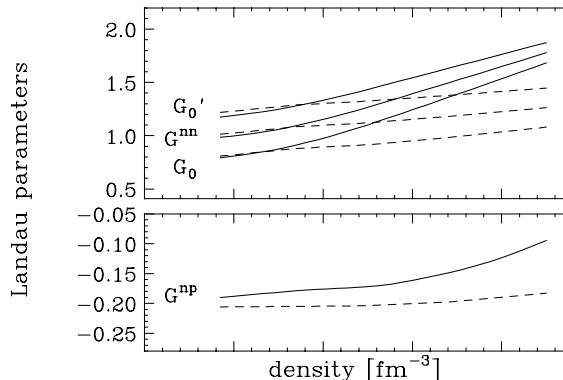


FIG. 3: Landau parameters G_0 and G'_0 in the BHF approximation (dashed lines) and BHF plus TBF (solid lines).

strong disagreement on this respect with the relativistic approaches because the three-body forces contain already important relativistic effects [16]. The accurate knowl-

edge of G_0 should lead to reliable predictions on the spin and spin-isospin giant modes as well as spin-spin part of the optical potential [8]. Extending the calculation to asymmetric nuclear matter, we can also calculate Landau parameter $G'_0 = G^{nn} - G^{np}$. The result is reported in Fig.3, where also G_0 is reported for comparison. The result is quite satisfactory equivalent with experimental data on the Gamow-Teller giant resonances. [17].

The above calculations have been also repeated for the case of pure neutron and reported in Fig. 2. The same conclusions can be drawn as to the absence of the ferromagnetic phase transition and the quenching of the magnetic susceptibility caused by the strong correlations from the two- and three-body forces. This quenching should have a strong influence on the neutrino propagation in dense matter such as supernovae and neutron stars. In the case of the transition to a ferromagnetic state it has been shown that the mean free path could drop to zero [3] that could have remarkable consequences as, for instance, on the neutron star cooling.

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Correlation effects in the superfluidity of neutron matter

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We study the superfluidity of neutron matter in the framework of the generalized gap equation. The second order effects of correlations have been included on the same footing, i.e. correcting the pairing interaction by the one-bubble exchange term and the selfenergy by the one-bubble insertions. The gap is calculated selfconsistently with the selfenergy in order to take into account the pairing effects on the selfenergy itself. Due to the energy dependence of the polarization potential the dynamical effects on the pairing gap have been studied. Preliminary results adopting the Gogny force as NN interaction are presented in this report.

Since nuclear matter is a strongly correlated Fermi system, the onset of superfluidity can be studied only if the correlation effects are properly taken into account. Short range correlations are already included in the BCS gap equation with the bare pairing interaction [1]. Long range correlations appear at the second order of the expansion of irreducible interaction block in the generalized gap equation [2]. These correlations also modify the self-energy as well as the depletion of the level density around the Fermi energy, which plays a crucial role in the formation of Cooper pairs. The screening of the pairing interaction and the selfenergy effects have been investigated separately, giving a sizeable suppression for the pairing gap [1, 2]. So far their simultaneous effect has never been investigated. Moreover the selfenergy appearing in gap equation should be also corrected by the effect of the gap itself on the quasiparticle spectrum, which entails a selfconsistent calculation of gap and selfenergy.

We have solved the generalized gap equation treating on the same footing the second-order corrections to the pairing interaction and to the selfenergy, i.e. one-bubble insertion in the selfenergy (as shown in Fig. 1) and one-bubble exchange in the interaction (as shown in Fig. 2).

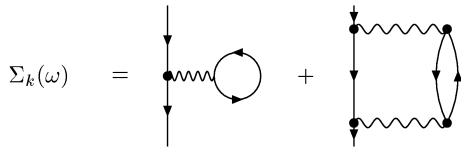


FIG. 1: Self-energy terms included in the gap equation. The wiggle represent the effective interaction, e.g. G-matrix

We have solved the generalized gap equation adopting as bare NN interaction (first term in Fig. 2) the Gogny force. We are aware that we should have adopted a true bare interaction at the lowest order according to Fig. 2, but it is not a bad approximation in this preliminary calculation. In Fig. 3 we present the solution of the gap equation. As a function of momentum the shape of Δ exhibits the expected oscillatory behavior but its magnitude is quenched in comparison with the prediction with-

out screening effect. The ω dependence exhibits a deep

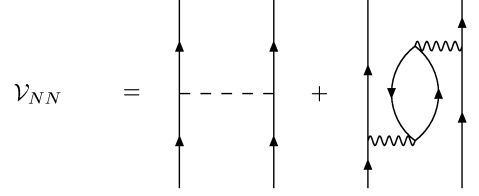


FIG. 2: Pairing interaction at the second order. The dashed line represents the bare interaction and the wiggles the effective interaction

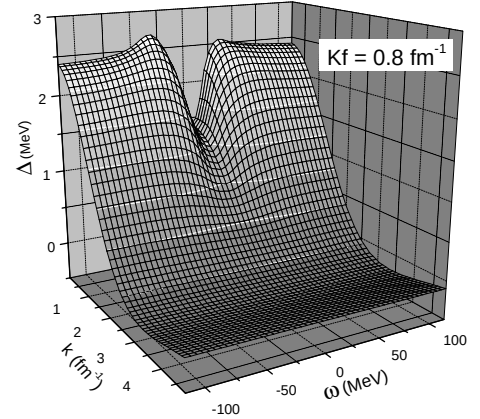


FIG. 3: Gap varying with ω and k for $k_F = 0.8 \text{ fm}^{-1}$

depression around the Fermi energy so that the gap at $k = k_F$ and $\omega = \omega_F$ turns about to be very close the prediction reported in Ref. [1]. Dynamical effects of the pairing gap are still to be studied in more detail.

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Asymmetric nuclear matter in Quantum Hadrodynamics

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We discuss the *EOS* and the collective response of Asymmetric Nuclear matter (*ANM*) based on the Quantum Hadro-Dynamics (*QHD*) effective field picture. We focus our attention on the equilibrium and dynamical effects of the interplay between scalar and vector channel contributions. An interesting “mirror” structure in the form of the effective meson contributions in the isoscalar/isovector degree of freedom is revealed. A complete parallelism is observed in the interplay between scalar and vector mesons in determining respectively compressibility and symmetry energy. All that seems to support the introduction of an explicit coupling to the scalar-isovector channel of the nucleon-nucleon interaction.

In particular we study the influence of this coupling (to a δ -meson-like effective field) on the collective response of asymmetric nuclear matter (*ANM*). Interesting contributions are found on the propagation of isovector-like modes at normal density and on an expected smooth transition to isoscalar-like oscillations at high baryon density.

Important “chemical” effects on the neutron-proton structure of the mode are shown. For dilute *ANM* we have the isospin distillation mechanism of the unstable isoscalar-like oscillations, while at high baryon density we predict an almost pure neutron wave structure of the propagating sounds.

The QHD effective theory

The *QHD* effective field model represents a very successful attempt to describe, in a fully consistent relativistic picture, equilibrium and dynamical properties of nuclear systems at the hadronic level [1–3]. Very nice results have been obtained for the nuclear structure of finite nuclei, for the *NM* Equation of State and liquid-gas phase transitions and for the dynamics of nuclear collisions.

In this project we will mainly focus our attention on the dynamical response of asymmetric nuclear matter since one of the main points of our discussion is the relevance of the coupling to a scalar isovector channel, the virtual $\delta[a_0(980)]$ meson, not considered in the usual Relativistic Mean Field (*RMF*) studies.

The isospin physics is assuming more and more relevance in connection to the new radioactive beam

facilities and to nuclear astrophysics. The introduction of the isovector/scalar channel in covariant approaches can play a key role in the effective interaction in asymmetric matter, see ref. [4]. This point has not received great attention before for two main reasons:

i) The δ -channel has not been considered *a priori*, just on the basis of the weak contribution to the free Nucleon-Nucleon interaction. But in the spirit of the *Effective Field Theory* as a relativistic *Density Functional Theory*, (the *EFT/DFT* framework, see [5]), the relevance of this channel could be completely different in nuclear matter, due to medium and many-body effects. In particular we can expect a large contribution from exchange terms of the strongly coupled isoscalar channels, see the discussion in ref. [6] as well as in [4].

ii) This extension is not well supported by the existing set of data. Clearly these negative outcomes are mainly derived from the lack of information on observables more sensitive to the density dependence of the symmetry term.

We like to note that very recently, see the conclusions of ref. [7], the δ -channel has been reconsidered as an interesting improvement of covariant approaches, in the framework of the *EFT/DFT* philosophy. One of the main tasks of our work is just to try to select the dynamical observables more sensitive to it, see also the conclusions of ref. [4].

Our results around normal density can be used as general guidelines in predicting the behaviour of volume collective modes in finite β -unstable nuclei. Similar study for asymmetric *NM* have been performed in Ref. [8] using Skyrme-like interactions.

In order to include the main dynamical degrees of freedom of the system we will consider the nucleons coupled to the isoscalar scalar σ and vector ω mesons and to the isovector scalar δ and vector ρ mesons.

For the nucleon fields we get a Dirac-like equation. All the equations can be consistently solved in a Mean Field Approximation (*RMF*), where most applications have been performed, in particular in the Hartree scheme.

The inclusion of Fock terms is conceptually important since it automatically leads to contributions to various channels, also in absence of explicit coupling

terms. A thorough study of the Fock contributions in a QHD approach with non-linear self-interacting terms has been recently performed [9], in particular for asymmetric matter [6].

Within a mean field picture of the QHD model we focus our analysis on a description of the many-body nuclear system in terms of one-body dynamics.

We perform the many-body calculations in the quantum phase-space introducing the Wigner transform of the one-body density matrix for the fermion field defined as:

$$[\hat{F}(x, p)]_{\alpha\beta} = \frac{1}{(2\pi)^4} \int d^4 R \epsilon^{-ip \cdot R} \langle : \bar{\psi}_\beta(x + \frac{R}{2}) \psi_\alpha(x - \frac{R}{2}) : \rangle, \quad (1)$$

where α and β are double indices for spin and isospin. The brackets denote statistical averaging and the colons denote normal ordering. The Wigner function is a matrix in spin and isospin spaces; in the case of Asymmetric NM it is useful to decompose it into neutron and proton components. Following the treatment of the Fock terms in non-linear QHD introduced in Refs. [9,6], we obtain from the Dirac eq. a kinetic equation for the Wigner function, that can be eventually solved in linear approximation in order to get the dispersion relations for normal, stable and unstable, modes in various regions of baryon densities [10].

Equilibrium properties: the nuclear Equation of State

The energy density and pressure for symmetric and asymmetric nuclear matter and the n, p effective masses can be self-consistently calculated just in terms of the four boson coupling constants, $f_i \equiv (\frac{g_i^2}{m_i^2})$, $i = \sigma, \omega, \rho, \delta$, and the two parameters of the σ self-interacting terms, $A \equiv \frac{a}{g_\sigma^3}$ and $B \equiv \frac{b}{g_\sigma^2}$, see ref. [9,6].

The isoscalar meson parameters are fixed from symmetric nuclear matter properties at $T = 0$. They have quite standard values for these minimal non-linear RMF models.

The symmetry energy in ANM is defined from the expansion of the energy per nucleon $E(\rho_B, \alpha)$ in terms of the asymmetry parameter $\alpha \equiv \frac{N-Z}{A}$:

$$\begin{aligned} E(\rho_B, \alpha) &\equiv \frac{\epsilon(\rho_B, \alpha)}{\rho_B} \\ &= E(\rho_B) + E_{sym}(\rho_B) \alpha^2 \\ &\quad + O(\alpha^4) + \dots \end{aligned} \quad (2)$$

and so in general

$$E_{sym} \equiv \frac{1}{2} \frac{\partial^2 E(\rho_B, \alpha)}{\partial \alpha^2} \Big|_{\alpha=0} = \frac{1}{2} \rho_B \frac{\partial^2 \epsilon}{\partial \rho_{B3}^2} \Big|_{\rho_{B3}=0} \quad (3)$$

In the Hartree case an explicit expression for the symmetry energy can be easily derived [4]

$$\begin{aligned} E_{sym}(\rho_B) &= \frac{1}{6} \frac{k_F^2}{E_F^*} + \frac{1}{2} \left[f_\rho - f_\delta \left(\frac{M^*}{E_F^*} \right)^2 \right] \rho_B \\ &\equiv E_{sym}^{kin} + E_{sym}^{pot} \end{aligned} \quad (4)$$

where k_F is the nucleon Fermi momentum corresponding to ρ_B , $E_F^* \equiv \sqrt{(k_F^2 + M^{*2})}$ and M^* is the effective nucleon mass in symmetric NM , $M^* = M_N - g_\sigma \phi$.

We see that, when the δ is included, the observed a_4 value actually assigns the combination $[f_\rho - f_\delta (\frac{M}{E_F})^2]$ of the (ρ, δ) coupling constants. If $f_\delta \neq 0$ we have to increase the ρ -coupling. In our calculations we use the value $a_4 = 32 \text{ MeV}$.

Now the symmetry energy at saturation density is actually built from the balance of scalar (attractive) and vector (repulsive) contributions, with the scalar channel becoming weaker with increasing baryon density [4]. This is indeed the isovector counterpart of the saturation mechanism occurring in the isoscalar channel for the symmetric nuclear matter. From such a scheme we get a further support to the introduction of the δ -coupling in the symmetry energy evaluation.

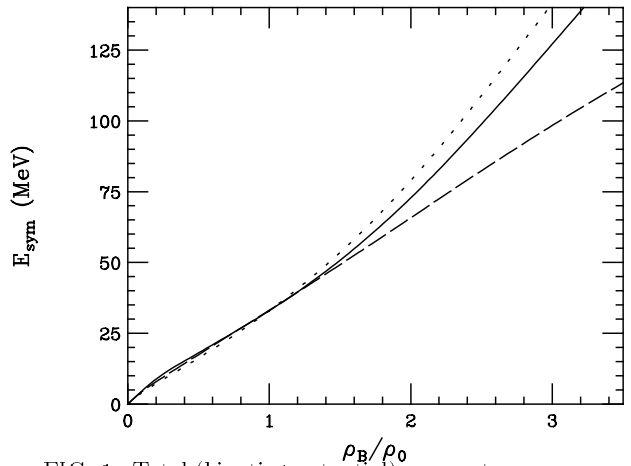


FIG. 1. Total (kinetic+potential) symmetry energy as a function of the baryon density. Long dashed: Hartree ($NLH + \rho$). Dotted: Hartree ($NLH + \rho + \delta$). Solid: Hartree-Fock ($NLHF$).

Details of the calculation can be found in Refs. [6,4]. In Fig.1 we report the symmetry energy as a function of the baryon density in the Hartree case (ρ and $\rho + \delta$) and with the Fock terms [$(\rho + \delta)$ case]. When the δ “channel” is included the behaviour is stiffer for the relativistic mechanism discussed before, see also ref. [4].

Linear Response

We study collective oscillations that propagate in cold nuclear matter due to the mean field dynamics. In some sense we follow a relativistic extension of the method introduced by Landau to study liquid- ^3He [11–13] and recently applied to investigate stable and unstable modes in nuclear matter [8,14]. The starting point is the relativistic kinetic transport equation. We look for solutions corresponding to small oscillations of $\hat{F}(x, p)$ around the equilibrium value. Therefore we put

$$\hat{F}(x, p) = \hat{H}(p) + \hat{G}(x, p) \quad (5)$$

where $\hat{H}(p)$ is the Wigner function at equilibrium and $\hat{G}(x, p)$ represent its fluctuations.

By Fourier transforming and integrating over four-momentum, in linear approximation we get the set of equations for the scalar and vector fluctuation of each species ($i = 1, 2$ for proton, neutron respectively), see ref. [10].

The normal collective modes are plane waves, characterized by the wave vector ($k^\mu = (k^0, 0, 0, |\mathbf{k}|)$), they are determined by solving the set of homogeneous linear Eqs.. The solutions correspond only to longitudinal waves and do not depend on k^0 and $|\mathbf{k}|$ separately, but only on the ratio

$$v_s = \frac{k^0}{|\mathbf{k}|}.$$

The sound velocities are given by values of v_s for which the relevant determinant of the set vanishes, i.e. the dispersion relations. In correspondence the neutron/proton structure of the eigenvectors (normal modes) can be derived. It should be remarked that in asymmetric nuclear matter isoscalar and isovector components are mixed in the normal modes. Here this can be argued by the fact that in each linearized Eq. both proton/neutron densities and currents are appearing.

However we remind that one can still identify isovector-like excitations as the modes where neutrons and protons move out of phase, while isoscalar-like modes are characterized by neutrons and protons moving in phase [8,15].

Isovector Modes

One may expect that once a_4 is fixed, the velocity of sound is also fixed. On the other hand our results clearly indicate a different dynamical response with or without the δ -meson channel, for interactions which give *exactly the same* a_4 parameter. In order to get a clear understanding of this effect we will consider the case of symmetric nuclear matter in the Hartree scheme, where the dispersion relations are assuming a transparent analytical form.

Now it is also possible to decouple the collective modes into *pure* isoscalar and isovector oscillations, [8]. After a straightforward rearrangement we have a dispersion relation for the isovector modes:

$$1 + \frac{6 E_F^*}{k_F^2} \left[E_{sym}^{pot} - \frac{f_\rho}{2} \frac{k_F^2}{E_F^{*2}} \left(1 - f_\delta \frac{M^*}{E_F^{*2}} \rho_S \right) \rho_B \right] \varphi(s) = 0. \quad (6)$$

where the potential part of the symmetry energy explicitly appears in the dispersion relations, but *joined to an important correction term* which shows a different f_ρ, f_δ structure with respect to that of E_{sym}^{pot} , Eq.(4). *We can easily have interactions with the same a_4 value at normal density but with very different isovector response.* E.g. when we include the δ channel we know that we have to increase the f_ρ coupling in order to have the same a_4 , but now the “restoring force” (coefficient of the Lindhard function in the Eq.(6)) will be strongly reduced.

Isoscalar Modes

As already remarked, we like to note that for symmetric NM there is a tight analogy between the isoscalar and the isovector response in the RMF approach. In the isoscalar degree of freedom the compressibility will play the same role of the symmetry energy in the dispersion relation equations. Also in this case we will have an important correction term coming from the interplay of the scalar and vector channel.

The isoscalar equivalent of the Eq.(6) takes the form:

$$1 + \frac{E_F^*}{3 k_F^2} \left[K_{NM}^{pot} - 9 f_\omega \frac{k_F^2}{E_F^{*2}} \left(1 - f_\sigma \frac{M^*}{E_F^{*2}} \rho_S \right) \rho_B \right] \varphi(s) = 0. \quad (7)$$

where the K_{NM}^{pot} is the potential part of the nuclear matter compressibility that in the Hartree scheme has the simple structure:

$$K_{NM}(\rho_B) = \frac{3 k_F^2}{E_F^*} + 9 \left[f_\omega - f_\sigma \left(\frac{M^*}{E_F^*} \right)^2 \right] \rho_B \\ \equiv K_{NM}^{kin} + K_{NM}^{pot}, \quad (8)$$

By means of such an analogy, the previous discussion can be extended to isoscalar oscillations with the role of E_{sym} now “played” by the compressibility. In this case however one always takes into account both the scalar and vector channel in any RMF models. However the coupling constant f_ω can assume very different values depending on the required value for effective masses M_0^* . This is easy to understand since in the RMF limit the saturation binding energy has the simple form

$$E/A(0) = E_F^* + f_\omega \rho_B(0) - M_N$$

where M_N is the bare nucleon mass. So we see that in order to have the same saturation values of $\rho_B(0)$, $E/A(0)$ when we decrease M_0^* we have to increase f_ω . We derive then the natural conclusion that if two *EOS* have different effective masses even if the compressibility is equal the dynamical behaviour is expected to be different. This is a very general feature present also in non-relativistic approaches.

Exotic High Baryon density modes

For asymmetric matter we have found that, in all the calculation schemes, with increasing baryon density the isovector modes disappear and the isoscalar-like excitations become dominant : we call such densities ρ_B^{cross} . Around this transition density we expect to have an almost *pure neutron wave* propagation of the sound.

Some results are shown in Fig.2. It should be noticed that the frequency of the isoscalar-like modes is essentially related to the compressibility of the system at the considered density. In Fig.2(a) we display the sound velocity obtained in Hartree and Hartree-Fock calculations at $\rho_B = 3.5 \rho_0$, as a function of the asymmetry α .

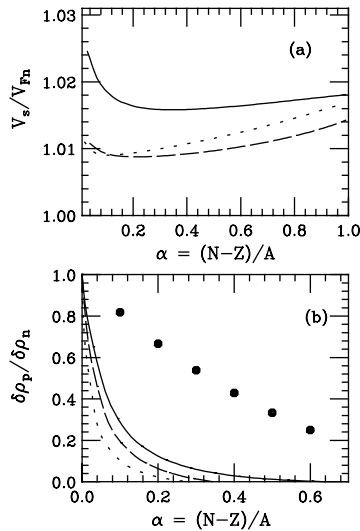


FIG. 2. Sound velocity (a) and chemical composition (b) of isoscalar-like modes at $\rho_B = 3.5\rho_0$. Solid line: NLHF. Long Dashed line: $NLH - \rho$. Dotted line: $NLH - (\rho + \delta)$. The full circles in panel (b) represent the behaviour of ρ_p/ρ_n vs. α .

At $\alpha = 0$ the two Hartree models have exactly the same isoscalar mean fields, but for asymmetric nuclear matter the different behaviour of the symmetry energy leads to a different compressibility. The case $NLH - (\rho + \delta)$ which has the stiffer E_{sym} (resulting in a greater incompressibility for $\alpha > 0$) with respect to $NLH - (\rho)$ shows also a greater increase of v_s/v_{Fn} with density.

Some differences are observed also in the chemical composition of the mode (Fig.2(b)). The black spots show the behaviour of ρ_p/ρ_n vs. α . Note the *pure neutron wave* structure of the propagating sound, since the oscillations of protons appear strongly damped ($\delta\rho_p/\delta\rho_n \ll \rho_p/\rho_n$); unfortunately this is an effect not experimentally accessible (at present).

Isospin Distillation in Dilute Matter

We have also investigated the response of the system in the region of spinodal instability associated with the liquid-gas phase transition, which occurs at low densities. It is known that in this region an isoscalar unstable mode can be found, with imaginary sound velocity, that gives rise to an exponential growth of the fluctuations. The latter can represent a dynamical mechanism for the multi-fragmentation process observed in heavy-ion collisions. We have found this kind of solution in the present approach. In Fig.3 we show the ratio $\delta\rho_p/\delta\rho_n$ as function of the initial asymmetry for such a collective mode. For all the interactions this ratio is different from the corresponding ρ_p/ρ_n of the initial asymmetry α . This is exactly the chemical effect associated with the new instabilities in dilute asymmetric matter [16,15].

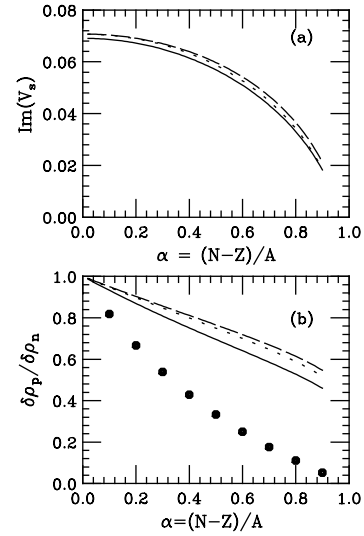


FIG. 3. Isoscalar-like unstable modes at $\rho_B = 0.4\rho_0$: Imaginary sound velocity (a) and ratio of proton and neutron amplitudes (b) as a function of the asymmetry α . Solid line: NLHF; Dotted line: $NLH - (\rho + \delta)$; Long Dashed line: $NLH - \rho$. The full circles in panel (b) represent the behaviour of $\delta\rho_p/\delta\rho_n$ vs. α .

In particular it is found that, when isoscalar-like modes become unstable, the ratio $\delta\rho_p/\delta\rho_n$ becomes *larger* than the ratio ρ_p/ρ_n (at variance with the stable modes at high densities, see Fig.2). Hence proton oscillations are relatively larger than neutron oscillations leading to a more symmetric liquid phase and

to a more neutron rich gas phase, during the disassembly of the system. This is the so-called isospin distillation effect in fragmentation, and signatures of this effect could be searched by looking at the ratio N/Z of fragments produced in dissipative heavy ion collisions [17].

We note here that in dilute asymmetric NM we can distinguish two regions of instability, mechanical (cluster formation) and chemical (component separation). There is however no discontinuity in the structure of the unstable modes which are developing. For all realistic effective nuclear interactions (relativistic and non) the nature of the unstable normal modes at low densities is always *isoscalar-like*, i.e. with neutrons and protons oscillating in phase, although with a distillation effect discussed before, see ref. [15] for a fully detailed study of this important property of asymmetric nuclear matter.

In Fig.3 we observe that Hartree results (with and the without δ meson) are very similar and, indeed, at low density the symmetry energy behaviour is nearly the same in the two cases. We can conclude that there are essentially no effects of the scalar isovector channel on isospin distillation in the spinodal decomposition.

Outlook

We have developed a linear response theory starting from a relativistic kinetic equations deduced within a Quantum-Hadrodynamics effective field picture of the hadronic phase of nuclear matter. In the asymmetric case we consider as the main dynamical degrees of freedom the nucleon fields coupled to the *isoscalar*, scalar σ and ω , and to the *isovector*, scalar δ and vector ρ , mesons.

We have singled out some qualitative new effects of the δ -meson-like channel on the dynamical response of ANM . Essentially, our investigation indicates that even if the symmetry energy is fixed, the dynamical response is affected by its internal structure, i.e. the presence or not of an isovector-scalar field. This is implemented by the explicit introduction of an effective δ -meson and/or by the Fock term contributions. Both mechanisms are absent in the present relativistic RPA calculations for finite nuclei. In the spirit of the EFT/DFT approach [5] it would be interesting to see the effect of an isovector scalar field extension, at the lowest order, on the existing covariant RPA results. The richer sensitivity of the collective response on the density dependence of the symmetry term can be of large importance for our knowledge of the isovector part of the in medium interaction.

We like to remark that the same interplay between scalar (σ -meson) and vector (ω -meson) contributions can be seen in the dynamical isoscalar modes. In general we clearly show a close analogy

in the structure of the linear response equations:

- Same form of the dispersion relations.
- Parallel role of E_{sym}^{pot} and K_{NM}^{pot} in the determination of the restoring force.
- Parallel structure of the corrections due to the scalar-vector meson competition.

This appears to be a beautiful “mirror” structure of the relativistic approach that seems to nicely support the introduction of a δ -meson-like coupling in the isovector channel, at least from a formal point of view.

From the numerical results on the collective response of ANM some general features are qualitatively present in all the effective interactions in the isovector channel:

- In asymmetric matter we have a mixing of pure isoscalar and pure isovector oscillations which leads to *chemical* effect on the structure of the propagating collective mode: the ratio of the neutron/proton density oscillations $\delta\rho_n/\delta\rho_p$ is different from the initial ρ_n/ρ_p of the matter at equilibrium. However we can still classify the nature of the excited collective motions as *isoscalar-like* (when neutron and protons are oscillating in phase) and *isovector-like* (out of phase). To note that similar effects can be obtained also using non-relativistic effective forces [8,15].
- For a given asymmetry the isovector-like mode is the most robust at low baryon density, always showing a larger neutron component in the oscillations. With increasing baryon density we observe a smooth transition, at a $\rho_B^{cross} \simeq 2 - 3\rho_0$, to an isoscalar-like branch, still with a dominant $\delta\rho_n$. In the region of the transition we predict a propagation of almost *pure neutron waves*. For relatively large asymmetries ($\alpha \equiv \frac{N-Z}{N+Z} = 0.5, N = 3Z$) this behaviour is present in a wide interval of densities around ρ_B^{cross} . All that seems to suggest the possibility of an experimental observation of related effects in intermediate energy heavy ion collisions with exotic beams. If the compressibility of nuclear matter is decreasing at high baryon density also these exotic isoscalar-like mode will disappear. This could be a nice signature of the softening of nuclear EOS at high densities.
- The isoscalar-like motions become unstable at sub-saturation densities still with a strong chemical effect, now in the opposite direction with respect to the one discussed before, present in the stable high density modes. Now the unstable oscillation is more proton-rich, eventually leading to the formation of more

symmetric clusters vs. a very neutron-rich gas phase. This is the *neutron distillation* effect [8,14–17], a new important feature of the liquid-gas phase transition in asymmetric nuclear systems.

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Testing Deconfinement with RIB Facilities

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We show that a systematic study of the isospin dependence of the Equation of State of matter at densities of the order of 2–3 times nuclear matter saturation density can give important information concerning quark deconfinement. In particular the region $Z/A \sim 0.3 - 0.4$ is the most interesting, since for these values of the asymmetry the critical density at which quarks start deconfining can drop dramatically.

The physics case

It is relatively easy to show that at high baryon density and low temperature we can expect a transition from hadronic matter to deconfined quark matter. The procedure is straightforward:

- Start from two "reasonable" model Equations of State (*EOS*), one for the hadronic phase, which can reproduce saturation properties, one for the quark phase, which can reproduce the hadron spectrum.
- Construct the phase separation boundary surface from the Gibbs phase rule [1]. See Ch.19 of the J.D.Walecka book [2] and ref. [3].

For symmetric matter the baryon density ρ_{tr} corresponding to the transition to the coexistence region is relatively high, as expected, ranging from 4 to 8 times the saturation value ρ_0 , depending on the stiffness of the hadronic *EOS* at high densities.

The new feature we would like to focus on in this report is the isospin dependence of such boundary location. We can foresee an interesting asymmetry effect, in the appealing direction of a decrease of ρ_{tr} , since the hadronic *EOS* becomes more repulsive. This has been actually seen in the calculations of ref. [3] (see the Fig.7): for a proton fraction $Z/A = 0.3$ the boundary density is shifted to the left of about a 10%, from the $4.0\rho_0$ of symmetric matter to a $3.5\rho_0$. The point we like to note is that this evaluation has been obtained in quite "adverse" conditions. The interaction symmetry part of the hadronic *EOS* is only coming from the charged vector ρ -meson coupling, which gives a linear increase of the symmetry energy with the baryon density, see the discussion in ref. [4]. The *EOS* of the quark phase is obtained

within the MIT bag model with a very high pressure-of-vacuum parameter $B^{1/4} = 190$ MeV, i.e. it is very repulsive.

We have repeated the study with new *EOS*'s in the two phases, with modifications, inspired by sensible physics arguments, which lead to a stiffer asymmetric matter and to a softer quark matter and therefore to an earlier transition.

For the hadronic phase we have enhanced the symmetry repulsion at high baryon density introducing also the coupling to the charged scalar δ -meson. As remarked in ref. [4], this is fully in agreement with the spirit of the effective field theories, and of course with the phenomenology of the free nucleon-nucleon interaction.

In the quark phase we use smaller values of the bag constant, in the range $B^{1/4} \simeq 140$ -150 MeV, consistent with the Witten-Bodmer hypothesis [5,6], which is considerably softening the quark *EOS*, allowing also the possibility of the existence of quark stars [7,8].

It is important to notice that the hadronic *EOS* depends more strongly on isospin than the quark *EOS*. When $B^{1/4} = 146.3$ MeV, the quark *EOS* has a minimum below the hadronic *EOS* for $Z/A = 0.3$, while for $Z/A = 0.5$ the minimum of the hadronic *EOS* is still the absolute one. In this situation, the critical density separating hadronic matter from the mixed phase of quarks and hadrons drops dramatically when the value of Z/A is reduced. For larger values of B the isospin dependence of the critical density is progressively reduced.

The proton fraction Z/A dependence of the ρ_{tr} is reported in Fig.1 with the bag constant value $B^{1/4} = 150$ MeV and $\alpha_s = 0$ for the quark phase and various choices for the hadronic *EOS*: *Dotted line* GM3 parametrization [9]; *Dashed line* NLH ρ parametrization [4]; *Solid line* NLH($\rho + \delta$) parametrization [4]. GM3 and NLH ρ have the same source of the interaction symmetry term (only the ρ -meson) while NLH($\rho + \delta$) has also the scalar charged meson contribution which gives an almost quadratic increase of the symmetry repulsion with baryon density.

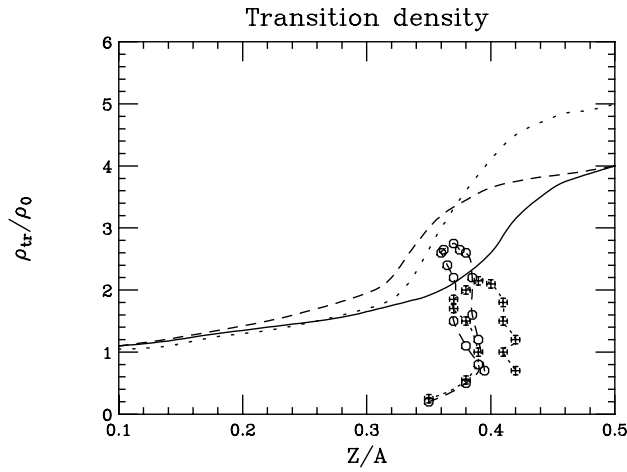


FIG. 1. Variation of the transition density with proton fraction for various hadronic *EOS* (see text). The points represent the path followed in the interaction zone during a semicentral $^{132}\text{Sn} + ^{132}\text{Sn}$ collision at 1 AGeV (circles) and 300 AGeV (crosses)

The effects of the asymmetry appears now quite dramatic: we see a ρ_{trans} as low as $2\rho_0$ for proton fractions between 0.3 and 0.4, conditions that with some confidence we could "locally" reach in a heavy ion collision at *intermediate* energy using exotic very asymmetric beams.

Realistic Collision Simulation

Using a Relativistic Transport Code, with the same effective interaction of the $NLH(\rho + \delta)$ *EOS*, we have performed some simulations of the $^{132}\text{Sn} + ^{132}\text{Sn}$ (average $Z/A = 0.38$) collision at various energies, for a semicentral impact parameter, $b = 6\text{fm}$, just to optimize the

neutron skin effect in order to get a large asymmetry in the interacting zone. In Fig.1 the paths in the $(\rho, Z/A)$ plane followed in the c.m. region

during the collision are reported, at two energies 300 AGeV (crosses) and 1 AGeV (circles). We see that already at 300 AGeV we are reaching the border of the mixed phase, and we are well inside it at 1 AGeV.

The direct use of equilibrium *EOS* concepts is supported by the results shown in Fig.2, where the time evolution of quadrupole moment, in momentum space, and density, in a cell of "2.5fm" lateral size around the Centre of Mass, is reported. At the time of maximum density of interest here the system appears quite well locally equilibrated.

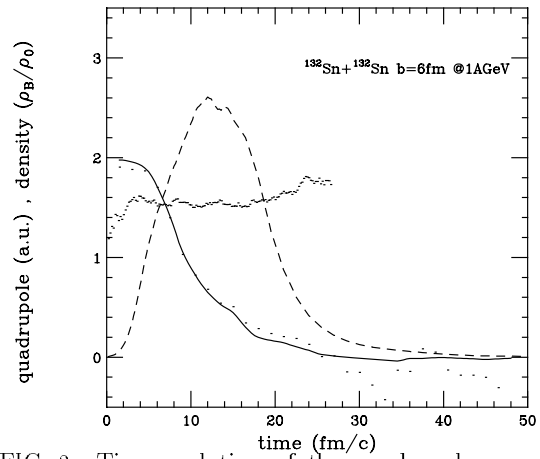


FIG. 2. Time evolution of the quadrupole moment (in momentum space), solid line, and of the density, dashed line, in a cell around the C.M. for a semicentral $^{132}\text{Sn} + ^{132}\text{Sn}$ collision at 1 AGeV

As it can be seen, precursory signals of deconfinement could appear at $\rho \sim 1.6\rho_0$ and $Z/A \sim 0.34$, a region explorable using the EURISOL facility.

In conclusion we support the possibility of observing precursor signals of the phase transition to a deconfined matter in violent collision (central and semicentral) of exotic (radioactive) heavy ions in the energy range of few hundred MeV per nucleon. A possible signature could be revealed through an earlier "softening" of the hadronic *EOS* for larger asymmetries, to see on the behaviour of the collective flows for particles with large transverse momentum, or on the softening of the symmetry energy as a function of Z/A .

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Asymmetric nuclear matter in Quantum Hadrodynamics

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We discuss the *EOS* and the collective response of Asymmetric Nuclear matter (*ANM*) based on the Quantum Hadro-Dynamics (*QHD*) effective field picture. We focus our attention on the equilibrium and dynamical effects of the interplay between scalar and vector channel contributions. An interesting “mirror” structure in the form of the effective meson contributions in the isoscalar/isovector degree of freedom is revealed. A complete parallelism is observed in the interplay between scalar and vector mesons in determining respectively compressibility and symmetry energy. All that seems to support the introduction of an explicit coupling to the scalar-isovector channel of the nucleon-nucleon interaction.

In particular we study the influence of this coupling (to a δ -meson-like effective field) on the collective response of asymmetric nuclear matter (*ANM*). Interesting contributions are found on the propagation of isovector-like modes at normal density and on an expected smooth transition to isoscalar-like oscillations at high baryon density.

Important “chemical” effects on the neutron-proton structure of the mode are shown. For dilute *ANM* we have the isospin distillation mechanism of the unstable isoscalar-like oscillations, while at high baryon density we predict an almost pure neutron wave structure of the propagating sounds.

The QHD effective theory

The *QHD* effective field model represents a very successful attempt to describe, in a fully consistent relativistic picture, equilibrium and dynamical properties of nuclear systems at the hadronic level [1–3]. Very nice results have been obtained for the nuclear structure of finite nuclei, for the *NM* Equation of State and liquid-gas phase transitions and for the dynamics of nuclear collisions.

In this project we will mainly focus our attention on the dynamical response of asymmetric nuclear matter since one of the main points of our discussion is the relevance of the coupling to a scalar isovector channel, the virtual $\delta[a_0(980)]$ meson, not considered in the usual Relativistic Mean Field (*RMF*) studies.

The isospin physics is assuming more and more relevance in connection to the new radioactive beam

facilities and to nuclear astrophysics. The introduction of the isovector/scalar channel in covariant approaches can play a key role in the effective interaction in asymmetric matter, see ref. [4]. This point has not received great attention before for two main reasons:

i) The δ -channel has not been considered *a priori*, just on the basis of the weak contribution to the free Nucleon-Nucleon interaction. But in the spirit of the *Effective Field Theory* as a relativistic *Density Functional Theory*, (the *EFT/DFT* framework, see [5]), the relevance of this channel could be completely different in nuclear matter, due to medium and many-body effects. In particular we can expect a large contribution from exchange terms of the strongly coupled isoscalar channels, see the discussion in ref. [6] as well as in [4].

ii) This extension is not well supported by the existing set of data. Clearly these negative outcomes are mainly derived from the lack of information on observables more sensitive to the density dependence of the symmetry term.

We like to note that very recently, see the conclusions of ref. [7], the δ -channel has been reconsidered as an interesting improvement of covariant approaches, in the framework of the *EFT/DFT* philosophy. One of the main tasks of our work is just to try to select the dynamical observables more sensitive to it, see also the conclusions of ref. [4].

Our results around normal density can be used as general guidelines in predicting the behaviour of volume collective modes in finite β -unstable nuclei. Similar study for asymmetric *NM* have been performed in Ref. [8] using Skyrme-like interactions.

In order to include the main dynamical degrees of freedom of the system we will consider the nucleons coupled to the isoscalar scalar σ and vector ω mesons and to the isovector scalar δ and vector ρ mesons.

For the nucleon fields we get a Dirac-like equation. All the equations can be consistently solved in a Mean Field Approximation (*RMF*), where most applications have been performed, in particular in the Hartree scheme.

The inclusion of Fock terms is conceptually important since it automatically leads to contributions to various channels, also in absence of explicit coupling

terms. A thorough study of the Fock contributions in a QHD approach with non-linear self-interacting terms has been recently performed [9], in particular for asymmetric matter [6].

Within a mean field picture of the QHD model we focus our analysis on a description of the many-body nuclear system in terms of one-body dynamics.

We perform the many-body calculations in the quantum phase-space introducing the Wigner transform of the one-body density matrix for the fermion field defined as:

$$[\hat{F}(x, p)]_{\alpha\beta} = \frac{1}{(2\pi)^4} \int d^4 R \epsilon^{-ip \cdot R} \langle : \bar{\psi}_\beta(x + \frac{R}{2}) \psi_\alpha(x - \frac{R}{2}) : \rangle, \quad (1)$$

where α and β are double indices for spin and isospin. The brackets denote statistical averaging and the colons denote normal ordering. The Wigner function is a matrix in spin and isospin spaces; in the case of Asymmetric NM it is useful to decompose it into neutron and proton components. Following the treatment of the Fock terms in non-linear QHD introduced in Refs. [9,6], we obtain from the Dirac eq. a kinetic equation for the Wigner function, that can be eventually solved in linear approximation in order to get the dispersion relations for normal, stable and unstable, modes in various regions of baryon densities [10].

Equilibrium properties: the nuclear Equation of State

The energy density and pressure for symmetric and asymmetric nuclear matter and the n, p effective masses can be self-consistently calculated just in terms of the four boson coupling constants, $f_i \equiv (\frac{g_i^2}{m_i^2})$, $i = \sigma, \omega, \rho, \delta$, and the two parameters of the σ self-interacting terms, $A \equiv \frac{a}{g_\sigma^3}$ and $B \equiv \frac{b}{g_\sigma^2}$, see ref. [9,6].

The isoscalar meson parameters are fixed from symmetric nuclear matter properties at $T = 0$. They have quite standard values for these minimal non-linear RMF models.

The symmetry energy in ANM is defined from the expansion of the energy per nucleon $E(\rho_B, \alpha)$ in terms of the asymmetry parameter $\alpha \equiv \frac{N-Z}{A}$:

$$\begin{aligned} E(\rho_B, \alpha) &\equiv \frac{\epsilon(\rho_B, \alpha)}{\rho_B} \\ &= E(\rho_B) + E_{sym}(\rho_B) \alpha^2 \\ &\quad + O(\alpha^4) + \dots \end{aligned} \quad (2)$$

and so in general

$$E_{sym} \equiv \frac{1}{2} \frac{\partial^2 E(\rho_B, \alpha)}{\partial \alpha^2} \Big|_{\alpha=0} = \frac{1}{2} \rho_B \frac{\partial^2 \epsilon}{\partial \rho_{B3}^2} \Big|_{\rho_{B3}=0} \quad (3)$$

In the Hartree case an explicit expression for the symmetry energy can be easily derived [4]

$$\begin{aligned} E_{sym}(\rho_B) &= \frac{1}{6} \frac{k_F^2}{E_F^*} + \frac{1}{2} \left[f_\rho - f_\delta \left(\frac{M^*}{E_F^*} \right)^2 \right] \rho_B \\ &\equiv E_{sym}^{kin} + E_{sym}^{pot} \end{aligned} \quad (4)$$

where k_F is the nucleon Fermi momentum corresponding to ρ_B , $E_F^* \equiv \sqrt{(k_F^2 + M^{*2})}$ and M^* is the effective nucleon mass in symmetric NM , $M^* = M_N - g_\sigma \phi$.

We see that, when the δ is included, the observed a_4 value actually assigns the combination $[f_\rho - f_\delta (\frac{M}{E_F})^2]$ of the (ρ, δ) coupling constants. If $f_\delta \neq 0$ we have to increase the ρ -coupling. In our calculations we use the value $a_4 = 32 \text{ MeV}$.

Now the symmetry energy at saturation density is actually built from the balance of scalar (attractive) and vector (repulsive) contributions, with the scalar channel becoming weaker with increasing baryon density [4]. This is indeed the isovector counterpart of the saturation mechanism occurring in the isoscalar channel for the symmetric nuclear matter. From such a scheme we get a further support to the introduction of the δ -coupling in the symmetry energy evaluation.

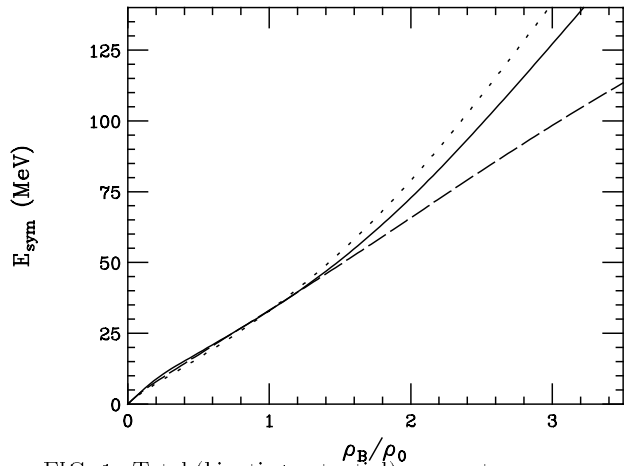


FIG. 1. Total (kinetic+potential) symmetry energy as a function of the baryon density. Long dashed: Hartree ($NLH + \rho$). Dotted: Hartree ($NLH + \rho + \delta$). Solid: Hartree-Fock ($NLHF$).

Details of the calculation can be found in Refs. [6,4]. In Fig.1 we report the symmetry energy as a function of the baryon density in the Hartree case (ρ and $\rho + \delta$) and with the Fock terms [$(\rho + \delta)$ case]. When the δ “channel” is included the behaviour is stiffer for the relativistic mechanism discussed before, see also ref. [4].

Linear Response

We study collective oscillations that propagate in cold nuclear matter due to the mean field dynamics. In some sense we follow a relativistic extension of the method introduced by Landau to study liquid- ^3He [11–13] and recently applied to investigate stable and unstable modes in nuclear matter [8,14]. The starting point is the relativistic kinetic transport equation. We look for solutions corresponding to small oscillations of $\hat{F}(x, p)$ around the equilibrium value. Therefore we put

$$\hat{F}(x, p) = \hat{H}(p) + \hat{G}(x, p) \quad (5)$$

where $\hat{H}(p)$ is the Wigner function at equilibrium and $\hat{G}(x, p)$ represent its fluctuations.

By Fourier transforming and integrating over four-momentum, in linear approximation we get the set of equations for the scalar and vector fluctuation of each species ($i = 1, 2$ for proton, neutron respectively), see ref. [10].

The normal collective modes are plane waves, characterized by the wave vector ($k^\mu = (k^0, 0, 0, |\mathbf{k}|)$), they are determined by solving the set of homogeneous linear Eqs.. The solutions correspond only to longitudinal waves and do not depend on k^0 and $|\mathbf{k}|$ separately, but only on the ratio

$$v_s = \frac{k^0}{|\mathbf{k}|}.$$

The sound velocities are given by values of v_s for which the relevant determinant of the set vanishes, i.e. the dispersion relations. In correspondence the neutron/proton structure of the eigenvectors (normal modes) can be derived. It should be remarked that in asymmetric nuclear matter isoscalar and isovector components are mixed in the normal modes. Here this can be argued by the fact that in each linearized Eq. both proton/neutron densities and currents are appearing.

However we remind that one can still identify isovector-like excitations as the modes where neutrons and protons move out of phase, while isoscalar-like modes are characterized by neutrons and protons moving in phase [8,15].

Isovector Modes

One may expect that once a_4 is fixed, the velocity of sound is also fixed. On the other hand our results clearly indicate a different dynamical response with or without the δ -meson channel, for interactions which give *exactly the same a_4 parameter*. In order to get a clear understanding of this effect we will consider the case of symmetric nuclear matter in the Hartree scheme, where the dispersion relations are assuming a transparent analytical form.

Now it is also possible to decouple the collective modes into *pure* isoscalar and isovector oscillations, [8]. After a straightforward rearrangement we have a dispersion relation for the isovector modes:

$$1 + \frac{6 E_F^*}{k_F^2} \left[E_{sym}^{pot} - \frac{f_\rho}{2} \frac{k_F^2}{E_F^{*2}} \left(1 - f_\delta \frac{M^*}{E_F^{*2}} \rho_S \right) \rho_B \right] \varphi(s) = 0. \quad (6)$$

where the potential part of the symmetry energy explicitly appears in the dispersion relations, but *joined to an important correction term* which shows a different f_ρ, f_δ structure with respect to that of E_{sym}^{pot} , Eq.(4). *We can easily have interactions with the same a_4 value at normal density but with very different isovector response.* E.g. when we include the δ channel we know that we have to increase the f_ρ coupling in order to have the same a_4 , but now the “restoring force” (coefficient of the Lindhard function in the Eq.(6)) will be strongly reduced.

Isoscalar Modes

As already remarked, we like to note that for symmetric NM there is a tight analogy between the isoscalar and the isovector response in the RMF approach. In the isoscalar degree of freedom the compressibility will play the same role of the symmetry energy in the dispersion relation equations. Also in this case we will have an important correction term coming from the interplay of the scalar and vector channel.

The isoscalar equivalent of the Eq.(6) takes the form:

$$1 + \frac{E_F^*}{3 k_F^2} \left[K_{NM}^{pot} - 9 f_\omega \frac{k_F^2}{E_F^{*2}} \left(1 - f_\sigma \frac{M^*}{E_F^{*2}} \rho_S \right) \rho_B \right] \varphi(s) = 0. \quad (7)$$

where the K_{NM}^{pot} is the potential part of the nuclear matter compressibility that in the Hartree scheme has the simple structure:

$$K_{NM}(\rho_B) = \frac{3 k_F^2}{E_F^*} + 9 \left[f_\omega - f_\sigma \left(\frac{M^*}{E_F^*} \right)^2 \right] \rho_B \\ \equiv K_{NM}^{kin} + K_{NM}^{pot}, \quad (8)$$

By means of such an analogy, the previous discussion can be extended to isoscalar oscillations with the role of E_{sym} now “played” by the compressibility. In this case however one always takes into account both the scalar and vector channel in any RMF models. However the coupling constant f_ω can assume very different values depending on the required value for effective masses M_0^* . This is easy to understand since in the RMF limit the saturation binding energy has the simple form

$$E/A(0) = E_F^* + f_\omega \rho_B(0) - M_N$$

where M_N is the bare nucleon mass. So we see that in order to have the same saturation values of $\rho_B(0)$, $E/A(0)$ when we decrease M_0^* we have to increase f_ω . We derive then the natural conclusion that if two *EOS* have different effective masses even if the compressibility is equal the dynamical behaviour is expected to be different. This is a very general feature present also in non-relativistic approaches.

Exotic High Baryon density modes

For asymmetric matter we have found that, in all the calculation schemes, with increasing baryon density the isovector modes disappear and the isoscalar-like excitations become dominant : we call such densities ρ_B^{cross} . Around this transition density we expect to have an almost *pure neutron wave* propagation of the sound.

Some results are shown in Fig.2. It should be noticed that the frequency of the isoscalar-like modes is essentially related to the compressibility of the system at the considered density. In Fig.2(a) we display the sound velocity obtained in Hartree and Hartree-Fock calculations at $\rho_B = 3.5 \rho_0$, as a function of the asymmetry α .

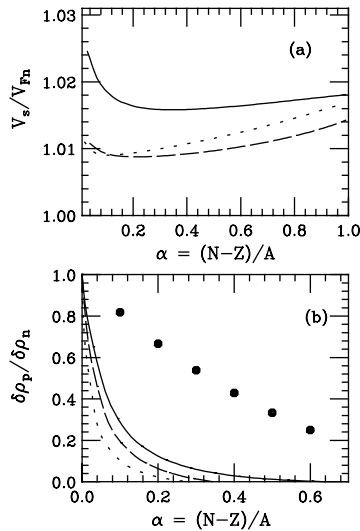


FIG. 2. Sound velocity (a) and chemical composition (b) of isoscalar-like modes at $\rho_B = 3.5 \rho_0$. Solid line: NLHF. Long Dashed line: $NLH - \rho$. Dotted line: $NLH - (\rho + \delta)$. The full circles in panel (b) represent the behaviour of ρ_p/ρ_n vs. α .

At $\alpha = 0$ the two Hartree models have exactly the same isoscalar mean fields, but for asymmetric nuclear matter the different behaviour of the symmetry energy leads to a different compressibility. The case $NLH - (\rho + \delta)$ which has the stiffer E_{sym} (resulting in a greater incompressibility for $\alpha > 0$) with respect to $NLH - (\rho)$ shows also a greater increase of v_s/v_{Fn} with density.

Some differences are observed also in the chemical composition of the mode (Fig.2(b)). The black spots show the behaviour of ρ_p/ρ_n vs. α . Note the *pure neutron wave* structure of the propagating sound, since the oscillations of protons appear strongly damped ($\delta \rho_p / \delta \rho_n \ll \rho_p / \rho_n$); unfortunately this is an effect not experimentally accessible (at present).

Isospin Distillation in Dilute Matter

We have also investigated the response of the system in the region of spinodal instability associated with the liquid-gas phase transition, which occurs at low densities. It is known that in this region an isoscalar unstable mode can be found, with imaginary sound velocity, that gives rise to an exponential growth of the fluctuations. The latter can represent a dynamical mechanism for the multi-fragmentation process observed in heavy-ion collisions. We have found this kind of solution in the present approach. In Fig.3 we show the ratio $\delta \rho_p / \delta \rho_n$ as function of the initial asymmetry for such a collective mode. For all the interactions this ratio is different from the corresponding ρ_p/ρ_n of the initial asymmetry α . This is exactly the chemical effect associated with the new instabilities in dilute asymmetric matter [16,15].

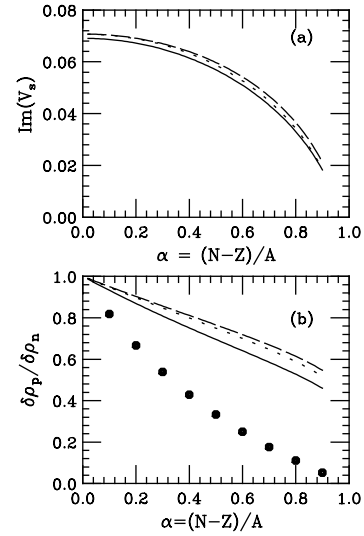


FIG. 3. Isoscalar-like unstable modes at $\rho_B = 0.4 \rho_0$: Imaginary sound velocity (a) and ratio of proton and neutron amplitudes (b) as a function of the asymmetry α . Solid line: NLHF; Dotted line: $NLH - (\rho + \delta)$; Long Dashed line: $NLH - \rho$. The full circles in panel (b) represent the behaviour of ρ_p/ρ_n vs. α .

In particular it is found that, when isoscalar-like modes become unstable, the ratio $\delta \rho_p / \delta \rho_n$ becomes *larger* than the ratio ρ_p/ρ_n (at variance with the stable modes at high densities, see Fig.2). Hence proton oscillations are relatively larger than neutron oscillations leading to a more symmetric liquid phase and

to a more neutron rich gas phase, during the disassembly of the system. This is the so-called isospin distillation effect in fragmentation, and signatures of this effect could be searched by looking at the ratio N/Z of fragments produced in dissipative heavy ion collisions [17].

We note here that in dilute asymmetric NM we can distinguish two regions of instability, mechanical (cluster formation) and chemical (component separation). There is however no discontinuity in the structure of the unstable modes which are developing. For all realistic effective nuclear interactions (relativistic and non) the nature of the unstable normal modes at low densities is always *isoscalar-like*, i.e. with neutrons and protons oscillating in phase, although with a distillation effect discussed before, see ref. [15] for a fully detailed study of this important property of asymmetric nuclear matter.

In Fig.3 we observe that Hartree results (with and the without δ meson) are very similar and, indeed, at low density the symmetry energy behaviour is nearly the same in the two cases. We can conclude that there are essentially no effects of the scalar isovector channel on isospin distillation in the spinodal decomposition.

Outlook

We have developed a linear response theory starting from a relativistic kinetic equations deduced within a Quantum-Hadrodynamics effective field picture of the hadronic phase of nuclear matter. In the asymmetric case we consider as the main dynamical degrees of freedom the nucleon fields coupled to the *isoscalar*, scalar σ and ω , and to the *isovector*, scalar δ and vector ρ , mesons.

We have singled out some qualitative new effects of the δ -meson-like channel on the dynamical response of ANM . Essentially, our investigation indicates that even if the symmetry energy is fixed, the dynamical response is affected by its internal structure, i.e. the presence or not of an isovector-scalar field. This is implemented by the explicit introduction of an effective δ -meson and/or by the Fock term contributions. Both mechanisms are absent in the present relativistic RPA calculations for finite nuclei. In the spirit of the EFT/DFT approach [5] it would be interesting to see the effect of an isovector scalar field extension, at the lowest order, on the existing covariant RPA results. The richer sensitivity of the collective response on the density dependence of the symmetry term can be of large importance for our knowledge of the isovector part of the in medium interaction.

We like to remark that the same interplay between scalar (σ -meson) and vector (ω -meson) contributions can be seen in the dynamical isoscalar modes. In general we clearly show a close analogy

in the structure of the linear response equations:

- Same form of the dispersion relations.
- Parallel role of E_{sym}^{pot} and K_{NM}^{pot} in the determination of the restoring force.
- Parallel structure of the corrections due to the scalar-vector meson competition.

This appears to be a beautiful “mirror” structure of the relativistic approach that seems to nicely support the introduction of a δ -meson-like coupling in the isovector channel, at least from a formal point of view.

From the numerical results on the collective response of ANM some general features are qualitatively present in all the effective interactions in the isovector channel:

- In asymmetric matter we have a mixing of pure isoscalar and pure isovector oscillations which leads to *chemical* effect on the structure of the propagating collective mode: the ratio of the neutron/proton density oscillations $\delta\rho_n/\delta\rho_p$ is different from the initial ρ_n/ρ_p of the matter at equilibrium. However we can still classify the nature of the excited collective motions as *isoscalar-like* (when neutron and protons are oscillating in phase) and *isovector-like* (out of phase). To note that similar effects can be obtained also using non-relativistic effective forces [8,15].
- For a given asymmetry the isovector-like mode is the most robust at low baryon density, always showing a larger neutron component in the oscillations. With increasing baryon density we observe a smooth transition, at a $\rho_B^{cross} \simeq 2 - 3\rho_0$, to an isoscalar-like branch, still with a dominant $\delta\rho_n$. In the region of the transition we predict a propagation of almost *pure neutron waves*. For relatively large asymmetries ($\alpha \equiv \frac{N-Z}{N+Z} = 0.5, N = 3Z$) this behaviour is present in a wide interval of densities around ρ_B^{cross} . All that seems to suggest the possibility of an experimental observation of related effects in intermediate energy heavy ion collisions with exotic beams. If the compressibility of nuclear matter is decreasing at high baryon density also these exotic isoscalar-like mode will disappear. This could be a nice signature of the softening of nuclear EOS at high densities.
- The isoscalar-like motions become unstable at sub-saturation densities still with a strong chemical effect, now in the opposite direction with respect to the one discussed before, present in the stable high density modes. Now the unstable oscillation is more proton-rich, eventually leading to the formation of more

symmetric clusters vs. a very neutron-rich gas phase. This is the *neutron distillation* effect [8,14–17], a new important feature of the liquid-gas phase transition in asymmetric nuclear systems.

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Testing Deconfinement with RIB Facilities

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We show that a systematic study of the isospin dependence of the Equation of State of matter at densities of the order of 2–3 times nuclear matter saturation density can give important information concerning quark deconfinement. In particular the region $Z/A \sim 0.3 - 0.4$ is the most interesting, since for these values of the asymmetry the critical density at which quarks start deconfining can drop dramatically.

The physics case

It is relatively easy to show that at high baryon density and low temperature we can expect a transition from hadronic matter to deconfined quark matter. The procedure is straightforward:

- Start from two "reasonable" model Equations of State (*EOS*), one for the hadronic phase, which can reproduce saturation properties, one for the quark phase, which can reproduce the hadron spectrum.
- Construct the phase separation boundary surface from the Gibbs phase rule [1]. See Ch.19 of the J.D.Walecka book [2] and ref. [3].

For symmetric matter the baryon density ρ_{tr} corresponding to the transition to the coexistence region is relatively high, as expected, ranging from 4 to 8 times the saturation value ρ_0 , depending on the stiffness of the hadronic *EOS* at high densities.

The new feature we would like to focus on in this report is the isospin dependence of such boundary location. We can foresee an interesting asymmetry effect, in the appealing direction of a decrease of ρ_{tr} , since the hadronic *EOS* becomes more repulsive. This has been actually seen in the calculations of ref. [3] (see the Fig.7): for a proton fraction $Z/A = 0.3$ the boundary density is shifted to the left of about a 10%, from the $4.0\rho_0$ of symmetric matter to a $3.5\rho_0$. The point we like to note is that this evaluation has been obtained in quite "adverse" conditions. The interaction symmetry part of the hadronic *EOS* is only coming from the charged vector ρ -meson coupling, which gives a linear increase of the symmetry energy with the baryon density, see the discussion in ref. [4]. The *EOS* of the quark phase is obtained

within the MIT bag model with a very high pressure-of-vacuum parameter $B^{1/4} = 190$ MeV, i.e. it is very repulsive.

We have repeated the study with new *EOS*'s in the two phases, with modifications, inspired by sensible physics arguments, which lead to a stiffer asymmetric matter and to a softer quark matter and therefore to an earlier transition.

For the hadronic phase we have enhanced the symmetry repulsion at high baryon density introducing also the coupling to the charged scalar δ -meson. As remarked in ref. [4], this is fully in agreement with the spirit of the effective field theories, and of course with the phenomenology of the free nucleon-nucleon interaction.

In the quark phase we use smaller values of the bag constant, in the range $B^{1/4} \simeq 140-150$ MeV, consistent with the Witten-Bodmer hypothesis [5,6], which is considerably softening the quark *EOS*, allowing also the possibility of the existence of quark stars [7,8].

It is important to notice that the hadronic *EOS* depends more strongly on isospin than the quark *EOS*. When $B^{1/4} = 146.3$ MeV, the quark *EOS* has a minimum below the hadronic *EOS* for $Z/A = 0.3$, while for $Z/A = 0.5$ the minimum of the hadronic *EOS* is still the absolute one. In this situation, the critical density separating hadronic matter from the mixed phase of quarks and hadrons drops dramatically when the value of Z/A is reduced. For larger values of B the isospin dependence of the critical density is progressively reduced.

The proton fraction Z/A dependence of the ρ_{tr} is reported in Fig.1 with the bag constant value $B^{1/4} = 150$ MeV and $\alpha_s = 0$ for the quark phase and various choices for the hadronic *EOS*: *Dotted line* GM3 parametrization [9]; *Dashed line* NLH ρ parametrization [4]; *Solid line* NLH($\rho + \delta$) parametrization [4]. GM3 and NLH ρ have the same source of the interaction symmetry term (only the ρ -meson) while NLH($\rho + \delta$) has also the scalar charged meson contribution which gives an almost quadratic increase of the symmetry repulsion with baryon density.

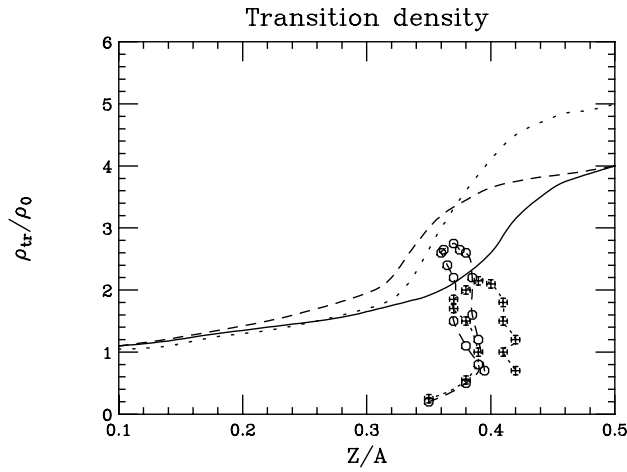


FIG. 1. Variation of the transition density with proton fraction for various hadronic *EOS* (see text). The points represent the path followed in the interaction zone during a semicentral $^{132}\text{Sn} + ^{132}\text{Sn}$ collision at 1 AGeV (circles) and 300 AGeV (crosses)

The effects of the asymmetry appears now quite dramatic: we see a ρ_{trans} as low as $2\rho_0$ for proton fractions between 0.3 and 0.4, conditions that with some confidence we could "locally" reach in a heavy ion collision at *intermediate* energy using exotic very asymmetric beams.

Realistic Collision Simulation

Using a Relativistic Transport Code, with the same effective interaction of the $NLH(\rho + \delta)$ *EOS*, we have performed some simulations of the $^{132}\text{Sn} + ^{132}\text{Sn}$ (average $Z/A = 0.38$) collision at various energies, for a semicentral impact parameter, $b = 6\text{fm}$, just to optimize the

neutron skin effect in order to get a large asymmetry in the interacting zone. In Fig.1 the paths in the $(\rho, Z/A)$ plane followed in the c.m. region

during the collision are reported, at two energies 300 AGeV (crosses) and 1 AGeV (circles). We see that already at 300 AGeV we are reaching the border of the mixed phase, and we are well inside it at 1 AGeV.

The direct use of equilibrium *EOS* concepts is supported by the results shown in Fig.2, where the time evolution of quadrupole moment, in momentum space, and density, in a cell of "2.5fm" lateral size around the Centre of Mass, is reported. At the time of maximum density of interest here the system appears quite well locally equilibrated.

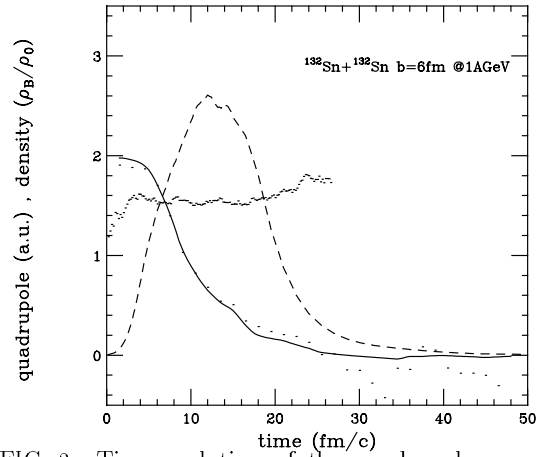


FIG. 2. Time evolution of the quadrupole moment (in momentum space), solid line, and of the density, dashed line, in a cell around the C.M. for a semicentral $^{132}\text{Sn} + ^{132}\text{Sn}$ collision at 1 AGeV

As it can be seen, precursory signals of deconfinement could appear at $\rho \sim 1.6\rho_0$ and $Z/A \sim 0.34$, a region explorable using the EURISOL facility.

In conclusion we support the possibility of observing precursor signals of the phase transition to a deconfined matter in violent collision (central and semicentral) of exotic (radioactive) heavy ions in the energy range of few hundred MeV per nucleon. A possible signature could be revealed through an earlier "softening" of the hadronic *EOS* for larger asymmetries, to see on the behaviour of the collective flows for particles with large transverse momentum, or on the softening of the symmetry energy as a function of Z/A .

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Isospin Effects in Nuclear Fragmentation

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We investigate properties of the symmetry term in the nuclear equation of state, *EOS*, from fragmentation experiments. For charge asymmetric systems we expect a qualitative new feature in the liquid-gas phase transition, the onset of chemical instabilities that will show up in a novel nature of the unstable modes, given by a mixture of isoscalar and isovector components, leading to a neutron distillation effect. The space-time structure of the instabilities is discussed, in particular for the dependence on the symmetry term. Relative effects on fragment observables (mass/charge-correlations, kinetic energies, radial velocities) and on reaction mechanism scenarios (interaction times) are discussed. Very important is the analysis of neck-fragmentation events for semi-central collisions, which represent a large part of the reaction cross section. The fragments produced with this mechanism appear systematically more neutron-rich for a dynamical nucleon migration effect which is very sensitive to the symmetry term in regions just below normal density.

In general the isospin dynamics has an important role in all the steps of the reaction, from prompt nucleon emission to the sequential decay of the primary fragments.

The elusive symmetry term: expected transport effects

A key question in the physics of unstable nuclei is the knowledge of the *EOS* for asymmetric nuclear matter away from normal conditions. We recall that the symmetry term at low densities affects the neutron skin structure [1], while in the high density region it is crucial for supernovae dynamics and neutron star cooling [2,3]. The paradox is that while we are planning second and third generation facilities for radioactive beams our basic knowledge of the symmetry term of the *EOS* is still extremely poor. Effective interactions are obviously tuned to symmetry properties around normal conditions and any extrapolation can be quite dangerous. Microscopic approaches based on realistic *NN* interactions, Brueckner or variational schemes, or on effective field theories show a quite large variety of predictions. As an example, in Fig.1 we collect the isospin dependence of some *EOS*'s which have the same saturation properties for symmetric NM: *SKM** [4], *SLy230b* (*SLy4*) [5] and *BPAL32* [2,6].

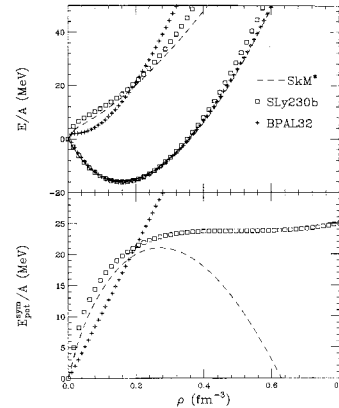


FIG. 1. *EOS for various effective forces. Top: neutron matter (up), symmetric matter (down); Bottom: potential symmetry term.*

The aim of this project is to select a series of observables in fragment production reactions particularly sensitive to the symmetry term of the *EOS*. In the following will refer to a "asy-stiff" EOS when we are considering a potential symmetry term linearly increasing with nuclear density and to a "asy-soft" EOS when the symmetry term shows a saturation and eventually a decrease above normal density [9,10]. In some cases, in order to enhance the dynamical effects, we will consider also "asy-superstiff" behaviours, i.e. with a roughly parabolic increase of the symmetry term above normal density [3,6]. In the nuclear equation of state we have a symmetry term in the form

$$\frac{E}{A}(\rho, I) = \frac{E}{A}(\rho) + \frac{E_{sym}}{A}(\rho) I^2 \quad (1)$$

with $I = (N - Z)/A$ asymmetry parameter, given by kinetic and potential contributions, see [9–11].

Single particle properties will show up a linear dependence on the asymmetry and so will be more sensitive to the symmetry term. The density dependence of the *n*- and *p*-mean fields for the various parametrizations are shown in Fig.2 for a $N = 1.5Z$ system ($I = 0.2$).

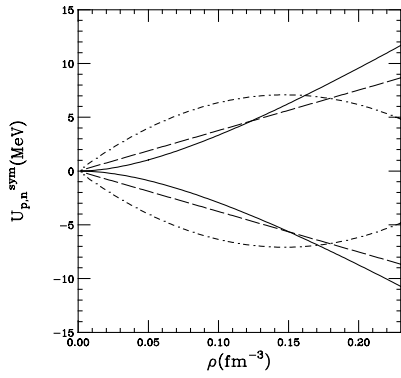


FIG. 2. Symmetry contribution to the mean field at $I = 0.2$ for neutrons and protons: dashed lines "asy-soft", long dashed lines "asy-stiff", solid lines "asy-superstiff"

In regions just off normal density the field "seen" by neutrons and protons in the three cases is very different. We can expect important transport effects during the reaction dynamics at intermediate energies since the interacting asymmetric nuclear matter can experience compressed and expanding phases before forming fragments around normal density conditions.

A complementary and maybe more complete picture of the isospin dynamics can be obtained from the analysis of the density dependence of the "local" values of the neutron/proton chemical potentials. We remind that the chemical potentials contain all the contributions to the energy per particle, including the scalar part and the kinetic symmetry term in asymmetric matter. In this sense their study is quite natural for the energetic arguments; the symmetry mean field of Fig.2, although very instructive, shows only the potential part. We note that in the non-equilibrium processes the mass flow is determined by the differences in the local values of chemical potential and it is directed from the regions of higher chemical potential to regions of lower values until equalization.

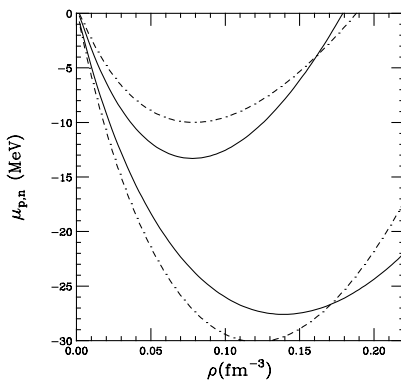


FIG. 3. Density dependence of proton (lower curves) and neutron (upper curves) chemical potentials for asy-superstiff (solid lines) and asy-soft (dashed line) EOS for asymmetry $I = 0.2$.

In Fig.3 we plot the n, p chemical potentials for a system having the ^{124}Sn asymmetry, $I = 0.2$, for two isospin EOS (soft, superstiff). We note that the difference is given by $\mu_n - \mu_p = 4(E_{\text{sym}}/A)I$, it thus directly reflects the density dependence of the symmetry term seen in the lower panel of Fig.1. Two regions below normal density will show different transport effects: in very dilute cases, below $.08\text{fm}^{-3}$, neutrons and protons will always move *both* to higher densities while in regions around and above ρ_0 we expect flows in opposite directions in the superstiff case.

Mechanical and Chemical instabilities in dilute Nuclear Matter: Isospin Distillation

For charge asymmetric systems we expect a qualitative new feature in the liquid-gas phase transition, the onset of chemical instabilities that will show up in a novel nature of the unstable modes, given by a mixture of isoscalar and isovector components. In the framework of Landau theory for two component Fermi liquids the spinodal border is determined by studying the stability of collective modes described by two coupled Landau-Vlasov equations for protons and neutrons. In terms of the appropriate Landau parameters the stability condition can be expressed as [12],

$$(1 + F_0^{nn})(1 + F_0^{pp}) - F_0^{np}F_0^{pn} > 0. \quad (2)$$

It is possible to show that this condition is equivalent to the following thermodynamical condition

$$\left(\frac{\partial P}{\partial \rho}\right)_{T,y} \left(\frac{\partial \mu_p}{\partial y}\right)_{T,P} > 0. \quad (3)$$

discussed in [13,14], where y is the proton fraction and μ_p the proton chemical potential. In Fig.4 we show the spinodal lines obtained from Eq. (2) (continuous line with circles) which for asymmetric nuclear matter is seen to contain the lines corresponding to "mechanical instability", $\left(\frac{\partial P}{\partial \rho}\right)_{T,y} < 0$ (crosses). The calculations are performed with non-relativistic Skyrme-like forces [14], but very similar results can be obtained with relativistic mean field approaches [13]. Therefore both Eqs. (2,3) describe the whole region of instability.

We note, however, that by just looking at the above stability conditions we cannot determine the nature of the fluctuations against which a binary system becomes chemically unstable. Indeed, the thermodynamical condition in Eq. (3) cannot distinguish between two very different situations which can be encountered in nature: an attractive interaction between the two components of the mixture ($F_0^{np}, F_0^{pn} < 0$), as is the case of nuclear matter, or a repulsive interaction between the two species.

We define density fluctuations as isoscalar-like in the case when proton and neutron Fermi spheres (or equivalently the proton and neutron densities) fluctuate in phase and as isovector-like when the two Fermi spheres fluctuate out of phase. Then it is possible to prove, based on a thermodynamical approach of asymmetric Fermi liquid mixtures [14], that chemical instabilities are triggered by isoscalar-like fluctuations in the first, i.e. attractive, situation and by isovector-like fluctuations in the second one. For the dilute asymmetric nuclear matter case because of the attractive interaction between protons and neutrons at low density the phase transition is thus due to isoscalar-like fluctuations that induce chemical instabilities while the system is never unstable against isovector fluctuations.

The apparent paradox that chemical instabilities are due to isoscalar-like fluctuations can be understood from the behaviour of the chemical potentials in Fig.3. In the low density region, where the instability occurs, both proton and neutron chemical potentials decrease giving rise to isoscalar-like oscillations. However the μ -slope is different for protons and neutrons, thus leading to a more proton-rich denser phase (the "liquid") and a "chemical" effect, the neutron distillation. The latter appears quite sensitive to the symmetry term of the used effective interaction *below saturation density* [15], providing a good opportunity to distinguish between different *EOS*.

When compared to equilibrium statistical multifragmentation calculations [16] sensitive observables appear to be the yield ratios of light isobars (e.g. $t/{}^3\text{He}$) and the formation of more stable primary intermediate mass fragments [17]. From "ab initio" dynamical simulations of central collisions we can study the effects of the structure of the instabilities on fragment observables (mass/charge yields, isospin content and multiplicity distributions) and on the reaction mechanism. Complementary important information will be obtained from the analysis of neck-fragmentation events in semicentral collisions, which represent a large part of the reaction cross section [18].

Stochastic transport simulations

A new code for the solution of microscopic transport equations of Boltzmann-Nordheim-Vlasov (*BNV*) type has been written where asymmetry effects are suitably accounted for [19,20] and the dynamics of fluctuations is included [21,11]. A density dependent symmetry term is used in the ground state construction of the initial conditions, isospin effects on nucleon cross section and Pauli blocking are consistently evaluated. The transport equations are solved following a test particle evolution on a lattice [22,23]. A parametrization of free *NN* cross sec-

tions is used, with energy and angular dependence.

Another approach to stochastic terms, computationally much easier [24,25], is based on the introduction of density fluctuations by a random sampling of the phase space. The amplitude of the noise is gauged to reproduce the dynamics of the most unstable modes [25]. For each system we have checked the equivalence of the two methods in the description of the collision dynamics, from fast particle emissions to the fragment production. The analysis of the results, presented in the following, is based on events collected with both numerical methods, see details in [11].

The dynamics of a fragmentation reaction is extremely rich. During the time evolution we can roughly distinguish various phases, prompt particle emission, compression-expansion stage, cluster formation and finally statistical decay from primary fragments after the freeze-out time. All the steps are quite isospin dependent and therefore it is essential to perform consistent "ab initio" simulations of the whole process in order to extract information on the symmetry term of the *EOS*. In particular since in the reaction dynamics with intermediate energy beams the asymmetric nuclear matter probes compressed as well as dilute phases the final output will be conditioned by the whole density dependence of symmetry term. Aim of this work is to show which fragmentation observables are particularly sensitive to the symmetry term of the *EOS* and how the physical interpretation of the results can be quite transparent in spite of the heavy numerical calculations.

We have studied the 50 *AMeV* collisions of the systems ${}^{124}\text{Sn} + {}^{124}\text{Sn}$ and ${}^{112}\text{Sn} + {}^{112}\text{Sn}$, where new data have just appeared or under analysis at *NSCL - MSU* [26]. We will comment around 500 events generated in semi-central ($b = 2\text{fm}$) and in semi-peripheral ($b = 6\text{fm}$) reactions.

For the *n-rich* case the results obtained with the *asy-soft* symmetry term are shown in Fig.4 (central, $b = 2\text{fm}$) and Fig.5 (peripheral, $b = 6\text{fm}$), to be compared with the correspondent *asy-superstiff* ones of Figs.6 and 7. Each figure is organized in this way:

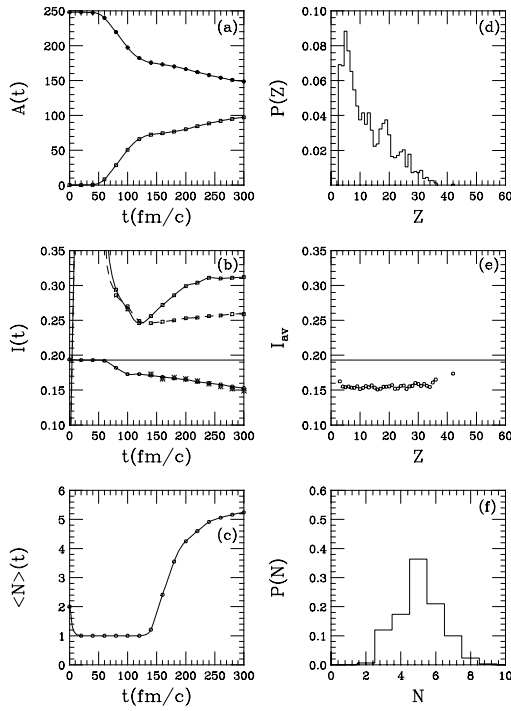


FIG. 4. $^{124}\text{Sn} + ^{124}\text{Sn}$ $b = 2\text{ fm}$ collision: time evolution (left) and freeze-out properties (right). See text. ASY-SOFT EOS

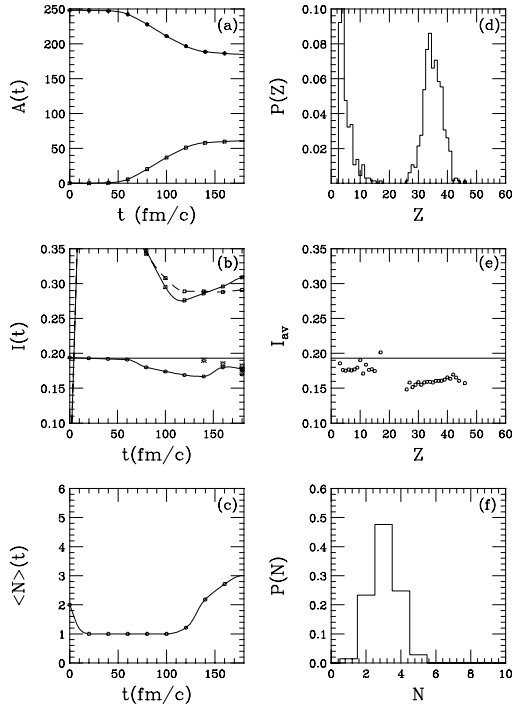


FIG. 5. $^{124}\text{Sn} + ^{124}\text{Sn}$ $b = 6\text{ fm}$ collision: time evolution (left) and freeze-out properties (right). See text. ASY-SOFT EOS.

Left column, time evolution of: (a) *Mass* in the liquid (up) and gas (down) phase ; (b) *Asymmetry* $I = (N - Z)/(N + Z)$ in the gas "central" (solid line and squares), gas total (dashed+ squares), liq-

uid "central" (solid+circles) and *IMF* (clusters with $3 < Z < 15$, stars). The horizontal line shows the initial average asymmetry; (c) *Mean Fragment Multiplicity* $Z \geq 3$. The saturation of this curve defines the freeze-out configuration.

Right column, properties of the "primary" fragments in the *Freeze-Out Configuration*: (d) *Charge Distribution*, (e) *Asymmetry Distribution* and (f) *Fragment Multiplicity Distribution* (normalized to 1).

Following the time evolution of the reaction for central collision, Figs.4a),b), we see a neutron dominated pre-equilibrium particle emission during the first 50fm/c. Some protons are subsequently emitted during the expansion phase but they are not enough to restore initial asymmetry in the gas phase. The liquid phase become more symmetric during the compression due to neutron emission and then it shows a bending during the expansion. At the beginning of the third phase, when density inhomogenities start to develop, an *isospin burst* of gas phase in the "central region" is observed, Fig.4b) . At the same time the central liquid phase is becoming more and more symmetric. This behaviour is consistent with the dynamical spinodal mechanism in dilute asymmetric nuclear matter leading to isospin distillation. In the cluster formation we see a clear transition from *bulk* to *neck* [18] instabilities. In central collisions the probability distribution of primary fragments as a function of charge has a decreasing trend, Fig.4d). On the other hand for $b = 6\text{ fm}$ (Fig.5d)) we clearly identify the *PLF* (and *TLF*) region having charges around 35 and then after a gap we see the *IMF's* produced dynamically in the neck zone with charges mostly below 10. On average we obtain around 4 – 5 *IMF's* in the first case and only 1 in the latter, see Figs. 4c) and 5c).

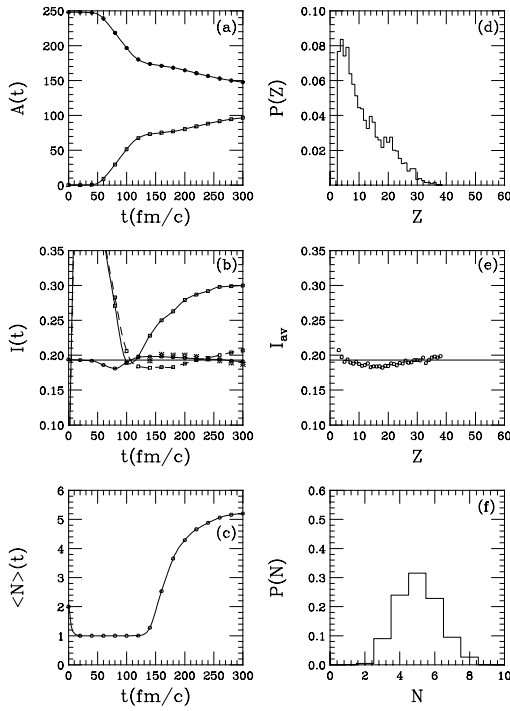


FIG. 6. $^{124}\text{Sn} + ^{124}\text{Sn}$ $b = 2\text{ fm}$ collision: time evolution (left) and freeze-out properties (right). See text. ASY-SUPERSTIFF EOS

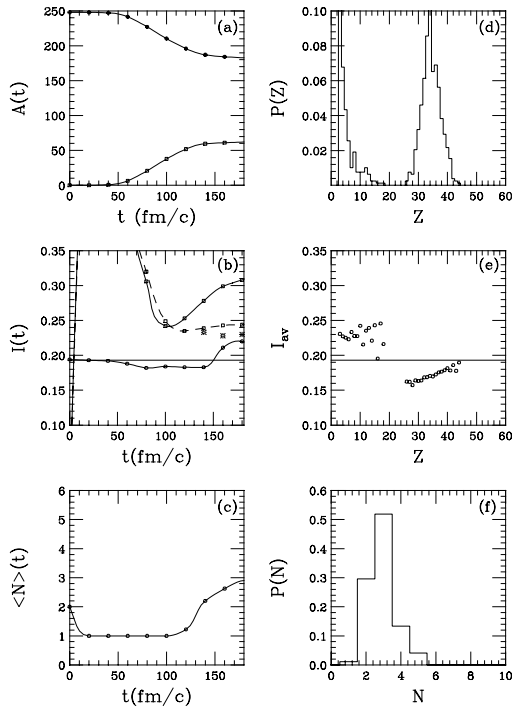


FIG. 7. $^{124}\text{Sn} + ^{124}\text{Sn}$ $b = 6\text{ fm}$ collision: time evolution (left) and freeze-out properties (right). See text. ASY-SUPERSTIFF EOS.

Symmetry Term Effects

As already observed, the reaction dynamics is very rich and also the fast particle emission, before the fragmentation process, is affected by the symmetry

term, in particular in the N/Z composition. Comparing Figs. a) and Figs. c) we see that before fragmentation starts (around $100 - 120\text{ fm/c}$) nucleons are emitted in the gas mostly in the time interval between 50 and 100 fm/c , i.e. already in the expansion phase. This means that the symmetry part of the mean field at subnuclear densities will have an important dynamical effect on the emission. In the *asysoft* case below ρ_0 neutrons are less bound than in the *asy-superstiff*, and opposite for the protons: we expect then a more neutron-rich prompt particle emission with the *asysoft* symmetry term and in correspondence a more symmetric initial dilute matter which will undergo fragment production. This is exactly what we see from the Figs. 4b) (*asysoft*) and 6b) (*asy-superstiff*) for central collisions. It is interesting to remark that the same effect is present also for semicentral collisions (compare Figs. 5b) and 7b)), although more weakly.

For fragment production we will focus first our discussion on the isospin content of the primary intermediate mass fragments (i.e. $3 \leq Z \leq 20$). From the comparison of Figs. 4e), 6e) for central events and of Figs. 5e), 7e) for semicentral we clearly see that the *asysoft* choice is the most effective for the neutron distillation effect (the most symmetric *IMF's*) in central collisions while the *asy-superstiff* choice is the most effective in forming neutron-rich *IMF's* in the neck region, for semicentral collisions. Following the above discussion we easily understand the two trends just considering the differences in the symmetry term at subnuclear densities, see Figs. 1, 2, 3. The *asysoft* parametrization is very steep at low densities while reveals a quite flat behaviour around normal density, so quite efficient during the chemical instability growth but not so important for the proton migration from neck to spectators. Exactly the opposite trend has the *asy-superstiff* parametrization, roughly a quadratic dependence and so a weak increase at low densities and a large slope around ρ_0 .

A quite similar information is contained, in a more averaged way, in the fragment multiplicity distributions, Figs. 5f), 7f). Multi neck-*IMF* events are decreasing with the increasing stiffness of the symmetry term: we note that in the *asy-superstiff* case we have $\simeq 30\%$ more binary events. This is indeed a clean signature of the larger repulsion in the neck zone due to the larger symmetry pressure. The interesting conclusion is that also the quite inclusive observable, just fragment multiplicity, appears to be sensitive to the symmetry term for semicentral collisions. We note that such slope around normal density is exactly the symmetry pressure we expect to see active in the neutron rich surface of heavy elements and so of large importance in determining the difference between matter and proton distributions, see the recent discussion in ref. [1]. Of course the point is absolutely critical for the discussion of unstable nuclei, neutron skins and so on. We clearly see

the complementarity between reaction and structure studies.

Results of $^{124}\text{Sn} + ^{64}\text{Ni}$ semiperipheral collisions

To illustrate the dynamics of semi-peripheral collisions of mass-asymmetric systems (n-rich) we have considered the reaction $^{124}\text{Sn} + ^{64}\text{Ni}$ at 35 MeV/A, $b = 6$ fm. This experiment has been recently performed at LNS by the REVERSE collaboration [27].

In Figs.8,9 we present the same kind of analysis as illustrated above (Figs.5,7) in the $\text{Sn} + \text{Sn}$ case. We observe that small IMF's are quite more neutron-rich than the larger ones. In fact they mostly originate from the neutron rich neck region. Again there is a clear difference between the asy-stiff and asy-soft predictions.

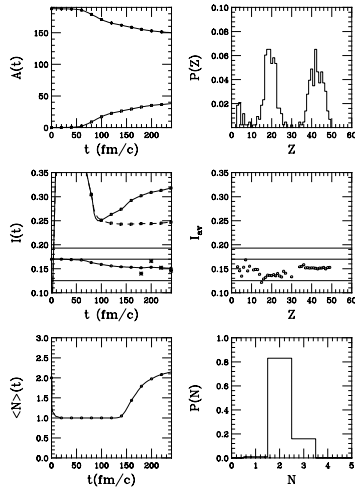


FIG. 8. $^{124}\text{Sn} + ^{64}\text{Ni}$ $b = 6\text{fm}$ collision: time evolution and freeze-out properties. See text. ASY-SOFT EOS.

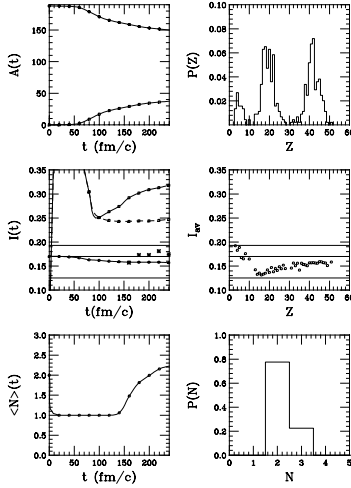


FIG. 9. $^{124}\text{Sn} + ^{64}\text{Ni}$ $b = 6\text{fm}$ collision: time evolution and freeze-out properties. See text. ASY-STIFF EOS

Outlook

We have shown that chemical instabilities and isospin transport properties can account for the results of microscopic simulations of fragmentation reactions of charge asymmetric ions in the medium energy range, between 20 and 100 A MeV. We have also selected some observables rather sensitive to the symmetry term of the nuclear EOS . A first conclusion of the detailed analysis of our dynamical simulations is that in this energy range we expect to see a characteristic behaviour of the N/Z of the intermediate mass fragments as a function of the centrality of the reaction, a typical *rise and fall* with decreasing impact parameter. For peripheral collisions IMF will be emitted in a statistical way from the excited PLF/TLF regions, and so close to the stability line. For semicentral events we have the *neck-mechanism* and more neutron rich fragments are formed from dynamical effects. For central collisions the neutron distillation will take place and fragments will be again much more symmetric. The relevance of such behaviour is related to the stiffness of the symmetry term at subnuclear densities, and this could be a very important information.

The proton fraction of fast particle emission appears also quite sensitive to the slope of the symmetry term around normal density. For central collisions this effect introduces the observed difference in IMF 's multiplicities between n-rich and n-poor systems.

Isospin migration in the "neck instabilities" will also induce interesting isotopic effects on the expected fast-fission breaking of the Projectile-Like and/or Target-Like Fragments.

Of course all the results discussed here refer to the Primary Fragments, i.e. at the *freeze-out* time. Of course they are quite excited and the subsequent statistical decay can modify the signal. Same of the effects discussed here appear quite robust and indeed from the first available data the isospin dependence of fragment production emerges quite clearly.

Moreover we have not presented here more detailed dynamical properties of the fragment emission, like velocity distributions, kinetic and excitation energies, angular distributions, collective flows. The present results are already very promising and we can be confident that with more exclusive data and more asymmetric (also radioactive) beams we will be able to perform detailed studies of the "elusive" symmetry term of the nuclear EOS .

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Collective Dipole Bremsstrahlung in Dissipative Reactions

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We estimate the dipole radiation emitted in fusion and deep inelastic processes. We show that a classical bremsstrahlung approach can account for both the pre-equilibrium and the thermal photon emission. We give an absolute evaluation of the pre-equilibrium component due to the charge asymmetry in the entrance channel and we study the energy and mass dependence in order to optimize the observation. Characteristic signatures are expected to be the low energy shift and the anisotropy of the photon emission. This dynamical dipole radiation could be a relevant cooling mechanism in the fusion path. We stress the interest in experiments with the new available radioactive beams.

The Dynamical Dipole

In the early stage of a heavy ion collision large amplitude collective motions can be excited. Monopole, dipole or quadrupole modes are typical examples. If the colliding nuclei have different N/Z ratios the charge equilibration process takes place. Several works have suggested that the related neutron-proton collective motion has the features of a Giant Dipole Resonance (*GDR*) mode [1–5]. In a microscopic approach based on semiclassical transport equations [6], it has been studied in detail how a collective Dipole oscillation develops in the entrance channel [7]. In connection to this analysis three main phases can be identified. First, during the *approaching phase* the two partners, overcoming the Coulomb barrier, still keep their own response. Then it follows a *dinuclear phase* when the conversion of relative motion energy in thermal motion starts to take place, mainly due to nucleon exchange. The composite system is not thermally equilibrated and manifests, as a whole, a large amplitude dipole collective motion. The charge equilibration has initiated. Finally, during the third phase, the *Compound Nucleus (CN) formation*, the nucleus is thermally equilibrated. In a *phonon* approach it was shown [2] for the first time that an enhancement of the *GDR* gamma emission should be observed if the number of *GDR* phonons, $n_{GDR}^{(0)}$, when the *CN* is formed, is larger than the value corresponding to a statistical equilibrium of the *GDR* (as oscillator) with the *CN* (as heat bath). Some first experimental evidences of this effect have been recently suggested [9–12].

However it is important to notice that also in the

second (*dinuclear*) phase some pre-equilibrium collective Dipole radiation can be emitted. In the attempt to estimate this contribution we cannot use straightforwardly the "phonon" approach which is based on the assumption of the existence of a thermally equilibrated nucleus. A way to face this problem is to directly apply a bremsstrahlung ("*bremss*") approach. Considering the evolution of the collective dipole acceleration from the time when it suddenly rises, at the beginning of the second phase, until it is completely damped to a pure "thermal" component, we can consistently calculate the whole contribution of the pre-equilibrium Dipole radiation to the photon yield.

The total photon emission probability from the dipole mode oscillations, as given by the bremsstrahlung formula, can be expressed as [13] ($E_\gamma = \hbar\omega$):

$$\frac{dP}{dE_\gamma} = \frac{2e^2}{3\pi\hbar c^3 E_\gamma} \left(\frac{NZ}{A}\right)^2 |X''(\omega)|^2, \quad (1)$$

where $X''(\omega)$ is the Fourier transform of the acceleration $X''(t)$ associated with the distance between the centers of mass of protons (P) and neutrons (N), $X = R_p - R_n$. $A = N + Z$ is the system mass. Thus following the time evolution of the dipole mode along the fusion dynamics it is possible to evaluate, in absolute values, the corresponding pre-equilibrium photon emission [14].

Statistical *GDR* in a "*bremss*" picture

It is interesting to notice that the "*bremss*" approach [15] actually provides a unified picture to account for the photon emission from both pre-equilibrium and thermal (*GDR*) Dipole modes. In fact Eq.(1) also allows to recover the usual expression for the γ -decay rate from a *GDR* in thermal equilibrium with a *CN* at temperature T . In this case the dipole mode will manifest thermal oscillations that by the fluctuation-dissipation theorem are completely determined *only* by its dissipative properties. We may consider equivalently that these are the consequence of the action of a fictitious, time dependent, random force $F(t)$ with spectral density

$$\langle |F(\omega)|^2 \rangle = \frac{\hbar\alpha_i(\omega)}{|\alpha(\omega)|^2} cth\left(\frac{\hbar\omega}{2T}\right) = M_{coll}\omega\Gamma cth\left(\frac{\hbar\omega}{2T}\right). \quad (2)$$

with $\alpha(\omega)$ dipole response function and $M_{coll} \equiv$

$\frac{NZ}{A}m$, with m nucleon mass, represents the collective mass of the neutron-proton relative motion and Γ is the decay width, [17].

Using the Parseval theorem and the ergodic hypothesis from some algebra we finally get from Eq.(1) the average photon emission probability per unit time, [18]:

$$\lim_{T_0 \rightarrow \infty} \frac{1}{T_0} \frac{dP}{dE_\gamma} = \frac{1}{\hbar} \left(\frac{E_\gamma}{\pi \hbar c} \right)^2 \frac{1}{3} \frac{4\pi e^2 \hbar}{mc} \frac{NZ}{A} \frac{\Gamma E_\gamma^2}{(E_\gamma^2 - E_0^2)^2 + \Gamma^2 E_\gamma^2} \exp\left(-\frac{E_\gamma}{T}\right) = \frac{1}{\hbar} \left(\frac{E_\gamma}{\pi \hbar c} \right)^2 \frac{\sigma_{abs}}{3} \exp\left(-\frac{E_\gamma}{T}\right), \quad (3)$$

where σ_{abs} is the γ -absorption cross section in the *GDR* region. This is the well known formula for the gamma emission rate from hot *GDR* [16]. It was previously obtained by using the detailed balance principle or from considerations on the statistical equilibrium between dipole mode and black-body radiation [17].

Dynamical evaluation of the pre-eq. radiation

Now we focus on the dynamical dipole mode in the entrance channel and we study the dependence of the pre-equilibrium dipole oscillations on the incident beam energy [6,7]. We look at the relative weight vs. the statistical contribution.

In the following we present results concerning the charge equilibration process for the systems ^{40}Ca ($N/Z = 1$) on ^{100}Mo ($N/Z = 1.38$), at 4AMeV and ^{16}O ($N/Z = 1$) on ^{98}Mo ($N/Z = 1.33$) at various beam energies (4, 8, 14 and 20AMeV), where some data are available [9,10].

The time evolution of the dipole moment $D(t) = \frac{NZ}{A}X(t)$ and of quantity $DK(t) = \Pi/\hbar$ for the $\text{Ca} + \text{Mo}$ reaction is shown in Fig.1a. Here $\Pi = \frac{NZ}{A}(\frac{P_p}{Z} - \frac{P_n}{N})$ with P_p (P_n) center of mass in momentum space for protons (neutrons) is just the canonically conjugate momentum of the X coordinate, $\Pi = M_{coll}X'(t)$.

We choose the origin of time at the beginning of the *dinuclear* phase [7]. The dipole acceleration as obtained by a second order numerical derivative of $D(t)$ is shown in Fig.1b. With a good approximation this is zero before $t = 0$. It suddenly rises when the collective dipole excitation is triggered and after few oscillations it becomes completely damped, around $250\text{fm}/c$. The corresponding power spectrum, $|D''(\omega)|^2$, calculated from the Fourier transform $D''(t) = 1/2\pi \int_0^\infty D''(\omega) \exp^{-i\omega t} d\omega$, is plotted in Fig.1c by a dashed line. In the same Fig.1c we have added (solid line) $|D''(\omega)|^2$ as obtained directly from the Fourier transform of the dipole moment, [18]. The nice agreement between the two

procedures indicates the numerical accuracy of the method.

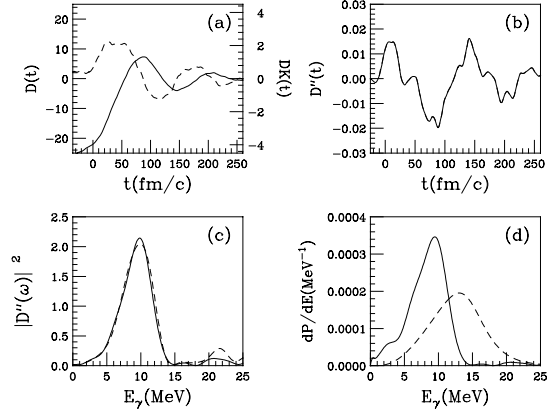


FIG. 1. System $\text{Ca} + \text{Mo}$ at 4AMeV : (a) Time evolution of $D(t)$ (solid line, in fm units), and $DK(t)$ (dashed line, in fm^{-1}). (b) The same for the acceleration $D''(t)$ (in c^2/fm). (c) Power spectrum $|D''(\omega)|^2$ (in c^2 units). (d) Bremsstrahlung spectrum (solid line) and the first step statistical spectrum (dashed line).

The total photon emission probability from the pre-equilibrium dipole mode, given by the bremsstrahlung formula Eq.(1), is reported in Fig.1d (solid line).

For comparison we show the first step statistical spectrum (dashed line). The latter is just the product of the statistical gamma decay rate [16], (see also Eq.(3)), times the mean life time of the compound nucleus τ_{CN} [18]. For the statistical *GDR*, the standard parameters from systematics, including temperature dependence of the width, are considered. We remark that the two contributions are comparable.

The pre-equilibrium spectrum is shifted toward lower values of energy as a consequence of the large quadrupole deformation along the fusion path. This effect cannot be present in the *phonon* approach, which deals only with equilibrium *GDR* properties.

We perform an analogous analysis for the reaction $^{16}\text{O} + ^{98}\text{Mo}$ at four beam energies. In Fig.2 the power spectra $|D''(\omega)|^2$ obtained with the two procedures described before are plotted. Again the two methods give close results.

In Fig.3 the corresponding "*brems*" spectra (solid lines) as well as the first step statistical spectra (dashed line) for the system $\text{O} + \text{Mo}$ are plotted. We remark the characteristic "*rise and fall*" behaviour of the pre-equilibrium contribution (already observed within the "*phonon*" approach [7]). This effect is more clearly evidenced in Fig.4 where the extra photon multiplicities due to the charge asymmetry in the entrance channel, obtained integrating over energy in the resonance region, are plotted as a function of excitation energy for both "*brems*" and "*phonon*" models. The resulting trend is determined by the interplay of several effects. At low

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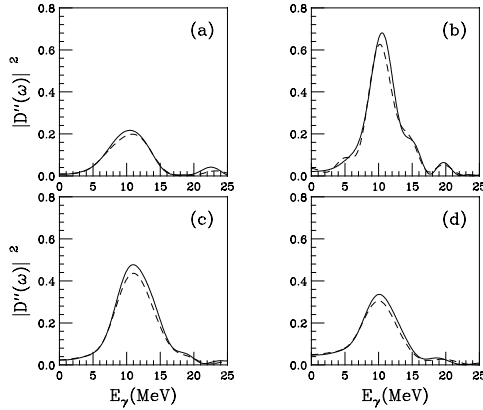


FIG. 2. Power spectrum $|D''(\omega)|^2$ for the system $O+Mo$ at the beam energies 4 (a), 8 (b), 14 (c) and 20 (d) AMeV as obtained directly from dipole acceleration (solid line) and from the Fourier transform (dashed line).

At higher beam energies a faster fusion dynamics can favor the dipole oscillation. Larger amplitudes of the acceleration and more dipole oscillations enhance the pre-equilibrium radiation. Around 8-14 AMeV an optimum effect is attained. With a further increase of the beam energy a larger damping manifests jointly to a non collective charge equilibration mechanism through fast particle emission. Consequently the gamma emission is again reduced [7].

From a comparison between the two systems, at the same energy available in the c.m., we observe a larger pre-equilibrium emission from $Ca+Mo$ (black square in Fig.4). This can be related to larger values of the dipole acceleration as a result of a larger initial dipole moment amplitude.

It is interesting to compare our results to the predictions of the *phonon* approach, where the main input quantity is the number of *GDR* phonons at the time of *CN* formation. In this model a *GDR* phonon gas is coupled to the *CN* [2]. The phonons are decaying with a rate $\mu = \Gamma/\hbar$ and excited with a rate λ . The enhancement of γ -decay probability is given by $\Delta P_{phonon} = (n_{GDR}^{(0)} - \lambda/\mu) \gamma_\gamma / (\mu + \gamma_{ev})$ where γ_γ is the partial width for photon emission and γ_{ev} is the evaporation decay rate. In this method one of the uncertainties is related to the estimation of the quantity $n_{GDR}^{(0)}$ which in turn requires the knowledge of the *CN* formation time [7]. The results presented here are obtained following the usual procedures in $\vec{r}$ - and $\vec{p}$ -space to fix the thermal equilibration time, see ref. [7]. We see from Fig.4 that the values obtained in the *phonon* approach (circles) are systematically below the *bremss* evaluation, as ex-

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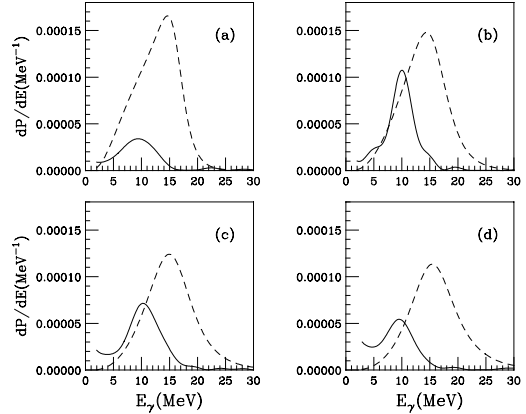


FIG. 3. Photon spectra for the $O+Mo$ system at the four energies as in Fig. 2: bremsstrahlung (solid line) and first step statistical contribution (dashed line).

In Fig.4 we report also the ratio between total pre-equilibrium and total statistical photon multiplicity as a function of the initial excitation energy of the compound system. This ratio is a good measure of the pre-equilibrium effect which should be seen in experiments when the total photon yields from a N/Z asymmetric reaction and a symmetric one, both forming the same *CN* in similar conditions (temperature, angular momentum) are compared. To calculate the total statistical *GDR* contribution we consider a very schematic cascade Montecarlo model including only gamma and neutron channel competition. The optimum range of beam energies to observe the pre-equilibrium effect appears to be around 8 AMeV. At higher beam energies a larger statistical contribution to gamma decay will lower the relative importance of pre-equilibrium contribution, which actually, as we have already discussed, starts to decrease in absolute value. We have to remark that, at the same E^* , the effect is still more important for the $Ca+Mo$ system, although now the total statistical emission is also larger, see Eq.(3). The $\simeq 16\%$ enhancement is also in quite good agreement with the experimental estimate of [9].

We have presented a bremsstrahlung approach to dipole radiation from both thermal *GDR* and dynamical dipole mode in fusion reactions. We stress that in our calculation we directly get absolute values for the emission probabilities without any normalization or adjusted parameters. Moreover the *bremss* approach can be extended in a similar way to dissipative deep-inelastic collisions where the observation of prompt γ - *Dipole* emissions has been recently claimed [12,19,20]. Very recent nice results for $S+Ni$ peripheral collisions can be found in refs. [21,22].

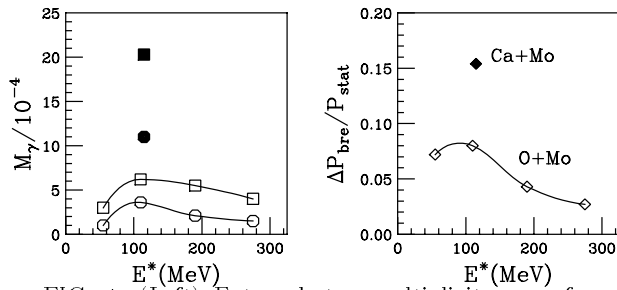


FIG. 4. (Left) Extra photon multiplicity as a function of initial excitation energy: bremsstrahlung (empty squares), phonon model (empty circles) for the $O + Mo$ system and $Ca+Mo$ (the corresponding full symbols). (Right) Ratio of total pre-equilibrium to total statistical GDR γ -ray emission (see text).

Outlook

We have shown that when we consider the full dynamics of the pre-equilibrium dipole in charge asymmetric fusion processes the extra radiation contribution appears to be systematically two times larger than the expectations, based on a *phonon* model, used so far [7,9,12] (see Fig.4). Moreover we predict also a clear shift to lower frequencies due to the elongation of the emitting source.

The pre-equilibrium dipole radiation due to the charge asymmetry in the entrance channel can be then comparable to the statistical *CN* emission. In this sense it can represent a new "*cooling*" mechanism in warm fusion reactions to form less excited residues, e.g. of interest for the synthesis of heavy elements.

A dependence of the pre-equilibrium gamma emission on beam energy has been evidenced. We conclude that this is a consequence of the interplay between fusion dynamics, damping properties of the dipole and statistical gamma emission. We expect a better observation of the effect in reactions between nuclei with a larger initial dipole amplitude, at beam energies where fusion dynamics is quite fast. Exotic (radioactive) beams are a good opportunity for studying these phenomena. However a caution is related to the fact that now a charge equilibration can take place also by an enhancement of fast nucleon emission.

We finally remark that the dynamical nature of the pre-equilibrium contribution will show up in a clear anisotropic γ -emission since it is due to dipole oscillations on the reaction plane (see details in [7]). This could be a nice characteristic signature of fusion paths in reactions induced by radioactive beams.

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Collective Dipole Bremsstrahlung in Dissipative Reactions

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We estimate the dipole radiation emitted in fusion and deep inelastic processes. We show that a classical bremsstrahlung approach can account for both the pre-equilibrium and the thermal photon emission. We give an absolute evaluation of the pre-equilibrium component due to the charge asymmetry in the entrance channel and we study the energy and mass dependence in order to optimize the observation. Characteristic signatures are expected to be the low energy shift and the anisotropy of the photon emission. This dynamical dipole radiation could be a relevant cooling mechanism in the fusion path. We stress the interest in experiments with the new available radioactive beams.

The Dynamical Dipole

In the early stage of a heavy ion collision large amplitude collective motions can be excited. Monopole, dipole or quadrupole modes are typical examples. If the colliding nuclei have different N/Z ratios the charge equilibration process takes place. Several works have suggested that the related neutron-proton collective motion has the features of a Giant Dipole Resonance (*GDR*) mode [1–5]. In a microscopic approach based on semiclassical transport equations [6], it has been studied in detail how a collective Dipole oscillation develops in the entrance channel [7]. In connection to this analysis three main phases can be identified. First, during the *approaching phase* the two partners, overcoming the Coulomb barrier, still keep their own response. Then it follows a *dinuclear phase* when the conversion of relative motion energy in thermal motion starts to take place, mainly due to nucleon exchange. The composite system is not thermally equilibrated and manifests, as a whole, a large amplitude dipole collective motion. The charge equilibration has initiated. Finally, during the third phase, the *Compound Nucleus (CN) formation*, the nucleus is thermally equilibrated. In a *phonon* approach it was shown [2] for the first time that an enhancement of the *GDR* gamma emission should be observed if the number of *GDR* phonons, $n_{GDR}^{(0)}$, when the *CN* is formed, is larger than the value corresponding to a statistical equilibrium of the *GDR* (as oscillator) with the *CN* (as heat bath). Some first experimental evidences of this effect have been recently suggested [9–12].

However it is important to notice that also in the

second (*dinuclear*) phase some pre-equilibrium collective Dipole radiation can be emitted. In the attempt to estimate this contribution we cannot use straightforwardly the "phonon" approach which is based on the assumption of the existence of a thermally equilibrated nucleus. A way to face this problem is to directly apply a bremsstrahlung ("*bremss*") approach. Considering the evolution of the collective dipole acceleration from the time when it suddenly rises, at the beginning of the second phase, until it is completely damped to a pure "thermal" component, we can consistently calculate the whole contribution of the pre-equilibrium Dipole radiation to the photon yield.

The total photon emission probability from the dipole mode oscillations, as given by the bremsstrahlung formula, can be expressed as [13] ($E_\gamma = \hbar\omega$):

$$\frac{dP}{dE_\gamma} = \frac{2e^2}{3\pi\hbar c^3 E_\gamma} \left(\frac{NZ}{A}\right)^2 |X''(\omega)|^2, \quad (1)$$

where $X''(\omega)$ is the Fourier transform of the acceleration $X''(t)$ associated with the distance between the centers of mass of protons (P) and neutrons (N), $X = R_p - R_n$. $A = N + Z$ is the system mass. Thus following the time evolution of the dipole mode along the fusion dynamics it is possible to evaluate, in absolute values, the corresponding pre-equilibrium photon emission [14].

Statistical *GDR* in a "*bremss*" picture

It is interesting to notice that the "*bremss*" approach [15] actually provides a unified picture to account for the photon emission from both pre-equilibrium and thermal (*GDR*) Dipole modes. In fact Eq.(1) also allows to recover the usual expression for the γ -decay rate from a *GDR* in thermal equilibrium with a *CN* at temperature T . In this case the dipole mode will manifest thermal oscillations that by the fluctuation-dissipation theorem are completely determined *only* by its dissipative properties. We may consider equivalently that these are the consequence of the action of a fictitious, time dependent, random force $F(t)$ with spectral density

$$\langle |F(\omega)|^2 \rangle = \frac{\hbar\alpha_i(\omega)}{|\alpha(\omega)|^2} cth\left(\frac{\hbar\omega}{2T}\right) = M_{coll}\omega\Gamma cth\left(\frac{\hbar\omega}{2T}\right). \quad (2)$$

with $\alpha(\omega)$ dipole response function and $M_{coll} \equiv$

$\frac{NZ}{A}m$, with m nucleon mass, represents the collective mass of the neutron-proton relative motion and Γ is the decay width, [17].

Using the Parseval theorem and the ergodic hypothesis from some algebra we finally get from Eq.(1) the average photon emission probability per unit time, [18]:

$$\lim_{T_0 \rightarrow \infty} \frac{1}{T_0} \frac{dP}{dE_\gamma} = \frac{1}{\hbar} \left(\frac{E_\gamma}{\pi \hbar c} \right)^2 \frac{1}{3} \frac{4\pi e^2 \hbar}{mc} \frac{NZ}{A} \frac{\Gamma E_\gamma^2}{(E_\gamma^2 - E_0^2)^2 + \Gamma^2 E_\gamma^2} \exp\left(-\frac{E_\gamma}{T}\right) = \frac{1}{\hbar} \left(\frac{E_\gamma}{\pi \hbar c} \right)^2 \frac{\sigma_{abs}}{3} \exp\left(-\frac{E_\gamma}{T}\right), \quad (3)$$

where σ_{abs} is the γ -absorption cross section in the *GDR* region. This is the well known formula for the gamma emission rate from hot *GDR* [16]. It was previously obtained by using the detailed balance principle or from considerations on the statistical equilibrium between dipole mode and black-body radiation [17].

Dynamical evaluation of the pre-eq. radiation

Now we focus on the dynamical dipole mode in the entrance channel and we study the dependence of the pre-equilibrium dipole oscillations on the incident beam energy [6,7]. We look at the relative weight vs. the statistical contribution.

In the following we present results concerning the charge equilibration process for the systems ^{40}Ca ($N/Z = 1$) on ^{100}Mo ($N/Z = 1.38$), at 4AMeV and ^{16}O ($N/Z = 1$) on ^{98}Mo ($N/Z = 1.33$) at various beam energies (4, 8, 14 and 20AMeV), where some data are available [9,10].

The time evolution of the dipole moment $D(t) = \frac{NZ}{A}X(t)$ and of quantity $DK(t) = \Pi/\hbar$ for the $\text{Ca} + \text{Mo}$ reaction is shown in Fig.1a. Here $\Pi = \frac{NZ}{A}(\frac{P_p}{Z} - \frac{P_n}{N})$ with P_p (P_n) center of mass in momentum space for protons (neutrons) is just the canonically conjugate momentum of the X coordinate, $\Pi = M_{coll}X'(t)$.

We choose the origin of time at the beginning of the *dinuclear* phase [7]. The dipole acceleration as obtained by a second order numerical derivative of $D(t)$ is shown in Fig.1b. With a good approximation this is zero before $t = 0$. It suddenly rises when the collective dipole excitation is triggered and after few oscillations it becomes completely damped, around $250\text{fm}/c$. The corresponding power spectrum, $|D''(\omega)|^2$, calculated from the Fourier transform $D''(t) = 1/2\pi \int_0^\infty D''(\omega) \exp^{-i\omega t} d\omega$, is plotted in Fig.1c by a dashed line. In the same Fig.1c we have added (solid line) $|D''(\omega)|^2$ as obtained directly from the Fourier transform of the dipole moment, [18]. The nice agreement between the two

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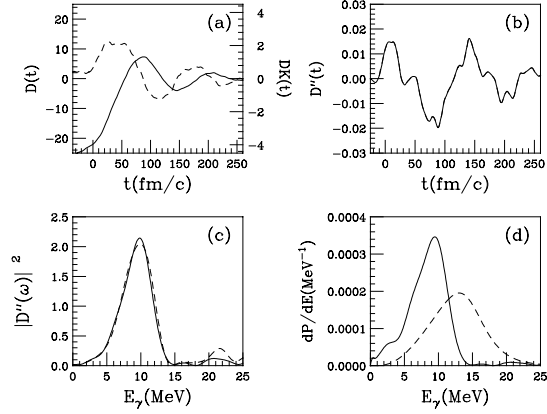


FIG. 1. System $\text{Ca} + \text{Mo}$ at 4AMeV : (a) Time evolution of $D(t)$ (solid line, in fm units), and $DK(t)$ (dashed line, in fm^{-1}). (b) The same for the acceleration $D''(t)$ (in c^2/fm). (c) Power spectrum $|D''(\omega)|^2$ (in c^2 units). (d) Bremsstrahlung spectrum (solid line) and the first step statistical spectrum (dashed line).

The total photon emission probability from the pre-equilibrium dipole mode, given by the bremsstrahlung formula Eq.(1), is reported in Fig.1d (solid line).

For comparison we show the first step statistical spectrum (dashed line). The latter is just the product of the statistical gamma decay rate [16], (see also Eq.(3)), times the mean life time of the compound nucleus τ_{CN} [18]. For the statistical *GDR*, the standard parameters from systematics, including temperature dependence of the width, are considered. We remark that the two contributions are comparable.

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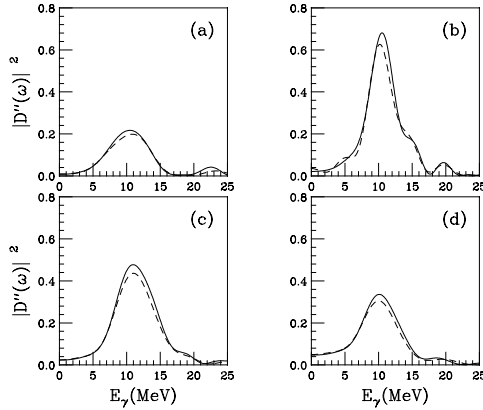


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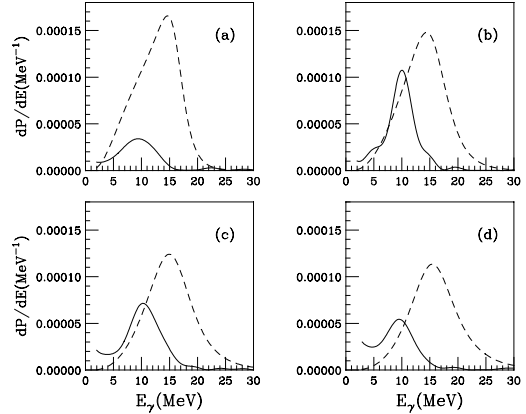


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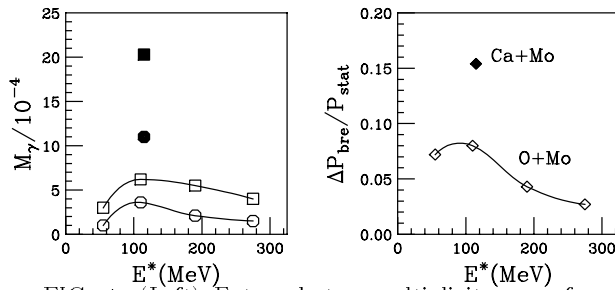


FIG. 4. (Left) Extra photon multiplicity as a function of initial excitation energy: bremsstrahlung (empty squares), phonon model (empty circles) for the $O + Mo$ system and $Ca+Mo$ (the corresponding full symbols). (Right) Ratio of total pre-equilibrium to total statistical GDR γ -ray emission (see text).

Outlook

We have shown that when we consider the full dynamics of the pre-equilibrium dipole in charge asymmetric fusion processes the extra radiation contribution appears to be systematically two times larger than the expectations, based on a *phonon* model, used so far [7,9,12] (see Fig.4). Moreover we predict also a clear shift to lower frequencies due to the elongation of the emitting source.

The pre-equilibrium dipole radiation due to the charge asymmetry in the entrance channel can be then comparable to the statistical *CN* emission. In this sense it can represent a new "*cooling*" mechanism in warm fusion reactions to form less excited residues, e.g. of interest for the synthesis of heavy elements.

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TeV NEUTRINO FLUXES FROM KNOWN MICROQUASARS

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Abstract

We estimate the neutrino fluxes produced by photopion production in the jets of a sample of identified microquasars and microquasar candidates, for which available data enables rough determination of the jet parameters. We demonstrate that in several of the sources considered, the neutrino flux at Earth, produced in events similar to those observed, can exceed the detection threshold of a km^2 neutrino detector. Sources with bulk Lorentz factors larger than those characteristic of the sample considered here, directed along our line of sight may be very difficult to resolve at radio wavelengths and hence may be difficult to identify as microquasar candidates. However these sources can be identified through their neutrino and gamma-ray emission.

1 INTRODUCTION

The composition of microquasars (MQs) jets is yet an open issue. The synchrotron emission both in the radio and in the IR is consistent with near equipartition between electrons and magnetic field, which is also implied by minimum energy considerations [1]. However, the dominant energy carrier in the jet is presently unknown (with the exception of the jet in SS433). A possible diagnostic of hadronic jets is emission of TeV neutrinos [2]. As shown in reference [2], the interaction of relativistic protons with synchrotron photons emitted by electrons is expected to lead to 1-100 TeV neutrino emission. The predicted fluxes are detectable by large, km^2 -scale effective area, high-energy neutrino telescopes, such as the planned IceCube [3], in the South Pole, or the proposed Neutrino Mediterranean Observatory (NEMO) [4]. In this paper we consider a class of identified Galactic MQs with either persistent jets or documented outbursts. For each source we provide, for illustrative purposes, our model prediction for the neutrino flux that should have been emitted during particular events, using radio data available in the literature. Although

the temporal behavior of many of these sources may be unpredictable, we demonstrate that some of the sources could have been detected by a neutrino telescope with effective area larger than $\sim 1 \text{ km}^2$ (in some cases even 0.1 km^2 , such as AMANDA [5] and ANTARES [6]) had such a detector been in operation during the time of the recorded events and, therefore, propose that they should be potential targets for the planned neutrino telescopes. In addition we consider a list of XRBs thus far unresolved at radio wavelengths, that are believed to be microquasar candidates. In §2 we briefly discuss the neutrino production mechanism in MQs. In §3 we estimate the jet parameters for each source and then use these parameters to derive the expected neutrino flux. The number of neutrino induce muon events in km^2 -scale neutrino telescopes is derived in §4. The implications of our results are discussed in §5.

2 INTERNAL SHOCK MODEL FOR MQs

In this section we give a brief outline of the model proposed by Levinson & Waxman (2001) [3] for production of neutrinos in MQs with the purpose to introduce the parameters relevant for the present analysis. The model assumes that on

sufficiently small scale ($\leq 10^{11}$ cm), inhomogeneities in the jet cause internal shocks that can accelerate protons and electrons to a power law distribution. For typical jet parameters, the maximum proton energy is roughly 10^{16} eV in the jet frame. Protons can interact both with the external X-ray photons emitted by the accretion disc and with the synchrotron photons produced inside the jet by the accelerated electrons, leading to pion production. Charged pions produced in photo-meson interactions decay to produce neutrinos. In a single collision, a pion is created with an average energy that is $\sim 20\%$ of the proton energy. This energy is roughly evenly distributed between the final π^+ decay products, yielding a neutrino energy that is $\sim 5\%$ of the proton energy, leading to a neutrino signal in the energy range of 1 to 100 TeV. The fraction of proton energy converted into pions, f_π , depends on the jet Lorentz factor, Γ , and on the kinetic luminosity of the jet, L_{jet} (see [7] for details). The expected neutrino flux (energy per unit area per unit time) of ≥ 1 TeV muon neutrinos at Earth from a jet ejection event is [2]

$$f_{\nu_\mu} \simeq \frac{1}{2} f_\pi \delta^4 \frac{L_{\text{jet}} / 8}{4\pi D^2}, \quad (1)$$

where $\delta = [\Gamma (1 - \beta \cos \theta)]^{-1}$ is the Doppler factor of the jet (θ is the angle between the jet axis and our line of sight), $\eta_p \sim 0.1$ is the fraction of L_{jet} carried by accelerated protons, and D is the source-Earth distance.

3 JET PARAMETERS AND NEUTRINO FLUXES

In order to determine the neutrino flux from (1) the main quantity to be estimated is the kinetic power of the jet. We have used two different methods for the sources with the relativistic jets resolved in the radio band (resolved MQs) and for the XRBs observed as point like sources, such as GX 339-4, henceforth referred to as unresolved MQs [8].

3.1 Resolved MQs

In events that have been monitored with sufficiently good resolution, it is often possible to obtain a rough estimate of the characteristic

source parameters, in particular the bulk speed of the jet, the angle between the jet axis and the sight line, and the size of the emitting blob. For a flux density $S_\nu \propto \nu^{-1/2}$ of the radio source, implying an electron energy distribution $dn_e/d\varepsilon_e \propto \varepsilon_e^{-2}$, we estimate the minimum of L_{jet} [e.g. [1]], obtained from:

$$L_{\text{jet}} \geq \frac{7}{24} c \frac{(\Gamma r_b B_*)^2}{\eta_e}, \quad (2)$$

where r_b is the size of the emitting blob, η_e is the fraction of jet kinetic energy converted to internal energy of electrons and magnetic field and B_* is the magnetic field that minimizes L_{jet} [7]. In Tab. 1 we report our estimates of the jet power and of the neutrino flux expected at Earth, calculated using equation (1), and adopting the source parameters quoted in literature. The two values of the periodic source LS I +61°303 ($P \sim 26.5$ days) refer respectively to bursting and quiescent states observed by Massi et al. (2001) [9]. The distance of V4641 Sgr, and therefore the jet parameters, is uncertain. We report calculations for both the values of D present in literature [10] and [11]. Several authors pointed out that the kinetic energy output of the SS433 jets can influence the radio emission of W50, moreover SS433 is the only MQ that shows a strong H_α -line emission from the jets [12,13,14]. In our estimate we assume the conservative value of $L_{\text{jet}} \sim 10^{39}$ erg/sec suggested by Margon [15].

3.2 Unresolved MQs

For the sources whose jet has not been resolved, we cannot deduce the value of L_{jet} from Eq.(3), since Γ , δ and the size of the jet are not known. We follow instead a different line of argument. We estimate the jet synchrotron luminosity, assuming a spectral index $\alpha_R \sim 0.5$ for the emitted radiation [8]:

$$L_{\text{syn}} = 4\pi D^2 \frac{1}{1 - \alpha_R} S_{\nu_{\text{high}}} \nu_{\text{high}}, \quad (3)$$

where ν_{high} is the highest observed frequency of synchrotron emission, and $S_{\nu_{\text{high}}}$ the flux density emitted at this frequency. Assuming that the total jet synchrotron luminosity is a fraction η_r of

the jet kinetic energy, carried by relativistic electrons and magnetic field, we estimate the total L_{jet} as:

$$L_{\text{jet}} = \eta_e^{-1} \eta_r^{-1} L_{\text{syn}} \quad (4)$$

A typical value of $\alpha_R \sim 0.5$ implies electrons do not cool fast on scales that are resolved by the VLA. Assuming that emission at ν_{high} originates from the same radius as the radio emission, for the typical parameters inferred for the resolved MQs (B of tens of mG corresponding synchrotron frequency of about 10 GHz), electrons

Table 1: Kinetic luminosity of the jet and neutrino fluxes.

Source name	L_{jet} (erg/sec)	$F_{\nu_{\text{H}}}$ (erg/cm ² sec)
Resolved MQs		
CI Cam	$5.66 \cdot 10^{37}$	$2.23 \cdot 10^{-10}$
XTE J1748-288	$1.84 \cdot 10^{39}$	$3.07 \cdot 10^{-10}$
Cygnus X-3	$1.17 \cdot 10^{39}$	$4.02 \cdot 10^{-9}$
LS 5039	$8.73 \cdot 10^{36}$	$1.69 \cdot 10^{-12}$
GRO J1655-40	$1.60 \cdot 10^{40}$	$7.37 \cdot 10^{-10}$
GRS 1915+105	$2.45 \cdot 10^{40}$	$2.10 \cdot 10^{-10}$
Circinus X-1	$7.61 \cdot 10^{38}$	$1.22 \cdot 10^{-10}$
LS I 61°303	$1.65 \cdot 10^{37}$	$4.49 \cdot 10^{-11}$
LS I 61°303	$5.69 \cdot 10^{36}$	$9.06 \cdot 10^{-12}$
XTE J1550-564	$2.01 \cdot 10^{38}$	$2.00 \cdot 10^{-11}$
V4641 Sgr	$8.02 \cdot 10^{37}$	$2.25 \cdot 10^{-10}$
V4641 Sgr	$1.17 \cdot 10^{40}$	$3.25 \cdot 10^{-8}$
Scorpius X-1	$1.04 \cdot 10^{38}$	$6.48 \cdot 10^{-12}$
SS433	10^{39}	$1.72 \cdot 10^{-9}$
Unresolved MQs		
GS 1354-64	$3.62 \cdot 10^{37}$	$1.88 \cdot 10^{-11}$
GX 339-4	$3.86 \cdot 10^{38}$	$1.26 \cdot 10^{-9}$
Cygnus X-1	$1.45 \cdot 10^{36}$	$1.88 \cdot 10^{-11}$
GRO J0422+32	$4.35 \cdot 10^{37}$	$2.51 \cdot 10^{-10}$
XTE J1118+480	$3.49 \cdot 10^{37}$	$5.02 \cdot 10^{-10}$

radiating at $\nu_{\text{high}} \sim 10^{14}$ Hz cannot lose more than $\eta_r \sim 0.1$ of their energy. The energy neutrino flux expected at Earth is:

$$f_{\nu_{\mu}} \simeq \frac{1}{16(1 - \alpha_R)} \frac{\eta_p}{\eta_e} f_{\pi} \eta_r^{-1} S_{\nu_{\text{high}}} \nu_{\text{high}} \quad (5)$$

where corrections associated with the relativistic expansion of the jets are neglected. In fact, since these corrections are the same for both the synchrotron and neutrino emission, the estimate of neutrino flux in Eq. (6) is independent of such

corrections. In Tab. 1 we quote, for a sample of unresolved MQ candidates, our estimates of L_{jet} and $f_{\nu_{\mu}}$ calculated from Eq.(5) and Eq.(6).

Recent observations with the VLBA array have confirmed the nature of MQs for the source Cygnus X-1, revealing an extended jet-like feature extending to ~ 15 mas from a core region, with an opening angle of $< 2^\circ$ [16]. The authors suggest for this source a bulk motion velocity of $\beta \sim 0.75$ and a viewing angle of $\theta \sim 40^\circ$, corresponding to a Lorentz factor of $\Gamma \sim 1.51$ and a Doppler boost factor $\delta \sim 1.55$. Adopting these jet parameters and a quasi-steady emission of $S_{\nu} \sim 5$ mJy at $\nu = 8.4$ GHz, the kinetic luminosity, calculated from Eq.(3), is $L_{\text{jet}} \sim 3.53 \cdot 10^{36}$ erg/sec. The new estimate of the L_{jet} for Cygnus X-1 is therefore consistent with the value in Tab. 1, obtained from the Eq.(5) for the unresolved sources.

4 MUON EVENTS IN A KM²-TELESCOPE

The detection of TeV neutrino fluxes from MQs could be the first achievable goal for proposed underwater(ice) neutrino telescopes. In this section we calculate the rate of neutrino-induced muon events expected in a detector with an effective area of 1 km². Since the signal is expected to be dominated by neutrinos of energy $E_{\nu} \geq 1$ TeV, for which the detection probability is $P_{\nu \rightarrow \mu} \sim 1.3 \cdot 10^{-6} E_{\nu, \text{TeV}}$ [17], we estimate the number of ν -induced muon events as [2]:

$$N_{\mu} \simeq 0.2 \eta_{p,-1} f_{\pi} \delta^4 D_{22}^{-2} L_{\text{jet},38} A_{\text{km}^2} \Delta t \quad (6)$$

where $A_{\text{eff}, \text{km}^2}$ is the effective detector area in km² units, Δt is the duration of the observed burst and $D = D_{22} \cdot 10^{22}$ cm. In Tab. 2 we report the number of events expected in a detector with $A_{\text{eff}} = 1$ km², during the bursts considered in section §3. In the case of persistent sources number of neutrino induced muon events is calculated for a 1 year period. In the same table, we also report the number of background atmospheric neutrino events collected in such a detector during the time Δt , assuming a neutrino spectrum $\phi_{\nu, \text{bkg}} \sim 10^{-7} E_{\nu, \text{TeV}}^{-2.5} / \text{cm}^2 \text{ sec sr}$ for $E_{\nu} > 1$ TeV and for a detector angular resolution of 0.3° .

Table 2: Muon events and atmospheric neutrino background.

Source name	Δt (days)	N_{μ}	$N_{\mu bkg}$
<i>Resolved MQs</i>			
CI Cam	0.6	0.05	0.002
XTE J1748-288	20	2.5	0.054
Cygnus X-3	3	4.8	0.008
LS 5039	Persistent	0.2	0.986
GRO J1655-40	6	1.8	0.016
GRS 1915+105	6	0.5	0.016
Circinus X-1	4	0.2	0.011
LS I 61°303	7	0.1	0.019
LS I 61°303	20	0.1	0.054
XTE J1550-564	5	0.04	0.014
V4641 Sgr	0.3	0.03	0.001
V4641 Sgr	0.3	3.9	0.001
Scorpius X-1	Persistent	0.9	0.986
SS433	Persistent	252	0.986
<i>Unresolved MQs</i>			
GS 1354-64	2.8	0.02	0.008
GX 339-4	Persistent	183.4	0.986
Cygnus X-1	Persistent	2.8	0.986
GRO J0422+32	1÷20	0.1÷2	0.003-0.1
XTE J1118+480	30÷150	6÷30	0.081-0.405

5 DISCUSSION

There are large uncertainties involved in the derivation of the jet parameters for most of the sources listed in Tab. 1 and 2. The best studied cases are perhaps GRS 1915+105, GRO J1655-40, and SS433. Nonetheless, we have demonstrated that if the jets in MQs are protonic, and if a fraction of a few percent of the jet energy is dissipated on sufficiently small scales, then emission of TeV neutrinos with fluxes in excess of detection limit of the forthcoming, km² scale, neutrino telescopes is anticipated. The present identification of MQs, and the inferred distribution of their jet Lorentz factors, may be strongly influenced by selection effects. It is quite likely that the class of Galactic MQs contains also sources with larger bulk Lorentz factors and smaller viewing angles, which should emit neutrinos with fluxes considerably larger than the extended MQs discussed in this paper. Such sources may be identified via their γ -ray emission with, e.g. AGILE and GLAST, or by their neutrino emission. The gamma-rays should originate from larger scales where the pair production opacity is

sufficiently reduced. Predictions for AGILE and GLAST will be discussed in a forthcoming paper [18]. There are currently about 280 known XRBs [19], of which ~ 50 are radio loud. These may also be potential targets for the planned neutrino detectors. Our results quoted in Tab. 1 are consistent with experimental upper limits on neutrino fluxes from point sources set by MACRO [20], AMANDA [21] and Super-Kamiokande [22].

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STATUS REPORT FOR THE MAGNEX SPECTROMETER

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Abstract

The status of the MAGNEX spectrometer project at the LNS is described. The year 2001 has seen the final design phase of almost all of the elements, including the focal plane detector, vacuum system, and rotating platform. The magnet and power supply construction has continued at DANFYSIK A/S. A major effort has been placed on developing the ray reconstruction software.

1 INTRODUCTION

The concept and layout of the MAGNEX spectrometer has been described in refs. [1-3]. In brief, it is a large-acceptance device (50 msr) based on a vertically-focussing quadrupole and 55° bend-angle dipole. The angles and profiles of the dipole entrance and exit pole faces are used to partly correct aberrations in the ion-optics. Further corrections are performed in software by a ray-reconstruction technique, resulting in an expected average momentum resolution of about 1/2000. A position-sensitive timing detector (PSD) between the target and quadrupole gives both the angle of the scattered particles and a start signal for the time-of-flight. The focal plane detector (FPD) must measure positions and angles as well as providing particle identification information.

2 MECHANICAL

During 2001, construction of the dipole and quadrupole magnets and associated power supplies has continued at DANFYSIK A/S, Jyllinge, Denmark. The iron yokes and pole pieces are complete (Fig. 1), the principal remaining task being the surface correcting coils within the pole gap of the dipole. These will be used for the correction of the kinematic factor k in nuclear reactions. The MAGNEX vacuum system is separated by gate valves into three sections: (i) the target chamber, (ii) the quadrupole and dipole chamber and (iii) the exit chamber. The focal plane detector is separated from the latter by a thin window foil.



Fig. 1 Photograph of quadrupole (foreground) and dipole (background) yokes at DANFYSIK A/S.

Initial design studies for the target chamber are based on a 40-cm radius cylinder with an extension on the opposite side to the spectrometer for coincident particle detector arrays. This could be substituted by a smaller chamber for the use of gamma-ray detectors close to the target. The chamber will be provided with both a 1000 l/s turbopump and a 3200 l/s cryopump.

The magnet chamber is almost complete. It will be pumped by a 3200 l/s cryopump before and a 1600 l/s turbopump after the dipole. The surface coils will be in a separate low-vacuum chamber, one side of which will be the dipole face and the other a thin steel wall.

The exit chamber includes a trapezoidal section to account for the 61° focal plane inclination and a rectangular bellows. The bellows must allow a possible 10 cm parallel movement of the focal plane detector in the case of kinematic shift at magnetic rigidity beyond that for which the surface coils can compensate. This section is pumped by a 1000 l/s turbopump.

3 FOCAL PLANE DETECTOR

3.1 Final test of the prototype

The prototype FPD described in last year's report has been further tested with ^6Li , ^{16}O and ^{40}Ca heavy ion beams from the LNS Tandem. The detector is based on two sequential drift chambers, each one consisting of two independent sets of wires for energy-loss measurement and 16 underlying strips per set of wires for position and angle determination. Silicon detectors at the back of the drift chamber provide the residual energy information as well as the trigger. The absence of intermediate foils and low isobutane gas pressure (5 - 30 mbar) result in a minimum energy threshold of 0.5 MeV/A. This makes application to nuclear astrophysics experiments in the region of the CNO cycle particularly interesting. The prototype itself could be used as a coincidence heavy-ion recoil detector in the target chamber.

The intrinsic position resolution was measured by a correlation analysis of adjacent sets of strips. Better than 0.35-mm resolution (FWHM) in the horizontal position is obtained for angles of track inclination less than 8° . Even at 12° it is close to the requirements for the MAGNEX FPD (< 0.5 mm). The shorter strip lengths (1.5 cm compared to the prototype's 5 cm) to be used in the final FPD should improve the resolution for particles with large angle of inclination. A vertical position resolution of 0.48 ± 0.03 mm was obtained from the drift time of the electron swarm. The image of a mask with five 0.8 mm holes is shown in Fig. 2.

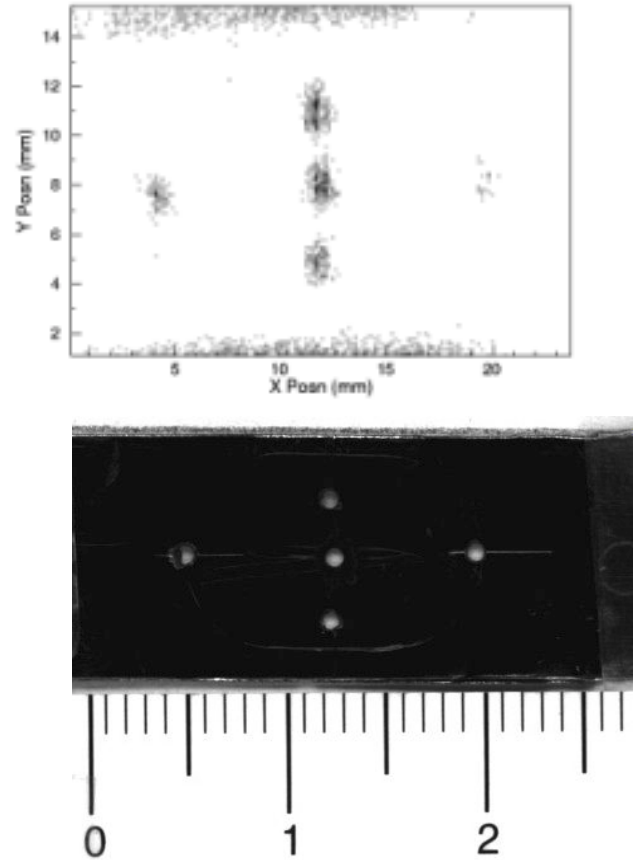


Fig. 2. Scatterplot (top) of vertical against horizontal position measured with the ^{16}O beam. A target with five holes, (bottom) was in front of the detector.

The angular resolution obtained with this detector is better than 7 mr for all ion species. This well-fulfils the requirements of the MAGNEX FPD (10 mr) for the ray reconstruction described below.

Finally, the energy-loss signals from the wires have been studied. The observed resolutions, given as percentage FWHM divided by the mean, are summarised in Table 1 both for a single set of wires and sets of wires summed together. Note that for ^6Li the 4th wire set was not recorded, thus the sum results are for three wire sets only. Rows 4 and 6 in the table are the predicted energy-loss straggling calculated by the SRIM-2000 [4] program. While this is seen to be a significant contribution to the observed resolution in general, it is clear that other effects such as electronic noise and instabilities in the gas pressure or wire voltage must also be important. In any case, we achieve the goal of better than 5% ΔE resolution for ^{40}Ca .

Table 1. Measured and calculated (SRIM) energy-loss resolutions (FWHM/mean).

	α	${}^6\text{Li}$	${}^{16}\text{O}$	${}^{40}\text{Ca}$
Energy (MeV)	5.5	44	63	95
Gas pressure (mbar)	20	31	20	13
$\delta(\Delta E_1)/\Delta E_1$ meas (%)	12	20	8	7
$\delta(\Delta E_1)/\Delta E_1$ SRIM (%)	7	18	5	4
$\delta(\Delta E_2)/\Delta E_2$ meas (%)	7	17	4	4
$\delta(\Delta E_2)/\Delta E_2$ SRIM (%)	5	11	2	1

4 SOFTWARE RAY RECONSTRUCION

A test of the ray reconstruction method has been done using the code COSY-INFINITY [5,6] for the generation of the spectrometer transfer map and its inversion. For this purpose, a complete set of subroutines for the specific case of MAGNEX has been written in the COSY language environment (FOXY language). Calculations were made using the fringe field fall-off in the quadrupole and dipole magnets predicted by TOSCA simulations. We carried out calculations up to the 11th order. In addition, the code COSYMAG was written to test the efficiency of the method, taking into account the angular and energy straggling of ions in the target and PSD and FPD detectors, as predicted by SRIM-2000. Realistic intrinsic resolutions of the detectors were used, based on experimental tests and simulations were done for different ions and energies. The results are very encouraging. Energy resolving powers up to 3000 were obtained in restricted regions of the phase space accepted by the spectrometer, with a mean value of 1800 for the higher rigidity (1.8 Tm) and about 500 for the lower one (0.5 Tm). A mass resolution up to 200 (mainly depending on the time resolution), and a maximum error on the scattering angle of about 0.2° were found. The reconstruction algorithm on which the code is based can be easily adapted in the future for the development of the data acquisition system.

A good representation of the magnetic field generated by the quadrupole and dipole magnets is crucial to obtain the high-order transfer map that we need. Therefore the problem of the interpolation of a 3-D measured data grid point has been studied in order to find the required precision of the field mapping.

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MonTe ARRAY: AN UPGRADING OF TRASMA MULTIDETECTOR SYSTEM AT LNS

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Abstract

A compact ΔE -E detection system, able to discriminate in charge light-medium mass ions with very low energy (300 keV_A for Carbon, Nitrogen) is described. The system, called "MonTe ARRAY" (**Mon**olithic **T**elelescope **ARRAY**), is located at 20° beam line and represents the upgrading of TRASMA multidetector system operating since 1995 at LNS.

The TRASMA multidetector system is located at the 20° beam line of LNS. It is used to detect charged particles in coincidence with γ -rays emitted in heavy ion nuclear collisions.

In its actual configuration [1] TRASMA consists of 63 BaF₂ crystals divided into 9 clusters placed outside the scattering chamber. They are exclusively devoted to detect and identify γ -rays and neutrons using TOF and pulse shape analysis techniques.

The charged particles are detected by the ΔE -E forward hodoscopes. The first stage is an annular silicon strip detector, 300 μ m thick, divided into 8 equal sections, each containing 9 strips. The second stage consists of 8 CsI(Tl) crystals placed very close to the silicon detector.

The usual ΔE -E technique permits a good charge identification for heavy ions when used in reactions at intermediate incident energy. However an high energy identification threshold is present due to the ΔE silicon detector thickness, ~ 14 MeV·A for masses $m=14$ -23 and

~ 20 MeV·A for $m=30$ -40.

By applying a pulse shape discrimination technique excellent charge identification from H to Ni (our projectile) is obtained in a wide range,

extending up to the punch through energy for different ions [2]. Typical charge identification thresholds are ~ 1.7 MeV·A for $m=12$, ~ 3.0 MeV·A for $m=20$ and ~ 5.5 MeV·A for $m=40$.

In several nuclear reaction studies, nevertheless, these charge identification energy thresholds are too high. These are the cases when light particles (C, N) at low energies have to be detected, for example in reactions induced by radioactive beams which will be delivered at LNS by EXCYT or when fusion and incomplete fusion evaporation residues have to be measured in coincidence with γ -rays.

In both cases an upgrading of the TRASMA multidetector system is necessary to include a large solid angle detection system, but small enough to be mounted in the inner ball ($R=100$ mm) of TRASMA scattering chamber.

MonTe ARRAY (**Mon**olithic **T**elelescope **ARRAY**) consists of monolithic strip ΔE -E detection units. One unit is formed by 2 strips each one having 5 separate ΔE stages (3×4 mm², 1 μ m thick) with a common E stage, 400 μ m thick, see Fig.1.

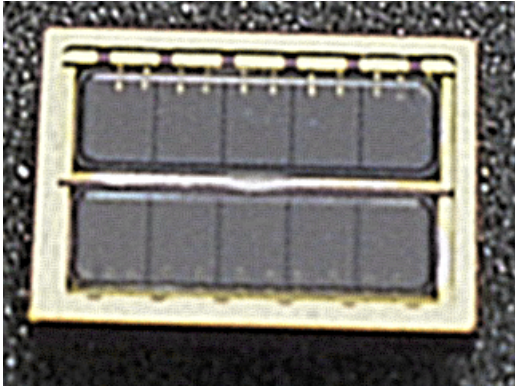


Fig.1 – Detection unit of MonTe ARRAY

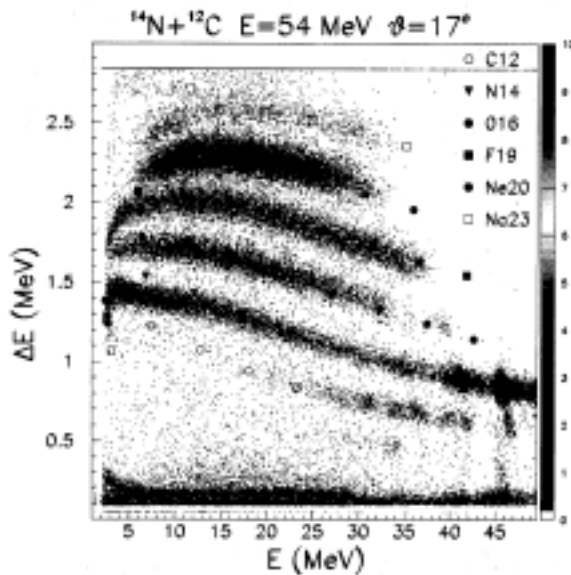


Fig.2 - ΔE -E scatter plot for $4 \times 4 \text{ mm}^2$ monolithic telescope.

The ΔE stage is built by Boron implantation (common anode) on E stage; its ultrathin thickness allows an excellent charge resolution, very similar to the single monolithic $4 \times 4 \text{ mm}^2$ ΔE -E prototype (up to 300 keV_A for Carbon and Nitrogen, see Fig.2) [3].

The detection units are mounted along 16 meridians of a hemisphere ($\Delta\Omega = 22.5$) whose center is the target position.

The target-detector distance is 50 mm and the single strip covers a solid angle $\Delta\Omega_{\text{strip}} = 4.8 \text{ msr}$. Inside the hemisphere can be place up to 28 detection units, reaching a total solid angle $\Omega = 1.34 \text{ sr}$ in the angular range $16^\circ \leq \theta_{\text{lab}} \leq 85^\circ$.

For the first experiment we have mounted 12 detection units covering the angular range $16^\circ \leq \theta_{\text{lab}} \leq 57^\circ$ and a solid angle $\Delta\Omega = 576 \text{ msr}$.

In Fig.3 is shown the hemisphere with 12 detection units mounted inside.

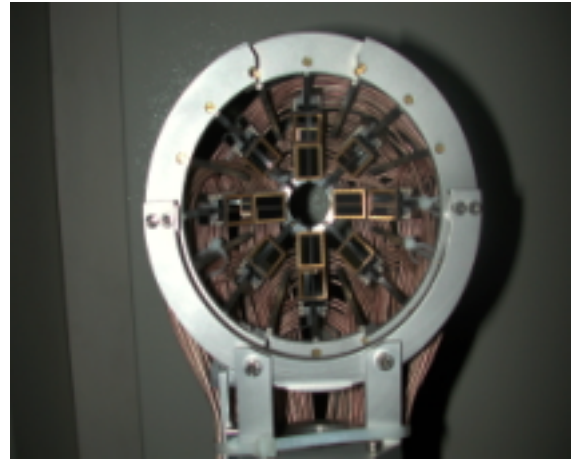


Fig.3 – Front view of hemisphere containing 12 detection units.

The signals coming from the detectors will be treated by a very compact charge preamplifier (PAC) system (eV Products 5194, gain 20 mV/MeV and 2 mV/MeV for ΔE and E stage respectively).

In Fig.4 a rear view of hemisphere including the PAC system is shown.

The preamplifier is followed by a shaping amplifier and timing amplifier (Silena 761F/R-16 channels shaping and timing amplifier).

The energy signal is integrated and converted by a QDC (Caen-VN1465S 64 channels VME QDC).

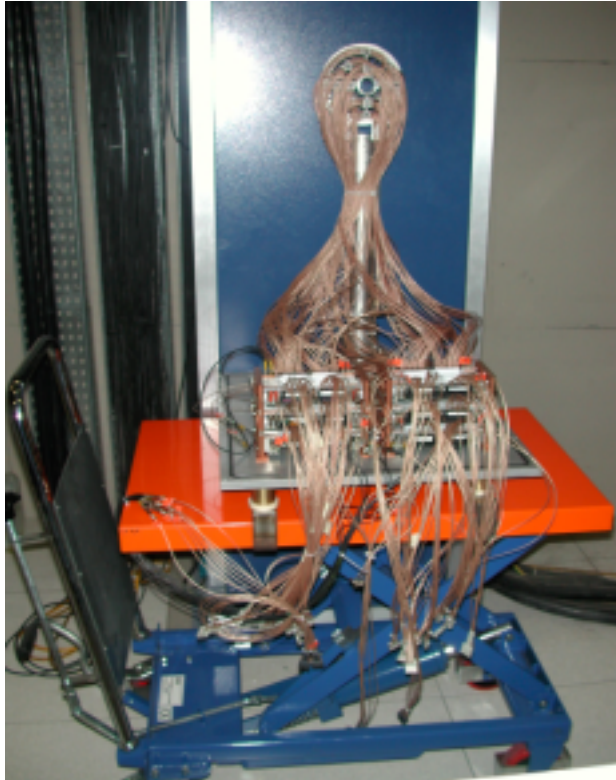


Fig.4 – Rear view of MonTe ARRAY

In its first configuration MonTe ARRAY will be used to study $^{40}\text{Ca} + ^{46}\text{Ti}$ reaction, at 10 MeV_A incident energy, at LNS.

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These very integrated electronics is inserted in the existing acquisition system of multidetector TRASMA.

THE HADES TIME OF FLIGHT WALL

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Abstract

In the framework of the HADES (High Acceptance DiElectron Spectrometer) collaboration a Time of Flight wall subdetector has been developed. In order to efficiently select rare events with dilepton pairs produced in the nuclear matter, in a high hadron multiplicity environment, such a wall must be able to resolve electrons from pions up to 0.5 GeV/c and from protons up to 2 GeV/c. The short flight path of about 2 m requires a time resolution better than 150 ps, while impact position and multiplicity measurements need adequate granularity. These requirements have been fulfilled by employing scintillator rods read-out at both ends by photomultipliers.

1 INTRODUCTION

The study of hadron properties inside nuclear matter as a function of density and temperature has recently gathered great interest, and now represents a lively fraction of present heavy-ion research. It turned out that several properties, like effective masses and decay widths, can be probed by spectroscopy of meson decays occurring inside the nuclear medium; the gross thermodynamic features of the collision region can be tuned by proper choice of hadron and/or heavy-ion projectile and target. A quite promising tool to study these properties is the electron-pair spectroscopy of the vector meson decays (ρ , ω and ϕ), as the emitted leptons do not undergo strong final-state interaction with the surrounding dense nuclear medium. To this purpose a dedicated spectrometer has been built: the High Acceptance DiElectron Spectrometer (HADES) [1].

HADES is a detector system for lepton-pair spectroscopy, installed at GSI (Darmstadt) by a European collaboration involving groups from 19 institutions in 9 different countries. After several

commissioning runs throughout the assembling phases, now the spectrometer has finally started to take preliminary data for the HADES physics program.

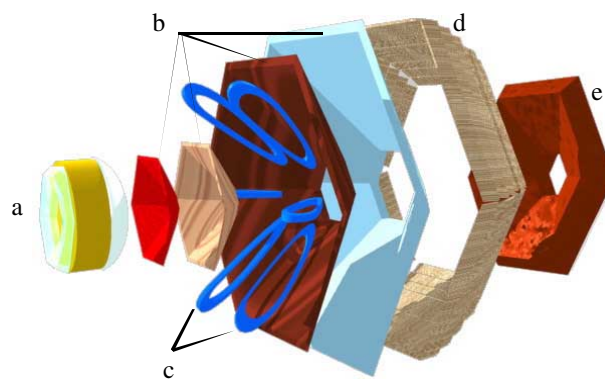


Fig.1 Sketch of the HADES spectrometer, spread along the longitudinal direction for clarity. In operating conditions all the detectors fit inside each. The height of the spectrometer is about 6 m. The RICH (a), the four planes of MDC (b), the superconducting magnet coils (c), the TOF (d) and the pre-Shower (e).

The spectrometer, whose six-meter high hexagonal structure is sketched in fig.1, is

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mainly designed for heavy ion collision studies in the $E=1\div 2$ A GeV incident energy range.

Azimuthally segmented into six sectors, the spectrometer covers polar angles $18^\circ < \theta < 85^\circ$ and aims at an invariant mass resolution of dilepton pairs $\Delta M/M \approx 1\%$ at $M \approx 800$ MeV/c².

2 THE TIME-OF-FLIGHT WALL

The time of flight (TOF) wall, shown in fig.2, is meant to three main purposes:

- Fast determination of the charged particle multiplicity of the event, in order to select central collisions and thus provide a first level trigger to the data readout electronics.
- Fast tracking, by determining the impact position of each hitting particle, in order to allow a fast second level trigger decision about the event.
- Measurement of the time of flight of each hitting particle, in order to separate electrons (and positrons) from more massive particles like protons and pions [2].



Fig.2 The Time Of Flight wall right after its installation on the HADES mechanical support frame.

It covers the angular region $44^\circ < \theta < 88^\circ$ in the same overall hexagonal geometry inherent to the whole spectrometer. The operating principle is based on a scintillating rod element structure. Each rod, being read out at its two ends by photomultipliers (PMT), when hit by a particle provides two signals, each one further split into two, that are suitably handled and then converted into numbers. By combining these informations one can extract time of flight (*tof*), hit position

(x)[†], deposited energy (ΔE) and redundant hit position ($\tilde{x}$).

The total number of rods is 384, arranged in six sectors of 64 rods. In each sector there are 8 modules of 8 rods, each module enclosed in a special carbon-fibre case[‡]. Such a case guarantees light tightness and mechanical support, while being light and thin enough for the particles to cross it with negligible perturbation and production of background e⁺e⁻ pairs from photon conversion. Each case, containing 8 rods of equal length, is suited to be fixed to the overall mechanical structure of the spectrometer.

3 DETECTOR FEATURES

The selected scintillating material is the BC408 from Bicron[§], mainly due to its good attenuation length (3.8 m in bulk) combined with scintillation efficiency ($\approx 10^4$ photons/MeV) and speed (2.1 ns decay time). The attainable time-of-flight (*tof*) resolution, as estimated from on-bench measurements, was of the order of 100÷150 ps [2], which is consistent with the experimental results that will be shown below. This assuming a time resolution well below 100 ps for the start detector, namely an 8-strip diamond detector placed in front of the target [3].

4 ELECTRONICS SET-UP

Timing is measured by an electronic chain which includes a constant fraction discriminator (CFD), followed by a logic active delay (LAD) [4] and then by a time to digital converter (TDC). The CFD's are 16-fold Camac modules C808 from CAEN^{**}, specially modified in order to better suit the plastic and PMT signal features.

The amplitude signal measurement is performed by an electronic chain made of a shaper and an amplitude to digital converter.

Actually the TDC and ADC modules employ a common motherboard, hosting the logic circuitry and the true analog to digital conversion electronics, while the time or amplitude type characterization is done by fitting in one of two different daughter boards [5, 6].

A calibration system has been built, based on a UV Nitrogen laser coupled to the scintillators by

[†]) The origin of the x axis is the midpoint of the rod.

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means of quartz optical fibres. Each rod has three fixed UV light entry points, at its center and 200 mm apart from each rod end, that can be alternatively used to excite the scintillator with sharp light pulses in a known hit point.

5 EXPERIMENTAL RESULTS

In fig.3 we show the ΔE - tof scatter plot after energy normalization and calibration; the time of flight has been renormalized to an equal flight path of 2.1 m for all particles.

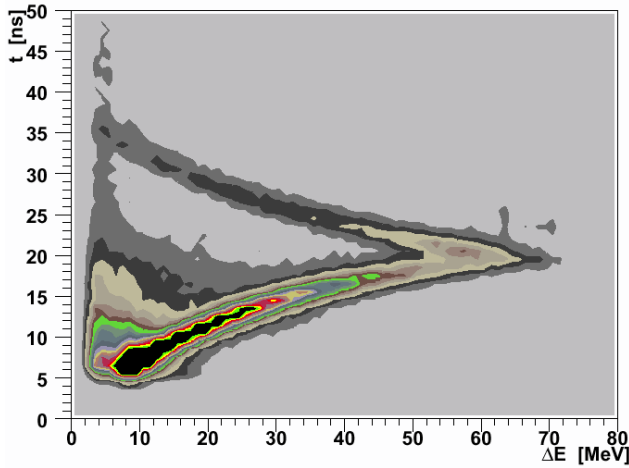


Fig.3 Normalized and calibrated ΔE - tof scatter plots ($C+C$ at 1A GeV beam data) for one TOF sector.

After determining the calibration constants, which allow us to measure absolute time, position and energy, we evaluated the precision of these measurements. The overall energy resolution, as measured along the upper branch of fig.3 corresponding to slow protons, is about 10%.

The really important parameter for TOF is however the time-of-flight resolution, being the position resolution bound to it by means of V_g , according to the formula

$$\sigma_x = \sigma_{tof} \cdot V_g$$

Therefore time-of-flight resolution is relevant for the overall performance of the TOF system, as it affects the capability of discriminating electrons from hadrons based on their velocity, as well as the precision fast tracking for triggering purposes.

In fig.4 we show the inclusive tof spectrum for all particles, integrated over the whole rod set after renormalization of the trajectories to equal flight path. In fig.5 we show the tof spectrum as before, but including only particles that produced a signal on the RICH within $|\Delta\theta| < 2^\circ$ and $|\Delta\phi| < 1^\circ$, i.e. electrons/positrons all moving at nearly the

speed of light. The bell-shaped distribution can be nicely fit by a gaussian, whose width is the overall tof resolution $\sigma_{tof} \approx 180$ ps.

Unfortunately, due to electronic noise during the beam run when these data were produced, the contribution introduced by the start detector to the tof resolution was relevant. Therefore, in order to estimate the effective resolution we used two additional methods described below.

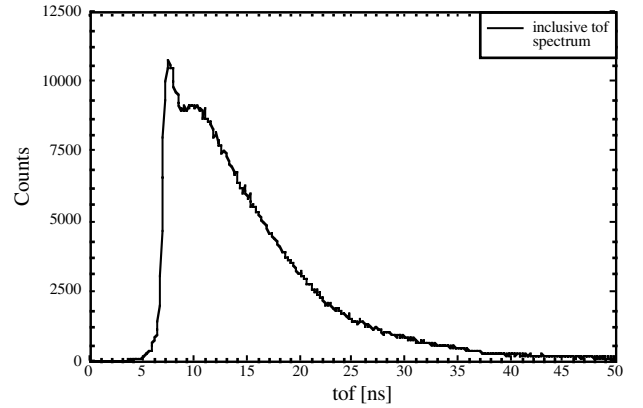


Fig.4 Inclusive time of flight spectrum, normalised to equal flight path, as measured in the reaction $Cr+Al$ at 1.8A GeV.

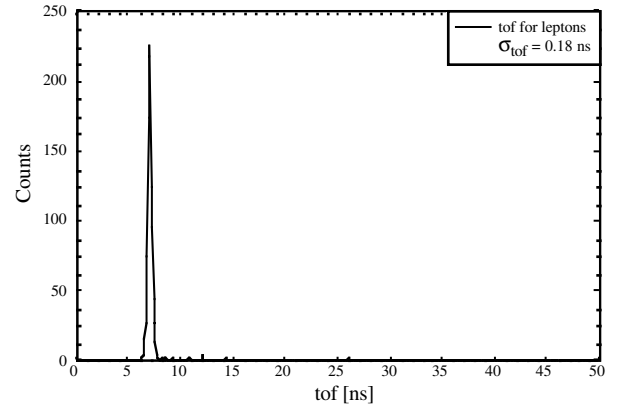


Fig.5 Exclusive time of flight spectrum for particles (electrons/positrons) in the TOF-RICH coincidence angular window $|\Delta\theta| < 2^\circ$ and $|\Delta\phi| < 1^\circ$. The overall time resolution, including the start detector, is $\sigma \approx 180$ ps.

By correlating the x position measured by TOF with the corresponding measurement done by the MDC tracking detectors, we get a nice straight line which indicates a perfect correlation. Then, in order to measure the position resolution, we can plot the distribution of the differences between the two positions, $d = (x_{TOF} - x_{MDC})$, where x_{MDC} has been geometrically projected onto the rod plane; as $\sigma_{xMDC} \ll \sigma_{xTOF}$ we can assume $\sigma_d \approx \sigma_{xTOF}$. This plot, reported in time units (as position and time are mutually bound in

TOF detector), shows a gaussian shape with $\sigma_{tof} \approx 150$ ps (fig.6).

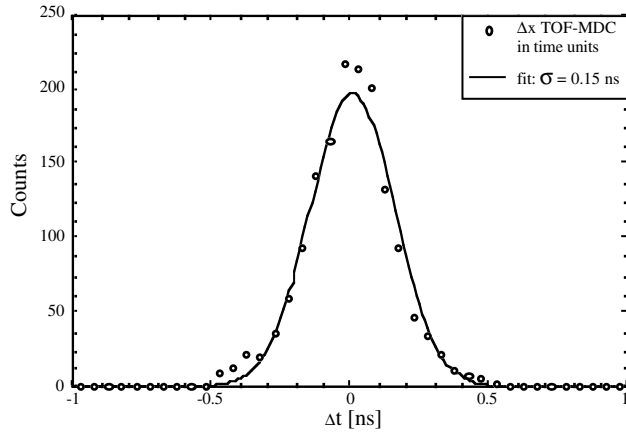


Fig.6 Overall time resolution of the TOF detector, determined by correlation with the MDC tracking detector, as position difference in time units (see text). $\sigma \approx 150$ ps.

During the same run we also detected a number of dileptons, i.e. e^+e^- pairs mainly coming from π^0 decays and/or gamma conversion in the target, practically moving at the speed of light. The tof difference between the two leptons (after renormalization to equal flight path length) should in principle be zero. The resulting plot is a gaussian distribution whose sigma value, divided by $\sqrt{2}$, is another independent measurement of $\sigma_{tof} \approx 150$ ps (fig.7).

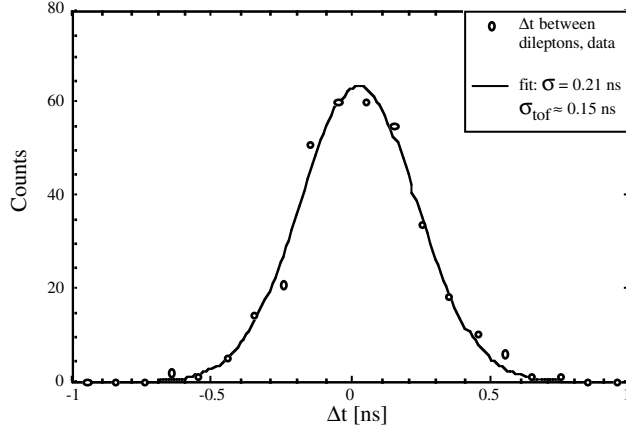


Fig.7 Overall time resolution of TOF detector, determined as distribution of the difference in the arrival time between the two members of dilepton pairs (see text). $\sigma = 210$ ps, $\sigma_{tof} = \sigma / \sqrt{2} \approx 150$ ps.

The last two σ_{tof} values, which are consistent with each other, express the overall tof resolution of the TOF detector excluding the contribution of the start detector with its related electronics.

6 CONCLUSIONS AND PERSPECTIVES

The HADES spectrometer for di-lepton physics is now nearly ready, with its TOF wall detector complete and already fully operational. It has shown capable of fulfilling the tasks it was meant for, achieving the design performance in terms of time-of-flight and position resolution: $\sigma_{tof} \leq 150$ ps, $\sigma_x \leq 25$ mm. In addition, TOF has shown to be quite stable and easily managed even throughout a long beam run.

A preliminary physics run in November 2001 has proved that TOF can efficiently operate in selecting and tracking the searched rare events with e^+e^- pairs produced in the nuclear matter, thus precluding the beginning of systematic physics investigations with HADES in 2002.

7 ACKNOWLEDGEMENTS

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- INTAS call-94-1233
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Pulse Shape method applied on silicon detector of CHIMERA Array

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In early '60, it has been shown that current pulses produced by ionising charged particles detected in silicon detectors were dependent on the atomic mass A and the atomic number Z of the detected particles[1,2]. Since then, Pulse Shape techniques applied on silicon detector (PSD) have inspired various works in the field of the heavy ions experimental physics. The rise time of the current signal (due to both electrons and holes mobility) is the result of a complex phenomenon strongly depending on the effective profile of the electric field that is established across the active detection area, and, consequently, on the microscopic properties of the silicon bulk material. A substantial progress on the PSD method was achieved by G. Paush et al.[3] by a coherent description of the physics underlying the signal rise time process. As a relevant result, it is suggested that the lower energy threshold for charge identification is obtained when the particle impinges the detector surface from the side where the electric field is expected to be the lower (reverse configuration). However this latter condition does not allow for suitable time of flight (TOF) measurements by using the common method of constant fraction (CFD) discrimination. Recently, the authors of Ref. [4] have shown new and impressive results. Best experimental conditions were found by using relatively small area ($\approx 5\text{cm}^2$) Si detectors with highly homogeneous n-doped bulk material, preferentially, obtained by the neutron transmutation technique (nTD). In particular, energy thresholds lower than 2.5 A.MeV were reported for charge identification of ions, with Z up to 10 atomic charge unit, which are stopped in the silicon

detector by using the reverse configuration detection condition. Simply, we note that the simultaneous employment of the PSD method and TOF method, if technical possible, could allow for a more efficient use of silicon detectors in heavy ion nuclear reaction studies. Recently, we studied PSD method in one of the silicon detector used in CHIMERA multi detector. The experimental study is useful for both future projects in the field of heavy ion collision at low and intermediate energy and for future upgrading of the multi detector. As an example of what has been recently done by the working group, in Fig. 1 it is shown the charge identification obtained in one of the CHIMERA silicon detector that has been cooled for the first time in order to strongly reduce the inverse current to a vanishing value. The silicon detector was a two-pad $300\mu\text{m} \times 20\text{cm}^2$ (500nA inverse current at full depletion and 20°C temperature) planar detector having good timing performance (400psec) and good energy resolution (50 KeV with 5.48 MeV alpha particle). Beams of ^{16}O , delivered with typical 0.7nAe current by the LNS Tandem at 100MeV, were used to bombard $100\mu\text{g}/\text{cm}^2$ self-supporting carbon target. The fragments produced in the collision were detected at 8° in the laboratory system. The nuclear particles impinge the detector surface from the side where the electric field is expected to be the higher (direct configuration). We note that, in a typical silicon CHIMERA detector we have charge signal with rise time of the order of 50nsec for the 5.48MeV alpha particle, as obtained by a fast charge preamplifier. In figure 1, we show this rise time as a function of the detected particle energy. The rise time

measurement was obtained by splitting the charge signal and using two CFD CHIMERA modules having respectively 30% and 90% of fraction and 20nsec internal delay. Charge identification of elements from alpha particles to oxygen ions with energy threshold of about 4.5 MeV/A is clearly seen. Also, isotopic identification of Li and Be elements is present. The results, as illustrated in Fig.1, are very promising and they indicate that the pulse shape method could be used systematically in CHIMERA. Also, from results as shown fig.1, it is expected that by using simultaneously TOF and PSD methods the energy threshold for full isotopic identification of charged particles could be lowered down to few MeV/nucleon. More detailed experiments on PSD method applied on CHIMERA detector are in progress.

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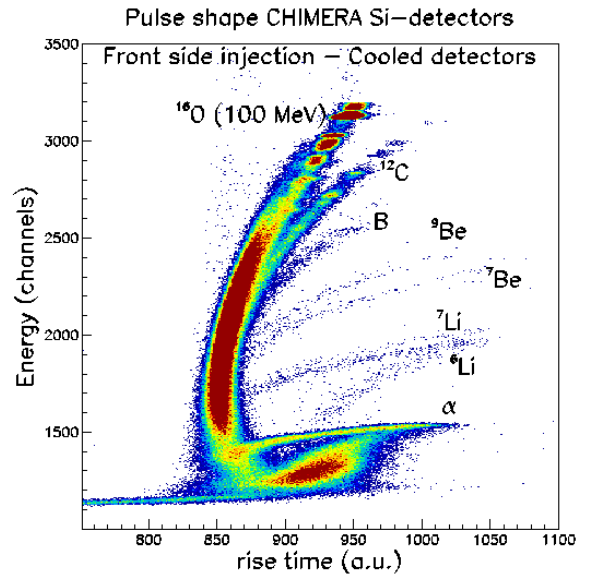


Fig.1: Charge identification of light ions in one module of the CHIMERA detector by a pulse shape method. In the figure, 100chs in the time scale correspond to about 3nsec of time spread.

IDENTIFICATION AND ENERGY CALIBRATION OF LIGHT CHARGED PARTICLES IN THE REVERSE EXPERIMENT

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Abstract

The inorganic crystal of CsI is often used as a detector of light charged particles and heavy ions. In this report we present useful method of identification of the isotopes detected in a CsI scintillator. This method allows to make quick mass and charge identification. We also present a method of energy calibration based on ΔE -E analysis for reaction $^{124}\text{Sn} + ^{64}\text{Ni}$ 35 MeV/A. The obtained parameters can be applied to analyze others reactions measured in the similar experimental conditions.

1 INTRODUCTION

The forward part of multi-detector Chimera consists of 688 telescopes arranged in a cylindrical geometry around the beam axis. It causes that energy calibration is usually the most time consuming process. It is profitable for the analysis to have an accurate procedure of mass and charge identification before energy calibration.

The CsI crystal provides a light signal with two components: fast and slow. The fast component depends on energy of the detected particle, while the slow component varies with the particle type. This property of the CsI crystal is the base of the pulse shape analysis. The discrimination technique applied for CHIMERA detector uses two gates method [1] adapted for photodiode readout [2].

The light response of the CsI crystal is not linear with energy and it depends on mass and charge of the particle. From this reason an accurate energy calibration of each detector is needed.

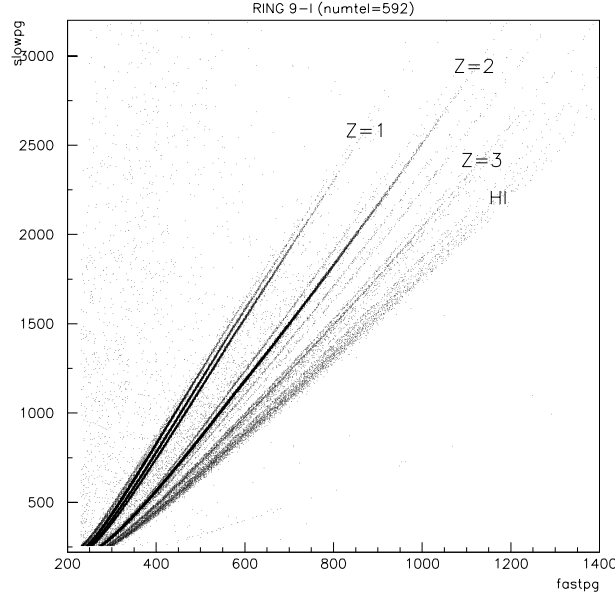


Figure 1: An example of standard slow-fast matrix.

2 MASS AND CHARGE IDENTIFICATION

We define a two-dimensional slow-fast spectrum for each ring as a standard matrix (see example in Figure 1).

Subsequently we transform all slow-fast scatter plots to the standard matrices, using elastic peaks from calibration runs:

$$\begin{aligned} &^7\text{Li}+^{197}\text{Au} \text{ 50 MeV,} \\ &^7\text{Li}+^{58}\text{Ni} \text{ 50 MeV,} \\ &\text{p}+^{197}\text{Au} \text{ 24.96 MeV.} \end{aligned}$$

This method simplify further consideration to analysis only one slow-fast matrix for each ring.

We share every matrix in two energy regions for each value of Z. Then the linearization of each region has been done separately. The power function of the slow component

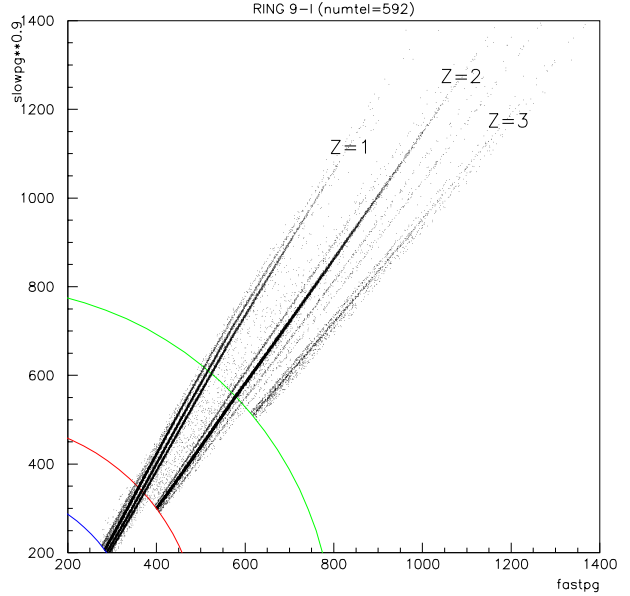


Figure 2: An example of linearization for 'higher' energy regions.

is used (see Figure 2) as a linearization function.

After linearization each slow-fast matrix is transformed to the new angle(Θ)-radius(R) system by using formula:

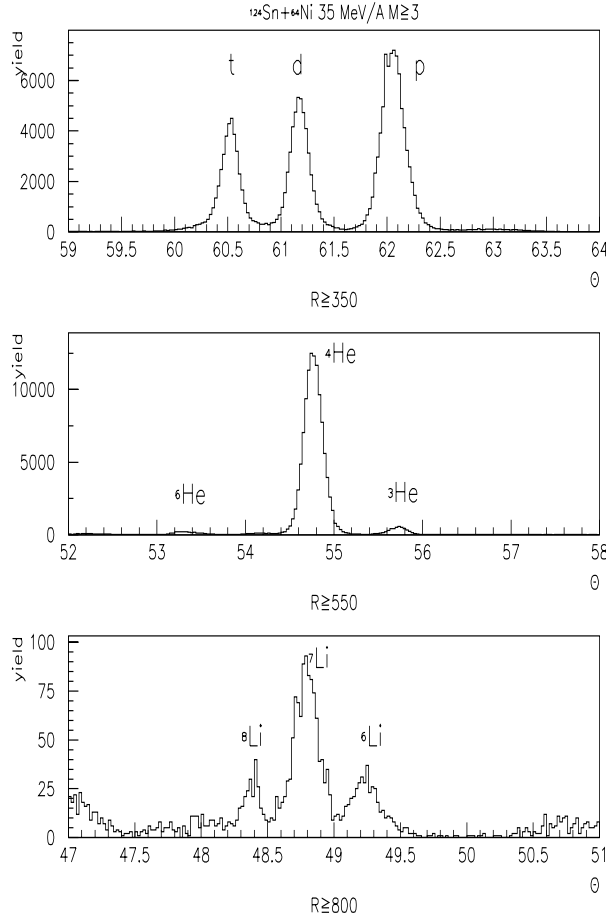


Figure 3: Mass and charge identification of H, He and Li isotopes.

$$R^2 = (slowpg^p - sl_0)^2 + (fastpg - fa_0)^2,$$

$$\sin\Theta = (slowpg^p - sl_0)/R,$$

where sl_0 , fa_0 are slow and fast value of new beginning of coordinate system, $slowpg$ and $fastpg$ are a channel number of the slow and fast component, respectively.

An example of one-dimensional projection onto angle-axis is shown in Figure 3. One can see very good separation between H, He and Li isotopes.

3 ENERGY CALIBRATION

The light output of scintillator, given by equation (1), depends on the energy

deposited in the CsI crystal (E), the atomic and mass numbers of incident ions (Z,A)[3]:

$$L = kA^\alpha Z^\beta E^\gamma. \quad (1)$$

Using above equation and the Bethe-Bloch formula we obtain following expression for the energy value:

$$E = k_1 A^{\alpha_1} Z^{\beta_1} (fastpg - f_0)^{\gamma_1}, \quad (2)$$

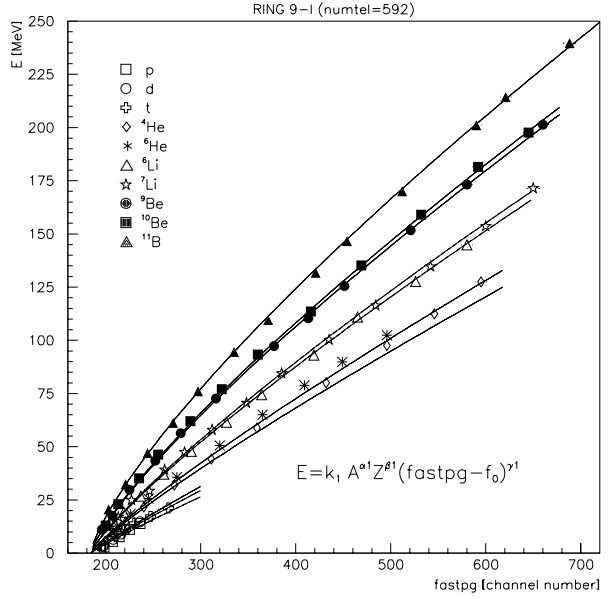


Figure 4: Calibration points for the CsI scintillator obtained in the REVERSE experiment. The curves are the results of a least-squares fit to equation (2).

where:

$$k_1 = a_k e^{b_k Z} + c_k,$$

$$\gamma_1 = a_\gamma e^{b_\gamma Z} + c_\gamma,$$

and:

$$a_k, b_k, c_k, a_\gamma, b_\gamma, c_\gamma,$$

α_1, β_1, f_0 are the fit parameters.

An example of global fit for one of standard detectors is shown in Figure 4.

The more detailed description of identification and calibration was presented on 5-th Meeting of the REVERSE Collaboration in

4 RESULTS

The numbers of counts of p, d, t, ^3He , ^4He , ^6He , ^6Li , ^7Li and ^8Li has been calculated by putting integration gates on one-dimensional mass spectra obtained for the reaction $^{124}\text{Sn}+^{64}\text{Ni}$ 35 MeV/A .

The computed parameters (common for

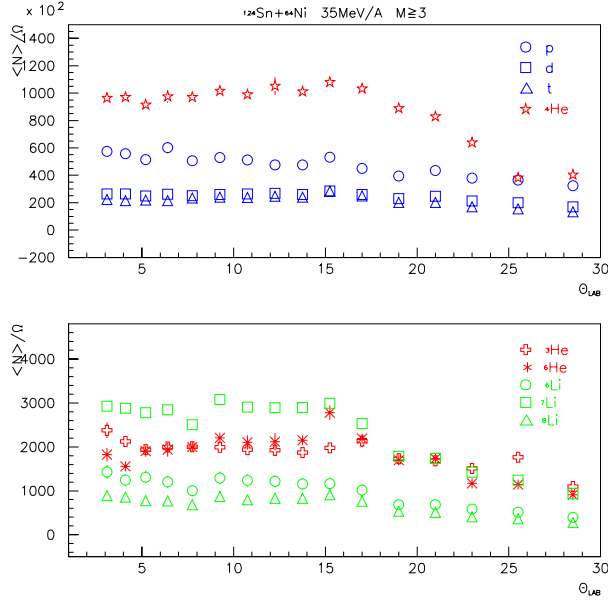


Figure 5: Angular distribution of isotopes.

each ring and individual for each detector) can be used to analyze any other reaction measured in similar experimental conditions.

Simply energy dependence on the fast component of the light output has been found (equation 2).

The energy spectra obtained from the method based on the pulse shape analysis do not give full energy information, what is clearly shown in Figure 6, especially for Li isotopes .

This lost information can be extracted by using $\Delta E(\text{Si})\text{-}E(\text{CsI}_{fastpg})$ analysis.

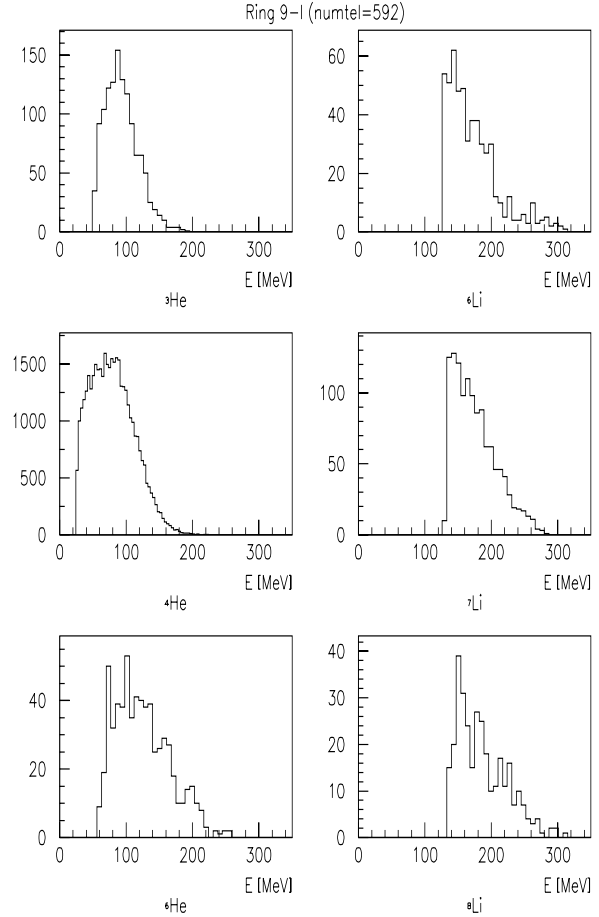


Figure 6: Energy plots for He and Li isotopes.

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Particle identification method in CsI(Tl) scintillators used for the CHIMERA 4 π detector

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Abstract

The charged particle identification obtained by the analysis of signals coming from the CsI(Tl) detectors of the CHIMERA 4 π heavy-ion detector is presented. The obtained quality of the identification scatter plot is explained as due to the use of the RF signal as reference time for the gate generation. Signals due to the interaction of neutron with CsI(Tl) scintillators are also shown.

1 INTRODUCTION

CsI(Tl) detectors with photodiode readout are used as second stage of the CHIMERA [1,2] telescopes. A photodiode readout of CsI(Tl) has been chosen. We show the particle discrimination obtained for the whole detector.

2 THE PARTICLE IDENTIFICATION METHOD

For the particle identification we use the so called two-gate method. It is based on the fact that the decay time of the unipolar signal of a spectroscopic amplifier keeps memory of the mass and charge of the detected particles. By integrating a portion of the tail of the amplifier output and plotting this value (SLOW-component) against a signal proportional to the peak value (FAST-component giving the energy information), the identification scatter plot shown in fig.1 was produced. This picture, obtained in the reaction $^{124}\text{Sn} + ^{64}\text{Ni}$ at 35 MeV/A for one of the CHIMERA detectors, mounted at $\theta=14^\circ$, illustrates typical features of the identification function in the experiment. As can be observed, a satisfactory particle identification is obtained. The mass separation is better seen in the insets in Fig.1, where $^{7,9}\text{Be}$ isotopes are clearly observed, and even Boron ions can be discriminated from heavier ions.

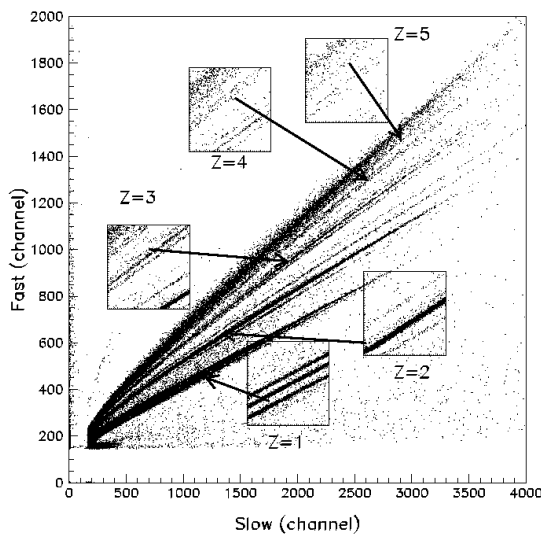


Fig.1 Fast-slow scatter plot for a detector mounted at $\theta=14^\circ$.

The isotopic identification has been verified using the information on the energy loss in the preceding silicon detector. In the next section will be shown that the quality of the obtained identification depends on the time stability reached with our gate generation method.

3 THE GATE GENERATION METHOD

For the charge integration, 9U QDC manufactured by CAEN (mod. VN1465) were used. Such QDC have a common gate and, for simplicity, the same gate for all the 688 telescopes was used. The CHIMERA detectors are mounted at large distances from the target up to 3.5 m for the very forward angles. The long fly paths ensure the time spread necessary for mass identification, but on the other hand, they result in a time jitter of the signals with respect to the used common gate. To overcome this problem, in analysing the FAST-component, high-quality low-cost 48-channel stretcher modules designed by INFN Milano, are used. In this way, the energy resolution of the CsI(Tl) detectors is not affected by any dynamical jitter. The SLOW gate

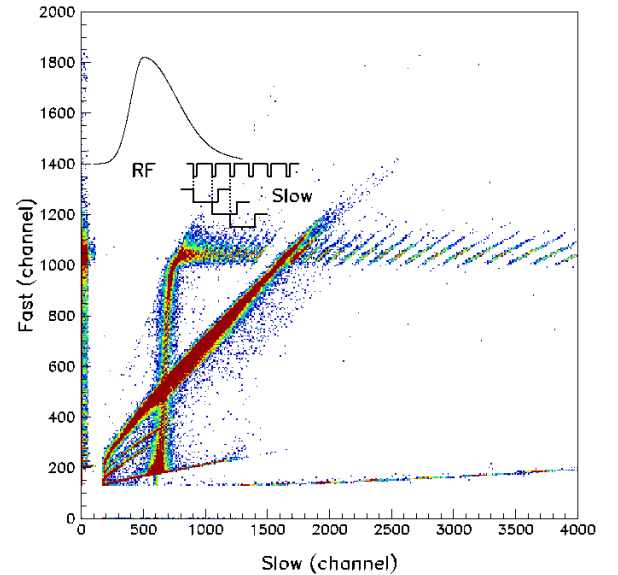


Fig.2 Fast slow scatter plot for a detector at $\theta=1^\circ$.

(as well as the others) is generated using as reference time the radiofrequency (RF) of the cyclotron accelerator validated by the trigger,

see fig.2. As a consequence of using the RF reference time, coincidences with particles produced within different beam bursts are characterized by a SLOW integrated signal quite different than the one collected for good coincidences. Particles produced in different beam bursts are clearly seen in fig.2 showing data from a detector of the first ring, mounted at $\theta=1^\circ$. From fig.2 we measure a 6% variation of the SLOW-component signal each 134 nsec, being this value the time difference between two consecutive beam bursts. This information was used to study the effect of the signal jitter on particle identification resolution. In fig.3 a typical Energy-SLOW scatter plot, expanded in the low energy region is shown. It can be seen that

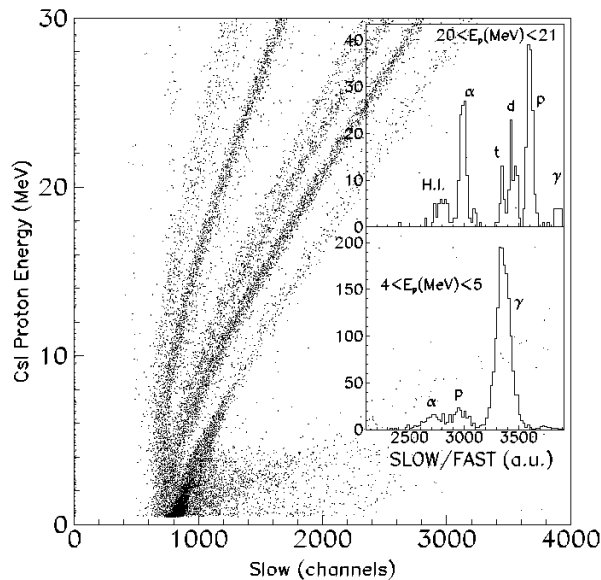


Fig.3 Expanded fast-slow scatter plot showing the threshold for particle discrimination.

above 20 MeV, one can easily distinguish tritons (t) from deuterons (d) (look also to the upper inset of fig.3 where a plot of the SLOW/FAST signal obtained for a slice around 20 MeV protons is shown). The distance along the SLOW axis between d and t lines at 20 MeV is of the order of 100 channels. With the time dependence of the SLOW signal determined from fig.2, one obtains the dispersion of about 0.5 ch/nsec. The very low RF time spread, 700-800 psec (FWHM) measured during the run, is therefore negligible. In comparison with the previous CHIMERA collaboration work [3], in

which the gates were generated by the time signal from the CsI(Tl), the main advantage obtained using the RF signal as time reference is a significant reduction of the identification thresholds. With the previous method [3], the charge identification threshold for proton and alpha particles was above 8 MeV, whereas in the present work a typical threshold for protons about 4-5 MeV is obtained, as can be seen from fig.3 looking also to the lower inset. The identification threshold for discrimination of charged particles against γ -rays is less than 2 MeV (proton energy). Taking into account the large size of crystals used in CHIMERA (typical size $5 \times 5 \times 12 \text{ cm}^3$), our results obtained in normal on-beam conditions are rather good in comparison with the best results reported in the literature [4,5] obtained with small crystals irradiated with radioactive sources.

4 THE NEUTRON IDENTIFICATION AND FINAL REMARKS

Effects of an influence of the time-of-flight on the FAST-SLOW identification scatter plots have interesting consequences allowing one to observe signals produced by neutrons interacting with CsI(Tl) detectors. In the inset in fig.1 for $Z=2$, a shadow near the alpha line can be seen. This shadow is produced by neutrons interacting with the CsI(Tl) detector through (n, α) reactions. The TOF of an α -particle generated by the (n, α) reaction corresponds to the velocity of the primary neutron. Therefore for alpha particles produced in the target or via (n, α) reactions the TOF differs by more than a factor of two. This produces a large time spread and thus the shadow observed in fig.1. To confirm this hypothesis, we have additionally used information from the silicon detector. Obviously, α -particles must give a signal also in the silicon detector placed in front of the CsI(Tl), whereas neutrons do not. In fig.4 is presented a zoom of the low energy region of an ENERGY-SLOW scatter plot obtained with the condition of no signal in the silicon detector. One can see the (n, α) line starting from about 14 MeV in the α -particle calibration scale. This is

in good agreement with the expected threshold for the (n,α) process. There is one more effect in fig.4 that we would like to comment: one can observe a concentration of events to the right of the γ line. These events can be produced by low energy neutrons interacting with the detector through (n,γ) reactions. The TOF delay for low energy neutrons of a few MeV, relative to γ -rays on the 1.6 m flight path, is of the order of 100 nsec. The signal is delayed with respect to the SLOW gate and therefore more charge is integrated

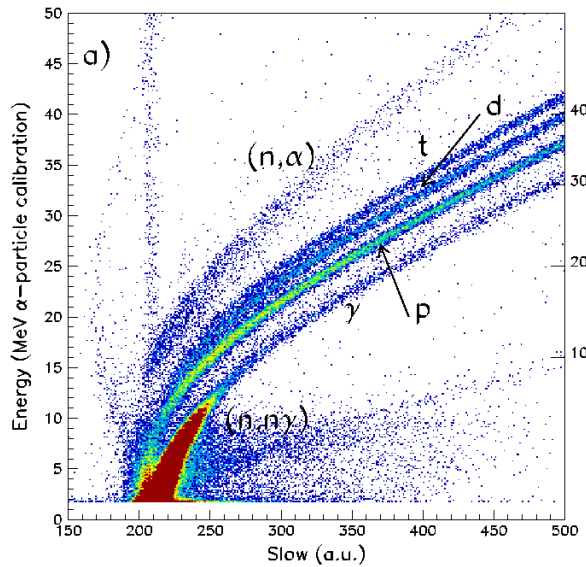


Fig.4 Fast-Slow scatter plot with the condition of no-signal released in the corresponding Silicon detector.

producing a larger SLOW signal for the same light output. Additional simulations and tests are necessary to confirm this hypothesis.

In summary, we have shown that a satisfactory identification of light particles can be obtained in a large array of CsI(Tl) detectors with photodiode readout and a compact cheap electronics when a stable reference time is used to generate the gates for the QDC analysis. Although in our work a particularly good reference time (<1 nsec) was used, our method could be effectively applied even with somewhat worst time resolution, probably up to 4-5 nsec. Using this method combining the pulse shape identification and the TOF information, for the first time particles up to

$Z=5$ are identified whereas isotopic identification is attained up to $Z=4$. The TOF influence on this particle identification method could be also fundamental to discriminate neutron from γ -rays.

The LNS cyclotron staff is greatly acknowledged for producing beams of very high quality. We would like also to thank all the technical staffs of the INFN Sezione di Catania and LNS for the enthusiastic effort that led to successful mounting of the CHIMERA detector.

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DIGITAL PULSE SHAPE ACQUISITION FROM CHIMERA CsI(Tl)

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Abstract

A sampling digital to analog converter (12-bit, 100 MS/s) has been used to perform a digital pulse shape acquisition of the signals coming from a typical CHIMERA 6x6x12 cm³ CsI(Tl) scintillator coupled to a standard CHIMERA electronic chain, up to the amplifier. The preliminary results obtained with Tandem beams are presented.

1 INTRODUCTION

CsI(Tl) scintillators are widely used to perform Light Charged Product (LCP) identification, as they emit light pulses whose shape varies with the type of incident radiation. As well known the decay of the light emitted by the CsI(Tl) is given by the sum of two exponential functions:

$$L(t) = \frac{A}{\tau_F} e^{-\left(\frac{t}{\tau_F}\right)} + \frac{B}{\tau_S} e^{-\left(\frac{t}{\tau_S}\right)},$$

where τ_F and τ_S denote the decay constant of the fast and slow components of the light pulse, respectively. The use of scatter plots of Fast vs Slow is a standard method employed in multidetector arrays for LCP identification.

In order to improve the LCP identification, we have carried out some tests using sampling digital to analog converters (SADC) to perform a real-time digital pulse-shape analysis of the signals coming from a standard CsI(Tl) scintillator of CHIMERA, 6x6x12 cm³ wide, coupled to a photodiode.

We have developed the on-beam and on-line LCP identification for the CsI(Tl) crystal, by means of a standard electronic chain, used in CHIMERA for measuring the slow component, except for the charge to digital converter (QDC) replaced by a sampling analog to digital converter. In the present contribution, the on-beam on-line results obtained are presented.

2 EXPERIMENT

In view of new 4 π A/Z multidetector projects, we have implemented an ad hoc system to digitally compute the fast and slow components for a typical CHIMERA scintillator. This work has been motivated by both the increasing employment of digital pulse shape analysis in γ -spectroscopy and our previous experience in on-line digital signal processing [1],[2]. To date only few results obtained off-line with radioactive sources and small crystals (1 cm³) have been reported on digital processing of CsI(Tl) signals [3].

2.1 Analog electronic chain

For CHIMERA, the classical two gate method [4], based on the charge comparison between Fast and Slow, is applied to collect Fast and Slow signals. In fig. 1 the typical electronic chain for a CHIMERA CsI(Tl) scintillator is shown. In the following we call this kind of electronic chain *analog chain*. The crystal is coupled to a Hamamatsu photodiode, connected to a charge preamplifier, and to a Silena 761F amplifier. The two output pulses, one shaped for collecting the Slow, the other stretched at maximum value to give the Fast, are simultaneously converted by QDC's 8 μ s later than the starting point, with a gate pulse 2 μ s wide (fig. 1).

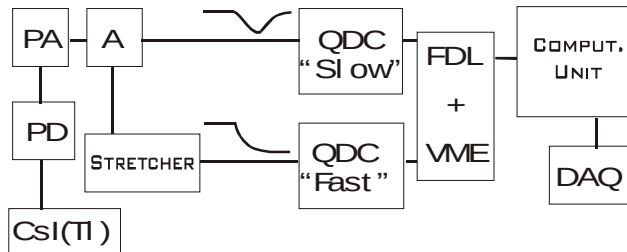


Fig.1: Standard analog chain for Fast and Slow acquisition.

2.2 Digital electronic chain

To perform the tests that we described here, the electronic chain of fig. 2 has been used. In the following we call it *digital chain*. The modules, up to the amplifier included, are unchanged. Only the shaped output of the amplifier was used, directly connected to the input of SADC. The trigger for the acquisition was generated using the tune signal delivered by the SILENA amplifier, filtered by a constant fraction discriminator. The sampling ADC used is a SIS3300 (by Struck Innovative Systems), an 8 channel 6U VME digitizer/transient recorder with a sampling rate of up to 105 MHz for the individual channel and 12-bit resolution. It manages a dual memory bank, a multievent functionality and pre/post trigger capability.

SADC, being a VME-module, was located in a VME crate, together with an embedded CPU module, a VP7 by SBS Technologies. The VP7 is a 6U all-in-one VME-bus CPU based on Pentium III processor (700 MHz).

VP7 was used as manager CPU for SADC. It collected, via VME bus the digital samples and stored them in a buffer, reconstructing at the same time, on-line and in real time, the fast and slow component, using the charge comparison method.

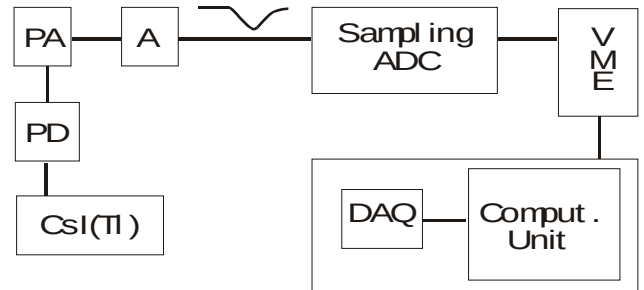


Fig.2: Digital chain used for Fast and Slow acquisition.

A host PC was connected to VP7 via Ethernet 100 Mb/s for presenting the results and for recording them on tape.

In fig. 3 the block diagram of the code running on VP7, and handling the acquisition, is shown. It is written in Visual C++ and runs under Windows NT 4.0 O.S..

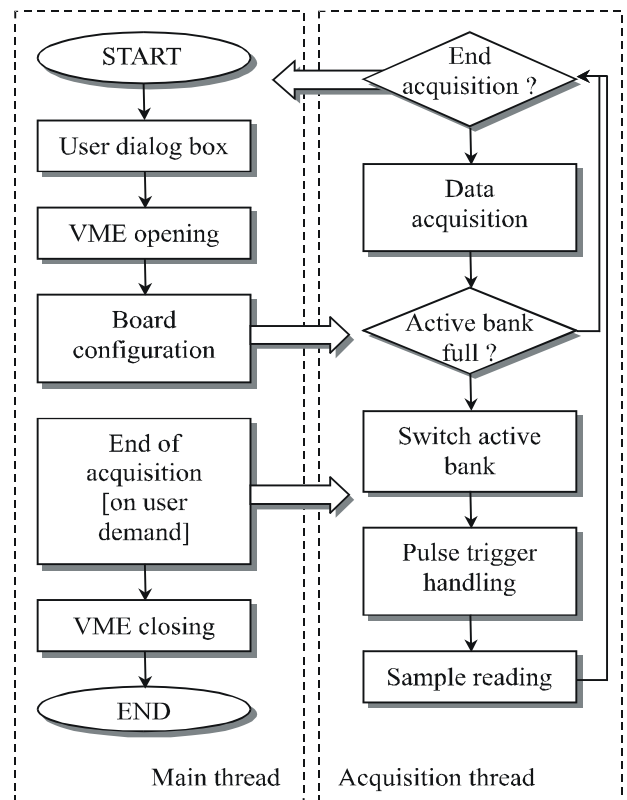


Fig.3: Acquisition code block diagram.

2.3 Experimental results

In the present tests, the shape of the amplifier output was up to 20 μs long (fig. 4). We worked at two different acquisition frequency: 100 and 25 MS/s. For every event SADC recorded a signal-form with 2048 (512) consecutive digital samples, collected at 100 MS/s (25 MS/s), i.e. at 10 (40) ns time intervals. In the two cases, no appreciable differences were seen in the pulse shape reconstruction.

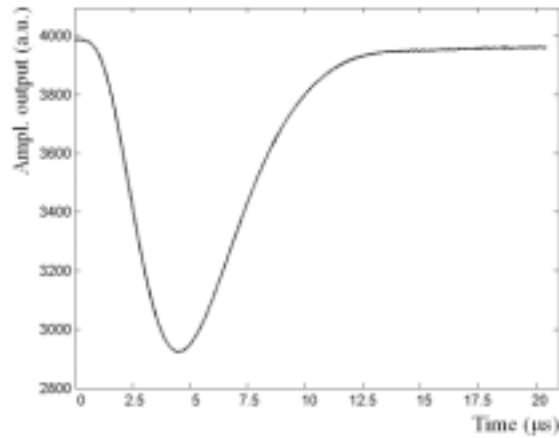


Fig.4: Typical amplifier output signal, digitally collected.

The acquisition rate reached was of ~ 600 Hz (for 25 MS/s), fully compatible with CHIMERA acquisition rate.

A typical $6 \times 6 \times 12 \text{ cm}^3$ CsI(Tl) scintillator of CHIMERA, was located in the 2000 reaction chamber of LNS and bombarded with different ion beams.

The results obtained with ^7Li and ^{16}O incident beams are shown in fig.s 5 and 6, respectively. The fast and slow components have been obtained in the same way as for the analog method.

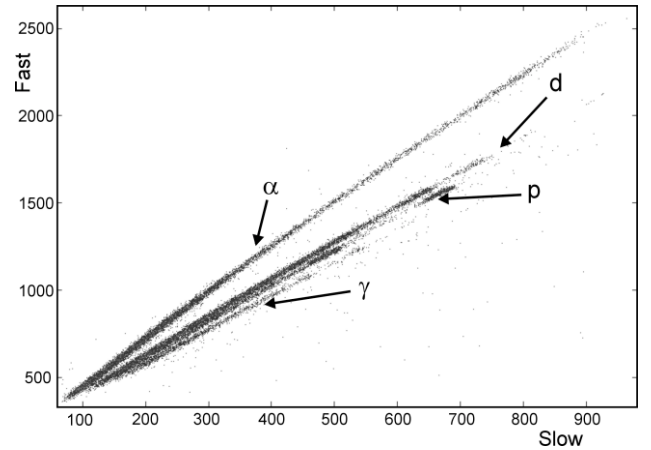


Fig.5: Results obtained with ^7Li incident beam (the ^7Li are not detected because of the presence of a Silicon detector in front of the crystal).

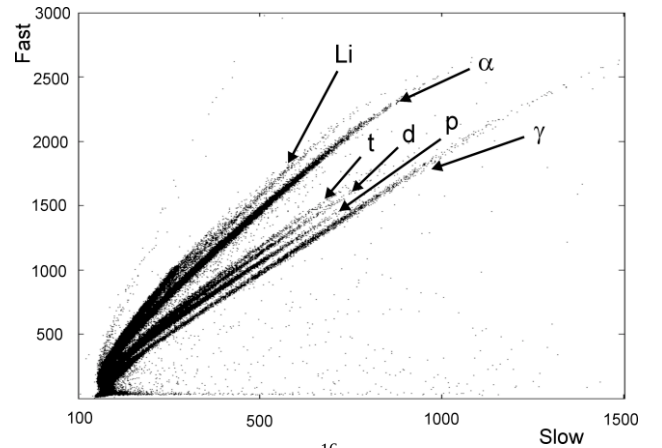


Fig.6: Results obtained with ^{16}O incident beam.

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THE PROGRAM DESIGNED FOR AID OF BUILDING BANANA-CUTS FOR CSI DETECTORS

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Abstract

This report describes the semiautomatic program for aid of analysis of Chimera – Reverse experiment. It is written for acceleration of speed of analysis for data taken from CsI detectors. The program uses two important procedures: looking for direction of crest on bidimensional spectrum and preparing projection of part of this spectrum on the pointed direction. It is based on Root An Object Oriented Data Analysis Framework. This program is proposed for use for analysis of data in next Chimera –Reverse experiment.

1 INTRODUCTION

The preparation of banana-cuts is one from most laborious procedure in time of analysis. This problem is very important for work with data taken from big multidetector systems.

It is intended to use this program in analysis of data from CsI detectors in next Chimera – Reverse campaign for decreasing amount of manual work.

2 DESCRIPTION OF THE PROGRAM

The described program uses two main procedures:

- the procedure looking for direction of crest on bidimensional histogram,
- the procedure for projection of part of a histogram on pointed direction.

The program is written under C++ language as script for root (Root An Object Oriented Data Analysis Framework) [1]. It can be used in interpreted or compiled form.

At present, the program is able to perform independent separation of light particles 1H, 2H 3H in hydrogen branches and 3He, 4He, 6He, double 4He in helium branches for data from CsI detectors.

The program has two basic modes of work: manual and automatic. The analysis starts with

correction (if needed) and confirmation. This is the semiautomatic mode of work.

The program saves points of banana cuts in the real scale of each histogram and also projections of each branch on energy axis (x) as supplementary feature.

The two-dimensional histogram with 2048x2048 channels is a working area for the program. The optimization of data for this space must be performed because of significant differences between heights of pulses from detectors. It is done manually by zooming and rereading an input file.

2.1 Structure of the program

The simplified functional structure of the program is shown on fig.1.

States of the program on fig.1 are presented

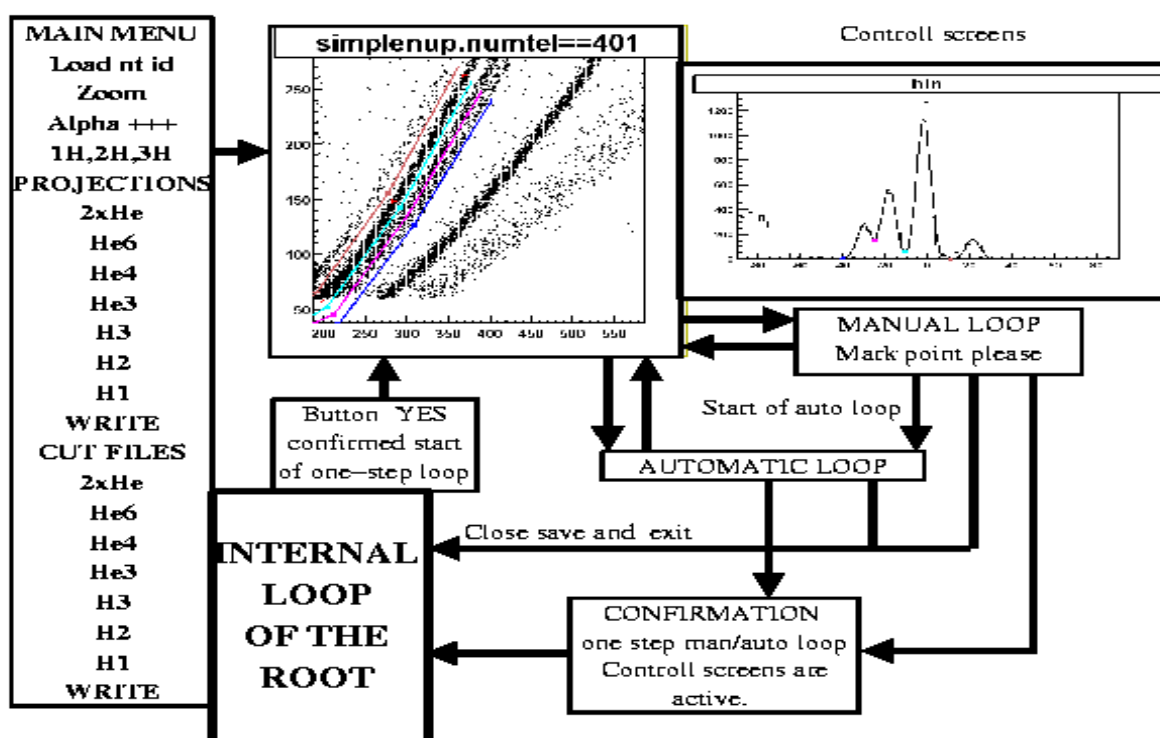


Fig. 1. Simplified structure of the program.

the manual mode and can be switched to the automatic mode at any moment, according to decision of an operator. The program displays actual status of separation on dynamically zoomed screen focused on the last placed point.

All modes have possibility of suspending of work after one step of analysis, waiting for

by an example of main canvas with bidimensional histogram and supplementary canvas and a label with description.

The running program can work in one from three states:

- Manual loop when it waits for the decision of an operator where to place the point.

-Automatic loop when the program places points itself.

-Main internal loop when the program waits for instructions.

It is important to stress that only in the last described state of work commands for interpreter and direct operations are accepted.

2.2 Main menu

The main menu is a basic way of controlling the program by activating its most important internal functions.

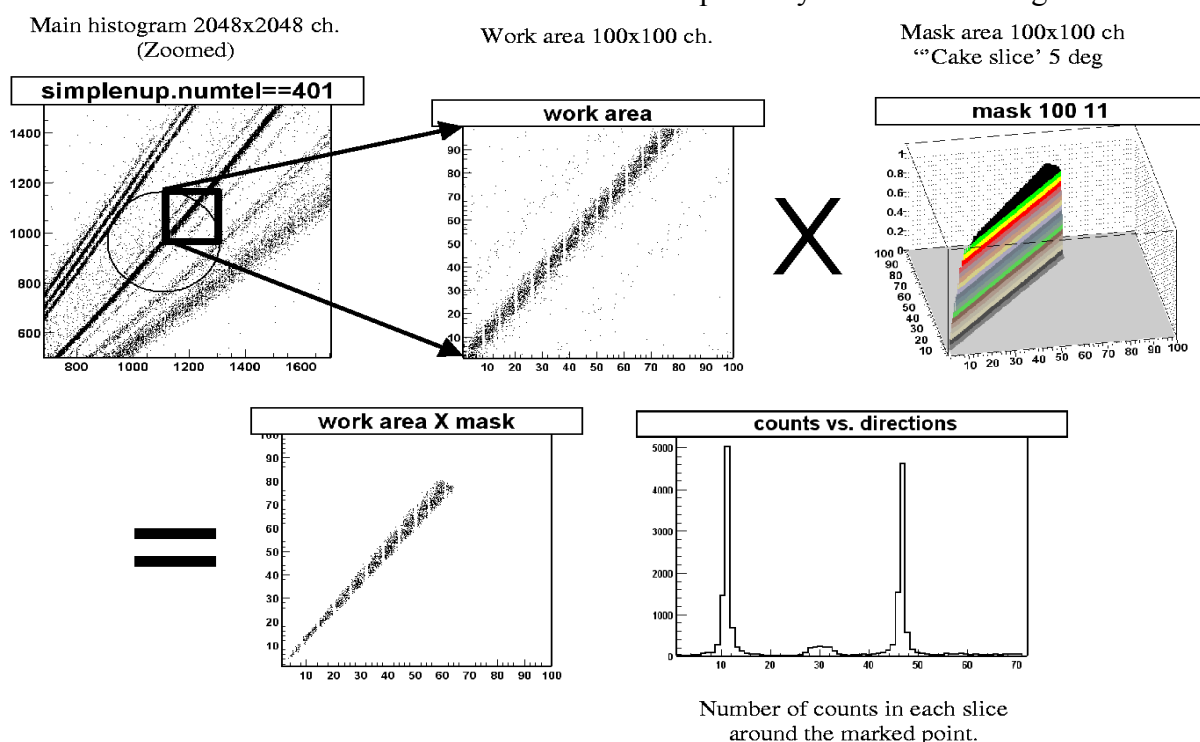


Fig .2 The base of procedure for determination of the crest direction.

First two buttons of the menu are used to load the spectrum from the pointed detector and adjust the normalization for them.

The next two buttons are for initialization of analysis of helium and proton part of the spectrum.

The "PROJECTIONS" button calls supplementary function generating an energy projection (in channel units) of previously analyzed branches of the bidimensional spectrum. They can be visualized on the second canvas or written to a file by pressing proper button.

The last group of buttons, starting from not active "CUT FILES" label, is used for visualization and writing of banana cuts.

2.3 Determination of the crest direction

The procedure for automatic determination of the crest direction is the basis in automatic mode of work. The scheme of it is shown on fig.2. The work area for this procedure (bidimensional histogram 100x100 channels) is extracted from the main histogram. It is multiplied by the mask histogram. The mask

histogram describes statistical weight of each cell for the each 1.5 deg "cake" slice like in the example on picture. The number of those masks is 240 for 360 deg but it can be reduced to 30 by using 8-times symmetry.

Next all histograms are being integrated. It gives the spectrum as a number of counts over directions around marked point. It is shown on the last example histogram (Fig.2).

2.4 Separation of crests

The way of analysis for hydrogen and helium suits of branches is different. In the hydrogen part three strong well-separated crests are seen,

distinct from the helium part where only one dominant line of alpha particles exists.

For the hydrogen analysis, events from the main histogram are projected on the direction perpendicular to the obtained direction of the crest. Next the gauss method of separation for four (1H, 2H, 3H and gamma) lines is used. It is performed after each analysis of the direction of crest. Locations of separation points between lines are transformed to appropriate locations on the main histogram and stored in memory. It is presented on fig. 3. The extra canvas shows separation of lines taken from the main histogram between the second and the third point. Those canvases show proposed limits for separation for the third point.

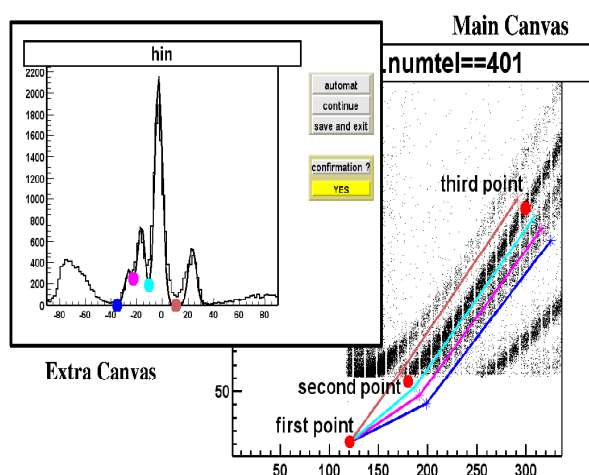


Fig. 3 First steps of analysis

In case of helium particles the separation by using of the gauss method is possible only for alpha particles. For other particles the number of counts is too low in the range of working area but the differences are much larger. It allows using mathematics formulae together with a possibility of corrections for separation of branches. The presented formulae are used for determining limits of each helium particles:

-outside area - 3he: $x - 30 - 3 \cdot 10^{-5} \cdot x^2$,
 -3he -4he: $x - 12 - 6 \cdot 10^{-6} \cdot x^2$,
 -4he -6he: $x + 20 + 8 \cdot 10^{-6} \cdot x^2$,
 -6he -2x4he: $x + 40 + 6 \cdot 10^{-5} \cdot x^2 - 1.1 \cdot 10^{-8} \cdot x^3$,
 -2x4he-outside: $x + 50 + 9 \cdot 10^{-5} \cdot x^2 - 1.5 \cdot 10^{-5} \cdot x^3$.

Where x means horizontal position of marker placed on leading branch and xb difference

between x and the first point of banana used for cutting part lower than threshold.

3 CONCLUSIONS

The proposed program is still under construction. The work concentrates on increasing stability of automatic procedures for weak helium branches.

The program reduces the tiredness of the operator in each mode of work but the other important problem regarding efficiency of analysis must be stressed - an organization of reading the data from tapes. It is important because the tape must be reviewed minimum two times for analysis of one telescope data.

The most effective is split the data to few temporarily stored disk files. We used for test of the program:- 24 from 688 telescopes from all runs of one measure - in one or few coupled files.

The time of reading of disc files was 1-4 minutes up to the computer hardware and it was acceptable for satisfying work (full data taken from Reverse spring 2000 experiment for $^{124}\text{Sn} + ^{64}\text{Ni}$ reaction).

4 REFERENCES

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2001 ACCELERATOR ACTIVITY

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1 INTRODUCTION

In 2001 the accelerator activity was quite intense as far as the amount of delivered beams is concerned. Beams accelerated by the Superconducting Cyclotron were delivered contemporarily to Tandem beams. This was possible thanks to the stand-alone operation of the two accelerators (from 2000) and also to the installation of the so-called by-pass line, allowing to deliver Tandem beams only to the 60° and 80° beam lines.

In fig. 1 the distribution of the beam time in 2001 is shown. Around 2550 hours of Cyclotron beam and 1200 hours of Tandem beam were delivered to users, while 1400 hours were spent for Cyclotron setting and beam development, 200 hours for Tandem preparation and 975 hours of failures occurred.

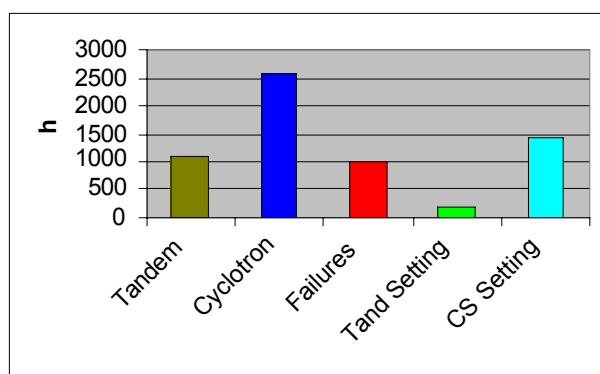


Figure 1: 2001 LNS beam time distribution

2 SUPERCONDUCTING CYCLOTRON

In 2001 a remarkably high number of new beam types were developed. Therefore the number of hours spent in beam developing is quite high. The beams delivered in 2001 are reported in Table 1.

Table 1 Cyclotron beams delivered in 2001

protons, 62 MeV	507 h
¹² C, 62 MeV/amu	36 h
¹⁸ O, 15 MeV/amu	195 h
⁵⁸ Ni, 40 MeV/amu	92 h
⁵⁸ Ni, ⁶² Ni, 35 MeV/amu	220 h
⁹³ Nb, 17 MeV/amu	142 h
¹¹⁶ Sn, ⁹³ Nb, 23 MeV/amu	290 h
¹¹⁶ Sn, ⁹³ Nb, 30 MeV/amu	290 h
¹¹⁶ Sn, ⁹³ Nb, 38 MeV/amu	286 h
¹¹⁶ Sn, 17 e 23 MeV/amu	245 h
¹² C, ⁵⁸ Ni, ¹⁹⁷ Au, 23 MeV/amu	124 h
¹⁹⁷ Au, 20 e 21 MeV/amu	116 h
Total	2543 h

When requested, the beam was delivered with a good timing quality, the FWHM being of 1 nsec and the inter-burst separation more than 120 nsec. In this case it was necessary to cut a big amount of beam intensity (to have a narrow time peak and to suppress beam bursts by means of a chopper). Consequently the axial buncher was used, yielding a factor of 4-6 in beam intensity.

The 62 MeV proton beam was delivered to the patient treatment room (Catana) for dosimetric and therapeutic characterization of the beam itself. Beam tests were done many times, consequently at the end of 2001 the facility was ready to make the first irradiations.

The electrostatic deflectors are still a critical system for the cyclotron as far as the voltage holding capability is concerned. Moreover, the cyclotron will be used as a primary accelerator for production of radioactive beams, therefore high intensity beams will be extracted. Consequently a high beam power will be dissipated in the septum of the electrostatic deflectors.

To reach a high electrostatic performance, new materials and conditioning procedures have been found out allowing to work with an electric field

of 100 kV/cm in a reliable way. In 2001 the project for a water-cooled deflector with a remote disconnection system has started. A new voltage feed-through able to dissipate a high beam power has been built and tested in a vacuum chamber. Beam tests have been performed to evaluate the possibility of accelerating a beam with intensity a few hundreds of enA. The aim was to estimate the beam transmission in the injection and acceleration processes. The obtained values are very close to the expected ones, in particular the measured injection efficiency is 9% (without buncher), to be compared with a theoretical value of 9.7%, and the acceleration efficiency is almost 100%.

3 TANDEM

In the first half of the year, the by-pass line was installed to send the Tandem beams to the 60° and 80° lines while at the same time the Cyclotron beam is sent to one of the other lines (0°, 20°, 40°, Ciclope, Medea, Neutroni).

In the second half of the year, the by-pass line was commissioned and then used for experiments.

The beams delivered in 2001 are reported in Table 2.

Table 2 Tandem beams delivered in 2001

Protons, 20 MeV	60 h
Protons, 26 MeV	72 h
Protons, 27 MeV	96 h
⁶ Li, 25 MeV	260 h
⁷ Li, 13 and 45 MeV	255 h
¹⁶ O, 91 MeV	286 h
¹⁸ O, 90 MeV	120 h
²⁸ Si, 120 MeV	72 h

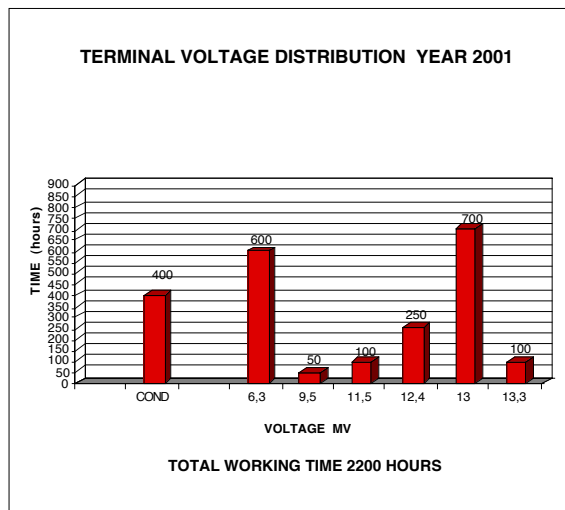
Total 1221 h

In Fig. 2 the distribution of the operating voltage during the year 2001 is shown.

Fig.2 Tandem voltage distribution in 2001

4 OTHER ACTIVITIES

Activities concerning accelerator systems, namely sources and injectors, RF systems, computer control and electrostatic deflectors, are described in dedicated reports.



THE LNS SUPERCONDUCTING CYCLOTRON: MEASURED B-FIELDS COMPARED TO 3-D SIMULATIONS

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Abstract

The Superconducting Cyclotron operating at LNS, Catania, has been simulated by TOSCA, the magneto-static module of OPERA 3D [1]. Average magnetic fields and flutter simulated for different values of the coil current were compared with the corresponding parameters extracted from high accuracy field measurements [2].

1 INTRODUCTION

The simulation of the cyclotron for the whole operating diagram has been done introducing the magnetic configuration with as many details as possible. Computational limitations, finite boundary conditions, and material property variations are all possible limitations on the accuracy of the model. A considerable effort was put into refining the computer calculations to obtain reproducible convergence to very high accuracy.

2 CYCLOTRON MODEL

The final structure of the cyclotron was built step by step, starting from a simplest model. Since it is not possible to reproduce the real structure of the machine, then the following assumptions were made:

- The 3D model, limited by symmetry (120 deg periodicity), tangential (on the sides of box air surrounding the cyclotron) and normal (respect to median plane, $Z=0$) magnetic boundaries, is restricted to 1/6 of the existing machine.
- The iron yoke does not be symmetrical respect to Z axis. Since the volume of the iron removed for radial penetrations (beam entry and exit, deflector and magnetic channel feed through) is relatively small compared to the total volume of the yoke, it was assumed that the yoke field contribution had cylindrical symmetry: all the holes of the yoke have been simulated by a cylindrical iron free ring enclosed in the yoke.
- In the real coils, the superconducting filaments are wound with the double pancake technique. Its distribution along R was made not uniformly, in order to reduce mechanical stress on the structure. In the model, it was

assumed that the coils have a uniform current density.

- The CS consist to different iron casts used for the magnet with different magnetization curves [3]. As first approaching, we have assumed only one high quality steel for the whole machine.

3 SIMULATION SETTING

We have simulated the structure for eight points on the working diagram of the cyclotron. Table 1 shows these points.

no. (q)	B_0 tesla	J_α (amp/cm ²)	J_β (amp/cm ²)
0	2.176	1194.75	-324.40
1	2.458	1741.50	-811.00
2	2.973	1640.25	648.80
3	3.469	2733.75	-324.40
4	3.695	2085.75	1622.00
5	4.018	2389.50	1865.30
6	4.334	2693.25	2108.60
7	4.704	2835.00	2838.50

Tab.1 : values of the current density (J_i) of coils (α e β) set for the simulations. B_0 is the measured field at center, q is a reference number.

An hexahedral meshing of the model has been made, generating approximately 300000 nodes in order to achieve a good geometrical accuracy for the design model.

4 RESULTS COMPARISON

The median plane field is divided into two parts:

$$B(r, \theta) = B_0(r) + \sum_{n=1}^{\infty} B_n(r) \cdot \cos(n(\theta - \phi_n(r))) \quad (1)$$

where $B_0(r)$ ($n = 0$) is the average field over the azimuth and the $B_n(r)$ are the harmonic components of the fields. The isochronous field provided for all ion beams within the cyclotron range depends on $B_0(r)$, while the main focusing

characteristics of the machine depends on the $B_n(r)$.

4.1 Average fields

Generally the measured average field was higher than the calculated one for values of center field bigger than 3 tesla. Figure 1 shows the relative difference ($\Delta B/B$) calculated for all the simulations.

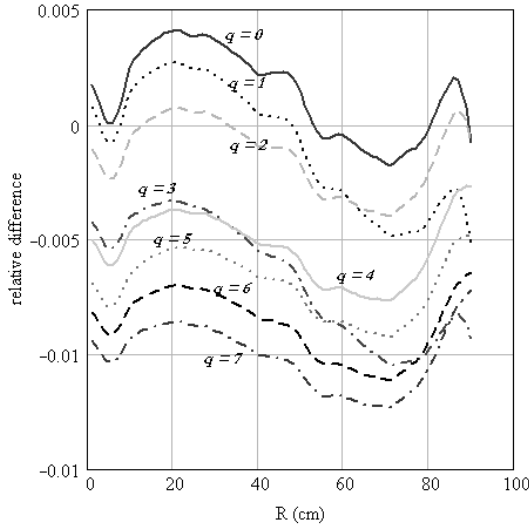


Fig.1: Relative difference calculated for all simulations.

While the shape of the curves shown in fig.1 is about the same, depending on the geometrical discrepancies between the model and the real machine, the increase of average value (2) with the current plotted in fig. 2 depends, mainly, on the difference in the magnetization curve of the materials used.

$$\frac{\Delta B}{B_{\sigma}} = \frac{1}{B_{\sigma}} \cdot \sqrt{\frac{\sum (B_{\text{MEASURED}} - B_{\text{SIMULATED}})^2}{n}} \quad (2)$$

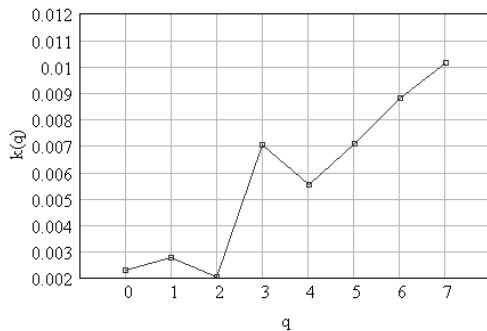


Fig. 2: Average relative difference (2) for all the simulations.

4.2 Main harmonic values

Since the simulated model is symmetric, only the main harmonics ($n=3,6,9,\dots$) can be extracted

from the simulated field maps. In this case the approximations of the poles design are the main cause of difference with the measured data. Thus the average level of accuracy is about constant (3%) for all simulations.

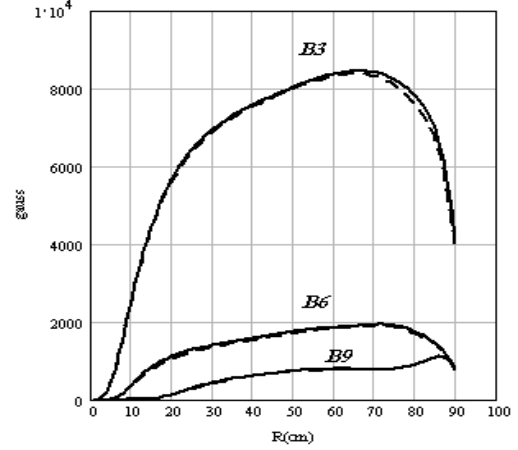


Fig. 3: Comparison between main harmonic components extracted from simulated (dashed) and measured (solid) field.

5 CONCLUSIONS

The difference in field level is less than 1% for average field comparison and less than 3% for the harmonic component one. Furthermore it is necessary to reduce the symmetry of the model from 6 down to 2 or even 1 if a realistic description of the machine is wanted.

6 REFERENCES

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NEW DEFLECTORS MATERIALS AND DESING

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Abstract

The Electrostatic Beam Deflectors for the K800 Superconducting Cyclotron have been re-designed after an accurate investigation from the microscopic point of view, leading to a better comprehension of the complex phenomena taking part in the breakdown mechanisms. New materials and new shapes have been studied and chosen for electrodes, liners, housing and electrical feedthrough.

1 INTRODUCTION

In this paper we present the study and the criteria that led to the re-design of the electrostatic beam deflector for the K800 Superconducting Cyclotron (CS) at LNS. Previous work [1], carried out on shorted cathodes, shown that the dark current depends on the cathode material and its treatments. Further investigations have been carried out in the real operational conditions i.e. during irradiation and deflection of accelerated beams [2]. It has been found that not only the cathode material plays an important role, but also all the materials constituent the whole electrostatic deflector give an important contribute to the breakdown mechanisms [3]. Also the shapes of the electrodes and Liners have been revised in order to increase the features of the deflectors in terms of deflected current, maximum operating voltage and medium time between failure. In addition a new electrical feedthrough has been designed in order to allow high intensity ion beams, this is at the moment under test. Figure 1 show a view of the new deflector.

2 EXPERIMENTAL

The deflectors were tested during the normal operation of the CS, in particular extracting a 62 MeV/u beam of H_2^+ by applying a voltage of -60kV to the cathodes. The gap between electrodes and septum was set at 5 mm, the vacuum environment was provided by the CS accelerator chamber (10^{-6} mbar) and the magnetic field was 3.5 T. The experiments on the deflector after their use,

were performed using current-voltage analysis both in linear and in Fowler-Nordheim plots [4] to study the macroscopic effects of breakdown; Rutherford Back Scattering (RBS) [5], X-Ray Fluorescence (XRF), for the surface investigation; Optical Microscopy and Secondary Electron Microscopy (SEM) for the surface morphology and 2D map by Energy Dispersion X-ray analysis (EDX) for the elements distribution on the surface.

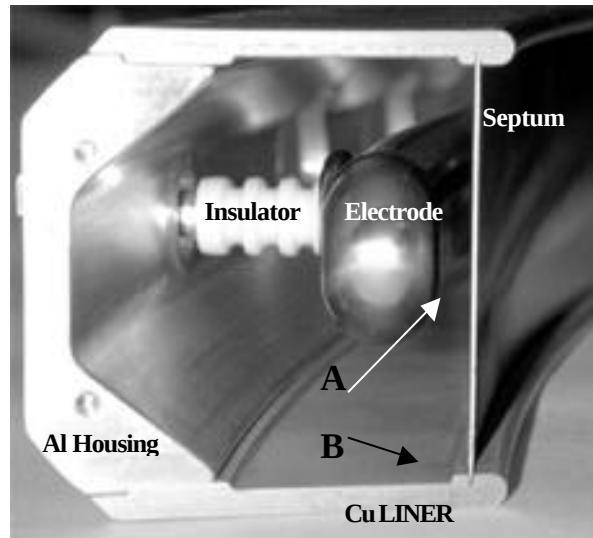


Figure 1 : Side view of the new deflector

3 OBSERVATION AND DISCUSSION

The macroscopic effect of the breakdown is the electrode higher absorption current. By comparing several current-voltage curve shape in Fowler-Nordheim plots it has been found [2] that two different effects are involved in the breakdown

mechanism: 1) enhanced Field Electron Emission (FEE) from the electrode, 2) conduction due to surface metal deposition (metalization) on the insulator, as confirmed by the RBS analyses.

In the operational condition, the trajectory of the electrons emitted by the electrode is strongly influenced by the presence of the magnetic field, from the calculations and the computer simulations [6] it turns out that they are emitted by the cathodes in correspondence to the highest curvature and the highest electric field (point 'A' in Fig. 1), once emitted they direct to the liner (point 'B' in Fig. 1), the magnetic field not only drives the motion but also acts as focusing in their trajectory. The focused electrons impinging on the liner surface are able to locally increase the temperature above the melting point, as confirmed by the RBS and XRF analyses [3].

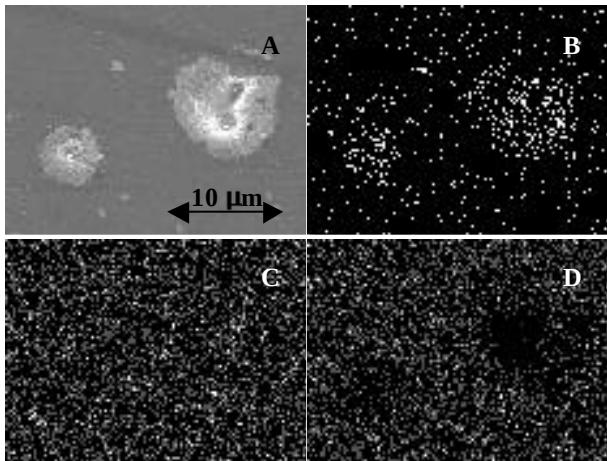


Figure 2: SEM (A) and EDX (B,C,D) analyses on the DLC on Ti electrode. Fig. 2B is the surface Mo distribution taken from the characteristic Mo $L\alpha$ line. The Fig. 2C is the Ti distribution from the Ti $K\alpha$ line. The Fig. 2D is the Carbon distribution from the C $K\alpha$ line. The tips here shown, are made of Mo evaporated from the liner.

Optical microscopies show that the electrodes exhibit a metallic halo on their surface and a dense distribution of metallic micro-tips and micro-craters [3], XRF analysis confirms that this is a thin Mo layer (in case of use with Mo liner).

In Fig. 2 B,C and D are reported the EDX analyses performed on a Ti electrode coated by 6

μm of Diamond Like Carbon (DLC), the electrode was used in combination with a Mo liner. The craters are made of Mo (Fig. 2B), the Ti of the substrate is uniformly distributed (Fig. 2C), and the carbon of the DLC is covered by the Mo in correspondence of the craters (Fig. 2D).

From the observation we can conclude that there is more than one phenomenon taking part in the breakdown mechanism. One is related to the insulator surface metalization, and the other one, concerning the electrodes, in which the material evaporates from liner will forms an high density of clusters (micro-tips). The last is responsible for enhanced FEE caused by the increasing field factor in proximity of the micro-tips. Therefore we propose the following model: the electrons emitted by the electrodes are able to locally melt the liner that evaporates onto insulators and electrodes. Then insulators starts to conduct through the surface, this increase the temperature that enhance the FEE. This results in an amplification of the first effect. By other hand the liner material evaporated onto the electrodes forms clusters in which the electric field is increased by a factor depending on their size. This enhance the electron emission from the electrodes resulting again in an amplification of the first effect. A further evidence of this phenomenon is given to the fact that around the tips the surface is free of metal (fig. 2A), in fact the temperature around the tip increases because of the FEE, this enhance the surface mobility of the Mo around the tips, therefore the Mo cluster or atoms are able to migrate and to coalesce together or to ripen into bigger cluster [7] because of its high surface tension. All these effects acting in synergy lead to a fast breakdown of the electrostatic deflector.

4 NEW DESIGN

Taking into account the experimental evidences of the breakdown phenomena and the future needs for high intensity beam deflection, a new deflector has been designed; fig. 1 shows its side view. From a mechanical point of view the new design allow an easier and quicker assembly and parts exchange

procedure, compares with the old one [2]. This is quite relevant since after its use some parts result activated. The shape of the electrode has been re-designed as shown in the cross section of fig. 3.

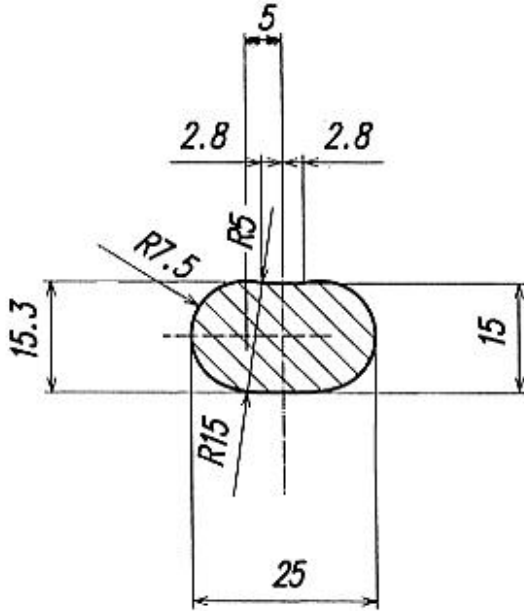


Figure 3 : Cross section of the new electrodes, sizes are in millimetres.

The double curvature, shown in fig. 3 (R 15 and R 7.5) reduce the electric field in proximity of the electrode zones of highest FEE (Fig. 1 point "A") by a factor 0.9. Also the Liner has been grooved to reduce the electric field in proximity of the impact zone of the electrons (Fig. 1 point "B"). These modifications result in an increasing of the maximum operating voltage.

Several materials have been tested for the electrodes. In particular: coatings on Ti alloy (6% Al, 4% V, Ti balance: TiAl_6V_4) such as DLC and TiN. It has been found that DLC exhibits very good performances at the beginning of the operation, but after several working hours show a quick breakdown: therefore its reliability is poor. This is probably due to its very low surface tension that enhance the probability of emitting micro-tip formation, as shown in fig. 2A. Moreover the TiN coated electrodes in the real operational conditions did not show the expected [1] low emission current, since their behaviour is similar to the non coated TiAl_6V_4 electrodes; i.e. generally good

performances. From the operational experience we can say that in the real working condition the deflector behaviour is different from that in the test bench, this means that many tests have to be done directly in the CS, this results in the additional problem of managing with activated parts. Since the role of all these materials are not fully understood the research on DLC and TiN is still on progress, and other materials and coatings are at the moment under study such as Au, Pt and SiC.

The septum is still in Ta; it is not screwed to the housing [2], but slides into the liners (fig. 1), this allow a quicker exchange of this component.

The Liners are on Oxygen-free Cu (Cu-OFHC), up to now this seems to be the best material for this application. Compared with Mo (old Liners) the Cu melting temperature is lower (1356 K for Cu, 2890 K for Mo), but its thermal conductivity is higher (401 W/ m K for Cu, 138 W/ m K for Mo), therefore the evaporation rate is lower. An other important feature of the Cu is that, since its surface tension is lower, there is a reduction in the formation of micro-tips and craters once it evaporates on the electrodes. Optical microscopy confirms these hypothesis.

At the moment is under study a Liner with water cooling for high intensity beam deflection. We are also studying other materials such as coated (by DLC or TiN) and bare Ti Liners, this materials should not form tips once evaporate on the Ti electrodes.

We also are testing the effects of a glow discharge treatment in presence of O_2 . These treatments are of strategic importance since they allow to quickly recover the deflectors in case of initial breakdown symptoms, moreover during deflector normal operation a small leak of O_2 is continuously kept in order to reduce the electrodes absorption current.

In fig. 4 is reported the Fowler-Nordheim plot of a deflector absorption current before and after the oxygen treatment (squares and triangles respectively). The maximum absorption current before the O_2 treatment was 240 μA at 50 kV, the plot shows that this current was mainly due to FEE

(dot line); after the O₂ treatment the current was 50 μ A at 50 kV, the plot show a FEE (continuous line) with a slightly higher work function (higher slope) and a lower number of emission sides (down shifted line).

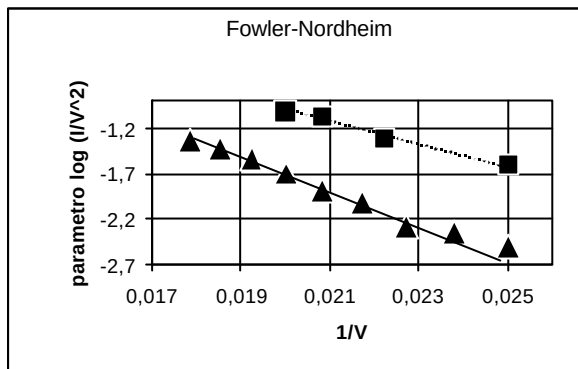


Fig. 4 : Fowler-Nordheim plot of a deflector absorption current, before (squares, dot line) and after (triangles) the O₂ treatment at a pressure of 10⁻⁴ mbar

It seems that O₂ is able to sputter the surfaces reducing the number and the shapes of micro-tips on the electrodes and the surface conduction on the insulators. This is also a reactive sputtering which should be able to oxidise the metal deposition layers in order to convert the metal in non-conductive material such as CuO, Cu₂O or TiO₂, which is a good insulator, in case of Ti Liners. The role of O₂ is not completely understood and further investigation is needed to make it clear and to increase the deflector performances.

We are testing also a new electrical feedthrough which is able to follow the deflectors movements by means of an electronically controlled pneumatic actuators. This component is completely new designed since the old one is in polypropylene directly screwed at the electrode. This model is at the moment under test. Fig.5 show a picture of the terminal part of the feedthrough which contacts the electrode.



Fig. 5 : new deflector electrical feedthrough in glazed alumina

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ION SOURCES R&D ACTIVITIES

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Abstract

The R&D of ion sources has been focused mainly on the completion of TRIPS and on the design of GyroSERSE. The TRASCO intense proton source (TRIPS) has been installed at INFN-LNS in 2000 and the commissioning was carried out in 2001. The goals in terms of beam energy (80 keV) and current (60 mA from 8 mm extraction aperture) have been achieved. Further optimisation of the source is under way, with special care to the reliability needed for ADS purpose and to the emittance minimization. The design of the GyroSERSE source has been also completed; in the following a few details of the project are given, along with the major constraints and the related solutions.

1 THE TRIPS SOURCE

The TRASCO Project is a R&D program which goal is the design of an Accelerator Driving System (ADS) for nuclear waste transmutation. The high current cw proton linear accelerator will drive a subcritical system to transmute nuclear wastes.[1]

The proton beams are available from the source TRIPS, a high intensity microwave discharge ion source, which goal is the injection of a minimum proton current of 35 mA in the following RFQ, with a rms normalized emittance lower than $0.2\pi\cdot\text{mm}\cdot\text{mrad}$ for an operating voltage of 80 kV.

Its design is described in [2] and is shown in figure 1. The microwave power obtained with a 2.45 GHz - 2 kW magnetron is coupled to the cylindrical water cooled OFHC copper plasma chamber through a circulator, a four stub automatic tuning unit and a maximally flat matching transformer.

Two coils, independently on-line movable and energized with separate supplies, allow to vary the position of the electron cyclotron resonance (ECR) zones in the chamber and to produce the desired magnetic field configuration. One of the major improvement in 2001 has been the definition of the optimum magnetic field profile. The optimum one has two ECR zones at both ends of the plasma chamber and with a value of magnetic field greater than the resonance value inside the plasma chamber. [3]

The maximally flat matching transformer has proved to be effective to optimize the coupling between the microwave generator and the plasma chamber. It realizes a progressive match between the waveguide impedance and the plasma impedance, thus concentrating the electric field at the center of the plasma chamber (in our design the field enhancement ratio is about 2). The automatic tuning unit permits to operate with low values of reflected power (below 5%). The major result of this enhancement was the high current density, attaining values up to 240 mA/cm^2 in the best case at 80 kV.

The extraction geometry was studied with the AXCEL code and the results were cross checked with the IGUN code and with the PBGUN code.

Fig. 2 shows the experimental set-up: the first section of the low energy beam transfer line (LEBT) devoted to the beam analysis consists of a current transformer (DCCT1), of a focusing solenoid, of a four sector ring to measure beam misalignments and inhomogeneities, of a second current transformer (DCCT2) and of an insulated 10 kW beam stop (BS) which measures the beam current.

In 2000 a current of 20 mA was obtained. In 2001 the 8 mm hole plasma electrode replaced the 4.5 mm one. Preliminary measurements have given results largely exceeding the TRASCO design current: up to 61 mA were extracted at 80 kV and about 90% of this current was transported to the beam stop, 285 cm far.

The RF power was 1 kW and the puller voltage was 42.5 kV during this test.

Two different types of electron donors were used to enrich the plasma density: the BN disk at injection and extraction sides of the plasma chamber, as used elsewhere, and Al_2O_3 coating (40 μm thick). This coating increased the plasma density and finally the current density during a 50 hours test (fig. 3). Further investigations will be carried out using coated electrodes for weeks.

Finally we have investigated the stringent request concerning the reliability with a 24 hours test, at 65 kV extraction voltage, with the puller at 32.5 kV and the repeller at -2 kV. Rf power was 480 W (reflected power was less than 20 W) and the proton current exceeded 15 mA at a source pressure of $8.5 \cdot 10^{-6}$ mbar (measured at the ground flange of the extraction column). A quiet plasma with two ECR zones inside the plasma chamber was obtained. After the conditioning (a couple of hours), the source have been operating without discharge for 24 hours. Following tests at 80 kV were less satisfactory, but some improvements on electromagnetic compatibility dramatically enhanced the situation at the end of the year.

The source have not required any particular tuning during 24 hours, except for a few variations of the inlet hydrogen pressure in the plasma chamber. This is really an important parameter that has a strong influence on the beam current stability; for this reason a feedback system on the mass flow of the inlet gas is under study. It must be remarked that the source can produce a very high current with quite low rf power.

In table 1 the status of the source is compared with the requirements of the TRASCO project. The requested reliability at 80 kV was not fully achieved, but the source performance have been already good in terms of beam intensity, reproducibility and stability. The innovative solutions presented above have confirmed their validity. In the firsts months of 2002 a more significant reliability at 80 kV was obtained and the emittance measurements were prepared.

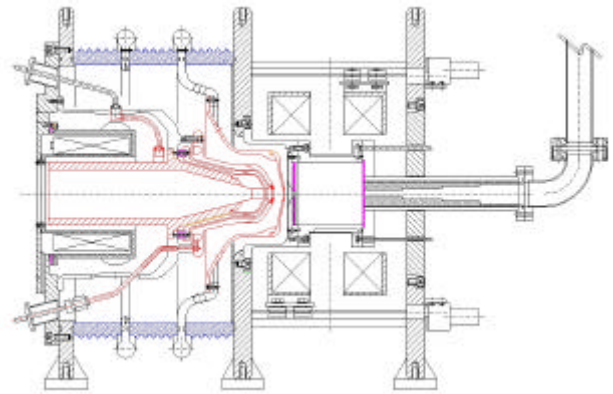


Figure 1: The TRIPS ion source

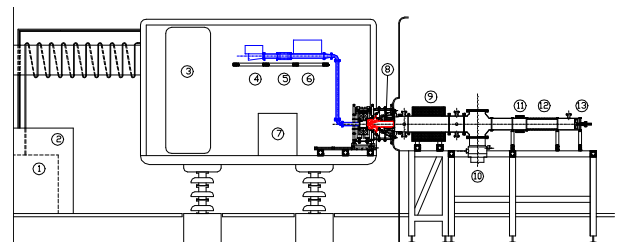


Figure 2: The experimental set-up (1- Demineralizer; 2- 120 kV insulating transformer; 3- 19" Rack for the power supplies and for the remote control system; 4- Magnetron and circulator; 5- Directional coupler; 6 – Automatic Tuning Unit; 7- Gas Box; 8- DCCT 1; 9- Solenoid; 10- Turbomolecular pump; 11- DCCT 2; 12- Quartz tube; 13- 10 kW Beam stop)

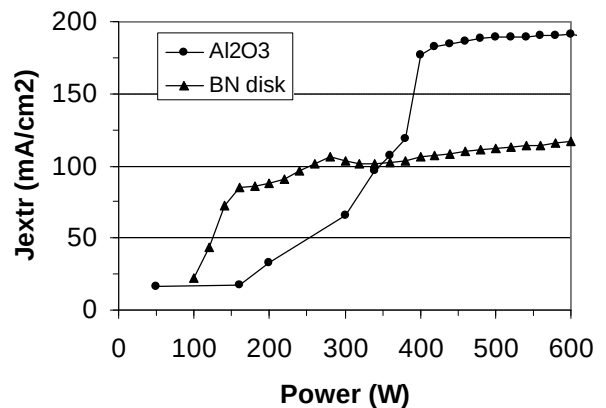


Figure 5 - RF power vs. current density for different electron donors.

Table 1: TRIPS status at the end of 2001

	Requirement	Status
Beam energy	80 keV	80 keV
Proton current	35 mA	55 mA (61 mA total)
Proton fraction	>70%	≈90% (estimated)
Reliability (24h)	≈100%	100% @ 15mA (65 keV over 24 hours)
Beam emittance	≤0.2 πmmrad	To be done

2 THE GYROSERSE SOURCE

In 1999 a research project called "Innovative ECRIS" was established to meet the requirement of intense highly charged beams production. High frequency operation of the source, cryogenic devices, sophisticated extraction systems, have been developed in the frame of this project or they are under way. In particular, the problem of ion extraction and transport in the new sources is fundamental: as high currents are extracted it is necessary to optimise the design of the extraction system. This need was particularly evident after the tests carried out with a high frequency-high power (28 GHz-10kW) microwave transmitter coupled to the superconducting source SERSE at INFN-LNS. The results were outstanding and beam intensities never obtained before were measured [4]. Anyway we perceived that with an adequate source design more intense beams can be obtained. The successful exploitation of the SERSE source at 28 GHz opened the way to the GyroSERSE source, a high confinement superconducting source optimised for 28 GHz and designed following the scaling laws [5]:

$$q_{\text{opt}} \propto \log B^{3/2} \quad (1)$$

$$I^{q+} \propto f^2 M_i^{-\alpha} \quad (2)$$

and the high B mode concept [6].

$$B/B_{\text{ECR}} > 2 \quad (3)$$

where q_{opt} is the optimal charge state, B is the peak field of the magnetic trap, f is the microwave frequency, I^{q+} is the intensity of the charge state q , M_i is the ions mass and α is an adjustable parameter variable between 0.5 and 1, which takes into account the difficulty to ionize the heaviest ions, and B_{ECR} is the magnetic field corresponding to the ECR frequency.

The first proposal of a 28 GHz SERSE-like source was outlined in 1994 [7], but only four years later its design began. In 2001 the conceptual design of the source was completed and submitted for funding, which has been allocated for 2002-2005. The source will permit a significant increase of energy for the CS beam, as outlined in fig. 4.

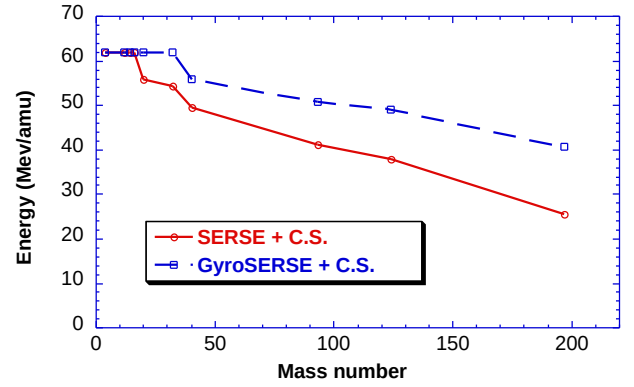


Figure 4: Maximum energies achievable from the K-800 superconducting cyclotron of INFN-LNS.

The main features of the magnet design are given in tab. 2. Fig. 5 shows a model of the magnetic system, with the solenoids and the hexapole surrounded by an iron yoke. The mechanical constraints have obliged to choose a well larger inner bore than for SERSE, because of the boundary conditions for the hexapole (the stored energy exceeds 300 kJ). The plasma chamber inner diameter is 180 mm, 50 mm larger than the one of SERSE.

The magnetic field has a mirror maximum of 4.5 T at the injection and of 3.5 T at the extraction, a minimum variable from 0.4 to 0.8 T and a radial field of 3.0 T in order to work in High B mode, with a β value below 0.01. In these operating conditions the confinement time should be increased and the electron temperature should raise with the power, thus obtaining very high charge states. Following the scaling laws we expect to obtain bare calcium nuclei and currents in the order of 1 μA (the typical values injected into the CS) for beams such as Au^{50+} , Pb^{52+} , U^{58+} provided that the pressure in the chamber will be in the order of a few 10^{-8} mbar without plasma and of 10^{-7} mbar in operating conditions.

Maximum field at injection	4.5 T
Minimum field	0.4 T
Maximum field at extraction	3.5 T
Hexapolar field on the wall	3.0 T
Cryostat length	2150 mm
Warm bore diameter	194 mm
Hexapole inner diameter	216 mm
Iron yoke thickness	45 mm / 70 mm
Maximum solenoids currents	200 A
Maximum coil current	340 A

Table 2: The design features of GyroSERSE

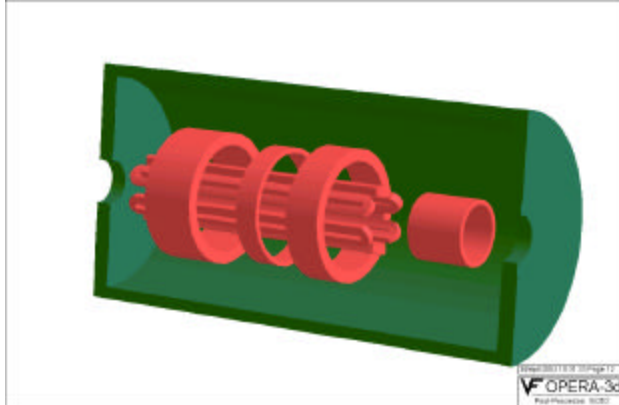


Figure 5: The OPERA-3D model of the magnetic system.

A detailed description of the GyroSERSE conceptual design is available in [8].

Simulations with KOBRA3D code have been carried out to minimize the effect of the large magnetic field (3.5 T) at the extraction on the emittance [9]. The triode topology was chosen for its simplicity and effectiveness. The distances and the shape of the electrodes have been optimized for high charge state extraction. Ray tracing of ion trajectories has been performed up to 10 cm downstream of the extraction aperture. The emittance values range between 120 and 200 π mm mrad; a value of 150 π mm mrad has been used as starting condition for the preliminary beamline simulations here described. Higher extraction voltage than 40 kV may further decrease the emittance. The analysis beamline design has started from the following assumptions: the focusing solenoid (fig.6) should be as close as possible to the extractor; the solenoid should not be used to shrink the ion beam to a narrow focus; the analysis magnet should have a large curvature radius to have a good mass selection and a large gap to keep the beam losses small; the beam pipe should have a diameter of 160 mm to avoid beam losses and to provide a good vacuum conductance. Some alternative designs have been also considered, because the GyroSERSE source will be built for different laboratories under different site constraints.

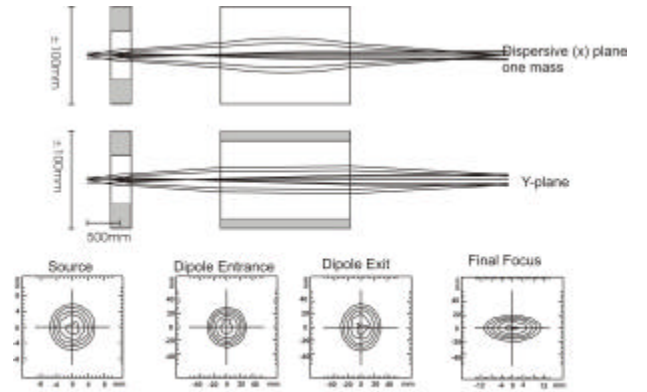


Figure 6: The GyroSERSE analyzing beam line using only one solenoid.

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THE AXIAL BUNCHER

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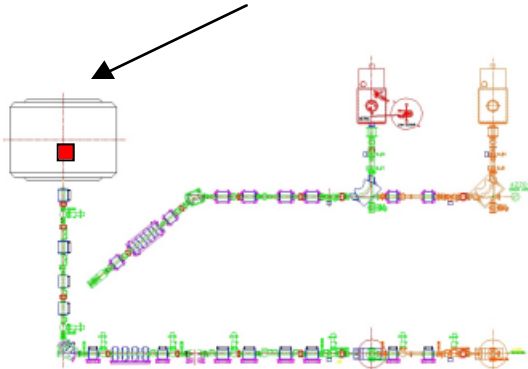
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Abstract

From January 2000 the beam delivered from a superconducting ECR source[1] has been injected through the axial beam line in the K-800 superconducting cyclotron[2]. Along the axial hole the beam is bunched by the Axial Buncher, placed at _ meter from the median accelerator plane of the cyclotron. From March 2001 an upgraded version of the buncher was successfully installed. We improved mainly the cooling system and the transmission RF line in order to improve the Q and reduce the losses of the system. A description and status report of the axial buncher is presented.

1 DESCRIPTION

The Axial Buncher[3] consists of a drift tube, placed in the axial hole of the cyclotron yoke, at 0.5 metre before the inflector. The electrode is driven by an RF signal, in the range of 15÷50 MHz. The length of the buncher electrode is 41mm equal to 210° when it works at the same frequency as the RF cyclotron or 105° when _



subharmonic is used.

Fig.1: Layout of the injection line, ECR sources and position of the axial buncher inside the cyclotron.

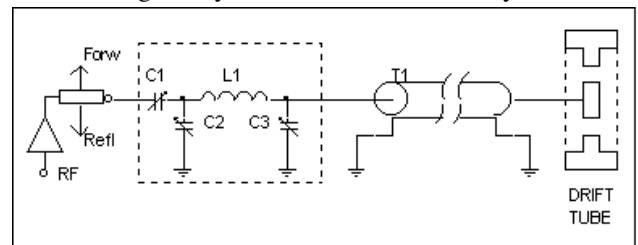
This means, in the case of 210° a factor gain of 1.95 times the modulation voltage and in the case of 105° a factor gain of 1.55. The position relatively near the median plane allows us to reduce the bunch length at the time focus but increase the modulation voltage. This solution was selected to achieve the shortest beam bunch length possible when used to deliver a beam to the experimental users. Although this kind of buncher has lower efficiency than a buncher driven by two frequencies, this should not be a limiting factor on the final beam current delivered from the cyclotron. The lower efficiency of the buncher is counter-balanced by the higher beam

current delivered by SERSE, the superconducting ECR source. On the other hand there are some advantages: the absence of grids on the beam line; both the length of the drift tube and the gap are not critical; a relatively easy tuning operation. A buncher efficiency between 3.5 and 4.5 has been measured on the extracted beam with a beam bunch shorter than 1ns FWHM. The new upgraded buncher is already installed in the cyclotron.

2 MAIN COMPONENTS AND FUNCTION

In figure 2 the layout of the axial buncher system is shown. The reference signal, coming from the RF cyclotron, is directly connected to the input of the system. This signal, delivered by an RF power amplifier, a 200 Watts broad band solid state, class A amplifier, is applied to the matching box. This is a tuning-box that normalises the impedance between the power amplifier and the drift tube at 50 Ohms, allowing perfect coupling.

Fig.2: Layout of the axial buncher system



At the same time ensures the higher voltage antinode on the electrode with the minimum RF power in the range of 15÷50 MHz. The matching box is a pi-filter with a fixed inductance L, of $0.2 \mu\text{H}$, two variable high voltage vacuum capacitors, C_2 and C_3 both covering a capacitance

from 2 to 500 pF and a third variable capacitor C_1 , from 3 to 30 pF in series with the input to ensure the coupling to the output of power amplifier at 50Ω .



Fig.3: The inner view of the matching box, with the inductance L and the three capacitors C_1 , C_2 and C_3

The coaxial line T_1 connects the matching box to the electrode. Inside the cyclotron, under 10^{-8} mbar of vacuum level for about 1 metre, we use a water cooled $\frac{1}{2}$ inch air dielectric coaxial line. Outside the cyclotron, a vacuum feedthrough matches another 2.5 metres of $1\frac{5}{8}$ rigid coaxial line. A ceramic feedthrough and a special T-junction permit the connection between the transmission lines and the water-cooled circuit, as shown in the figure below.

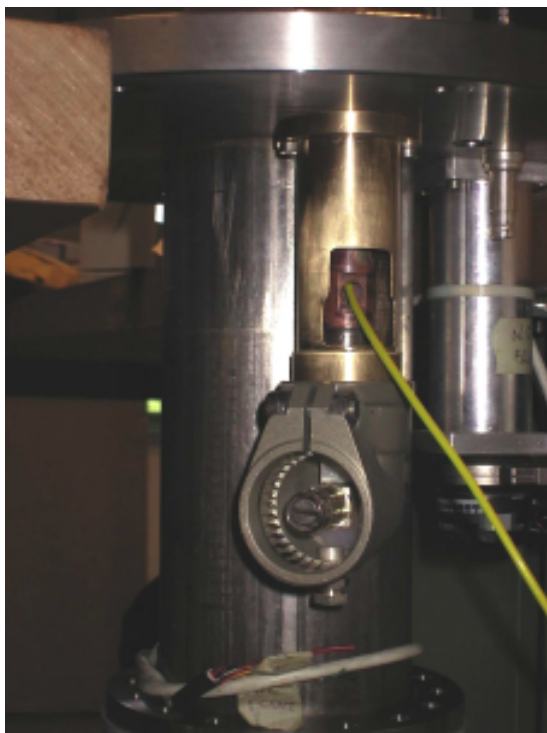


Fig.4: The connection between the water cooled yellow pipe inside the inner conductor of the $1\frac{5}{8}$ inch coaxial line.

The termination of the coaxial line is the drift tube, from the electrical point of view an equivalent capacitance of about 20pF.

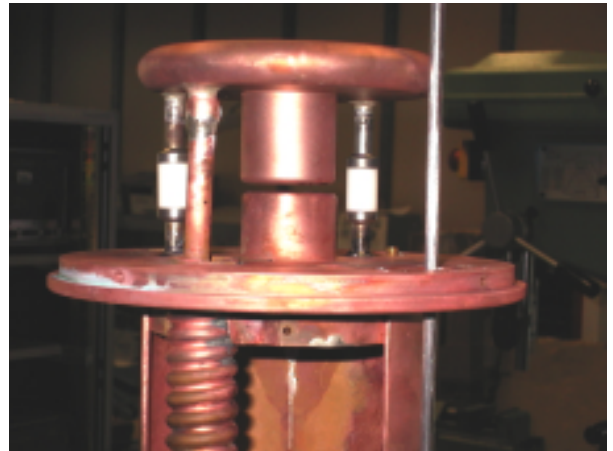


Fig.5: The picture shows the uncovered drift tube, before mounting inside the cyclotron.

Not shown in the layout of figure 2 but already present is the control system. It contains the turn on/off device, the protection circuits, the vswr alarm, the electronic motor system to position the capacitance value and the automatic tuning system. The system have two types of operation: manual and the automatic. The first is usually used for the tuning at low power, the second, with protections and correction loops inserted, at high power. We do not really use the auto-tuning loop often because the self stability of the buncher system, with forced air and cooled water, respectively in the matching box and in that part of the coaxial line under vacuum, is enough to ensure a very low mismatching. The drift tube with the coaxial line could be considered as a fixed frequency resonator. A resonance of 76 MHz was found with a Q-factor of about 600. With the help of the matching box, we are able to reduce the resonant frequency down to our range, 15÷50 MHz. At the same time the 50 Ohms matching for the output stage of the RF amplifier is achieved. Therefore, the combination of the matching box, the coaxial line and the drift tube is a sort of variable resonator with the voltage antinode localised on the electrode. In 2001, during the period of cyclotron maintenance programme, we installed the new design water-cooled circuit of the electrode, because in the past a leakage in the old circuit compromised the normal operation of the axial buncher. Now there is a local cooled system with a water pump, a tank and a refrigerator. All the cooling system serves basically the inner conductor of the 1 metre, $\frac{1}{2}$ inch air dielectric coaxial line. This 1 meter line is the main part of

the system where part of current antinodes are localized and due to the high vacuum is impossible to dissipate the thermal power effect, without the water. The dissipation in the electrode we have estimated, after a right tuning should be very low, because a voltage antinode is localized.



Fig.6: The covered axial buncher before the insertion inside the cyclotron. Clearly visible is the current beam probe which intercepts the beam when placed directly over the central hole. Other apertures have been made to improve the vacuum level inside the buncher.

3 CONCLUSIONS

Since we improved the cooling system and we installed the low loss rigid transmission line we have seen a better performance of the axial buncher. To obtain a bunching efficiency around a factor 4, no more than 100 watts of RF power are necessary for all the accelerated beams in the range of 15-50 MHz. Until now the buncher operates with the same harmonic of the cyclotron, same radio frequency signal. In the next future we are thinking to improve the control system in order to reading and driving the main parameters by central computer control of the cyclotron. Now the system is controlled from the main accelerators console but it is not integrated in the PC-based main control system. We would like also to reduce the time for the tuning of the system. We are going to install a power RF switch between the output of the power amplifier and the input of the matching box. The switch will be remote controlled from the main console, to allows the automatic connection with a network analyser. Every time we want retune the system for another beam will be enough, from the main console, connect the network analyser, with the rf switch, moving the capacitors of the matching box and find on the displayed smith

chart the right vswr and the right new frequency resonance.

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THE ECLISSE PROJECT

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Abstract

The ECLISSE project (ECR ion source Coupled to a Laser Ion Source for charge State Enhancement) started in 1999 with the aim to obtain intense beam of highly charged ions (pulsed mode) by means of the coupling between a Laser Ion Source (LIS) and an electron cyclotron resonance (ECR) ion source. The major points to be investigated appeared to be the coupling efficiency between the ion beam produced by the LIS and the ECR plasma, as well as the possibility to enhance the available charge state by an ECRIS with respect to the standard methods which are used to produce ion beams from solid samples (i.e. evaporation and sputtering). The calculations have confirmed that this concept may be effective, provided that the ion energy from the LIS is not higher than a few hundreds of eV. The main features of the calculations will be shown, along with the results obtained in the off-line test at LNS facility (Nd:YAG laser 0.9 J / 9 ns) and at IPPLM facility (Nd:glass laser 1.5 J / 1 ns). The hybrid ion source is described in the following and the programme of the final tests will be outlined.

1 INTRODUCTION

The hybrid source [1,2] will combine the advantage of a LIS (intense beam, availability of metallic ions) with the advantage of an ECRIS in terms of continuous beam, good emittance, stability and energy spread. We have studied the main limitations to the efficient cooperation of the two ionisation methods and particularly we have measured and/or simulated the efficiency of the coupling process of ions from the LIS beam to the ECRIS plasma; the energy distribution and charge state distribution (CSD) produced by the LIS at different laser power density; the etching rates and the amount of the ionic and neutral components extracted from the target; the effect of the magnetic field on LIS output; the effect of biasing the metal target.

1.1 The coupling

The main requirement for multicharged ion loading is that the ions should be slowed down and trapped in the ECR plasma. By using the theory of elastic Coulomb collisions in the plasma, the ion beam absorption by the plasma which length is L , is:

$$N_i = N_0 (1 - \exp(-L/l)) \quad (1)$$

where L is the length of the plasma volume along the ion beam axis, and l the mean free path of the beam ions in the plasma. For example, either for chromium and gold ions, beam absorption in the oxygen plasma (density $n_e = 4 \cdot 10^{12} \text{ cm}^{-3}$, $L_{\text{plasma}} = 12 \text{ cm}$) is efficient provided that the ion energy per charge does not exceed a few hundreds of eV [3]. The coupling efficiency is close to zero for $E_i = 1 \text{ keV}$, being E_i the energy per charge state i . It should be also considered

that the ion beam which stops in the plasma transfers its kinetic energy to the plasma particles. If the total ion number in the beam is determined as $N_i = 6.2 \cdot 10^{18} I t_i$, then the total beam energy (eV) will be:

$$E = 6.2 \cdot 10^{18} I t_i E_i \quad (2)$$

where I is the current (A) and t_i is the pulse duration (s). Beam ions interact mostly with the plasma ions and heat them. The initial total ion energy in the plasma of volume V and ion temperature T_i is

$$E_0 = T_i V n_e k \quad (3)$$

The energy transfer from the beam to the plasma should be lower to avoid that the beam perturbs the plasma. Fig. 1 shows the total beam energy E in terms of the energy per charge E_i (the two lines are corresponding to a beam current $I=0.1 \text{ A}$ and 0.3 A) in comparison with the total energy of ions E_0 in the plasma which parameters are: $k = 6$, $n_e = 4 \cdot 10^{12} \text{ cm}^{-3}$, $V = 600 \text{ cm}^3$, $T_i = 20 \text{ eV}$. A current of 100 mA can be absorbed up to energies of 300 eV in such plasma.

Calculations have been carried out for different metallic ions, and for the typical axial field profile of the SERSE superconducting ion source [4]. For sake of simplicity, the injection of a constant flux of 0.1 A burst, $20 \mu\text{s}$ long pulse of ions with an average charge state equal to 2 was assumed. It was also assumed that a pure oxygen plasma is created with total RF power of 1500 W before the laser injection.

Fig.2 presents the results of calculation for chromium ion production with external injection in to the plasma.

It may be observed that we can choose an optimum charge state with the maximum output current by selecting the time for the given element and the plasma parameters. For the highest charge states a nearly dc beam can be obtained.

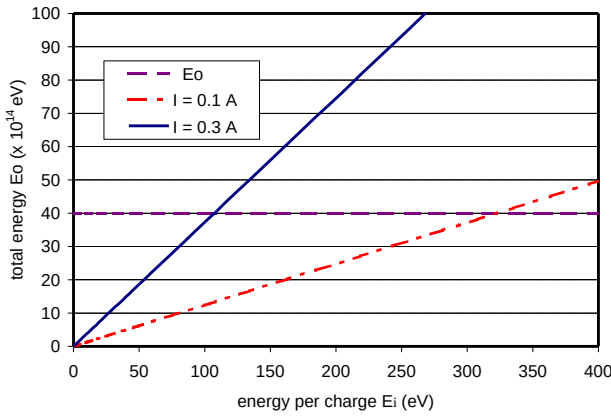


Figure 1: Comparison of the ion beam energy and of the the plasma energy content.

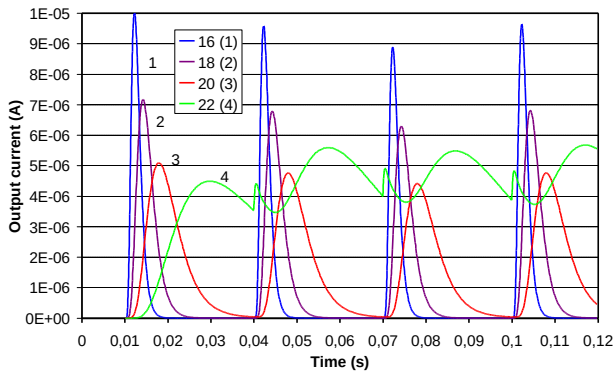


Figure 2: Cr high charge states buildup vs. time.

2 THE EXPERIMENTAL SET-UP

The LIS operating at INFN-LNS is based on a 30 Hz, 1064 nm Nd:Yag laser, with 9 ns pulse width and a maximum power density of the order of 10^{10} W/cm². The laser light is focused on metal targets with a spot size ranging between 1 mm² and 6 mm². In these tests, the irradiated targets were pure sheet of tantalum, 1 mm thick. An electrostatic deflection ion energy analyzer (IEA) is used along the normal to the target surface to detect the energy-to-charge ratio, E_i , as a function of the laser pulse energy, and of the focusing position. By changing the plates' bias, it is possible to select different ratios and to detect the transmitted ions by means of a windowless electron multiplier (WEM). The IEA is employed for time-of-flight (TOF) measurements with a target-WEM distance of 1.5 m. More details on the experimental apparatus are report in literature [5].

3 LASER ION SOURCE (LIS) TESTS

The laser interaction with metallic surface produces either etching, neutral emission and ion emission above a well defined threshold. At LNS we have demonstrated that the experimental thresholds for the ion emission is very close to the threshold for the neutral emission [6].

The atomic neutral emission was monitored by a mass quadrupole spectrometer and by the vapor thin film deposition technique. The energy thresholds, the emission yields, the angular distribution, the fractional ionization, the kinetics and characteristics of the plasma production and the ion charge state have been studied for Al, Ti, Ni, Cu, Nb, Sn, Ta, W, Au and Pb targets [6,7]. Another interesting aspect concerns the yield of the ion emission from the irradiated tantalum target. This yield is of the order of 0.8 μ g/pulse at 10^{10} W/cm², corresponding to an atom emission of 2.6×10^{15} /pulse. However, in this case only about the 20% of the emission is ionised while at higher power density a higher fractional ionisation occurs [8]. If we compare the corresponding flow of neutrals from sputtering system and oven used to provide metal atoms to ECRIS plasma, it is evident that the yield is much higher in the case of the LIS, so that a careful tuning will be necessary. Anyway the ion component should obey to the limitations in §1, then the laser energy cannot exceed few hundreds of mJ and the useful charge states are low. Fig. 3 shows a typical IEA spectra corresponding to the tantalum irradiation at 150 mJ, featuring only five charge states. At 500 mJ laser pulse the maximum charge state increases to 8⁺ [8].

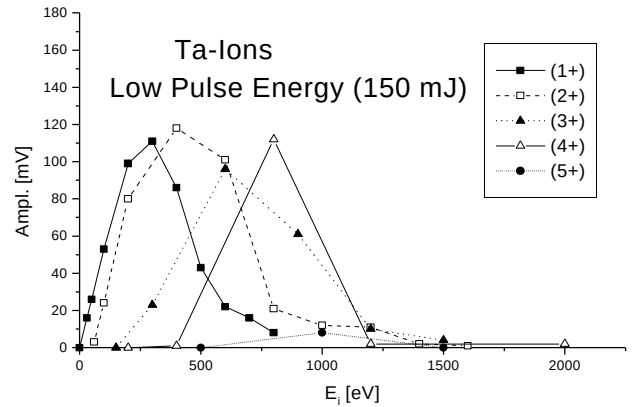


Figure 3: A typical IEA plot for a laser pulse energy of 150 mJ, irradiating a Ta target at LNS.

3.1 The influence of electric and magnetic fields

The ion velocity distributions of W plasma expanding in presence of magnetic and electric fields have been compared to the case of freely expanding plasma (Fig.4 [2,3]). The distributions for $B = 0$ and $U_t = 0$ significantly differs from the ones obtained for $B = 0$, $U_t = -5$ kV, and $B = 0.45$ T, $U_t = 0$. The application of $U_t = -5$ kV results in the decrease of the maximum velocity of ions from the original value of $(4.5-5) \cdot 10^7$ cm/s to about $2 \cdot 10^7$ cm/s but a significant fraction of the ions is lost. For W ion velocity of $2.5 \cdot 10^6$ cm/s the intensity in the case $B = 0$, $U_t = -5$ kV is about 5 times lower then in the case $B = 0.45$ T, $U_t = 0$; the amplitudes for $B = 0$, $U_t = 0$ and $B = 0$, $U_t = -5$ kV are similar in that range, whereas many more fast ions are present in the case $B = 0$, $U_t = 0$ [9]. Fig 5 shows the

simulation of beam path from the target to the resonant surface (about 20 cm). The beneficial effect of the magnetic field on spatial distribution of the ions emission from a W target is clearly shown for different values of the magnetic field, up to 2.5 T. The results in

fig.4 correspond to the case described in fig.5b), i.e. about 0.4 T. We can expect a further improvement if the axial field will be much higher as in the case of SERSE (2.5 T, fig. 5d)

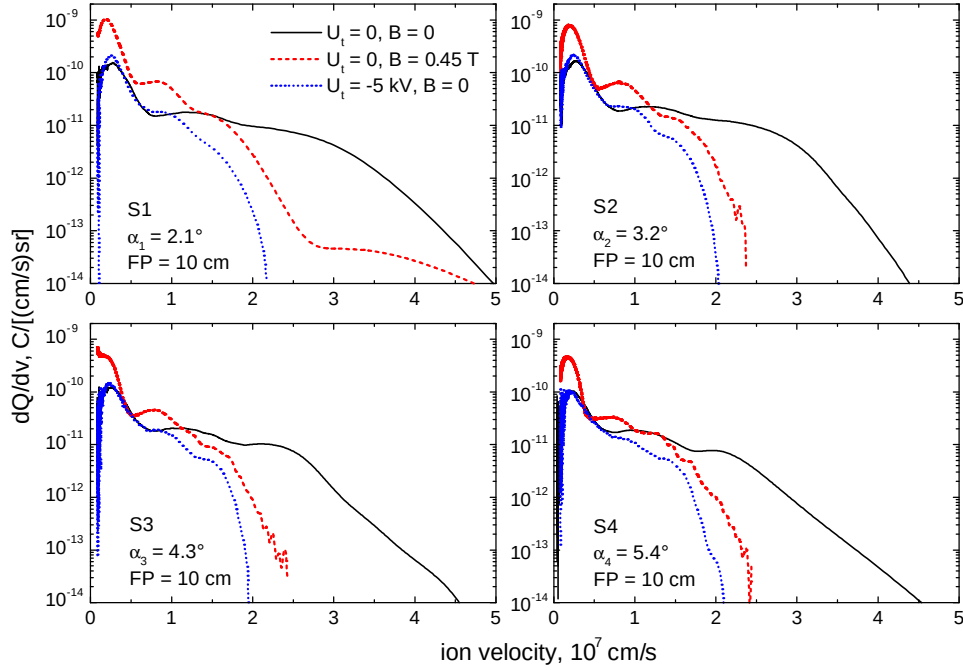


Figure 4. Influence of external magnetic and electric fields on ion velocity distributions of W plasma ($E_L = 480 \pm 30$ mJ).

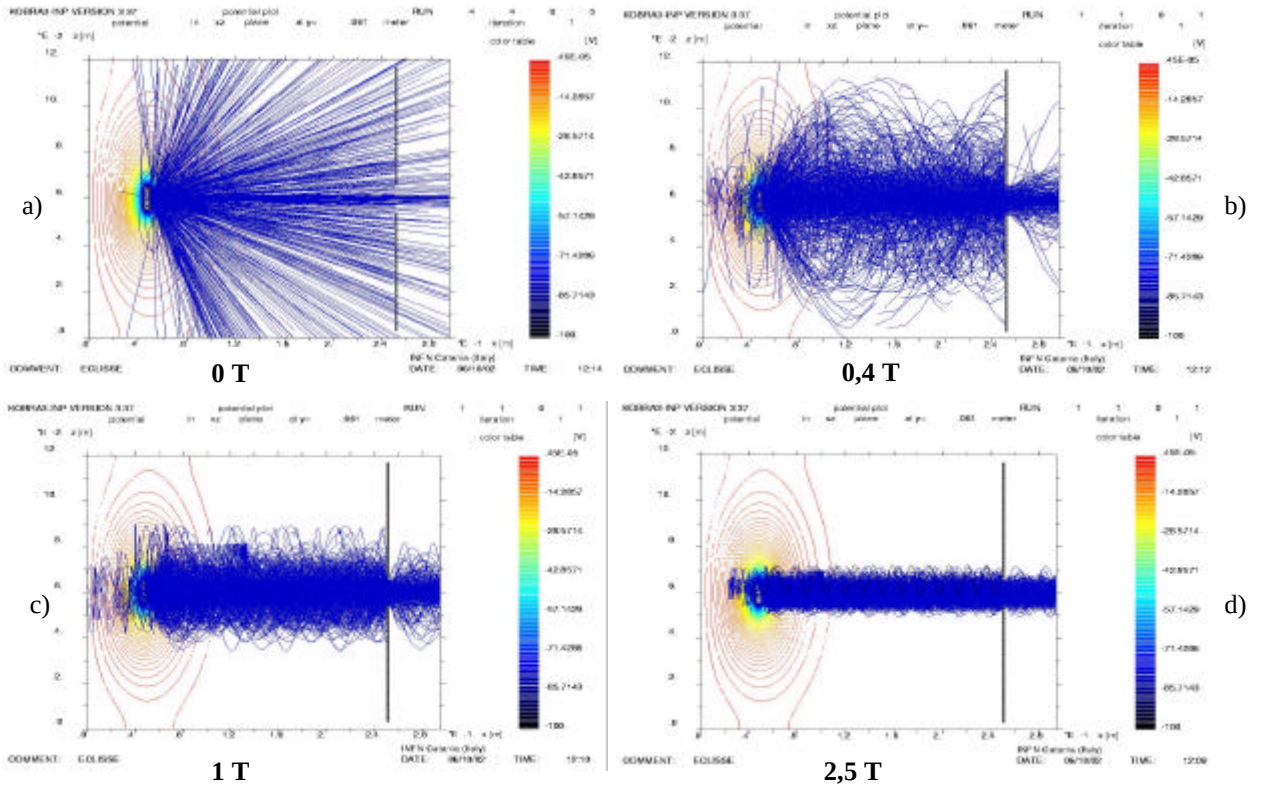


Figure 5: Effect of the magnetic field on ionic spatial distribution from W target after a 150 mJ laser pulse

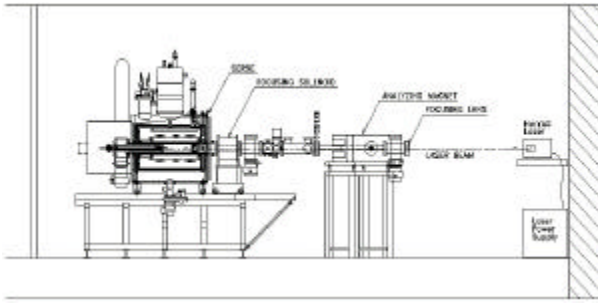


Figure 6: Lateral view of SERSE installation

4 THE HYBRID SOURCE

The assembly of the hybrid ion source will be carried out in 2002. The complete setup is shown in fig.6 where a lateral view of the SERSE beamline is presented along with the laser beamline. A displacement system will be installed inside the plasma chamber; it has been tested to continuously irradiate a sample on fresh surface. High repetition rate (30 Hz) was offline tested for hours with different metals. A typical emitted plume is shown in fig. 7. Fig. 8 shows oscillations of the current density about 30%.

The Nd:YAg laser will be aligned onto the target, by means of a He-Ne laser, and a focusing lens will be placed at about 20 cm from the 0° flange of the magnet, in order to have a beam spot dimension variable from 1 to 8 mm at the target position.

The tests of the hybrid source will be limited not only to the production of highly charged heavy ions, but also to the study of ECRIS plasma in such a regime. In fact the perspective which can be opened by the new generation of ECRIS as the GyroSERSE source [10] is attractive, because their larger plasma length and higher plasma density will make less critical the limits on some parameters of the LIS and about one order of magnitude higher energy will be allowed. The larger plasma energy content $n_e kT_e$ will be much higher and higher beam currents injected by the LIS may be absorbed by the plasma.

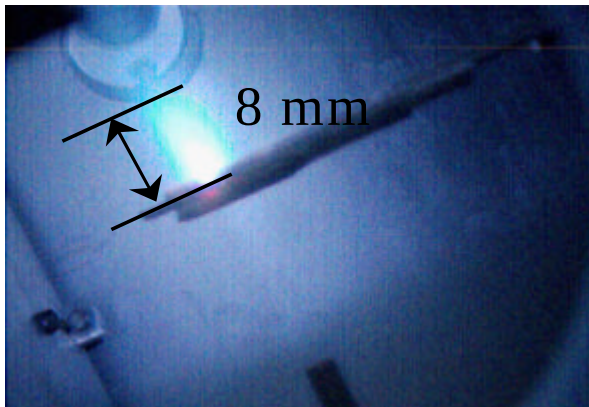


Figure 7: Plasma plume from the target (30 Hz repetition rate).

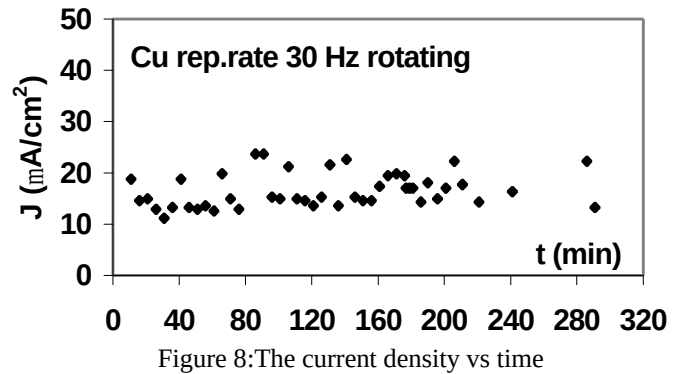


Figure 8: The current density vs time

5 ACKNOWLEDGEMENTS

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A STATUS REPORT OF THE EXCYT FACILITY

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Abstract

The EXCYT project (EXotics with CYclotron and Tandem) is based on the two-accelerator method: a primary beam from the cyclotron will be axially injected into an ISOLDE-type target-ion source complex to produce the required nuclear species, while the Tandem acts as the final accelerator. This paper reports the upgrading of the facility as well as the new developments achieved during the year

1 ECR ION SOURCES

Two ECR ion sources are used for the axial injection into the superconducting cyclotron (CS): the superconducting SERSE working at 18 GHz [1] and a conventional one named CAESAR working at 14 GHz. Both sources have already accomplished the currents of fully stripped light ions needed for EXCYT: 5 to 7 μA for SERSE and 1 to 3 μA for CAESAR [2-4]. In 2000 the beam transmission through the analysis section of the beamline relevant to CAESAR has been improved by means of a new extraction system. Two results are particularly valuable for the production of intense primary beams: the optimisation of Ne^{9+} (14 μA) and of fully stripped nitrogen (25 μA). In the next future further improvements to the SERSE cryostat are under study, so that no manpower will be necessary for refilling; the aim is to obtain a zero-boiloff system by using HTC current leads and a 1.5 W cryocooler.

Moreover, the results obtained in a few weeks of tests at 28 GHz [5] with SERSE supported the validity of the conceptual design of a further development, named GyroSERSE. The expected currents for such a source are about 0.2 μA for U^{60+} and Kr^{34+} (nuclear physics at intermediate energies) and 5 to 7 μA of Ne^{10+} and Ar^{16+} , thus extending the range of useful projectiles for EXCYT.

2 SUPERCONDUCTING CYCLOTRON

During the last two years we focused our efforts to improve the performance of the CS [6]

and of its axial injection line, axial buncher and central region.

In particular during the 2001 a couple of weeks were dedicated to maximize the injection efficiency and the acceleration through the cyclotron.

Since the beginning of 2000 the injection line works quite well.

The main elements of the axial injection line are 12 solenoids and 4 quadrupoles. The solenoids maintain the beam well confined but at the same time provide only a weak focusing, thus minimising the space charge effects and the related emittance growth. By the four quadrupoles the beam emittance can be rotated in the phase space to allow for matching the acceptance of the cyclotron.

The tuning of the beam line is done according to the following procedure:

1. Tuning of the line elements to maximize the beam current at each faraday cup;
2. Tuning of the line elements to maximize the beam current inside the cyclotron.

Using this procedure we are able to transport about 90% of the beam produced by the sources up to the last Faraday cup at the entrance hole of the cyclotron and to accelerate a maximum of 9% of the continuous beam inside the cyclotron with the buncher switched off. This measured value is very close to the calculated value of 35° phase acceptance of the central region.

Using the the axial buncher, which consists of a drift tube placed inside the CS 50 cm away from the median plane [7,8], the accelerated beam current increases of a factor about 4-5. Along the injection line, before the 90° vertical

magnet, a deflecting plate acting as a Low Energy Chopper (LEC) has also been installed [7,8]. This chopper has been used to reduce the duty cycle of the injected beam. This procedure is very important to check the ability of the cyclotron to accelerate ion beam with current of several μAmp . Of course the acceleration of such current create problems to our diagnostic devices, like the radial probe which is designed to measure a maximum current of 500 nA. Moreover the cyclotron vacuum chamber and mainly the electrostatic deflectors (ED) became seriously radioactive if the beam is not extracted with high efficiency. For these reasons tuning of the cyclotron to deliver ion beams for EXCYT is made using or pepper pot attenuators or the LEC. The pepper pot device is able to reduce the beam current of a factor 10, 100 or 1000. This method preserve the beam emittance and it is easy and sure to be used, unfortunately in this case the space charges effects are strongly reduced. To handle the beam with the full space charge effect but whit low power the LEC is used. In this case the beam is injected to the cyclotron only for 100 microsecond with a repetition rate in the range 1 to 1 kHz (duty cycle $10^{-4} - 10^{-1}$).

The use of the chopper shows that the effects of the space charge are not significant for the injection and the acceleration efficiencies. Similar investigation are not yet done for the extraction efficiency.

The ED are the most critical elements of the beam extraction system, their optimum performance and reliability being a crucial point for EXCYT [9]. Anyway at the end of the 2001 the deflectors were tested during the normal operation of the CS: we extracted a 62 MeV/u beam of H_2^+ with an applied voltage of -60 kV to the cathodes, the gap set at 5 mm, vacuum. This was an important step ahead but a lot of work have to be done in near future to allow beam extraction of about 500 W.

3 PRIMARY BEAM LINE AND HV PLATFORMS

The commissioning of the primary beam line until the 90° dipole magnet has been already performed.

The HV system (fig. 1) consists of two platforms located in two separated rooms: both platforms work at 250 kV and are connected by a HV conduit. Most of the radioactivity is generated and confined in the first platform area which is contained in a shielded pit. The first platform (A) houses the target-ion source assembly and the pre-separator while in the second (B) there are the charge exchange cell and the first stage of the isobaric mass separator. The conduit consists of two concentric pipes: a continuous, electrically conductive, inner pipe and a continuous fibre glass/epoxy outer pipe with flanges extending into the 250 kV platforms by a few centimetres. The space between the two pipes is filled with 2 atm of SF_6 insulating gas. Moreover, within the span of the shielding wall the fibre glass/epoxy tube is covered with a stainless steel tube, which ends with the field termination rings. POISSON simulations show that the electrical gradients are appropriate to prevent sparks and electrical instabilities. Platforms and conduit are already installed at LNS.

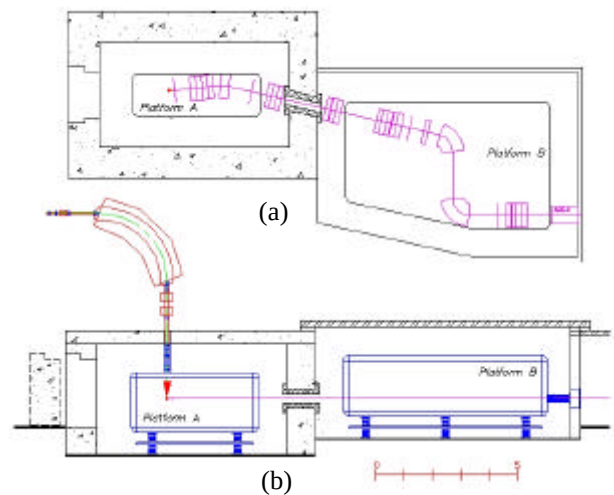


Figure 1: Plan (a) and front (b) views of the HV platforms

4 TARGET-ION SOURCE ASSEMBLY

4.1 Target

The first tests performed on the target-ion source assembly (TIS) showed misalignments that caused tilting and twisting of the target with respect to the source axis. Hence the target and its heater was redesigned, currently they are in stock and prospective tests are under

discussion.. Some prospective radioactive ion beams as ^{18}F and ^8Li have been investigated at EXCYT [10, 11]. An easy way to produce ^{18}F is by means of ^{19}F fragmentation in a thick target. Since this nuclear reaction is quite insensitive to the target material, graphite has been chosen for its well-known characteristics (e.g. high thermal conductivity, refractory behaviour, etc.). Graphite is an ideal target material also for the other prospective beams, namely ^7Be , ^{17}F and possibly some nuclides of lithium, oxygen and chlorine to be investigated in the near future. However graphite easily pollutes the ISOLDE-type negative surface ion source and alternative target materials are under study.

4.2 RIB Sources

During the year three of the four types of sources to be used for the EXCYT facility have been tested: the positive (PIS) and negative (NIS) surface ionisation sources and MIDAS. In 2002 we plan to test the hot plasma ion source (HPIS) as well as a new negative ion source called KENIS (Kinetic Ejection Negative Ion Source). developed at the Oak Ridge National Laboratory.

4.2.1 ISOLDE-type ion sources

Measurements of the ion-source efficiency have been performed at LNS both for PIS (Li^+) and NIS (Cl^-). The PIS proved to be very reliable: the efficiency obtained for Li^+ was steeply depending on the Li flow ranging from a few percent for very high rates to more than 70% for medium-low rates. The NIS showed good stability and reproducibility, but attempts to determine its efficiency with chlorine salts failed. Further tests with gaseous chlorine compounds are planned.

4.2.2 The MIDAS source

MIDAS is a compact microwave discharge source which exploits the principle of the off-resonance discharge to generate an overdense low-temperature plasma which is an effective tool to generate 1^+ ion beams with high efficiency, short delay time and low energy spread. The source has fulfilled our request: the production of singly charged ions is largely

dominant and currents up to 30 μA have been extracted for Ar, Kr, Xe with measured efficiencies ranging between 2% and 50% [12]. The source will be redesigned in order to allow the coupling to the target and to comply with remote handling.

4.3 The EXCYT front-end

The EXCYT front-end has been already installed on the platform A. At the moment it has been temporarily moved in another room of the LNS where it will be extensively tested.

5 ISOBARIC MASS SEPARATOR

The EXCYT mass separator has been described in the previous LNS report [13]. Here we only show the layout (fig. 2), including the magnets and electrostatic elements and the diagnostic elements that will be installed. All the magnetic elements are already installed at LNS and the fine alignment is planned in the next stop of the Tandem operation. The mechanical construction of the triplets and quadrupole quadruplets is already finished and some of them have been already tested, while the multipoles and the steerer elements of platform B as well as some ancillary devices are in progress. The vacuum pumps are in house; the power supplies of all magnetic elements are at LNS since April 2000, while the power supplies of the electrostatic elements will be delivered at the end of November 2002. Modification of the shielding walls between the cyclotron and tandem room has been done: this new configuration allows us to work in the area of the EXCYT platform also during the operation of the cyclotron with a maximum extracted beam current of about 10 nA.

6 CONTROLS AND BEAM DIAGNOSTICS

6.1 Computer control

Several new components are now in operation, most of them being devoted to the production of the primary beam to be delivered to the TIS. We developed control systems for: 1) the CAESAR source; 2) the power supplies of the axial injection beam line; 3) the cyclotron inflector;

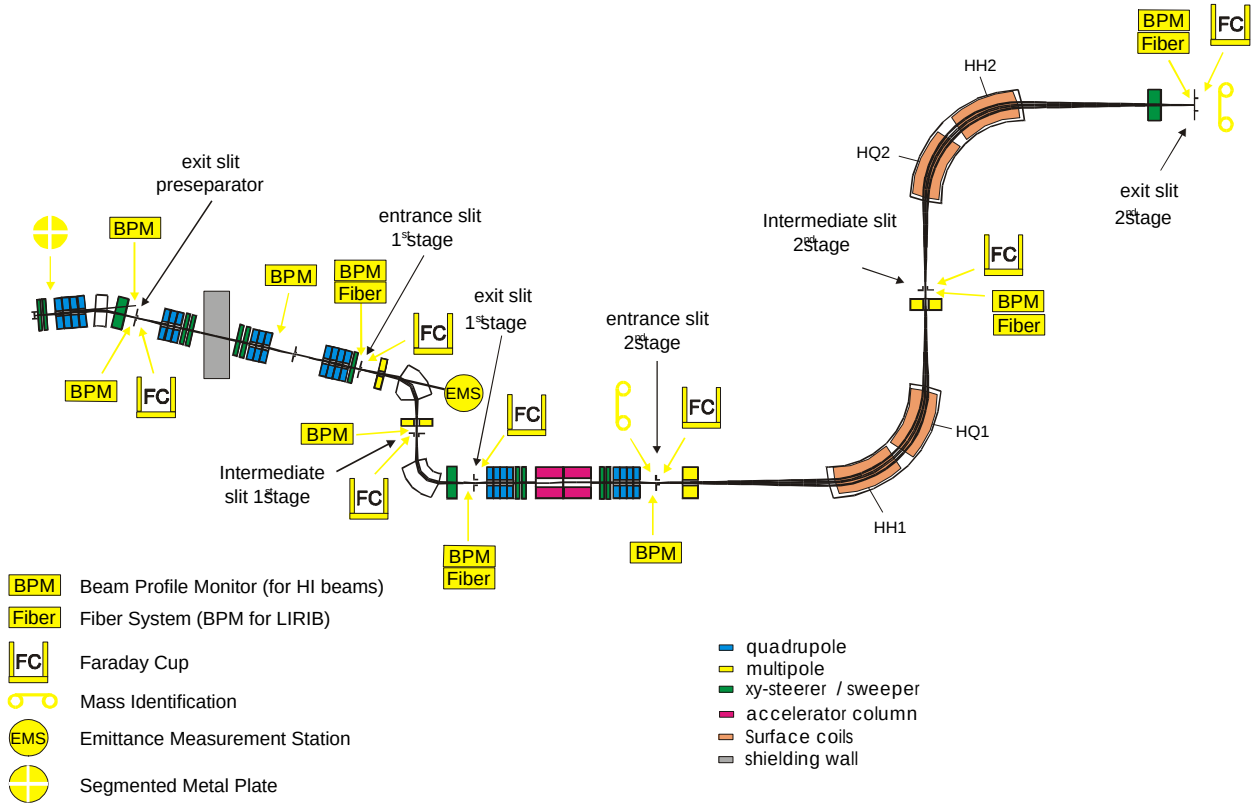


Figure 2: Layout of the EXCYT mass separator and diagnostic elements

4) the cyclotron phase probes; 5) the power supplies of the primary beam line.

In addition we also developed the beam diagnostics for the cyclotron axial-injection beam line and for the primary beam line. As for the beam diagnostics, the time schedule and all the specifications for the beam instrumentation in terms of sensitivity, reliability, versatility, clear and fast readout of the information at the operator console have been respected. The most important components of the control system are already installed and positively tested. All the technical and scientific solutions foreseen by the project have been successfully verified and will be adopted also for the remaining systems to be installed next year.

6.2 Beam diagnostics

The need of diagnostic tools for low energy-low intensity radioactive beams for the EXCYT facility has lead us to the development of a series of suitable devices based on scintillators and semiconductors. The peculiarities of these devices are

compactness, handiness and good performance for very low intensity beams ($I < 10^5$ particles/s). The solutions we have carried out distinguish between the diagnostics for low-energy radioactive beams (50 keV to 300 keV), needed before the acceleration, and the one concerning the accelerated beams (up to 8 MeV/A) [14, 15]. The glass-fibre based beam sensor (GFIBBS) for beam profiling after post-acceleration proved to be reliable and cheap. It is based on a couple of perpendicular scintillating glass or plastic fibres scanning the beam. The readout by means of a single photomultiplier allows to reconstruct the X and Y beam profiles in a single scan [16].

The region between the target ion-source complex and the Tandem accelerator, needed particular care because of the low kinetic energy of the particles (300 keV) and the possible presence of highly radioactive contaminants. Tests on the LEBI (Low Energy Beam Imager/Identifier) device (fig. 3) with a 1 mm collimated ^{90}Sr beta source showed a spatial resolution $\Delta x \approx 1.5$ mm for a

plate 1mm thick [17]. With a Monte Carlo simulation code, we were capable to simulate the shape of the light spot produced by the radiation crossing the plate (fig. 4). In any case a more suitable identification is performed by using a couple of high-purity germanium detectors, thus allowing to build the gamma spectrum of the implanted nuclear species and to identify them.



Figure 3: A picture of the LEBI device. The spherical vacuum chamber containing the plate-tape set-up and the germanium detectors will be installed along the beam pipe

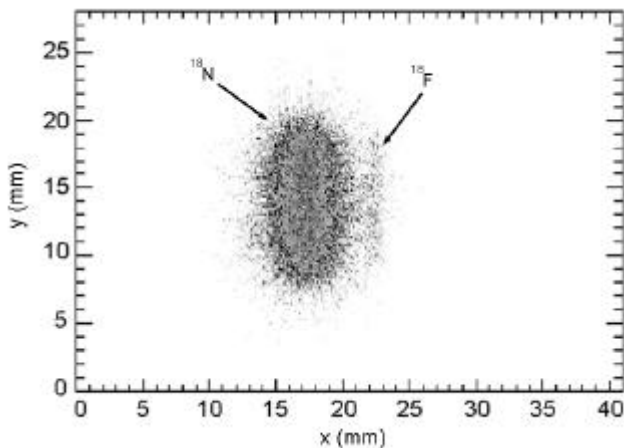


Figure 4: Simulated response of LEBI for a ^{18}F beam and its contaminant ^{18}N . The predominance of the contribution due to ^{18}N ions depends on the value of its decay constant ($\lambda_{^{18}\text{N}} \gg \lambda_{^{18}\text{F}}$)

7 REMOTE HANDLING AND VENTILATION

7.1 Remote handling

This problematic is certainly one of the most important in a RIB facility. We designed and manufactured the following: 1) a shielded

temporary deposit to stock the activated sources; 2) a robot for the manipulation of the activated sources; 3) a mobile robot for special purposes. The latter will remove the activated TIS from the high voltage platform and move it to the shielded storage area. The robot will also perform the reverse operation, i.e. to move a TIS from the shielded deposit to the high voltage platform.

7.2 Ventilation

We are developing the pressure control system for the areas with activation and contamination hazards: the source platform, the second high-voltage platform and the shielded deposit. In the operative mode the system must keep the air dry in the platform rooms, the depression at -25 mm H₂O for the source platform room and at -15 mm H₂O for the other rooms and finally to filter the local air by prefilter and carbons filters.

8 CONCLUSIONS AND TIME SCHEDULE

In conclusion, we can state that the completion of the EXCYT facility is not following the original schedule. The main reason of the delay is the higher priority given by the INFN management to the operation with stable beams of the CS and of the Tandem with respect to the other activities at the LNS. Thus, for the next year the EXCYT facility should be focused on the following tests: high power primary beam acceleration, operation of the electrostatic deflectors at high beam power and efficiency of the ion sources for the TIS. In 2002 the EXCYT facility could be completed if the decision to increase its priority will be taken; we estimate that about one year will be needed from the moment of that decision.

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STATUS OF THE CATANA PROJECT AT INFN-LNS

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This is a progress report of ongoing of **CATANA project** at the Istituto Nazionale di Fisica Nucleare-Laboratori Nazionali del Sud (INFN-LNS) in Catania (Italy), developing a new proton therapy facility for the treatment of ocular lesions with 62 AMeV proton beams from a Superconducting Cyclotron. The proton beam line is ready with all its main components including the chair for the patient positioning (Figure1).

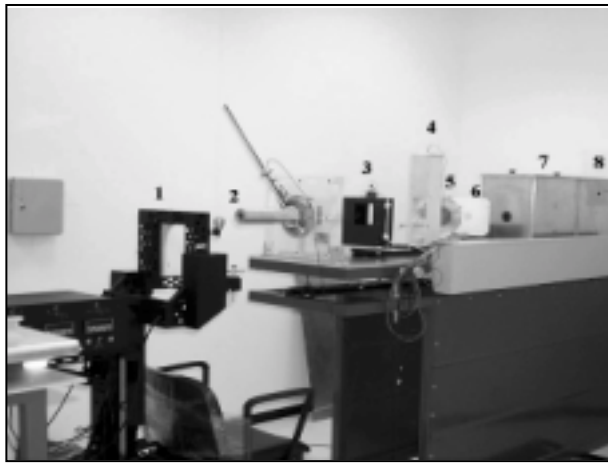


Figure 1. View of the CATANA beam line: 1.Treatment chair for patient immobilization, 2. Final collimator, 3.Positioning laser, 4. Light field simulator; 5. A Monitor chamber; 6. Intermediate collimator, 7-8.Boxes for the location of modulator wheel and range shifter, 9.Proton beam output window.

The proton beam exists in air through 50 μm Kapton window placed at about 3 meters from isocenter. Before the window, under vacuum, is placed the first scattering foil made by a 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 (Figure 2). The double foils scattering system is optimized to obtain a good homogeneity in terms of lateral dose distribution, minimizing the energy loose. Figure 3 shows an experimental lateral dose distribution of the 62 AMeV proton beam obtained for a final collimator of 25 mm diameter; data are acquired in water, at the treatment depth with a silicon diode. In following table the main characteristics of distribution are reported.

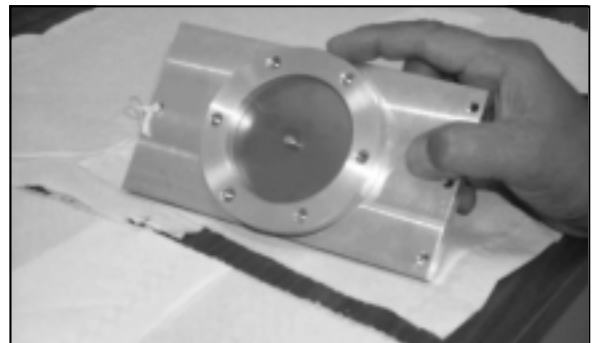


Figure 2. The second tantalum scattering foil with the central stopper

Range shifter and range modulator are placed downstream the scattering system and mounted on two different boxes.

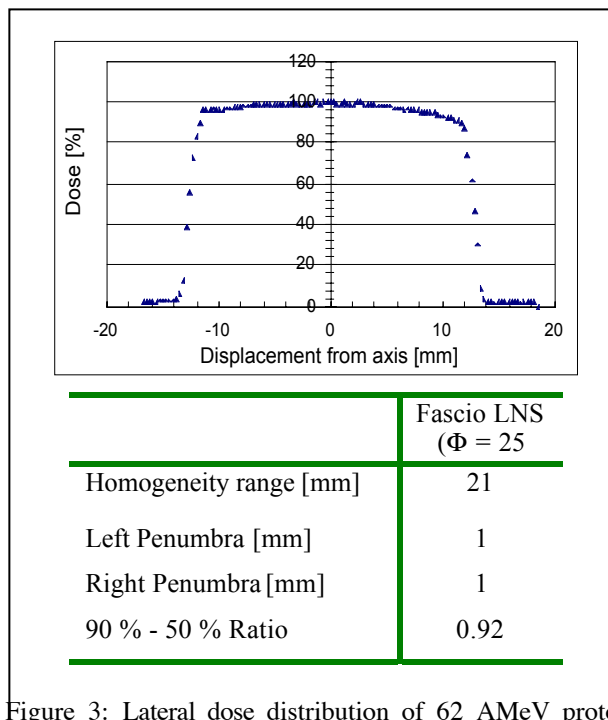


Figure 3: Lateral dose distribution of 62 AMeV proton beam and its main features

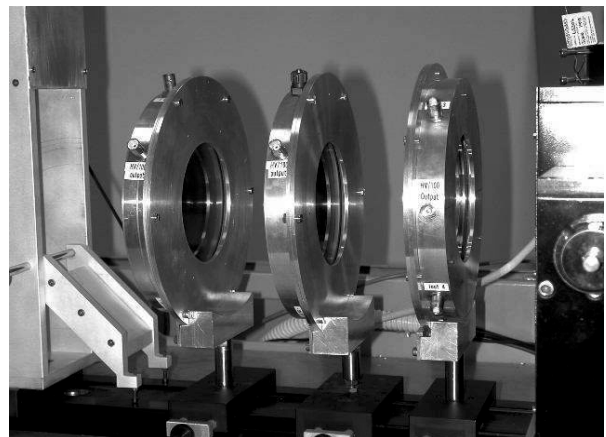
Two diode lasers, placed orthogonally, provide a system for the isocenter identification and for patient centering during the treatment. The emission light of a third laser is spread out to obtain the *simulation field*.

A key element of the treatment line is represented by the two *transmission monitor chambers* (Figure 3) and by the *four sector chamber*, implemented to have an on-line control of the dose furnished to the patients and an information on beam symmetry respectively.

The last element before isocenter is a patient collimator located at 8 cm upstream of the isocenter. Finally two back and lateral Philips *Practics* X-Rays tubes are mounted for the verification of the treatment fields.

Inside CATANA collaboration particular care is going to be devoted to the development of dosimetric techniques for the determination of absorbed dose in clinical proton beams and 2D and 3D dose distribution reconstruction. Figure 4. A view of the two monitor chambers and four sectors chambers

A parallel-plate calibrated *Markus ionization chamber* has been chosen as reference detector for the absolute dose measurement, while *gaf chromic* and *radiographic* films, *TLD* (ThermoLuminescent Detectors), natural diamond and silicon detectors are the choices for the relative one. Depth dose curves and transverse dose distributions, either for the full



energy and modulated proton beams, are acquired with a water-tank system provided of three fully computer-controlled step motors. This system, entirely developed at Laboratori Nazionali del Sud, is controlled by a software providing the acquisition and dosimetric analysis of data. At the moment the dosimetric characterization of the proton beam is in progress to test its effective depth dose distribution, flatness, symmetry and penumbra. Figure 5 shows a depth dose distribution peak in water obtained with the water-tank system and Markus chamber for an unmodulated 25 mm diameter beam at the energy of 62 AMeV.

The Full Width at Half Maximum of the Bragg Peak is 2.76 mm while the 90-10 % and 80-20% distal fall-off are 0.8 mm and 0.6 mm respectively. The entrance to peak ratio is 4.72.

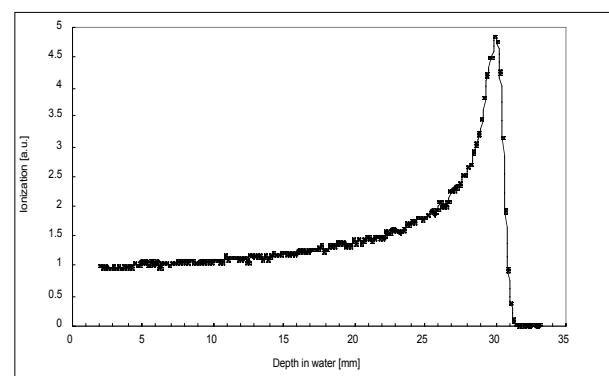


Figure 5. Bragg peak of 62 AMeV proton Beam acquired with a water-tank system and a Markus chamber ionization chamber at CATANA facility

The next step was the realization, in collaboration with the Clatterbridge Center for Oncology (UK), of a wheel modulator to obtain a spread out therapeutic Bragg peak. To do this various

Bragg peaks, for different proton beam energies ranging from 62 AMeV to 10 AMeV, were acquired with the Markus chamber in a water phantom (Figure 6). Proton beam energy lower than 62 AMeV are obtained inserting PMMA range shifters of different thickness along the beam path.

Finally Figure 7 shows the Spread Out Bragg Peak obtained with the first prototype of the modulator wheel.

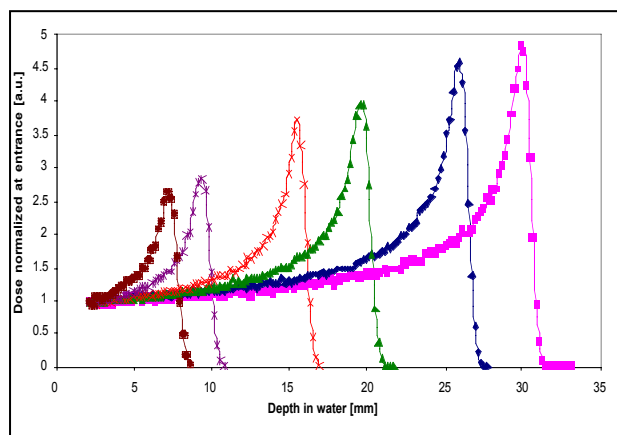


Figure 6: Various Bragg peaks for different energies of the proton acquired in water with the Markus ionization chamber

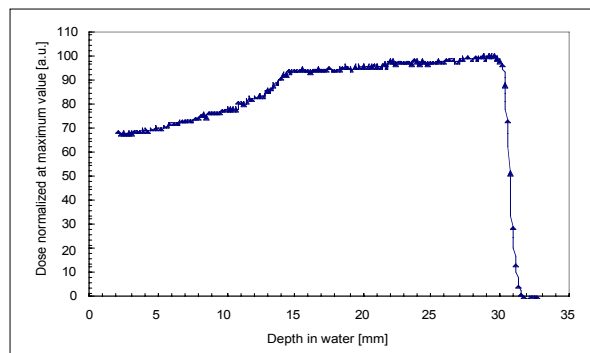


Figure 7: Spread Out Bragg Peak obtained with a modulator wheel; Data acquired in water phantom with the Markus ionisation chamber

In this condition we were able to carry out the dosimetric characterizations of the therapeutic proton beam verifying, at the same time, our dosimetric systems. Actually a first set of modulator wheels (10, 12, 15, 20, 25 mm SOBP), developed for therapeutic purposes, has been tested and the results demonstrating

CATANA facility is ready to start the first treatment in the next months.

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ION MICRO-BEAM DIAGNOSTICS WITH PHOTODETECTORS FOR DEEP LITHOGRAPHY APPLICATIONS

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Abstract

We have developed two techniques for microscopic ion beam imaging and profiling, both based on scintillators, particularly suitable for applications in Deep Lithography with Protons (DLP) or with heavier ions. The first one employs a scintillating fiberoptic plate and a CCD camera with suitable lenses, the second makes use of a small scintillator optically coupled to a compact photomultiplier. We have proved the possibility of spanning from single beam particles counting up to several nA currents. Both the devices are successfully exploited for on-line control of proton beams, down to a beam size of less than 50 μ m, in the framework of DLP application.

1 INTRODUCTION

One of the interesting goals of the optoelectronics in the field of data communication, is to increase the transmission bandwidth by making use of fibre bundles coupled to arrays of integrated lasers (like e.g.VCSEL) [1]. As a possible solution for the optical coupling between a VCSEL and the related fibre bundle, a lens-based approach has recently been proposed. This raises the problem of producing arrays of spherical microlenses, along with the related mechanical supports, and other microcomponents like mirrors and prisms. One of the envisaged solutions is to make use of the Deep Lithography with Protons (DLP), which allows to produce several microscopic optical and mechanical structures [2].

The main purpose of DLP is to use a microscopic proton beam to produce a controlled damage in PMMA samples, which are later run through a selective chemical treatment (etching, swelling) in order to realize the needed microstructures.

It is rather evident that controlling size and shape of the proton beam becomes of utmost importance, as the “a posteriori” check of the developed samples shows. This is why we decided to build two different devices, described in the following, improving previous schemes which proved to be useful in an environment of low-intensity radioactive beam diagnostics [3, 4, 5].

2 THE μ -SFOP BEAM IMAGING SENSOR

This device is mainly meant to get live images of the beam intensity distribution on the transverse plane. To this purpose we employed a Scintillating Fiber Optic Plate (SFOP), made from a bundle of Terbium-glass scintillating fibres, and a compact CCD camera watching it (fig.1).

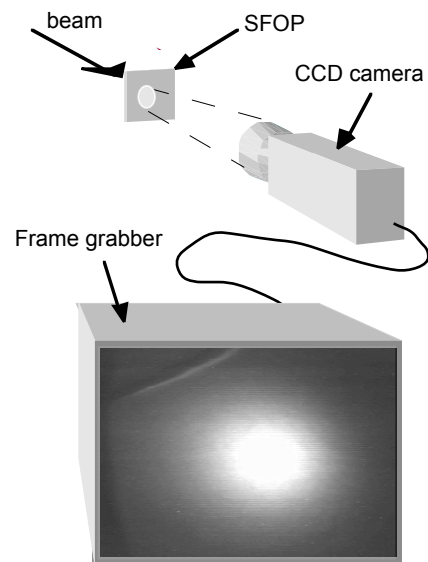


Fig.1 – Scheme of the μ -SFOP beam sensor.

Each fibre in the bundle is 10 μ m in diameter, while the overall plate size is 25x25x1.6 mm³. From a practical point of view, we decided to make these first experiments in air. Hereby we separate the accelerator beam pipe, which is

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under vacuum, from our setup by means of a 75 μm thin Aluminum window. A first collimation stage, made from an Aluminum block 12 cm long, has a 1 mm square aperture. This insures an output beam size of the order of 1 mm², as compared to the input one typically of several square millimeters; moreover, such a long collimator provides an output beam with a high degree of parallelism (low divergence). The second, and final, collimation stage is a lithographic Nickel mask featuring an array of high precision round holes of decreasing diameter from 1 mm to 20 μm . The thickness of this specific mask is 300 μm , which guarantees a full stop of the 11 MeV proton beam.

A remotely controlled device allows to perform the coarse and fine positioning of the mask in front of the first collimator, in order to select a particular aperture to be used for the irradiation. A second remotely controlled stage allows to translate the PMMA sample in the proton beam.

Finally, the SFOP and its CCD camera are installed in front of the beam. In fig.2 we show a picture of the described setup.

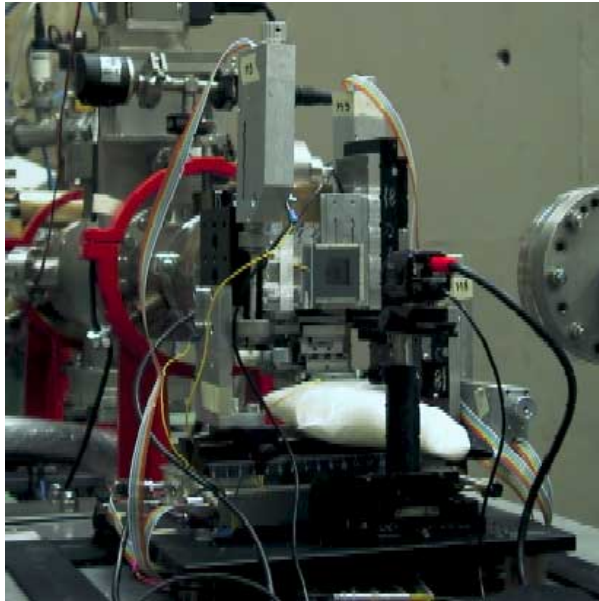


Fig.2– The μ -SFOP beam sensor in the irradiation set-up.

When the beam impinges on the SFOP it produces scintillation light, which is detected by the camera and displayed on a computer screen by means of a frame grabber device.

In fig. 3 we show a sample picture taken with a primary beam current of 30 pA and a mask hole of 150 μm (the current on the sensor was well below 1 pA).



Fig.3 – Live picture of a 30pA proton beam after the 1mm collimator and the lithographic mask while selecting a 150 μm aperture.

The corresponding measured X and Y diameters are 133 and 139 μm (FWHM), as can be seen in figs.4 and 5.

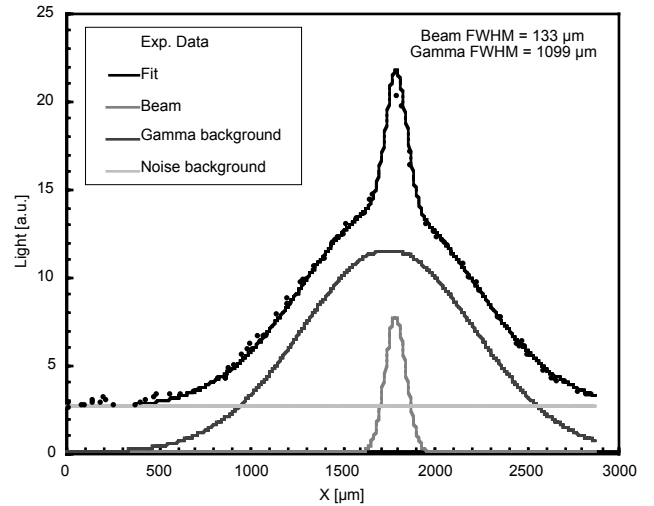


Fig.4 – X profile of the previous picture. The measured width is 133 μm for the beam spot and 1099 μm for the gamma background (FWHM), in good agreement with the collimator and mask apertures.

We remark that the SFOP is also sensitive to photons, namely X and gamma rays. X-rays are ruled out because of the Nickel mask thickness, as comes out from a simple evaluation of all the possible energy levels available and the attenuation coefficient in Nickel. Gamma rays are produced rather copiously by the proton beam, both inside the long Aluminum collimator and on the Nickel mask. This is clearly seen in the two plots, where the larger bell-shaped curve is produced by gamma rays and has an FWHM of about 1 mm, consistent with the 1 mm collimator size.

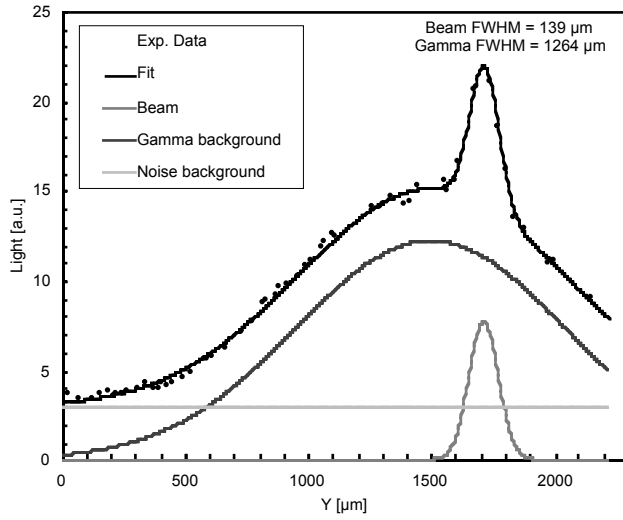


Fig.5 – Y profile of the previous picture. The measured width is 139 μ m for the beam spot and 1264 μ m for the gamma background (FWHM), in good agreement with the collimator and mask apertures.

The gamma background is quite useful for the precision alignment between the collimator and the mask: figs. 4 and 5 show how the X alignment was pretty good, while there was a slight misalignment in the Y direction.

3 THE μ -SBBS BEAM SENSOR

The μ -SBBS as a profiling sensor

The μ SBBS (Scintillator Based Beam Sensor) device is meant to reconstruct the x and y beam profiles. It basically consists of a 1x1x0.2 cm³ CsI(Tl) scintillator optically coupled to a compact photomultiplier (Hamamatsu 5774) by means of a prism-shaped lightguide. In front of the scintillator we should place a beam stopper with two 20 μ m slits, perpendicular to each other. A suitable single 1D translation (at 45° with respect to both slits) would allow to reconstruct the X and Y beam intensity profiles. Unfortunately producing such a stopper is not straightforward, therefore for the time being we fixed an aluminum beam stopper with two sharp edges perpendicular to each other, as shown in fig.6.

The output signal from the photomultiplier is handled by an I-V converter, which converts the anodic current into a more friendly voltage one that is fed into an ADC; at the same time the I-V converter provides the unperturbed pulse output, useful in case of single particle counting.

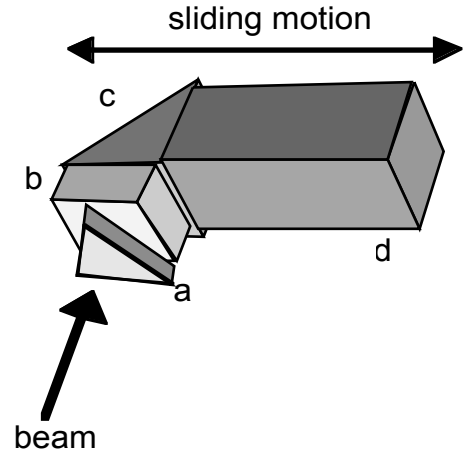


Fig.6 – Scheme of the μ SBBS beam sensor: Aluminum stopper (a), CsI scintillator (b), lightguide (c), photomultiplier (d).

A 1D scan of the beam with this device, by means of a high precision translation stage, provides incremental information about the fraction of beam stopped by the aluminum. The derivative of the measured function, after suitably scaling the translation axis by square root of 2 ($\cos 45^\circ$), represents the intensity profile along the x and y directions in the transverse plane, as shown in fig.7.

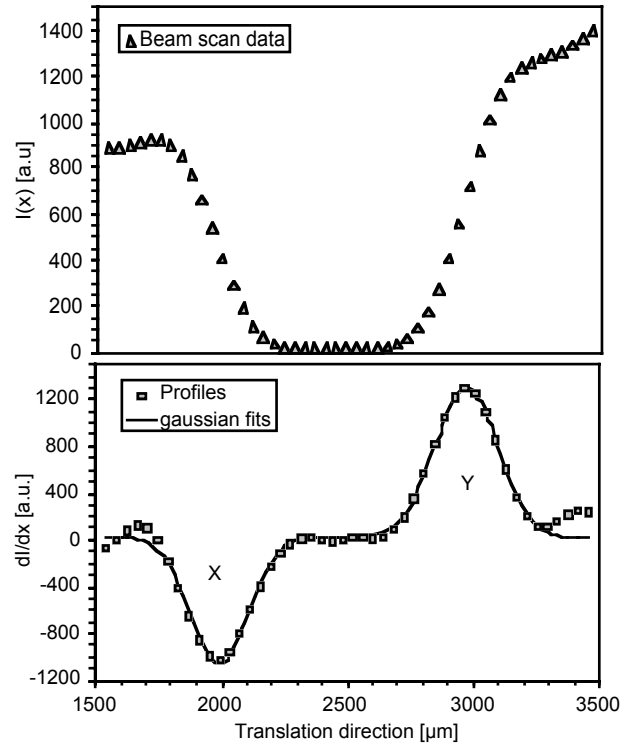


Fig.7 – X and Y profiles as measured with the μ SBBS beam sensor. Upper part: the raw data; lower part: the derivative represents the X and Y profiles.

The μ -SBBS as a beam current sensor

The μ SBBS has also been used for single beam particle counting, as each proton impinging on the scintillator produces a characteristic scintillation pulse. As long as the beam rate is low enough (below 10^5 particles per second) a discriminator with the proper threshold setting is sensitive to the beam particles and blind to the background radiation pulses. With a fixed primary beam current we selected several different intensities by using different collimators, and then counted the number of detected protons in 20 seconds. The beam stopper in front of the scintillator was removed for these integral measurements, and the sensor was positioned in front of the collimator hole. Fig.8 shows the count rate as a function of the square of the collimator diameter, that is expected to be roughly proportional to the beam current emerging from the collimator itself and hitting the sensor.

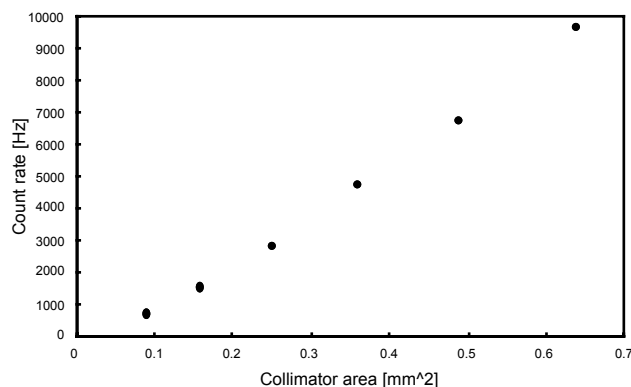


Fig.8 –Proton count rate on μ -SBBS as a function of the square of the beam diameter.

4 DISCUSSION

The starting point of our development was the need for a better control of the DLP process, in order to have an on-line check of the beam quality, and as a consequence to improve the overall quality of the final samples. Our results tell us that a beam of several tens fA intensity ($\approx 10^5$ particles per second) and a few tens μ m width can be imaged on-line using the nearly off-the-shelf μ -SFOP sensor. We have also proved that such a device is truly interactive, indeed during our tests its display screen was installed on the accelerator console in order to help the operators. While in most cases the standard accelerator equipment was unable to sense any beam, the 8-bit frame grabber reading out the μ -SFOP was often close to saturation because of

the large amount of scintillation light produced by the sensor. Moreover, the short decay time of the Terbium-glass light, about 3 ms, gives no appreciable afterglow: this means that even fast beam fluctuations, in terms of intensity, position, shape or size, can be observed on-line. To prove this we have also recorded digital movies while moving the mask up and down in front of the beam, showing the different holes sliding in and out on the display in real time.

Concerning the μ -SBBS we have to admit that even though it is very sensitive and powerful, it has been to some extent overruled by the μ -SFOP with respect to beam profiling: the latter showed to be surprisingly more sensitive than expected. However, should a space resolution below 20 μ m be needed, μ -SBBS with a high precision beam stopper could be the optimum solution.

On the other hand μ -SBBS has shown to be a friendly and reliable device to measure the deposited dose: it can count the beam particles one by one at very low intensity, and at the same time it provides a DC output signal which can be used for its absolute self-calibration versus the count rate. At higher beam intensity only the DC output is meaningful, and its absolute calibration still holds.

5 CONCLUSIONS

The two sensors we developed for microscopic ion beam imaging and profiling, both based on scintillators, showed to be quite promising for applications in Deep Lithography with Protons and with heavier ions. Their surprisingly good performance make them suitable candidates for any other application where ion micro-beams are involved.

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THE LNS PIXE-ALPHA PORTABLE SYSTEMS IN THE QUANTITATIVE CHARACTERISATION OF SULPHUR AND CHLORINE SUPERFICIAL POLLUANTS IN CARBONATE STONES

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Abstract

An application of PIXE-alpha techniques for the evaluation of quantitative amounts of S and Cl in building stones is presented. The analysis have been carried out on Cl and S samples prepared in carbonate matrix at the ICR of Rome, with the aim to determine the MDL of the two elements.

1 INTRODUCTION

Soluble compounds of sulphur and chlorine are considered to be some of the most responsible factors in stone monuments deterioration [1,2].

In recent years, non destructive and portable systems have been developed in order to detect the presence of sulphur and chlorine in the building stones which are considered to be of historic interest in the field of Cultural Heritage.

2 INSTRUMENTAL TECHNIQUES

At LNS, two portable systems have been developed [3]. They are based on the well known PIXE technique:

- 1) the first one is characterised by a large beam spot (2 cm of diameter), a high particle flux and it's equipped with a good resolution (146 eV at Mn line) Ortec-Iglet Ge detector;
- 2) the second one displays a smaller beam spot (0.8 mm of diameter) and works under He gas flux.

It's equipped with a good resolution Peltier cooled Si drift detector.

Both the systems, thanks to the PIXE characteristics, are particularly suited for superficial analysis of light elements [4].

In the present work the capability of the two systems in analysing the above described elements is studied.

3 THE MEASUREMENTS

14 samples of carbonate matrix and known S and Cl concentration have been prepared at the ICR (Roma).

In Figg. 1-2 the fluorescence energy spectra obtained on two samples containing respectively 0.75 % of sulphur and 0.75 % of chlorine are shown.

The quantitative analysis has been carried out by using the known GUPIX code [5]. A preliminary calibration, which is a very important step in order to extract the geometric constant, has been performed by a careful measure of a geological standard (SCO-1).

The carbonate matrix has been assumed for all the data, and sulphur and chlorine were considered as trace elements.

Fig. 3 shows a comparison between the obtained concentrations values and the known ones.

As can be seen, the agreement is satisfactory.

The estimated Minimum Detection Limit is 0.1% for Cl and 0.05% for S.

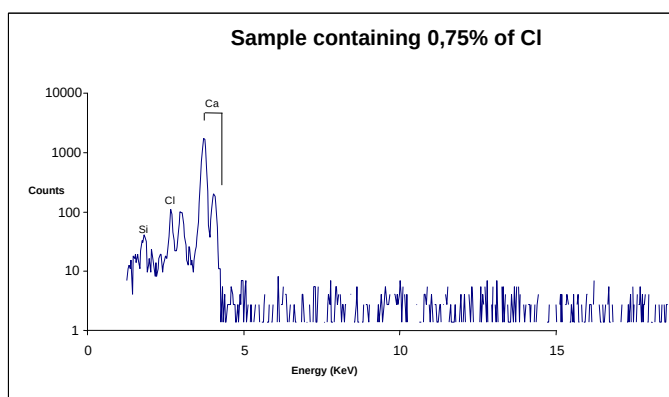
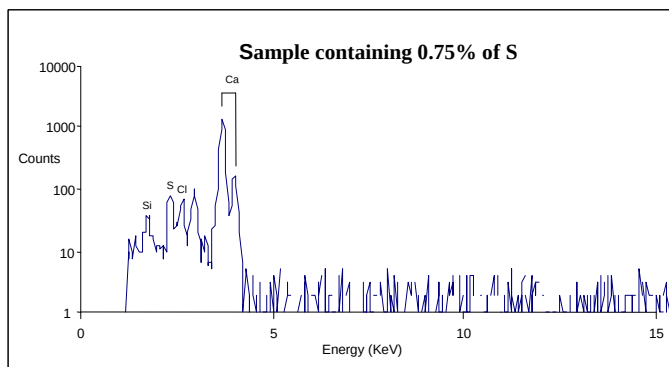


Fig. 1, 2 – The X-ray spectra obtained on two S and Cl samples.

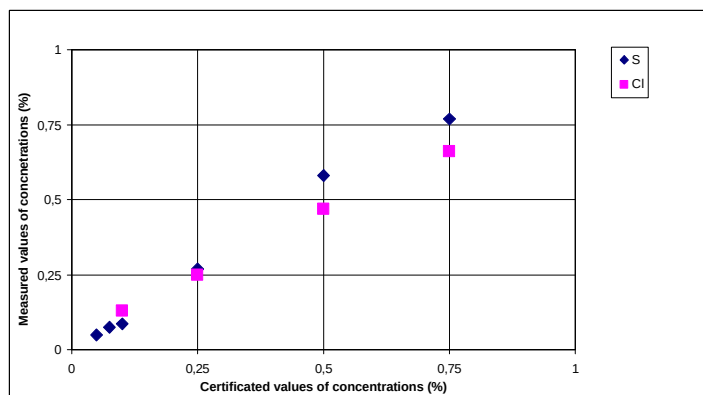


Fig. 3 – Comparison between the known compositions and the measured ones. Errors are between 5-20%.

4 CONCLUSIONS

The described PIXE alpha systems are very suited for S and Cl superficial analysis of stones.

The concentration's absolute values are easily performed by determining the geometric constant in the calibration procedure.

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Foxing spots: chemical and spectrometric characterisation++

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1 INTRODUCTION

Foxing is a complex phenomenon, not yet well understood. The term is applied to stains of reddish-brown, brown, or yellowish colour, generally of small dimensions, with sharp or irregular edges, most of which, if excited with UV light, show fluorescence. Fluorescence is also often present in areas in which the alteration is not yet visible under natural light, but which is probably in formation¹⁻⁹. Its formation mechanisms have been studied since 1935, however, despite more recent intensive research since the 1980s there are still no conclusive results. Some authors found evidence of bacterial and fungal stains in some foxed areas sometimes associated with the presence of iron.

We decided to analyse some foxed stains present on naturally aged papers from the 16th to 18th centuries, trying to find a common trend for a better comprehension of the foxing phenomenon and also for finding restoring procedures and methods. We applied non-destructive techniques and, when it was possible, destructive techniques to carry out a more complete analyses.

Some samples were treated with borane tert-butylamine complex, a reducing compound¹⁰, to test its effectiveness in reducing oxidised functional groups present in the foxed areas. In the present work we will focus our attention on the XRF results obtained from ancient papers.

2 EXPERIMENTAL

We analysed different samples: 1 (manuscript of the second half of the 17th century); 2 (manuscript of the first half of the 16th century); 3 (printed book of the second half of the 18th century); 4, 5 and 6 (printed book of the second half of the 17th century).

We measured surface pH, thickness, carbonyl content, average viscometric degree of polymerisation, we observed all spots under UV light and, for a better characterisation, we applied XRF spectrometry IR spectroscopy.

3 RESULTS

Samples 1, 2 and 3 were fully tested. It was possible, in fact, to carry out destructive measurements; for the other samples only non-destructive techniques were employed (surface pH, thickness, XRF, appearance under UV illumination), except for a micro-analysis to detect the fibre composition of samples 4 to 6 and the IR micro-analyses of some foxed stains in sample 4.

Under UV light at 365 nm, sample 1 showed white fluorescent points dispersed all over the paper and not localised on the foxed spots; in sample 2 the foxed areas were not fluorescent, while the not foxed areas had a yellow-orange fluorescence; in sample 3, 4, 5, and 6 all spots had a pale yellow fluorescence.

The results of the chemical¹¹ analyses are summarised in Table 1 and fully reported in ref. 11.

Table 1: chemical and infrared analyses on foxed papers

Sample	fibrous composition; sizes	pH ± 0.02	IR revealed groups
1	linen, hemp, cotton (5%); gelatine	3.08	C≡C R ₁ R ₂ C=O C=C=C
2	linen, cotton (20%); gelatine	5.82	C≡C COO ⁻ R ₁ R ₂ C=O
3	linen, cotton (10%); starch	6.50	C≡C R ₁ R ₂ C=O C=C=C
4, 5, 6	linen, hemp, cotton (60%); gelatine	5.65	C≡C COO ⁻ R ₁ R ₂ C=O
Sample	measured point	m. moles C=O in g 100 paper	polymerisation degree
1	foxed area after reduction	40.5 ± 0.8 18.5 ± 0.6	80 ± 5 106 ± 10
2	foxed area after reduction	32.8 ± 1.6 15.9 ± 0.8	248 ± 25 269 ± 28
3	foxed area after reduction	16.9 ± 0.9 8.9 ± 0.4	416 ± 30 429 ± 30

N.B. pH was measured by contact method; reported functional groups, revealed by IR spectroscopy, are present only in the foxed areas and not in the “clean” papers; average degree of polymerisation was evaluated by viscometric measurement of intrinsic viscosity¹² and the carbonyl groups content was measured as reported in ref. 13.

All samples were analysed by means of the XRF (X-Ray Fluorescence) non destructive technique^{14,15}.

The measurements were performed with the 400 μm X-ray microbeam of the INFN/LNS LANDIS laboratory (Catania)¹⁶. The use of a 400 μm beam is particularly suited to analyse the foxing stains, whose dimensions are usually of the order of 1 mm or less.

The intensity of the incident beam is maximum at about 8.4 keV (emission energy of the tungsten anode of the X-ray tube coupled with the microbeam) and it is particularly suited for the excitation of many elements (in particular metals like copper and iron) that could be connected with the foxing process.

The analysis was performed comparing the fluorescent counts of the detected elements both on the not damaged paper and on the foxing

stains. In this way it was possible to evidence any variation on the content of the detected elements and, in some cases, it was possible to characterise the foxing process.

The data were normalized to the argon counts in order to minimize the errors eventually due to variation in the geometry or in the intensity of the incident beam. It is to note that argon is present in the air during the measurements and it is excited by the incident X-ray beam. The error on the data is about 10-15%.

Results are shown in Tables 2, 3 and 4.

The measurements performed on sample 1 showed the presence of copper and iron both on the paper and on the foxing stains (Table 2). As shown in the table, the Fe/Ar ratio and the Cu/Ar ratio are similar for the different measuring points and it was not possible to relate the presence of those elements with the foxing damage.

Table 2: Results for sample 1

Sample	K/Ar	Fe/Ar	Cu/Ar	Measured point
1	-	5.2	59.0	Paper
1	0.4	1.5	33.8	Paper
1	0.6	1.9	43.9	Paper
1	0.5	3.2	35.9	Foxing
1	0.3	1.8	38.5	Foxing
1	-	4.0	66.0	Foxing
1	-	3.4	37.6	Foxing

Table 3 shows the results obtained from the analysis of samples 2 and 3. The Fe/Ar ratio is similar for the paper and for the foxing stains: also in this case it was not possible to find a relationship between the foxing process and the iron content of the stains. However the measurements revealed in both samples the presence of titanium traces and of chloride in the stains of sample 2.

Samples 4, 5 and 6 contained two different kind of foxing stains: light spots with irregular edges and dark nucleated spots. The measurements on these samples were performed both on dark stains and on light stains. The experimental data were compared to those obtained from not foxed paper.

Table 3: Results for samples 2 and 3

Sample	Cl/Ar	Ti/Ar	Fe/Ar	Measured point
2	-	1.4	3.2	Paper
2	12.6	3.9	3.1	Dark foxing
2	8.8	2.3	3.0	Light foxing
3	-	-	3.5	Paper
3	-	0.3	3.7	Dark foxing

The analysis (Table 4) underlined the presence of potassium and iron and showed an increase of Fe/Ar and K/Ar ratios for the measurements carried out on the dark stains (Figure 1).

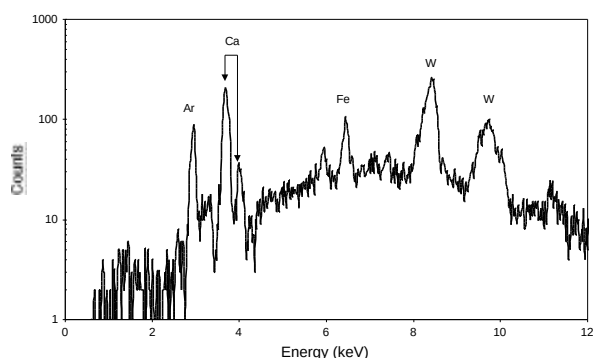


Figure 1: X-ray spectrum obtained from the measurement of a dark stain on sample 5. It shows the X-lines of K, Ca and Fe (emitted from the sample), the X-lines emitted from the tungsten anode of the X-ray tube coupled with the microbeam and those emitted from the argon present on the air during the measurements

Table 4: Results for samples 4, 5 and 6

Sample	K/Ar	Fe/Ar	Measured point
4	0.1	1.5	Paper
4	6.6	111.0	Dark foxing
4	9.9	114.2	Dark foxing
4	2.6	27.7	Dark foxing
4	2.3	54.1	Dark foxing
4	2.3	62.8	Dark foxing
4	4.5	62.0	Dark foxing
4	3.3	39.3	Dark foxing
4	0.3	2.4	Light foxing
4	0.5	2.0	Light foxing
4	0.6	2.0	Light foxing
4	0.5	2.3	Light foxing
4	0.4	2.0	Light foxing
5	-	1.3	Paper

5	-	1.3	Ink
5	2.4	73.4	Dark foxing
5	1.8	81.6	Dark foxing on the ink

6	-	2.1	Paper
6	-	10.5	Dark foxing
6	-	0.8	Light foxing
6	-	1.3	Light foxing

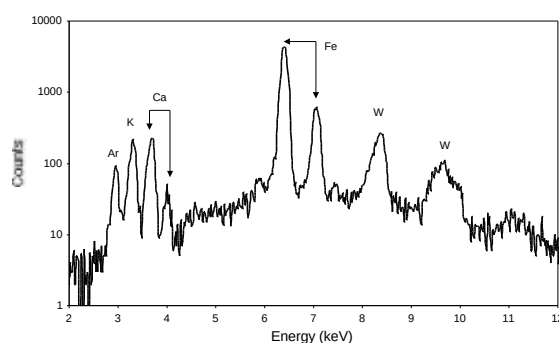


Figure 2: X-ray spectrum obtained from the measurement of the not damaged paper of sample 5. It shows the fluorescent peaks of Ca and Fe emitted from the sample, the peaks of the tungsten due to the anode of the X-ray tube and those of the argon of the air. The calcium content is similar for all measured points and it is due to the paper. The iron content is in this case lower than the dark stain.

The light stains showed different results: the Fe/Ar and the K/Ar ratios are similar to those obtained for the not damaged paper (Figure 2) and it is not possible to connect their content with the foxing process.

In order to identify any possible source for the iron detected on the dark stains, the analysis of the ink was performed in a not damaged region (see sample 5 on Table 4). In this case the Fe/Ar ratio is low and comparable with the data obtained for the not damaged paper. This suggested that the iron was not present in the used ink.

These results allowed to correlate the formation of dark stains in samples 4, 5 and 6 with the presence of iron and potassium in localised areas.

4 CONCLUSIONS

IR and chemical analysis pointed out that the foxing phenomenon is related to a strong oxidation of the cellulose chain, as has been

underlined by other researchers, with subsequent dehydration of the macromolecule. The oxidation can lead to carbon-carbon double or triple bonds, to carbonyls or carboxyls (both acid or esters), to lactonic, ketenic or allenic structures. The use of reducers can be helpful in contrasting foxing, especially when carbonyls and carbon-carbon double bonds are formed

The XRF analysis performed by means of the LANDIS X-ray microbeam allowed to detect some characterising elements of the foxing stains. The analysis were performed by comparing the experimental data obtained from the foxing stains and those obtained from the not damaged papers. The measurements on samples 1, 2 and 3 did not allow to connect the foxing process to any detected element. They indicate the presence of a biological process or the presence in the cellulose chain of a non-constant relationship between the crystalline and the amorphous phase. The prevalence of the amorphous phase, more easily degradable, could be responsible for the formation of the foxing stains.

The measurements of samples 4,5 and 6 evidenced an increase of the iron and the potassium content in the dark stains and they allowed to connect these elements with the foxing process. On the contrary, the content of those elements in the light stains and in the not damaged paper is similar. In this case it is possible to suppose the presence of a biological process.

We can conclude that the foxing phenomenon seems to be related to an intrinsic heterogeneity of the cellulose chains in the paper: greater or lower extensions and amount of amorphous phases can induce different water content and different absorbing capability of pollutants and impurities. This could explain the presence of areas with different oxidation capability.

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SILVER PATINA INVESTIGATION ON ANCIENT COINS BY MEANS OF PIXE-a AND XRF COMPLEMENTARY METHODS++

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Abstract

A new method suitable to study ancient silvered coins is presented and discussed. It is based on the complementary use of the non destructive PIXE and XRF techniques; these present different penetration depth and their use enables to analyse different layers of the metallic alloy composing the coins.

Measurements have been performed by using the portable non destructive spectrometers operating at the LNS/INFN (Laboratori Nazionali del Sud, Istituto Nazionale di Fisica Nucleare) laboratories of Catania.

Three roman silvered coins have been analysed. PIXE and XRF results allowed to establish if a silver enriched patina is present on the coin surface; in such cases it has been possible to determine the surface composition of the alloy.

1 INTRODUCTION

Since few years a scientific collaboration has been established between the LANDIS laboratory (Laboratorio di Analisi non Distruttive) of the LNS/INFN and the IBAM/CNR (Istituto per i Beni Archeologici e Monumentali, Consiglio Nazionale delle Ricerche) of Catania within sight of the study of the Misurata Roman treasure (Libya) by the use of non destructive techniques and portable systems.

The aim of the research deals with the study of silvered ancient coins with particular attention on the spatial distribution of the silver content[1] [2]. Its knowledge is very important because it is related to different coinage techniques used in the past [3] [4].

In this work we present results obtained from the non destructive analysis of three roman silvered coins. Figs. 1-3 show both the obverse and the reverse side of the analysed coins.



Fig. 1 – The silvered roman coin analysed by means of the non destructive PIXE and XRF techniques. The obverse side (on the left) has been labeled Mon1 during the measurement, while the reverse one (on the right) has been labeled Mon2.



Fig. 2 – The silvered roman coin analysed by means of the non destructive PIXE and XRF techniques. The obverse (on the left) has been labeled on the text Mon3 during the measurements, while the reverse one (on the right) has been labeled Mon4.



Fig. 3 – The silvered roman coin analysed by means of the non destructive PIXE and XRF techniques. The obverse (on the left) has been labelled GARRA2 during the measurements, while the reverse one (on the right) has been labelled GARRA1.

A previous macroscopic observation of coins has evidenced the presence of a silver patina on their surface. In order to determine their composition at different depths, the research has been addressed to the complementary use of the PIXE and the XRF techniques [5] [6] [7].

The PIXE method is particularly suitable to perform surface measurements: the use of low energy charged particles offers in fact the possibility to analyse the first 2 or 3 μm of the coin.

Moreover charged particles are completely stopped in such a thickness and the acquired X-ray spectra do not present any influence from the other layers of the alloy.

The 59.6 keV X-rays emitted by a ^{241}Am source used for the XRF measurements, penetrate deeply into the coin and the thickness involved in the analysis is of some tens of microns.

2 PIXE-a MEASUREMENTS

PIXE measurements have been carried out by using a new version of the LANDIS portable PIXE- α system (Fig.4) [8].



Fig. 4 - The portable PIXE- α system during the measurement of a silvered roman coin. The ^{210}Po source

and the Si-drift detector Peltier cooled are visible on the picture.

It consists of a ^{210}Po source emitting 5.1 MeV α particles and of a 8 μm beryllium window Si-drift detector (produced by the KETEK company and assembled by the EIS company) with an energy resolution of 140 eV at 5.9 keV. The system works in a helium atmosphere allowing to inhibit the influence of the air during the measurements (displayed on the spectrum at 2.95 keV in relation of the argon K-line) and to well analyse the silver L-line at 2.98 keV.

In Fig. 5 the PIXE spectra are reported for the three analysed coins.

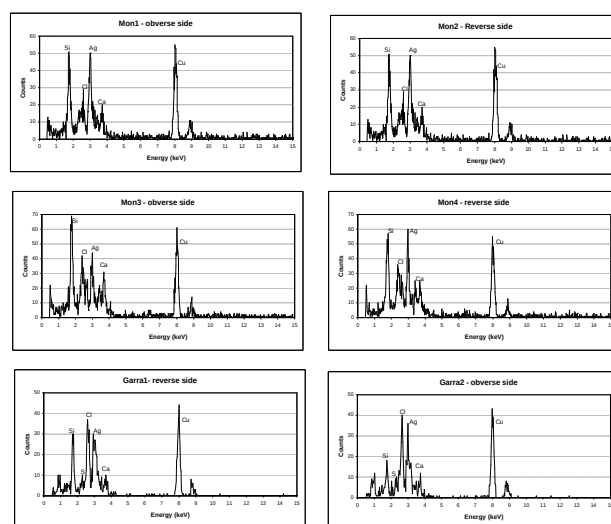


Fig. 5 – Characteristic X-ray spectra of the silvered coins obtained by using the portable PIXE- α system. The silver and copper K_{α} -lines are visible on the spectra respectively at 2.98 keV and 8.04 keV.

3 XRF MEASUREMENTS

XRF measurements have been carried out with an annular HPGe detector (EURYSIS, Mod. EGPA50/15) coupled to a 1 mCi ^{241}Am radioactive source [9]. The system is shown in Fig.6.

The 59.6 keV X-rays emitted by the source ensure an efficient excitation of elements that present a characteristic X-ray emission in the energy range between 8 keV and 55 keV. The sample thickness involved during the measurement is of some tens of microns.

Finally, the annular geometry of the system allows to operate fast measurement (typically

1000 seconds) even if the activity of the ^{241}Am radioactive source is low.

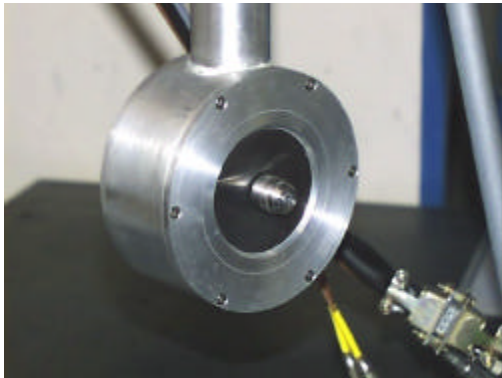


Fig. 6 - The annular XRF spectrometer designed and realised at the LNS/INFN LANDIS laboratories in collaboration with the EURISYS MESURES company (France).

In order to explore its accuracy in quantitative studies, the system has been tested with six bronze standards of known composition. The uncertainty of each measurement is less than 10%. Results are reported on Fig. 7.

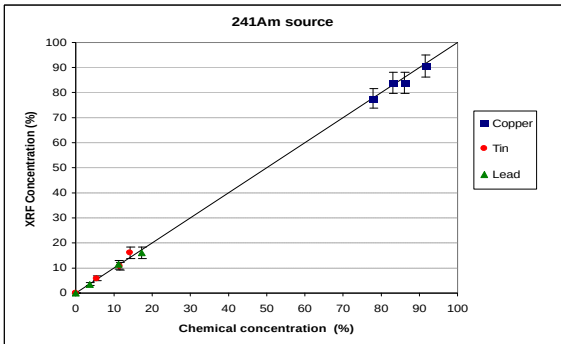


Fig. 7 - Quantitative results obtained by using the annular XRF spectrometer on six bronze standards of known composition. Analyses have been performed using the IAEA QXAS code in the Fundamental Parameter option.

The quantitative analysis has been performed by means of the IAEA QXAS (Quantitative X-Ray Analysis System) code in the Fundamental Parameters option [10].

In Fig. 8 the characteristic X-ray spectra obtained during the measurements of the silvered coins are reported. The copper, silver and tin K-lines are visible on the spectra as well as the Pb L-lines and the scattering peaks of the ^{241}Am source.

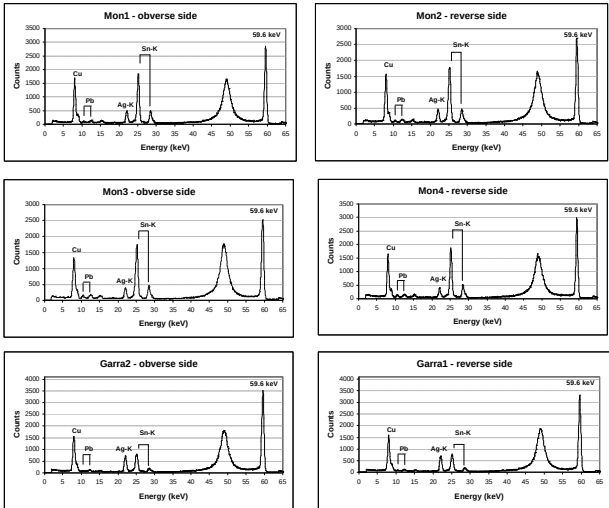


Fig. 8 – Characteristic X-ray spectra carried out by means of the annular XRF spectrometer.

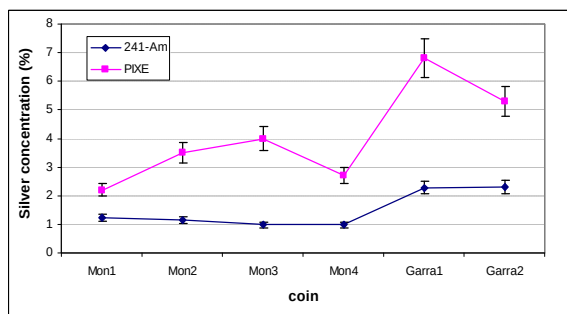
4 RESULTS

The results of the quantitative analysis obtained by using both XRF and PIXE- α techniques are reported on Table 1.

Table 1: Comparison between quantitative data obtained from the PIXE analysis and those obtained from XRF one. Uncertainties on the data are less then 15%.

PIXE	Cu	Ag	Sn	Pb
Mon1	68.5	2.2	3.7	6.5
Mon2	56.3	3.5	3.8	5.3
Mon3	59.0	4.0	2.7	3.1
Mon4	63.8	2.7	1.7	4.7
Garra1	75.1	6.8	-	-
Garra2	74.0	5.3	0.5	0.9
XRF	Cu	Ag	Sn	Pb
Mon1	88.3	1.2	5.1	5.3
Mon2	84.7	1.2	4.9	5.3
Mon3	81.4	1.0	5.4	8.5
Mon4	85.4	1.0	5.1	7.1
Garra1	96.2	2.3	2.1	1.1
Garra2	96.4	2.3	2.2	1.3

As we can observe (Fig. 9) the silver concentration deduced by the PIXE analysis, performed using the well known GUPIX code, is systematically higher than that estimated by the XRF one supporting the conclusion that a silver enriched patina is present on the coins surface.



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Fig. 9 – Comparison between quantitative data on the silver content obtained from the PIXE analysis and those obtained from XRF one. The silver concentration deduced by PIXE analysis is systematically higher of that estimated by the XRF one, supporting the conclusion that a silver enriched patina is present on the coins surface.

5 CONCLUSIONS

The complementary use of the PIXE- α method and of the XRF technique allows to obtain information on different layers of the sample being analysed. In the case of the ancient roman coins they allow to identify the silvered ones. In such cases the patina composition (limited to the first 2 or 3 μm of the coin) can be determined by using the PIXE quantitative analysis.

Results obtained from the analysis of three roman coins have been presented and discussed. Further investigation are in progress in order to obtain the patina thickness by using simulation procedures.

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A NEW VERSION OF THE LNS PIXE-ALPHA SYSTEM

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Abstract

A new version of the LNS portable PIXE-alpha system is presented. This version allows to perform measurements on small dimension (few millimeters) details of artefacts. By the use of a He flux it is possible to reduce the air absorption of low energy X-rays and to evidence the presence of light mass number elements as well as of silver patina thanks to the Ag L-lines detection.

1 INTRODUCTION

PIXE (Particle Induced X-Ray Emission) is a well known non destructive analytical technique based on the excitation of X-ray fluorescence by means of charged particles (protons, alpha particles, etc.). From the measurement of the energy of the X-rays emitted from the analysed sample, it is possible to determine its elemental composition.

Due to the well defined range of the charged particles in matter, the PIXE technique allows the analysis of only the surface layers avoiding the interference with the substratum. This property is of fundamental importance when pigments or surface patina have to be characterised.

As it is known, the PIXE technique is carried on at the particle accelerators.

A portable PIXE system has been realised by our Laboratory in collaboration with the DIMRI Laboratory of Saclay. The system is made up of an annular ²¹⁰Po 1 mCi alpha source with a conical geometry. The beam spot diameter is $\phi = 25\text{mm}$. A detailed description of the system is given in [1,2]. The source is certified as non contaminant by the Saclay Laboratory.

The main limitation on the use of the above system is due to the large diameter of the

source head and consequently of the beam spot. This was due to the necessity of depositing the ²¹⁰Po on a large surface in order to minimise the radiation damage on the backing. Also, the air absorption of low energy X-rays reduce the possibility of low mass number element analysis.

2 THE NEW PIXE-ALPHA SYSTEM

To overcome the above difficulty a new source has been designed in which the Polonium is deposited over a smaller surface. Fig. 1 shows a schematic view of the new source.

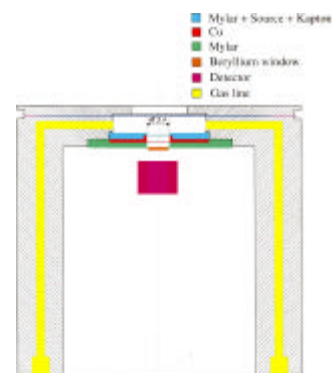


Fig. 1 – A schematic view of the PIXE-alpha source head

Over a Mylar backing, a $0.2\ \mu\text{m}$ layer of Ag is evaporated. The internal diameter of the Ag is

$\phi = 5.5$ mm and the external diameter is $\phi = 10$ mm (see fig.2).



Fig. 2 – The mylar support of the ^{210}Po source. The annular evaporation of silver is visible on the picture

Over the Ag layer, 1 mCi of ^{210}Po is electrolytically deposited. A 0.2 mm thin epoxy resin cover the Po deposit to assure the confinement. Finally, a 2 μm kapton foils cover the whole system. The diameter of the source spot is 8 mm. After a period of one year no radiation damage has been evidenced.

The source (fig.3) is coupled to a Peltier cooled Si drift detector, produced by the KEVEK and assembled by EIS company, having a resolution of 146 eV at 5.9 KeV and a 8 μm Be window.



Fig. 2 – The ^{210}Po source

In fig. 4 the system is shown in operation. Fig. 5 shows an X-ray energy spectrum obtained on a petrological standard (SCO-1).

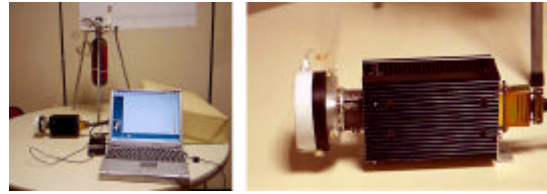


Fig. 4 – The portable PIXE-alpha system

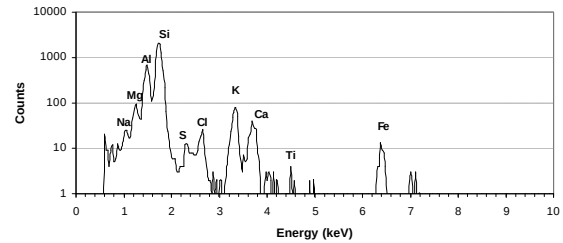


Fig. 5 – The X-Ray spectrum obtained from the measurement of a petrologic standard SCO-1. The measurement time was 30 min. The deduced instrumental constant value is $H = 0.617 \times 10^{-5}$

In tab. 1 the absolute values of the concentration obtained by inserting our data in a code (GUPIX) [4] that takes into account various quantities and corrections (cross sections, energy loss of the incoming particles, self absorption, etc.) are compared to the certified values. Tab. 2 shows a comparison of our results with the certified data of some glass standard. In both cases the agreement is good.

Table 1: Comparison between results of PIXE analysis and certified data of the reference standard SCO-1

	SCO1 data	PIXE analysis
MgO	2.88	2.7 ± 1.3
Al_2O_3	14.4	14.0 ± 1.5
SiO_2	66.54	63 ± 2
K_2O	2.93	2.8 ± 0.3
CaO	2.97	2.6 ± 0.3
Fe(III) tot	5.37	5.1 ± 0.7

Table 2: Comparison between results of PIXE analysis and certified data of some glass standards. Data with * are expressed in ppm and have been obtained by using the XRF method

	PIXE	STD621
SiO_2	70.3 ± 2	71.13 ± 0.03
Na_2O	11.2 ± 1.7	12.74 ± 0.05
CaO	11.1 ± 1.1	10.71 ± 0.05
Al_2O_3	3.7 ± 0.7	2.76 ± 0.04

K ₂ O	2.1 ± 0.3	2.01 ± 0.03
MgO	-	0.27 ± 0.03
SO ₃	-	0.13 ± 0.03
BaO*	< 1500	1200
Fe ₂ O ₃ *	400 ± 120	400
As ₂ O ₃ *	400 ± 120	300
TiO ₂ *	-	140
ZrO*	< 100	70
PIXE		STD1412
SiO ₂	49.7 ± 4	42.38 ± 0.18
Na ₂ O	4.5 ± 1.4	4.69 ± 0.07
CaO	4.97 ± 0.7	4.53 ± 0.1
Al ₂ O ₃	8.6 ± 0.9	7.52 ± 0.24
K ₂ O	4.9 ± 0.6	4.14 ± 0.1
MgO	5.1 ± 0.8	4.69
BaO	6.6 ± 0.8	4.67 ± 0.16
PbO	4.3 ± 1.3	4.4 ± 0.17
CdO	3.8 ± 1.0	4.38 ± 0.08
ZnO	-	4.48 ± 0.12
SrO	5.6 ± 1.4	4.55 ± 0.09
PIXE		STD610
SiO ₂	68.22 ± 1	72
Na ₂ O	14.2 ± 1.4	14
CaO	11.2 ± 0.67	12
Al ₂ O ₃	2.9 ± 0.43	2
K*	< 1000	461
Mn*	< 1000	485
Fe*	548 ± 164	458
Co*	372 ± 111	390
Ni*	596 ± 178	458
Cu*	355 ± 106	444
Zn*	350 ± 105	433
Rb*	377 ± 113	425
Sr*	440 ± 132	515
Nb*	423 ± 129	-
Mo*	438 ± 131	-
Pb*	< 1000	426
Th*	< 1000	457
U*	781 ± 234	461
PIXE		STD612
SiO ₂	80.0 ± 1.2	72
Na ₂ O	12.7 ± 1.3	14
CaO	12.6 ± 0.8	12
Al ₂ O ₃	3.4 ± 0.5	2

3 RECENT APPLICATIONS

Recently the system has operated at the Bargello [5] Museum in Florence to characterise

the blue pigments of several Della Robbia artefacts (see fig.6). The analysis of the data is in progress.

Another important application concerns the analysis of the silvered coins. In fact, the He flux eliminates the air presence- and the Ar - L line - and gives the possibility of observing the Ag - L line ($E_x = 2.98$ KeV).



Fig. 6 – The portable PIXE-alpha system during the characterization of a Della Robbia artifact at the Bargello Museum of Florence (Italy).

This fact has opened the possibility to perform a complete characterisation, in our laboratory, of silver contents of surface silvered coins. In fact, the PIXE- α analysis gives the concentration of the Ag present in the patina (a few microns), the XRF analysis gives information on the substratum (a few tens of microns), the neutron activation analysis gives the Ag contents in the body of the coin.

4 CONCLUSIONS

The new PIXE-alpha system is very suitable in performing accurate non destructive analysis of very thin layers (2-5 μm) in small areas of different kind of materials, with the great advantage to well evidence not only the presence of low atomic number elements, but also that of the medium and high atomic number elements (like Ag, Pb, As, Hg, etc.) thanks to the good resolution of the detector. The presence of the He flux opens the possibility to characterise the patina of silvered coins.

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PSEUDO-PERIODIC NANOSTRUCTURING OF AG-CLADDED BSCCO-2223 MULTIFILAMENTARY TAPES AS A TOOL TO TUNE IN-FIELD SUPERCONDUCTING PERFORMANCES

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Abstract

A technology has been developed to create nanostructures by heavy-ion irradiation on “large area” surfaces of superconductors. The in-vacuum apparatus consists into a moving sample-holder, automatically driven at a given velocity in order to obtain the exposure of collimated zones of the moving target to a programmed ion fluence. The irradiation facility has been employed to implant 4.2 GeV gold-ions into a 30 cm long multifilamentary Ag/BSCCO-2223 tape, at the dose equivalent field of 0.5 T. The paper is focused on the enhanced performances and on the matching effects between the pseudo-periodic array of ion-induced columnar defects and the vortex lattice. The enhancements exhibit a maximum near the dose equivalent field, clearly pointing out the tunability of the performances through the modulation of the distance between nanotracks.

1 INTRODUCTION

Irradiations with high-energy heavy-ions have been extensively used on high-temperature superconductors to investigate the fundamental interaction between vortices and defects, in particular columnar defects, as well as to exploit the defects-induced enhancements of the superconducting properties. It was routinely done on small single crystals or on millimetric square areas [1, 2, 3, 4, 5]. The need to extend the irradiation on “large area” samples having size useful for applications is compelling. This task is of great interest in the case of Ag-cladded BSCCO-2223 high-quality tapes, because of their technological impact. Moreover, nanoengineered pinning arrays induced by heavy-ion irradiation with pseudo-periodic distribution (at a given dose the average distance between columnar defects can be tailored) provide a unique opportunity to modulate the in-field superconducting properties [6]. We pursued this aim by means of a suitable apparatus designed to move the sample under the ion beam by means of an automatic sample-

driving set-up. This apparatus is, at our best knowledge, the first one especially designed to create nanostructures across large area superconducting devices. In the framework of power applications, the final aim is to create the possibility to “heal” part of a cable or of a single component in critical network positions as well as to develop networking tools.

2 EXPERIMENTAL DETAILS

The irradiation equipment has been set-up at the Superconducting Cyclotron facility of the INFN – Laboratori Nazionali del Sud, Catania, Italy. It consists into a moving apparatus automatically driven at a given velocity in order to obtain the in-vacuum exposure of contiguous zones of the moving target at a programmed ion fluence. The whole apparatus is automatically controlled by a home-made remote control program. The main parts of the apparatus are: i) the mechanical set-up and the electronic circuit to create feedback signals to control both the beam current and the velocity of the sample holder, ii) the high accuracy system for the measurement of the integrated charge and

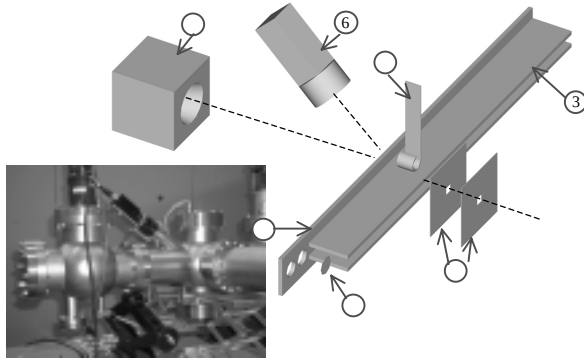


Fig. 1. Schematic diagram of the experimental arrangement of the irradiation facility used for GeV heavy-ion irradiation: (1) collimator and electron-suppressor, (2) scintillating screen, (3) Faraday cup, (4) sample holder, (5) sliding contact, (6) CCD camera, (7) calibration Faraday cup.

iii) the beam calibration set-up (beam shape and homogeneity) [7]. Fig. 1 shows a schematic diagram of the experimental arrangement of the irradiation facility. This facility has been used to enhance the superconducting properties of a 0.24 mm thick multifilamentary (55-filaments) Ag/BSCCO-2223 tape, prepared by means of the powder in-tube (PIT) technique by CESI SpA [8]. A total length of 30 cm was irradiated with 4.2 GeV gold ions. The irradiation was made at room temperature, perpendicularly to the tape surface. Because of the limited penetration depth of Au-ions, the tape was irradiated on both sides. The irradiation dose was $\phi = 2.5 \times 10^{10}$ ions/cm² corresponding to a dose equivalent field, B_ϕ of 0.5 T [9]. During the irradiation of the multifilamentary tape the velocity of movement of the sample holder was 0.04 mm/s and the beam current was 500 ± 20 pA. The velocity was calculated with the formula $v = I/(e \cdot n \cdot l \cdot \phi)$ where I is the beam current, e is the elementary charge, n is the ion charge, l is the transversal dimension of the beam spot after the collimator and ϕ is the irradiation dose. The chosen single step of the movement was 5 μ m. The beam homogeneity was checked by means of the evaluation of the beam profiles. Fig. 2 shows the beam spot profiles evaluated along the central transverse axes of the beam spot after crossing a 5 mm $\times$ 10 mm aperture of a collimator and electron-

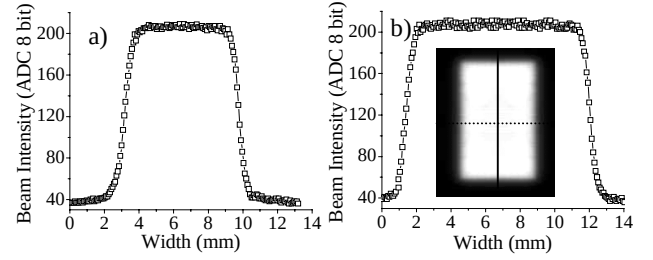


Fig. 2. Beam spot profiles evaluated a) along the direction of movement (dotted line in the beam spot image) and b) perpendicular to the direction of movement (straight line), respectively.

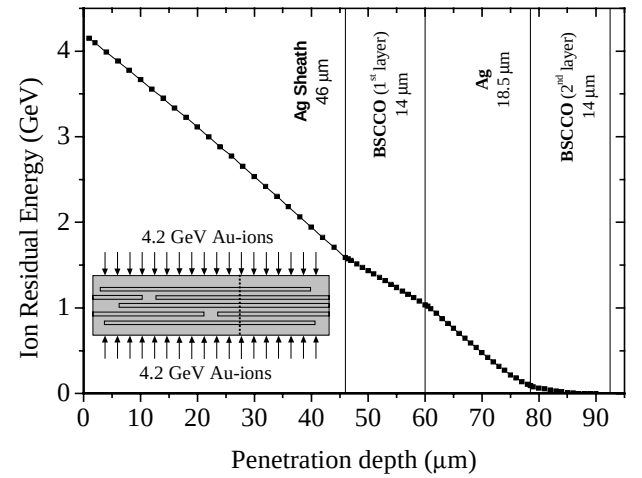


Fig. 3. Au-ion residual energy as a function of the penetration depth for the Ag/BSCCO-2223 multifilamentary (55-filaments) tape. In inset: a sketch of the tape geometry used in the simulation. The dimensions of the silver and BSCCO layers were obtained from optical micrographs (not shown). from V-I curves

suppressor system. These profiles were obtained digitizing the beam spot image (in a scintillating screen) coming from a CCD camera (see Fig. 1). We verified that the intensity of the beam spot through the collimator changes less than 5% in the direction of movement.

3 RESULTS

3.1 Electric transport characterisation

In Fig.4 the transport critical currents as a function of the applied magnetic field before and after irradiation at 77.4 K are plotted. The ratios between the transport critical current values obtained after and before irradiation are reported in inset. At 77.4 K a lower limit of the obtainable

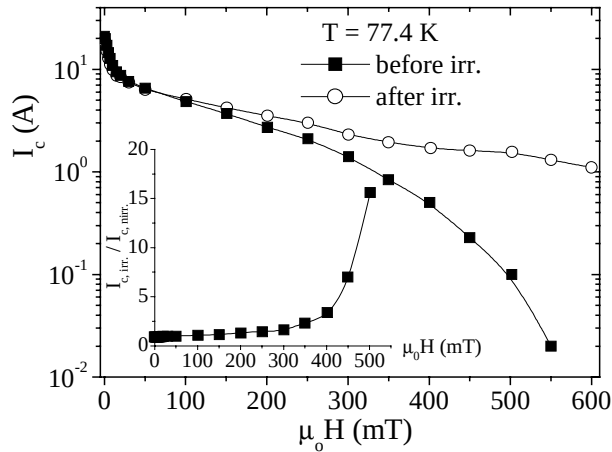


Fig. 4. Transport critical current, I_c , as a function of magnetic field applied perpendicular to the tape surface (i.e. parallel to the ion tracks), before (solid symbol) and after (open symbol) 4.2 GeV Au-ion irradiation ($B_\phi = 0.5$ T). Inset: ratio between the current density values, after and before irradiation.

enhancements in an application context is checked. The curves were obtained using the 1 μ V/cm criterion. The magnetic field was applied perpendicular to the tape surface (i.e. parallel to the ion tracks). It turns out that at 600 mT the after-irradiation critical current is the same exhibited at about 300 mT before irradiation. This results could be particularly significant from the point of view of applications. Namely it implies that a multifilamentary irradiated tape does not change its performances with respect to the unirradiated one when the external field due to all the tapes in the same cable is nearly twice. Thus this performance would allow more tapes in a single cable. Such results as well as the ones reported below are in part unexpected if we consider that we are dealing with a multifilamentary tape with a partial implantation [12].

2.2 Magnetic characterisations: dc magnetic measurements

In Fig. 5 the curves of dc magnetization before and after irradiation at 77 and 50 K are plotted. The curves are effective to stress out the large enhancements after irradiation at 77 K and at 50 K. The measurements, before and after irradiation, were performed in the same experimental conditions. The changes are very significant especially if we look at the closing-

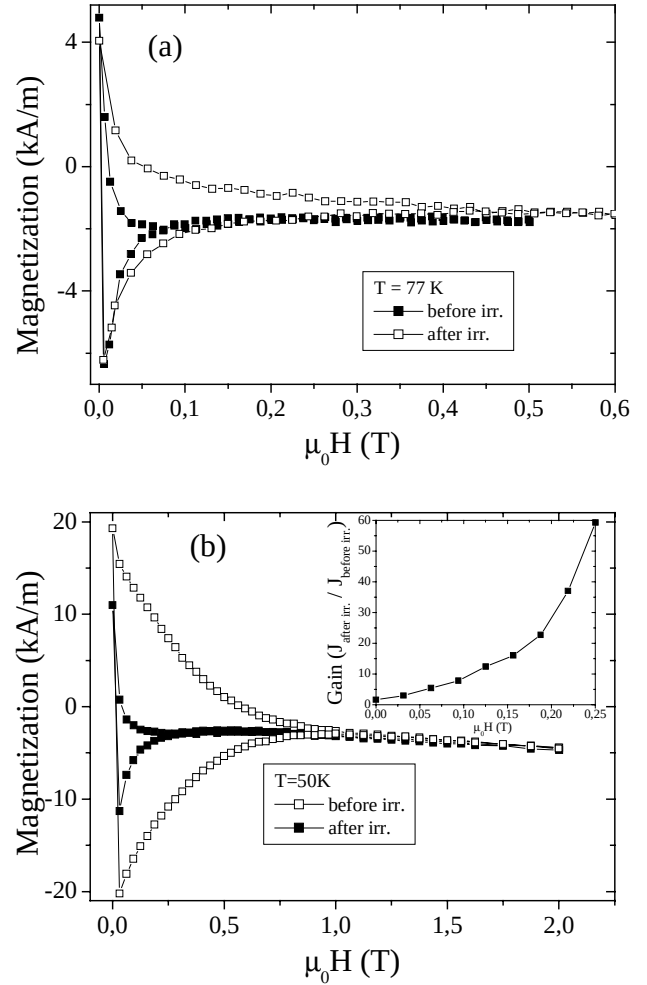


Fig. 5. Hysteresis cycle before and after 4.2 GeV Au-ion irradiation ($B_\phi = 0.5$ T) at (a) 77 K and (b) 50 K. Inset: ratio between the current density values, after and before irradiation, estimated in the same experimental conditions.

up points of the hysteresis cycles. However, a quantitative evaluations of the critical current enhancements as well as a comparison with transport measurements would be misleading. Namely the creep rate in BSCCO is very strong and moreover the creep rate of not irradiated / irradiated samples is very different [4].

2.2 Magnetic characterisations: ac magnetic measurements

Ac magnetic characterization was employed to study:

a) the influence of irradiation on the critical temperature, T_c . Fig. 6 shows the real part of the ac susceptibility versus temperature, in zero

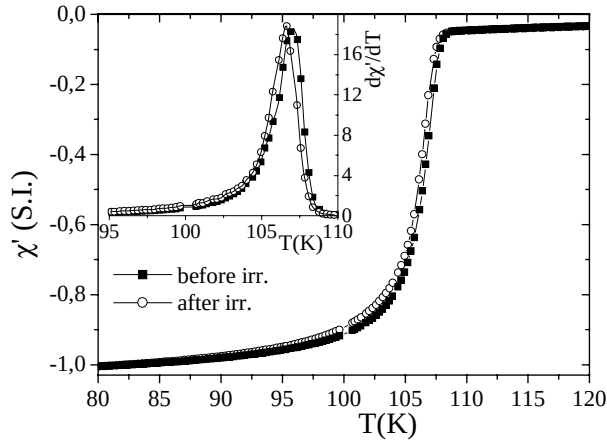


Fig. 6. Real part of the ac susceptibility versus temperature, in zero magnetic field, before and after 4.2 GeV Au-ion irradiation at $B_0 = 0.5$ T. Inset: the first derivative of the same curves. The maxima of the two curves provide an evaluation of the critical temperature before and after irradiation.

magnetic field, before and after Au-ion irradiation. In the inset of Fig. 6 the first derivative of the same curves are represented. The maxima of the two curves give an evaluation of the critical temperature before and after irradiation. After irradiation the shift is less than 0.5 K: the critical temperature is barely affected.

b) the influence of the irradiation on the anisotropy of the irreversibility lines, ILs. The onset of the third harmonic generation, at a frequency of 1 kHz, was used for the identification of the IL. Strong effects are produced by the irradiation on the anisotropy properties. Fig. 7 shows the ILs measured for four different angles, θ , between the applied magnetic field and the ion tracks ($\theta = 0^\circ, 45^\circ, 66^\circ, 90^\circ$). After irradiation the ILs at $0^\circ, 45^\circ$ and 66° are shifted towards higher magnetic fields and temperatures, while the IL at 90° is unaffected. Moreover, after irradiation the difference between the ILs at different angles is strongly reduced across the full investigated range of magnetic fields. In particular at $B = B_0$ there is a “condensation point”. It is the signature of a remarkable matching effect that points towards easy tunability.

In analogy with the anisotropic factor γ , defined as the ratio between the upper critical

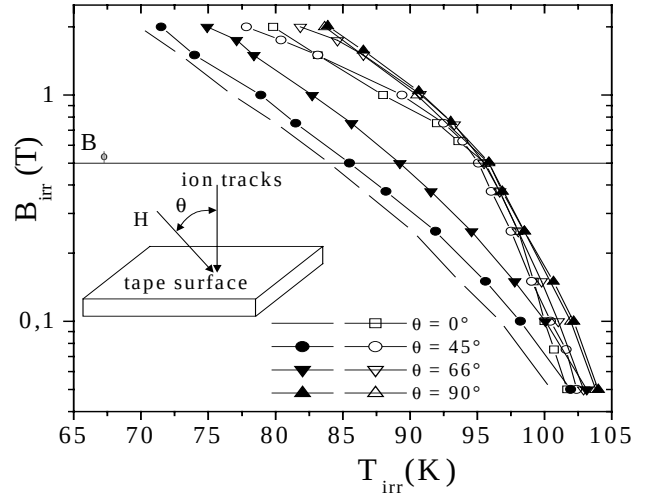


Fig. 7. Irreversibility lines (ILs) before (full symbols) and after (open symbols) Au-ion irradiation at $B_0 = 0.5$ T. The ILs were measured for four different angles, θ , between the applied magnetic field and the ion tracks ($\theta = 0^\circ, 45^\circ, 66^\circ, 90^\circ$).

magnetic field parallel to the layers to the upper critical magnetic field perpendicular to the layers, we introduce a γ^* parameter defined as the ratio between the irreversible magnetic field, B_{irr} , perpendicular to the ion tracks and the B_{irr} parallel to the ion tracks.

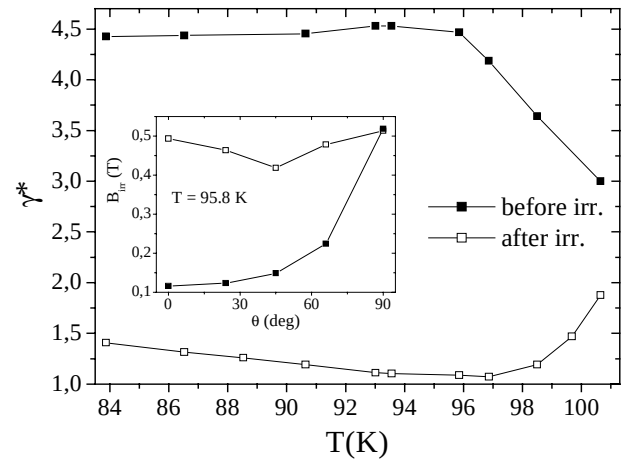


Fig. 8. γ^* parameter, defined as the ratio between the irreversible magnetic field perpendicular to the ion tracks with the irreversible magnetic field parallel to the ion tracks, as a function of the temperature, before and after 4.2 GeV Au-ion irradiation at $B_0 = 0.5$ T. Inset: angular dependence of the irreversible magnetic field before and after irradiation. The chosen temperature ($T = 95.8$ K) is that of to the maximum shift of the IL measured with the magnetic field parallel to the ion tracks. The lines are guide for eyes.

In Fig. 8 the values of the parameter γ^* as a function of the temperature are plotted. In the inset of the same figure the angular dependence of the irreversible magnetic field at 95.8 K, before and after Au-ion irradiation is reported.

4 CONCLUSIONS

A new irradiation equipment for “large area” and nanostructuring of superconducting materials has been calibrated and used to enhance the superconducting properties of a 30 cm long multifilamentary Ag/BSCCO-2223 tape.

The irradiation causes a quite interesting recover of electric transport properties at 77 K in a significant range of fields near the dose equivalent field.

Dc magnetic characterisation shows that the effect of columnar defects is huge if we consider that only 70% of the tape volume is affected and the tape is irradiated without removing the Ag cladding.

The ac magnetic characterisation allows to address the following issues:

- i) the irradiation does not practically affect the critical temperature;
- ii) a shift of the ILs toward higher magnetic fields and temperatures is exhibited in a large range of angles in respect with the ion tracks direction. A strong effect on the anisotropy is found. The main result is that all curves collapse one over the other one at the dose equivalent field.

All the obtained results show that after irradiation the matching condition is the outstanding interaction and deeply affects the collective behavior of the vortices. Thus the possibility of tuning not only the in-field behavior of the critical currents but also the anisotropy by changing the irradiation dose (average distance between columnar nanostructures) is stressed out.

The proposed technology can be further developed, eventually in air, and aimed at healing critical parts in a transport network submitted to either “hard” conditions or shut - down danger. Studies aimed at using irradiation – induced nanostructuring for networking are in progress.

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MEASUREMENTS OF WATER OPTICAL PROPERTIES BY AC9 TRANSMISSOMETER IN LAKE BAIKAL

the NEMO Collaboration

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Abstract

Measurements of optical properties in water Cherenkov neutrino telescopes are important not only at the moment of the selection of an adequate site for the telescope construction, but also for the continuous characterisation of the water as a function of time. The NEMO Collaboration, aiming to the construction of a km^3 Cherenkov neutrino detector in the Mediterranean Sea, has developed an experimental setup for the measurement of oceanographic and optical properties of deep sea water. This setup is based on a commercial transmissometer, the AC9. During March and April 2001 the NEMO Collaboration conducted together with Baikal Collaboration a joint campaign of optical measurement using the AC9 and other devices specially designed by Baikal Collaboration. The goal of the campaign was to measure the optical properties of the deep water in Lake Baikal (Siberia) where, since April 1998, the neutrino telescope NT-200 is in operation. In the same time the two collaboration cross checked the validity of the used instruments and measurement techniques. The results are compatible with previous ones reported by the Baikal Collaboration and confirm the reliability of the used measurement technique.

1 INTRODUCTION

After a pioneering activity of designing and R&D work, large underwater Cherenkov detectors are going to enter in the phase of construction. Their goal is to explore the Universe by means of high energy neutrinos to obtain a view of astrophysical object complementary and possibly more accurate compared to the present gamma ray observations. The so called neutrino telescopes are arrays of photomultiplier constructed in open water or ice, covering an instrumented volume of roughly 1 km^3 . The cubic kilometre scale is set by various predictions on the fluxes of high energy neutrinos expected from cosmic sources.

In underwater Cherenkov neutrino telescopes, water acts not only as a target but also as radiator of Cherenkov photons produced by relativistic charged particles. The detection volume, as well as the angular and energy resolutions strongly depend on the water transparency. The transparency of water as a function of photon wavelength λ , is described by the so called inherent optical properties, like the coefficients for absorption $a(\lambda)$, for

scattering $b(\lambda)$, for attenuation $c(\lambda)=a(\lambda)+b(\lambda)$, and by the volume (or phase) scattering function $\beta(\lambda, \theta)$ which is the probability for a photon to be diffused at an angle θ . The optical properties of natural water have to be measured in-situ in order to allow an unbiased knowledge of light transmission properties in the medium. Due to severe environmental constraints acting on the instrumentation, optical measurements in deep waters are extremely difficult, and possible systematic errors related to these measurements suggest careful cross checks of results by different methods.

Since a few years, the NEMO Collaboration [1] is performing an intensive R&D program aiming to the construction of a km^3 Cherenkov neutrino telescope in the Mediterranean Sea. The collaboration has been investigating oceanographic and optical properties of several deep sea marine sites close to the Italian coast in order to select the optimal site for the construction of a km^3 detector in the Mediterranean Sea.

In 1993, the Baikal Collaboration succeeded to build the first deep underwater Cherenkov neutrino detector, which has been upgraded to the present stage: the NT-200 [2]. The Baikal collaboration has been investigating the fresh

water deep in Lake Baikal since 1980 using a series of specially designed devices. The water transparency information serves as input for Monte-Carlo simulations of Cherenkov light transport from the particle to be tracked to the photomultipliers array.

During March-April 2001, the NEMO and Baikal Collaborations have conducted a joint campaign to measure the optical properties of deep water in Lake Baikal using two different devices. One is based on the transmissometer AC9, operated by the NEMO group, the other device, ASP-15 (Absorption, Scattering and Phase function meter) was developed and operated by the Baikal Collaboration. The cross check of experimental results during this campaign has been crucial for both devices. Both have indeed an excellent sensitivity in measuring water optical properties. However, they can be affected by different sources of systematic errors which could worsen the absolute accuracy. The measurements reported in the following sections have been carried out during March-April 2001, from the ice camp above the neutrino telescope NT-200.

2 INSTRUMENTATION AND DATA ACQUISITION

The AC9, manufactured by WETLabs, is a commercial transmissometer capable to measure absorption and attenuation coefficients at nine different wavelengths in the range 412÷715 nm [3]. Using an accurate calibration procedure, the NEMO collaboration has achieved an accuracy of about $1.5 \cdot 10^{-3} \text{ m}^{-1}$ in a and c measurements [4]. During the measurements in Lake Baikal, the AC9 device and a CTD (a probe that measures water conductivity, temperature and pressure) were operated through an electro-mechanical cable. With this set-up we have obtained two vertical profiles of the water column (50m<depth<1100m), collecting about ten data-sets per meter of depth. Each data-set consists of a measurement of temperature and optical properties, $a(\lambda)$ and $c(\lambda)$, over the nine wavelengths.

In figure 1 we show, as a function of depth, the water temperature and the values for absorption and attenuation coefficient at $\lambda=488 \text{ nm}$

measured during the first and the second deployment in Lake Baikal. The two sets of AC9 data were collected with about ten hours time difference. Each measurement was preceded by an accurate cleaning of the instrument optics and by a calibration. The agreement between the results obtained from the two data sets confirms the reliability of the calibration procedure.

During the campaign, the Baikal Collaboration operated a custom made device called ASP-15, equipped with two receiving channels: one used for the measurement of $a(\lambda)$ and $b(\lambda)$ over 15 wavelengths in the range 369÷715 nm and the other one for the measurement of the phase scattering function. The device is extensively described in [5]. In this paper we report the measured values only for the $a(\lambda)$ and $b(\lambda)$ measurement channel.

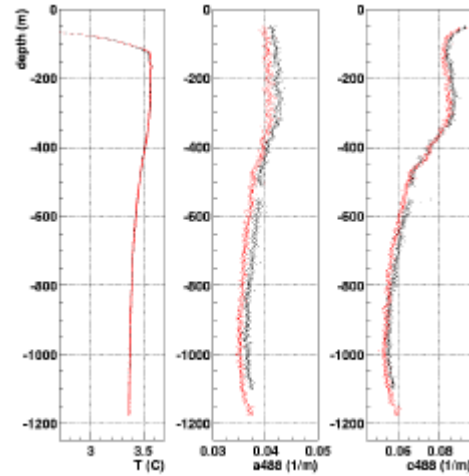


Fig. 1: Profiles of water temperature and absorption and attenuation coefficients, $a(488)$ and $c(488)$, as functions of depth, obtained by two measurements (red and black dots) with the AC9-CTD set-up in Lake Baikal during March 2001. The NT-200 telescope is located between 1100 m and 1170 m depth.

3 RESULTS

In figure 2 we present the absorption length ($L_a(\lambda)=1/a(\lambda)$) measured by the ASP-15 during three different deployments and by the AC9 during two deployments. Results are obtained operating the ASP-15 at the depth of 1000m and averaging AC9 data over the interval of depths 980÷1020 m. The figure shows a fair agreement between the data recorded by the two instruments.

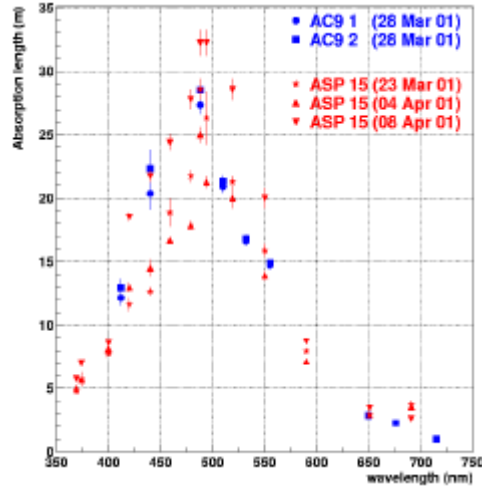


Fig. 2: Light absorption length measured by ASP-15 at depth of 1000 m and averaged by AC9 data in the interval of depths 980÷1020m.

In figure 3 we present the attenuation length ($L_c(\lambda)=1/c(\lambda)$) as a function of wavelength measured in the interval 980÷1020 m with the AC9. In the same figure we plot the values of L_c evaluated using the values of L_a and L_b measured by the ASP-15 at 1000m depth. Once more the data show a good agreement in spite of the fact that they come from different instruments, measurement techniques and data analysis procedure.

Both devices show that the maximum of the water transparency is located in the blue-green region, at $\lambda=488$ nm. The average values are: $L_a=27.9\pm0.7$ m and $L_c=18.3\pm0.3$ m (for the AC9); $L_a=28.3\pm1.0$ m $L_b=19.0\pm1.5$ m (for the ASP-15). These values also agree with previous measurements published by the Baikal Collaboration [5].

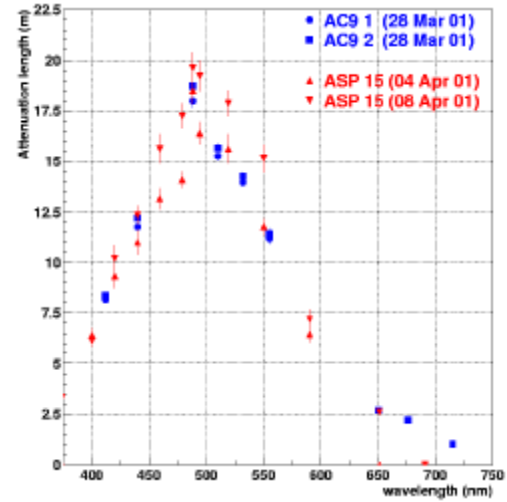


Fig. 3: Light attenuation length averaged by AC9 data in the interval of depths 980÷1020m and estimated by the L_a and L_c data measured by ASP-15 at 1000m depth.

4 CONCLUSIONS

Measurements of the optical water properties in Lake Baikal confirm that the NT-200 telescope is located at optimal depth, where light absorption and attenuation lengths reach the maximum values.

The contemporary operation of the AC9 and ASP-15, two devices based on different techniques, permitted to evaluate the amounts of systematic errors associated to the measurements of the two instruments. The agreement shown by data demonstrate that these errors are small and validate the use of the AC9

The results of the chemical¹¹ analyses are summarised in Table 1 and fully reported in ref. 11.

Table 1: chemical and infrared analyses on foxed papers

Sample	fibrous composition; sizes	pH ± 0.02	IR revealed groups
1	linen, hemp, cotton (5%); gelatine	3.08	C≡C R ₁ R ₂ C=O C=C=C
2	linen, cotton (20%); gelatine	5.82	C≡C COO ⁻ R ₁ R ₂ C=O
3	linen, cotton (10%); starch	6.50	C≡C R ₁ R ₂ C=O C=C=C
4, 5, 6	linen, hemp, cotton (60%); gelatine	5.65	C≡C COO ⁻ R ₁ R ₂ C=O
Sample	measured point	m. moles C=O in g 100 paper	polymerisation degree
1	foxed area after reduction	40.5 ± 0.8 18.5 ± 0.6	80 ± 5 106 ± 10
2	foxed area after reduction	32.8 ± 1.6 15.9 ± 0.8	248 ± 25 269 ± 28
3	foxed area after reduction	16.9 ± 0.9 8.9 ± 0.4	416 ± 30 429 ± 30

N.B. pH was measured by contact method; reported functional groups, revealed by IR spectroscopy, are present only in the foxed areas and not in the “clean” papers; average degree of polymerisation was evaluated by viscometric measurement of intrinsic viscosity¹² and the carbonyl groups content was measured as reported in ref. 13.

All samples were analysed by means of the XRF (X-Ray Fluorescence) non destructive technique^{14,15}.

The measurements were performed with the 400 μm X-ray microbeam of the INFN/LNS LANDIS laboratory (Catania)¹⁶. The use of a 400 μm beam is particularly suited to analyse the foxing stains, whose dimensions are usually of the order of 1 mm or less.

The intensity of the incident beam is maximum at about 8.4 keV (emission energy of the tungsten anode of the X-ray tube coupled with the microbeam) and it is particularly suited for the excitation of many elements (in particular metals like copper and iron) that could be connected with the foxing process.

The analysis was performed comparing the fluorescent counts of the detected elements both on the not damaged paper and on the foxing

stains. In this way it was possible to evidence any variation on the content of the detected elements and, in some cases, it was possible to characterise the foxing process.

The data were normalized to the argon counts in order to minimize the errors eventually due to variation in the geometry or in the intensity of the incident beam. It is to note that argon is present in the air during the measurements and it is excited by the incident X-ray beam. The error on the data is about 10-15%.

Results are shown in Tables 2, 3 and 4.

The measurements performed on sample 1 showed the presence of copper and iron both on the paper and on the foxing stains (Table 2). As shown in the table, the Fe/Ar ratio and the Cu/Ar ratio are similar for the different measuring points and it was not possible to relate the presence of those elements with the foxing damage.

Table 2: Results for sample 1

Sample	K/Ar	Fe/Ar	Cu/Ar	Measured point
1	-	5.2	59.0	Paper
1	0.4	1.5	33.8	Paper
1	0.6	1.9	43.9	Paper
1	0.5	3.2	35.9	Foxing
1	0.3	1.8	38.5	Foxing
1	-	4.0	66.0	Foxing
1	-	3.4	37.6	Foxing

Table 3 shows the results obtained from the analysis of samples 2 and 3. The Fe/Ar ratio is similar for the paper and for the foxing stains: also in this case it was not possible to find a relationship between the foxing process and the iron content of the stains. However the measurements revealed in both samples the presence of titanium traces and of chloride in the stains of sample 2.

Samples 4, 5 and 6 contained two different kind of foxing stains: light spots with irregular edges and dark nucleated spots. The measurements on these samples were performed both on dark stains and on light stains. The experimental data were compared to those obtained from not foxed paper.

Table 3: Results for samples 2 and 3

Sample	Cl/Ar	Ti/Ar	Fe/Ar	Measured point
2	-	1.4	3.2	Paper
2	12.6	3.9	3.1	Dark foxing
2	8.8	2.3	3.0	Light foxing
3	-	-	3.5	Paper
3	-	0.3	3.7	Dark foxing

The analysis (Table 4) underlined the presence of potassium and iron and showed an increase of Fe/Ar and K/Ar ratios for the measurements carried out on the dark stains (Figure 1).

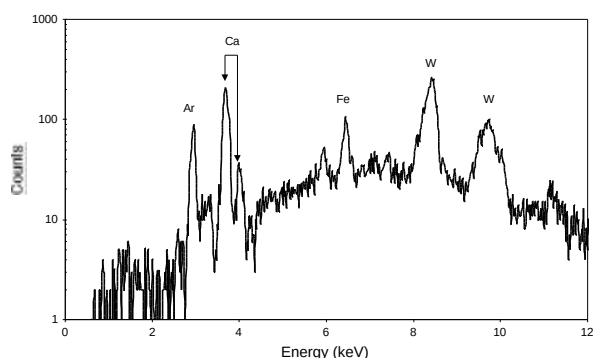


Figure 1: X-ray spectrum obtained from the measurement of a dark stain on sample 5. It shows the X-lines of K, Ca and Fe (emitted from the sample), the X-lines emitted from the tungsten anode of the X-ray tube coupled with the microbeam and those emitted from the argon present on the air during the measurements

Table 4: Results for samples 4, 5 and 6

Sample	K/Ar	Fe/Ar	Measured point
4	0.1	1.5	Paper
4	6.6	111.0	Dark foxing
4	9.9	114.2	Dark foxing
4	2.6	27.7	Dark foxing
4	2.3	54.1	Dark foxing
4	2.3	62.8	Dark foxing
4	4.5	62.0	Dark foxing
4	3.3	39.3	Dark foxing
4	0.3	2.4	Light foxing
4	0.5	2.0	Light foxing
4	0.6	2.0	Light foxing
4	0.5	2.3	Light foxing
4	0.4	2.0	Light foxing
5	-	1.3	Paper

5	-	1.3	Ink
5	2.4	73.4	Dark foxing
5	1.8	81.6	Dark foxing on the ink

6	-	2.1	Paper
6	-	10.5	Dark foxing
6	-	0.8	Light foxing
6	-	1.3	Light foxing

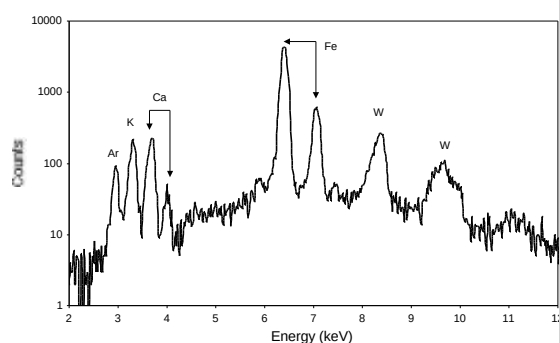


Figure 2: X-ray spectrum obtained from the measurement of the not damaged paper of sample 5. It shows the fluorescent peaks of Ca and Fe emitted from the sample, the peaks of the tungsten due to the anode of the X-ray tube and those of the argon of the air. The calcium content is similar for all measured points and it is due to the paper. The iron content is in this case lower than the dark stain.

The light stains showed different results: the Fe/Ar and the K/Ar ratios are similar to those obtained for the not damaged paper (Figure 2) and it is not possible to connect their content with the foxing process.

In order to identify any possible source for the iron detected on the dark stains, the analysis of the ink was performed in a not damaged region (see sample 5 on Table 4). In this case the Fe/Ar ratio is low and comparable with the data obtained for the not damaged paper. This suggested that the iron was not present in the used ink.

These results allowed to correlate the formation of dark stains in samples 4, 5 and 6 with the presence of iron and potassium in localised areas.

4 CONCLUSIONS

IR and chemical analysis pointed out that the foxing phenomenon is related to a strong oxidation of the cellulose chain, as has been

underlined by other researchers, with subsequent dehydration of the macromolecule. The oxidation can lead to carbon-carbon double or triple bonds, to carbonyls or carboxyls (both acid or esters), to lactonic, ketenic or allenic structures. The use of reducers can be helpful in contrasting foxing, especially when carbonyls and carbon-carbon double bonds are formed

The XRF analysis performed by means of the LANDIS X-ray microbeam allowed to detect some characterising elements of the foxing stains. The analysis were performed by comparing the experimental data obtained from the foxing stains and those obtained from the not damaged papers. The measurements on samples 1, 2 and 3 did not allow to connect the foxing process to any detected element. They indicate the presence of a biological process or the presence in the cellulose chain of a non-constant relationship between the crystalline and the amorphous phase. The prevalence of the amorphous phase, more easily degradable, could be responsible for the formation of the foxing stains.

The measurements of samples 4,5 and 6 evidenced an increase of the iron and the potassium content in the dark stains and they allowed to connect these elements with the foxing process. On the contrary, the content of those elements in the light stains and in the not damaged paper is similar. In this case it is possible to suppose the presence of a biological process.

We can conclude that the foxing phenomenon seems to be related to an intrinsic heterogeneity of the cellulose chains in the paper: greater or lower extensions and amount of amorphous phases can induce different water content and different absorbing capability of pollutants and impurities. This could explain the presence of areas with different oxidation capability.

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I protoni e la radioterapia delle patologie oculari: il progetto CATANA

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Schwarz C, Fritz S, Bassini R, Begemann-Blaich M, Gaff-Ejakov SJ, Gourio D, Gross C, Imme G, Iori I, Kleinevoss U, Kunde GJ, Kunze WD, Lynen U, Maddalena V, Mahi M, Mohlenkamp T, Moroni A, Muller WFJ, Nociforo C, Ocker B, Odeh T, Petruzzelli F, Pochodzalla J, Raciti G, Riccobene G, Romano FP, Saija A, Schnittker M, Schuttauf A, Seidel W, Serfling V, Sfienti C, Trautmann W, Trzcinski A, Verde G, Worner A, Xi HF, Zwieglinski B

Time scales in spectator fragmentation

NUCL PHYS A 681: 279C-286C JAN 29 2001

Torrise L

Gold ions produced by 1064 nm pulsed laser irradiation

NUCL INSTRUM METH B 183 (3-4): 271-278 OCT 2001

Torrise L

Luminescence degrading in polyvinyltoluene by ion beam irradiations

RADIAT EFF DEFECT S 154 (2): 89-98 2001

Torrise L, Andò L, Ciavola G, et al.

Angular distribution of ejected atoms from Nd : YAG laser irradiating metals

REV SCI INSTRUM 72 (1): 68-72 Part 1 JAN 2001

Torrise L, Andò L, Gammino S, et al.

Ion and neutral emission from pulsed laser irradiation of metals

NUCL INSTRUM METH B 184 (3): 327-336 NOV 2001

Tumino A., M. Lattuada, S. Romano, C. Spitaleri, D. Vinciguerra, Z. Basrak, O.Yu. Goryunov, V. Ostashko, S. Szilner, P. Figuera, D. Lo Presti, C. Petta, N. Randazzo, S. Reito, G.V. Russo, S. Tudisco
 ^{16}O - ^8Be break up states and cluster structure of ^{24}Mg

EUROP. PHYS. JOUR. A 12(2001)327

Zwieglinski B, Odeh T, Gross C, Schwarz C, Bassini R, Begemann-Blaich M, Fritz S, Gaff-Ejakov SJ, Gourio D, Imme G, Iori I, Kleinevoss U, Kunde GJ, Kunze WD, Lynen U, Maddalena V, Mahi M, Moroni A, Mohlenkamp T, Muller WFJ, Nociforo C, Ocker B, Petruzzelli F, Pochodzalla J, Raciti G, Riccobene G, Romano FP, Saija A, Sann H, Schnittker M, Schuttauf A, Seidel W, Serfling V, Sfienti C, Trautmann W, Trzcinski A, Verde G, Worner A, Xi HF

Interplay of equilibrium and nonequilibrium phenomena in the nuclear liquid-gas phase transition

NUCL PHYS A 681: 275C-278C JAN 29 2001

**LNS Publications at Conferences Proceedings & Workshops
2001**

C. Agodi, R. Alba, C. Maiolino, A. Del Zoppo, M. Colonna, G. Bellia, M. Bruno, N. Colonna, R. Coniglione, M. D'Agostino, M. L. Fiandri, P. Finocchiaro, F. Gramegna, I. Iori, K. Loukachine, P. M. Milazzo, G. V. Margagliotti, P. F. Mastinu, E. Migneco, A. Moroni, P. Piattelli, R. Rui, D. Santonocito, P. Sapienza, F. Tonetto, G. Vannini

Thermal photons as a probe of the dynamical character of IMF emission

Proceedings of the XXXIX International Winter Meeting on Nuclear Physics Bormio (Italy) January 22-27, 2001

C. Agodi,

Investigating nuclear dynamics around the FERMI energy by hard photon and IMF emission

XIII Th Colloque GANIL, Sept. 17-22, Corsica

C. Agodi

Hard photons and IMF emission: studying nuclear dynamics around the Fermi energy

"International Workshop on Multifragmentation and related topics", Catania, Italy, 28 Novembre-1 Dicembre 2001

R. Alba, et al. C. Maiolino, A. Del Zoppo, M. Colonna, G. Bellia, M. Bruno, N. Colonna, R. Coniglione, M. D'Agostino, M. L. Fiandri, P. Finocchiaro, F. Gramegna, I. Iori, K. Loukachine, G. V. Margagliotti, P. Mastinu, E. Migneco, P. M. Milazzo, A. Moroni, P. Piattelli, R. Rui, D. Santonocito, P. Sapienza, P. Tonetto, G. Tannini

**Hard photons: a probe of dynamical effects in heavy ion collisions at intermediate energy
photons as a probe of the dynamical character of IMF emission**

"Nuclear Physics at Border Lines", Lipari, Italy, 21-24 Maggio 2001

M. Alderighi for CHIMERA collaboration

Pre-analysis computation unit for the CHIMERA DAQ using DSP-based VME modules

Oral and paper contr. Selected by proc. of the 12th IEEE real time congress on Nuclear and Plasma Sciences, Valencia (Giugno 2001), pag. 214.

F. Amorini, G. Cardella, A. Di Pietro, P. Figuera, G. Lanzalone, J. Lu, A. Musumarra, M. Papa, S. Pirrone, F. Rizzo, S. Tudisco.

GDR excitation close the liquid gas transition of nuclear matter

Proceedings of the Int. Conf. Nuclear Physics at the Border Lines Lipari 21-24 Maggio 2001

F. Amorini, G. Cardella, A. Di Pietro, P. Figuera, G. Lanzalone, J. Lu, A. Musumarra, M. Papa, S. Pirrone, F. Rizzo, S. Tudisco.

Limiting excitation energy for GDR gamma decay

Proceedings of the Int. Conf. IWM2001 Catania Dicembre 2001.

V. Baran, Ph. Chomaz, M. Colonna and M. Di Toro

Pre-Equilibrium Hot Giant Dipole Resonance Excitation in N/Z Asymmetric Nuclear Reactions

"Isospin Physics in Heavy-Ion Collisions" Ed.s Bao-An Li and U. Schroeder, Nova Sci. Publ. New York 2001, ch.8, pp.223-238

V. Baran, M. Colonna, M. Di Toro, M. Zielinska-Pfabe, H. H. Wolter,

What can we learn from nuclear matter instabilities?

Int.Conf.on Nuclear Physics, Bologna 2000,

Ed.s G.C.Bonsignori et al., World.Sci. 2001, Vol.I pp.293-298

L. Calabretta et al.,

The Radio Frequency Pulsing System at INFN-LNS

Int. Conf. On Cyclotrons and their Applications, East Lansing, 2001, pag. 297-299

L. Calabretta, D. Rifuggiato

Status and future plans at LNS Catania

Proc. of the XVI Int. Conf. on Cyclotrons and their Appl., East Lansing, Michigan, 2001, p. 79-83

G. Ciavola, L. Celona, S. Gammino, F. Chines, S. Passarello, C. Campisano

First beam from the TRASCO intense proton source at INFN-LNS

Proc. Part. Acc. Conference, Chicago (2001)

M.Colonna and M.DiToro

Nuclear Transport Models and Effects of Isospin-Dependent Equation of State on Dissipative Heavy-Ion Collisions

"Isospin Physics in Heavy-Ion Collisions" Ed.s Bao-An L and U.Schroeder, Nova Sci.Publ. New York 2001, ch. 9, pp.239-256

R. Coniglione, P. Sapienza, E. Migneco, C. Agodi, R. Alba, G. Bellia, M. Colonna, A. Del Zoppo, P. Finocchiaro, V. Greco, K. Loukachine, C. Maiolino, P. Piattelli, D. Santonocito, P.G. Ventura, N. Colonna, M. Bruno, M. D'Agostino, P.F. Mastinu, M.L. Fiandri, F. Gramegna, I. Iori, L. Fabbietti, A. Moroni, G.V. Margagliotti, P.M. Milazzo, R.Rui, F. Tonetto, G. Vannini, Y. Blumenfeld, J.A: Scarpaci

Hard gammas and energetic protons as probes of nuclear dynamics

"INPC 2001" Berkeley, U.S.A., 30 Luglio-3 Agosto 2001

G. Cuttone, L. Raffaele, S. Lo Nigro, G.A.P. Cirrone, M.G. Sabini, V. Zsalamone,

I protoni e la radioterapia delle patologie oculari: il progetto CATANA

Atti del corso di aggiornamento: Metodi per la conformazione della dose in radioterapia, 22-23 giugno 2001, Villa Gualino, Torino

E De Filippo, A.Anzalone, M.Baldo, R.Barnà, A.Bonasera, B.Borderie, A.Botvina, R.Bougault, M.Bruno, M.G.Campisi, G.Cardella, S.Cavallaro, M.Colonna, M.D'Agostino, E.D'Amico, R.Dayras, N.De Cesare, E.Defilippo, D.De Pasquale, M.Di Toro, S.Feminò, E.Geraci, M.Geraci, A.Grzeszczuc, F.Giustolisi, P.Guazzoni, D.Guinet, M.C.Iacono Manno, A.Italiano, S.Kowalsky, G.Lanzalone, G.Lanzanò, U.Lombardo, S.Lo Nigro, C.Maiolino, D.Mahboub, G.Margagliotti, T.Paduszynski, A.Pagano, M.Papa, M.Petrovici, E.Piasecki, S.Pirrone, G.Politi, F.Porto, A.Rapisarda, M.F.Rivet, E.Rosato, S.Sambataro, V.Simion, M.L.Sperduto, J.C.Steckemeyer, C.Sutera, L.Tassan-Got, G.Vannini, M.Vigilante, J.Wilczynski, L.Zetta, W.Zipper.

Global results of the reverse experiment

Proceedings of the conference Int. Conf. IWM2001 Catania Dicembre 2001.

A. Di Pietro P.Figuera, A.Musumarra, F.Amorini, C.Angulo, G.Cardella, S.Cherubini, T.Davinson, J.Lu, M.Milin, A.Ninane, M.Papa, F.Rizzo, C.Ruiz, A.Shotter, S.Tudisco, L.Weissman.

$^6\text{He}+^{64}\text{Zn}$ around the coulomb barrier

Proceedings of isol01 Oak-Ridge USA - 2001

M.DiToro, V.Baran, M.Colonna and V.Greco

Reactions mechanisms with radioactive beams: isospin effects on nuclear dynamics

Int.Symposium on Exotic Nuclei, Baikal 2001, World Sci.,

M.DiToro, V.Baran, M.Colonna, V.Greco, M.Zielinska-Pfabe' and H.H.Wolter

Dynamical influence of the isospin degree of freedom on fragment production

Proc.Int.Workshop on Multifragmentation, LNS Catania Nov.2001,

P.Figuera, A.Di Pietro, A.Musumarra, F.Amorini, C.Angulo, G.Cardella, S.Cherubini, T.Davinson, J.Lu, M.Milin, A.Ninane, M.Papa, F.Rizzo, C.Ruiz, A.Shotter, S.Tudisco, L.Weissman.

The reaction $6\text{He}+64\text{Zn}$ around the coulomb barrier

Proceedings of the Int. Conf. Nuclear Physics at the Border Lines,

Lipari 21-24 Maggio 2001

S. Gammino, G. Ciavola, L. Celona, P. Romano, L. Torrisi, D. Hitz, A. Girard, G. Melin

Operation of the SERSE superconducting ECR source at 28 GHz

Proc. 16th Int. Conf. on Cyclotrons & Applications, East Lansing, Michigan (2001)

S. Gammino, G. Ciavola, L. Celona, P. Romano, L. Torrisi, D. Hitz, A. Girard, G. Melin,

Comparison of operation of the SERSE source at 18 and 28 GHz

Proc. Part. Acc. Conference, Chicago (2001)

E.Geraci, M.Di Toro ,and REVERSE Collab.

Reverse Experiment at Laboratori Nazionali del Sud

Int.Conf.on Nuclear Physics, Bologna 2000,

Ed.s G.C.Bonsignori et al., World.Sci. 2001, Vol.I pp.293-298

V.Greco, V.Baran, M.Colonna, M.DiToro, G.Fabbri and F.Matera

Instabilities in a mean field dynamics of asymmetric nuclear matter

in "Theoretical Nuclear Physics in Italy", Cortona Oct.2000,

Eds. G.Pisent et al., World Sci. 2001, pp.385-392.

G.Imme' et al.

Systematic study of the nuclear caloric curve

International Workshop on Multifragmentation and related topics 28th November - 1st December 2001 LNS, Catania, Italy

L. Laska, K. Jungwirth, J. Krasa, K. Marek, M. Pfeifer, K. Rohlena, J. Ullschmied, J. Badziak, P. Parys, J. Wolowski, E. Woryna, L. Andò, G. Ciavola, S. Gammino, L. Torrisi,

Comparison of ions emitted from different Laser-produced plasmas

Proc. of PLASMA01, Warsaw, 2001

A.Pagano

Influenza del Grado di libertà di ISOSPIN nelle reazioni di multiframmentazione alle energie di Fermi: prime osservazioni con l'apparato CHIMERA

LXXXVII Cong. SIF MILANO, 24-29 settembre 2001, Boll. SIF (2001) pag. 55

E.Piasecki for Reverse collaboration

Invited Oral and paper contr.

IWM2001 int. Workshop on Multifragmentation and related topics, Catania 28-November 2001 Ed. G.Agnello, A.Pagano, S.Pirrone, proc. in press.

S.Pirrone for the REVERSE collaboration

isospin investigation with the REVERSE experiment

Oral and paper contr. Selected by NPBL (2001) , pub. On proc. on Nuclear Physics at Border Line May-21-24 ,2001 World Scientific, pp.267

G.Politi, M.Di Toro, and REVERSE Collab.

Reverse: the first experiment with the CHIMERA detector

Int.Conf.on Nuclear Physics, Bologna 2000,

Ed.s G.C.Bonsignori et al., World.Sci. 2001, Vol.I pp.293-298

M. Re, G. Cuttone, E. Zappalà, S. Passarello;

Breakdown mechanisms in electrostatic deflector

Sixteenth International Conference, East Lansing, Michigan 2001

P. Sapienza, R. Coniglione, M. Colonna, E. Migneco, C. Agodi, R. Alba, G. Bellia, Y. Blumenfeld, M. Bruno, N. Colonna, M. D'Agostino, A. Del Zoppo, M.L. Fiandri, P. Finocchiario, F. Gramegna, I. Iori, K. Loukachine, C. Maiolino, P.M. Milazzo, G.V. Margagliotti, P.F. Mastinu, A. Moroni, P. Piattelli, R.Rui, D. Santonocito, J.A. Scarpaci, F. Tonetto, G. Vannini,

Pre-equilibrium emission and cooperative effects in heavy ion reactions around the Fermi energy

“International Workshop on Multifragmentation and related topics”, Catania, Italy, 28 Novembre-1 Dicembre 2001

C.Sfienti

Transizione di fase liquido-gas nella materia nucleare: risultati e prospettive

LXXXVII CONGRESSO NAZIONALE SOCIETÀ ITALIANA DI FISICA

Milano - Bicocca, 24 - 29 settembre 2001

J.C.Steckmeyer for CHIMERA-INDRA Collaboration

Study of the dissipative binary Channels in the $107\text{Ag}+58\text{Ni}$ reaction at 52MeV/nucleon

Invited Oral and paper contr. IWM2001 int. Workshop on Multifragmentation and related topics, Catania 28-November 2001 Ed. G.Agnello, A.Pagano, S.Pirrone

J.C.Steckmeyer, S.Aiello, a.Anzalone, G.Auger, M.Bini, B.Borderie, R.Bougault, B.Bouriquet, Am.Buta, G.Cardella}, G.,Casini, S.Cavallaro, J.Colin, D.Cussol, R.Dayras, N.De Cesare, E.Defilippo, R.De Meyer, D.Dore, D.Durqand.

S.Feminò, m.Geraci, et al.(CHIMERA-INDRA J.Wilczynski, L.Zetta, W.Zipper.

Study of the dissipative binary channels in the $107\text{Ag}+58\text{Ni}$ reaction at 52 MeV/nucleon

Proceedings of the XL int. winter Meeting on nuclear physics Bormio Italy jan.21-26, 2002 conference Int. Conf. IWM2001 Catania Dicembre 2001.

L. Torrisi, S. Gammino, L. Andò, G. Ciavola, L. Laska,

Plasma production by Nd:Yag pulsed laser irradiation of metals

LXXXVII Congresso Nazionale SIF, Milano, (2001)

J. Wolowski, E. Woryna, P. Parys, J. Krasa, L. Laska, K. Rohlena, L. Andò, L. Celona, G. Ciavola, S. Gammino, L. Torrisi,

Expansion of laser produced ion beams in an axial magnetic field

3rd French-Polish Seminars on Thermal Plasmas in Space and Laboratory, Warsaw,

J. Wolowski, E. Woryna, P. Parys, J. Krasa, L. Laska, K. Rohlena, L. Andò,
S. Gammino,

Influence of light contaminants on properties of an ion beam emitted from the high-Z laser produced plasma

3rd French-Polish Seminars on Thermal Plasmas in Space and Laboratory, Warsaw, (2001)

E. Woryna, P. Parys, J. Wolowski, L. Celona, G. Ciavola, S. Gammino, L. Torrisi, J. Krása, L.
Láska, K. Rohlena,

Influence of external magnetic and electric field on properties of an ion beam emitted from laser-produced plasma

Proc. of SPIE vol 4424 (26th Eur. Conf.on Laser Interaction with Matter, Prague), ed. M. Kalal, K. Rohlena, M. Sinor (2001) 476-479

18-01-2001 A. Sedrakian KVI, Groningen

Neutrino Radiation from Supernovae and Neutron Stars

23-01-2001 P. Chomaz GANIL

News from phase transitions

5-03-2001 Gianni Pavan Univ. Pavia

Rivelazione acustica in ambiente sottomarino e studio dei cetacei

16-03-2001 Todor Stanev Bartol Institute Univ. Delaware (USA)

Ultra high energy neutrinos in astrophysics

30-03-2001 C. Rolfs Ruhr - University of Bochum

On the quest of electron screening

12-04-2001 C. Aurisicchio, CSESMR-CNR di Roma

S. Nunziante Cesaro CSTCAT-CNR Roma

Metodi non distruttivi per l'identificazione della provenienza di smeraldi archeologici

16-05-2001 S. Libertino IMETEM - CNR

Optoelettronica su silicio

18-05-2001 R. Wolski FLNR Dubna and Univ. of Krakow

Radioactive beam experiments on the structure of neutron rich nuclei

24-05-2001 Burkhard Kolb GSI

The slow control system for the HADES spectrometer

29-05-2001 L. Dedenko Moskow State University

Giant cosmic rays Showers in the atmosphere and in water at superhigh energies

26-07-2001 A. Zucchiatti INFN Sez. di Genova

Analisi non distruttive di smalti Robbiani

13-09-2001 G. Bellettini Università di Pisa

La scoperta del Quark Top al Collider Detector di Fermilab

13-09-2001 G. Pauletta Università di Udine

Alle soglie della Fisica oltre il modello standard con CDF

12-10-2001 Tom Lonnroth Department of Physics, Abo Academy, Turku, Finland
Abo Academy, its Department of Physics and the Nuclear Alpha-Cluster project

15-10-2001 Tom Lonnroth Department of Physics, Abo Academy, Turku, Finland
Macroscopic Physics behind Alpha-Cluster States

15-11-2001 Marisa GULINO IKS, Katholieke Universiteit Leuven
Study of alpha-cluster states of ^{22}Mg from resonance scattering of a post-accelerated
 ^{18}Ne radioactive ion beam

13-12-2001 L. Laska Accademia delle Scienze, Repubblica Ceca, Istituto di Fisica di
Praga
Jodine lasers and activities at Prague(with film about laser system PALS)

13-12-2001 P.K. Sahu INFN Sez. Catania
Hadrons in relativistic heavy-ion collisions under extreme conditions

Conferences, Workshops, Schools & Meetings at LNS

European Summer School on Experimental Nuclear Astrophysics
1st - 6th October

International Workshop on Multifragmentation and Related Topics
28th Nov - 1st December

5th AZ-4 π group Meeting
November 27th

NuPECC Meeting
27th - 28th April

LNS Scientific Committee,
15th -16th June

XI Week of Science and Technology Culture" organized by the Italian Minister of Education, University and Research
26th March - 1st April

Formazione d'ingresso per i Neo-assunti INFN
30th - 31st October

Celebrazioni del 50° Anniversario dell'INFN
16th Novembre

26th March – 1st April "XI Week of Science and Technology Culture"
2318 Students have been received in the framework of the organized by the Italian Minister of Education, University and Research.

Liceo Classico Spedalieri, CT	209
Liceo Classico Gorgia, Lentini	100
Istituto A. Einstein, CT	50
Liceo Scientifico A. Volta, Caltanissetta	51
Liceo Scientifico S. Cannizzaro, Vittoria	80
Liceo Scientifico "Saluta", Augusta	80
Liceo Scientifico "E. Majorana", S.G. La Punta	50
Ist. Statale Istruzione Secondaria E. Vittorini, Lentini	80
Maria Ausiliatrice, Catania	37
Mliceo Clasico Megara, Augusta	78
Liceo Ginnasio "F.lli Testa", Nicosia	74
Liceo Artistico Statle, Catania	81
Ist. Tec Commerciale "E. De Nicola", S.G. La Punta	200
Liceo Scientifico "E. Majorana", Caltagirone	68
Liceo Scientifico "Archimede", Acireale	50
Istituto Tecnico Industriale, Belpasso	50
Liceo Scientifico "Gorgia", Lentini	50
Liceo Classico "M. Cutelli", Catania	50
Maria Ausiliatrice, Caltagirone	31
Leonardo da Vinci, Catania	40
Liceo Classico "Capizzi", Bronte	13
Ist. Tec. Geometri, Lentini	30
Liceo Scientifico Galilei, Modica	36
ist. Istr. Second. "Amari", Giarre	24
Ist. Istruz. Second. "O.M. Corbino", Siracusa	88
ist. Tec. Statle "P. Branchina",	30
Liceo Ginnasio Statle "G. Verga", Adrano	153
Liceo Scientifico Statale "G. Galilei", Catania	273
Liceo Scientifico Statale "P. Umberto, Catania	162