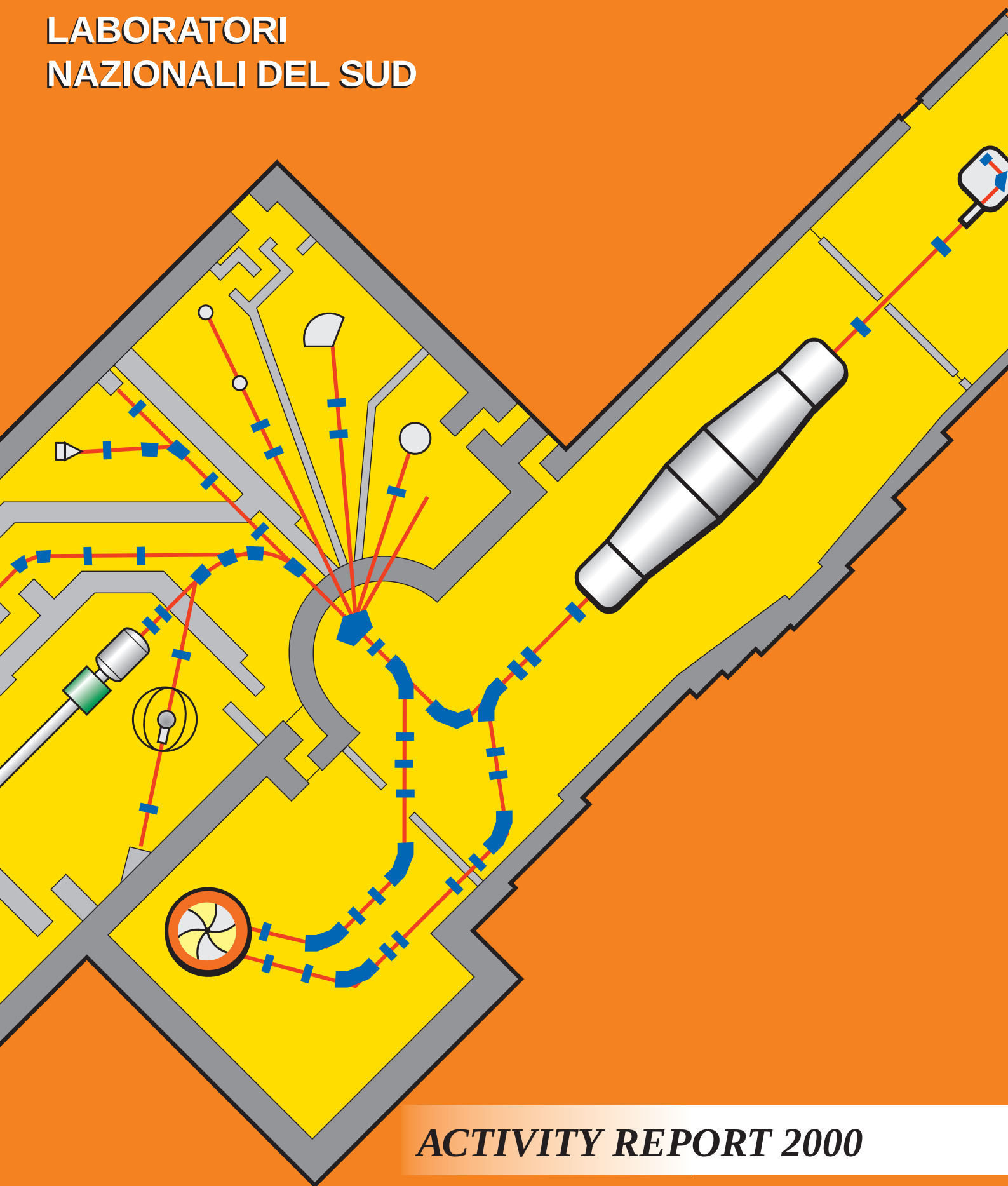


INFN-LNS

LABORATORI
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ACTIVITY REPORT 2000

LNS Activity Report 2000

LNS Director D. Vinciguerra (till 6-8-2000), S. Sambataro (from 7-8-2000 till 13-10-2000),
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Foreword

The present report contains a description of scientific and technological activities at LNS in the year 2000.

During this time big efforts have been done both by the research and the technical staff of LNS in order to improve the performances of the accelerators and exploit them to achieve scientific results. In the middle of the year the electrostatic deflectors allowing for extraction of the beam from the Superconducting Cyclotron (SC) showed their limits. In order to make the cyclotron working in a reliable way even with high energy beams, a stop of the accelerator activities was planned during the last months of the year. This time was used to achieve two goals: *a)* new electrostatic deflectors with new shapes and materials were tested which can allow for higher extraction fields and thus higher energy beams to be extracted; *b)* two new tandem beam lines were installed, by-passing the switching magnet and consequently allowing for simultaneous delivering of SC and tandem beams to the experimental areas. The first goal was a necessary step also in view of the completion of the therapeutic facility CATANA that uses 62 MeV proton beams. The second one was required by the needing to allocate large amount of tandem beam time for nuclear astrophysics experiments, without interference with the Cyclotron beam schedule.

Despite this four months stop, a relevant experimental activity has been carried out during the first half of the year. The detector CHIMERA was installed, in a partial configuration made of the most forward 688 telescopes, inside the reaction chamber CICLOPE and was successfully used for the first experiments on the multifragmentation process, thanks also to the improved timing characteristics of the SC beams. In the meanwhile a lot of work was performed, related to the CHIMERA trigger control system and the associated electronics. The activity around the spectrometer MAGNEX led to the beginning of the magnet construction and the definition of the focal plane detector. The superconducting solenoid SOLE was aligned and tested in view of its coupling with the MEDEA-MACISTE ensemble.

A number of other experiments on nuclear astrophysics, features of the GDR, α cluster states in light-medium nuclei and electron emission in intermediate energy nuclear reaction have been performed both with tandem and SC beams. Finally, at the end of the year, the installation of the mentioned by-pass lines allowed the first tests on the production of a secondary ^8Li beam through the $^2\text{H} + ^7\text{Li}$ reaction, aimed to the study of the astrophysically relevant process $^4\text{He}(^8\text{Li},n)^{11}\text{B}$, that represents the key reaction leading to the elements with $A > 11$ in the Inhomogeneous Big Bang picture.

A relevant activity was also performed from the theoretical point of view, with studies on nuclear dynamics and properties of nuclear matter carried on by the LNS Theory Group.

Looking at applications of nuclear techniques to different disciplinary fields, during this year a number of activities have been performed with the LNS facilities, concerning biological applications, solid state physics and safety of cultural heritage.

Moreover it is worth to mention the improvements achieved with the ECR superconducting sources, in terms of reliability, and with low intensity beam monitoring techniques, two crucial steps needed for the realisation of the EXCYT facility.

Lastly R & D activities related to the NEMO Project led to start the installation of the test site, located 2000 m under the sea in front of Catania, and stimulated a number of multidisciplinary enterprises that will take advantage of the development of the sub-marine technologies required by the project.

Emilio Migneco
LNS Director

Foreword

A. EXPERIMENTAL NUCLEAR PHYSICS

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LIMITING EXCITATION ENERGY FOR GDR GAMMA DECAY

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Abstract

γ -ray spectra in coincidence with charged particles for the reactions $^{40}\text{Ca} + ^{48}\text{Ca}, ^{46}\text{Ti}$ at $E_{\text{inc}}=25$ MeV/A are presented. The spectra statistical analysis shows the survival of the GDR up to an excitation energy around 4 MeV/A for a system with mass of 50-60 amu. This result was obtained by improving statistical calculations by including the deuteron decay channel, the mass dependence of the GDR parameters in the decay chain, and the GDR isospin splitting. The dependence of the GDR yield from the different N/Z ratio of projectile and target nuclei reported at lower beam energy has been also evaluated.

1 INTRODUCTION

The region around 15 MeV in the γ -ray energy spectra produced in heavy ion reactions is dominated by the GDR decay[1]. The GDR disappearance is a signature of the loss of collectivity of the nuclear matter. Recently a connection between this disappearance and the liquid-gas phase transition of nuclear matter has been proposed [2]. However the limiting excitation energy (2.5 MeV/A) for GDR presence extracted from previous measurements [3,4] seems too low with respect to the energy at which the phase transition is expected. The statistical analysis performed in ref.[3,4] can be today improved. In fact the used statistical code CASCADE [5] accounts only for neutron (n), proton (p) and α -particle decays. More complex fragments that can be evaporated at this high excitation energy [6] are neglected. The main aim of this work was to improve the reliability of the statistical calculations at high excitation energy in order to extract more precise information on the maximum excitation energy at which we still observe collective excitations in nuclear matter. We studied the systems $^{40}\text{Ca} + ^{48}\text{Ca}, ^{46}\text{Ti}$ at 25 A MeV. The two systems were used also to evaluate the presence of a GDR yield dependence on the N/Z ratio of

projectile and target nuclei [$N/Z(^{40}\text{Ca})=1$, $N/Z(^{48}\text{Ca})=1.4$, $N/Z(^{46}\text{Ti})=1.09$]. Such dependence was in fact observed at lower beam energy [7,8] and it could influence the evaluation of the limit GDR excitation energy $E_{\text{cut-off}}^*$.

2 EXPERIMENTAL SETUP AND RESULTS

The experiment was performed at the Superconducting Cyclotron of the Laboratori Nazionali del Sud (LNS) Catania. A 25 A MeV beam of ^{40}Ca was used impinging on 3 mg/cm² thick, self-supporting targets of $^{48}\text{Ca}, ^{46}\text{Ti}$ 95% isotopically enriched. We used the 63 BaF₂ crystals of the multidetector system TRASMA described in ref. [9].

Charged particles in coincidence with γ -rays were detected by using a ΔE -E hodoscope placed at forward angles. The first stage was an annular silicon strip detector 300 μm thick covering the whole ϕ and $\theta_{\text{Lab}} = 3^\circ - 6^\circ$. The second stage was provided by CsI detectors with photodiode readout. Fragments stopped in the strip detector were charge identified by using a pulse shape analysis of the signal [10,11].

In fig.1 a typical Energy-"Rise-Time" (rise time in the silicon detector signal) scatter plot is reported showing the charge identification. A

concentration of events can be observed in the low energy region (box in fig.1). The corresponding energy spectrum is peaked around 200 MeV.

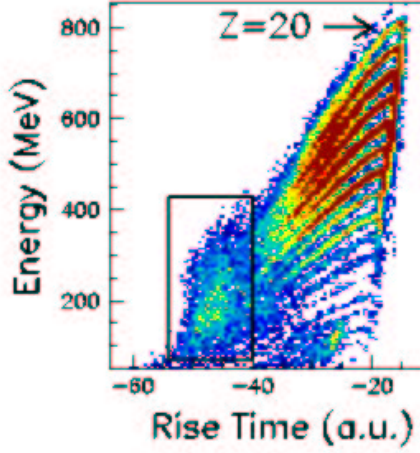


Fig.1 E-rise time scatter plot

From simple kinematical calculations, further confirmed by GEMINI [6] simulations, we expect around this energy evaporation residues (ER) produced in fusion-like reactions. This assignment is also confirmed by a recent work on the $^{40}\text{Ca}+^{48}\text{Ti}$ reaction [12] measured at the same beam energy.

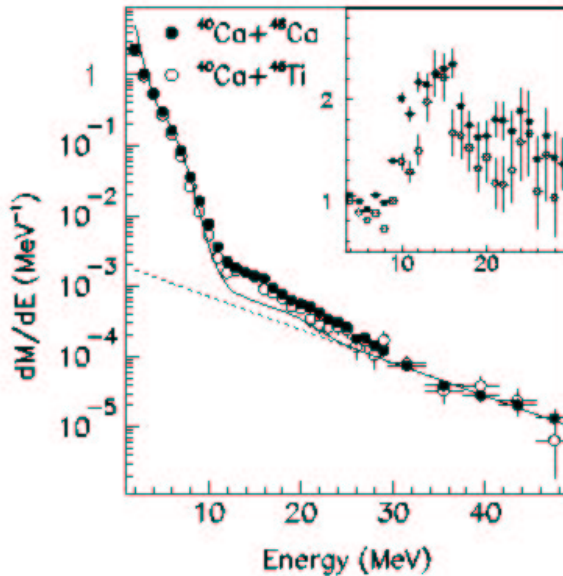


Fig.2 experimental γ -ray multiplicities

In fig.2 we compare the yields obtained for the $^{40}\text{Ca}+^{48}\text{Ca}$ (full dots) with those relative to the

$^{40}\text{Ca}+^{46}\text{Ti}$ reaction (open dots) measured in coincidence with the ER. Multiplicity was obtained normalizing the spectra to the number of detected ER and taking into account the γ -ray detection efficiency. To increase the statistics γ -rays measured at different angles are summed event by event after Doppler shift correction, assuming a source with the CM velocity. The presence of the GDR γ -decay can be observed around 15 MeV. This can be better evidenced by comparing the data with the statistical model calculation (full line) for the ^{48}Ca target data assuming zero strength for the GDR (NO-GDR). The bremsstrahlung contribution [13], that dominate the spectra at energy above 30 MeV, was summed in the "NO-GDR" calculations. The GDR yield for the $^{40}\text{Ca}+^{46}\text{Ti}$ reaction is somewhat smaller (10-15%) than for the $^{40}\text{Ca}+^{48}\text{Ca}$ one. The difference is better observed in the inset where both data are presented divided by the "NO-GDR" calculation.

The bremsstrahlung γ -ray yield is connected to the number of n-p first chance collisions. This number can be used to estimate the average impact parameter [13,14]. We note in fig.3 that

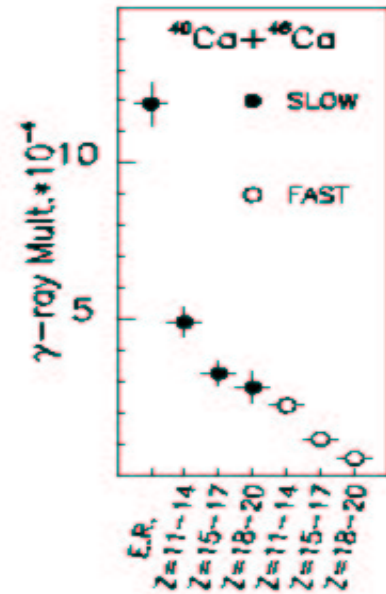


Fig.3 High energy γ -ray multiplicities

the largest probability to generate such high energy γ -rays ($E_\gamma \geq 30$ MeV) is in coincidence with ER. The SLOW and FAST selections

reported in such figure correspond respectively to slow particles stopped in the silicon detector and faster particles punching through it. Scaling the yield for the average number of n-p collisions one obtain an average impact parameter for the ER selection of about 2-3 fm. This confirms that these events come from fusion like reactions mechanisms excluding more peripheral dissipative reactions expected around an impact parameter of 4-5 fm. As a further confirm of that, we note a large difference between the high energy γ -ray multiplicities measured for ER and dissipative reactions (on average a factor 4) excluding large contamination of such reactions in the selection performed.

3 STATISTICAL CALCULATIONS AND CONCLUSIONS

Starting from the study of ref. [12] the average mass and excitation energy that can be evaluated for our systems was of 335 MeV for the ^{46}Ti target and 354 MeV for the ^{48}Ca target. The most powerful code to compute statistical γ -ray decay is CASCADE [5]. Following the suggestions of ref. [15], we used an isospin dependent [16] version of the code with the Reisdorf parameterization of the level density. As suggested in [17] we assume in all following calculations zero for the isospin mixing parameters. We added the deuteron decay channel to the CASCADE code because such particles have, for the investigated systems, an emission probability similar than α -particles. Also the mass dependence of the GDR centroid [1] was included due to the large mass variation of the emitting nuclei (from 60 to 40 amu) along the decay path of the excited nucleus. Moreover the even larger isospin splitting of the GDR into two components $T_{\leq} = T$ and $T_{\geq} = T+1$ has been considered [18,19]. In fig.4 we report the obtained results for the reaction $^{40}\text{Ca} + ^{48}\text{Ca}$. The agreement of calculations with experimental data can be better observed in the inset, where calculation and data are reported as divided by the “NO-GDR” line already presented in fig.2. The two lines of this figure are obtained performing different choices for GDR width (Γ_{GDR}) behavior. The dashed line is obtained assuming $\Gamma_{\text{GDR}} = 15$ MeV (i.e. the largest GDR

width reported around mass 60 [20]) in order to test the constant Γ_{GDR} hypothesis assumed at high excitation energy in the standard systematics [1].

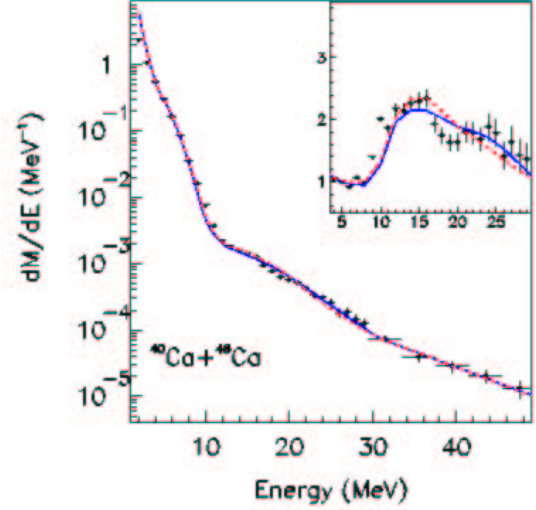


Fig.4 Fit of the $^{40}\text{Ca} + ^{48}\text{Ca}$ data

In this case to reproduce the data it is necessary to assume an energy cut-off $E_{\text{cut-off}}^* = 260$ MeV. However one can obtain a better χ^2 value (0.20 ± 0.10 against 0.37 ± 0.15) using a $\Gamma_{\text{GDR}} = 26$ MeV without any cut-off, full line fig.4. The differences between the two calculations are mainly in the region above 20 MeV better reproduced using $\Gamma_{\text{GDR}} = 26$ MeV.

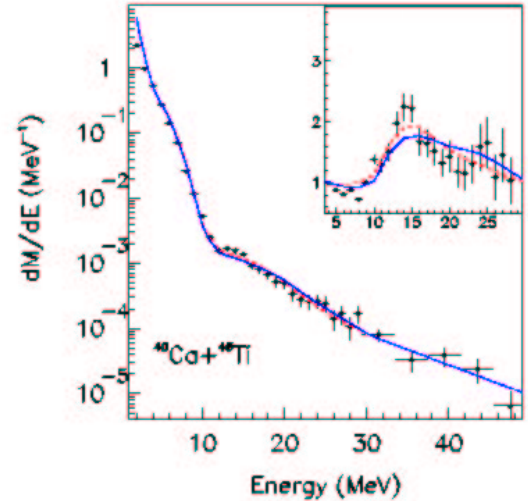


Fig.5 Fit of the $^{40}\text{Ca} + ^{46}\text{Ti}$ data

In fig.5 we show the fit of ^{46}Ti data. For $\Gamma_{\text{GDR}} = 15$ MeV the best χ^2 (0.88 ± 0.4) is obtained for

$E_{\text{cut-off}}^* = 200$ MeV (dashed line). No improvement in the χ^2 is obtained using a Γ_{GDR} smaller than 15 MeV. Assuming no cut-off and a GDR strength of 1 W.U. we cannot obtain a minimum of the χ^2 for Γ_{GDR} lower than 30 MeV. If one reduces the strength to 0.8 W.U. one obtains the fit shown as full line in fig. 4d with $\Gamma_{\text{GDR}} = 25$ MeV ($\chi^2 = 0.92 \pm 0.4$).

On the basis of the obtained results it is difficult to decide between the hypotheses of constant Γ_{GDR} or increasing Γ_{GDR} with excitation energy. From the point of view of the limiting excitation energy at which GDR is still surviving, the first hypothesis ($\Gamma_{\text{GDR}} = 15$ MeV) gives a smaller value. Therefore we can assume this value to be the lower limit. The cut-off is reached only after the evaporation of some particles. From the average excitation energy carried away by each evaporated mass unit (about 13 MeV), a mass of 56 amu can be evaluated for ^{48}Ca data at the $E_{\text{cut-off}}^*$, and the corresponding excitation energy is of 4.6 ± 0.5 MeV/A. For the ^{46}Ti target the $E_{\text{cut-off}}^*$ extracted is slightly smaller and a mass of 53 amu can be evaluated for the system with 200 MeV average excitation energy i.e. 3.8 ± 0.6 MeV/A.

The evaluation of the error accounts for the different assumptions made. Some uncertainties come from the errors on the estimation of the source. Assuming a higher mass for the system populated with the ^{48}Ca target ($A=70$ $\Delta A/A=13\%$) we obtain $E_{\text{cut-off}}^*$ around 280 MeV instead of 260. However because of the higher mass, the variation in terms of excitation energy per nucleon is negligible. Small variations were also observed by changing the initial excitation energy. A larger error (of the order of 10%) is produced by the bremsstrahlung evaluation. Because of the low statistics the bremsstrahlung evaluation for the ^{46}Ti target was not possible. We used the same exponential function as for the ^{48}Ca target. This gives a systematic error evaluated below 5% due to the different number of n-p collisions. A further improvement of the calculations could be obtained if all available decay channels would be added to Cascade. These corrections are expected to be small due to the low particle decay probability and should in any case increase the cut-off measured and

consequently the maximum excitation energy per nucleon. The same effect is expected for small contamination of DR that reduce the GDR γ -ray yield.

In conclusion the extracted excitation energy per nucleon at which we still have GDR excitation is 4.6 ± 0.5 MeV and 3.8 ± 0.7 MeV for ^{48}Ca and ^{46}Ti respectively. They represent the lower limit energy at which a collective behavior persists. In fact, in case an increasing Γ_{GDR} is assumed, a higher excitation energy (5.6 MeV/A for the ^{48}Ca target) is obtained. The measured difference between the lower limits for the limiting excitation energies measured for the two targets is inside the error bars. However the higher $E_{\text{cut-off}}^*$ is obtained for the system more asymmetric in the N/Z ratio between projectile and target. This could be connected with the results obtained at lower beam energy [7,8] where a higher yield in the GDR region was measured for N/Z asymmetric systems.

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Exploring the ^{11}Be structure by many-body approach

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Abstract

The $^{11}\text{B}(^7\text{Li}, ^7\text{Be})^{11}\text{Be}$ reaction at 57 MeV incident energy was analyzed within a new theoretical framework that accounts for the direct reaction mechanism to the Charge Exchange cross sections. A fundamental point is the use of QRPA theory for the calculation of the transition densities for the $^{11}\text{B} \rightarrow ^{11}\text{Be}$ route. QRPA calculations reproduce ^{11}Be level structure below 2 MeV of excitation energy. The strength observed at higher excitation energies is very likely produced mainly by core-excited components of ^{11}Be . The structure results are used for the calculation of the form factors within the double folding model. The form factors are then used as input for the DWBA calculations of the cross sections. The sensitivity of the results to different optical potentials is explored.

INTRODUCTION

Heavy-ion charge exchange reactions (CEX) are a powerful tool for spectroscopic studies in exotic nuclei, and may be used to investigate the isovector response of near drip-line nuclei. An exotic nucleus of great current interest is ^{11}Be because of its one-neutron halo structure [1,2]. Effects such as the inversion of $2s_{1/2}$ and $1p_{1/2}$ neutron orbitals [3,4], the coupling in the ground state of the d-wave orbital of the valence neutron with the 2^+ excited state of the ^{10}Be core [5], and the shift to lower excitation energy of the strength associated to the Spin Dipole

Resonance (SDR) [6,7] have been observed via direct reactions. However, despite the many experimental [3-16] and theoretical studies [17-19], a satisfactory description of both the structure of ^{11}Be and the dynamics of reactions involving such a nucleus is not yet accomplished. The main difficulty arises from the necessary description of the continuous strength distribution of such a light exotic nucleus. In this paper, we analyze the $^{11}\text{B}(^7\text{Li}, ^7\text{Be})^{11}\text{Be}$ CEX reaction by a specially developed many-body approach.

¹¹BE DYNAMICAL LEVEL DENSITIES

. In 1998 the $^{11}\text{B}(^7\text{Li},^7\text{Be})^{11}\text{Be}$ CEX reaction has been performed at the Tandem laboratory of the IPN Orsay. The excited states populated in the experiment are presented in Table 1 [20].

In order to get a first insight into the structure of the observed strength distribution a theoretical approach based on charge exchange QRPA theory was used. From former applications to stable nuclei [21] the model is known to account well for states which are predominantly given by a superposition of neutron particle-proton hole, i.e. two quasi-particle (2QP), states with respect to the ground state of the parent nucleus, in this case ^{11}B . The ^{11}B ground state was obtained in Hartree Fock Bogoliubov theory using the D3Y interaction of ref. [22], including blocking of the $1p_{3/2}$ proton and neutron orbits. States in ^{11}Be are described in QRPA as correlated proton-neutron 2QP excitations. The coupling to 4QP and higher order configurations was taken into account schematically by introducing a complex 1QP self-energy, similar to the structure model used ref. [23]. Transition strength distributions for multipolarities from 0^+ , 0^- to 5^+ , 5^- have been calculated, as shown in Fig.1. Obviously, the model emphasizes the single particle content of the $^{11}\text{B} \rightarrow ^{11}\text{Be}$ transitions, but will not account for details of core polarization.

Table 1. States populated in the $^{11}\text{B}(^7\text{Li},^7\text{Be})^{11}\text{Be}$ reaction.

Ex (MeV)	Γ (keV)	J^π [3,12]	Structure [12,17]
		$1/2^+$	$^{10}\text{Be}(0^+) \otimes (s_{1/2})$
0.32±0.02		$1/2^-$	$^{10}\text{Be}(0^+) \otimes (p_{1/2})$
1.77±0.02	100±10	$5/2^+$	$^{10}\text{Be}(0^+) \otimes (d_{5/2}, d_{3/2})$
2.67±0.02	200±10	$3/2^-$	$^{10}\text{Be}(0^+) \otimes (p_{3/2})^{-1}$
3.41±0.02	130±10	$3/2^-$	$^9\text{Be}(\text{g.s.}) \otimes (\text{sd})^2_{0+}$
3.89±0.02	<50	$3/2^+ [12]$	$^{10}\text{Be}(2^+) \otimes (s_{1/2})$
		$5/2 [3]$	
3.96±0.02	<50	$3/2^-$	$^9\text{Be}(\text{g.s.}) \otimes (\text{sd})^2_{2+}$
6.05±0.02	320±20		
9.5±1	9±1	SDR [3]	
	MeV		

The results indicate that the ground state of ^{11}Be is excited by 1^- and 2^- transitions obtained by the coupling of the $3/2^-$ ^{11}B ground state with the $1/2^+$ state in ^{11}Be . Similarly, a sharp concentration of 1^+ and 2^+ strengths around 0.3 MeV indicates a $1/2^-$ state at that energy in ^{11}Be . These results agree with the well-known observation of a $2s_{1/2}$ and $1p_{1/2}$ shell inversion in ^{11}Be . Since these states are known to contain a strong single particle component they should indeed be reproduced by the QRPA calculations. Hence, the fact that they are described by the model calculations might be taken to confirm the applicability of the QRPA approach to a dripline nucleus as ^{11}Be . One also notes a minor contribution (around 5%) of the 0^+ transition to the strength at 0.3 MeV. This is compatible with a $3/2^-$ component to the first excited state. At higher excitation energy noticeable components of 1^- , 2^- , 3^- and 4^- strengths concentrated around 1.8 MeV are obtained. This is in agreement with the $5/2^+$ single particle interpretation of the 1.77 MeV state in ^{11}Be . So, we can conclude that at least up to this energy the spectrum may be understood in terms of single particle degrees of freedom. However, the afore mentioned constraint of charge exchange QRPA to the dynamics of the leading particle becomes evident from a comparison to the spectra at higher energies. At excitation energy above 2 MeV the QRPA strength is distributed over a broad energy region of almost structureless shape. It is obvious that the observed fragmentation of the ^{11}Be spectrum is not reproduced, most likely owing to the neglect of the coupling of the valence neutron to ^{10}Be core excited states. More involved DCP investigations of core polarization effects in ^{11}Be are in progress, similar to the approaches in refs. [24,25]. The principal importance of DCP in ^{11}Be was already shown by Vinh-Mau [26]

using the phenomenological particle-vibration model.

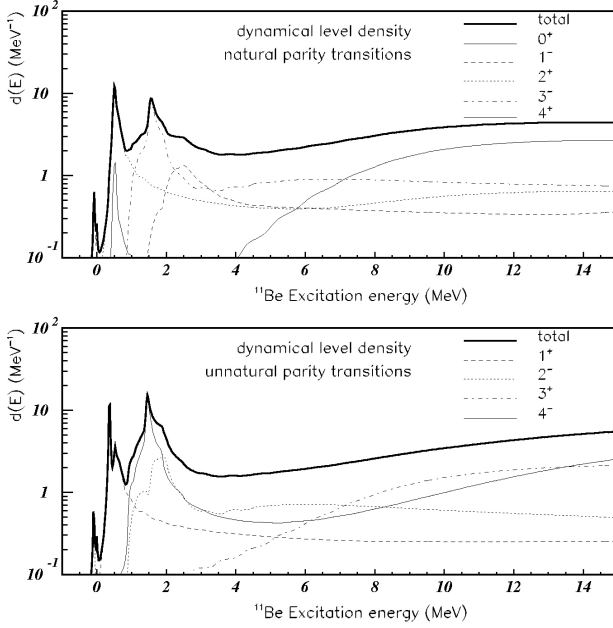


Figure 1. Dynamical level densities for transitions from the $^{11}\text{B}_{\text{gs}}$ to the excited states of ^{11}Be . See text for details.

FORM FACTORS

The charge exchange form factors are well described within a microscopic approach based on the double folding model. In this paper the formulas of [27] have been used. The transition densities for the $^7\text{Li} \rightarrow ^7\text{Be}$ pair are calculated via OBTD model structure [28].

In a first attempt the interaction parameters at 8 MeV/u have been deduced by interpolation of the Love-Franey interaction down to 50 MeV/u [29] and the G matrix obtained by Brueckner calculations for the low energy limit. The results obtained indicate considerable uncertainties in the strengths of the direct charge exchange interactions at these low incident energies, mainly in the tensor component.

Better results have been obtained by using effective interactions derived by G matrix calculations. In particular the D3Y effective

interaction accounting for both direct and exchange contributions to the central and tensor force is used.

CROSS SECTIONS

A quantitative description of the observed cross sections could, at least in principle, be obtained by an approach similar to ref. [30], including the interfering contributions from direct charge exchange and sequential proton-neutron two-step transfer processes. A first attempt in this direction was made by comparing one-step direct charge exchange cross sections to the data. A considerable overestimation of the magnitude of cross sections is obtained, especially when using the same optical potentials parameters for the entrance and the exit channel. In these cases the calculated cross sections exceed the observed ones by more than one order of magnitude. A detailed analysis show the strong influence played by an arbitrary addition of an extra surface term in the exit channel potential. This term, containing both real and imaginary parts is described as surface derivative of a Woods-Saxon shape with a large diffusivity (~ 3 fm) and small strengths (~ 3 MeV) and radius of around 1.2 fm. The introduction of such a potential can reduce the magnitude of the calculated cross sections to the measured ones. The sensitivity of the calculated cross sections to the extreme peripherals of the colliding nuclei may be associated to the polarization effects produced by the halo wave functions in the exit channel.

We have also tried optical potentials obtained by the double folding model. Here the same D3Y interaction used for the form factor calculations is folded with nuclear densities obtained in the QRPA approach for the exotic system and single particle shell model for the projectile. In this approach the break up contribution to the optical potential is completely missed. The results are better than

by phenomenological potentials, but still the calculated cross sections overestimate the measured by factors of three or more. This indicates the not negligible influence of the peripheral part of the optical potential on the cross sections.

The shapes of the angular distributions leading to the $^{11}\text{Be}(1/2^+, \text{g.s.})$ and the $^{11}\text{Be}(1/2^-, 320 \text{ keV})$ states were reasonably well reproduced for angles below 15° to 20° . Increasing deviations in shape to the measured angular distributions are observed at larger scattering angles. Standard two-step transfer theory is not directly applicable in the present case because unbound intermediate states will be involved. Beside the fact that adequate theoretical methods are not available or impossible to apply in a realistic calculation, also neither the structure nor optical potentials and other projectile-target interactions are known at present with sufficient accuracy for the intermediate channels populated in the $^7\text{Li}+^{11}\text{B} \rightarrow ^7\text{Be}+^{11}\text{Be}$ reaction.

CONCLUSIONS

Exploratory QRPA calculations indicate that the strength distribution, especially at excitation energies larger than 2 MeV should include correlations involving the excitation of the core. Valuable spin and parity information at low excitations energies, can be obtained from a comparison of the observed excitation energy spectra to the present QRPA-based approach with the observed one. The theoretical results indicate the sharp structures seen at higher excitation energies cannot be understood in terms of simple single particle configuration attached to an inert ^{10}Be core. In particular, the small widths obtained are in clear disagreement with a single particle interpretation and indicates the presence of more complicated configurations, involving core degrees of freedom. Alternative interpretations in terms of rotational cluster structures in ^{11}Be , proposed by

Bohlen et al. [13], cannot be excluded but it is an open question whether they could be excited with a noticeable cross section in a charge exchange reaction. It is also not clear if they would lead to such sharp resonance structures as seen in the measured spectra.

Cross section calculations show the sensitivity of the results to the optical potential in the exit channel. To understand the influence of the halo structure on the cross sections a specific model of the optical potential based on double folding and a microscopically derived break up contribution is necessary.

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${}^6\text{He}+{}^{64}\text{Zn}$ AROUND THE COULOMB BARRIER

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Abstract

The reaction ${}^6\text{He} + {}^{64}\text{Zn}$ was studied in order to investigate the effects of the halo structure on the fusion cross-section at low bombarding energy. The fusion excitation function was performed using the activation technique. The evaporation residues were detected by measuring off-line the X-ray emission which follows the radioactive Electron Capture decay. The reaction ${}^4\text{He}+{}^{64}\text{Zn}$ was also measured and the results are presented.

1 INTRODUCTION

Controversial effects on the fusion cross-section have been predicted by different theoretical models in reactions induced by halo nuclei at low bombarding energies (i.e.[1]). These models agree that the larger spatial extent of halo nuclei, and the coupling with possible low lying resonant states, would increase fusion cross-section. However different models disagree about the role played by the break-up of the loosely bound halo nucleons on the fusion cross-section. Break-up in fact can be considered either as a loss of flux for fusion decreasing the cross-section, or as an additional channel which enhances the cross-section [2-4].

The experimental investigation is very difficult owing to the low intensity of radioactive beams, the small fusion cross-section and the low evaporation residue (E.R.) recoil energies. Moreover indirect E.R. detection, via on-line or off-line γ -ray spectroscopy is difficult due to the high background compared with the very low γ yields. The systems studied so far are ${}^6\text{He}+{}^{209}\text{Bi}$ [2], ${}^6\text{He}+{}^{238}\text{U}$ [5], ${}^{11}\text{Be}+{}^{209}\text{Bi}$ [6].

In these experiments fission cross-section or E.R. α radioactivity were measured and apparently controversial results were obtained.

In the reactions induced by ${}^6\text{He}$ beam a strong enhancement of the fusion cross-section below the Coulomb barrier was observed but this was not seen in the ${}^{11}\text{Be}$ induced reaction.

We recently studied at the CRC laboratory of Louvain la Neuve the reaction ${}^6\text{He}+{}^{64}\text{Zn}$ at two beam energies around the Coulomb barrier. To overcome the experimental difficulties we measured off-line the X-ray activity of the radioactive E.R. produced in the reaction. The choice of the ${}^{64}\text{Zn}$ as target was made, with the help of statistical model calculations, in order to have the largest fraction of fusion cross-section going to radioactive E.R. The reaction ${}^6\text{He}+{}^{64}\text{Zn}$ produces E.R. decaying by Electron Capture (E.C.) which then emit low energy X-rays. The fusion excitation function was performed at fixed beam energy using the activation technique. As a comparison but also to check the normalisation procedure, the reaction

$^4\text{He}+^{64}\text{Zn}$ was investigated at the same centre of mass energy.

2 EXPERIMENTAL TECHNIQUE

The experiments were performed at Louvain la Neuve with an average ^6He beam current of 3×10^6 pps.

In the first run was measured the reaction $^6\text{He}+^{64}\text{Zn}$ at $E_{\text{cm}}=9.1$ MeV.

The experimental set-up consisted of an array of highly segmented large solid angle Si strip detectors (LEDA array [7]) with a total solid angle $\Omega \approx 2\pi$. The angular range covered was $0 \leq \varphi \leq 2\pi$ and $5^\circ \leq \theta \leq 64^\circ$ and $120^\circ \leq \theta \leq 160^\circ$. In this run only light charged particles such as p , α and ^6He were detected. Hydrogen was discriminated by He with the Time of Flight (ToF) technique using the cyclotron HF as time reference. The resolution was not enough to discriminate α from ^6He owing to the small flight path for the particles. In this run the elastic scattering angular distribution was measured. The results are shown in fig.1 along with optical model calculations performed with the code PTOLEMY. From the elastic scattering angular distribution a total reaction cross-section $\sigma_r = 360 \pm 70$ mb was extracted.

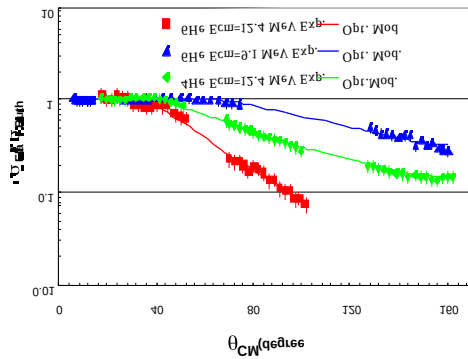


Figure1: Elastic scattering angular distributions. $^6\text{He}+^{64}\text{Zn}$ at $E_{\text{cm}}=9.1$ MeV (triangles), $^4\text{He}+^{64}\text{Zn}$ at $E_{\text{cm}}=12.4$ MeV (diamonds) and $^6\text{He}+^{64}\text{Zn}$ at $E_{\text{cm}}=12.4$ MeV (squares). Full line optical model calculations.

For this run events having charged particle multiplicity 2 were also analysed. This analysis

showed the presence of a peak in the α particle energy spectra which, from the comparison with Monte Carlo CASCADE [8] statistical model calculations, was not due to alpha particles emitted in fusion evaporation processes. This was also confirmed by the extracted angular distribution. The angular distribution was however peaked in the region around 90° where no detector was placed due to the energy straggling of particles into the target material. This contribution was attributed to 2n transfer reaction, a 1n transfer or ^6He break-up cannot in fact contribute to events having charged particle multiplicity two. This hypothesis was confirmed also by kinematics calculations.

The second run was performed at $E_{\text{cm}}=12.4$ MeV and at this energy the reaction $^4\text{He}+^{64}\text{Zn}$ was also measured. In the second run the experimental set-up was modified in order to cover also the angular region around 90° . To allow this measurement the target was angled at 45° with respect to the beam direction. The detector used was the LEDA array covering $0 \leq \varphi \leq \pi$ and $15^\circ \leq \theta \leq 50^\circ$ as front detector and $\pi \leq \varphi \leq 2\pi$ and $125^\circ \leq \theta \leq 160^\circ$ as back detector. An array of Double Sided Si Strip Detectors (DSSSD) was also used in order to cover the region around 90° (see fig.2). As for the first run, light charged particles were detected and H was discriminated by He using the ToF technique.

The elastic scattering angular distributions for the two reactions $^6\text{He}+^{64}\text{Zn}$ were measured. Optical model calculations were performed using the code PTOLEMY. The results are shown in fig.1. The total reaction cross-section extracted from the data is $\sigma_r = 1420 \pm 280$ mb for the reaction $^6\text{He}+^{64}\text{Zn}$ and $\sigma_r = 720 \pm 140$ mb for $^4\text{He}+^{64}\text{Zn}$ measured at the same c.m. energy.

Protons and α angular distributions for the $^6\text{He}+^{64}\text{Zn}$ reaction were also extracted showing that p are emitted from fusion evaporation processes whereas different reaction mechanisms contribute to the α s emission. This can be seen from the angular distribution which is isotropic for protons and forward peaked for α s.

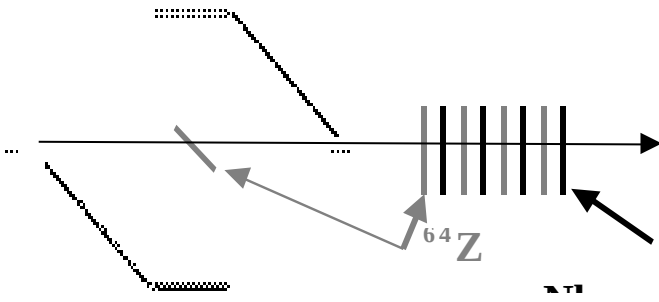


Figure2: Experimental set-up for the second run.

3 ACTIVATION EXPERIMENT

Residues produced after ${}^4\text{He}+{}^{64}\text{Zn}$ fusion evaporation process are radioactive and decay by Electron Capture with different half-lives ranging from 18 minutes to 270 days. After E.C. decay, X-rays are emitted. By detecting these X-rays one can extract the cross-section for the production of different radioactive E.R.. X-ray energies characterise different elements but not different isotopes. However in our case it was possible to discriminate isotopes according to the different half-lives.

The activation experiment was performed at the same time as the "standard" experiment described above. The excitation function was done at fixed beam energy by putting downstream the target used for the standard experiment, a stack of four ${}^{64}\text{Zn}$ targets (thickness $2\text{mg}/\text{cm}^2$) plus ${}^{93}\text{Nb}$ catchers (as shown in fig.2). Different stacks were irradiated with ${}^4\text{He}$ and ${}^6\text{He}$ beams. X-rays coming from the E.C. decay of E.R. were measured off-line using a Si(Li) detector surrounded with a lead shield to suppress the background. The advantages of detecting X-rays instead of γ -rays are: 100% intrinsic detection efficiency in the energy region of interest and a more effective background suppression. We were able to measure with a counting rate of less than 1 count per hour.

We started by analysing the targets irradiated with ${}^4\text{He}$ beam. A previous measurement existed [9] and therefore we could compare our results with that of [9]. We identified two radioactive E.R. the same as in [9] ${}^{67}\text{Ge}$ and

${}^{67}\text{Ga}$. In the ${}^6\text{He}$ activation experiment we identified 5 E.R.. These are shown in tab.1. Gallium isotopes were identified by following the activity curve as a function of time. The fusion excitation function was obtained by summing up the contributions of all E.R. identified. Preliminary results are shown in figure 3. Here is shown a comparison between the fusion excitation function for ${}^4\text{He}+{}^{64}\text{Zn}$ measured by [9] (squares), ${}^4\text{He}+{}^{64}\text{Zn}$ measured in this work (open triangles) and ${}^6\text{He}+{}^{64}\text{Zn}$ measured in this work (diamonds). In this analysis the efficiency was extracted by normalising the ${}^4\text{He}+{}^{64}\text{Zn}$ data to the ones of [9]. From this preliminary results it seems that at low energy (the calculated Coulomb barrier being around 11 MeV) the data sets for the two reactions ${}^6\text{He}+{}^{64}\text{Zn}$ are very similar. They differ at the higher energy point. At this energy there could be the opening of an additional E.R. channel which is stable. Data analysis is in progress to verify this possibility.

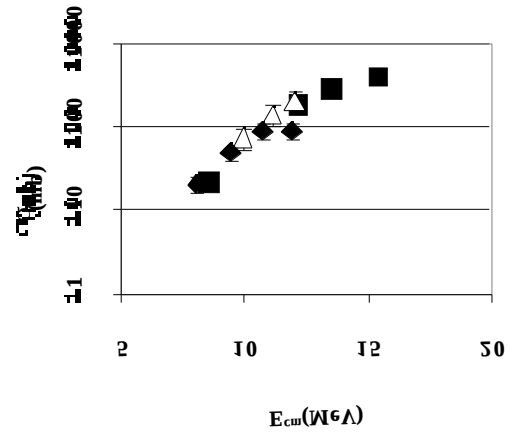


Figure 3: Excitation function ${}^4\text{He}+{}^{64}\text{Zn}$ from [9] (squares) this work (triangles), ${}^6\text{He}+{}^{64}\text{Zn}$ this work (diamonds)

E.R.	$T_{1/2}$	Decay Chain
${}^{65}\text{Zn}$	244 d	$\alpha+1n$
${}^{66}\text{Ga}$	9.49 h	$1p+3n$
${}^{67}\text{Ga}$	3.26 d	$1p+2n$
${}^{68}\text{Ga}$	67.6 m	$1p+1n$
${}^{68}\text{Ge}$	271 d	$2n$

Table 1: Evaporation Residues identified in ${}^6\text{He}+{}^{64}\text{Zn}$ experiment.

4 CONCLUSIONS

The reaction ${}^{6,4}\text{He}+{}^{64}\text{Zn}$ were studied at energies around the Coulomb barrier. The elastic scattering angular distribution was measured at two beam energies and from it the total reaction cross-section was extracted. The results show that at the same centre of mass energies the total reaction cross-section is a factor of two higher for reactions induced by the halo nucleus ${}^6\text{He}$ than for the non-halo ${}^4\text{He}$ nucleus. The excitation function for fusion reaction was measured for the ${}^6\text{He}+{}^{64}\text{Zn}$ and compared with ${}^4\text{He}+{}^{64}\text{Zn}$. It seems that in the energy region explored in this experiment, no strong enhancement of the fusion cross-section is present. This results seems different than what previously found in other ${}^6\text{He}$ induced reactions [4,5] but in agreement with the results of [6] for reaction induced by ${}^{11}\text{Be}$.

5 ACKNOWLEDGEMENT

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PRODUCTION OF A SECONDARY ^8Li BEAM: RESULTS OF PRELIMINARY TESTS

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Abstract

We report on preliminary tests concerning the production of a secondary ^8Li beam to be used for a possible study of the $^8\text{Li}(\alpha, n)^{11}\text{B}$ reaction, one of the key processes for the Inhomogeneous Big Bang Model.

1 INTRODUCTION

A key reaction in the Inhomogeneous Big Bang model is the $^8\text{Li}(\alpha, n)^{11}\text{B}$ producing ^{11}B and thus starting, by subsequent n-capture reactions, the synthesis of elements with $A \geq 12$. The relevant thermal energy region of this reaction is $E_0 = 0.3 \div 0.8$ MeV for the Big Bang temperature of 10^9 K. The cross section for $^8\text{Li}(\alpha, n)^{11}\text{B}$ was inferred for the first time [1] by using the inverse reaction $^{11}\text{B}(n, \alpha)^8\text{Li}$ revealing a surprisingly large cross section also at thermal energies (Figure 1). However this technique measures only the reaction yield for the $^8\text{Li}(\alpha, n)^{11}\text{B}$ reaction to the ^{11}B ground state, whereas the reaction ($Q = + 6.6$ MeV) can proceed to several excited bound states of ^{11}B . Thus the inverse reaction measures a lower limit of the $^8\text{Li}(\alpha, n)^{11}\text{B}$ cross section and direct data taken using radioactive ^8Li beams are necessary. Such experiments have been carried out [2-4]. The data in [2,3] suggests that the cross section

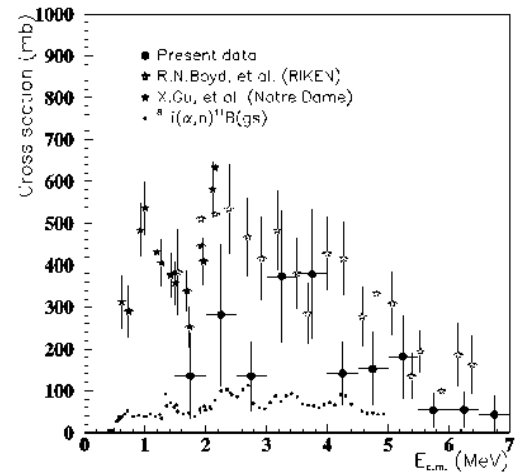


Figure 1: experimental results for $^8\text{Li}(\alpha, n)^{11}\text{B}$. Dots: data from the inverse reaction [1]; asterisks [2,3]; full circles [4]

inferred from the inverse reaction study may have to be increased by about a factor 5. Results in [4] have been obtained with errors of the order of 50% or more and are in disagreement with [2,3] showing cross sections which, on average, are a factor 2 or more lower than

[2,3]. Therefore new direct measurements with different experimental techniques are necessary for a better understanding of the problem.

2 PROPOSED EXPERIMENTAL TECHNIQUE

The experimental technique we are studying is sketched in figure 2. The experiment uses the

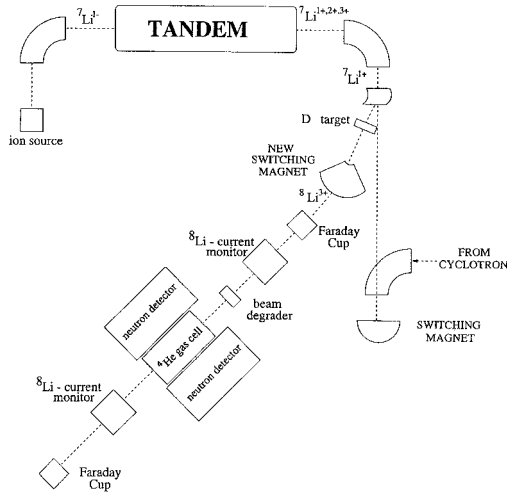


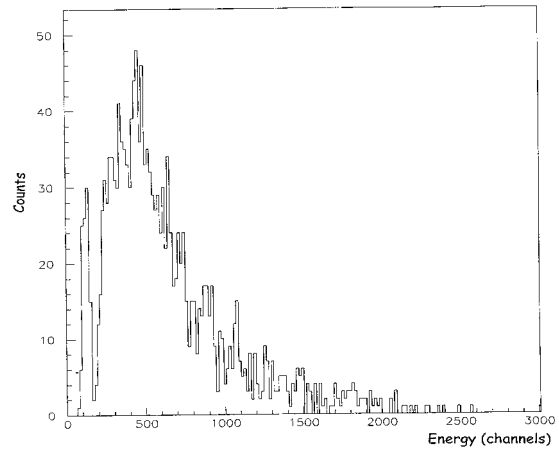
Figure 2: Sketch of the experimental set-up. Quadrupoles along the lines are not shown.

‘tandem by-pass’ beam line, which allows to use in parallel the two LNS accelerators. Such a beam line is essentially based on a dipole (placed just after the tandem 90° magnet) which can deflect the Tandem beam towards a second switching magnet. This, in turn, can send the beam into the 60° beam line or into the new 80° beam line where the present experiment can be installed. The radioactive ^8Li nuclides can be produced, via the reaction $^7\text{Li}(d,p)^8\text{Li}$ in inverse kinematics, in a primary target placed before the new switching magnet. The produced ^8Li are then focused using quadrupoles, and separated from the primary ^7Li beam passing through the new switching magnet. The beam is then focused again by another group of quadrupoles and sent through a ^8Li current monitor.

The monitoring of the ^8Li beam current ($E_{^8\text{Li}} \approx 9$ MeV in the present test) is performed using a device in which a Ta disk is inserted into the beam axis and then moved close to a Si detector, in a repeating cycle. The Si detector measures

(Figure 3) the β -delayed α -activity of ^8Li leading to α -events in the energy range $E_\alpha \approx 0.3 \div 5$ MeV. The plate with the Ta disc was

Figure 3: β delayed α particles observed in the ^8Li current monitor. The spectrum extends up to $E_\alpha \approx 5$ MeV and has a maximum around $E_\alpha \approx 1.2$ MeV.



mounted on a rotor shaft and moved periodically between the beam axis and the Si detector with a waiting time of 1.2 s at each location (and a transfer time of about 0.15 s between both locations). In order to implant the ^8Li ions near the surface of the Ta disc, and thus to observe the full α -spectrum of the ^8Li decay (Figure 3), degrading Al foils were also inserted on the beam axis near the rotating disc to reduce the ^8Li energy to about 0.5 MeV (“soft ^8Li landing”). The setup has an efficiency of about 3.5% for ^8Li detection, including the effect of the decay time of ^8Li and taking into account the solid angle covered by the Si detector. This ^8Li monitor operated reliably in the production tests we performed.

In the case ^8Li beams with appropriate quality will be obtained, we plan to study the $^4\text{He}(^8\text{Li},n)^{11}\text{B}$ reaction with the detection set-up sketched in figure 2. Here a large solid angle neutron detector measures the neutrons emitted in the reaction, which takes place in an ^4He gas target with windows. A neutron detector provided by the California Institute of Technology has recently been assembled at LNS. The detector consists of 12 ^3He -filled proportional counters embedded in a polyethylene moderator. The moderator is a cube having each side 40 cm long, with an 11

cm x 11 cm hole through the center for the beam pipe. A 4π Cd shielding (0.6 mm thick) surrounds the polyethylene cube, and is in turn surrounded by a 4π passive layer of moderator. This passive shielding is used to absorb externally produced background neutrons. The 12 ^3He proportional counters are positioned around the beam pipe in a circle of about 12 cm radius. Past experience, from the previous use of the detector at Caltech, has shown typical detection efficiencies of the order of 20% and background rates of the order of 200 n/h.

As an example, assuming a neutron detection efficiency of 20%, a current of 10^4 ^8Li /s, a cross section of 200 mb, an ^4He gas target 10 cm long operated at $P=100$ mbar, and a background rate of 200 n/h, one would obtain a statistical error of about 10% with two days of data taking.

3 RESULTS OF THE PRELIMINARY TESTS

Waiting for the completion of the ‘tandem by-pass’ beam line, preliminary tests have been performed by using the already existing beam lines. In these tests ^8Li has been produced in a target placed before the old switching magnet. It was then focused and sent into the switching magnet where it was separated from the primary beam. The ^8Li secondary beam was then focused again and sent into the ^8Li current monitor. Most of the test measurements were carried out at a ^7Li energy of 10.5 MeV, using as primary targets CD_2 foils coated with a thin layer ($30\mu\text{g}/\text{cm}^2$) of C which greatly improved the resistance of the foils to the primary beam current. At this energy the maximum primary current $i_{^7\text{Li}} \approx 100$ pA was obtained with a charge state +1 using a gas stripper. The tuning of the beam optics for the ^8Li nuclides was done in the following way: in a first step, the ^7Li beam emerging from the primary target (being predominantly now in the 3^+ charge state) was tuned through the switching magnet onto a quartz monitor and a Faraday cup both positioned just after the ^8Li monitor, using two quadrupoles (one before and one after the

switching magnet) and steerers. In the second step, the ^8Li monitor was turned on and the ^8Li number of counts were measured as a function of the field strength of the switching magnet. This procedure is valid because the ^7Li and ^8Li particles emerging from the primary target have the same charge state (3^+) and nearly the same energy and angle straggling (difference in rigidity $\approx 3.5\%$).

The resulting rigidity curve for the ^8Li nuclides obtained with a CD_2 target of $160\mu\text{g}/\text{cm}^2$ is shown in Figure 4. Two ^8Li groups were observed, which were identified as originated from ^8Li production in its ground state (high-energy group) and in its first excited state (low-energy group). Data taken

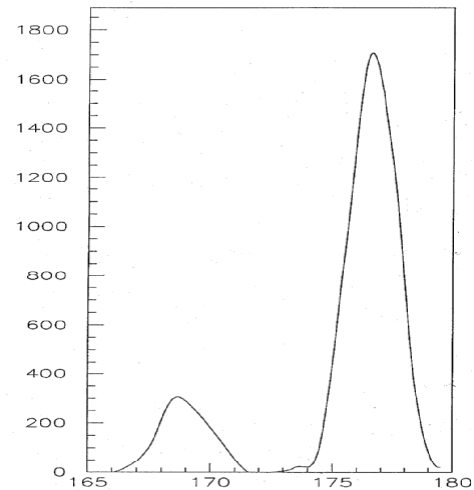


Figure 4: ^8Li current (arbitrary units – y axis) as function of the field in the switching magnet (arbitrary units – x axis)

with a thicker target of $1000\mu\text{g}/\text{cm}^2$ showed a larger energy straggling of both groups and thus a significant overlap of the ^7Li beam with both groups. We measured then the acceptance of the switching magnet (plus subsequent apertures) and found it to be 1.4%, i.e. much smaller than the width of the ^8Li peaks obtained with the thin target. Thus, there is no advantage in using a relatively thick primary target because only a fraction of the produced ^8Li is accepted by the switching magnet. As a cross check we also performed some tests replacing the CD_2 foil with a CH_2 foil. As expected no counts were observed in the ^8Li current monitor.

The maximum ^8Li current of 1100 $^8\text{Li/s}$ has been obtained with a $160\text{ }\mu\text{g/cm}^2$ CD_2 primary target and a primary current of 120 pA.

After these tests performed with a CD_2 target, we also investigated the possibility to use a deuterium gas cell as primary target. The cell was about 10 cm long, with Al windows 1.6 mg/cm^2 thick, and was operated between 100 and 150 mbar pressure. Selecting the forward kinematic solution for the ^8Li we obtained a ^8Li current about a factor 3 larger than the one found with the CD_2 target. However, due to energy loss problems in the thick Al windows a very strong ^7Li contamination was present. Encouraging results, similar to the ones with CD_2 target, were obtained increasing the primary beam energy and selecting the backward kinematic solution for ^8Li . Further tests have to be performed using the gas cell (e.g. optimising the window material, window thickness and operating pressure) to find the best working conditions.

Even if in the preliminary tests ^8Li currents similar to the ones used in other laboratories [e.g. 4] have been obtained, additional on-beam tests need to be performed to understand if actual studies of $^4\text{He}(^8\text{Li},n)^{11}\text{B}$ can be started reliably. One test addresses the proper choice of window material for the ^4He gas cell, i.e. kapton foils versus metallic foils (such as Al), in view of minimising a possible neutron background generated by the ^8Li beam in the foils themselves. This can be measured by the difference of neutron fluxes with and without ^4He gas in the cell. Another test is devoted to the primary target. Foil (CD_2) and gas targets should be tested again to understand which is the best solution. Finally, systematic tests have to be performed to quantitatively study the presence of possible impurities in the ^8Li beam.

The above tests will be performed using the new tandem by pass beam line with the following advantages :a)larger solid angle acceptance of the new switching magnet and therefore larger expected ^8Li currents; b)possibility to operate independently from the Cyclotron activity.

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STRONG ENHANCEMENT OF EXTREMELY ENERGETIC PROTON PRODUCTION IN CENTRAL HEAVY ION COLLISIONS AT INTERMEDIATE ENERGY

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Abstract

The energetic proton emission has been investigated as a function of the reaction centrality for the system $^{58}\text{Ni} + ^{58}\text{Ni}$ at 30A MeV and compared with dynamical calculations. Extremely energetic protons ($E_p^{\text{NN}} \geq 130$ MeV) were measured and their multiplicity is found to increase almost quadratically with the number of participant nucleons thus indicating the onset of a mechanism beyond one and two-body dynamics.

1 INTRODUCTION

Heavy ion collisions at intermediate energy allow to investigate the properties of nuclear matter far from stability. Particles such as subthreshold mesons or energetic photons and nucleons, which are produced in the early non equilibrated stage of the reaction where high temperatures and densities are reached, can provide information on the nuclear dynamics at the pre-equilibrium phase (see [1] and reference therein). In particular, experimental evidences, such as the observed γ -proton anti-correlation [2] and the energetic proton angular distributions [3], show that the energetic protons are emitted in the first stage of the reaction according to expectations [1] and therefore are good candidates to probe the pre-equilibrium phase.

On the other hand, the observation of extremely energetic nucleons or deep subthreshold particles over a broad range of incident energy addresses the question of which mechanisms could enable to concentrate a relevant fraction of the available energy in the production of a single energetic or massive particle [4] which is a challenging aspect

of heavy ion collisions both experimentally and theoretically.

The experiment described in this report is one of experiments performed with the MEDEA & MULTICS apparatus at LNS which have allowed to explore new aspects of the nuclear dynamics owing to the simultaneous measurement of photons, light charged particles and fragments.

In the following we present results concerning the emission of protons with energy extending up to almost 20% of the total available energy in the reaction $^{58}\text{Ni} + ^{58}\text{Ni}$ at 30A MeV [5]. Since these energies largely exceed the maximum energy expected in first chance NN collisions due to the coupling of the relative motion with a sharp nucleon Fermi momentum distribution (kinematical limit), this investigation can also provide a clue for the comprehension of the deep subthreshold particle emission in this energy domain.

2 EXPERIMENTAL APPARATUS

The experiment was performed at Laboratori Nazionali del Sud with the MEDEA [6] and MULTICS [7] apparatus. A ^{58}Ni beam at 30A MeV delivered by the Superconductive Cyclotron (CS) system bombarded a ^{58}Ni target 2 mg/cm² thick.

MEDEA consists of a ball made of 180 BaF₂ detectors placed at 22 cm from the target which covers the polar angles from 30° to 170°. The BaF₂ permits to detect and identify light charged particles ($E_p < 300$ MeV) and photons up to $E_\gamma \cong 200$ MeV.

The MULTICS array is made of 55 telescopes covering the angular range $3^\circ < \theta_{\text{lab}} < 28^\circ$. Each telescope consists of an Ionization Chamber, a Silicon detector and a CsI crystal, and allows the identification of charged particles up to $Z=83$.

The threshold for charge identification was about 1.5 A MeV. The total geometric acceptance was larger than 90% of 4π .

Altogether approximately 4×10^8 events were collected and analysed.

3 RESULTS AND DISCUSSION

According to the standard three moving source analysis, the high energy proton emission at large polar angles can be described by a source emitting with velocity close to the half beam velocity and a high inverse slope parameter in good agreement with the systematics (pre-equilibrium emission) [8].

Protons with energy well above the kinematical limit expected in the hypothesis of first chance NN collisions and sharp Fermi momentum distribution ($V_{\text{max}} = V_F + 0.5 \times V_{\text{beam}}$) (arrows of fig.1) are observed in the spectra.

Simulations with a BNV code, which is based on mean field and two body dynamics, were performed, using a Gale-Bertsch-Das Gupta momentum dependent interaction (GBD) (open circles of fig.1b) [9]. Experimental and calculated spectra in the NN frame are reported in fig.1 for central collisions. The calculated spectrum appears in good agreement with data concerning both the yield and the slope (at least up to about 110 MeV).

However, the calculated yield 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

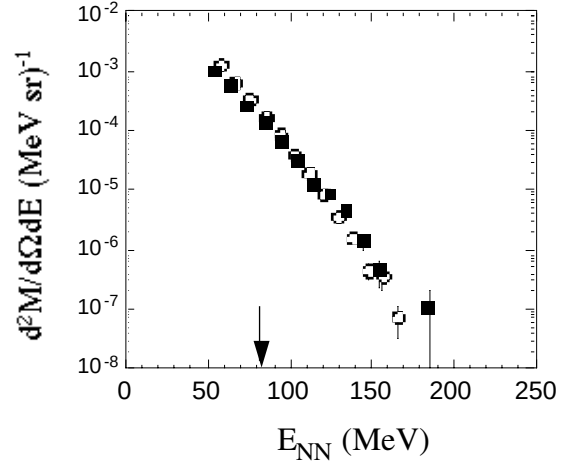


Fig. 1 Proton energy multiplicity spectrum in the NN reference frame for central collisions. Data (full squares) and BNV calculations (open circles) are reported. The arrow indicates the expected kinematical limit for first chance NN collisions.

experimentally [8].

Extremely energetic protons were already observed in heavy ion collisions (see [3] and refs. therein), but those experiments did not allow a conclusive answer on the production mechanism to be drawn.

Therefore, with the aim of improving the overall understanding of the energetic proton emission and disentangling between the various hypotheses for the production of the most energetic protons, we have investigated the impact parameter dependence. Indeed, the dependence of multiplicity on the number of nucleons participating in the reaction A_{part} can provide information about a change in the production mechanism. A stronger than linear increase of the multiplicity as a function of the number of participant nucleons has been observed, at much higher incident energy, in the deep subthreshold production of K^+ [10], η [11] and energetic π^0 [4]. In particular, the trend of the multiplicity of high transverse-mass π^0 which scales as $A_{\text{part}}^{4/3}$, has been interpreted in terms of rescattering of the pion (two step process) [4].

At energy as low as 30 A MeV, the fluctuations on global variables such as the charged particle multiplicity and transverse energy affect the determination of the impact parameter especially for the most central collisions [12].

To cover a wide range of impact parameters, we exploit the reaction mechanism and hard photon multiplicity information to determine the size of the interaction zone [13,14]. Indeed, the detection of heavy fragments from projectile-like fragments to evaporation residues allows to select classes of events with different centrality. A few classes of events were also selected in terms of total charged particle multiplicity. For the various classes of events, the number of participant nucleons $A_{\text{part}}(b)$ has been extracted from the hard photon ($E_\gamma \geq 30$ MeV) multiplicity, according to the relation $M_\gamma(b) = P_\gamma \times N_{\text{np}}(b) \equiv P_\gamma \times 0.5 \times A_{\text{part}}(b)$ where P_γ is the probability of emitting a hard photon in a np collision deduced from inclusive data ($P_{\gamma(E_\gamma \geq 30 \text{ MeV})} \equiv 2.7 \times 10^{-5}$) and $N_{\text{np}}(b)$ is the number of first chance np collisions occurring in the overlap region [13].

In fig.2 the average proton multiplicity is reported as a function of the number of nucleons participating $A_{\text{part}}(b)$ in the collision for different energy bins in the NN reference frame ($60 \div 80$ MeV ($M_p(60)$), $100 \div 120$ MeV ($M_p(100)$), $130 \div 150$ MeV ($M_p(130)$)).

The experimental proton multiplicity (full squares) displays the expected linear dependence on $A_{\text{part}}(b)$ [15], for energy close to the kinematical limit ($60 < E_{\text{p}}^{\text{NN}} < 80$ MeV fig. 2a), while a stronger dependence is observed with increasing proton energy. In particular, the multiplicity of extremely energetic protons ($M_p(130)$) exhibits an almost quadratic increase with A_{part} (fig.2c). Only protons emitted in the angular range $75^\circ < \theta_{\text{lab}} < 138^\circ$ were considered. Within this angular range the contribution of double hits is reduced due to the focusing of the emitted particles at forward angles. In particular for the most energetic protons $130 < E_{\text{p}}^{\text{NN}} < 150$ MeV, where this effect is expected to be larger, an upper limit for this contribution of about 7% has been estimated in the b range investigated.

The BNV calculations, filtered with the experimental apparatus, are also reported in fig. 2 (open circles). The $A_{\text{part}}(b)$ assignment relies on the hypothesis of a geometrical correlation between b and $A_{\text{part}}(b)$ [14]. The 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 good agreement with the data

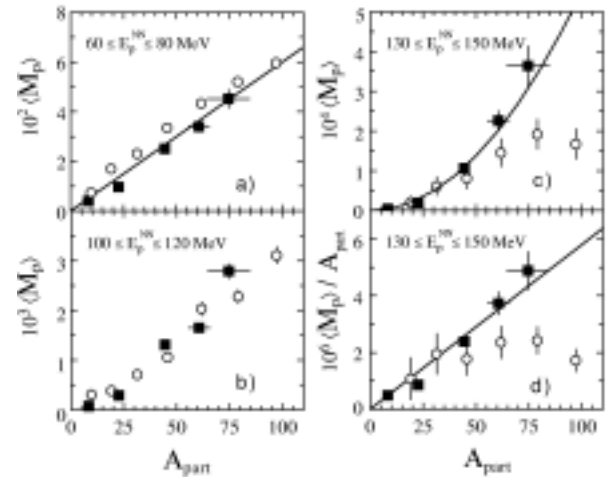


Fig. 2 Proton multiplicities as function of the number of participant (see text) for different energy bins. Experimental values (solid squares) and momentum dependence BNV calculations (open circles) scaled by a factor 0.6 are reported. In panel d) the points of panel c) are divided by A_{part} and reported versus A_{part} . A linear (panels a-d full lines) and a quadratic dependence (panel c full line) are reported.

is observed in fig.2a and fig.2b, confirming that the energetic proton production is described with good accuracy up to about 110 MeV. On the other hand, BNV calculations fail in the most energetic bin ($M_p(130)$, fig.2c) where the almost quadratic dependence on A_{part} observed experimentally is not reproduced. It is interesting to notice that a non linear dependence is observed, both experimentally and theoretically, also for $M_p(100)$. The calculation can account for this behaviour due to the increasing importance of multistep two-body collisions in the production mechanism of protons with energy higher than the kinematical limit similarly to the trend observed for high transverse-mass π^0 [4]. However, this mechanism seems not to be able to explain the almost quadratic behaviour observed for $M_p(130)$. Indeed, for extremely energetic protons, this multistep process is associated with larger time scales. Therefore the system can emit nucleons and rapidly evolves far from the initial geometrical overlap configuration. This can explain the weaker dependence on the impact parameter observed in the calculations (fig. 2c). To emphasize the difference between data and BNV multiplicity per participant nucleon $M_p(130) / A_{\text{part}}$ is reported in fig. 2d. The experimental value (full squares) is found to increase linearly with $A_{\text{part}}(b)$, as expected since $M_p(130)$ scales as $A_{\text{part}}^2(b)$, in contrast with calculations (open circles) which exhibit a

different trend. This discrepancy indicates the onset of effects beyond the mean field and two body collisions. The observed behaviour of the multiplicity of very energetic protons on the number of participant nucleons (figg. 2c and 2d) puts constraints on the mechanism responsible for the production of extremely energetic protons. We have found that multistep two body collisions, which play an important role in the production of protons with energy between 100 and 120 MeV, do not reproduce the trend of the most energetic protons ($E_p^{NN} \geq 130$ MeV) which exhibits a stronger dependence on A_{part} (b). Dynamical fluctuations [16], are not expected to lead to the A_{part} quadratic behaviour observed experimentally. Other effects, such as high momentum tails, are weakly dependent on density and, at the energy considered, density variation from central to peripheral impact parameters are small [17]. Cooperative effects, where more nucleons or clusters of nucleons participate in the collision, seem very promising and should be investigated.

4 SUMMARY

In summary, the energetic proton production has been investigated up to proton energy corresponding to about 20% of the total energy available in the system. The energetic protons up to about 110 MeV are emitted as a consequence of NN collisions in the first stage of the reaction and their characteristics are well reproduced by BNV calculations which include the momentum dependence in the effective potential. On the other hand, the BNV approach fails to explain the almost quadratic dependence on the number of participant nucleons of the yield of very energetic protons ($E_p^{NN} \geq 130$ MeV). This behaviour calls for the introduction of mechanisms beyond the mean field and two body nucleon-nucleon collisions such as cooperative effects. These results shed some light on the emission of extremely energetic protons and can improve the understanding of the mechanism responsible for deep subthreshold particle production.

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Probing IMF production mechanisms with thermal photons

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Abstract

Thermal photons have been used as a clock to determine the time of IMF emission during the evolution of the nuclear reaction. The method has been applied to the reaction $^{58}\text{Ni} + ^{197}\text{Au}$ at 30 and 45 MeV/amu incident energy. The results put in evidence that the relative contribution of the two possible production mechanisms (dynamical and statistical) is quite different in the two cases. A comparison with theoretical calculations strongly supports the experimental findings.

1 INTRODUCTION

Heavy ion reactions at intermediate energy are known to proceed through density oscillations (fig.1) from an early pre-equilibrium phase, where nucleon-nucleon (n-n) collisions play the dominating role, to an equilibrium phase, where the de-excitation of the system is purely statistical. At the beginning of the reaction the system experiences a strong compression during which nucleons collide and this leads the system to a following expansion. During this expansion phase, if the system is driven into the spinodal region, instabilities can start and disassemble it. If the system survives this phase, it will undergo a new compression to restore the normal density and, at the end, a heavy and hot system (HHS) will be produced. During this time evolution several interesting processes can occur, that are typical of the intermediate energies. Let's focus on some of them. During the first compression, as a consequence of first chance n-n collisions, high energy ($E_\gamma \geq 25$ MeV) bremsstrahlung photons ("direct") are produced

[1]. Their production stops as soon as the system starts to expand and it is not influenced by the following evolution of the reaction. If, while the system is expanding, very low densities are reached and the system enters the spinodal region (as at $t = t_0$ in fig.1), another interesting phenomenon can occur, i.e. the dynamical production of Intermediate Mass Fragments (IMF) that destroys the original composite system and interrupts the path towards the formation of a HHS. If this doesn't happen, the second compression forces the n-n collisions to start again and, with them, the bremsstrahlung photon production, with the difference that now their energy spectrum reflects the energy distribution of the nucleons in the equilibrating system. It's important to note that this contribution, called "thermal"[2], is observed only if the dynamical evolution of the reaction leads to the formation of a HHS and, in this sense, it is a signature of its formation. The hot HHS can later loose its energy by statistical decay, including statistical IMF emission.

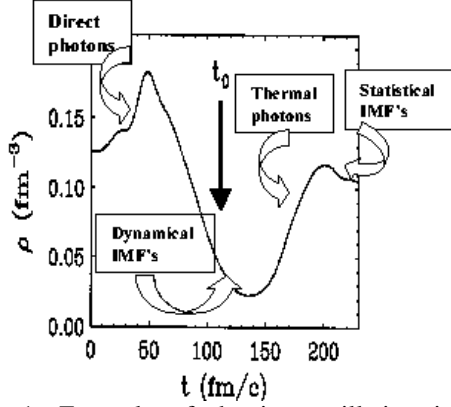


Figure 1: Example of density oscillation in central collisions (BNV calculations) and related phenomena.

2 THE EXPERIMENT

With the aim of investigating the mechanisms of IMF production, an experimental program has been undertaken at Laboratori Nazionali del Sud with beams of the Superconducting Cyclotron. The idea was to use thermal photons to tag the presence of a HHS surviving the density oscillation. To observe IMF's in coincidence with such photons is an evidence of their statistical origin, while their dynamical origin is signaled by an anticoincidence.

Since these studies require a very performant apparatus, able to detect and identify simultaneously hard photons and IMF's, we have used the two multidetector arrays MEDEA[3] and MULTICS[4], measuring with good efficiency and granularity hard photons in MEDEA, light charged particles (LCP) in both and IMF's in MULTICS.

The system chosen for this study had to be heavy enough to experience a significant compression and following expansion and, also, two different bombarding energies, where the two possible production mechanisms could be expected to show up with different probabilities, were necessary to make a comparison. For these reasons the system $^{58}\text{Ni} + ^{197}\text{Au}$ at 30 and 45 MeV/amu incident energy was chosen.

3 EXPERIMENTAL RESULTS

First, a detailed analysis of the hard photons has been performed. Fig.2 shows the experimental hard photon energy spectrum for the system $^{58}\text{Ni} + ^{197}\text{Au}$ at 45 MeV/amu.

Superimposed the results of a two exponential component fit to the data are also shown. The presence of the thermal photons is evident. Similar results are observed for the 30 MeV/amu data [5].

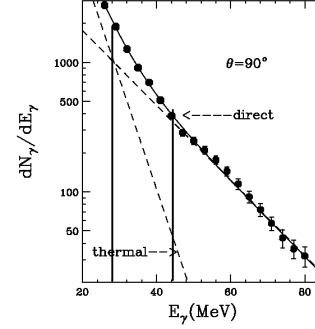


Figure 2: Experimental hard photon energy spectrum. Dashed lines represent the contribution of direct and thermal photons. It can be seen that thermal photons mainly affect the lower energy part of the spectrum.

Using LCP's to select impact parameter b the hard photon energy spectra have been sorted in several b bins as a function of the detection angle. A simultaneous fit to the energy and angular distributions for each b interval allowed us to determine some characteristics of the thermal photon source. A source velocity approaching that of the nucleus-nucleus center of mass with increasing centrality and a very small anisotropy have been deduced, supporting the interpretation [2] of a late production mechanism. Thermal photons are always present in the spectra stating that a HHS is formed in a significant fraction of events. The ratio of the thermal component to the direct one, however, is observed to decrease with increasing bombarding energy, qualitatively indicating the onset of a competing mechanism.

The experimental tool chosen to put in evidence the main source of IMF's was the study of the thermal photon-IMF correlation factors, defined as

$$1 + R_{\gamma\text{-IMF}} = \frac{\langle m_{\text{IMF}} \rangle^{\gamma}}{\langle m_{\text{IMF}} \rangle}$$

where $\langle m_{\text{IMF}} \rangle^{\gamma}$ and $\langle m_{\text{IMF}} \rangle$ are the mean values of the multiplicity distribution of IMF's in events gated by thermal photons and not gated, respectively. Values of this quantity smaller than one signal that in the events in which a hard photon is emitted a decrease in IMF production is observed. In the framework of

Fig.1 this can be easily understood if a relevant fraction of IMF's is of dynamical origin. Indeed, due to the large excitation energies expected mainly in central collisions (of the order of GeV) the emission of a thermal photon is not expected to affect the emission of statistical IMF's. For the gamma's gating the IMF multiplicities an energy between 25 and 40 MeV was selected to maximize the ratio of thermal to direct photons without losing too much in counting statistics. In this energy range this ratio is almost 1. When the correlation factors are deduced in such a way, what is observed, in effect, is the sum of the thermal and direct correlation factors weighted by the fraction in which each source contributes to the total photon yield in the selected photon energy range:

$$1+R_{\gamma\text{-IMF}} = \sum \frac{N_{\text{therm,direct}}^{\gamma}}{N^{\gamma}} (1+R_{\gamma\text{-IMF}})_{\text{therm,direct}} \quad (1)$$

The photon and IMF data have been sorted as a function of the impact parameter for both the beam energies. For each impact parameter bin, the correlation factors have been determined in three IMF parallel velocity windows: the window W_1 centered at the nucleus-nucleus center of mass, the window W_2 centered at half-beam velocity and the window W_3 around the projectile-like velocity.

First, we have checked in the data that the direct photon-IMF correlation factor is always very close to one and this is consistent with the production of IMF's occurring later and independently of the direct photons. Therefore, the effect of the $(1+R_{\gamma\text{-IMF}})_{\text{direct}}$ contamination in (1) is that it tends to maintain the correlation factors close to one. Then we have considered the experimental correlation factor (1). We have found that it is always close to 1 with the only exception of the IMF velocity window W_1 in central collisions at 45 MeV/amu, where it is significantly smaller than one. In other words photons and IMF are always uncorrelated except one case, at 45 MeV/amu, where they are anticorrelated. Fig.3 shows the results for the window W_1 for both the incident energies.

We can distinguish two different reasons for the absence of correlation. First, IMF's and photon's are emitted by independent sources moving with different velocities: this is likely

the case of the correlation factors with IMF's located in W_2 and W_3 . Second, IMF's and thermal photons are produced independently within the same source: this is the case of the 30 MeV/amu central collisions with IMF's in W_1 . This is a case of particular interest in this work since it signals a dominance of statistical fragmentation. The observation of a correlation factor smaller than 1 at 45 MeV/amu for IMF's in W_1 is also of very special interest for the aim of this work, since it is the type of signal expected when dynamical fragmentation dominates. Moreover, in the correlation factors shown in Fig.3 the true signal of dynamical fragmentation is partially dimmed by the contamination of the direct photons. Then, with the caution due to the experimental error bars, from the correlation data in Fig.3 and using (1) we can deduce that the **thermal** photon - IMF correlation factor in central Ni + Au collisions decreases from 1 at 30 MeV/amu to 0.25 at 45 MeV/amu. The indication of the whole set of data is that at 30 MeV/amu the IMF production is dominated by statistical decay while at 45 MeV/amu, at least in central collisions, it is strongly affected by the dynamical evolution of the collision.

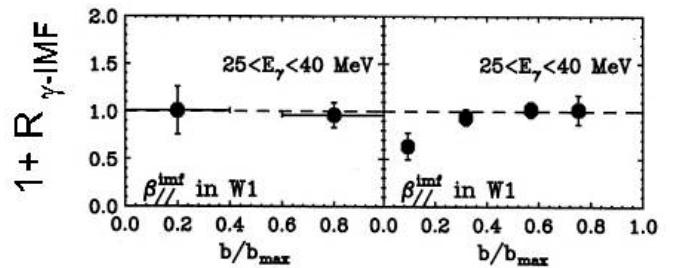


Figure 3: Experimental correlation factors as a function of centrality. Left: 30 MeV/amu; right: 45 MeV/amu.

4 THEORETICAL CALCULATIONS

In order to corroborate the interpretation of these data with a theoretical model, we have performed a three steps simulation of the IMF production in the reactions studied in this work. In the first step, for each bombarding energy, we have calculated the density profile versus time of Fig.1 by means of dynamical BNV simulations of central collision events. In the second step, the BNV configuration at the time t_0 at which, during the expansion phase, the system enters the spinodal region was used as

the starting point to introduce density fluctuations, that could lead to fragmentation, and solve the Boltzmann-Langevin equation [6]. Although the BNV density profiles at the two energies are very similar, the fragment charge distributions predicted by the BNV+Boltzmann-Langevin calculations are completely different. At 30 MeV/amu in most of the events the system experiences a second compression resulting in a HHS formation. On the other hand, at 45 MeV/amu this happens in only a small fraction of the total number of events. At this stage of the simulation we have calculated the ratio of the mean multiplicity $\langle m_{\text{IMF}} \rangle^{\text{HHS}}$ of the IMF production which is followed by the transit through a HHS to the mean inclusive multiplicity $\langle m_{\text{IMF}} \rangle$. Similarly to (1) this ratio expresses the correlation factor between dynamical IMF production and heavy remnant formation. Full lines in Fig.4 show this theoretical correlation factors for each bombarding energy and for central collisions, calculated for heavy remnant charge $Z > Z_{\text{cut}}$ versus Z_{cut} . For both energies the calculations predict a negative correlation which becomes stronger with increasing Z_{cut} and reflects mainly charge conservation: the larger the charge of the heavy remnant the smaller the multiplicity of fragments. Since the heavy remnant formed is excited we introduce in our simulation a third step, i.e. the statistical deexcitation. Using the statistical code Simon we have deduced the mean multiplicity of IMF's emitted at this stage, for each Z_{cut} . This contribution has been added to the previous one and the new correlation factors resulting from this procedure are shown as dashed lines in Fig.4. The different behaviour of the system at the two energies is evident. While at 30 MeV/amu the statistical contribution dominates and let the correlation factors tend to 1, at 45 MeV/amu almost nothing changes since the dominating contribution comes from the dynamical evolution of the collision. The possible emission of a photon bringing away about 40 MeV excitation energy before starting the deexcitation was checked to be ininfluent at 45 MeV/amu because of the large total excitation energy and to affect only slightly the results at

30 MeV/amu. This seems to exclude the observed anticorrelation to be a trivial energy balance effect.

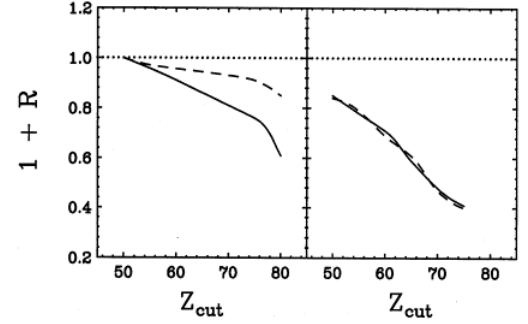


Figure 4: Theoretical correlation factors as a function of Z_{cut} . Left: 30 MeV/amu; right: 45 MeV/amu.

5 CONCLUSIONS

Using thermal photons as a probe, the main source of IMF emission in Ni + Au reactions at 30 and 45 MeV/amu incident energy has been deduced exploiting the hard photon - IMF correlation function versus the reaction centrality and IMF velocity. IMF's produced by statistical deexcitation of a heavy system formed **at the end** of the dynamical evolution of the collision have been found to dominate at 30 MeV/amu while IMF's emitted **during** the dynamical evolution dominate at 45 MeV/amu.

The set of calculations we have performed largely agrees with our experimental results and supports our interpretation and, implicitly, the use of thermal photons as a signature of the formation of a HHS.

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Mid-velocity IMF emission in peripheral heavy-ion collisions at Fermi energies

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Abstract

The emission pattern in the $V_{\text{perp}} - V_{\text{par}}$ plane of Intermediate Mass Fragments with $Z=3-7$ (IMF) has been studied in the collision $^{116}\text{Sn} + ^{93}\text{Nb}$ at 29.5 A MeV as a function of the Total Kinetic Energy Loss of the reaction. This pattern shows that for peripheral reactions most of IMF's are emitted at mid-velocity. Coulomb trajectory calculations may be used to shed light on geometrical details of these emissions.

Recent experiments have found an intense emission of intermediate mass fragments (IMF) at mid-velocity [1-7] in collisions of heavy ions in the "Fermi regime", i.e. at bombarding energies from 30 to 50 A MeV.

For non-central collisions, the mid-velocity particles have been easily identified in the $V_{\text{perp}} - V_{\text{par}}$ plots (the velocity components being usually defined with respect to the asymptotic separation axis of the two heavy reaction partners) and their intensity cannot be explained on the basis of the statistical emission from the hot, fully accelerated main fragments.

Presently, the isospin composition of the mid-velocity light charged particles ($Z \leq 2$, LCP) and IMF's is a subject of broad interest, as it can be related to the composition of the emitting source (see, e.g., [8] and references therein). Equally controversial is the mechanism responsible for these mid-velocity emissions, which may be of dynamical nature, but claims of a pure statistical emission perturbed by Coulomb interaction have also been made [9].

Investigations by the Indra collaboration [7] have shown that, for a given bombarding energy, the ratio of mid-velocity to evaporative IMF's increases with increasing impact parameter up to a value of about 3 for the largest measured impact parameters.

However, due the relatively high thresholds for TLF detection the very peripheral collisions could not be reliably selected.

One of the aims of our experiment (FIASCO, Florentine Initiative After Superconducting Cyclotron Opening) was to fill this gap and to perform an accurate investigation of the mid-velocity IMF emission.

The system $^{93}\text{Nb} + ^{116}\text{Sn}$ was studied in direct and inverse kinematics with beams delivered by the Superconducting Cyclotron of the "Laboratori Nazionali del Sud" in Catania (Italy).

Thin targets of ^{93}Nb and ^{116}Sn were bombarded with pulsed beams of ^{116}Sn and ^{93}Nb , respectively, characterized by an intensity < 0.1 nA and a time resolution < 1 ns. Because of the limited statistics of the data collected in the first production runs, only data referring to the inverse system $^{116}\text{Sn} + ^{93}\text{Nb}$ could be used.

The newly built experimental setup basically consisted of 24 position-sensitive Parallel Plate Avalanche Detectors (PPAD) [10,11], which covered about 70% of the forward solid angle, where most heavy reaction products ($A > 20$) of a nearly symmetric reaction are concentrated.

The PPAD measured, with very low thresholds (< 0.1 A MeV), the impact time and position of the heavy reaction products: the time resolution was about 600 ps (FWHM) and the position resolution 3.5 mm (FWHM).

Primary (i.e. pre-evaporative) quantities were then deduced, event-by-event, from the velocity vectors, using an improved version [12] of the Kinematic Coincidence Method (KCM).

With respect to previous experiments [13,14], the new setup included also 160 phoswich scintillators mounted behind most of the PPAD's.

The phoswiches detected LCP's and IMF's with $Z < 20$ in about 40% of the forward solid angle; a reduced sampling was available also in the backward hemisphere.

The phoswiches were of two types: two-element modules (consisting of a thin fast plastic BC404 and a thick CsI(Tl) crystal) or three-element ones (consisting of the same thin fast plastic BC404, plus a thicker slow plastic BC444 and a thick CsI(Tl) crystal). They were coupled via light guides to fast phototubes with especially designed active bases.

The fast scintillators had been carefully machined down to about 200 microns in our workshop, with thickness uniformity better than 5%, as required to achieve Z identification up to about $Z=20$.

The thickness of the slow BC444 was 5 mm and that of the CsI(Tl) was 50 mm for those at smaller angles and 30 mm for the others.

In the three-element modules, the lack of dead layers and the good optical transmission (obtained by coupling the two plastic elements with the heat-pressing technique) allowed to identify IMF's with low thresholds (about 3-10 AMeV for $Z=2-20$).

From the measurement of the time of flight the velocities of LCP's and IMF's could be obtained directly, with no need for time consuming and tricky energy calibrations of the scintillators.

A detailed description of the apparatus can be found in [15].

We present here some first results concerning binary events, where only two major fragments are detected in the PPAD's while the coincident LCP's and IMF's hit the phoswich detectors. Using the Total Kinetic Energy Loss (TKEL) as an ordering variable, it is possible to select events with increasing impact parameter up to grazing collisions.

Equivalently, this corresponds to a selection of events with a decreasing interaction time between the collision partners.

The TKEL was obtained from the KCM with the 2-body kinematics, not only for LCP, but also for IMF emission. In fact, it was found that in case of emission of just one IMF (the average IMF multiplicity is well below 1 for semiperipheral

collisions) there is good agreement between the results of the analysis with the 2-body kinematics (ignoring the IMF) and with the 3-body kinematics (including the IMF as a third body).

Preliminary results were presented in Ref. [8].

In fig.1 we present the yields of p, d, t, He and IMF ($Z=3-7$) in the plane of the center-of-mass velocity components parallel and perpendicular, respectively, to the asymptotic separation axis of the two major fragments. The experimental data are in the left panels and refer to the bin $\text{TKEL}=240-400$ MeV. The dotted lines show the velocity thresholds caused by the thickness of the fast plastic scintillator.

The data have been corrected for the finite

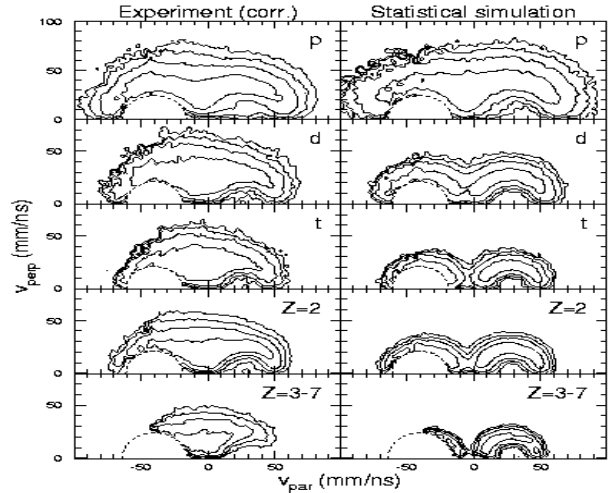


Figure 1. *Left:* experimental yields in the $V_{\text{perp}}-V_{\text{par}}$ plane for p, d, t, He and IMF's ($Z=3-7$) in $^{116}\text{Sn} + ^{93}\text{Nb}$ at 29.5 AMeV, for $\text{TKEL} = 240-400$ MeV (corrected for the setup geometry). Contour level spacing is logarithmic, dashed lines indicate velocity thresholds.

Right: same results for the simulated statistical evaporation from the hot reaction partners.

geometry of the apparatus [15], the efficiency of the detectors and the energy loss in the target. Because of large acceptance and axial symmetry of the setup, the correction is largely independent of the emission pattern.

In the backward lab-hemisphere (corresponding to CM parallel velocities < 40 mm/ns), owing to the reduced detector coverage, the correction is not as effective as forwards.

For comparison, the right panels of the figure show the corresponding yields obtained with the simulation of a pure evaporative emission from fully accelerated fragments, filtered with the setup acceptance and then corrected as the experimental data. The excitation energy of the fragments was estimated from TKEL assuming "equal energy" sharing as found in [16], while first guesses of the parameters of the evaporation step were obtained from calculations with Gemini [17].

For protons the experimental emission pattern is similar to that expected in a sequential evaporation, but with increasing particle mass the mid-velocity yield increases until for IMF's it represents almost the whole intensity.

The multiplicities of mid-velocity particles were obtained with a procedure similar to that used in [6], namely as the difference between the total experimental emission and the corresponding estimate of the statistical component (performed, for the PLF emission, in the angular range 10-40 degrees in the PLF reference frame).

Figure 2 shows the so obtained multiplicities as a function of TKEL, separately for p, d, t, He and IMF (full circles for the statistical evaporation, full squares for the mid-velocity particles).

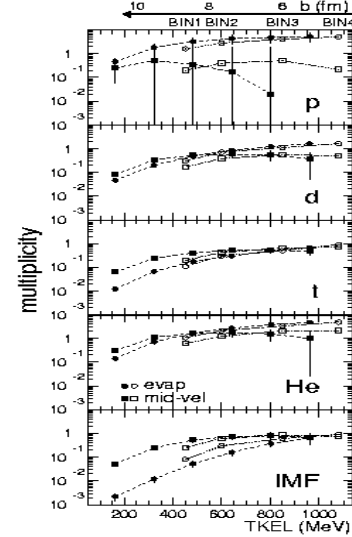
As it was already visible in fig.1, the mid-velocity component of IMF's greatly overcomes the evaporative emission, by more than a factor of 20 for the most peripheral collisions.

In these events the nuclear matter tends to produce IMF's, this process successfully competing with LCP emission.

The multiplicities of fig.2 have been compared with those of the system Xe+Sn measured by Indra (open symbols) at similar bombarding energies [7]. In order to find a correspondence between our ordering variable (TKEL) and that (transverse energy of LCP's, E_{trans12}) used by the Indra collaboration, we used the same QMD code CHIMERA [18] as an event generator for our reaction. Analyzing simulated events with the same procedure as the experimental ones, we found a narrow correlation of the reconstructed TKEL with the impact parameter. The so obtained impact parameter scale (and the binning used by the Indra collaboration) are drawn on top of fig.2.

More details are given in [15].

Figure 2. Experimental multiplicities of p, d, t, He and



IMF's ($Z=3-7$) against TKEL in $^{116}\text{Sn} + ^{93}\text{Nb}$ at 29.5 AMeV. Full squares (circles) refer to the mid-velocity (evaporative) component; open symbols refer to the system Xe + Sn at 32 AMeV measured by Indra. Lines are to guide the eye. On top, correspondence between TKEL and impact parameter (or centrality binning of Indra), estimated from the QMD code CHIMERA.

It has to be noted that the results of both experiments are in good agreement in the common region, but our experiment, purposely designed to study also peripheral collisions, can probe significantly larger values of the impact parameter than those accessible with INDRA.

The interpretation of the observed emission pattern is in progress.

The question about the nature of the production mechanism of mid-velocity IMF's is a very interesting, but also a very difficult one, requiring coordinate experimental and theoretical efforts.

However, already from the peculiar emission pattern observed in the very peripheral collisions (where it is almost free from significant contaminations due to evaporation from PLF and TLF) one can obtain information on the time-space configuration of the emitting system.

Namely, it is possible to infer the time scale and

the geometrical configuration at the end of the reaction from Coulomb trajectory calculations reproducing the observed emission pattern.

First results [19] indicate that the mid-velocity IMF's are emitted from a configuration in which the distance between the surfaces of the two flying-apart main fragments is smaller than about 12 fm. From this value one can estimate that they are emitted at the end of the interaction on a time scale no longer than about 60 fm/c.

While more microscopic approaches may be necessary to fully understand the role of dynamics in these emissions, these result are not in contradiction with the simple picture of an elongated neck randomly rupturing in the reseparation phase of the reaction.

The mid-velocity IMF emission may represent a link between the so-called aligned (or fast oriented) fission [20] observed at lower energies and the "fireball" phenomenology at higher energies.

We wish to thank J. Lukasik for the QMD code CHIMERA. We thank R. Ciaranfi and M. Montecchi for developing dedicated electronics, and P. Del Carmine for his help in the setup preparation. Many thanks are due also to L. Calabretta and to the machine crew of the LNS for their efforts to provide a good quality pulsed beam.

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REVERSE: First experiments

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Abstract

The forward part of CHIMERA multidetector was installed in the Ciclope reaction chamber at LNS in order to perform the REVERSE experiment. After some calibration runs $^{124,112}\text{Sn}$ beams were accelerated at 35 MeV/A. The experiment and the identification techniques are presented

INTRODUCTION

A first campaign of experiments with the multidetector CHIMERA was performed at the LNS facilities in the framework of REVERSE collaboration.

In order to understand the reaction mechanism in the Fermi energy domain a threefold experiment was planned and approved by the LNS PAC in October 1998.

The REVERSE experiment is mainly based on three topics:

- 1) ISOSPIN
 $^{112,124}\text{Sn} + ^{58,64}\text{Ni}$ 35 MeV/A

The isospin experiment intends to study the isospin dependence of mid-rapidity region formation in semi-central collisions. Important information can be extracted on the symmetry term of the nuclear matter equation of state.

2) CLUSTER

$^{124}\text{Sn} + ^{58,64}\text{Ni}, ^{27}\text{Al}$ 25, 35 MeV/A

It aims to study IMF (Intermediate Mass Fragment) production in central collision as a function of the energy of the system in order to disentangle dynamical and thermodynamical properties of multifragmentation.

3) DYNAMICAL

$^{238}\text{U} + ^{64}\text{Ni}, ^{197}\text{Au}$ 18 MeV/A

It intends to study the existence and the characteristics of dynamical fission processes looking at the properties of fission fragments' kinetic energy and angular correlation.

In order to perform these three experiments the forward part of CHIMERA multidetector was installed in the Ciclope reaction chamber at LNS. In June and July 1999 several Tandem and Cyclotron beams were used in order to calibrate the Silicon and the CsI(Tl) detectors. In March 2000 $^{112,124}\text{Sn}$ beams were delivered at 35 MeV/A to perform the ISOSPIN experiment and a part of CLUSTER experiment [1].

The second part of the CLUSTER experiment and the DYNAMICAL fission experiment are planned for the beginning of 2002.

2 REVERSE EXPERIMENT

2.1 Experimental Apparatus

We remind that CHIMERA multidetector is a new generation 4π array, characterised by a large coverage of the total solid angle (94%), a very high granularity, obtained using 1192 detection modules and a very low detection threshold both for heavy ions and light charged particles (LCP). It is characterised by a systematic measurement of the Time of Flight (ToF) of the detected fragments allowing a measurement of the velocity and a ΔE -E and E-ToF method for charge and mass identification. In addition a pulse shape method is performed for the LCP identification.

The REVERSE experimental apparatus, using the forward 9 wheels of CHIMERA, consists of 688 telescopes arranged in a cylindrical geometry around the beam axis covering an angular range from 1° to 30° . Each telescope is made of a $300\mu\text{m}$ Silicon detector, as first step, followed by a CsI(Tl) scintillation detector of 12 cm length. In addition 40 INDRA silicon strip

detectors were placed in one plane in order to detect fragments emitted in the angular range from 30° to 90° .

2.2 Calibrations and Identification Techniques

After the experimental runs the activities were mostly devoted to the energy calibration analysis and to the refinement of the identification techniques.

The Tandem and Cs beams collected during the calibration campaigns were analyzed in order to study the response of both silicon and CsI(Tl) detectors. Dedicated program's routines were developed to obtain the energy calibration of both the high and low gain QDC (Fig 1)

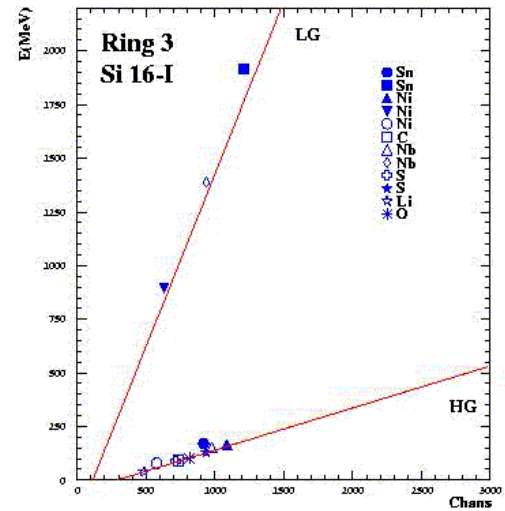


Fig.1): The energy-channel relation for a silicon detector placed at 5.2° . The calibration lines for the LG (Low Gain) and HG (High Gain) QDC channels are shown.

The charge identification of the nuclear products emerging from a collision is realised using the ΔE -E method. For a particle that punches through the first step of the telescope the pulse coming from the silicon detector can be used as ΔE signal while the CsI pulse is used as residual energy signal. In fig. 2) an example of ΔE -E matrix is shown for a detector in the first ring, at a polar angle of 1.6° .

A particle identification function customised for CHIMERA detectors was used in order to linearize the matrix obtaining a one-dimensional charge spectrum (fig.3), for almost all the reaction products, used for charge calibration. A

very high charge resolution is obtained also for the detector placed at very forward angles.

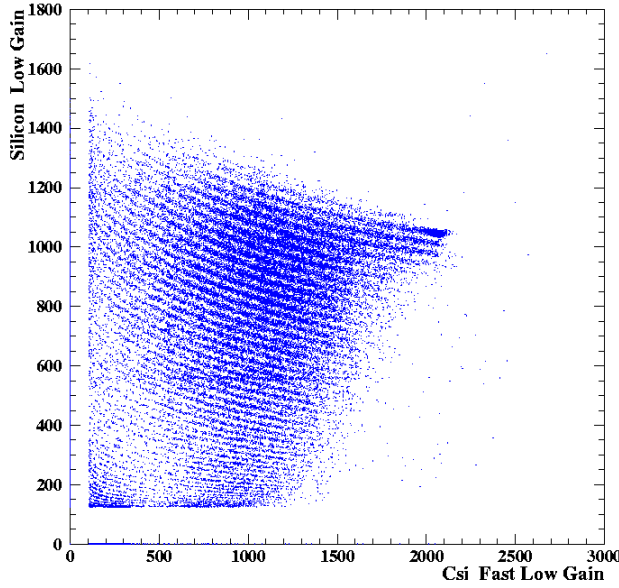


Fig. 2): Silicon-CsI Fast matrix for a detector placed at a 1.6° for the reaction $^{124}\text{Sn} + ^{64}\text{Ni}$ at 35 MeV.

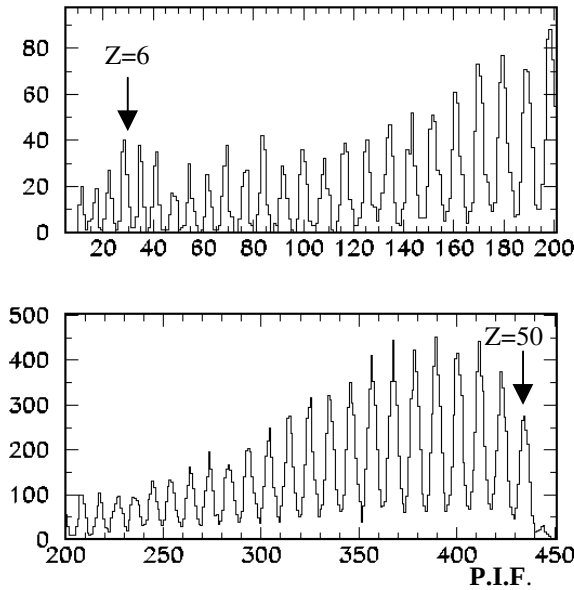


Fig. 3): PIF (Particle Identification Function) spectrum used for charge calibration.

An extension of the ΔE -E method is also used for isotopic identification of light ions up to Fluorine elements.

The special procedure that has been developed for this mass identification is illustrated in

details in the contribution [2] of this LNS annual report.

Mass measurements for reaction products stopped in silicon detectors are realized using the ToF technique. In a start-stop logic, the silicon detector was used as a starting signal and the Cyclotron high frequency signal as a stop. In fig.4 a ΔE -ToF matrix is shown. On the matrix one can see the fragments that stopped in the silicon detector, allowing an isotopic separation and, consequently, the mass measurement. Moreover the fragments that punch through the silicon detector can be identified in charge.

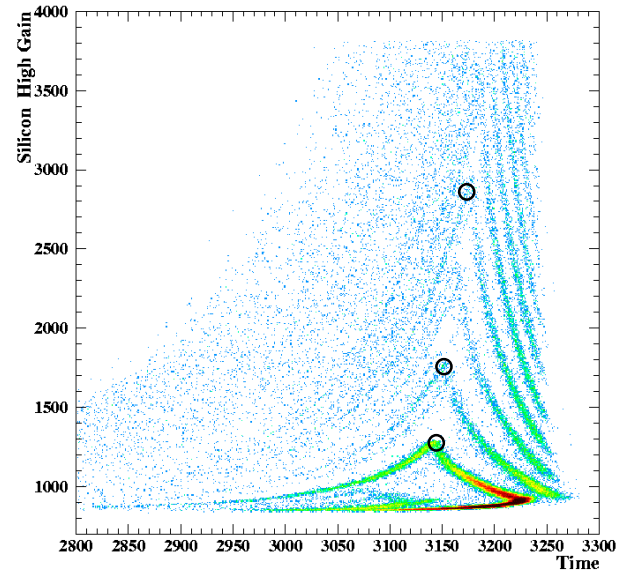


Fig. 4) ΔE -ToF matrix for $^{124}\text{Sn} + ^{64}\text{Ni}$ at 35 MeV/A system for a detector of the 8th ring ($\vartheta_{\text{lab}} = 21.5^\circ$). The punch through points for ^4He , ^7Li and ^{11}B , used for time calibration, are shown by a circle.

A comparison of several procedures for the time calibration is in progress in order to obtain the faster and the more accurate method for the calibration of the time of flight.

In fact, in order to obtain an absolute time scale, the value of an electronic start-stop delay t_0 , which is contained in the classical kinetic energy equation (1), has to be known with a great accuracy.

Using the kinetic energy definition

$$E = M \frac{D^2}{\alpha} \frac{1}{(t_0 - t)^2} \quad (1)$$

where D is the base of flight and α a time-channel conversion constant, mass

measurements are realised and a one-dimensional mass spectrum (fig.5) is obtained for each detector, where the mass of the fragments up to mass around 30 are clearly separated.

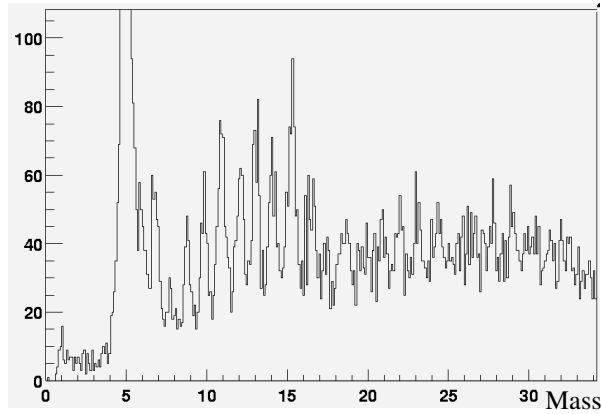


Fig. 5): Mass spectrum obtained using Time of Flight measurement.

Light Charged Particles identification is performed using the fast and slow components of CsI(Tl) detectors. In fig.6 a fast-slow matrix is shown where light charged particles have been separated with our pulse shape method up to Berillium.

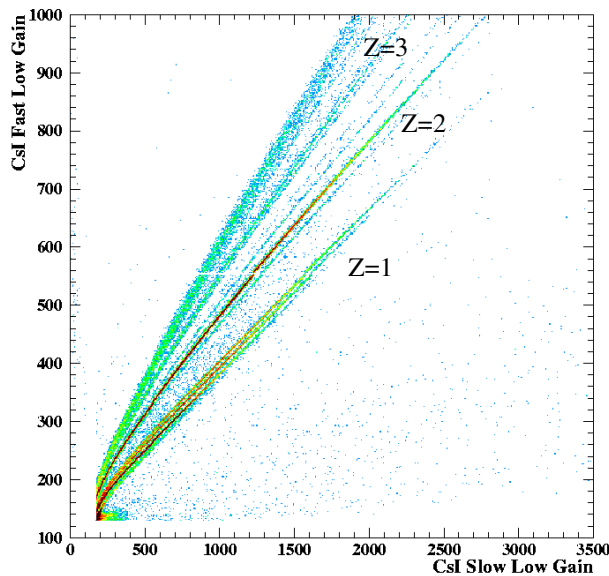


Fig. 6) Fast-Slow matrix for $^{124}\text{Sn}+^{64}\text{Ni}$ at 35 MeV/A for a detector placed at $\vartheta_{\text{lab}}=21.5^\circ$.

In order to speed up the analysis a special procedure has been developed. Each point of a fast-slow scatter plot was identified by the angle

of the isotopic line respect to the fast axis and the distance from the scatter plot origin. A projection of the different identification lines on the angle axis (fig.6) is thus used for light charged particles identification.

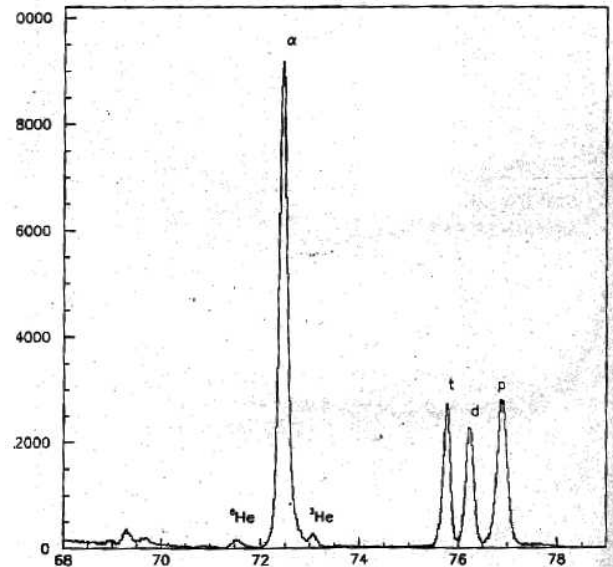


Fig. 7): The one-dimensional spectrum used for the LCP identification.

3 CONCLUSION

A first experimental run was performed in the framework of REVERSE collaboration. Calibration and identification procedures were performed in order to start the data analysis that is now in progress.

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ABSOLUTE CROSS SECTION MEASUREMENTS FOR FAST ELECTRON EJECTION BY SWIFT HIGHLY CHARGED IONS AT INTERMEDIATE ENERGIES

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The study of fast electrons emitted in reaction induced by heavy ions at intermediate energies ($20 \text{ AMeV} < E < 200 \text{ AMeV}$), can give information to test atomic ionization theories. The basic ionization mechanism in swift ion-atom collision is the ejection of binary encounter electrons (BE) from the target atom producing electrons with a centroid velocity of almost twice the projectile velocity v_P [1] and a distribution that reflects the initial momentum distribution of the bound electrons in the atomic target shells (“Compton profile”). Also, in the forward beam direction target electrons may be captured or projectile electrons may be lost into low lying projectile centered continuum states. These so-called “convoy” electrons travel with a velocity close to that of the projectile and lead to a cusp shaped peak in electron spectra. Absolute cross section measurements for BE electrons are quite scarce or lacking at these intermediate beam energies. Recent experiments performed at LNS (with $45 \text{ AMeV } ^{58}\text{Ni}$ beam) [2,3] and GANIL (with $95 \text{ AMeV } ^{36}\text{Ar}$ and $29 \text{ AMeV } ^{208}\text{Pb}$ beam) [4] with the multidetector Argos have permitted to obtain new data in this field making stringent comparison to ionization theories possible. Such data are also important in view of application of heavy ion beams in radiobiology and material science.

The experiment has been accomplished at the CS Supraconductor Cyclotron of Catania, using a pulsed $45 \text{ AMeV } 19^+ ^{58}\text{Ni}$ beam and a $28^+ ^{58}\text{Ni}$ beam obtained by post-stripping the 19^+ beam. Different targets, ^{12}C , ^{27}Al , ^{58}Ni and ^{64}Ni , $^{\text{nat}}\text{Ag}$,

^{197}Au , of almost the same thickness, $300 \mu\text{m}/\text{cm}^2$ were used. To study the possible dependence on the target thickness, we also used 5 different Carbon targets of 10, 20, 90, 300, 1000, 2000 and $8000 \mu\text{m}/\text{cm}^2$ thickness. The burst time resolution was $\approx 1.2 \text{ ns}$.

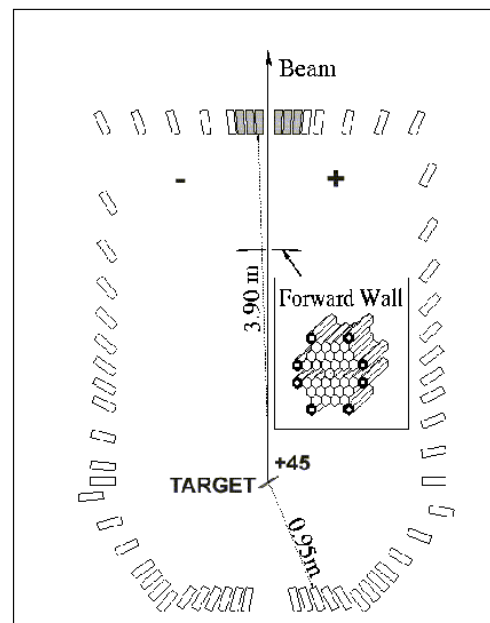


Fig. 1 Sketch of the experimental apparatus made by a forward wall and an ensemble of 63 scintillation detectors positioned in the horizontal plane.

The multidetector Argos, consisting of about 100 scintillation “phoswiches” detectors was placed inside the scattering chamber CICLOPE and used to detect either the particles issued from nuclear reactions or electrons and low energy

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gamma-rays. The electrons were detected in a wide angular range, from 1.5° to 170° , with a flight path varying from ≈ 4 m for the most forward detectors to ≈ 1 m in the backward direction. Shape discrimination of the photomultiplier signals (the ‘fast’ and ‘slow’ component signals) and time-of-flight techniques have been adopted for a full identification of all the charged reaction products.

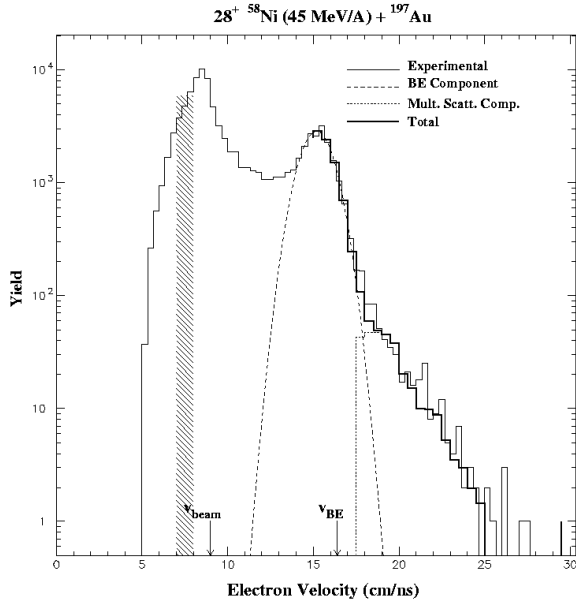


Fig. 2 Electron velocity spectrum for the reaction $28^+ {}^{58}\text{Ni}$ (45 A.MeV) + ${}^{197}\text{Au}$ at 6° (thin solid line). A gaussian function fitting the BE (dashed line) peak is also shown. The high velocity part of the spectrum is compared with the result of a Monte-Carlo simulation based on a simple two step Fermi shuttle mechanism (see text).

Fig. 2 gives an example of the electronic velocity spectra shapes at a forward angle (6 degrees) for the reaction ${}^{58}\text{Ni}$ 28^+ (fully stripped) Au target. We observe two main distinct components: binary encounter electrons and electrons with velocity close to the beam velocity (convoy), near the electronic threshold (indicated by the shaded area). The comparison of the velocity spectra for different targets shows that the centroid of the two peaks are independent from the target material, but increasing the target nuclear charge from C to Au, the intermediate velocity region between the two peak tends to be filled. The convoy component shows a dependence from the target atomic number, only for a bare $28^+ {}^{58}\text{Ni}$ projec-

tile. In fact, in this case, convoy electrons are due essentially to a capture mechanism of electrons in the atomic medium, with subsequent reemission, while for a $19^+ {}^{58}\text{Ni}$ convoy electrons come essentially from the projectile itself, so the production cross-section is in this last case almost target independent as observed in Ref. [2]. Moreover the spectrum for the gold target presents a tail at high velocity as shown in Fig. 2. This can only in part due to the complex Compton profile for the Au target. An additional mechanism involves multiple collision sequences of electrons between target and projectile nuclei. This kind of multiple collision is often referred as ‘Fermi shuttle’: a part of the BE electrons produced in the collision interacts with the target atoms along the ion trajectory. BE electrons that are scattered back have a certain probability of colliding again with the same incident nucleus. We made simple Monte-Carlo calculations, described in Ref. [2,3] which account satisfactory for the tails of the BE velocity spectra as can be seen in Fig. 2.

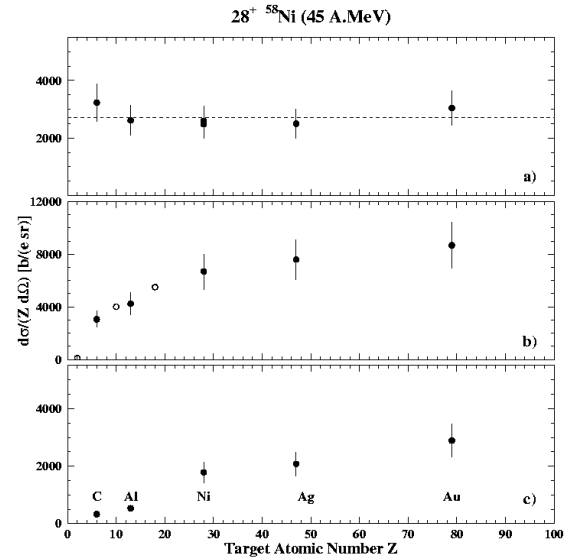


Fig. 3 Absolute yield of forward-emitted binary encounter (a), convoy electrons (b) and backward emitted electron induced by $28^+ {}^{58}\text{Ni}$ (45 A.MeV) as a function of the target atomic number. Data obtained by Breinig et al [5] with swift Ar ions are included for comparison.

In Fig. 3 the absolute cross sections for BE electrons, convoy electrons and backward emitted

electrons are shown as a function of the target atomic number. As a function of the target atomic number Z_T the BE production cross section per target electron is constant within error bars. This means that the BE intensities are proportional to the number of electrons “seen” by the projectile on its way through the target, i.e. to the number of electrons per unit area. The convoy electron cross section shows a more marked dependence from the target atomic number as can be seen in the central part of Fig. 3.

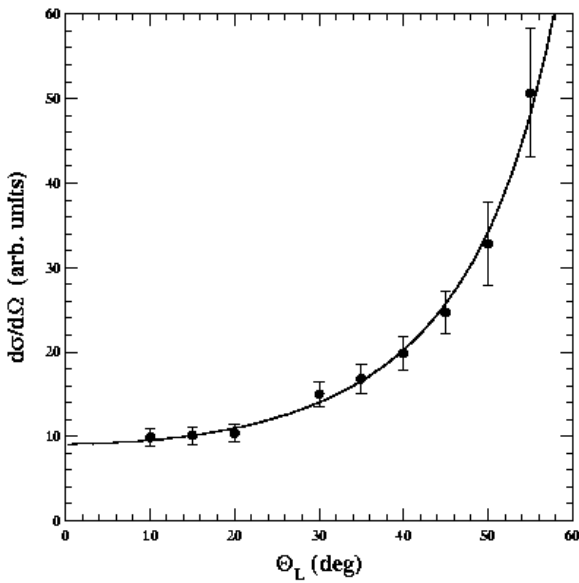


Fig. 4 For the reaction $19^+ {}^{58}\text{Ni} + {}^{12}\text{C}$, the binary encounter emission cross section is shown as a function of the laboratory detection angle. The line represents the function $\text{const}/\cos^3\theta_L$.

Fig. 4 shows the angular dependence of the binary encounter cross section as a function of the laboratory angle θ . This dependence ($\sim 1/\cos^3\theta$) is the one expected from a simple two body Rutherford scattering between a free target electron and the projectile nucleus.

The electron convoy component production is strongly influenced by the projectile charge state. One interesting aspect of the LNS experiment was in fact the possibility to compare results for a totally ionized ${}^{58}\text{Ni}$ projectile (28^+) and a $19^+ {}^{58}\text{Ni}$ projectile. In this last case it is possible to observe a convoy component almost a factor ≈ 80 greater than the BE component in the most forward spectra independently from the target: the convoy

electrons came in this case essentially from the projectile itself. Finally we have reported (Fig. 3c) the production cross section for backward emitted electrons ($\theta = -140^\circ$, $v_e > 7.5$ cm/ns) as a function of the target atomic number. An increase of the cross section with target atomic number is observed. A possible explication of the electron production at very backward angles is the interaction of the forward emitted electrons with the atomic medium producing backscattered electrons in the backward direction. This effect should depend on the size of the atomic scattering center, and hence on the target atomic number.

A comparison of experimental data with a relativistic ionization and transport theory is being performed right now. Further measurements with Au and C beams at 27 A.MeV are planned at LNS in order to study the projectile dependence of both binary encounter electron emission and, in particular, the contribution of the Fermi shuttle process. The latter one can be expected to strongly increase with projectile and target atomic number.

Acknowledgements

We would like to thank the CS staff for providing the 45 A.MeV ${}^{58}\text{Ni}$ beam, N. Giudice, N. Guardone, V. Sparti and S. Urso from INFN Catania for helping during the mounting of the experiment, and C. Marchetta for target preparation.

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DILEPTON SPECTROMETRY WITH HADES

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Abstract

A Time-Of-Flight wall for the dilepton spectrometer HADES has been developed at LNS, in the framework of a large international collaboration. The spectrometer is now installed at GSI (Darmstadt, Germany) where it is going to start the physics data taking after having completed a complex commissioning phase.

1 INTRODUCTION

The study of hot and dense nuclear matter, by means of relativistic collisions between nuclei, is nowadays a main topic of heavy ion physics. As the incident kinetic energy increases, well above the Coulomb barrier, the nuclear shell structure becomes less and less relevant in the reactions; up to 30A MeV collective states of nuclei still play an important role then, beyond Fermi energy, the scenario evolves toward nuclear matter dynamics (fig.1).

Within such a scenario we try to understand the nuclear matter behaviour in terms of an Equation

Of State that, connecting variables like pressure, temperature and density, could provide an explanation to the multi-fragmentation of the colliding nuclei as a liquid-gas phase transition.

At higher energies, around 1A GeV, several authors have argued a possible partial chiral symmetry restoration [1], precursor of a new phase transition: from hadron matter to quark-gluon plasma [2]. This hypothesis stems from the sigma model which implies that the hadron masses could be generated by the pion and its chiral partner, namely the sigma meson, by means of a spontaneous symmetry breaking. The sigma, in fact, has got a much larger mass than

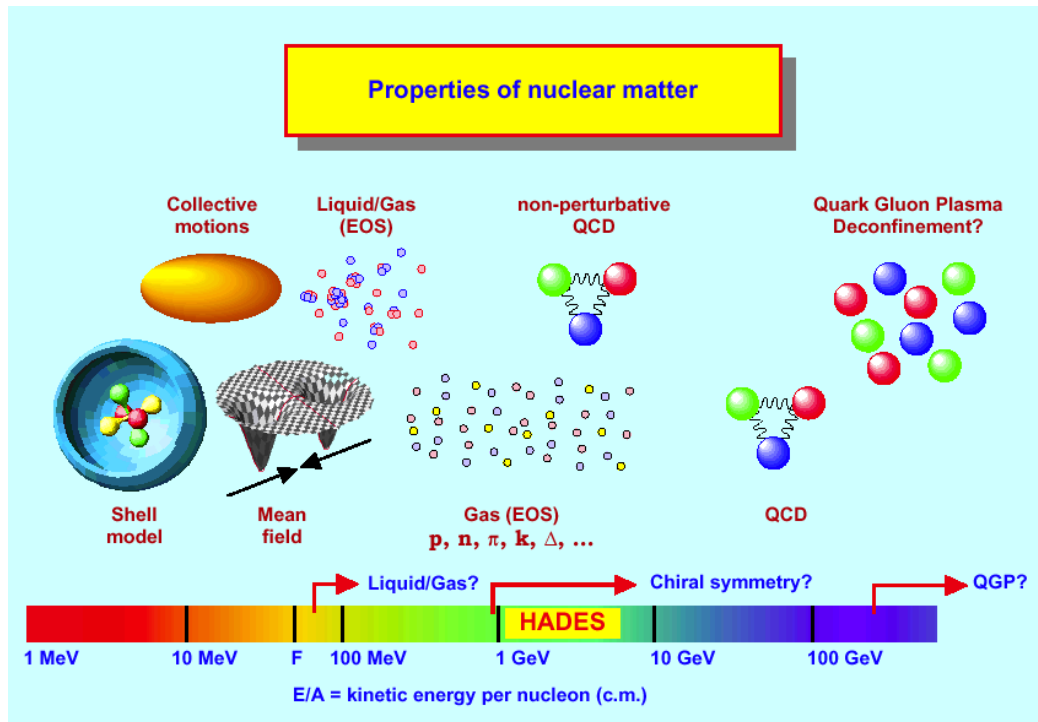


Figure 1 - Properties of nuclear matter as a function of the collision energy

the pion and this breaks the chiral symmetry. In particular this model foresees the existence of the sigma, identified by several authors as the f_0 resonance, and a consistent variation of the hadron masses as a function of density and temperature of the surrounding hadronic medium. In fig.2 we show the expected behaviour of the “up” quark current mass as a consequence of the chiral symmetry restoration. The mass approaches zero both with increasing temperature and density, even though the latter gives rise to a smoother decrease than temperature does in a step-like profile.

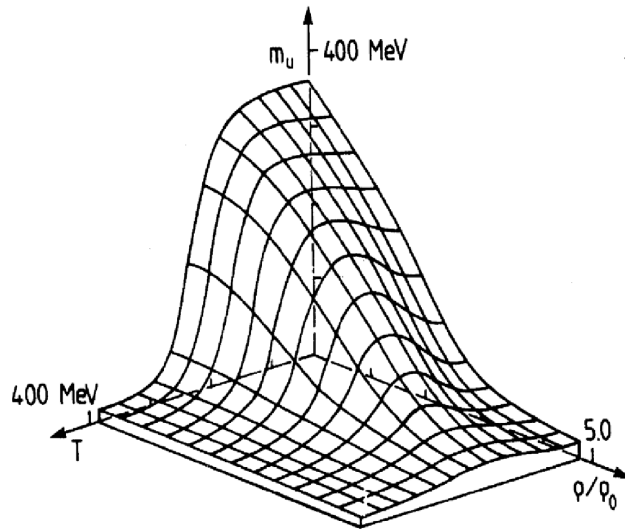


Figure 2 - Typical behaviour of the “up” quark current mass, which at high temperature and/or density approaches zero according to QGP expectations.

2 MODELS AND EXPECTATIONS

Several models have been proposed and developed throughout the last years, in order to try to foresee the behaviour of hadronic matter at higher and higher temperature and density. The most frequently faced problem concerns the mass of mesons, mainly because their structure is intrinsically simpler than barions (two components instead of three). In this context the most relevant mesons have been π , η , ρ , ω , k and ϕ . Nearly all the proposed models do not foresee relevant variations in the mass of π , η and k , while concerning ρ , ω e ϕ (vector mesons because of their $\text{spin}=1$) the subject is somewhat intricate. It is thus useful looking into it with some more detail.

The ρ meson is a broad resonance centered around 770 MeV with a width of 150 MeV; its extremely short mean life, $\hbar/2\pi E$, is of the order of $4 \cdot 10^{-24}$ s. The ω meson mass is 782 MeV, its

width 8.4 MeV and the corresponding mean life is $7 \cdot 10^{-23}$ s; the ϕ meson has a mass of 1020 MeV and a width of 4.4 MeV, with a corresponding mean life of $1.3 \cdot 10^{-22}$ s. Obviously the very short mean lives of these particles prevent us from any faintest possibility of direct measurement, and therefore any experimental method in order to study these mesons has to be indirect.

There is a variety of theoretical papers, showing how different approaches lead to different conclusions about the vector mesons properties in nuclear matter: each model tends to foresee a different behaviour for each different vector meson. Sometimes a broadening of the resonance, sometimes a shift toward lower or higher energy, sometimes both [4-9]. The very few available experimental data seem to indicate a shift toward lower energy, namely the dropping mass of vector mesons [10, 11]. As a direct consequence it comes out to be quite important to measure the vector mesons masses as a function of the medium density, but unfortunately both mass and density are tough to be kept under control. Density can however be deduced from the dynamical conditions of the collision, i.e. projectile, target, incident energy, impact parameter (this latter can be inferred by measuring the charged particle multiplicity). Measuring the mass is still relatively “simple” in vacuum, but it comes out to be prohibitive in medium.

3 MASS MEASUREMENT

Direct measurements of vector mesons are not possible, as already seen; needless to say, direct in-medium measurements are clearly impossible. A possible alternative solution is to measure their decay products, in order to reconstruct the original mass by exploiting the invariant mass method. Once again, unfortunately, this is not realistic: mesons strongly interact with the nuclear matter, in light of their preferentially hadronic decay channels ($\pi\pi$, $\pi\pi\pi$, ...). This means that the initial information about the vector meson, that is what we are interested in, is washed out by the final state interaction, as we are no longer able to determine energy and momentum of the decay products. The method is not directly applicable but there is a solution: a possible decay channel of vector mesons, though extremely rare, consists of its transformation into a virtual photon which, in its turn, decays into an e^+e^- pair: this represents an ideal undisturbed probe.

Even though the branching ratio of such a decay is definitely tiny, of the order of 10^{-4} , the process

is rather useful: leptons do not undergo strong interaction and therefore they carry undisturbed information about the original meson. The energy available in the c.m. frame, nearly completely converted into kinetic energy, can be of several hundreds MeV (that is the rest mass of the vector meson), therefore the perturbation of the e^+e^- pair motion due to the Coulomb interaction is negligible.

4 THE e^+e^- DECAY CHANNEL

The possible solution just examined seems to be ideal, as it allows to use a “pure” measurement channel with unperturbed probes from the decay; anyhow, even in this case there are some inconveniences. Many different processes can indeed lead to an e^+e^- pair in the final state, and these will represent a consistent background noise in the mass spectrum we plan to look at: these processes have therefore to be taken into account, if we want to extract significant informations from the measured data. The most relevant among such processes are the three body decay of neutral pions ($\pi^0 \rightarrow \gamma e^+e^-$), the proton-neutron bremsstrahlung ($pn \rightarrow pne^+e^-$), the three body decay of eta mesons ($\eta \rightarrow \gamma e^+e^-$), the three body decay of delta barions ($\Delta^0 \rightarrow ne^+e^-$, $\Delta^+ \rightarrow pe^+e^-$), even though there are other possible channels, some of them not well known yet.

The experimental apparatuses built so far for di-electron measurements are mainly two: CERES and DLS. The former, in operation at SPS-CERN, has produced interesting data showing an overproduction of di-electrons in the mass region just below the ρ meson, but only occurring in case of nucleus-nucleus collisions. Such an excess, not yet understood in terms of the known mechanisms, does not show up in proton-nucleus collisions. Unfortunately the operating regime of CERES is at very high energy, hundreds of GeV/A, thus consistently over the production threshold for the vector mesons under examination. This implies that the number of open reaction channels is large, and consequently the data interpretation can be manifold. The latter, which operated at BEVALAC for several years around 1-2A GeV, was ideal from the energy point of view since it run just beyond the mentioned threshold, but its geometrical acceptance was rather small. DLS has produced indications for an excess of e^+e^- pairs as well, and in the same mass region below the ρ meson (figs.3,4).

Unfortunately the common result of the two experiments is their poor statistics: the total number of “pure” di-electrons is around a few thousands in both cases.

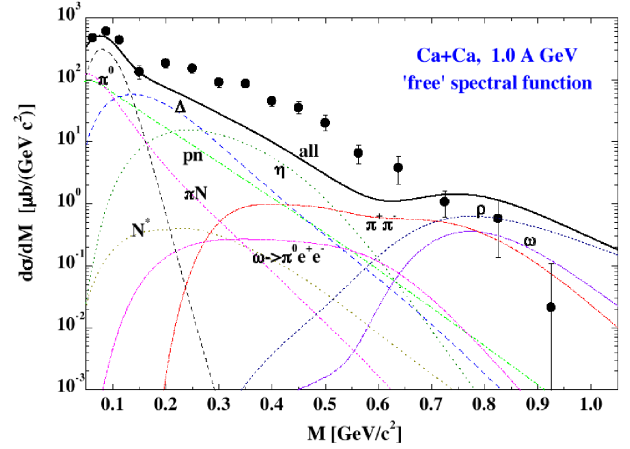


Figure 3 - e^+e^- invariant mass spectrum from Ca+Ca at 1A GeV, compared with a BUU simulation which incorporates all of the known processes with an e^+e^- pair in the final state. The solid curve is the sum of all these contributions [4], black circles are DLS experimental data [10]. The excess between 0.2 and 0.6 GeV is clearly seen.

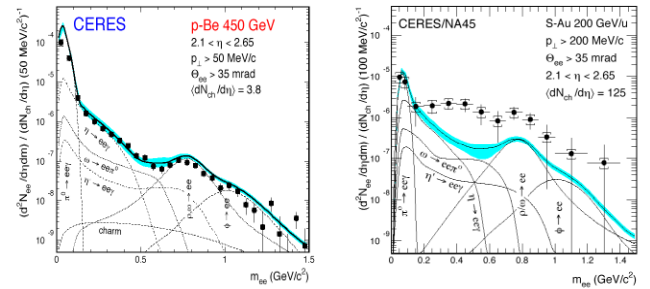


Figure 4 - CERES e^+e^- invariant mass spectra from p+Be at 450 GeV and S+Au at 200A GeV [12]. The shaded region is the expectation from theoretical calculations, including systematic errors. While the proton beam case is well reproduced, the clear excess in the nucleus-nucleus collision is still a matter of discussion.

Moreover, in order to be able to appreciate slight variations in the mass spectrum, i.e. the ω resonance (8 MeV wide), we need a mass resolution of 1-2%; in such a case a histogram containing a few thousands counts would be distributed over a large number of bins and therefore dominated by the statistical error. The same applies in case one wants to study exclusive processes, for instance by characterizing the mass spectrum as a function of the transverse momentum of the decaying vector meson.

The experiments so far performed give us the following message: we need an e^+e^- spectrometer with large geometrical acceptance and capable of operation at high counting rates, in order to achieve invariant mass and momentum resolution

around 1%. Furthermore, it is extremely important to characterize the di-electron production as a function of the different colliding systems, therefore a variety of them has to be studied, likely ranging from p+p up to Au+Au and in the energy domain between 1 and 2A GeV. This is the reason why the HADES (High Acceptance Di-Electron Spectrometer) collaboration has been formed, with the precise issue of studying hot and dense nuclear matter by exploiting the di-electron decay channel. A dedicated spectrometer has been built for this purpose, and after a series of commissioning runs it is now ready to take off and start physics operations.

5 THE HADES SPECTROMETER

The HADES spectrometer, built at GSI Darmstadt by a collaboration between 19 institutions from 9 european countries, is a highly selective tool specially suited for the study of the high energy di-electron decay channel in nucleus-nucleus collisions around 1-2A GeV. An additional important entrance channel is represented by pion-nucleus collisions, and to this purpose a pion beam facility has been recently developed at GSI.

The detector, depicted in fig.5, is made up of several cascaded detection systems in hexagonal symmetry. Moving along the same direction as the particles to be detected, there are respectively:

- a ring imaging Cherenkov detector (RICH), equipped with an ultralight carbon mirror, that reflects the produced photons back to a gas-based photon detector placed behind the target position; this system allows to uniquely identify the leptons and accurately measure their emission direction;
- two layers of multi-drift chambers (MDC), followed by six superconducting solenoids, producing a toroidal field, and by other two layers of MDC: this system can determine with a very high precision the particle momenta, by measuring the trajectory displacement induced by the magnetic field within a position error of $<100\mu\text{m}$;
- a time of flight wall (TOF), made of 320 rods of BC408 scintillator, covering the polar angles between 44° and 88° , to measure the event-by-event multiplicity that is an indication of the centrality of the collision, and the time of flight and direction of each detected particle;
- a pre-shower detector (SHOWER), placed on the polar range 13° - 45° , made of three gas chambers intermixed with two lead converter

layers, in order to operate the lepton/hadron discrimination; in front of the SHOWER a 24-slab low-granularity tof wall (TOFINO) furtherly helps in lepton/hadron discrimination.

Several tests and commissioning runs have been performed throughout last years, mainly using C beams at 1-2A GeV, finally showing that the spectrometer is capable of fulfilling all the design requirements.

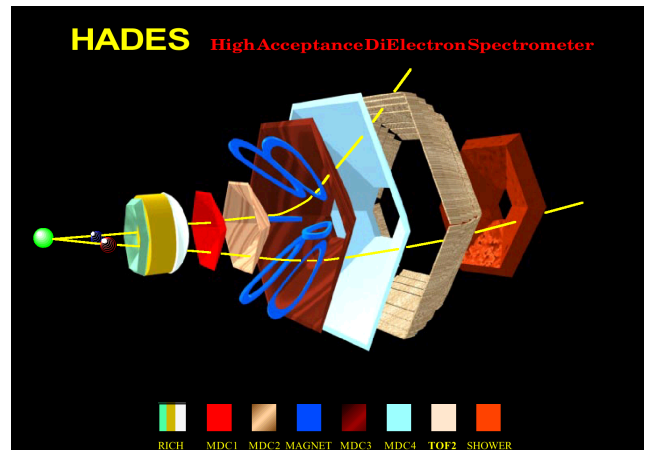


Figure 5 - 3D sketch of the HADES spectrometer, split along the longitudinal direction for clarity. In operating conditions all the shown elements fit into each other making the whole structure much more compact.

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Nuclear Dynamics under extreme conditions

LNS Theory group

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The aim is to develop new trends in nuclear dynamics of large interdisciplinary interest, like the competition between regular and chaotic motion in correlated systems, the nuclear collective response in stable and unstable regions, the thermodynamics of finite systems, the nuclear equation of state under extreme isospin and density conditions and related compact star problems.

Of course the starting point is the problem of the effective nuclear interactions in the medium, in non-relativistic and relativistic approaches. In the last year some attention has been also focussed on the transition to a deconfined nuclear matter, in particular at high baryon densities.

At the same time a great effort is put in maintaining always a close connection to experimental groups, not only at the LNS. In particular we note the nice results obtained in the last year working with the collaborations Medea-Multics, Chimera and Trasma at the LNS, Indra at Ganil and Miniball at MSU. Some members are also actively participating in NuPeCC working groups, in particular in the discussion of the new European Radioactive Beam Facilities. In the following the main results obtained in the last year are listed, mentioning some relevant papers and including the corresponding links and collaborations.

1) **Hot nuclei.**

- Formation: entrance channel effects, in particular charge and mass symmetry; The Dynamical Dipole.
- Hot collective response. Possibility of the observation of a transition zero-to-first sound.

Interesting papers:

V.Baran et al. "The dynamical dipole mode in dissipative heavy ion collisions"
Nucl.Phys. A679 (2001) 373.

This is a collaboration with Dubna (I.N.Mikhailov), Oxford (D.M.Brink), Kurchatov (A.B.Larionov), Sofia (J.Piperova, N.Tsoneva) and Bucharest (V.Baran). Connection to exp.s performed at LNS (MEDEA-MULTICS and TRASMA Collabs.), LNL and Seattle (K.Snover).

2) **Nuclear fragmentation and liquid-gas phase transition.**

- Dynamical mechanisms based on the spinodal decomposition
- Mid-rapidity emissions and neck instabilities
- Fluctuations in transport approaches
- Critical phenomena in finite systems
- Chaos in quantum field theories
- Volume and shape instabilities: quantum vs semiclassical predictions

Interesting papers:

A.Bonasera, M.Bruno, C.Dorso and P.F.Mastinu "Critical phenomena in nuclear dynamics" Riv.Nuovo Cimento 23 (2000) pp.1-101;

V.Baran, M.Colonna, M.DiToro and V.Greco "Nuclear fragmentation: sampling the instabilities of binary systems" Phys.Rev.Lett. 86 (2001) 4492;

B.Borderie,...M.Colonna et al."Evidence for spinodal decomposition in nuclear multifragmentation" Phys.Rev.Lett. 86 (2001) 3252.

Linkage: LNS, CT and FI. Collaborations with GANIL (Ph.Chomaz), Buenos Aires (C.Dorso), Kyoto (H.Horiuchi) and JAERI (T.Maruyama, A.Iwamoto).
Contacts with exp. groups at LNS, GANIL, MSU, Orsay and Lund.

3) Asymmetric nuclear matter.

- Collective response and new mechanical plus chemical instabilities
- Density dependence of the symmetry term: critical observables in fragmentation and collective flows
- Nucleon-Nucleon cross sections in nuclear matter
- Pairing correlations in dilute asymmetric NM
- Microscopic approaches and predictions for stellar evolution and neutron star properties
- Effective Field Theories: the role of Fock terms on the symmetry energy

Interesting papers:

A. Lejeune, U.Lombardo and W. Zuo
"Nuclear matter EOS with a three-body force" Phys. Lett. 477 (2000) 45;

M.DiToro et al. "Asymmetry effects on nuclear fragmentation" Nucl.Phys. A681 (2001) 426-433c;
V.Greco et al. "Fock exchange terms in non-linear quantum hadrodynamics" Phys.Rev. C63 (2001) 035202.

Linkage: FI, PI, CT and LNS. Collab.s with Liege (A.Lejeune), Rostock (G.Roepke), Grenoble (P.Schuck), Kurchatov (E.Saperstein), Lanzhou (W.Zuo), Muenchen (H.Wolter), LPC Aubere (J.M.Mathiot), KVI Groeningen (A.Sedrakian), IHEP Beijing (LiuBo, G.X.Peng), EMF Barcelona (H.J.Schulze), INR Shanghai (H.Q.Song) and Bucharest (N.Sandulescu).

4) Quark-Gluon Plasma and Chiral Symmetry Restoration

- In medium meson modifications
- Color molecular dynamics for high baryon density matter
- Relativistic hadron and string cascade models
- Hadronization features: bag models and kinetic approaches

Interesting papers:

A.B.Santra and U.Lombardo, "Effect of in-medium meson parameter modification on nuclear matter equation of state", Phys. Rev. C62 (2000) 18202;

A.Bonasera, "Color dynamics in phase space" Phys.Rev. C62 (2000) 052202

Linkage: CT and LNS. Collab. with Oxford (D.M.Brink) and JAERI (J.Niita, T.Hatsuda, T.Maruyama) and Bhabha (A.B.Santra).

In the last year the group has published more than forty papers on international journals and presented numerous contributions and invited talks at international conferences and schools.

Theses:

Joseph Rizzo, (laurea)
Flussi collettivi in collisioni fra ioni pesanti ad energie intermedie: test di interazioni nucleari effettive
(rel.ri: M.DiToro, M.Colonna)

Nicola Pellegriti, (laurea)
Emissione dipolare di pre-equilibrio in collisioni dissipative fra ioni pesanti
(rel.ri: M.DiToro, V.Baran)

Vincenzo Greco, (Ph.D, XIV)
EOS and dynamical response of asymmetric nuclear matter in a Relativistic Mean Field approach: the Fock terms.
(rel.ri: M.DiToro, M.Colonna)

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2) M.Colonna and M.DiToro
"Nuclear Transport Models and Effects of Isospin-Dependent Equation of State on Dissipative Heavy-Ion Collisions" in "Isospin Physics in Heavy-Ion Collisions"
Ed.s Bao-An Li and U.Schroeder, Nova Publ. 2001 in press

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"Superfluidity in Neutron Star Matter"
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The Equation of State (*EOS*) for asymmetric nuclear matter is discussed starting from a phenomenological hadronic field theory of Serot-Walecka type including exchange terms. In a model with self interactions of the scalar sigma-meson we show that the Fock terms naturally lead to isospin effects in the nuclear *EOS*. These effects are quite large and lead to a density dependence of the isovector couplings. We obtain a potential symmetry term of "stiff" type, i.e. increasing with baryon density and an interesting behaviour of neutron/proton effective masses of relevance for transport properties of asymmetric dense matter.

I. INTRODUCTION

Phenomenological hadronic field theories (Quantum Hadrodynamics, *QHD*) are widely used in dense nuclear matter studies [1]. In most of the previous works on the subject, the Relativistic Mean Field (*RMF*) approximation of *QHD* has been followed. In the *RMF* the meson fields are treated as classical fields and consequently a Hartree reduction of one body density matrices is used. Each meson field is introduced, with appropriated readjusted couplings, just to describe the dynamics of a corresponding degree of freedom, without mixing due to many-body effects. Neutral σ and ω mesons are in charge of saturation properties, isospin effects are carried by isovector δ [a₀(980)] and ρ mesons. In a sense the model represents a straightforward extension of the One-Boson-Exchange (*OBE*) description of nucleon-nucleon scattering. In the context of the *QHD* model, essential properties of nuclear matter come mostly from the two neutral strong meson fields. Hence the Fock contributions associated with these fields are expected also to be large.

We get qualitative new features of equilibrium (Equation of State, *EOS*) and dynamical properties of asymmetric nuclear matter [2]. In particular a new density dependence of the symmetry term is expected, at variance with the simple linear increase predicted by the ρ -exchange mechanism in the Hartree scheme.

II. A KINETIC APPROACH TO THE FOCK TERMS

We start from a *QHD-II* model [1] where the nucleons are coupled to neutral scalar σ and vector ω mesons and to the isovector ρ meson. Self-interaction terms of

the σ -field were originally introduced for renormalization reasons [4] and can also be considered as a way to parametrize in a phenomenological way many-body effects beyond the mean-field approximation. So they are able to reproduce important properties (compressibility and nucleon effective mass) of nuclear matter around saturation density.

The Lagrangian density for this model is given by:

$$\begin{aligned} \mathcal{L} = & \bar{\psi}[\gamma_\mu(i\partial^\mu - g_V\mathcal{V}^\mu - g_\rho\mathbf{B}^\mu \cdot \boldsymbol{\tau}) - (M - g_S\phi)]\psi + \\ & \frac{1}{2}(\partial_\mu\phi\partial^\mu\phi - m_S^2\phi^2) - \frac{a}{3}\phi^3 - \frac{b}{4}\phi^4 - \frac{1}{4}W_{\mu\nu}W^{\mu\nu} \\ & + \frac{1}{2}m_V^2\mathcal{V}_\nu\mathcal{V}^\nu - \frac{1}{4}\mathbf{L}_{\mu\nu} \cdot \mathbf{L}^{\mu\nu} + \frac{1}{2}m_\rho^2\mathcal{B}_\nu \cdot \mathcal{B}^\nu \end{aligned} \quad (1)$$

where $W^{\mu\nu}(x) = \partial^\mu\mathcal{V}^\nu(x) - \partial^\nu\mathcal{V}^\mu(x)$ and $\mathbf{L}^{\mu\nu}(x) = \partial^\mu\mathcal{B}^\nu(x) - \partial^\nu\mathcal{B}^\mu(x)$.

Here $\psi(x)$ is the nucleon fermionic field, $\phi(x)$ and $\mathcal{V}^\nu(x)$ represent neutral scalar and vector boson fields, respectively, $\mathcal{B}^\nu(x)$ is the charged vector field and $\boldsymbol{\tau}$ denotes the isospin matrices.

In our approach 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. In such way it's possible a direct derivation of a dynamical transport equation [6].

In order to take into account the contribution of exchange terms in a manageable way we assume, as a basic approximation, that in the equations of motion for the meson fields the terms containing derivatives can be neglected with respect to the mass terms. Therefore the meson field operators are directly connected to the operators of the nucleon scalar and current densities:

$$\begin{aligned} \widehat{\Phi}/f_S + A\widehat{\Phi}^2 + B\widehat{\Phi}^3 &= \bar{\psi}(x)\psi(x) , \\ \widehat{V}^\mu(x) &= f_V\bar{\psi}(x)\gamma^\mu\psi(x) , \\ \widehat{\mathbf{B}}^\mu(x) &= f_\rho\bar{\psi}(x)\gamma^\mu\boldsymbol{\tau}\psi(x) , \end{aligned} \quad (2)$$

where $f_S = (g_S/m_S)^2$, $f_V = (g_V/m_V)^2$, $f_\rho = (g_\rho/2m_\rho)^2$ and $\widehat{\Phi} = g_S\phi$, $\widehat{V}^\mu = g_V\mathcal{V}^\mu$, $A = a/g_S^3$, $B = b/g_S^4$, $\mathbf{B}^\mu = g_\rho\mathcal{B}^\mu/2$. Using these expressions for the meson field operators, we can describe the nuclear matter in terms of nucleon field operators.

An attempt to include exchange terms in the *QHD* approach was previously performed without self-interaction terms for the σ field [3], but with the drawbacks of high compressibility (similar to the corresponding Hartree calculations) and/or too large Weizsaecker symmetry coefficient a_4 . Here we evaluate the effects in a more suitable approach, with self-interacting higher order σ terms.

Exchange corrections are considered up to next-to-leading term, but we have verified the fast convergence and the thermodynamical consistency of the expansion (details can be found in [6]).

III. EQUILIBRIUM PROPERTIES: THE NUCLEAR EQUATION OF STATE

In order to evaluate the energy density we calculate the statistical average of the canonical energy-momentum density tensor. For asymmetric nuclear matter, in analogy to the Hartree case, it can be rewritten in the following form:

$$\epsilon = \langle T_{00} \rangle = \sum_{i=n}^p \frac{1}{4} [3E_{Fi}^* \rho_{Si} + M_i^* \rho_{Bi}] + U(\Phi) + \frac{1}{2} \tilde{f}_S \rho_S^2 + \frac{1}{2} \tilde{f}_V \rho_B^2 + \frac{1}{2} f'_S b^2 + \frac{1}{2} f'_V b_0^2 \quad (3)$$

where ρ_B is the baryon density and $b_0 = \rho_{Bp} - \rho_{Bn}$ is the corresponding isovector density, while ρ_S and b are the analogous isoscalar and isovector scalar densities,

$$\tilde{f}_S = \frac{1}{2} f_V - \frac{1}{8} \left(\frac{d\Phi}{d\rho_S} + \rho_S \frac{d^2\Phi}{d\rho_S^2} \right) + \frac{3}{2} f_\rho; \quad (4)$$

$$\tilde{f}_V = \frac{5}{4} f_V + \frac{1}{8} \left(\frac{d\Phi}{d\rho_S} - \rho_S \frac{d^2\Phi}{d\rho_S^2} \right) + \frac{3}{4} f_\rho; \quad (5)$$

$$f'_S = \tilde{f}_S - 2f_\rho, \quad f'_V = \tilde{f}_V - f_V; \quad (6)$$

are density dependent effective coupling constants.

$E_{Fi}^* = \sqrt{p_{Fi}^2 + M_i^{*2}}$ and M_i^* are the effective masses, see Eq.s.(7).

Here we explicitly obtain a density dependence arising also in the vector, isovector and isoscalar couplings, like in the phenomenological approach of Ref. [7] or in effective field theory [8].

We remark that, as in non-linear mean-field models, we have in total five parameters. As usual, the ones related to isoscalar mesons, f_V, f_S, A, B are fixed in order to reproduce equilibrium properties of symmetric nuclear matter: saturation density $\rho_0 = 0.16 \text{ fm}^{-3}$, binding energy $E/A = -16 \text{ MeV}$, compressibility modulus $K_0 = 245 \text{ MeV}$ and nucleon effective (or Dirac) mass at ρ_0 , $M_0^* = 0.7 M$. The coupling constant f_ρ can then be adjusted in order to get a good value for the symmetry energy at saturation density. In our calculations we have a symmetry coefficient of the Weizsaecker mass formula $a_4 = 31.5 \text{ MeV}$. The values obtained for the five parameters are $f_V = 4.00 \text{ fm}^2$, $f_S = 9.73 \text{ fm}^2$, $A = 0.088 \text{ fm}^{-1}$, $B = -0.015$, $f_\rho = 0.60 \text{ fm}^2$.

According to these values, we see that the dominant contributions to the density dependent coupling functions $\tilde{f}_S, \tilde{f}_V, \tilde{f}'_S, \tilde{f}'_V$, Eq.s(4,5,6), come essentially from the isoscalar σ and ω mesons.

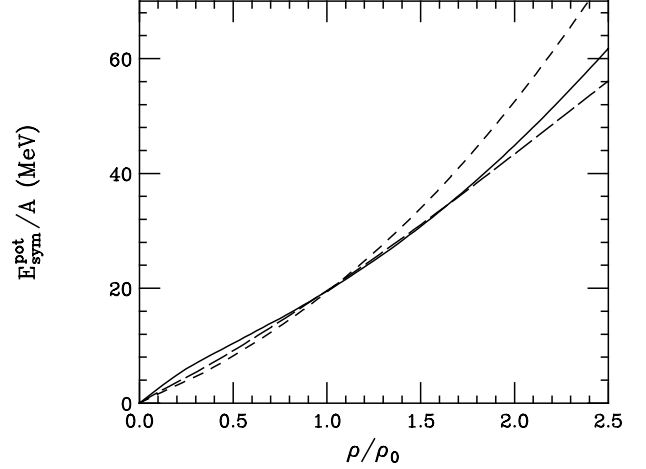


FIG. 1. Potential symmetry energy per nucleon vs. baryon density (in units of saturation density). Solid line: *NLHF* results. Dashed line: Hartree results with ρ and δ mesons (*NLH*). Long-dashed: Hartree results with only ρ meson.

IV. SYMMETRY ENERGY AND EFFECTIVE MASS SPLITTING

We discuss now some results for the *EOS* of asymmetric nuclear matter. We show the comparison between our *Non Linear Hartree-Fock (NLHF)* present calculations and those of the *Non Linear Hartree (NLH)* model including the isovector ρ [1] and δ mesons [9], with parameters chosen in order to give the same saturation properties.

The comparison for potential symmetry energies per nucleon is presented in Fig.1. We define potential symmetry energy the total one minus the kinetic contribution in a Fermi-gas $p_F^2/6E_F$, where $E_F = \sqrt{p_F^2 + M^2}$, with M the bare mass.

In the *NLHF* results a large contribution to the symmetry term comes from the Fock contributions associated with the σ and ω mesons, with the corresponding four parameters of the theory fitted on properties of symmetric nuclear matter. We stress that the Fock mechanism naturally leads to a scalar-vector structure of the symmetry part of the *EOS*. This has important dynamical effects, as we will discuss in the following.

In Fig.1 we show also *NLH* calculations including both vector, ρ , and scalar, δ , isovector mesons (dashed line). In this case the coupling constants f_ρ and f_δ have been chosen in order to reproduce the same a_4 and neutron-proton effective mass splitting that we get within our model. Now we need a $f_\rho = 2.3 \text{ fm}^2$ for a δ coupling $f_\delta = 1.4 \text{ fm}^2$ (in the range of free space values [10]). For

reference we show also the result of a NLH calculations including *only* the ρ contribution (long-dashed line). In order to have the same a_4 value at saturation density we need a $f_\rho = 1.2 fm^2$, almost twice the value of ρ decay into two pions [1]. In fact the inclusion of the δ contribution in the Hartree scheme, necessary for the neutron-proton mass splitting, gives also an attractive term in the symmetry energy, see Ref. [9], and so a much stronger ρ coupling is required in order to reproduce the correct a_4 coefficient around saturation density. We note that when the scalar-isovector channel is included (i.e. in $NLHF$ or $NLH - (\rho + \delta)$) one gains the genuine structure of relativistic interaction where one has a balance between scalar (attractive) and vector (repulsive) "potentials".

This is indeed the fully consistent way of studying isospin physics in a relativistic framework. Dynamical effects can be very important, particularly in connection with heavy-ion collisions where the repulsion generated by the vector field strongly increases with energy up to a substantial breaking of the balance with the scalar field present in the equation of state (as shown for the isoscalar channel in ref. [11]). How much variance is built during the collision depends on the strength of vector channel and so relevant differences could be found between $NLHF$ (or $NLH - (\rho + \delta)$) and $NLH - \rho$ because of the different vector-isovector strengths.

In all these relativistic models a quite repulsive density dependence of the symmetry term of the EOS is obtained.

We notice that the density dependence of the symmetry energy that one obtains in the complete $NLH - (\rho + \delta)$ model is quite different with respect to our results. The main point is that in the $NLHF$ model the coupling functions in the isovector channels (f'_S, f'_V) become density dependent. This represents a qualitative new effect of the exchange terms in a non-linear QHD model.

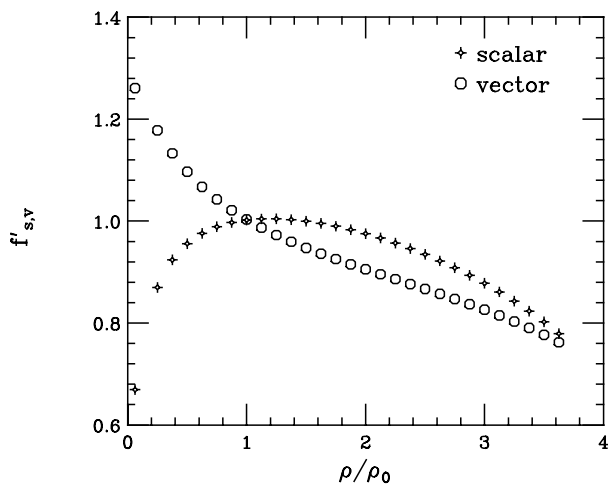


FIG. 2. Density dependence of f'_S and f'_V . Each curve is normalized to the value at saturation density.

Such density dependence is shown in Fig.2 it results in a smaller symmetry pressure around normal density [13] with expected important effects on the structure and the reaction dynamics of asymmetric ions, see also the discussion in the conclusions.

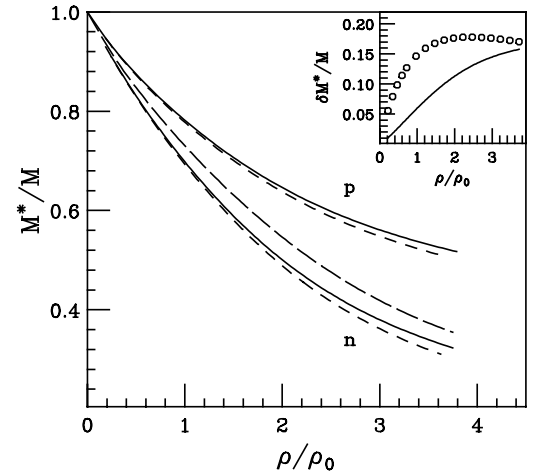


FIG. 3. Proton (top curves) and neutron (bottom curves) effective masses vs. baryon density for $I = \frac{N-Z}{N+Z} = 0.8$. Long dashed line: $NLH - \rho$; solid line: $NLHF$; dashed lines: $NLH - (\rho + \delta)$. In the insert, the difference between neutron and proton effective masses normalized to the bare nucleon mass. Solid line: $NLHF$ results; circles: SLy4 non-relativistic results.

In Fig.3 we report the density dependence of neutron (bottom) and proton (top) effective masses for various asymmetries ($I = (N - Z)/A$) as predicted by $NLHF$ (solid lines) and $NLH - (\rho + \delta)$ (dashed lines). We remind that in the usual Hartree approximation this effect is associated with the scalar isovector δ meson. The Fock terms lead to a behaviour:

$$M_{n,p}^*(NLHF) = M^* \pm f_S^m b + \frac{b^2 + b_0^2}{16} \frac{d^2 \Phi}{d\rho_S^2} \quad (+ \equiv n, - \equiv p) \quad (7)$$

where M^* is the nucleon effective mass in symmetric nuclear matter, and

$$f_S^m = \frac{f_V}{2} - \frac{1}{8} \frac{d\Phi}{d\rho_S} - \frac{f_\rho}{2}. \quad (8)$$

Since the coefficient f_S^m is positive we get an effect very similar to what expected from the contribution of the δ meson [9], dashed lines in Fig.3. On this point we would like to make two more remarks:

i) This difference in n and p effective masses can be relevant for transport properties of asymmetric, dense nuclear matter that can be formed in intermediate energy reactions with radioactive beams, naturally apart neutron star properties;

ii) The proton effective masses are systematically above the neutron ones. This trend, also in agreement with δ calculations [9,12], is just the opposite of what expected from Brueckner-Hartree-Fock calculations with realistic NN potentials [15]. Although relativistic and non-relativistic effective masses cannot be directly compared, see refs [14,3], it is interesting to look at the predictions given by Skyrme-like effective forces. Concerning the splitting of neutron and proton effective masses in asymmetric matter, the most recent parametrizations, SLy-type [16], of Skyrme forces give the proton effective mass above the neutron one, in agreement with our calculations. Previous parametrizations, instead, yield a splitting in the opposite direction, but also show unpleasant behaviours in the spin channel (collapse of polarized neutron matter, see discussion in [16]). In the insert of Fig.3 the ratio of the splitting, $\delta M^* = M_p^* - M_n^*$, to the bare nucleon mass is displayed for the SLy4 force and for our approach.

The sign of the splitting depends on the chosen effective interaction. This puzzle can be disentangled by a detailed analysis of the transport properties of dense asymmetric nuclear matter.

V. OUTLOOK

In conclusion we have shown the evaluation, *in a non-perturbative scheme*, of Fock term contributions in a non linear effective field theory for asymmetric nuclear matter. The density dependence of the isovector couplings due to the Fock contributions leads to a new interesting *softer* behaviour (see the $NLHF$ curve in Fig.1) at sub-nuclear densities, with direct nuclear structure effects. Indeed we expect a reduced symmetry pressure in the surface of neutron-rich nuclei and consequently a thinner neutron skin. We remark that a similar result has been recently obtained in the Hartree approach adding new non-linear $\sigma - \rho$ and $\omega - \rho$ couplings [17].

It could be interesting to study related dynamical effects in heavy ion collisions at intermediate energies in fragmentation events [18] and collective flows [19,20], to test also the importance of a scalar-vector structure in the isospin channel with increasing energies, due to genuine relativistic effects. This can be done, in a self-consistent way, solving numerically the transport equation (Eq.(9) in [6]) as in RBUU calculation [21].

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Formation and decay of super heavy systems

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Abstract

We investigate the formation and the decay of heavy systems which are above the fission barrier. By using a microscopic simulation of constraint molecular dynamics (CoMD) on Au+Au collision, we observe composite states stay for very long time before decaying by fission.

The typical reaction mechanisms of heavy-ion collisions at lower incident energy are, depending on the energy and impact parameters, complete fusion, incomplete fusion, fusion-fission, molecular resonance, and deep inelastic collisions.

Among the huge amount of studies in this field, collisions of very heavy nuclei have been investigated mainly for the creation of super heavy element (SHE). SHEs are produced in two ways:

one is "cold fusion" which is complete fusion below the classical barrier, and the other is "hot fusion" which allows several neutrons to be emitted. Even though the name is "hot", such reactions are still at very low energy near the barrier and the total mass number is very close to the aimed one.

As far as the formation of SHE is concerned, the "fusion" of very heavy nuclei where the fission barrier no more exists is found to be ineffective.

Apart from the formation of SHE, the study of fission dynamics, including the spontaneous fission and the fusion-fission of heavy composite, has been one of the most important subjects. The competition of neutron emission between the fission and the fission delay have been discussed intensively.

However almost all the discussion are done for mass regions where the classical fission barrier exists.

Sometime ago many physicists paid attention to the low energy collision of very heavy nuclei in regard to the spontaneous positron emission from strong electric fields. If a molecule state of, say, U and U is formed and stays sufficiently long time, the binding energy of a electron can exceed the electron mass and might create electron-positron pair by a static QED process.

Unfortunately no clear evidence of static positron creation was observed below the Coulomb energy region.

It has been pointed out the importance of nuclear reaction which causes the time delay of separation of two nuclei. Although there increases the background component of positrons from nuclear excitation, which in this case is not interested in, the electron-positron from the static QED process is also expected to increase.

However, the reaction mechanism of very heavy nuclei has not been discussed by fully dynamical models.

In this paper we discuss the possibility of molecule-like states of heavy nuclei and the time scale of very heavy composite system formed by the fusion-fission or deep inelastic processes[1]. To investigate these problems theoretically we use a recently developed constraint molecular dynamics (CoMD) model[2]. This model has been proposed to include the Fermionic nature of constituent nucleons by a constraint that the phase space

distribution should always satisfy the condition $f=1$. The CoMD model mainly consists of two parts: classical equation of motion of many-body system, and stochastic process which includes constraint of Pauli principle and the two-body collisions. The Pauli principle is taken into account in two ways:

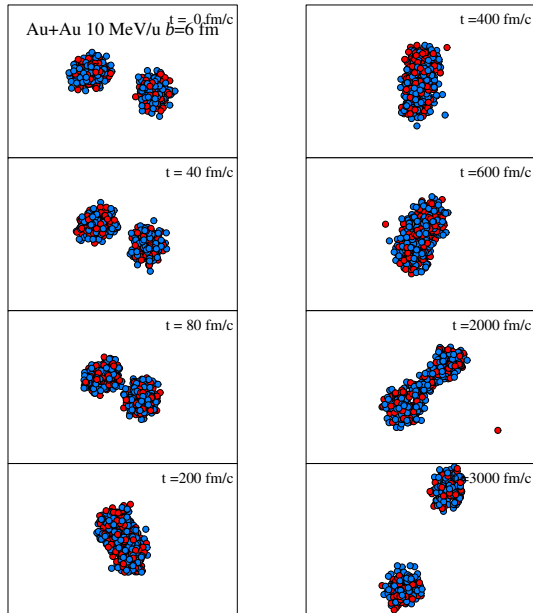
One is the Pauli blocking of the final state of two-body collision and the other is the constraint which brings into the system the Fermi motion in a stochastic way.

Figure 1 shows a typical event of CoMD calculation with incident energy $E_{lab}=10$ MeV/nucleon with impact parameter $b=6$ fm. The two nuclei form a quite deformed compound system, they keep such a deformation almost 2500 fm/c and finally fission takes place. The system does not show much rotation since the angular momentum per nucleon is not so large and the elongated shape makes the moment of inertia larger than that in the initial stage. Therefore the reaction mechanism we are observing here may be in-between the deep inelastic and molecular resonance.

At higher energy, the compound system is highly excited and fragmentation set in. Since the energy discussed are easily reachable at the LNS-cyclotron for instance, it would be very interesting to test these findings experimentally.

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From our simulations we see that the longest contact time between the gold nuclei occurs approximately at 10 MeV/nucleon for central collisions. At lower energy the system separates rapidly because of the strong Coulomb force.

Nuclear fragmentation by tunneling

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Abstract

Fragmentation of nuclear system by tunneling is discussed in a molecular dynamics simulation coupled with imaginary time method. In this way we obtain informations on the fragmenting systems at low densities and temperatures. These conditions cannot be reached normally (i.e. above the barrier) in nucleus-nucleus or nucleon-nucleus collisions. The price to pay is the small probability of fragmentation by tunneling but we obtain observables which can be a clear signature of such phenomena.

For a long time the problem of spontaneous fission has been of large interest for both experimentalists and theorists. In fact spontaneous fission is a nice example of a quantum many body problem. Both the N-particle nature of the system, the atomic nucleus, and the quantum aspect, penetration of a barrier, has stimulated a huge literature production and still the problem is largely unsolved from a quantum mechanical point of view. To a minor extent, the "inverse process" of SF i.e. subbarrier fusion has also stimulated many workers. It is the purpose of this work to suggest a similar problem which involves the quantum N-body features as well as the possibility of critical phenomena.

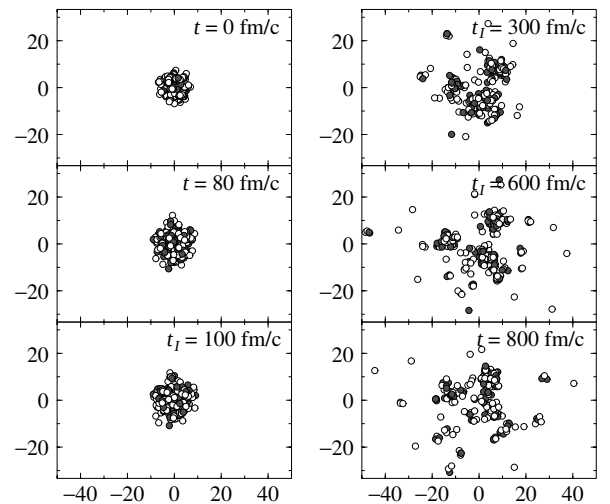
Finite systems might show signatures which are typical of a phase transition. Experiments on fragmentation of atomic nuclei display typical features of a second order, power laws, critical exponents, etc. or a first order phase transition (caloric curve). More recently similar features have been observed in metallic clusters and fullerenes. These are systems that in the infinite size limit have an equation of state that resembles a Van Der Waals. Finite size effects smooth divergences which become maxima for some function. Nevertheless careful analysis are

able to extract to a good accuracy the values of critical exponents which are very close to the liquid-gas values. The problem of these experiments is that the role of dynamics is dominant[1]. As a consequence it is not possible to prepare the system at all desired excitation energies, densities or temperatures as for a macroscopic system. For instance in heavy ion collisions if the energy of the particle is too low we observe fusion-fission of the two nuclei, while, if too large, fragmentation occurs. Imagine that in some way we have been able to prepare the system at density ρ and temperature T . Because of the compression and/or thermal pressure, the system will expand. If the excitation energy is too low the expansion will come to an halt and the system will shrink back. This is some kind of monopole oscillation. On the other hand if the excitation is very large it will quickly expand and reach a region where the system is unstable and many fragments are formed. It is clear that in the expansion process the initial temperature will also decrease. We could roughly describe this process with a collective coordinate $R(t)$, the radius of the system at time t and its conjugate coordinate. Here we are simply assuming that the expansion is spherical. These coordinates are somewhat

the counterpart of the relative distance between fragments in the fission process. Similarly to the fission process we can imagine that connected to the collective variable $R(t)$ there is a collective potential $V(R)$. When the excitation energy is too low it means that we are below the maximum of the potential. That such a maximum exists comes, exactly as in the fission process, from the short range nature of the nucleon nucleon force (or the typical Lennard-Jones force for metallic clusters) and the long range nature of Coulomb. Thus, similarly to SF, we can imagine to reach fragmentation by tunneling through the collective potential $V(R)$. When this happens, fragments will be formed at very low T not reachable otherwise than through the tunneling effect. The price to pay as in all the subbarrier phenomena is a low cross section. We call the fragments formed via tunneling Quantum Drops (QD). Of course a necessary conditions to make such fragments is to have enough energy and this could be easily estimated from the mass formula. For instance one could imagine to search for the events where 3 intermediate mass fragments (IMF) are formed (for which $Z=3$) from an initial nucleus of mass A . From these informations one can calculate the Q -value of the reaction and the corresponding excitation energy to obtain IMF. The closer the excitation energy to the Q -value the smaller the probability to observe the events. It is the purpose of this paper to show through a microscopic simulation that this process is indeed possible and to discuss some features that undoubtedly characterize the formation of the Quantum Drops and that can be verified experimentally for instance in proton nucleus, gentle nucleus-nucleus or cluster-cluster collisions.

We simulate the expansion of ^{230}U system. First we prepare the ground state of a nucleus and then compress uniformly to an excitation energy E^* from 5 to 8 MeV/nucleon. Due to the fluctuations between events caused by the different initial configurations of the nuclei, the potential energy during the expansion is different for different events. Therefore the tunneling fragmentation occurs in some events where the potential energy is eventually high, while there is no tunneling for events with lower

potential energy. At sufficiently low E^* , fragmentation occurs via tunneling only. In Fig.1 we display snapshots of a typical tunneling event. The collective coordinate $P(t)$ becomes zero at $t=100$ fm/c. At this stage we turn to imaginary times as described above and the tunneling begins. Notice that the system indeed expands and its shape can be rather well approximated to a sphere at the beginning. But already at 300 fm/c (in imaginary time) due to the molecular dynamics nature of the simulation, the spherical approximation is broken. This shortcoming of our approach should be kept in mind because the calculated actions will be quite unrealistic. This is similar to the use of one collective coordinate (the relative distance between centers) in SF process. In that case many calculated features are quantitatively wrong but qualitatively acceptable. Since our Quantum Drops is a proposed novel mechanism we can only give qualitative features and the model assumption must be refined when experimental data will start to be available.



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PULSE SHAPE DISCRIMINATION OF CHARGED PARTICLES WITH A SILICON STRIP DETECTOR

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Abstract

A simple and effective pulse shape discrimination technique is applied to a silicon strip detector array. Excellent charge identification from H up to the Ni projectile has been obtained and isotope separation up to N has also been observed. The method we systematically studied is essentially based on a suitable setting of the constant fraction discriminators, and its main advantage is that no additional electronic modules are needed compared to the ones used in the standard TOF technique.

1 INTRODUCTION

Since the early sixties, it has been known that the shape of signals from solid state detectors can be used for particle identification [e.g. 1]. Recently, this idea has been deeply revised in a group of papers by G. Pausch et al. [2-6], where it has been shown that the shape of current signals from solid state detectors is mainly governed by the combination of plasma erosion time and charge carrier collection time effects. When ions are injected from the rear side (i.e. opposite to the junction side) the two effects act coherently, and pulse shape differences for different incident ions are enhanced [3]. Different methods have been proposed in [2-6] to extract information on the incident ions from the pulse shape showing that, for rear side injection, a good identification can be obtained with energy thresholds down to ~ 3.0 and ~ 4.0 MeV/nucleon for Z ranging between 6 and 11 respectively [e.g. 5,6]. Even though some of the proposed methods are rather simple, they all require the use of a dedicated electronic chain. Therefore their application to existing or new silicon multi-detectors would introduce non negligible costs. In the present paper we will present the results of a systematic study on a

pulse shape identification method based on the use of the same electronic chain normally used in the conventional time of flight technique.

2 EXPERIMENTAL DETAILS

The on beam tests have been performed at the cyclotron of the Laboratori Nazionali del Sud in Catania, using a 25.7 MeV/nucleon ^{58}Ni beam impinging on a 3 mg/cm^2 ^{51}V and ^{45}Sc composite target. The studied PSD method has been applied to the first stage of the Si-CsI(Tl) hodoscope of the Trasma multidetector [7]. The first stage of the hodoscope is a 300 μm thick, ion implanted, silicon annular strip detector with an inner radius of about 16 mm and an outer radius of about 88 mm. The detector, manufactured by Eurisys Mesures (Type IPS13-73-74-300-N9), consists of 8 independent sectors (each covering 45° in Φ) divided into 9 circular strips and was placed 80 cm downstream the target location. The block scheme of the electronics for a single strip is shown figure 1. The signals from each strip are first processed by a charge preamplifier (eV-5092) so that the original pulse shape differences are mainly reflected by different rise times of the output signals. The preamplifier is



Figure 1: Block scheme of the electronics for a single strip. SSD-silicon strip detector; PA-charge preamplifier; AMP-spectroscopy amplifier + timing amplifier; CFD-constant fraction discriminator; QDC-charge to digital converter; TDC-time to digital converter; HF-Cyclotron radio frequency time reference. See text for details.

followed by a shaping amplifier and a timing amplifier (Silena - 761F/R - 16 channel shaping+timing amplifier). The energy signal is then integrated and converted by a QDC (Caen-VN1465S 64 channels VME QDC). The use of these highly integrated and double dynamics QDCs allows to easily handle large energy ranges and improves noise rejection. The timing signal, whose rise time reflects the original pulse shape information, is sent to a constant fraction discriminator (CDF) (Caen-C208 16 channels CAMAC-CFD). Our goal is now to enhance the dependence of the CFD timing output on the charge, mass and energy of the ions impinging on the detector. To enhance the Si detector pulse shape differences for different ions and energies, we did not overbias the detector using (with rear side injection) the factory suggested operating voltage of 40 V only a bit above the full depletion one (35 V). In addition we operated the CFDs with rather large delays and fraction settings to maximize the dependence of the CFD output time on the rise time of the input signals. Using the Cyclotron HF as reference, the measured “time”, carrying information on the original pulse shape (t_{ps} in the following), is converted by a TDC (Caen-VN1488S 64 channels VME TDC). The cyclotron has been operated in a pulse suppression mode corresponding to a time dynamics between two beam bursts of 155 ns and intrinsic burst width of about 1.5 ns.

3 RESULTS AND DISCUSSION

In this section we will present the obtained results, and discuss how the identification “quality” depends on the fraction and delay settings of the CFDs.

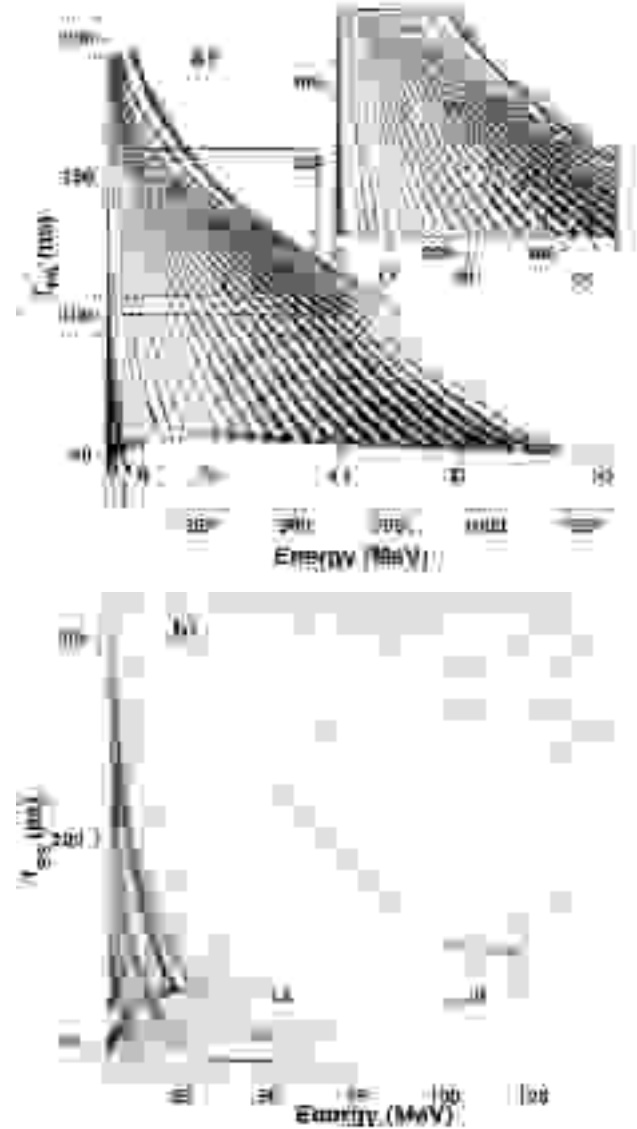


Figure 2: a) The $E-t_{ps}$ scatter plot obtained with a CFD fraction setting $F=0.33$ and a CFD delay time of 100 ns. The region marked by a box is expanded in the inset. b) Same $E-t_{ps}$ plot as fig 2(a), but for the high gain conversion output of the QDC. In both figures the events in the branches marked by the arrows are due to low energy heavy particles whose t_{ps} range is larger then the interburst time. The time scale is calibrated in ns with an arbitrary choice of the $t_{ps}=0$ instant.

As an example, in figure 2(a) we show a scatter plot of t_{PS} versus energy (low gain QDC output) obtained with a fraction setting $F=0.33$ and a delay setting of 100 ns. Figure 2b) represents the same spectrum as figure 2(a) but the energy corresponds to the high gain output of the QDC. A clear charge identification from H up to the Ni projectile is observed in a wide energy range extending up to the punch through energies for the different ions. Typical charge identification thresholds are ~ 1.7 MeV/nucleon for $Z \approx 6$, ~ 3.0 MeV/nucleon for $Z \approx 11$ (figure 2b) and ~ 5.5 MeV/nucleon for $Z \approx 20$ (inset in figure 2a). Isotope identification up to $A \approx 13$ is observed with an energy threshold of about 6 MeV/A (figure 2b). Unfortunately, the experimental t_{PS} range for heavier particles is larger than the beam interburst time used in the present test. Therefore branches corresponding to low energy heavy particles (marked by arrows in figure 2) “wrap round” and are observed at low t_{PS} times blurring the identification for low energy particles. Note that the measured t_{PS} is a combination of pulse shape effects and real time of flight. However, the real time of flight difference, between two adjacent charges at a fixed incident energy, typically accounts only for 20% or less of the time difference measured and is of the same order as our time resolution. Therefore the observed particle identification is essentially due to pulse shape effects.

We have now to discuss how the identification “quality” depends on the fraction and delay settings of the CFDs. To quantitatively evaluate this “identification quality” we use the energy threshold for particle identification and the “resolving power” M for the charge separation which we defined in the following way:

$$M = 0.2 \cdot \frac{\Delta E}{\Delta \delta}$$

Here ΔT , ΔZ , and $\Delta \delta$ have the following meaning. In the $E-t_{PS}$ plot, we divided the energy range into fixed width bins. We then projected each energy bin onto the time axis observing peaks corresponding to the different charges. ΔT is the t_{PS} interval between two peaks, ΔZ is the

corresponding charge difference and $\Delta \delta$ is the average σ of these two peaks extracted with gaussian fits. The so defined M factor may remind a similar factor [8] frequently used to characterize the n- γ discrimination ability.

In order to compare identification energy thresholds obtained with different CFD settings, we defined the following standard procedure to estimate the thresholds and their associated uncertainty. In the $E-t_{PS}$ 2D spectrum we performed a fit of the different charge branches, in a low energy region where different charges were still clearly separated. These fits were then extrapolated to lower energy. The intersection point of two neighboring fit lines, taking into account their finite widths due to the experimental resolution, defined the energy threshold.

It is well known that operating the CFD with small delay times (ARC mode) one can at least partially compensate for different input rise times. Since our goal is now the opposite, one qualitatively expects to obtain a better identification for larger CDF delay settings. As expected, we experimentally found that both the thresholds and the M factors improve by increasing the delay, therefore we decided to keep it constant at 100 ns (i.e. the maximum possible delay setting in our modules).

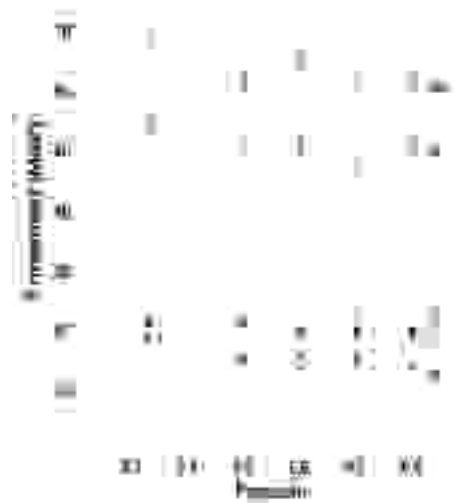


Figure 3: Observed threshold variation as a function of the CDF fraction setting for a fixed CDF delay of 100ns.

In Figure 3 the identification thresholds for different elements are reported as a function of the fraction setting, for a constant delay of 100 ns. As one can see the pulse shape discrimination threshold is only a weak function of fraction setting, slightly decreasing for increasing fractions.

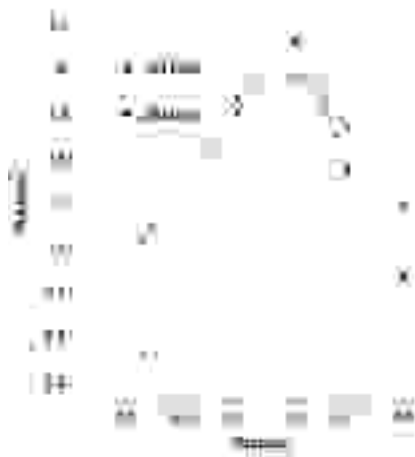


Figure 4: Observed M factors as a function of the CDF fraction setting at E=600 MeV (full circles) and E=300 MeV (full squares) for a fixed CFD delay of 100 ns. See text for details.

Finally, in figure 4, we show the observed dependence of the M factor as a function of the fraction setting, again for a constant delay of 100 ns. The M factors have been extracted considering the peaks of Ca and Cr at E=600 MeV and the peaks of Na and S at E=300 MeV with an energy bin of ± 5 MeV. As one can see relatively large fractions, of the order of 0.5÷0.6, give the best results for particle identification. This result was qualitatively expected. In fact, as a preliminary test, we digitized some output signals from the timing amplifier, and observed the simulated CFD zero crossing calculated for these signals with a simple program. Larger zero crossing time ranges were observed for larger fraction settings, in qualitative agreement with the above presented experimental results.

The method discussed in the present paper has been applied to all the strips of the 8 independent sectors of our detector, and already successfully used in a real experiment [9].

4 CONCLUSIONS

In summary, a good identification from H up to the Ni projectile has been observed with energy thresholds comparable or better (especially for low charges around $Z \approx 6$) than the ones obtained in [2-6]. The most prominent features of the method we studied are that no additional electronic modules are needed compared to the conventional TOF technique, and that commercial and highly integrated electronics can be used. Therefore the method appears to be very promising, especially for its possible application to existing silicon multidetectors with no additional costs for new dedicated electronic chains.

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ISOTOPE IDENTIFICATION IN THE REVERSE EXPERIMENT BASED ON AN IMPROVED ΔE -E METHOD

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Abstract

A procedure has been developed for mass and charge identification of charged products detected in nuclear heavy ion reactions with a ΔE -E telescope. The procedure does not require energy calibration of the detectors and prior measurements with beams of known energy, mass and charge. An identification function, based on the Bethe-Bloch formula, is developed. A minimization routine determines the atomic and mass numbers of the detected charged products directly from uncalibrated ΔE -E matrices. An application of this technique to the Chimera Si-CsI(Tl) telescopes is described.

1 INTRODUCTION

In the last years several new detectors for charged particle identification, with large solid angle coverage and high geometrical efficiency, have been built in order to investigate heavy ions reactions at intermediate energies (10 A.MeV ~1 A.GeV). These experimental devices give possibilities for simultaneous measurement of quantities related to energy, emission angle,

atomic number and mass number of nearly all the charged reaction products. A very rich information can be extracted from these experimental studies, in particular if the mass resolution of the apparatus is high.

The necessary step before the data analysis is the calibration of the measured signals. However, due to the number of different detectors used and to the rich variety of nuclear

species produced, this preliminary step is quite man-power and time consuming.

Another difficulty to be taken into account is that, in principle, not necessarily all the detectors of a multi-modular ΔE -E telescope have response linear in energy. Indeed, due to the relatively high stopping power, no limits in the geometrical shape, negligible radiation damage, low cost and good resolution, scintillators are largely used as residual energy detector, in the last generation of 4π devices. In this case, since the light output of scintillators strongly depends both on the energy deposited in the crystal and on the atomic and mass numbers of the incident ion, an accurate identification in mass and charge, before the energy calibration, is needed.

For the charge identification, semi-automatic techniques have been set [1], but mass identification is usually performed through graphical cuts around each A-line in the ΔE -E scatter plot [2]. This method has the disadvantage that the number of contour lines that can be drawn is limited by the statistics and extrapolation to rare isotopes cannot be performed. Part of the physical information for isotopes populated with low statistics is then lost.

A fast and reliable method to assign the mass and charge of the detected ions is therefore highly desirable. In this paper we present a very effective mass and charge identification method which, as compared with other methods, considerably saves time without loss of precision. We present also application of our procedure to a part of the data collected for the first time with the Chimera apparatus [3]. The mass and charge distributions obtained through usual methods, like graphical cuts, are compared with those obtained from our procedure.

2 MASS IDENTIFICATION FUNCTION

Specific energy loss (dE/dX) of a charged particle in matter depends on the characteristics of the incident ion (mass, charge and energy) and of the absorbing medium (density and

atomic number) and is well described by the classical Bethe-Bloch formula (1), see [4]. The specific energy loss is:

$$\frac{dE}{dX} = \frac{Z^2}{f(E/A)} \quad (1)$$

However experimentally we face up to different peculiarities due to the choice of the detector and the electronic chain.

- When the residual energy becomes low, the atomic charge is no longer equal to Z , especially for heavier elements.
- In experiments, some discrepancies can appear when E is measured from the light output of a scintillator like CsI. For a scintillator indeed, the response suffers of non linearities at low energy, which depend on Z .
- Due to presence of thresholds in the QDC (ADC) signals, it would be very difficult to look at the values of ΔE of the A-lines at $E=0$.

In order to take into account all these constraints we'll use a formula (2), based on the classical Bethe-Bloch formula, and using 7 free parameters ($\alpha, \beta, \lambda, \mu, \nu, \xi, g$), which reproduce the energy ΔE lost by a charged particle (Z, A) of energy E through a thickness of matter ΔX . However if pedestals are still contained in the signals, then one has to add 2 additional parameters.

$$\Delta E = \left[(gE)^{\mu+\nu+1} + (\lambda Z^\alpha A^\beta)^{\mu+\nu+1} + \xi Z^2 A^\nu (gE)^\nu \right]^{\frac{1}{\mu+\nu+1}} - gE \quad (2)$$

This formula results from a compromise to rely the behaviours at low, intermediate and high energies. (see [5] and [6] for more details)

3 MASS IDENTIFICATION PROCEDURE

The identification procedure consists of two steps:

- We sample on the ΔE -E scatter plot some points on the lines of well defined isotopes (^4He , ^7Li , ^7Be , ^{11}B , ^{13}C). In experiments, these isotopes can be easily recognized, due to their abundance (^4He , ^7Li , ^{11}B , ^{13}C)

or separation from other masses (^7Be). The charge, mass, ΔE and E coordinates of these points are put in a table. A minimization routine determines the parameters α , β , λ , μ , ν , g and ξ , giving the best agreement between sampled points and the energy-loss from eq.(2).

- For each event, every pair (ΔE , E) is transformed into the (Z , A) pair, identifying the detected charged fragment. Since the identification function (2) can not be analytically solved in terms of Z and A , a two-step process has to be used. The first step is to find the charge Z (simply assuming $A = 2 \cdot Z$), by looking for the value of Z giving the shortest distance between the experimental ΔE and the energy loss given by eq.(2) at the residual energy E . After the charge Z has been identified, one has to repeat the procedure, by solving eq.(2) with respect to A .

We would like to emphasize that the procedure we propose has the advantage of determining a unique set of parameters for the whole ΔE - E matrix. Consequently, the interpolation or extrapolation to not sampled values of A and Z should be under control.

4 EXPERIMENTAL RESULTS

In this Section we show the results of the identification procedure applied to experimental data. The data have been collected, for the reaction $^{124}\text{Sn} + ^{64}\text{Ni}$ at 35 A.MeV incident energy, in an experiment performed at the Cyclotron of LNS (Catania) by the Reverse collaboration [7]. The forward part ($\theta_{\text{lab}} \leq 30^\circ$) of Chimera array was used for this experiment. In this configuration, 688 telescopes made of 200 or 300 μm ΔE Silicon detector thick (depending on the θ_{lab}) and CsI (Tl) stopping detectors were used.

4.1 Experimental procedure

We start the analysis by sampling a set of (ΔE - E) points, see figure 1. As mentioned before we have chosen the ^4He , ^7Li , ^7Be , ^{11}B , ^{13}C isotopes.

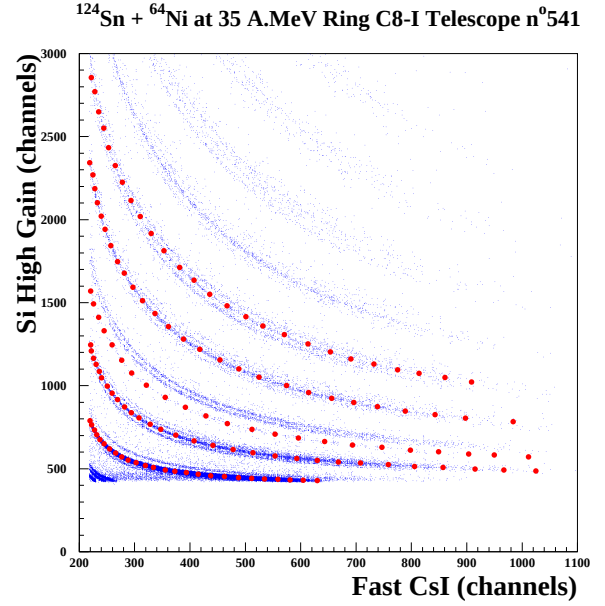


Figure 1 : Experimental ΔE - E matrix for a Chimera telescope. Red symbols are the sampled points used for the fit procedure ^4He , ^7Li , ^7Be , ^{11}B , ^{13}C

Then we fit the data points with the equation (2), with 7 parameters plus 2 parameters for both ΔE and E pedestals.

4.2 Check of the procedure

As we want to check the accuracy of our method in the determination of the isotopic yields, we have compared our results with the ones obtained by the usual method, the graphical cuts, in a region where A -lines are clearly visible and distinguishable. As you can see on table (1) the yields result in excellent agreement in both cases.

Table 1: Comparison of isotopic yields through graphical cuts and the method using equation (2)

Isotope	Yield from Graphical cut	Yield from eq. (2)
^6Li	864	865
^7Li	1950	1948
^8Li	547	520
^7Be	264	244
^9Be	1114	1080
^{10}Be	1173	1109
^{10}B	350	354
^{11}B	1673	1600
^{12}B	494	519
^{12}C	745	707
^{13}C	860	858
^{14}C	616	579

We have also tested our method by following the same procedure applied to ideal generated events [6]. A very good agreement is observed.

4.3 Preliminary experimental results

In figure (2) we report the isotopic resolutions obtained for charges 3 to 8, belonging to the ΔE -E matrix shown in figure (1), for the same system with different N/Z ratio. All the spectra are normalized at the same area, and no selection is applied. However we can already observe the different population of isotope with the N/Z entrance channel. On the other hand for two different systems $^{124}\text{Sn}+^{64}\text{Ni}$ and $^{124}\text{Sn}+^{27}\text{Al}$ with the same N/Z ratio, we observe a quite similar isotopic distribution.

5 CONCLUSION

We have presented here a new method based on the classical Bethe-Bloch formula adjusted to the experimental ΔE -E matrices obtained with the new generation of 4π detectors like Chimera. The main advantages of our procedure are the following:

- Any beams of known mass charge and energy are needed for charge and mass identification of ΔE -E matrices.
- Same accuracy with the graphical cut method used up to now.
- Possibilities for interpolation and extrapolation, with a unique set of parameters, to mass regions where low statistics makes graphical cuts not easy to draw.
- Check of possible drift of the electronic chain during experiment and control of the stability of each telescope.
- Fast, standardized and reliable mass and charge identification for 4π array.

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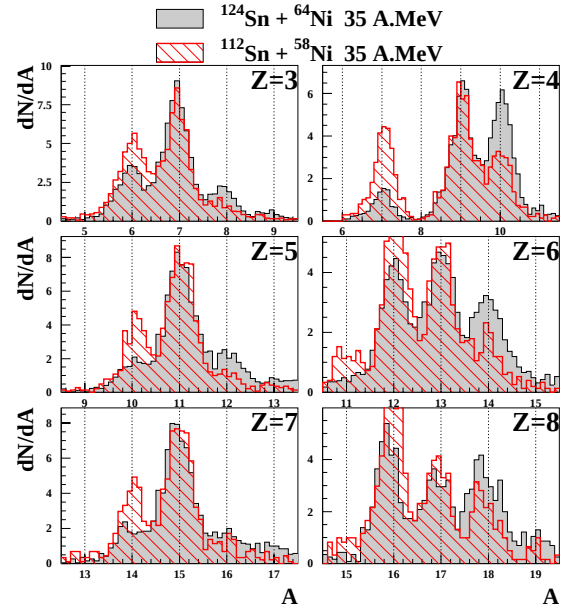


Figure 2 : Experimental isotopic distributions obtained from Eq. (2) for charge Z=3-8, for the same system with different N/Z ratio, 1.41 and 1.18.

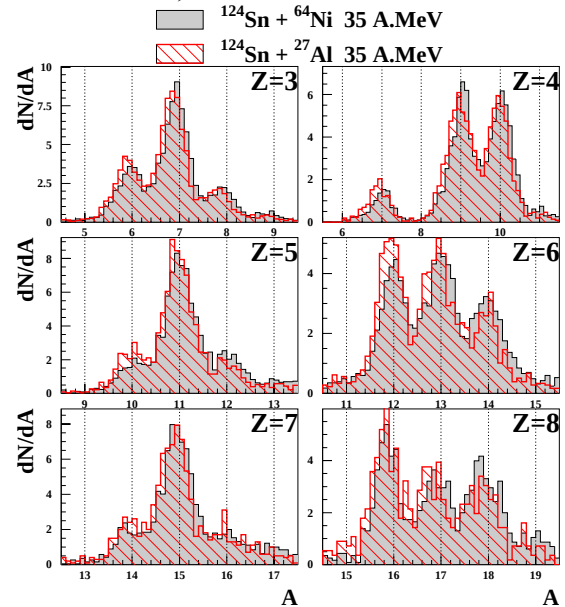


Figure 3 : Experimental isotopic distributions obtained from Eq. (2) for charge Z=3-8, for two different systems with a similar N/Z ratio, 1.41 and 1.40.

A SPATIAL DENSITY ANALYSIS TECHNIQUE FOR THE AUTOMATIC CLASSIFICATION OF 4π DETECTOR DATA

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Abstract

This paper presents a novel approach to the automatic classification of $(\Delta E, L)$ 2D scatter plots. The method is based on spatial density data processing and produces frequency distributions of the most significant physical parameters, more easily analyzed than the standard matrices. With respect to manual or semi-automatic procedures, presently used for data analysis, our method offers the advantages of drastic time reduction and unbiased criteria for cluster identification. The proposed method can be successfully used in both off-line data analysis and multidetector stability control.

1 INTRODUCTION

In this paper we present a different approach to the automatic analysis of $(\Delta E, L)$ scatter plots. It answers the need that has arisen for algorithms yielding data representations more suitable for automatic on-line control than standard 2-D scatter plots (Fig. 1); in particular, 1-D frequency distributions match this requirement. Such representations can already be obtained, for example, by means of particle identification techniques. To obtain higher quality results, we developed special algorithms that operate a projection to one dimension of a 2-D scatter plot. They rely on the presence of carrier lines, related to the Z-classes (points clusters) of reaction products appearing in the considered matrices. In the proposed system, carrier lines drawing is automatically accomplished by analyzing point density information of matrices.

The system is able to process scatter plots of 4096×4096 pixels automatically and produces

1-D charge frequency distributions showing the peaks of detected ions. The proposed technique is also suitable for the on-line control [1] of CHIMERA [2] stability.

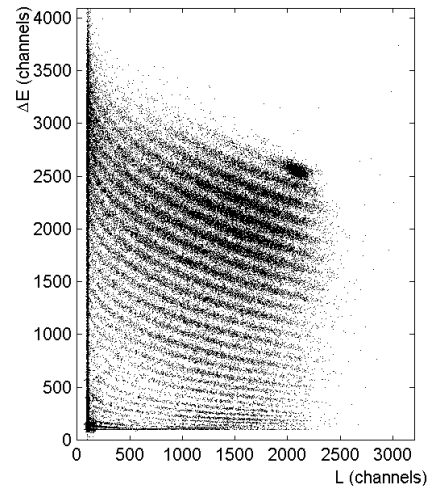


Fig. 1. 2-D scatter plot for the reaction $^{58}\text{Ni} + ^{27}\text{Al}$ at 30 MeV/u ^{58}Ni incident energy and for $\theta_{\text{lab}} = 3^\circ$.

Semi-automatic methods, in which cluster identification is performed by a human operator,

constitute a viable and valid alternative, although to the detriment of an efficient cluster extraction procedure. In addition they introduce unavoidable subjective criteria in cluster determination. Semi-automatic methods yielding 1-D frequency distributions starting from manually drawn cluster carrier lines were described in [3]. With respect to manual or semi-automatic procedures, the method we present here offers the advantages of drastic time reduction and unbiased criteria for cluster identification.

2 AUTOMATIC SYSTEM

The approach we present is based on the analysis of spatial point density information of data matrices. We have defined a system that automatically detects areas whose point density is higher than average, corresponding to clusters, and then in those areas searches for the points with maximum density value [5]. These points are expected to lie along cluster edges. Further algorithms elaborate such information to obtain cluster carrier lines and then 1-D frequency distributions.

At present the system operates on the 2-D CIF vs. Light data representation [3] (see Fig. 2), where CIF is obtained by applying the power-law [4] to the $(\Delta E, L)$ data, i.e. $CIF = (L + \Delta E)^x - L^x$ [3].

This, as will be shown later on, allows some steps of the procedure to be speeded up. The technique, however, can be easily extended to the case of 2-D $(\Delta E, L)$ scatter plots.

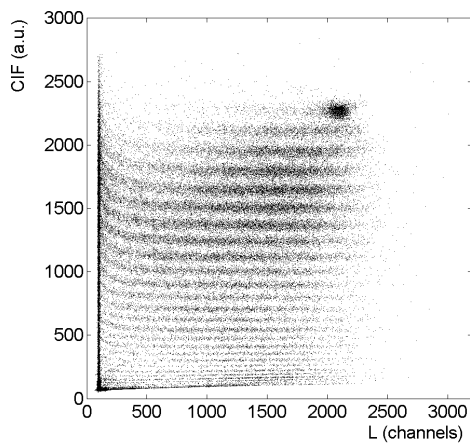


Fig. 2. 2-D scatter plot of CIF vs Light pulse

2.1 Carrier lines automatic determination

Since the goal is to determine cluster carrier lines, and a line is given when some its points are determined, the idea was to analyze how point density varies in a number of predefined areas of each cluster. Let us call these areas sections. It should be observed that the value associated with each point in the (CIF, L) matrix, i.e. the count, is meaningless for this computation. Given the trend of clusters, we defined vertical segments as cluster sections. Each point in the section determines a window, of fixed dimension, centered on it. The density for a point in a section is defined as the point density of its corresponding window.

It is expected that, in a cluster, maximum density values lie all along the cluster edge or carrier line. As the cluster is cut by a number of sections, its carrier line can be determined by identifying the maximum density point in each of its own sections. The whole line is obtained by selecting, among the points resulting from the maximum search, those for which a given relationship holds, specifically that they belong to the same carrier line. Given the specific choice of (CIF, L) representation, carrier lines are almost parallel to L axis. Thus, points having the same CIF coordinate, up to a percentage of acceptance, belong to the same carrier line.

Briefly, the following steps have to be accomplished:

1. generate the desired cluster sections for the (CIF, L) matrix;
2. determine the points in each cluster section corresponding to maximum density value;
3. find out for each point (maximum) to which carrier line it belongs, thus univocally identifying every carrier line by the set of its points;

In step 1, we supposed a number of straight lines, parallel to the CIF axis, intersecting the data in the matrix (secants). In this way each secant generates a section for every cluster it intersects. The number of secants depends upon the kind of matrix being analyzed. Generally, a constant step among them is used. In case of low statistics, this value may be small (e.g. 10)

and, thus, lines may be close to each other, as the meaningful information is very sparse. In case of high statistics, on the other hand, a larger constant step (e.g. 100) can be used. In the present application, secants were defined for $300 \leq L \leq 2000$ with step=50.

The variation of point density along the specified secants (step 2) is then analyzed. Given a line, windows of increasing size are defined for each of its points, and point density is computed in each window. For each point the maximum of the resulting values is saved. Window size varies in a range which makes it possible to accommodate both narrow and large clusters. In the present case, 8 square windows were used with increasing size, from 21×21 to 33×33 points. As expected, given a window size, the procedure generates local maxima in each cluster section. The global maximum density value is then searched for. Moreover, since more windows are defined for each point of a cluster section, we compute the highest value among the maxima for all windows of the point. An *ad hoc* algorithm derived from classical maximum search algorithms has been implemented for this purpose. Results are shown in Fig. 3, displaying a set of points, corresponding to maximum density points, in the expected positions within clusters.

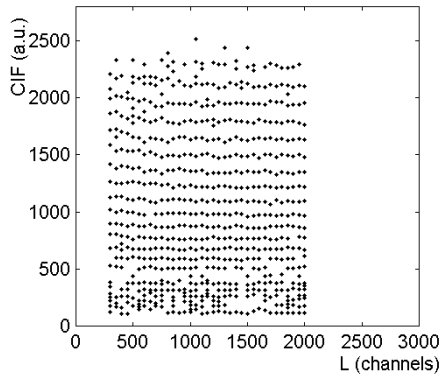


Fig. 3. Computed maximum density points with secant step=50.

In step 3, carrier lines are determined, or more precisely it is determined which points belong to the same carrier line. A series of procedures operates incrementally on the points resulting from step 2, so as to univocally define a carrier

line for all of them. Fig. 4 displays the automatically identified carrier lines for the (CIF, L) matrix of the scatter plot in Fig. 2, as resulting from the elaboration of the points shown in Fig. 3.

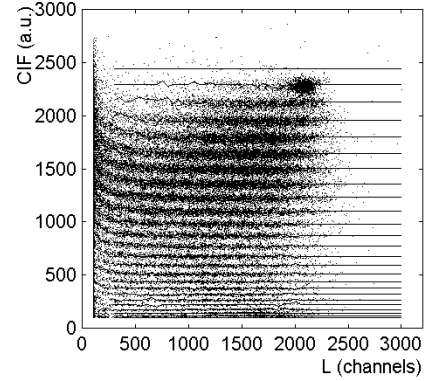


Fig. 4. 2-D scatter plot of CIF vs. L with automatically determined cluster carrier lines.

2.2 First-order (linear) straightening

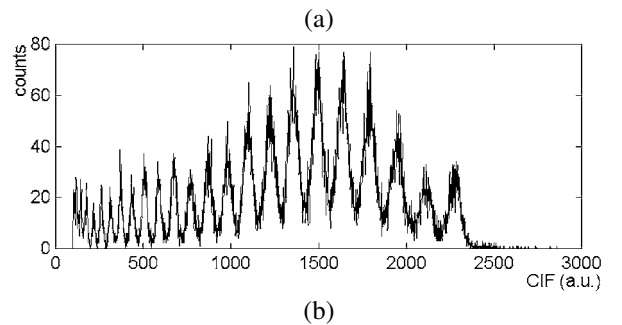
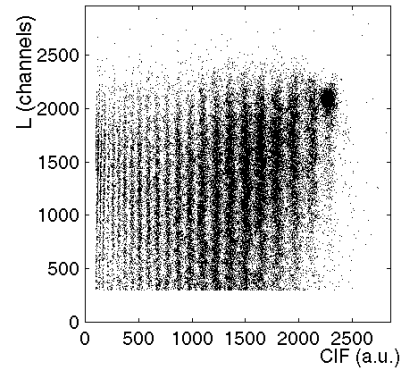


Fig. 5. First-order straightening for $L \geq 300$ obtained with computed cluster carrier lines. (a) 2-D representation CIF vs. L. (b) 1-D Z-spectrum.

Once carrier lines have been defined, the system makes use of the procedures developed for the semi-automatic method [3], i.e. first-order and second-order straightening, to obtain final 1-D Z-spectra: keeping the carrier lines as the references, to the (CIF vs. L) scatter plot is

applied an isomorphic transformation (*first order straightening*):

$$y' = L \quad (1a)$$

$$x' = Z'_p = Z'_1 + (Z'_2 - Z'_1) * d_1 / (d_1 + d_2) \quad (1b)$$

Z'_p is the “straightened” CIF (i.e. x') value of each particle, while d_1 and d_2 are the distances to the two closest Z-central lines. Clearly the central lines are rendered as vertical straight lines: Z'_i are their x' positions. The result is the new 2-D representation shown in Fig. 5a. Fig 5b shows the related 1-D representation.

It can be noted that, in order to obtain the results presented in Fig.5, not all the carrier lines have to be necessarily drawn on the 2-D scatter plot of Fig. 2. Of course, the more the carrier lines, the more the transformation is accurate.

2.3 Second-order (squared) straightening

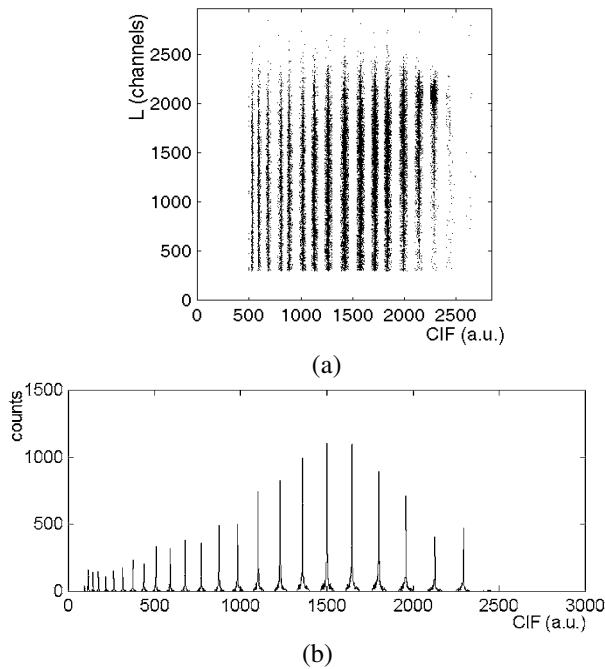


Fig. 6. Second-order straightening for $L \geq 300$ obtained with computed cluster carrier lines. (a) 2-D representation CIF vs. L. (b) 1-D Z-spectrum.

The quality of resulting spectra, i.e. the separation among different charge peaks, can be improved by applying a second-order or *squared* straightening algorithm:

$$Z'_p = Z'_1 + (Z'_2 - Z'_1) * (d_1 / (d_1 + d_2))^2 \quad \text{if } d_1 \leq d_2 \quad (2a)$$

$$Z'_p = Z'_2 - (Z'_2 - Z'_1) * (d_2 / (d_1 + d_2))^2 \quad \text{if } d_2 < d_1 \quad (2b)$$

The results obtained are shown in Fig. 6. The charge peaks are clearly separate even if the number of counts for each peak is relatively poor and no smearing function has been applied to the frequency distribution.

On the other hand, the second-order straightening heavily relies on carrier lines: one carrier line less will mean that the corresponding Z-line is missing. Points that should cluster around it are instead redistributed to the two nearest Z-lines.

The final energy spectra obtained for $Z=28$ with the semi-automatic and the automatic system are identical to those obtained by using the traditional procedure. Therefore the accuracy of results is comparable with that of the traditional procedure (with a mean disagreement of about 1.5%), but by being automatic the method proposed in the paper optimizes computation time.

The same procedure can be directly applied to the 2-D (ΔE , L) histogram, obtaining similar results, obviously using a larger number of points for drawing carrier lines.

The system is implemented using Matlab 5.3 developing environment. In the present release it runs on a PC Athlon K7 850 MHz, and the time needed to produce a 1-D spectrum is about 15-30 minutes.

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AUTOMATIC PROCESSING OF FAST-SLOW SCATTER PLOTS

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Abstract

The present work is concerned with the possibility to perform automatic analysis of 2D Fast-Slow scatter plots. The followed approach consists in applying image processing techniques: Grossberg's pre-attentive neural networks are used first, in order to isolate the regions of physical interest in the matrices and to roughly identify the directions depicted by the most intense lines. A successive step of filtering is then performed, based on Markov Random Fields.

1 INTRODUCTION

In this paper we present an automatic method to analyze the matrix of data collected from the multidetector CHIMERA [1].

We have already verified that the use of the biology-based Grossberg's Neural Networks (NN) is a good tool for the automatic analysis of (ΔE , Fast) matrices [2-4].

Now we consider the so-called *Fast-Slow* matrices, which are particularly important for light particle identification, because they allow to recognize different isotopes for each Z (Fig.1).

In this case the use of Grossberg's N) does not suffice for our goals. Thus, to process this kind of images we decided to apply a technique which mixes the biology-based Grossberg's NN with Markovian field based filters.

Markov Random Fields (MRF) realize isotopic discrimination by using clues regarding Z clusters orientation, extracted by Grossberg's NN, as prior information. 1D frequency distributions are then easily derived by means of simple procedures, as shown in [5].

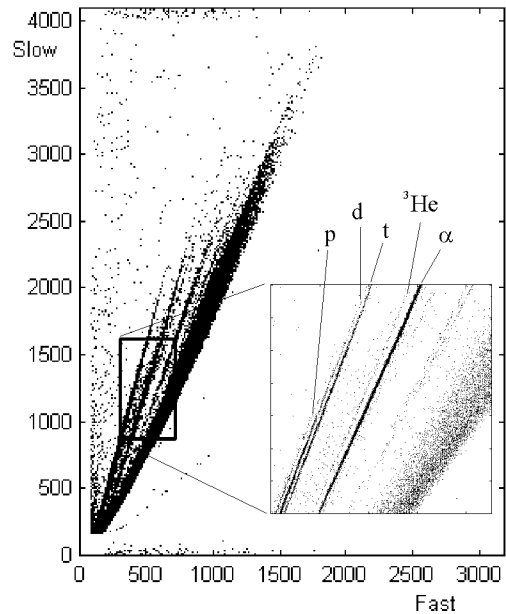


Fig. 1 Typical 2D-matrix of Fast-Slow data.

2 DESCRIPTION OF THE METHOD

2.1 Grossberg layer

The NN employed for the prior information extraction are Grossberg's *on-center off-surround shunting* Neural Networks [6,7]. They

perform a contrast enhancement on their input patterns, their dynamic being described by the following equation:

$$\frac{d}{dt}x_{ij} = -(x_{ij} - E) + \sum_{(p,q) \in N_C} [(U - x_{ij})C_{ijpq}]I_{pq} + \sum_{(p,q) \in N_S} [(x_{ij} + L)S_{ijpq}]I_{pq} \quad (1)$$

C_{ijpq} and S_{ijpq} , respectively the center and the surround neighborhoods of the neurons, define the weight distribution applied to the stimuli entering each neuron. Being functions of the distance from the incoming input to the destination neuron, they equally refer to all the network's neurons. NNs of this kind, called self-similar, do not need to be trained, in that they are wholly configured just by setting a weight function and a few parameters. This is a very interesting feature, because learning is always a critical step when using NNs.

We use weight functions that are uniform over a circular area centered on each neuron:

$$C, S_{ijpq} = \begin{cases} (1 - q^2) + (1 - p^2) \leq r_{C,S}^2 \\ 0 & \text{otherwise} \end{cases} \quad (2)$$

Only two parameters are thus required to define the shape of the neighborhoods: r_C and r_S , the radii of the excitatory and inhibitory stimuli pattern areas to which the neurons are sensitive. We set $r_C=4$ and $r_S=100$ (in pixels). The other parameters to be set, E , L and U , limit the dynamical range of the results: for the properties of shunting networks [6,8,9], neuron activity x_{ij} always lies within the range $[-L, U]$, while E is the baseline activity.

The matrices we consider are highly sparse scatter plots, characterized by the presence of “quasi-linear shaped” clusters corresponding to the different isotopes identified. Sparse events located outside the region of the clusters, need not to be considered. Applying a shunting NN to input stimuli of such a type, results in output patterns that show maxima (values high above the baseline activity) along the (most populated) isotope clusters, which are the most dense areas, surrounded by minimum values (below baseline activity).

We have used both maxima and minima localization information. First we emphasize the minimum values by appropriately setting the values for U and L : in particular we set $U=10$ and $L=10$, $E=0$. The result is used to isolate the isotope cluster region, within each matrix, which is always very small compared to the dimensions of the complete matrices. This helps the successive computations and speeds up execution times.

The NN is then applied again, on the selected region only, and the emphasis is put on the maximum values ($U=100$, $L=10$, $E=0$) in order to reveal the cluster outlines. Fig. 2 shows NN output for the matrix of Fig. 1: the mean slopes for $Z=1$ and $Z=2$ are clearly highlighted.

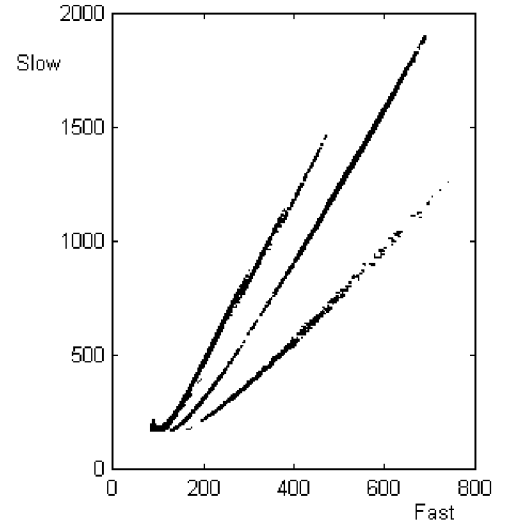


Fig. 2. Results of NN elaboration on data of Fig. 1, highlighting $Z=1$ and $Z=2$. The rightmost cluster represents unresolved heavy ion events.

2.2 Markov Random Field Layer

The goal of this second layer is to use the coarse information about the orientation given by the first layer in order to identify the isotope clusters.

Since the seminal work of Geman and Geman [10], the use of contextual constraints or prior information in conjunction with Bayesian methods is a common practice in image analysis. Bayesian methods utilize probability models to incorporate information and join prior and data information to construct posterior probability distribution [11]. The encoding of prior information can be accomplished using

Markov Random Fields. MRF allow to model different types of local spatial interaction and contextual constraints between the pixels.

The MRF model is generally used in image processing for the construction of prior probability distribution that model piecewise smooth (also blob-like or cartoon) images [10-12]. The simplified assumption in piecewise-smooth model of image analysis is the use of smoothness prior information over the entire image. The smoothness prior is generally encoded using a homogeneous (neighborhood system equal for each pixel) and isotropic MRF. Another MRF (line field [10] defined on a lattice dual to the one of the intensity field) is introduced to take into account boundaries between pixel sites. For the present application a non-homogeneous MRF model has been defined. The model exploits the information about local orientation in order to select the local neighborhood structure.

In MRF models an image f is considered as a realization of a random field F over a lattice (or a 2D array) S . A neighborhood system $N = \{N_i, i \in S\}$ is a collection of subsets of S , such that 1) $i \notin N_i$, and 2) $i \in N_i \Leftrightarrow j \in N_i$. A subset c of N is a clique if every pair of distinct pixels in c are neighbors of each other. The set of all cliques will be denoted with C . A probability distribution is a MRF distribution with respect to N if

$$p(f_i | f_j, j \neq i) = p(f_i | f_j, j \in N_i) \quad (3)$$

where f_i and f_j denote the random variables representing pixel values at sites i and j .

According to the Hammersley-Clifford theorem [13] the joint posterior distribution of an MRF obeys a Gibbs distribution. A Gibbs distribution with respect to a neighborhood system N is:

$$p(f) = \frac{1}{Z} \exp \left\{ - \sum_{c \in C} V_c(f) \right\} \quad (4)$$

where Z is the normalizing constant (or partition function), and $V_c(f)$ is a function of the pixels in the clique c . In our model:

$$\sum_{c \in C} V_c(f) = \sum_{\{a\}} V_2(f_{i,j}, f_{k,l}) + \sum_{\{b\}} V_3(f_{i,j}, f_{k,l}, f_{m,n}) \quad (5)$$

where $f_{q,r}$ denotes pixel value, $\{a\} = \{(i,j), (k,l) \in C_2\}$, $\{b\} = \{(i,j), (k,l), (m,n) \in C_3\}$, and C_2 and C_3 denotes cliques composed by pairs and triples of pixels respectively.

The cliques are function of orientation angle θ and charge Z , i.e. $C_k = C_k(\theta, Z)$, $k = 2, 3$. Obviously $\theta = \theta(i,j)$. The general form of the clique potential adopted is:

$$V_2(f_{i,j}, f_{k,l}) = (f_{k,l} - f_{i,j})^2 \quad (6)$$

$$V_3(f_{i,j}, f_{k,l}, f_{m,n}) = (s(\theta)f_{m,n} + t(\theta)f_{k,l} - f_{i,j})^2 \quad (7)$$

with $s(\theta)$ and $t(\theta)$ scalars,

$$(k,l) = (i + dx_1(\theta, Z), j + dy_1(\theta, Z)) \quad (8)$$

$$(m,n) = (i + dx_2(\theta, Z), j + dy_2(\theta, Z)) \quad (9)$$

By using these clique potentials we model prior information for Z lines with slope between 60° and 80° , which are the orientations of interest in our data image, and also take into account the slight variations of slope along each single isotope line. Modeling both the given data image g and prior information by means of a Gibbs distribution, we obtain the posterior distribution using Bayes theorem. The estimate of f can be obtained using a Maximum a Posteriori (MAP) criterion. This procedure leads to the optimization of an energy function En over all possible images f :

$$\begin{aligned} f_{MAP} &= \arg \min_f En(f) = \\ &= \arg \min_f \left\{ (g - f)^2 / 2\sigma^2 + \sum_{c \in C} V_c(f) \right\} \end{aligned} \quad (10)$$

The parameter σ plays the role of smoothness parameter and is considered constant over the entire image. It is assumed, for the observed data image g and the field f , the following conditional probability distribution:

$$p(g | f) = \prod_{i,j \in S} \frac{1}{\sqrt{2\pi}\sigma} \exp \left[- (g_{i,j} - f_{i,j})^2 / 2\sigma^2 \right] \quad (11)$$

The optimization procedure is performed by means of a gradient descent algorithm [14]:

$$f_{i,j}^{k+1} = f_{i,j}^k - \alpha_k \frac{\partial En}{\partial f_{i,j}} \quad (12)$$

where k denotes the iteration number. Although the use of deterministic algorithm instead of stochastic ones can yield non-optimal solutions, they are computationally less expensive. Once the estimate of f is obtained, the boundaries of isotope lines can be determined using some classical edge detector filters like Laplacian of Gaussian (LoG) [15] or Canny edge detector [16].

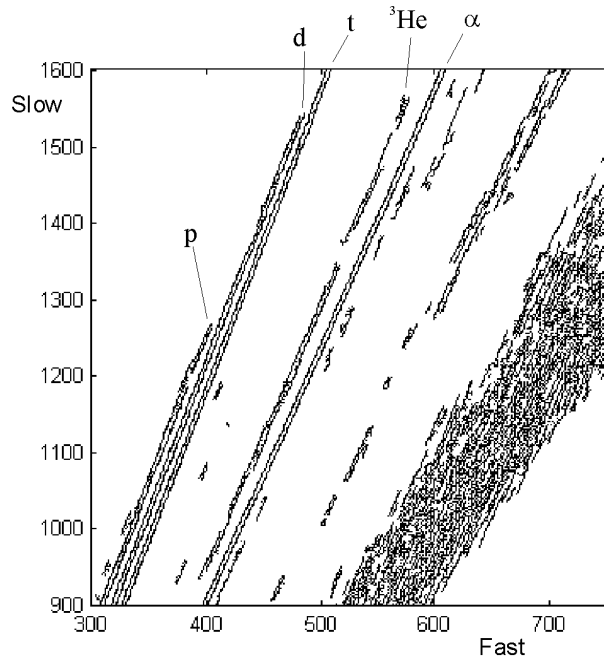


Fig. 3. Results obtained applying the Canny detector to the area zoomed in Fig. 1.

In Fig. 3, the results obtained by applying the Canny detector to the matrix of Fig. 1 are shown. As previously said, as prior information to apply MRF, we have used the orientations extracted by the Grossberg's network (Fig. 2).

The system has been implemented by using the Matlab 5.3 programming language on a Pentium III 733 MHz platform. The total time

needed for a typical full matrix processing is about 30 min.

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MUSE: AN INTEGRATED TRIGGER AND READOUT CONTROL SYSTEM FOR CHIMERA

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Abstract

The CHIMERA 4π detector trigger system is described. The trigger decisions are based on a combination of geometrical multiplicity of detected particles and other logic signals. The trigger can manage the FIFO memory of the used analog to digital converters. This allows the performing of parallel data conversion and readout, and a substantial improving of the acquisition system dead time performances. The trigger module generates all the necessary gate signals for the converters and the control signals necessary to synchronize the readout. It allows also the remote control of the whole system.

1 INTRODUCTION

The forward part of the CHIMERA [1] 4π -charged particle array for intermediate energy nuclear physics experiments heavy ion intermediate energy reactions is now running at the Laboratorio Nazionale del Sud in Catania. It consists of 688 Silicon-CsI telescopes over the 1192 of the complete system. The main improvement of the CHIMERA detector compared to other existing 4π detectors [2-4] for heavy ion nuclear reactions at intermediate energy, is its ability to perform a complete mass and charge identification in a large energy range for nuclei of low and medium mass. This is due to the good timing performance of the silicon detectors used [5] and to the long flight path allowed to the particles by the detector design. Light particles charge and mass identification is also performed in CsI detectors using a pulse shape method [6]. To fully exploit the good characteristics of the detector we need an integrated trigger and readout control system. Such trigger system has to perform an accurate event selection in order to enhance the visibility of the relevant events. The event rejection has to be fast enough to avoid dead time increasing. The trigger has to be flexible enough to allow a simple coupling with ancillary detector arrays.

Moreover, some other requests must be satisfied due to the peculiar structure of CHIMERA. The used identification techniques require a good reference signal that the trigger system has to generate. The number of electronic channels of CHIMERA (about 5000) the event size (1-2 Kbytes on average) and the expected rate (around 1kHz) impose also a relatively fast readout. As a final request our trigger and readout control system has to be remotely controlled since all the CHIMERA electronics is near the reaction chamber and cannot be accessed during beam time. In this paper we describe the trigger and read-out control system prototype built to satisfy all these requirements. It is split in two modules. The first one is a VME 6U interface that allows the readout and the control of the system via simple standard VME instructions. The second module hosts all the electronics for the trigger and readout systems. The front panel of this module has enough space to house all the input and output connectors. The two modules are linked by means of a custom bus.

2 THE DAQ DESCRIPTION

To understand the trigger system we shortly describe the Chimera DAQ system, better described elsewhere [7]. For the signal conversion we use the 9U VME QDC and TDC manufactured by CAEN[8] (VN1465 and VN1488 mod. respectively). A useful feature of such converters is the FIFO buffer memory able to store up to 16 complete events. This allows the readout of old events in parallel with the conversion of a new one enabling a strong reduction of dead time. All the convertes are accomodated on 5 9U VME crates. A CPU is placed on a master crate receiving all the data from the slave converter crates. We use the Fast Data Link (FDL) modules[9] (developed by CES) to perform the data readout. A strobe signal acting on the FDL placed in the converter crates starts the readout. Following the strobe signal, the FDL begins the data readout from the QDC, seen as a memory location. Data are transferred trough the FDL link to a memory in the master VME crate. The CPU collects the data written in the memory by the FDL and builds the event in a net buffer block. When it is full, this block is sent, through the Ethernet line, as UDP-packet, to the workstations for the on-line data analysis and storage or for multi-detector control operations [10].

It allows in fact the overall control of the DAQ system and one or two levels of system trigger.

The block scheme of the system is shown in fig.1.

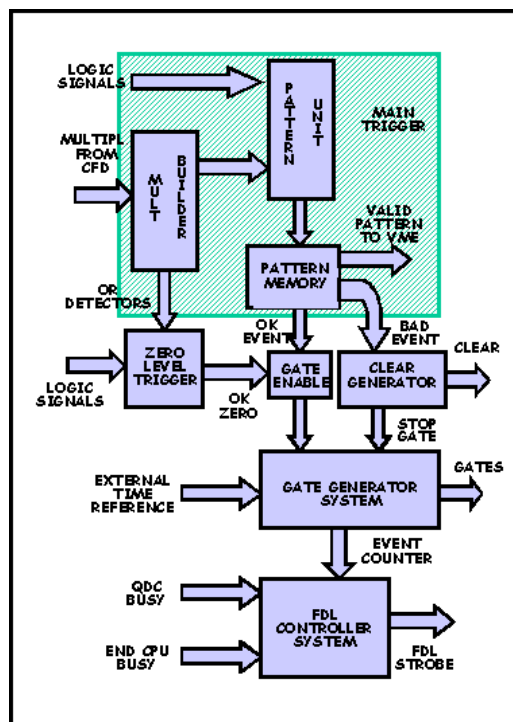


Fig.1 Block scheme of the MUSE system

3 THE LAYOUT OF THE SYSTEM

In most experiments involving heavy ion intermediate energy reactions the trigger system is based on the selection of a given detected particle multiplicity. To build such total multiplicity for CHIMERA we use the multiplicity signals provided by the constant fraction discriminators (CFD) that can be connected in a daisy chain. The multiplicity builder section of our trigger system has 8 inputs, each one corresponding to defined angular regions of the detector. The 8 inputs are summed 4 by 4 to give two partial sums, typically corresponding to the most forward part of the detector (rings up to 30°), and to the backward region of CHIMERA. A final sum stage produces the total multiplicity information. The different multiplicity signals produced are sent to remotely controlled discriminators, that allow the setting of the required multiplicity thresholds. We have called the trigger and readout control system MUltiplicity SElector (MUSE), even if the task performed by the module is much more complex.

The main trigger is based on the analysis of a combination of multiplicity and logic signals coming from the CHIMERA array and/or from any other coupled device. These signals generate an event pattern compared to the predefined valid patterns in order to accept or reject the events. The pattern of a valid event is used as an event marker and can be read via VME to be written on tape. In order to allow also the coupling with slow detector arrays, the trigger system handles a coincidence time ranging from 100 nsec up to 2 μ sec. Our QDC needs a common gate signal and cannot self trigger the conversion as the QDC adopted, for instance, by the INDRA detector [2]. Therefore when a coincidence time larger than 500 nsec is used, the QDC gate signals must be generated before the event acceptance decision is taken. In this case, to open the gates we must use a "zero level trigger" section. The fast decision of this section is based on the analysis of few fast logic signals (typically the detector fast OR-signal from part or the whole detector). Thus the gate generation system may start in a time ranging from 30 to 100nsec. If the event is rejected by the pattern analysis, the gates are

closed and a clear signal is sent to all modules (bad event). To obtain good time stability we generate all our gate-signals using the timing of a reference signal, typically the Radio Frequency (RF) of the LNS Super-Conducting Cyclotron. The proper timing is kept by validating the RF in presence of an event selected from the zero level trigger (OK zero) or from the pattern analysis system (OK event). The obtained gate stability obtained with the gate generation system is better than 0.1%.

After the event selection the system must handle the data readout. This task is performed by the FDL controller system. MUSE generates the FDL strobe signal and the pattern required for the readout. Two possible readout modes are available, the single-event and the multi-event mode. The single-event mode can be used when CHIMERA is coupled to detectors without readout buffer. In this case the system at each event is waiting for the end of conversion. After this conversion time data can be read and MUSE delivers the FDL strobe signals. Data are transferred to the CPU in the master crate and, when the transfer is complete, the CPU sends the End-CPU-Busy-signal to MUSE. Only after this signal the dead time is removed and a new event can be accepted. In this case the total dead time for the processing of each event is the sum of conversion dead time and readout dead time. An improvement of the effective dead time can be obtained working in the multi-event mode. In this case the QDC memory buffer able to store up to 16 events is used. The data readout can be performed during the conversion of a new event. After the event conversion, the dead time is removed and a new event can be immediately accepted. In the same time, if the CPU is ready to accept a new event, MUSE sends the FDL strobes to start the event readout. The End-CPU-Busy-signal is delivered at the end of this data transfer. An MUSE internal counter takes care of other events ready in the buffer memory and, if any, new FDL strobes are sent to the converter crates immediately after the End-CPU-Busy-signal to read in sequence all the events.

4 OBTAINED PERFORMANCES AND CONCLUSIONS

The major improvement of CHIMERA performances obtained by using MUSE is the gain in dead time due to the use of the multi-event readout system. With such readout mode not only the readout dead time does not affect the arriving particles, but also the long time needed

by the CPU to transfer data via Ethernet network does not influence the acquisition dead time at the standard experimental rates. During this time in fact the new events can be stored in the QDC memory buffers. In Fig.2 we show an example of the obtained reduction in the total dead time.

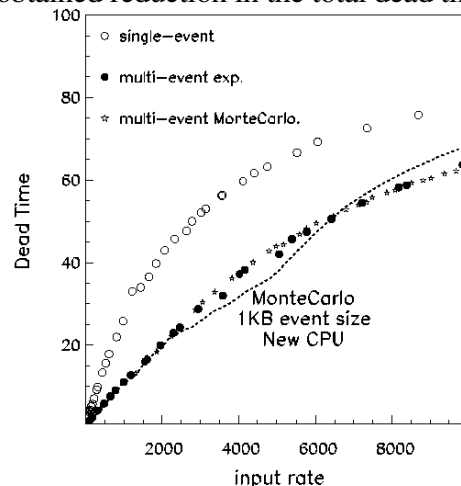


Fig.2 Dead time performances obtained using the MUSE system

The two sets of points are measured in single (open dots) and multi-event mode (full dots). In this test an event of about 100 bytes was read with a conversion time of 120 μ sec (the time includes: gate signal widths; conversion time for all the channels; cutting of channels without valid data performed directly by the QDC's digital pedestal subtraction software). An old 40 MHz FIC8234 CPU manufactured by CES with 10Mb/s Ethernet interface was used for the event building. As can be seen in fig.2, an improvement of the total dead time of a factor 2 up to 3 kHz input rate is obtained. At higher rate the combined effects of the Ethernet saturation and of the low speed of the used CPU reduce the MUSE gain. The measured behavior can be reproduced by means of a simple MonteCarlo code where all the dead time contributions have been considered (open stars). Using the same code we can simulate the performances for the conversion and readout of real events. We obtained the dashed line of fig.2 assuming an average event size of 1 Kbytes and a 90% reduced CPU dead time, as it will be the case using a faster CPU with 700 MHz clock and fast-Ethernet interface we obtain the dashed line of fig.2. Up to 2 kHz the total dead time is equal to the one measured for the small size events with the old CPU. In this part of the Dead Time line the main contribution is in fact due to the conversion time of the QDCs, independently from the event size. In the region up to 4 kHz the contribution of the faster CPU gives a reduction of the total dead time. At a rate

over 4 kHz the dead time increases and a saturation of the acquired rate appears. This is due to the maximum data flux allowed by the FDL readout. The sparse data scan used to read the QDC allows in fact an event-by-event data collection, but simplifying the event reconstruction is paid by slowing the transfer rate in the FDL line. Due to physical reasons, to avoid pile up in the detectors, the rate of the measurements generally used by CHIMERA will be lower than 2 kHz, and in this range we will work with an effective total dead time around 20%.

In summary the MUSE trigger and readout control system allows a useful setting of the CHIMERA acquisition system, and substantially improves the dead time of the readout system. It gives also new flexibility to the trigger system allowing angular multiplicity selections that will be very useful for future measurements with CHIMERA. The prototype system was built with standard electronic components. In the future we are planning to implement it by using FPGA devices.

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SMALL SCALE PARALLEL AND DISTRIBUTED ARCHITECTURE FOR THE CONTROL SYSTEM OF CHIMERA

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Abstract

The Control System of CHIMERA, based on Digital Signal Processors, is presented. It is able to control the working mode of the multidetector, by computing special algorithms performing Z and M identification.

1 INTRODUCTION

To control the working mode of CHIMERA, we have designed an heterogeneous architecture of PCs and Digital Signal Processor boards. It is able to process the data coming from the DAQ, by means of on line computation of algorithms that allow charge and/or mass identification of reaction products. In this way, it is possible to use the same physical data collected by the detector for testing the working mode of CHIMERA.

2 THE CONTROL SYSTEM

The Control System of CHIMERA [1] is based on a small scale parallel and distributed architecture involving PCs, used as host and user and network interface, and Digital Signal Processor (DSP) boards, up to three for each host, used as computational units. We have chosen DSPs for the computation to avoid the necessity of using O.S. on the computational boards.

The system is able to accomplish the on-beam control of CHIMERA, by means of the on-line computation of special algorithms. Fig.1 shows the schematics of the hardware platform.

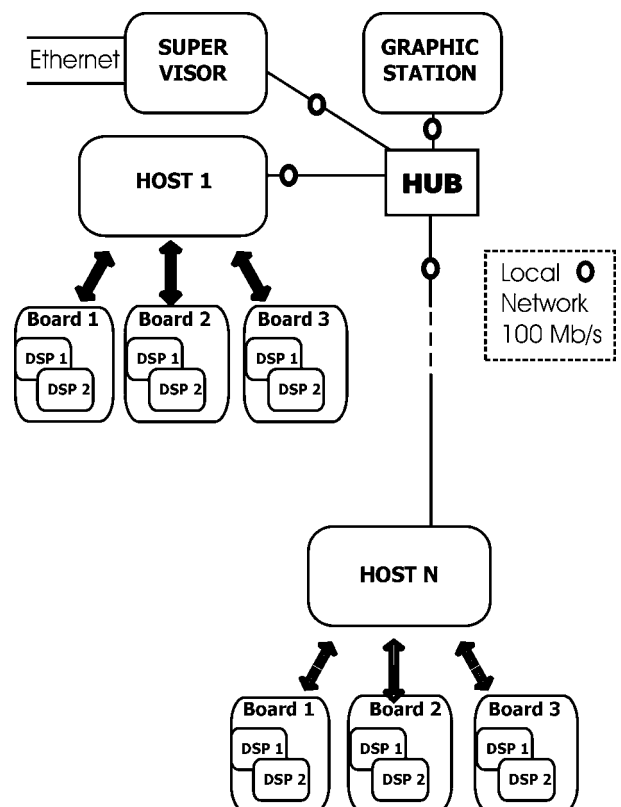


Fig.1 Schematics of the H/W platform of the Control System showing up to N computational stations.

The Control System is functionally subdivided into a Supervisor station, a number of

Computational stations, embedding the DSP boards, and a Graphic station, used for visualization, all connected via high speed local network. The Supervisor is also connected, through an external network, to the CHIMERA Data Acquisition System: the physical data, collected and organized in UDP-packets by the CHIMERA DAQ, are broadcast through the network as UDP packets. The Supervisor station reads data packets and dispatches them to the Computational stations. The actual data elaboration is performed by the DSPs embedded on the Computational stations.

The algorithms used allow particle identification in charge (power-law) and in mass (ToF) [2]. We have shown [1,3] that, if ΔE is the energy lost in the Silicon detector and L is the light pulse from the CsI(Tl) scintillator, the power-law can be directly applied to the uncalibrated values. This results in a monodimensional Charge Identification Function $CIF = (L + \Delta E)^X - L^X$ (usually $1.5 < X < 1.8$), where each peak corresponds to a determined charge of the reaction products. In the same way, if Δt is the time of flight, in non relativistic approximation the Mass Identification Function is given by the ToF formula, $MIF = E \Delta t^2 \div A$, where E is the energy lost in the Silicon detector by the non punching-through particles, and A is the mass of the reaction product.

The general scheme of the software architecture of the Control System is shown in Fig.2.

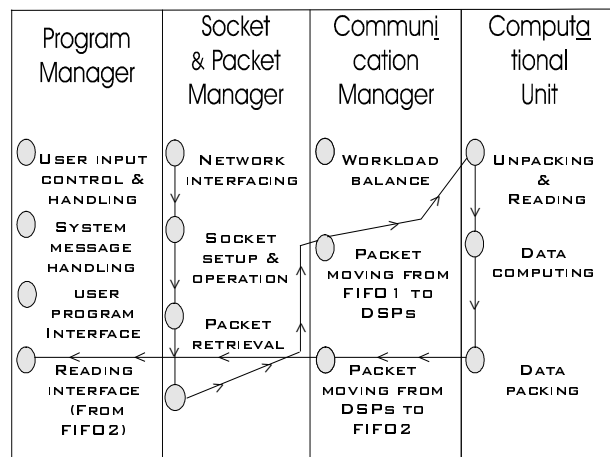


Fig. 2 General structure of the Control System S/W architecture.

2.1 The Hardware Platform

The adopted computational unit is a commercial PCI-board WS3112 [4], mounting two ADSP 21060 SHARC DSPs [5] with a peak rate of $(120 + 120)$ MFlops at clock frequency of 40MHz.

As for the Computational station host PCs, four different types of processors were tested during the experiments: AMD K6-II (400MHz), AMD K7 (700MHz), Pentium MMX (166MHz) and Pentium II (450MHz). As we expected, there are no relevant differences in the system performances, the computation workload being completely ascribed to the DSPs. In fact, the job of the host processor is limited to transferring data packets from the Ethernet to the DSPs and vice versa, in order to broadcast the results of the DSPs to the network, and to balancing the DSPs workloads. The host PCs run the Microsoft Windows NT 4.0 operating system.

The workload balance among various Computational stations is managed by the Supervisor station. This also is a standard PC (the one we use mounts an AMD K7 processor, 700MHz). Its only peculiarity is the presence of two 100Mb/s network cards: one providing interface towards the DAQ network, the other accessing the Control System local network, as shown in Fig. 1.

2.2 The Implemented Software

The software for the Control System (Supervisor, Computational & Graphic station) was entirely developed using the Microsoft Visual C++ 6.0, except for the DSP software, which is written in ANSI C programming language. The Graphic station software uses the ROOT [6] libraries for the visualization.

The Supervisor station two main tasks run: the first one is devoted to receive the data packets and to transmit them into the local network. The second one receives control packets, generated by the Computational stations, which are used for workload balancing. In fact, every Computational station periodically sends the Supervisor information about its own occupation. The Supervisor relies on such information in order to decide to which Computational station do send the new data

packets. The application implementing these two tasks uses the Microsoft Foundation Classes (MFC), which allow to maintain both an high-level approach even in the network connection management, and code portability and reusability.

The Computational station hosts run two tasks for network/host interface, one for data packets and one for the control packet generation, and a collection of tasks for host/DSP interface, one for each DSP board present in the host computer. The Computational station host software, too, was developed using the MFC.

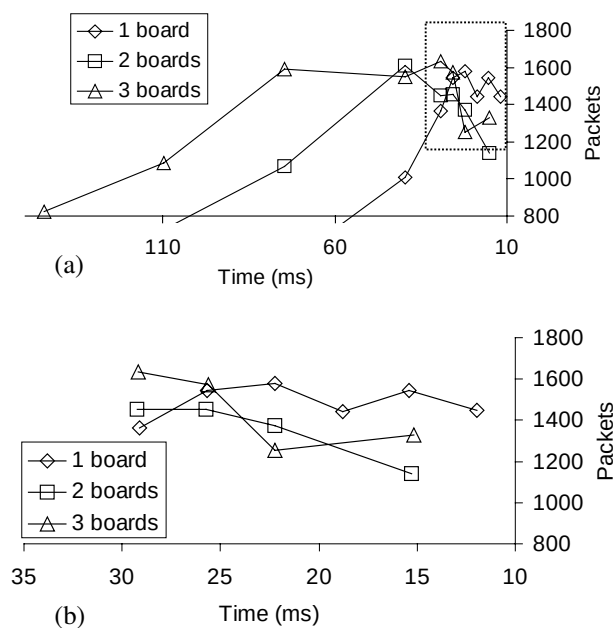


Fig. 4: Number of calculated data packets (coming data flow constant) vs. time taken by algorithm elaboration. In (b) the area highlighted in (a) is zoomed.

The computing of both functions, MIF and CIF, on the used DSPs takes about 10 μ s/telescope. To this time, it must be added the unpacking time, necessary to extract data from the UDP packets, and the time for data presentation on the Graphic station. The total time is ~ 4 ms/UDP packet.

We tried to vary the time taken by the DSPs to elaborate each UDP packet (unpacking + CIF/MIF calculation), making more complex the algorithm computed by the DSP code. We measured then, how the number of elaborated packets varied as a function of the DSP calculation time, in a fixed interval of time. Tests were carried out using one, two and three active DSP boards. A graphic of the results is shown in Fig. 4.

3 CONCLUSIONS

The Control System has been tested on beam. The fast computation allows to handle more than 60% of the total number of collected events using a single computational station with one DSP board.

For the chosen algorithms the best improvement is obtained using more computational units with one board each. Only more complex computations (computing time up to one order magnitude larger) benefit from the use of the maximum number of allowed boards (3/PC).

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CHIMERA COMPUTATIONAL UNIT USING DSP-BASED VME MODULES

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Abstract

We have designed and tested a computational unit for on-line processing of special algorithms to be embedded in the VME-crate of the CPU of CHIMERA data acquisition system. The computational unit consists of a number of VME-DSP commercial boards delivering up to 4x720 MFlops.

1 INTRODUCTION

Our previous works on the Control System of CHIMERA [1-3] presented the use of special algorithms for on-line reaction product identification in mass and charge. They are based on the power-law function and the ToF formula [4], directly applied to the signals coming from the detectors without any preliminary calibration [5], in order to obtain information on charge and mass of the detected reaction product, respectively.

On the other hand, using a multidetector allows a variety of experiments to be performed, each having its own peculiar characteristics. Thus, the parameters of interest in a measurement depend on the particular experiment accomplished.

Moreover, each experiment may require different physical quantities to be monitored on-line, such as isotopic ratio for some elements or event total charge.

Last but not least, the rough data are necessarily uncalibrated, while an on-line energy or gain calibration may directly allow the superposition of different scatter plots, making them more legible and interpretable.

All these considerations led us to upgrade the computational unit of the Control System in order to not only label data with mass and charge tags, but also perform various real-time computations on each collected event, during the measurements.

2 THE EXISTING H/W PLATFORM

The Data Acquisition System of CHIMERA [6],[7] has been designed to manage the about 5000 channels of the detector. It comprises a number of VME crates connected via Fast Data Link bus (FDL) [8]. Specifically, 5 9U-VME front-end crates allocate 76 units of ADCs, while a 6U VME crate called Readout Crate, houses the DAQ CPU board, a FIC8243 [8] running the real-time operating system OS9.

The first level event selection and control during the readout is assured by a trigger system, MUSE [9], fully integrated with the FDL readout system.

Event data coming from the ADCs crates are collected by the DAQ CPU and broadcast through a local Ethernet to the analysis and control stations for on-line visualization, control and storage. The transfer through the Ethernet employs the asynchronous UDP/IP protocol, so

the DAQ CPU rearranges event data. into UDP-packets

The Control System of CHIMERA is based on a heterogeneous architecture of host PCs and PCI-DSP-boards, and works on the UDP-packed data broadcast by the DAQ CPU. This makes practically impossible to synchronize the DAQ and Control System triggers. Moreover it takes time to unpack data. The PCI-bus management, too, is time expensive. The resulting dead time for the Control System is about 40%.

The solution we have implemented is to integrate the computational boards in the VME bus of the DAQ-CPU, in order to allow a faster exchange of information among them.

3 THE PROPOSED ON-LINE COMPUTATIONAL VME-UNIT

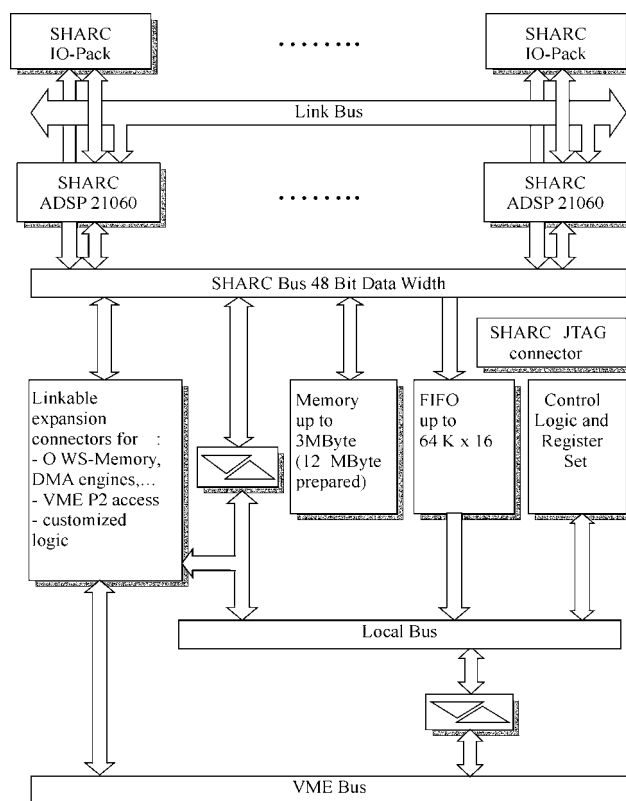


Fig. 1 Schematic of a WS2126 board.

In order to develop an on-line Control-and-Computational (C&C) unit able to achieve full compatibility, synchronization and dead-time overlapping with the data acquisition system, we have improved the computational resources of the Control System, and placed them directly

in the VME crate of the DAQ-CPU. As computational unit, commercial DSP-VME boards (WS2126 [10], see Fig. 1) equipped with up to 6 ADSP 21060 SHARC [11] were chosen, fully compatible with the previously used WS3112, thus reducing development costs and time.

A standalone CPU, a VP7-CPU [12] based on a Pentium III 700 MHz processor, running Windows NT 4.0 operating system, manages the DSP boards (program download and data transfers) and the user/Ethernet interface. It actually attends to all the tasks that, in the Control system, pertained to the Computational Station host PC: therefore the name of "Computational unit host CPU".

The Computational unit together with its host CPU composes the C&C unit.

Since the foreseen Integrated DAQ+C&C system is based on existing systems, as a first step we have chosen to modify them as little as possible, and just add or adapt the features necessary to interface them.

This brings two main advantages: the first is that modifications to the existing systems are limited, in particular the software running on the FIC-CPU requires only minor changes. This allows satisfying the constraint that the existing acquisition system is available and operative while implementing and testing the new architecture. The second is that the two parts of the complete VME system, the DAQ and the C&C, can be tested separately as standalone systems first, and then connected to be tested as a whole. This helps reducing development and testing time.

The general structure of the hardware platform adopted for this first implementation of the data acquisition and on-line computing and control system is shown in Fig. 2.

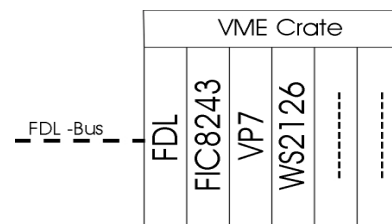


Fig.2 Schematic of the H/W platform of the DAQ and C&C.

Even though H/W implementation changes radically when porting the Control System from PCI- to VME-bus, the underlying philosophy is pretty much the same. In particular, the computational section of the existing S/W, implemented in the DSPs, is completely unchanged. The S/W development environment is still MS Visual C++. The Universe DLL, managing the drivers of VP7 on-board Universe PCI-VME bridge, provides an easy to use access to the VME bus: a set of C-functions, performing all kinds of accesses to the bus, are available just by adding a library to the list of linked libraries.

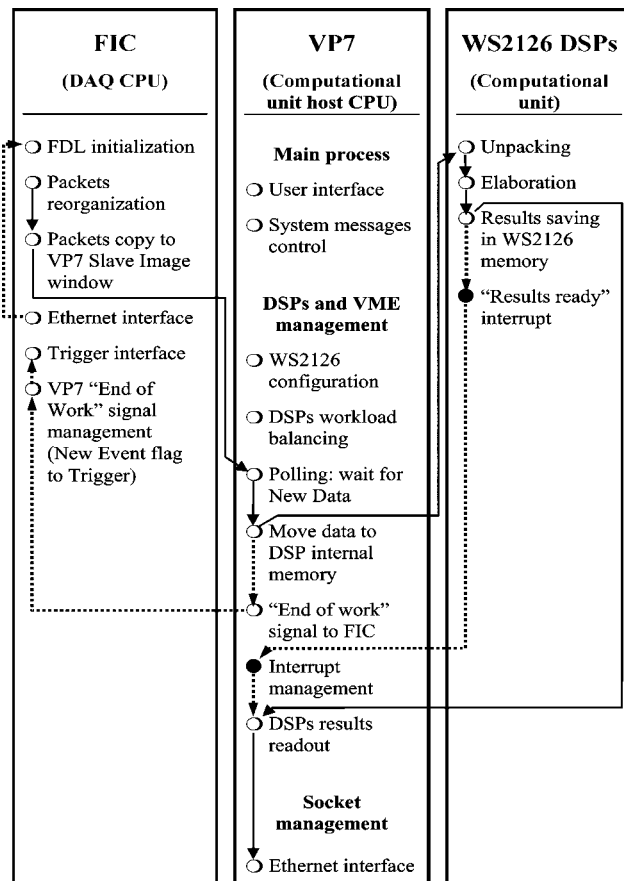


Fig. 3 General structure of the VME-C&C system S/W architecture: active processes, data flow (solid line), and control signals (dotted line).

The general structure of the software of the Control System has been preserved. Only the input section was altered, as data are no more coming from the Ethernet but from the VME-bus and a new interrupt handling section has been added (Fig. 3).

While the DSP software concerning data processing is unaltered, the host CPU board interface has been changed, because of the different protocol of the two buses. DSP programs are still written in ANSI-C, except for the interrupt management that has proved to be more reliable if written in Assembly language.

As for the DAQ system, no H/W changes are required. Just a few S/W adjustments make the new system operative. In particular, the DAQ CPU, after packing the data received from the converters in the UDP format, as usual sends them to the Ethernet, but also writes them onto the VP7-board memory. To this aim, a slave image window is opened on the VP7, always at the same address: let's call it Buffer Area. This step realizes the DAQ to C&C interface. After that, the DAQ CPU just waits for an acknowledge signal (End of Work – EoW) from the VP7, meaning that the C&C system is ready to receive new data. The EoW flag realizes the C&C to DAQ interface. In the end, the DAQ CPU sends a flag, New Event (NE), to the Trigger which starts a new acquisition process.

The VP7-CPU waits for new FIC data, polling on a flag called New Data (ND), specifically the first location of the Buffer Area. FIC writes this location as last, meaning that the new data have been copied. Once data are transferred to VP7, their flow proceeds within the C&C system. VP7 resets the ND flag, and transfers data to the DSPs working area, in the DSPs internal memory. Note that this memory is VME-mapped, so it can be straightly accessed by VP7.

VP7 is then ready to receive new data, and to notify its state to FIC, it delivers the EoW flag. This is an essential step, because it makes the Buffer Area available for accepting new data.

VP7 serves the non-working DSPs in a strictly cyclical strategy. Each DSP performs its calculations, and when processing is over, writes the results in its own Results Area, defined in the WS2126 board memory. Eventually it delivers an interrupt, called "Results Ready", to the VP7. The host CPU takes the results to broadcasts them to Ethernet. Then it adds the DSP unique identification number to the list of the non-working DSPs.

Following this implementation the computing and unpacking time has to be added to the DAQ dead time. The distribution of the computation over an enough number of boards (2-3) allows reducing the increment of dead time to a negligible value.

The graphic station, used for visualization, is connected to VP7 via Ethernet, and so are the stations that can be used to perform additional calculations on data, if needed. The visualization tool was implemented on the ROOT [13] system, which provides a powerful framework for the analysis of data from high energy and nuclear physics experiments.

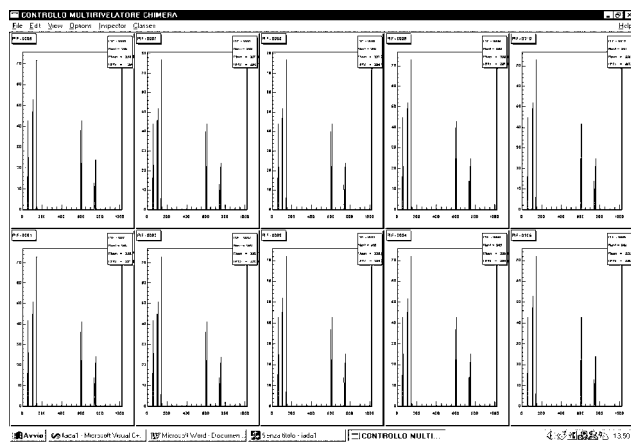


Fig. 4 Visualization of results of power-law computation as they appear on the graphic station, simulating the reactions ($p+^{27}\text{Al}$) and ten telescopes.

Testing of this architecture was accomplished by using a simplified unit consisting of just one DSP-VME-board and the VP7-CPU. The VP7-CPU was also used as emulator of the DAQ and did directly output FDL packets on the VME-bus. The data employed for this test simulated simple reactions induced by 30 MeV protons on ^{27}Al target. Fig. 4 shows the results as they are visualized in the ROOT window on the graphic station. The computed algorithm is the power-law and the five peaks correspond to emitted p, d, t, ^3He , α .

After that, the actual system, comprising the DAQ, the VP7 and one WS2126 with 6 DSPs, was implemented and tested.

To carry out the test, a pulser has been used to generate the analog data sent to a QDC. From the converter on, the data flow follows the

illustrated course (Fig.3): digitized data, collected using the MUSE trigger system, through the FDL reach the FIC-CPU that writes them to the VP7 memory. Then they are transferred to the DSP internal memory. The DSPs computation has been inhibited, because these data were just to be straightly visualized. At last, data have been visualized on the graphic station, following the same procedure employed for testing the architecture.

The illustrated prototype allowed to achieve a realistic functionality control in a considerably small amount of time, and operating within the existing hardware environment with the advantage of keeping the DAQ system operative during implementation and testing operations.

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STATUS OF THE MAGNEX SPECTROMETER

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Abstract

The status of the MAGNEX spectrometer at the LNS is given. The chief activities in 2000 have been the start of the magnet construction, the purchase of the electronics for the silicon array and the construction and test of a new prototype for the focal plane detector.

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 momentum resolution of about 1/2000. A position-sensitive timing detector between the target and quadrupole gives both the vertical 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. A new prototype FPD is described in section 3.

2 MAGNETS, SILICON ARRAY

2.1 Magnets

During the year 2000, a major milestone was passed with the award of the contract for the magnets (dipole and quadrupole) to DANFYSIK A/S of Denmark. This includes the manufacture of the surface correcting coils within the pole gap of the dipole [4]. These are a crucial element for the correction of the kinematic factor k in nuclear reactions. In fact, the entrance and exit pole faces of the dipole have been re-optimised to compensate aberrations at a k -value of -0.25 . A range of $0 > k > -0.5$ can then be covered by the use of the surface coils, together with a small

(<10 cm) shift of the focal plane detector at maximum field.

2.2 Silicon Array electronics

The electronics for the silicon hodoscope at the back of the focal plane detector are based on 16-channel NIM spectroscopy amplifiers. A schematic drawing of the silicon electronics is shown in Fig. 1. The shaped, slow outputs are sent to 32-channel VME peak-sensing ADCs as the measurement of the particle's residual energy. The fast outputs from the amplifiers are sent to 16-channel CFDs (also VME standard). The logic outputs of these are used to start the TDCs (32-channel VME), which are common-stopped by the delayed entrance PSD, thus giving the time-of-flight information. Because of the high-density modules, only eight slots in total is needed in the VME crate to handle up to 64 silicon detectors. All these modules including the high-powered VME crate have been purchased and are now in house.

The sum outputs from the CFDs are used for the master trigger of the acquisition system.

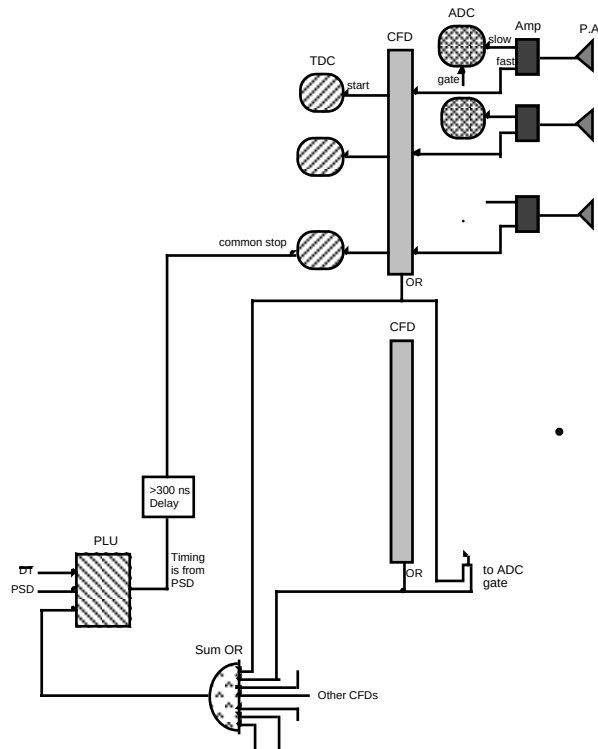


Fig. 1 Schematic of electronics for silicon hodoscope.

3 NEW FPD PROTOTYPE

3.1 Description of the prototype

The excellent results obtained with drift chambers (see, e.g., [2]) by the MAGNEX collaboration gave rise to the development of a new prototype FPD. This is based on two sequential drift chambers, each one consisting of two independent series of wires and underlying strips. Thus the position of a particle is measured in four places along its track in the gas. This prototype permits a test of the trajectory reconstruction capability that is necessary for the software compensation of the aberrations of the spectrometer [2,5]. Secondly, we could test the use of the drift chamber section of the FPD as a supplemental energy-loss section. The latter allows an overall reduction in the size of the FPD.

A photograph of the disassembled ionisation chamber with the anode strips and the wire supports is shown in fig. 2.

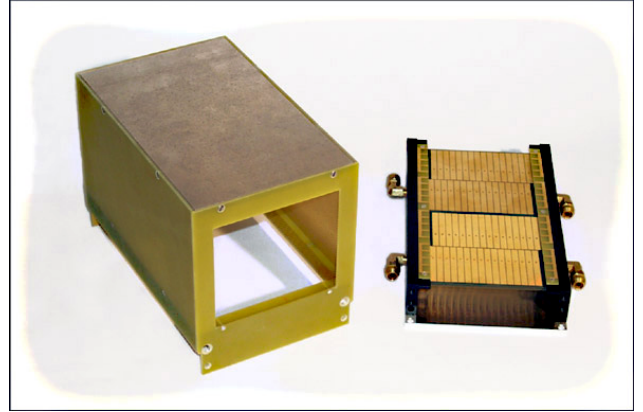


Fig. 2 The new prototype focal plane detector.

No intermediate foils separate the sections. Each strip is 5 cm long and 5 mm wide and separated by 0.8 mm from its neighbour. There are 16 strips in each set, thus covering a horizontal span of about 9.5 cm and a range of angles of about $\pm 15^\circ$. To reduce a possible non-linearity in the position measurement, the second set of strips is shifted by half a strip width from the preceding one. There are five wires normal to and above each row of strips; they are 20 μm in diameter and made of gold-plated tungsten. The vertical opening of the entrance to the chamber is 10 cm.

The ionisation produced by the passage of charged particles through the gas leaves a track of primary electrons and positive ions. A uniform electric field of about 70 V/cm makes the electrons drift at constant velocity toward the Frisch grid. After passing through the grid, the electrons are accelerated towards the wires, where the field reaches values sufficient for a multiplication of around 200. The avalanche both induces charge on the nearest several strips underneath and produces a direct signal that can be read out from the wires. Since the counter is operated in the proportional region, the signal from the wire measures the number of primary electrons produced, which is in turn a measure of the energy lost by particles in the ionisation region above the wire.

Every strip is read out through separate preamplifiers located under the anode board and through separate shaping amplifier channels into the acquisition system. The position parameter is made by constructing the centre of gravity of the induced charge distribution on the strips. In our case, we only used three strips (the one with the maximum charge and its immediate neighbours) to determine the centroid based on the SECHS method [6]. In the prototype, the four separate measurements of the position of the track allow

the determination of the particle angle with redundancy.

3.2 Test set-up

The test of this prototype for the reconstruction of trajectories and horizontal position resolution was performed at GANIL. An Am-241 source was used to illuminate the detector with a continuous range of angles. A diaphragm with three apertures was placed in front of the source. The central slit was 0.5 mm in width; it was separated horizontally by 3.0 mm from the outer openings, which were 2-mm diameter holes. The detector was filled with pure isobutane at 20 mbar pressure. Because of the low-energy of the α -particles, the source was placed within the gas volume, 76 mm from the middle of the first row of strips. The voltages applied to the cathode and the anode wires were -700 V and $+500$ V, with the Frisch grid connected to ground.

3.3 Observations and results

The amplitude of the signals from the wires was approximately 1.4 V after the preamplifier, which had a gain of 200 mV/MeV. This indicates a gas gain of about 180. The signals from the strips were about four times smaller. The cross-talk between strips, measured by turning off the voltage to one set of wires and observing the residual induced signals, was about 10% of the peak signal. This is well below the threshold set in the software for determining the three strips with highest charge.

After the preamplifiers, each individual signal from the strips was sent into a 16-channel spectroscopy amplifier and then into an ADC. The gains were matched by applying the voltage signal from a pulse generator directly to the anode wires and reading the induced charge from all strips. The reconstruction of the image of the source, made by extrapolating event-by-event the best straight-line fit to the position measurements, is shown in fig. 3.

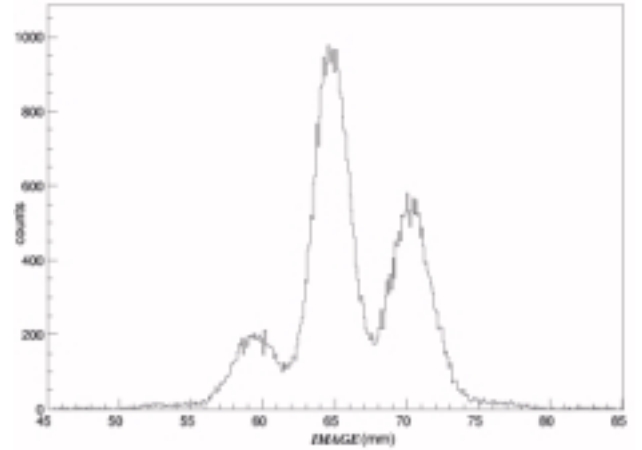


Fig. 3 Histogram of reconstructed image of the source.

To measure the intrinsic position resolution, narrow gates (0.5 mm wide) were set on the position parameters (centroid determinations) of the third and fourth sets of strips. Then a correlation plot was made between the centroids measured from the first and second sets of strips. This correlation plot is shown in fig. 4, where the intrinsic resolution is represented by the width of the line, as indicated by the arrows. A value of 0.22 ± 0.02 mm (FWHM) is obtained. For the angle reconstruction, a narrow gate was applied to the 4th wire position spectrum and the events coming from the central slit have been selected. In this way a fixed direction has been defined within 4 mr. The position centroids from the 1st, 2nd and 3rd wires were taken with these conditions. The angular spread observed is about 7 mr FWHM, giving an intrinsic contribution of about 6 mr.

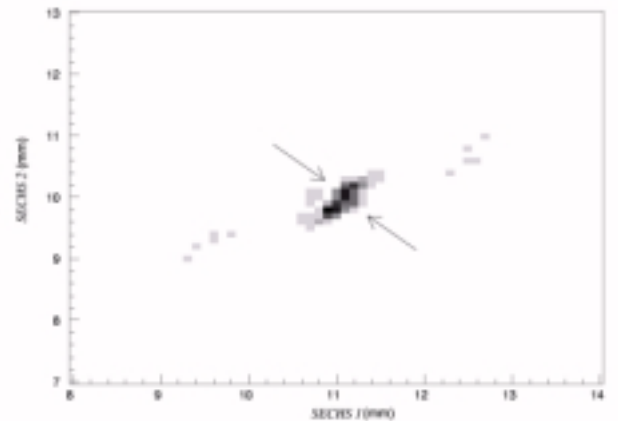


Fig. 4 Correlation plot between the centroids determined by the 1st and 2nd sets of strips, gated on a narrow region in the 3rd and 4th sets of strips and the central slit.

Finally, the energy-loss signals from the wires have been studied. Although the small signal size from the α -particles meant that the actual observed resolutions would be poor in

comparison to the actual values obtained with heavy-ion beams, a proof-of-principal test of using the proportional wires as energy-loss sections could be made.

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. One sees that there is little improvement in resolution beyond 15 cm of track length (three wire sets summed together).

Table 1 Observed energy loss signal resolution (FWHM) and estimated energy-loss straggling for the wire signals.

Each "wire set" represents about 5 cm of gas layer.

Wire set	Observed resolution	Energy-loss straggling (TRIM)
1	12%	8%
1+2	9%	6%
1,2,3	7.5%	5%
1-4	7%	4%

3.5 Final FPD design

Based on the tests of prototype detectors and the results of simulations, we have designed the final focal plane detector for MAGNEX. The configuration is two PSDs separated by a relatively short ΔE section with gas amplification, followed by a silicon hodoscope, all in an overall trapezoid (fan-shaped) geometry. (Note, however, that the vacuum vessel will be rectangular for convenience of construction). The depth of the FPD (along the central trajectory) is a compact 16 cm, which owes to the use of the PSDs for supplemental energy-loss measurement. The readout and processing of the ~800 strips will be done through the use of GASSIPLEX-0.7 multiplexing technology [7].

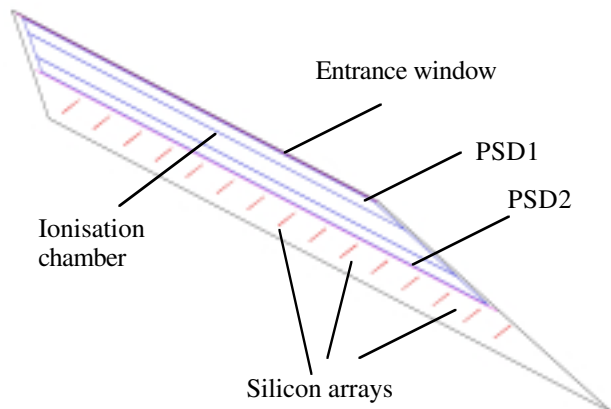


Fig. 5 Schematic layout of the MAGNEX FPD detector.

The common gas pressure is 20 mbar of isobutane. We emphasise that no intermediate foils are used in the detector, thus keeping the energy/nucleon threshold to a minimum.

ACKNOWLEDGEMENTS

We thank P. Gangnant, J.F. Libin and C. Spitaels for help with the prototype FPD.

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FIRST RESULTS ON CHARACTERIZATION OF THE MACISTE DETECTOR

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Abstract

Two wide area gas ionization position detectors were tested at the LNS using a ^{58}Ni beam at 40 MeV/amu impinging on C and Au targets. Some preliminary results concerning the resolution in position and the dependence of the response function of both drift chamber and plastic scintillator to the impact point are reported.

1 INTRODUCTION

In the intermediate energy heavy ion collisions many problems, as the study of excitation energy and angular momentum in nuclei produced by fragmentation in peripheral reactions or the study of the evolution of the properties of GDR up to the limits of existence of the collective motions in hot nuclei, may receive a strong impulse from the detection and the identification of the massive forward reaction products.

In this perspective the MACISTE [1] detector (MAss and Charge Identification Spectrometry with Telescopes) has been designed to complete, at the forward angles, the detection system formed by the coupling of the two multielement detectors MEDEA [2] and MULTICS [3], aiming to study the above mentioned physical problems.

MACISTE works as a wall detector, placed downstream about 16 m from the target to minimize the uncertainties in the time of flight measurements. A Superconducting solenoid, SOLE [4], has been placed at the exit of the vacuum chamber and conveys the emitted particles to MACISTE, according to their magnetic rigidity. From this point of view SOLE and MACISTE constitute a unique tool to complete in the forward direction the experimental apparatus formed by MEDEA and MULTICS. Nevertheless, due to its

characteristics and modularity, MACISTE may be intended and used as a standalone detector for the detection and identification of different classes of particles, according to physical needs.

2 THE DETECTOR

MACISTE consists of four telescopes arranged on a 70*70 cm² surface leaving a variable central hole for the beam transit. Each telescope, with a useful area of 30x40 cm², consists, in turn, of a drift chamber for the energy loss measurements, a wire chamber for the impact position and time of flight measurements and, for the energy measurements, a large area, 2 cm thick, plastic scintillator detector coupled to a photomultiplier through a suitable light guide.

Each section has been divided into two parts in order to reduce pile-up effects.

The MACISTE wire chambers consist of two anodic planes, made of 20 μm gold plated tungsten wires with, in between, a double-sided aluminized 6 μm thick mylar foil acting as a cathodic plane for both anodic planes. The anode-cathode gap width is about 2 mm. The anodic wires are stretched, equally spaced in steps of 1 mm and glued onto an epoxy (stesalite) frame; one end of each wire is soldered to a printed circuit integrated onto the frame and a delay of about 4 ns is placed between adjacent couples of wires. The two anodic planes are assembled in such a way that

the wires of one plane are perpendicular to those of the other plane, to form a structure similar to a weaving loom. In this way it is possible to have the impact position of the particle with respect to a x-y coordinate system linked to the epoxy frame. An incoming charged particle ionizes the low pressure gas inside this detector; the produced electrons drift in the electric field, giving rise to a multiplication around the wires. The charge collected on the wires is read at both ends of the delay chain and the time difference relative to a reference taken from the cathode is used to deduce the impact point of the particle.

The useful detection area of a single telescope of MACISTE is a 30x40 cm² rectangle area. The longer side (40 cm length, the x coordinate) has been split into two equal parts and therefore two delay chains are used to read the electric signals. The shorter side (30 cm length) constitutes the y coordinate and was not split.

3 ASSEMBLING OF THE WIRE CHAMBERS

The main features of wire chambers as, e.g., their ability to localize particle trajectories with an indetermination lower than one millimeter even on a wide detection surface, their relative ease of operation and maintenance and their reasonable cheapness make them attractive as focal plane detector. Therefore we decided to make use of the structure of the LNS User Support Service to build a gas ionization position detector following the main features of the MACISTE wire chambers.

Some metallic frames were realized to wind¹ the 20 μ m gold plated tungsten wire; the wires were positioned very accurately on the final epoxy frame and glued to form the x or the y coordinate structure wires. The cathodic plane, a double sided aluminized 6 μ m thick mylar foil, was electrically divided into two parts on both sides by using the sparkling effect of a point (about 0.3 mm in diameter), polarized at about

20 volts with respect to the mylar foil; dragging the point the aluminum layer vaporizes leaving a free aluminum line, about 0.2 mm wide; the foil was very accurately assembled on the x-wires frame so that the free aluminum line was in correspondence of the breaking of the delay line. Two different wire chambers in the x coordinate plane were then obtained. The y-wire plane was then glued on it.

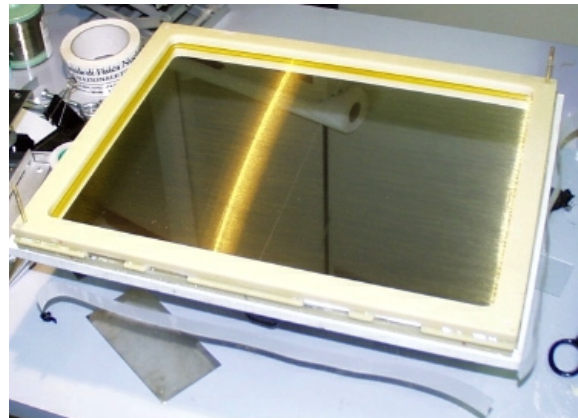


Fig. 1 - The x-wire and y-wire frames glued together seen from the y side. The 6 μ m aluminized foil acts as a light reflector showing the y-wire structure. The ends of the wires to be soldered to the printed circuit are glued to the white ribbon.

One end of each 700 tungsten wires from both anodic planes was soldered to the delay line of a printed circuit and the electrical connections were done. The outer epoxy surface of the wire chamber was covered with a thin layer of glue to ensure a tight vacuum seal. Fig 1 shows the y-wire frame assembled to the x-wire one (hidden in the photograph); one end of the tungsten wires is glued to the white ribbon before soldering.

4 IN BEAM TEST

The wire chamber was assembled with the drift chamber and a 2 μ m aluminized mylar foil was placed in between acting as entrance window for the wire chamber and exit window for the drift chamber. Foils of the same thickness were also used as entrance window of the drift chamber and exit window of the wire chamber. The wire chamber was backed with a 2 cm thick scintillator completing the telescope.

¹ The frames were wound at the Sezione di Firenze of the INFN, where a winding machine, capable to handle objects as large as 80 cm x 80 cm, is available.

Two telescopes, one of the old type and one of the new type, were assembled on their supports into the vacuum chamber for an in-beam testing comparison. The wire and the drift chambers were filled with isobutan gas, the first at a pressure of about 5 mbar and the second at a pressure of about 50 mbar. The revised gas flowing system ensured the keeping of the correct pressure values. The elastic scattering of a 40 MeV/amu ^{58}Ni beam, delivered by the LNS CS, on carbon and gold targets was used to study the response functions of each stage of the telescopes. In the same test the magnetic field delivered by SOLE was used to focus the beam in the hole left between the telescopes.

The signal from the cathode plane was used to measure the time of flight of the particles relative to the radiofrequency of the cyclotron and was also used to trigger the events. Time of flight information allowed to separate the elastic scattering events from the reactions.

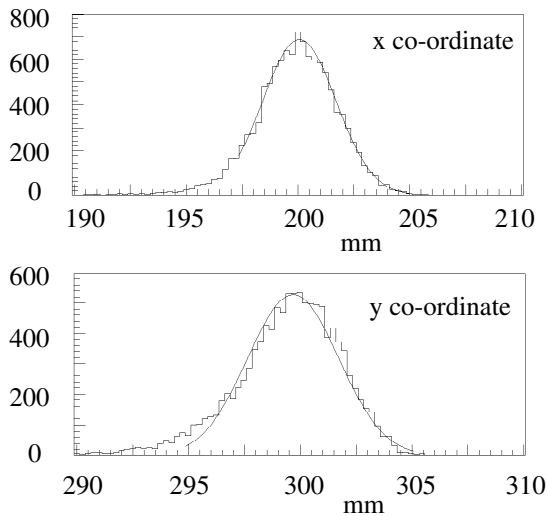


Fig. 2 - Sum of the signals collected on the left and on the right of the delay lines for x-wires (top) and y-wires (bottom). The FWHM are, respectively, about 3 mm in x coordinate and about 5 mm in y coordinate.

The impact point on the detector was determined by collecting the charge at both ends of each delay line. The preamplifier output signals were sent to a CFD discriminator whose output was used as a stop to a TDC started by the signal from the cathode. The sum of the left and right signals of the delay line represents the

length of the wire chamber and it was used as a condition to select the events giving clean signals out of the detector. The impact point was then calculated only among the events fulfilling the previous condition.

The signals from the drift chambers and from the scintillating detectors were sent to a QDC; the analysis of these signals as a function of the x coordinate or the y coordinate shows a marked dependence on the impact point.

A preliminary analysis of the data from the two telescopes was performed to check the consistency of the results between the two wire chambers. The response of the newly built one to the elastically scattered Ni indicate that the main features of the chamber were properly reproduced.

Fig. 2 shows the results of a very preliminary analysis on the spatial resolution. A rough calibration of the sum of the signals from both ends of the delay lines was performed and a resolution (FWHM) of about 3 mm in the x direction and about 5 mm in the y direction was deduced.

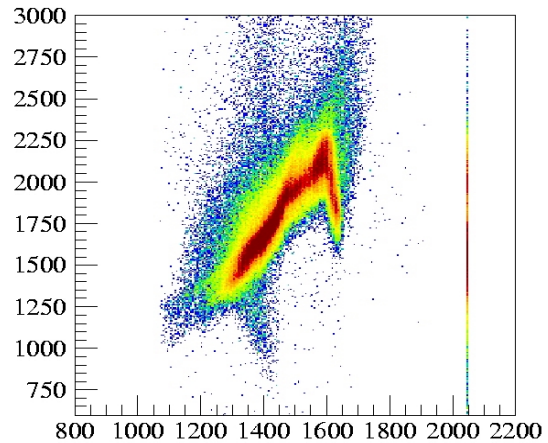


Fig. 3 - Energy loss vs x coordinate (abscissa). Low x values indicate impact points near the drift chamber cathodic plane. It is evident the effect of the drift path. The closer to the collection anode the larger the energy loss signal.

The response of the drift chambers shows a dependence on the impact point in both x and y directions; this effect can be clearly observed in the ΔE -vs-x and ΔE -vs-y matrices, and it has been interpreted as due to a combination of

charge recombination, space charge effects and non linearity of the electric field near the chamber edges. Fig. 3 shows the ΔE -vs- x matrix where lower x values are related to longer drift path. The dependence on the impact point is clearly observed.

In order to study the dependence of response function of the plastic detector on the impact point a mask with a grid formed by 15 holes each of 1cm diameter and a regular spacing of 5 cm in both x and y directions was placed in front of the detector. Events associated to different impact points were selected with the wire chamber and the obtained energy spectra were used to deduce the amount of the average light collected associated to the same deposited energy. The result is shown in fig.4 where the light yield as a function of the impact point on the detector is presented.

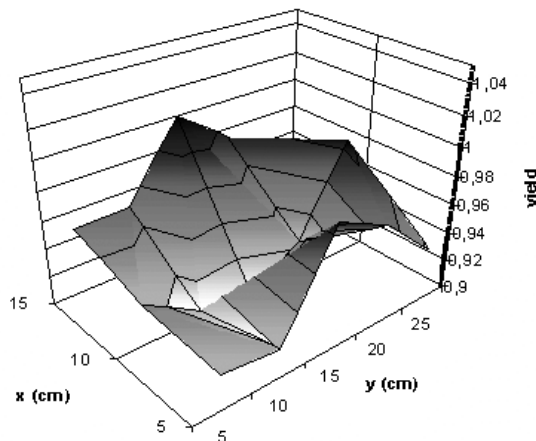


Fig.4 Response function of the plastic scintillator detector as a function of x and y positions.

A position dependence response was observed with a maximum difference of about 15% in the yield confirming a previous measurement of the response function of the scintillation detector [5]. In particular, a minimum of the light yield was observed in correspondence to the middle of the detector. This behavior could be explained as due to an incomplete light collection related to a combined effect of the shape of the light guides and the multiples reflections on the surface of the scintillator detector driving the light towards the photomultiplier.

The analysis is still in progress in order to deduce the full response functions of the three elements of each telescope.

5 ACKNOWLEDGEMENTS

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LOW INTENSITY BEAM DIAGNOSTICS

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Abstract

The need of diagnostic tools for low energy - low intensity beams has lead us to the development of a series of suitable devices, in order to perform imaging, profiling and identification of ion beams, with particular care for the EXCYT radioactive beams. The peculiarities of these devices are compactness, handiness and good performance for very low intensity beams ($I_{\text{beam}} < 10^5$ particles/s), in a range of energy from 50 keV up to 8 MeV/A.

1 INTRODUCTION

The research and development activity of the past few years has lead to the definition of a series of devices suitable to be used for a rather reliable beam diagnostics and handling, for the EXCYT facility [1]. At first we have addressed the question of beams after the acceleration, that was simpler, while studying the problems posed by the low energy / low intensity radioactive beams.

During the last year we have finalised our studies, building and testing a couple of prototypes that have shown how the radioactive beam should be handled and identified both at low and high energy. This subject, together with a brief status review of the available devices, will be discussed in the following.

2 POST-ACCELERATION BEAM PROFILING

The glass fibre based beam sensor (GFIBBS) represents our general solution for beam profiling, since we proved it is reliable, cheap and simple [2]. It is based on a couple of scintillating fibres, made from glass or plastic, scanning the beam. The two fibres are mutually perpendicular and are readout by means of a single photomultiplier. This allows to reconstruct the X and Y beam profiles in a single scan.

Either thin scintillator plates or thicker scintillating fiberoptic plates (SFOP) have been characterized, and they showed to be useful even at low intensity for direct beam imaging with CCD cameras. A gas detector with micro

strip readout electrode has shown to be rather stable, reliable and interactive. Though it is non-destructive and very sensitive, it has the disadvantage of being a gas device along a beam line, involving the well known risks.

Concerning the microchannel plate (MCP) imaging sensors, we have concluded that even though they look promising in terms of final performance, their operation is not as easy as for the other kinds of sensors already developed [3].



Fig.1. The GFIBBS device.

Either thin scintillator plates or thicker scintillating fiberoptic plates (SFOP) have been characterized, and they showed to be useful even at low intensity for direct beam imaging with CCD cameras.

Another device is the moving slit sensor, named SBBS (Scintillator Based Beam Sensor) and shown in fig.2. It consists of an inorganic scintillator crystal (CsI) placed behind a thick graphite screen with a 0.5 mm slit. The scintillator is optically coupled with a compact photomultiplier, and the whole structure can be moved to scan the beam. Quite good results

have been obtained in terms of sensitivity, even though the device completely stops the beam while in operation. The same device has also been successfully used to count the single particles of the beam in case of very low intensity, allowing the self calibration (light versus counts). We also proved that this device can operate at very low energy, by easily sensing a 1 pA beam of ^{12}C at 50 keV [4].



Fig.2. The SBBS device.

3 PRE-ACCELERATION BEAM PROFILING

A difficult task is sensing, imaging and identifying the beam before its acceleration, because of the low energy and intensity of the radioactive beam, as it emerges from the mass separator. However the space separation between its different isobaric components, which depends on their mass excess, can range from a few millimeters to a few hundred microns.

Making use of CsI(Tl) plates we have developed a device for the beam imaging and identification, to be installed on the preacceleration stage along the beam pipe, between the target ion-source complex and the Tandem accelerator [5]. This device, named LEBI (Low Energy Beam Imager/Identifier), basically consists of a CsI(Tl) plate, 1 or 2 mm thick, and of a 6 μm mylar tape arranged in front of the plate at a distance of 0.5 mm, see Fig. 3. When the radioactive beam hits the tape, it gets implanted because of its low energy (up to 300 keV). After the decay roughly half of the emitted β and γ rays cross the plate. This radiation is emitted isotropically, and since a large fraction of the solid angle covered by the plate is close to the emission point, the sum of

the contributions due to each beam particle gives rise to a light spot, whose diameter is larger than the transversal size of the beam. The spot intensity is related to the beam intensity, to the activity of the implanted nuclei, to the type and energy of the radiation produced by the decay.

The spatial resolution of LEBI is rather modest, in fact if a hypothetical point-like source is placed in front of the plate, the radiation will cross the plate in all directions (the plate covers a solid angle of about 2π sr), thus producing a light spot with a halo around it. The FWHM of the spot profile represents the spatial resolution of the system, which is of the order of the plate thickness, in our case between 1 mm and 2 mm.

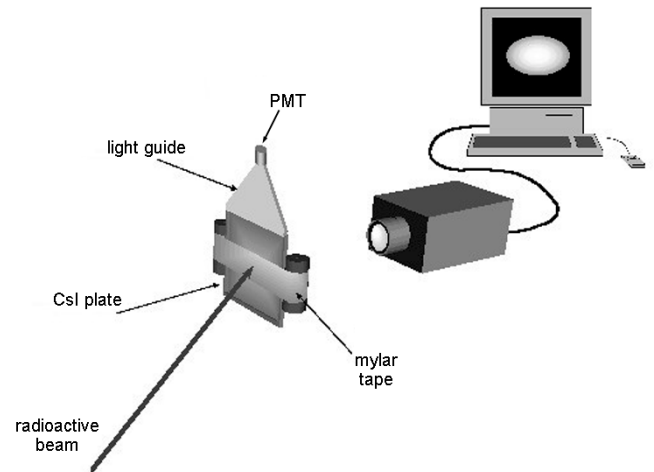


Fig. 3. Sketch of the LEBI device for low energy beam imaging and identification.

Since no radioactive beam is available so far from EXCYT, an experimental test has been performed by using a 1mm collimated ^{90}Sr beta source, producing a micro beam with intensity down to 10^3 pps. It was placed in front of the 2 mm thick CsI plate at a distance of 1 mm from it. The well visible light spot obtained with this plate is shown in Fig. 4. Its transversal profile has been fitted by using a gaussian curve with $\text{FWHM} \approx 1.7$ mm. The rule of the sum of the squares, allows us to calculate a spatial resolution $\Delta x \approx 1.5$ mm.

The LEBI prototype we have built is made of a spherical vacuum chamber containing the plate-tape set-up. The tape is rolled up in two spools and can be slid on, whenever it becomes

contaminated, by means of a DC motor (Minimotor 3557K012). An external high sensitivity CCD camera (Watec WAT-902H, sensitivity of $3 \cdot 10^{-4}$ lux) watches the plate in order to acquire the images. A pneumatic cylinder allows to insert and remove the plate-tape set-up from the beam line via remote control, Fig. 5.

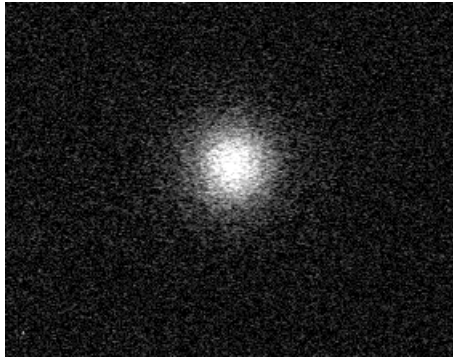


Fig. 4. Sample picture taken with LEBI using a 1mm collimated ^{90}Sr source. The FWHM of the profile is 1.7 mm.



Fig. 5. The LEBI device.

In order to study how LEBI should display the beams transported along the beam pipe of EXCYT, we developed a Monte Carlo simulation code, based on the energy loss of beta rays inside the crystal. It is capable of simulating the shape of the light spot produced by the radiation crossing the plate. As an example where a realistic beam is simulated, we assumed to produce a ^{18}F beam that contains ^{18}N as a contaminant.

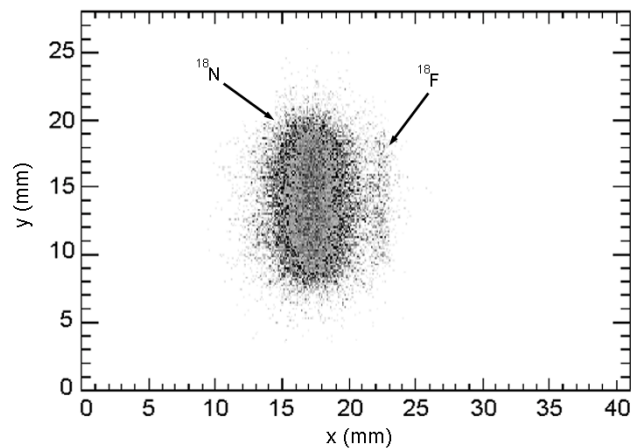


Fig. 6. Simulated response of LEBI for a ^{18}F beam. Main contaminant ^{18}N contributes very much to the image, because of its higher decay constant.

Using beam transport calculations, we derived the transverse distribution of the two ion species after the mass separator; the foreseen separation between the centroids is 4.8 mm. Then we used these results as input to the LEBI simulation code, whose output is reported in Fig. 6. The spatial separation between the main beam and the contaminant is evident. The predominance of the contribution due to ^{18}N ions depends on the value of its decay constant ($\lambda_{18\text{N}} = 1.11 \text{ sec}^{-1}$), much larger than ^{18}F ($\lambda_{18\text{F}} = 1.05 \cdot 10^{-4} \text{ sec}^{-1}$).

4 BEAM IDENTIFICATION

In the LEBI device, in order to get as much information as possible to identify the beam, a small photomultiplier (Hamamatsu R7400U) used in pulse counting mode is optically coupled to a plate side, by means of a specially suited light guide. It may be helpful for the identification of the implanted nuclei, allowing to reconstruct its decay curve by measuring the counting rate, and then to evaluate the decay constant λ . A more accurate analysis can be carried out by using two germanium detectors, which are foreseen to be installed sideways, and that may allow to identify the implanted nuclides by acquiring their gamma spectra.

For the cases where the peaks are confused or the background contribution is dominant, we foresee the possibility to use both detectors: the first one would be used to select a particular peak, while the second would build the conditioned spectrum, thus putting in evidence

the gamma cascades bound to the selected peak and strongly reducing the background. We tested this technique with two germanium detectors and a ^{60}Co source, showing that it is reliable.

The HEBI device (High Energy Beam Identifier), based on a revolving silicon telescope as previously proposed, has been tested with an alpha source and a ^{16}O beam run, Fig.7. We used the experimental error in E and ΔE for alphas and oxygen, to interpolate the foreseen error to the intermediate species. This way we have been able to estimate the capability of the system to discriminate the interesting beam from the close contaminants, see Fig. 8 and table 1.

A smart method for the calibration of the silicon telescope is putting HEBI after the Tandem but before the analysis magnet: this way we collect on the telescope all the charge states for each species, that give rise to several spots on the ΔE -E plot whose positions (in MeV) are perfectly known.

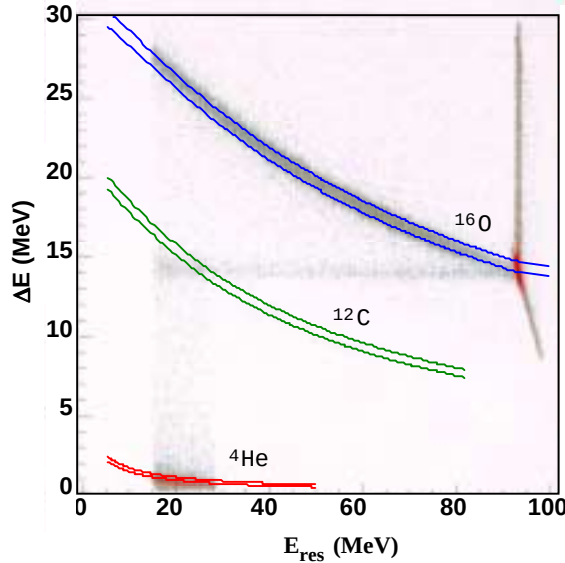


Fig.7. Calibrated bands ($\pm\sigma$) superimposed to the experimental data taken with HEBI. From the $^{16}\text{O}+^{196}\text{Au}$ reaction we get mainly elastic scattering, plus many alphas and some ^{12}C product.

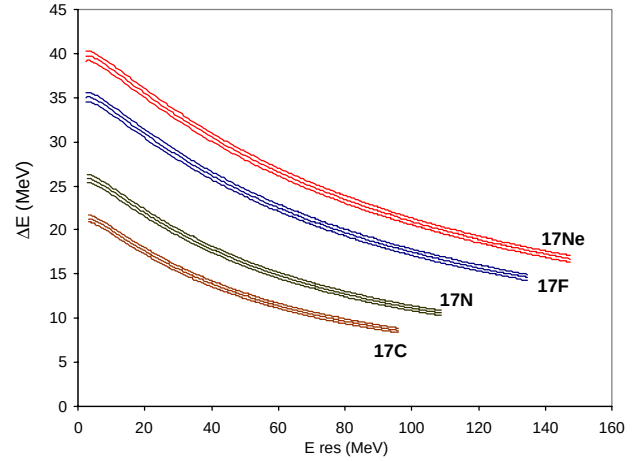


Fig.8. Discrimination plot ($\pm\sigma$) for ^{17}F . The three main contaminants are shown.

Table 1: Example of three nuclear species and the foreseen probability of misidentification with HEBI.

Nuclear species	Neighbor contam.	Contam. fraction ($\pm 2\sigma$)
^{11}Be	^{11}Li	$< 2.887 \times 10^{-15}$
^{11}Be	^{11}C	$< 2.887 \times 10^{-15}$
^{11}Be	^{11}B	2.90×10^{-13}
^{17}F	^{17}N	$< 2.887 \times 10^{-15}$
^{17}F	^{17}Ne	1.561×10^{-10}
^{17}F	^{17}O	2.90×10^{-13}
^{18}F	^{18}N	$< 2.887 \times 10^{-15}$
^{18}F	^{18}Ne	8.072×10^{-11}
^{18}F	^{18}O	2.90×10^{-13}

We have already started to design a final version of HEBI, that should be available at the very beginning of 2002.

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PARTICLE DETECTORS FOR LOW INTENSITY ION BEAM DIAGNOSTICS

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Abstract

In the framework of the new interests in radioactive ion beam facilities, as well as in hadron therapy projects, special diagnostic tools are needed in order to cope with low and very low intensity beams, sometimes also at very low energy. Particle detection techniques seem attractive under several aspects, so in this paper we describe the main features of the devices that could be used in an accelerator environment.

1 INTRODUCTION

There is an increasing interest in the production of radioactive ion beams (RIB), together with renewed efforts on the cancer therapy by means of protons and ions. These two subjects share a common feature, namely the low intensity of the produced ion beams.

Sometimes one might wish to handle very low intensity beams, and this task can be greatly simplified if a suitable device is available. Moreover, sometimes the need arises for single particle counting, hence the ideal device should be able to operate in two partially overlapped intensity regimes.

In the following a few possible ways are traced to borrow some hints from the nuclear detection techniques, in order to develop new beam diagnostic tools. Citation of work already done in this field will be helpful in this task.

2 PHYSICAL BACKGROUND

The main request for low intensity beam diagnostic tools comes from the RIB facilities, some already in operation, most of them still under development. Unfortunately the produced beams may have weak intensity, due to the small cross section for the production of several interesting nuclear species and to the obvious limitations in the primary beam intensity. A general recipe cannot be formulated since each particular species has a different cross section and lifetime: the final beam current can span several orders of magnitude, becoming critical when decreasing below $\approx 10^8$ particles per second (pps), and still worsening when below 10^5 pps.

On the other hand in the case of therapeutic ion beams the low intensity is a strict requirement coming from dose considerations, making still

more important a quick and reliable beam diagnosis and handling.

In such an intensity range the ordinary diagnostic techniques approach their intrinsic electromagnetic limitations, that are mainly due to electronic noise, that limits the attainable signal-to-noise ratio, and to the contamination of the useful signal by secondary emission of electrons from parts of the sensor exposed to the beam.

The required features, whenever possible, are: improved sensitivity, non-interceptivity, reliability, ease-of-use, robustness, this last especially regarding sudden variations of the beam intensity, operator mistakes, failures.

3 AVAILABLE TECHNIQUES

In order to increase the sensitivity of a beam sensor there are two possible strategies: reducing the noise or increasing the signal. The former should be attained by improving the electronic design and the shielding of usual devices, while the latter can be pursued by borrowing some hints from the experimental nuclear physicists. In fact a convenient method to increase the useful signal is to use a particle detector, that is usually sensitive to the energy released by the particle rather than to the carried charge.

Conversely, the main drawback of devices based on particle detectors is that their response is strongly dependent on the beam type and energy: we do not measure anymore the electric current carried by the beam. Moreover the thickness of eventual dead layers can introduce an energy threshold on the detectable beams, while the radiation hardness, as compared to the cost, is one of the most important parameters that have to drive the choice of a type of detector.

Available techniques are based on semiconductors, gas detectors, secondary emission (with physical amplification), scintillators; some further technique, like

Cherenkov detectors and others, that can be used in particular cases, will not be described here.

4 SEMICONDUCTOR DETECTORS

The most used semiconductor detector is silicon. The signal in a silicon detector is due to the energy lost in it by an impinging particle, that can cross it or be stopped inside. The silicon is quite efficient in this process, since the average energy needed to produce an electron/hole pair in the depleted region is 3.62 eV. Unfortunately its radiation hardness is not high, while its cost, including the needed electronics, is a little bit expensive. Nevertheless the ease-of-use and reliability are enough to allow its use for specific applications.

Several groups have already developed and used a silicon microstrip detector for high energy physics experiments. It consists of a structure with typical pitch of $\approx 100\ \mu\text{m}$ and thickness of $\approx 100\text{-}300\ \mu\text{m}$; the transverse size can be up to 10-15 cm. Such a device is best suited for single particle counting and tracking, even though it can also measure the energy deposition. Its use in current mode is obviously possible, but radiation hardness and cost impose severe limitations to it.

In particular cases a silicon detector can however represent a useful tool, as for instance the beam isotopic identification (1). Such a device consists of a thin Au target and a silicon telescope that can be positioned around it. This method, that can be applied for not too energetic beams, allows the unambiguous isotopic identification of particles by building a typical ΔE -E scatter plot.

Another well known semiconductor detector is germanium, generally used as very high resolution gamma ray detector. Due to the very poor radiation hardness and to the high cost these detectors are completely unsuitable for particle detection. Nevertheless, in spite of their complex usage and low reliability as beam sensors, they can be successfully employed to identify very weak RIBs by means of their gamma decay “fingerprints” (2, 3).

5 DIAMOND DETECTORS

Unlike semiconductors diamond is rather a good insulator, even though its operating mode resembles the semiconductors. The detection principle is still the creation of pairs by energy loss, but in this case the noise is strongly reduced because of the high energy gap. The average energy to create a pair is $\approx 18\ \text{eV}$, the radiation hardness is very good since it is not a diode that is damaged because of the displacement of its

dopants. Moreover the thermal conductivity of diamond is better than copper, hence it can tolerate a high power deposition. So far the chemical vapour deposition (CVD) technique allows the production of good diamond films, that however are not monocrystalline: this implies that the charge collection length is limited by crystal defects that trap charges.

Nowadays detectors with 50-100 μm collection length are available, that can be usefully exploited both in pulse counting mode and in current mode. In addition the high electron mobility and dielectric constant, together with the short collection length, make the signal development very fast, thus allowing to build also segmented devices with $<50\ \text{ps}$ time resolution (4) and capable to sustain up to 10^8 pps count rate in pulse counting mode (5).

An example of the performance of CVD diamond films in current mode readout can be found in (6), where the authors report on tests made with a strip electrode structure of 100 μm pitch. The overall cost of this technique is still high, even though it is expected to decrease in the next future; concerning reliability and ease-of-use the technique looks promising.

6 GAS DETECTORS

6.1 Gas chambers

Gas detectors are very well known, and they have been developed in a wide variety of shapes and sizes. The signal in a gas detector is due to the energy lost by a particle in a chamber filled with a suitable gas. The average energy to produce an e/ion pair is generally of the order of 30 eV.

The radiation hardness is good since the gas continuously flows through the chamber, and the cost is usually cheap. Several operating modes are possible for gas detectors, depending on the pressure and on the electric field applied to the electrodes.

The main techniques mentioned here as suitable for beam diagnostics purposes are the ionization chamber and the wire chamber. Both of these detectors have been employed in a large number of nuclear physics experiments so far, and they are already used as beam counters and/or trackers in several laboratories. They can be used in pulse counting and in continuous mode, starting to lose linearity around an incoming rate of $\approx 10^9$ pps due to space-charge effects.

A remarkable improvement in gas detectors has come a few years ago with the introduction of the microstrip gas chamber (MSGC) (7). Such a

detector is based on the same principle of the wire chamber, with the difference that the wires (cathodes and anodes) are lithographically drawn and lay on the same plane. The main advantages are:

- high precision, with a pitch of $\approx 100\text{-}200\ \mu\text{m}$;
- simplification of the overall mechanical structure.

A prototype beam profile monitor employing an MSGC has been recently tested with remarkable results (8). It is based on a $5\times 5\ \text{cm}^2$ glass microstrip plate used as collecting electrode of a small ionization chamber. The collecting field is perpendicular to the beam direction, while the strips are parallel to it. It can be inserted/removed on the beam path and the signals, collected strip by strip, give rise to the beam profile.

A variation of this technique, still with transverse collecting field but with strips perpendicular to the impinging particle direction, becomes a multilayer ionization chamber. Such a device used in single particle counting can replace a silicon telescope in applications where low energy beams are involved: Z values up to 10 have been recently identified with an energy threshold around $200\ \text{keV/amu}$ ($< 1\ \mu\text{m}$ silicon equivalent) (9).

6.2 Residual Gas Detectors

These detectors are based on the ionization produced by beam particles on the residual gas along the beam pipe. The very few ionizing collision events need some sort of physical amplification. What is generally used is a microchannel plate (MCP) onto which the electrons (or ions) produced are driven by a transverse electric field. Care has to be taken to prevent the MCP from being accidentally hit by the beam, that would destroy it.

6.3 MCP: Readout by Electrodes

This kind of device is rather sensitive and is mainly used in pulse counting mode. It can be employed for transverse beam profiling, with the collecting electrodes shaped in separate strips parallel to the beam (10, 11). It is also used successfully for longitudinal beam profiling, due to its good timing resolution ($\approx 150\ \text{ps}$) (10).

A nice application of such a device has been recently proposed, where both ion and electron drift times are recorded, also allowing to identify the ion species drifting toward the electrodes (12).

6.4 MCP: Readout by Scintillating Screen

An interesting device is made of an MCP coupled with a phosphor scintillating screen. By means of a suitable choice of the voltages applied to the MCP electrodes, the output electron cloud can be further accelerated toward the screen, thus producing a visible image that can be observed by means of a usual CCD camera. The device can easily reconstruct the beam trace across the active field of the sensor and the image is best acquired with a frame grabber that also allows a digital analysis (13).

A more complicated configuration can also reconstruct the 2D transverse profile of the beam, by exploiting two different field cages, as shown in (14).

7 SECONDARY EMISSION DETECTORS

These detectors exploit the emission of secondary electrons from several materials when hit by energetic particles (15, 16). To this aim wires and/or thin foils are generally used, choosing a material with a sufficient mechanical strength and capable of withstanding or dissipating the foreseen power deposition. The generally used foils are made from carbon or aluminium, the wires from tungsten.

In case of low intensity beams the number of electrons produced is very low - usually from few units to two hundred per incident ion (16) - thus a physical amplification process is needed to get a useful signal.

This technique, exploiting an MCP to amplify the number of electrons, is well known since many years in heavy ion physics for time of flight measurements (17), and has also been used for longitudinal ion beam profiling (18). Recently some new device has been proposed using a channeltron for integral beam current measurements (12) or an MCP plus scintillating screen combination to get an immediate 2D transverse profile image by means of a CCD camera and a frame grabber (13).

8 SCINTILLATORS

Scintillators are well known to physicists. Their basic property is to emit as light part of the energy deposited by an impinging particle. A large family of polymeric plastic scintillators is today available on the market, and they are usually rather cheap and easy to be produced in any shape. Plastics can be practically chosen within a large spectrum of characteristics like decay time, emission wavelength, attenuation length, etc.

Their main drawbacks are the poor radiation hardness and power dissipation; so special care should be put when using a plastic scintillator in a high counting rate environment. The usage of a plastic on the beam is practically limited to a low intensity regime and for short time intervals; after irradiation with $\approx 10^{10}$ - 10^{12} particles/cm² all hydrogen atoms are completely ejected, and only carbon atoms are left (graphite) (19).

During the last fifteen years new families of inorganic scintillator crystals have come to the attention of physicists, with rather good mechanical properties, radiation hardness, scintillation efficiency, and some of them have a surprisingly short decay time, even shorter than plastics.

Most of the currently used scintillators have an average energy to produce a scintillation photon of the order of ≈ 10 -100 eV. The cost has large variations due to type, shape, quantity, doping, purity, but we can still say that it is cheap.

Among the inorganic scintillators we can also list some amorphous materials, like glasses, usually doped with rare earths elements like terbium, gadolinium, cerium, etc.

Concerning the light readout devices, many types of photosensors exist on the market, some of them suitable for current readout (photodiodes), some others for pulse counting (photomultipliers, avalanche photodiodes). Special devices also exist that are suitable for single photon counting (photomultipliers, hybrid photodiodes).

So far the application of scintillators for beam diagnostics has been basically limited to plastics, mainly used for timing (e.g. (20)) or for integral current measurement (e.g. (21)) in pulse counting mode; the count rate limit is $I < 106$ pps. The timing resolution of such a device can easily reach < 100 ps (22, 23), and if used in shape of a scintillating optical fibre bundle it can also be used as tracker, allowing a transverse profile reconstruction (24).

Recently a R&D activity has been started at INFN LNS concerning the application of scintillators to low intensity beam diagnostics, moving along different lines. Hence the main results so far obtained are outlined here.

8.1 Scintillating Fibres

Our interest has been attracted by scintillating fibres since they allow to rebuild a scanning wire beam profiler by replacing the wire with a fibre. The sensitivity is improved since the signal is due to energy loss, the electronic noise is strongly reduced. Such a device, named FIBBS (Fibre

Based Beam Sensor) is capable of sensing even the single beam particle (25). The usage of only one fibre per direction avoids calibrations, while the fibre diameter and the step size can be varied more or less at will.

The photosensor is a hybrid photodiode (HPD), if a precise energy response is needed, or simply a compact photomultiplier. A special I-V converter has been developed for the photosensor readout: it allows both the pulse counting and the continuous readout modes to be simultaneously performed on two different outputs (25).

Two fibres are installed on the same moving structure, rotated by 90° with respect to each other but still connected to the same photosensor, thus allowing to reconstruct both the X and Y profiles in a single scan.

Three types of fibres have been tested so far: plastic, Ce doped glass, Tb doped glass. The plastic and Ce glass fibres allow the pulse counting mode, since their decay time is short (3 and 40 ns respectively); unfortunately they are not enough radiation hard, so they need to be used with care. Tb glass fibres are pretty harder but their decay time of 3 ms only allows the continuous readout mode. Nevertheless their light yield is good, and makes the device capable of sensing beam profiles even down to 10^5 pps integral current.

8.2 Scintillating Plates

We have also developed a beam diagnostic set-up based on the direct optical inspection of the transverse profile (26). To this aim we use some scintillating screen, directly hit by the beam, and a CCD camera that looks at it sending the images onto a TV monitor and to a frame grabber system for digital analysis.

Several different plates have been tested so far, each one with interesting features and minor drawbacks. Among them it is worth mentioning CHROMOX6 (a doped alumina), Lanex (a radiographic scintillating sheet), NE102A, CsI(Tl).

An interesting screen type is the scintillating fiberoptic plate (SFOP): we tested thin plates made from a slice of a bundle of Tb doped glass fibres, whose light can thus be readout from the back. The light diffusion is constrained within the fibre diameter (≈ 10 μ m), and the light yield allows to sense beam images even at 10^5 pps; the 3 ms decay time gives no evident afterglow. The SFOPs are rather cheap and radiation hard, but they break at high temperature; hence they need some care when exposed to the beam.

8.3 Bulk Inorganic Crystals

We have also built a scanning slit beam profiler, based on a moving slit and a small CsI(Tl) brick ($1 \times 1 \times 0.5 \text{ cm}^3$). The operating principle of such a device is quite similar to the FIBBS, with a few differences. On the one hand it is completely interceptive while scanning the beam; on the other hand its overall light yield is about 50 times higher than a fibre.

The output signal is sent to the already mentioned I-V converter, in order to have both pulse and current measurements. This device has allowed us to reconstruct profiles even down to 10^4 pps integral beam current in continuous mode, and at the same time it is able to count pulses in order to have an absolute intensity calibration. A very strong point in favour of this device is that we have recently proved it is useful also for very low energy beam profiling. In fact it showed it can easily reconstruct a beam profile of 10^6 pps of $^{12}\text{C}^+$ ions at 50 keV (27).

9 SUMMARY AND CONCLUSIONS

Several techniques have already come out in order to help in ion beam diagnostics at low intensity, and the know-how already available with particle detectors has been quite useful in this respect. The envisaged devices, mainly based on semiconductors, gas detectors, secondary emission and scintillators, seem capable of satisfying most of the requirements so far needed. However the most promising techniques seem to be diamond detectors, inorganic scintillators, doped glasses, even though many ad-hoc devices based on other types of detectors are (and will be) helpful.

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ACCELERATORS DIVISION

The heavy ion facility of the LNS is based on two accelerators, the Tandem and the Superconducting Cyclotron (CS). The CS was operated as booster of the Tandem until October 1999 when the assembling of the injection line and of the central region started.

On 12 January 2000 the first beam of ^{58}Ni was injected axially into the Cyclotron and accelerated up to extraction radius. Since that data the cyclotron was operated in the stand alone mode. After a couple of months spent to understand and overcome problems due both to the dark current on the electrostatic inflector and to a vacuum leak in the cooling pipe of the axial buncher, the cyclotron was able to deliver beams to the experiments. Unfortunately, due to serious problems on the electrostatic deflectors (E.D.) we were forced to stop the scheduled program of beam to users for about 5 months, to allows for extra maintenance and E.D. tests.

Meanwhile experiments whit tandem have been performed and a lot of works have done inside the accelerator room for the project EXCYT. In particular we installed the so called primary beam line from the cyclotron to the production target for EXCYT, the H.V. platform at low activity, and plants for cooling and main line.

During the period of extra maintenance (July — November) the activity was focused on the Electrostatic deflectors, on the two ECR sources, on the axial inflectorand replacing of a the belt charge of the tandem.

At the end of the maintenance period a proton beam at energy of 62 MeV was delivered to the Catana site as demonstration of the good work done. In figure 1. are shown all the beams accelerated up to the end of 2000.

The division staff has guaranteed the operations, the maintenance and the development of the accelerators including the beam lines. Moreover the accelerator division staff was involved in the following activities:

- Development of EXCYT project;
- Support to CATANA project;
- Participation to the project TRASmutazione SCOrie radioattive (TRASCO) ;
- Developing of SERSE, the superconducting ECR source;
- Developing of CESAR, a room temperature ECR source;
- Improving of the axial injection line;
- Design and construction of the chopper-500 and of its RF amplifier ;
- Maintenance and developing of the high energy chopper for the cyclotron beams;
- Design of a mini-chopper, to change with continuity the duty cycle of the cyclotron.

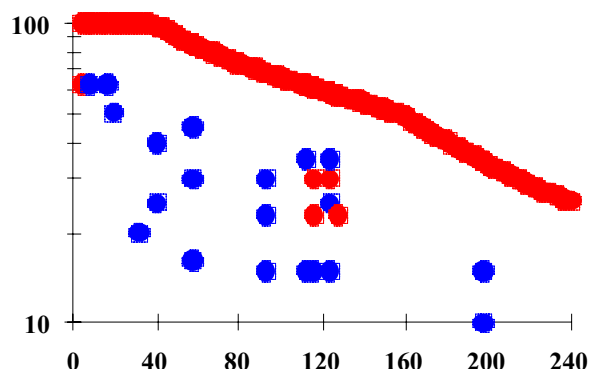


Fig.1: Ions Beam accelerated by Cyclotrons up to date. The red dots are the beams accelerated in the stand alone mode.

Tandem beam delivered	1670 h	Cyclotron beam delivered	420 h
Beams preparation	455 h	New beams developed	394 h
Scheduled stops	4770 h	Failures	1051 h
Tandem s beams to users		Cyclotron s beams to users	
^7Li	612 h	$^{112,124}\text{Sn}$ 35 MeV/u	370 h
$^{16,18}\text{O}$	448 h	Protons 62 MeV/u	50 h
Protons	430 h	New beams	
^{12}C	122 h	^{16}O and He at 62 MeV/u	
^{28}Si	58 h		

Tandem Status

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This year the electrostatic SMP tandem accelerator has been in operation for 2400 h. The beam has been delivered to users for experiments approved by PAC of LNS and for detector s test, fig.1). The tandem beam has been used also to align the magnetic axis of the superconducting solenoid SOLE to the axis of beam line. In November a ^7Li beam was delivered to produce on a deuterium target to produce a secondary radioactive beam of ^8Li . The production rate of ^8Li was measured and the problems related with the production and detection set-up were investigated. results were very promising and beam intensity should be enough if the transfer beam line will be improved by the installation of the new switching magnet and of the by-pass line. The by-pass line was designed at beginning

of the 2000. The dipoles magnets of by-pass will be delivered on January 2001 and installed on March-April 2001,fig.2).

On September-October the old belt was replaced later a working time of 28.700 h. The belt was deteriorate but not yet destroyed. The belt, until the replacement, allows to reach working voltage of 13 MV. In figure 3) the time distribution (1997-2000) of the beams delivered by the tandem accelerator for the experiments and for the injection into the cyclotron is shown.

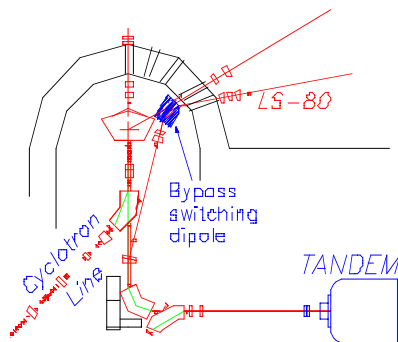


Figure 1: New By-pass line for the Tandem beams

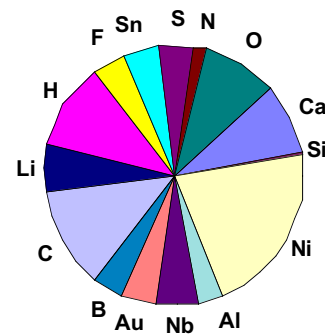


Figure 1: Beams delivered by Tandem.
Years 1997-2000

TERMINAL VOLTAGE DISTRIBUTION YEARS 1994/2000 (28710 h)

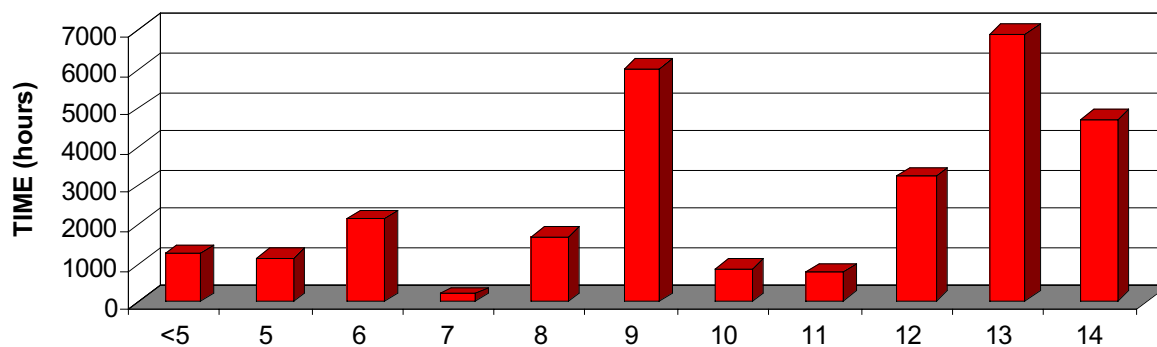


Figure 3: Operation voltages distribution of the tandem from the 1994 to 2000. working time of last belt 26.760 hours (up to date December 1999)

High Intensity Beams from Superconducting Cyclotrons

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1. Introduction

The EXCYT project at the LNS is based on the K800 superconducting cyclotron working as a primary accelerator to deliver Carbon, Oxygen and other light ion beams with energies up to 80÷87 MeV/amu. These beams will be used to produce Radioactive Ion Beams (R.I.B.) [1], which will be used at low energy (≤ 1 MeV) or at medium energy after acceleration by the 15 MV Tandem. Of course many efforts have to be made in order to achieve a reasonably high intensity of R.I.B.

The superconducting cyclotron is by now strongly intensity limited by the extraction process, which is accomplished by electrostatic deflectors. The maximum deliverable beam power should be about 0.5-1 kW. There would be a significant advantage for the EXCYT facility if a primary beam with a 10-20 times higher power is available.

According to this perspective we envisaged the hypothesis to build a new cryostat for the existing K800 cyclotron, including the superconducting coils, which would allow the extraction by stripping of a set of ions like H_2^+ , D_2^+ , C^{5+} , N^{6+} , O^{7+} , Ne^{8+} . All of the other beams for nuclear physics experiments would be extracted by E.D., as it is presently done.

Electrostatic deflectors present several problems in superconducting cyclotrons if high intensities have to be extracted: this is due to the compactness, which is an intrinsic characteristic of such machines. The turn-to-turn separation is never of the order of the deflector clearance, and multi-turn extraction always occurs. Then a certain amount of beam power is dissipated on the septum, which

represents a limit due both to the heating effect and to activation.

2. Upgrading of the K800 cyclotron

The goal of the proposed modification is to make extraction by stripping of H_2^+ and light ions possible in the K800 cyclotron so as to achieve high power beams. At the same time we need to maintain the versatility of our cyclotron, which is asked to deliver any kind of ions in a wide energy range. For this reason the cyclotron will be equipped with two extraction modes: extraction by stripping and extraction by electrostatic deflectors.

To deliver light ions beams with high power we propose to accelerate ions as C^{5+} , N^{6+} , O^{7+} , Ne^{8+} to the maximum energies achievable with our cyclotron and use a stripper foil placed at a proper radius and azimuth to change their charge state to C^{6+} , N^{7+} , O^{8+} , Ne^{10+} , [2,3].

The maximum energies achievable by our cyclotron for these light ions are $T/A = K_{\text{foc}} \times q/A = 200 \times q/A$ MeV/amu, then for the above ions the energy range is 80÷87.5 MeV/a.m.u. Due to these high energies these ions crossing a stripper foil of $100 \mu\text{g}/\text{cm}^2$ will be fully stripped, the stripping efficiency being 100%, [4].

The H_2^+ beam can be extracted by stripping too, but the extraction trajectory is very different as compared to that of the above mentioned ions (C-Ne). In this case in fact the stripper foil breaks the molecule and produces 2 protons, which have a magnetic rigidity two times less than the H_2^+ beam.

A right position of the stripper allow to deliver all the ion beams of our interest in a new extraction beam line. The extraction trajectories for the different ions C^{6+} , N^{7+} , O^{8+} , Ne^{10+} to be extracted by stripping have a little differences in position and directions.

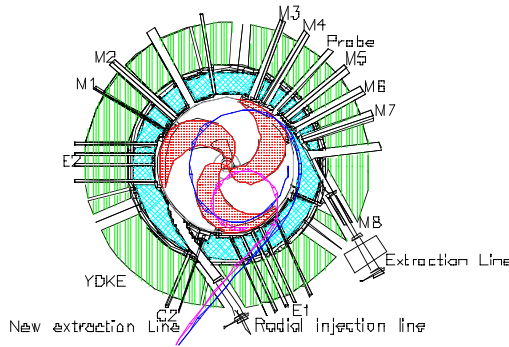


Figure 8: Layout of the existing K800 cyclotron with the trajectories of proton and oxygen beams extracted by stripping.

But by a couple of steering magnets it will be possible to send these beams along a common axis of the new extraction beam line. In fig. 8) the drawing of the K800 cyclotron with the new extraction trajectories for the $H_2^+ \rightarrow P$ case and the $O^{7+} \rightarrow O^{8+}$ case are shown. It is evident that the new cryostat needs a proper penetration hole through the cryostat, while the existent radial injection channel became unnecessary.

A lot of work has been done to find out the radius and azimuth of the stripper that allows to have the different extraction trajectories for H_2^+ and the light ions inside one extraction channel with minimum differences. The main difference among the extraction trajectories for H_2^+ and D_2^+ and those of the light ions is the position of the stripper foil. To extract the proton and deuteron beams the stripper foil should be placed in a hill, while for the extraction of the other light ions it is placed in a valley.

The trajectories of the ions extracted by stripping are very different respect to the trajectories of ions extracted by Electrostatic

deflector. Between the final directions of the two families of trajectories there is an angle of about 60° . A new extraction beam line have to be constructed.

The solution that we propose is to build a new cryostat, including a new set of superconducting coils. The new cryostat should be designed with two extraction channels. One similar to the present one, which allows the extraction of all the ion beams with low power (<50 W) by the E.D. An additional extraction channel will be provided to allow for extraction by stripping of ion beams with power of 10-20 kW. In particular, the design of the extraction channel requires a stress analysis of the cryostat structure to evaluate the maximum size of each penetration across the cryostat.

To increase the size of the penetration holes across the cryostat a thicker median plate is mandatory. To achieve a thicker median plate, the size of the main coils has to be reduced to increase the distance from the median plane.

The main modifications of the magnetic configuration should be:

- the increased distance between the main coils to have more room for the beam and for a thicker median plate of the cryostat;
- larger extraction channel and penetration holes to get better performances of the cyclotron;
- use of impregnated coils, like in the Agor cyclotron, vs. the present coils which are directly wheat by helium. This new type of coils should reduce the construction costs as compared to the technique of the double pancake, adopted in the present coils;
- the inner CuBe tie rods should be removed and replaced by a different compression system to fix the coils to the median plate in order to achieve a

- more room on the inner side of the cryostat;
- new kind of nitrogen shields to reduce the consumption of Liquid Nitrogen;
- replacement of all the cryogenic lines with more efficient lines to reduce the losses and the maintenance operations.

3. Expected performances and conclusions

The maximum beam power for some ions deliverable from the existing K800 with E.D. and from the upgraded K800 with stripper are presented in table 1).

Table 1: Performances comparison between the present K800 and the K800 with stripping

	K800 E.D.	K800 Stripper
Beam current at source for Oxygen ion	90 μ A	300 μ A
Charge state	8	7
Energy (MeV/amu)	83.3	87.5
Current accelerated at extraction radius	32.4* μ A	108* μ A
Extraction efficiency by E.D. 50%	16.2 μ A	
Voltage on the deflector (Gap=6 mm)	70 kV	
Extraction efficiency by stripper 100%		108 μ A
Beam power extracted	2.7 (1') kW	21.6 kW
Beam current at source for Carbon ion	100	300
Charge state	6	5
Beam power extracted	2.7 (1')	21.6
Beam current at source for Neon ion	50	100
Charge state	10+	8+
Beam power extracted	1.5 kW	7.9 kW

*Injection efficiency 90%, Buncher efficiency 40%

^ Expected upper power limit due to the Electrostatic Deflector system

The proposal to upgrade the existing K800 cyclotron has other advantages respect to the construction of a completely new cyclotron.

- The construction of a completely new cryostat allows to start the project in very short time and without any interference with the scheduled operation for the activity of the cyclotron nor for the operation of the EXCYT project.
- Exist more companies which are interested to design and to build the cryostat and the magnet
- The cost of this upgrading is less than half of the construction of a new cyclotron (6-7 M_ respect to 15 M_)
- The accelerator staff does not need to be increased at regime
- We know already the accelerator
- We estimate to deliver the new beams in 4 years from the starting time (for the K440 the time of realization is more than 5 years)

Moreover our cyclotron was designed about 20 years ago and a lot of experience has been gained in the construction of this kind of magnet which could be of great advantage in the design of the new cryostat and magnet. In particular new superconducting cables with better performances have been developed which allow a new design for the coils.

A critical point is the shut down of the K800 cyclotron for the nuclear physics experiments to replace the cryostat.

In conclusion due to the high performances, the low costs, the short time of construction, the low efforts required to the LNS staff, we believe that the proposal to upgrade the K800 cyclotron is a good solution.

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COMMISSIONING OF THE SUPERCONDUCTING CYCLOTRON WORKING IN THE AXIAL INJECTION MODE

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Abstract

The Superconducting Cyclotron has been commissioned after the installation of the axial injection equipment. The first problems and beam operations are described. The new mode made possible to develop a proton beam with an energy of 62 MeV, which allows to use the cyclotron beam for radiotherapy. Intrinsic advantages of the new injection mode are outlined.

1 INTRODUCTION

The superconducting cyclotron, installed at LNS in 1990, was commissioned in 1994 as a postaccelerator of a 15 MV Tandem, already working since 1984.

In November 1999, after 5 years of operation, we decided to change injection mode, switching to axial injection mode. There are several reasons why we decided to do that. Firstly, the need to have a simpler and more reliable accelerator system, decoupling the two accelerators. Secondly and more important, the possibility of improving the performance of the cyclotron, in terms of intensity and maximum energy. The cyclotron is going to become the primary accelerator in a facility for radioactive ion beams, EXCYT. When the injector is the superconducting ECR source Serse, the maximum energy is increased for heavy ions as compared with the previous mode: with gold, it should be possible to reach an energy of 30 MeV/n while in the previous mode the maximum energy was 15-20. As for intensity, the final target set by the EXCYT project is to have a primary beam (from C to Ne) of 1 μ A on the target.

With radial injection, we developed a fluorine beam at 50 MeV/n, but with an injected current of 120 enA, charge state 3, we got approximately 20 enA of extracted beam, which was corresponding with estimates taking account of all the efficiency factors. Since the maximum possible injected current is 500 enA, the maximum extracted current is 9 pA.

With axial injection, the real problem is not due to injection, but to extraction. Extraction is most frequently done in multi-turn mode, with an efficiency by far less than 100%. This implies that a certain amount of beam is dissipated on the

septum of the electrostatic deflector, causing possible melting or activation.

2 AXIAL INJECTION EQUIPMENT

The designed equipment (central region and inflector), necessary to perform axial injection, has been described in the previous LNS report and elsewhere [1]. It works in constant orbit mode with $h=2$. The maximum source voltage has been fixed to be 30 kV.

A spiral inflector has been chosen to bend the beam from the cyclotron axis to the median plane, as it has been demonstrated that it is convenient from the point of view of centering as compared to other types (mirror, hyperboloid). The gap has been chosen to be 6 mm. With an electric field of 22 kV/cm the exit radius turns to be 18 mm.

The central region accelerates particles in the first 2 orbits. A residual off-centering can be compensated by a first harmonic of about 10 gauss, in these 2 orbits the vertical motion is well confined in ± 2 mm.

2.1 Phase slits

The central region performs a rough phase selection, reducing the phase range to approximately 35° RF, which corresponds to the acceptance of the cyclotron. Without selection, particles with phases out of this range could possibly be accelerated until a region close to extraction and cause activation. In the central region the energy is low, therefore there is no activation, but due to a strong mixing effect between the longitudinal and the transverse motion, the phase range is not well defined when considering beam ellipses.

Therefore, to have a fine selection, another system, consisting of a slit system, has been

installed out of the central region, 20 cm far from the center. They are 3 wedges, placed one in each dee. The 3 main holes of the dees host the mechanism that allows to adjust their position. The slits can be moved by 1 cm in the median plane and can also be removed from the median plane, going inside the dees.

3 BEAM OPERATIONS

In December 1999 the central region and inflector were assembled in the cyclotron. When we tried to raise the inflector voltage, even at voltages as low as 500 V, we had immediately problems of dark current when switching on the magnetic field. Later we discovered that this problem was not on the inflector, but on the voltage leading system before the inflector and was due to a bad geometry of the insulators. The problem was solved by replacing the above insulators with the one shown. After, we could reach the maximum design voltage, 6 KV, without the inflector. This demonstrates that even at low voltages, electrostatic problems can become serious with magnetic field, which focuses electrons emitted by field effect.

In January 2000 a ^{58}Ni beam, charge state 16+, coming out from the ECR source Serse at 17.7 KV, was injected into the cyclotron, then accelerated to 30 MeV/amu and extracted. This was a really important result, because allowed to verify that the whole axial injection equipment was working. It was relatively quick to have the beam inside the cyclotron once everything was working, although there is no beam diagnostics at the entrance of the inflector. This thanks to a preliminary focusing test of the beam in the center of the cyclotron, accomplished by means of a TV camera placed along the axis instead of the inflector voltage leading system.

The voltage needed in the spiral electrodes of the inflector was 3.7 KV, just the value resulting from calculations.

When trying to inject a different beam, ^{124}Sn , to be accelerated to 35 MeV/amu, we had again problems with the inflector voltage consisting in a high dark current. In this case the required voltage was 5 KV instead of 3.7 and this time the problem was on the inflector: surfaces were rounded as much as possible, and when possible parts at opposite voltage, facing each other, were encapsulated with ceramic. Evacuation was made easier by opening the bottom of the housing and drilling an additional hole. After these modifications, the voltage of 5 kV was reached, but the ^{124}Sn , $q=29+$, was not yet accelerated.

We discovered that the problem was a bad vacuum level in the buncher region along the cyclotron axis, probably due to a small leak in the cooling circuit of the buncher, which prevented the ions from reaching the inflector with the original charge state, 29. This was understood by accelerating an oxygen beam, analogue of the ^{124}Sn , which was regularly accelerated. The vacuum was improved in the above mentioned region by installing two getter pumps in the final section of the injection beam line, which allowed to reach a pressure 10 times better than before and finally the ^{124}Sn 35 MeV/n was successfully accelerated and extracted.

We got an estimate of the transmission of the central region, which is around 7% for heavy ions like ^{124}Sn and is close to 10% for light ions. This last figure was achieved when accelerating H_2^+ molecules to 62 MeV/amu and is the maximum achievable, since the central region selects approximately 35 °RF.

The axial buncher, which consists of a drift tube, and is installed inside the cyclotron yoke, has been switched on, operating with a voltage of about 500 V on the electrode. A factor more than 4 has been obtained, but we have also had problems of coupling between the amplifier and the buncher, probably due to the narrow space where the connection of the line is.

Extraction of the two developed beams, Ni and Sn, was accomplished with the same parameters as in the radial injection mode. Again a centering first harmonic, of the order of 10 gauss, the same as in the previous mode, was necessary to maximise the extraction efficiency.

A few words on the use of phase slits. They were used to get a good beam quality. Most of the recent experiments are requiring a very narrow, 1 nsec, and well shaped, without tails, time peak, with an inter-burst separation of 100-150 nsec. Phase slits cut particles and since there is a radial-longitudinal correlation in the region where the phase slits are installed, they also cut phases. Of course a big amount of beam is intercepted, about 70%, but we observe a quite good stability of the time structure to which we were not used, by far better than in the case of radial injection. In this case the pre-injector instability affected the buncher behaviour, resulting in a frequent displacement of the time peak.

4 THE PROTON BEAM

At the end of 2000 a beam of hydrogen molecules, H_2^+ , was accelerated to 62 MeV/amu

and extracted. This was made possible by axial injection, with radial injection it was not possible to have protons from the cyclotron. This beam is particularly important because it will be used for radiotherapy in the Catana project [2]. The development of this beam was particularly difficult. In fact the H_2^+ beam is produced by the ECR source together with many contaminants (ion beams like oxygen, nitrogen, etc.) having a Q/A ratio very close to 0.5. The injection line is not able to separate these contaminants, therefore the H_2^+ molecules are injected in the cyclotron together with them. Different beams are separated during acceleration, the H_2^+ beam arrives at the extraction radius alone, but it was difficult to follow the acceleration process of the H_2^+ beam because of the long range and the small thickness of the current probe, so the molecules broke in the probe, and the two protons escape, giving a negative current read-out. The scintillator of the probe helped very much to find the accelerated beam at the extraction radius, for which a big adjustment of the main field (1A on the alpha coil) was necessary. Extraction was accomplished with a voltage of 58 KV in the electrostatic deflectors, corresponding to an electric field of 116 KV/cm, the maximum reached value up to now.

The H_2^+ molecules accelerated to 62 MeV/amu are broken into two 62 MeV protons by a thin stripper foil placed in the beam line, close to the extraction point of the cyclotron.

5 CONCLUSION

In conclusion, the LNS Superconducting Cyclotron is now working in stand alone mode with axial injection. The replacement of the radial injection mode with the axial injection mode took approximately 4 months, including the commissioning, although many problems were encountered.

Advantages of the new operating mode have to be outlined:

- easier setting and tuning;
- higher beam stability in the transverse phase space;
- higher beam stability in the longitudinal phase space (timing).

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MICROSCOPIC INVESTIGATION OF BREAKDOWN MECHANISM ON THE ELECTROSTATIC DEFLECTORS

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Abstract

The Electrostatic Beam Deflectors for the K800 Superconducting Cyclotron are the most critical elements of the beam extraction system. Achieving their full performances and reliability is a crucial point for both: eye cancer therapy and exotic nuclei production. It has been carried out an accurate investigation from the microscopic point of view using the investigation techniques and methods of the material science. This study has lead to a better comprehension of the complex phenomena taking part in the breakdown process. The environmental conditions are high electric field (up to 130 kV/cm), high magnetic field (up to 5 T) in addition with high energy (70 MeV/u) and high power ion beam. It has been found that all the materials in the electrostatic deflector give a significant contribute to the mechanism of breakdown that occurs in two main ways: insulator surface conduction and enhanced electrodes electron emission. These two effects are involved in a feedback process which enhance the initial current absorption leading to a fast breakdown. Some solutions are at the moment under test using several bulk (Mo, Ti, Cu) and coating materials (TiN, Diamond Like Carbon, Al_2O_3).

1 INTRODUCTION

This study was carried out performing an accurate investigation from the microscopic point of view. on the electrostatic beam deflector for the K800 Superconducting Cyclotron (CS) at LNS. This have lead to a better comprehension of the complex phenomena tacking part in the breakdown process. The environmental conditions of high electric field, high magnetic field, in addition with high energy and high power of the accelerated beam, make this component peculiar in his behaviour when the voltage is applied at the cathodes. A cross-sectional view of the electrostatic deflector is shown in Fig. 1. Previous work were conducted in a test bench. It were found [1] that the dark current depends on the cathode material and its treatments. Present work has been carried out during the deflection of accelerated beams. It has been found that not only the cathode material plays an important role, but also the liner and the insulator materials give an important contribute to the breakdown mechanisms.

2 EXPERIMENTAL

The cathodes where in Titanium alloy (TiAl_6V_4) or in TiAl_6V_4 coated with 6-7 μm of Diamond Like Carbon (DLC), the liners where in Molybdenum or in oxygen free copper (Cu-OF), the insulators where in glazed Alumina (99.5%)

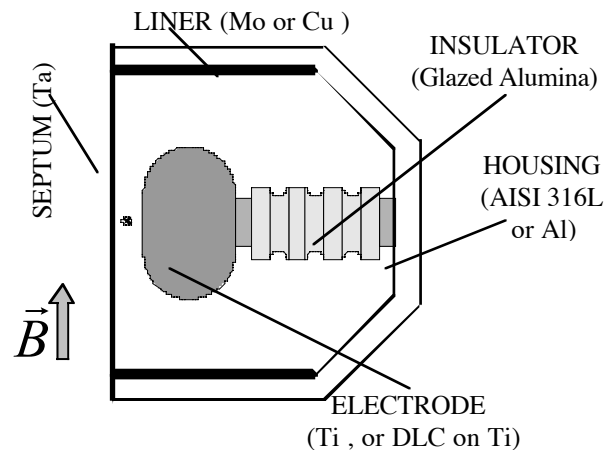


Figure 1: Cross Section of the Electrostatic Beam Deflector.

the septum was in Tantalum and the housing in Aluminium alloy or in stainless steel (AISI 316L). The alumina's glazing reduces surface outgassing, porosity and crystallographic defects which are responsible for the current leakage due to secondary electron avalanche emission [2]. The deflectors were tested during the normal operation of the CS, 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 magnetic field was 3.5 T. Deflectors breakdown occurs when the absorption current increases above 500 μA , leading to a voltage limitation by the power

supply. The experiments were performed using current-voltage analysis both in linear and in Fowler-Nordheim plots [3] to study the macroscopic effects of breakdown. Were performed also methods and techniques of the material science analysis, i.e. Rutherford Back Scattering (RBS) using a 1.7 MeV He^+ beam, X-Ray Fluorescence (XRF) using a 22.1 keV Cd source and Optical Microscopy.

3 OBSERVATION

The macroscopic effect of the breakdown is the electrode higher absorption current. In Fig. 2 are reported two current-voltage curves in linear

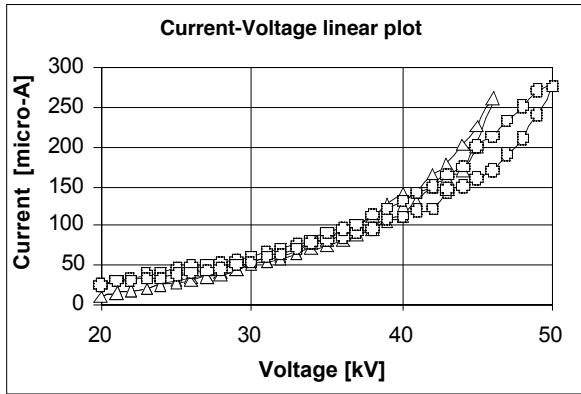


Figure 2: Current-Voltage linear plot of two different deflectors behaviour.

plot, they show quite the same quasi-exponential shape (circles and triangles), by comparing these same data in Fowler-Nordheim plots (Fig. 3: circles and Fig. 4 triangles) it has been found that different effects are involved in these two breakdown mechanisms. In Fig. 3 is reported the case of Field Electron Emission (FEE) plus other mechanism of current adsorption (conduction on insulator surface): data point are not aligned in a straight line. In Fig. 4 is reported the case of a deflector with enhanced FEE: the data points are quite aligned in a straight line.

After the breakdown the liners on their surface exhibit a high density of spot. RBS and XRF analyses on the liners show that these spots are re-solified liner material. This means that electrons emitted by the electrodes and impinging on his surface are able to locally increase the temperature above its melting point (2896 K for Mo).

The electrodes exhibit a metallic halo on their surface, XRF analysis, shown in Fig. 5, confirms that this is a thin Mo layer (in case of use with Mo liner).

The analyses performed on the insulators show that in many cases the breakdown occurs because

Figure 3: Current-Voltage Fowler-Nordheim plot of circles data from Fig. 2. This plot can put in evidence the FEE phenomenon (points aligned in a straight line shape). In this case the curve shape is not straight.

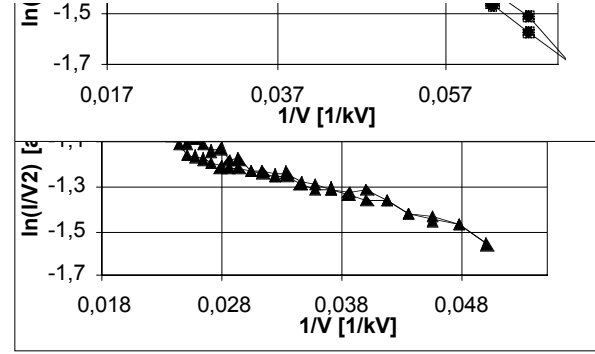


Figure 4: Current-Voltage Fowler-Nordheim plot of triangles data from Fig. 2. The curve shape is quite linear i.e. the current absorption is mainly due to FEE.

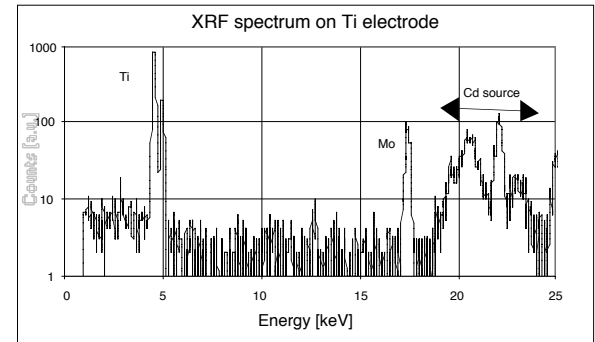
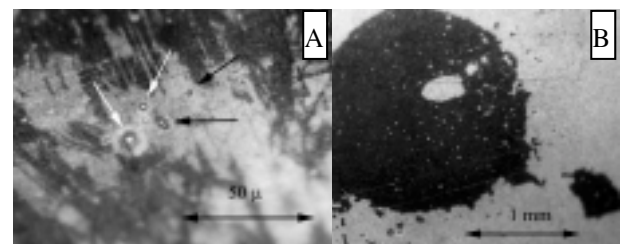


Figure 5: XRF spectrum on a Ti electrode, the metallic halo on its surface is Mo. This electrode was used with Mo liner.

of surface metalization. The RBS analyses performed on the insulators confirm that the metal on their surface is the same of the liner material.

From these observation it is clear a first mechanism of breakdown. The electrodes emit electrons that the magnetic field focuses in the liner, this locally melts and evaporates depositing a metallic layer on electrodes and insulators, then insulators starts to conduct on the surface and the current increase above the power supply limit (typical current-voltage plot: Fig. 3).

In some cases the typical current-voltage curve was quite a straight line, similar to that in Fig. 4, which is related to a strong FEE. Actually in these cases the optical microscopy and the RBS analyses performed on the insulator surface did not show any evidence of metallic conductive layer on their surface. In Fig. 6A and 6B are reported two observed optical microscopy of a DLC coated electrode surface used with Mo



liner. These analyses had put in evidence on the electrodes surface the presence of a metallic layer and a dense distribution of Mo micro-tips.

4 DISCUSSION

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 (Fig. 3), but there is at least an other one concerning the electrodes, in which the evaporated liner material forms high density of clusters (micro-tips, Fig. 6). These are responsible for the enhanced FEE (Fig. 4) caused by the increasing field factor in proximity of the micro-tips. By summarising we can say that the electrons emitted by the electrodes are able to locally melt the liner, which evaporates metalizing the insulators and the electrodes. Then insulators starts to conduct through the surface, this increase the temperature that enhance the FEE. At the same time the liner metal onto the electrodes forms clusters in which the electric field is increased, this enhance the FEE. A further evidence of this phenomenon is given to the fact that around the tips the surface is free of Mo (Fig. 6A), in fact the temperature around the tip increases because of the FEE, this enhance the surface mobility of the Mo around the tips, therefore Mo cluster or atoms are able to migrate and to coalesce together or to ripen into bigger cluster [4]. All these effects acting in synergy lead to a fast breakdown of the electrostatic deflector. One possible reason for tips formation is the surface tension ' γ ', i.e. the energy spent to create a surface. In general a material with a lower γ try to uniformly cover another one with higher γ . In the opposite case this will forms clusters. Mo has the highest γ value ($\sim 2.3 \text{ J m}^{-2}$) compared with Ti and Cu (~ 1.7 and $\sim 1.4 \text{ J m}^{-2}$ respectively) i.e. it will easily forms tips on other materials. This suggests that Cu from Cu-OF liner on Ti electrodes should not forms tips.

5 CONCLUSIONS

The Electrode should be made by a material with a low primary and secondary electron emission in order to reduce the FEE: like DLC or TiN, or in alternative by a material with high γ value (Ti, Pt, Mo or Re) used also as coating materials. The liner should have high melting point, high thermal conductivity and low γ value with respect to the electrode material, i.e. Cu, Ti,

Au. The insulator should be glazed and have high thermal conductivity, i.e. BeO or AlN.

These materials are at the moment under study and test; further investigation is needed to increase the deflector performances.

4 ACKNOWLEDGEMENTS

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ION SOURCES R&D

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Abstract

During 2000 different R&D activities have been carried out at LNS and the most significant are summarized in the following. These activities include the design and the construction of a high intensity proton source for the TRASCO project and the development of new techniques to improve the performances of ECR ion source either for charge state and for beam intensity (higher frequency, electron donors).

1 TRIPS

The TRASCO Project is a R&D program which goal is the design of an Accelerator Driving System for nuclear waste transmutation. The high current cw proton linear accelerator will drive a subcritical system to transmute nuclear wastes. LNS is in charge of the proton source design and construction.

The proton source TRIPS is based on the principle of microwave discharge and it is optimized to produce a minimum proton current of 35 mA at the RFQ entrance, with a rms normalized emittance lower than $0.2\pi\cdot\text{mm}\cdot\text{mrad}$ for an operating voltage of 80 kV.

The design of TRIPS is described in [1] and it is shown in figure 1. The microwave power from a 2.45 GHz - 2 kW magnetron is coupled to the cylindrical water cooled OFHC copper plasma chamber (100 mm long and 90 mm in diameter) through a circulator, a four stub automatic tuning unit and a maximally flat matching transformer. A microwave pressure window is placed behind a water-cooled bend in order to avoid any damage due to the back-streaming electrons.

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. The design have been aimed to simplify the maintenance especially in the extraction zone.

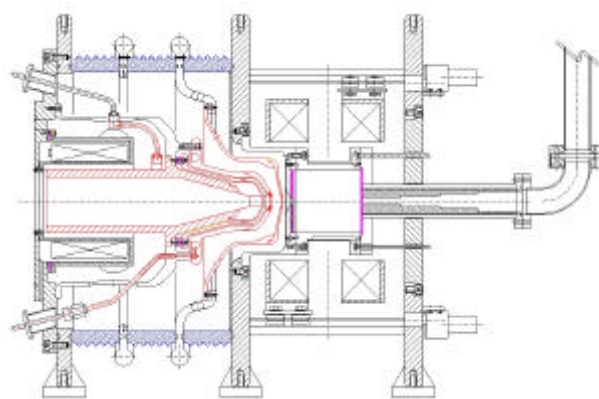


Figure 1: The TRIPS ion source

Fig. 2 shows the source placed on the 100 kV high voltage platform and fig. 3 shows the first section of the low energy beam transfer line (LEBT) devoted to the beam analysis and characterization. The LEBT line consists of a first current transformer (DCCT1), a solenoid to provide the beam focusing, a four sector ring to measure beam misalignments and inhomogeneities, a second current transformer (DCCT2) and a 10 kW beam stop to measure the proton beam current.

The first operations of TRIPS have been performed at an extraction voltage of 65 kV (instead of 80 kV requested) and with an extraction aperture of 4.6 mm (instead of 8 mm as in the design), in order to work at relatively low currents to verify the functionality of all the ancillary equipment and to find the optimum parameters of the source. In this configuration a proton beam of 20 mA can be routinely generated (the Child-Langmuir limit for the current configuration is about 24 mA) and then

transported through the LEBT line with high transmission. Typically more than 90% of the HV drain current is detected by DCCT2 and the same current is measured by the beam stop. The beamline transmission is almost 100% and the proton fraction is anyhow above 90% if the discharge power exceeds 300 W.

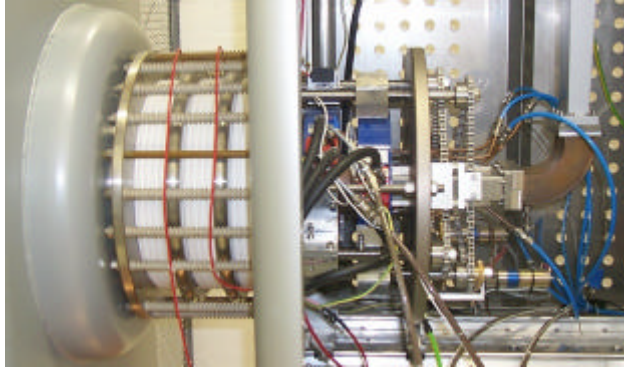


Figure 2: The TRIPS ion source on the 100 kV platform

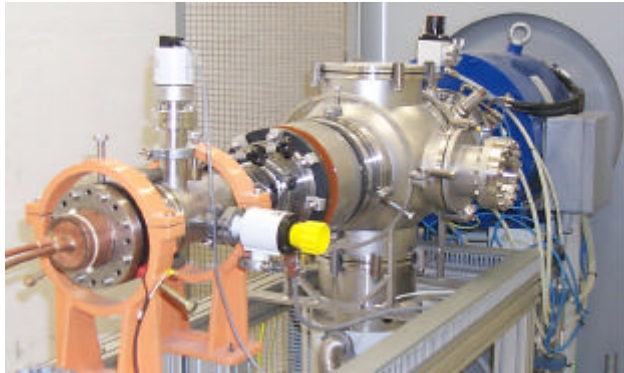


Figure 3: The LEBT line.

2 OPERATION OF THE SERSE ECR ION SOURCE AT 28 GHZ

The design and operation of the SERSE source at 14 and 18 GHz has been described in previous papers [2,3]. Because of its high magnetic field, this source has been able to operate at 28 GHz. High frequency operation is expected to produce a higher plasma density and higher currents of multiply charged ions.

Very encouraging results have been obtained indeed, which are promising for the next generation of superconducting high frequency ECR Ion Sources.

At first, an original transmission and coupling of the microwaves to SERSE has been designed (fig. 4). The microwaves were emitted from a 10 kW-28 GHz gyrotron through a circular

wave guide (TE_{02} mode). Then some components were added to protect the gyrotron from any reverse power (arc detector, mode filter) and a mode converter is used to transform the microwaves from TE_{02} to TE_{01} mode to reduce the losses. Just before the source, a 30 kV dc break has been installed and a mechanical compensator was used to prevent from any thermal expansion. The rf window was placed at the entrance of the plasma chamber.

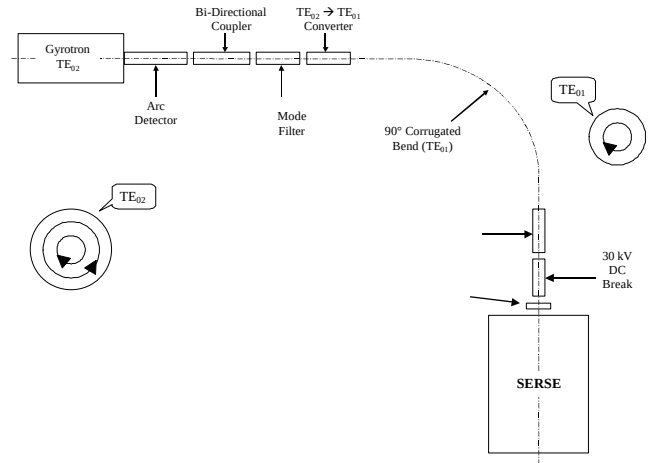


Figure 4: 28 GHz transmission line

When 10 kW were extracted from the gyrotron, the losses in the 8 m long rf line are were 400-500 W, most of them (300 W) being in the mode filter. Typically less than 2% of the rf power was reflected. The positive results are relevant because it was the first time that a coupling with a TE_{01} mode, which is not linearly polarized, is performed with an ECRIS; the low level of reverse power have shown that there is always a zone in the source where an efficient energy transfer takes place.

The main goal of this experiment was the study of the production of medium charge states. Xenon species has been chosen for our tests. As usual, oxygen was used as a mixer to enhance the performances. At 28 GHz, the resonance magnetic field value being 1 T, the magnetic configuration of the source was no longer in high-B mode because of the magnetic limits of SERSE. This means that the condition $B_{\max}/B_{\text{resonance}} = 2$ is not maintained completely around the resonance zone. It has been observed that higher axial and radial magnetic fields

would be suitable to enhance the performances of the source for any charge states. [4,5]

About 3 kW were necessary for the optimization of the medium charge states. Higher power led to cooling problems and high outgassing of the plasma chamber. However, despite these drawbacks, more than 0.3 emA of Xe^{20+} have easily been extracted, with a maximum of 0.4 emA and even more in afterglow mode. With more than 6 kW, we have extracted more than 0.5 emA of Xe^{20+} and Xe^{25+} . Higher charge states of Xenon, up to 42^+ , were obtained at 1 μA level, but their optimization could not be completed (the experiment lasted about 5 weeks in total). Figure 4 shows the intensities of Xenon ions for SERSE and other ECRIS.

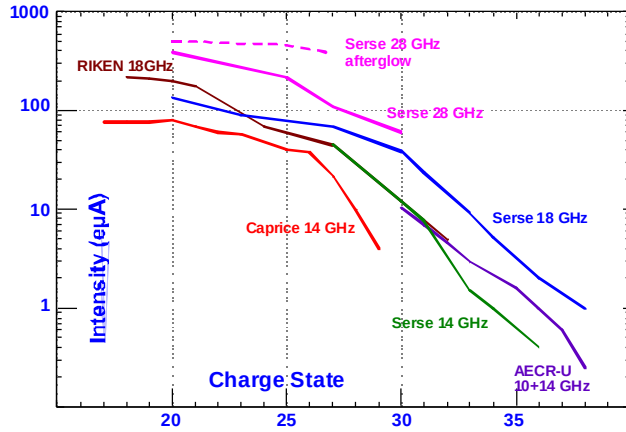


Figure 4: Extracted Intensities of Xenon ions for Serse at different frequencies and for other ECRIS

The complete description of the test of SERSE at 28 GHz is given in [4,5].

With the optimization of the source magnetic configuration, of the extraction system and of the beam transport, 1 emA of Xe^{20-25+} or Pb^{27+} will be certainly obtained with the third generation superconducting ECRIS. The design of such a source was carried out recently and it is described in [6]. The design of the "GyroSERSE" source is now almost complete and its construction may begin in 2001.

3 ELECTRON DONORS IN PLASMAS

The effectiveness of the electron donors in plasma has been studied since ten years. A new approach was studied in collaboration with a team of University of Milan, which consisted of

the insertion of ferroelectrics cathodes inside the ECR source chamber. The CAESAR source has been chosen for the test because of its simple layout which simplifies any kind of test and of its magnetic field lower than that of SERSE, so that the ECR plasma electron deficit is more pronounced. The experimental setup is shown in fig. 5: the ferroelectric cathode held by the long thin support of the bias disk was inserted into the injection channel. The cathode was set for most of the experiment at a potential of -150 V, so as to take advantage of the positive effect of the bias on the plasma yield and stability. Taking into account that the plasma charges up positively to about 100 V, the potential difference between cathode and anode was about 250 V.

The high voltage power supply and the bipolar pulse generator, which produces the HV pulse sequence, were installed in a Faraday cage placed on top of the CAESAR source.

The extracted ions with a kinetic energy equal to 20 keV per charge state were focused by a solenoid and deflected by a 90° dipole magnet, to be analyzed with a Faraday cup located at its image point.

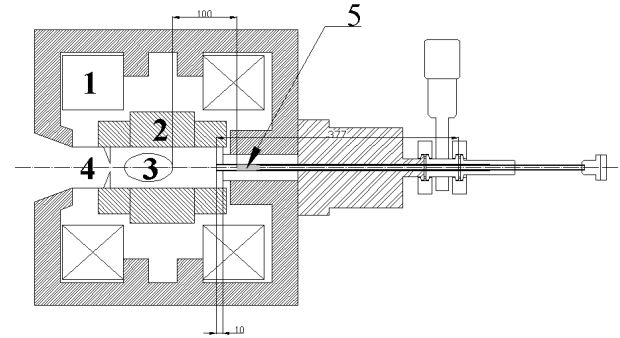


Fig. 5: Basic test setup with ECR ion source chamber, (1) the coils, (2) the hexapole, (3) the ECR plasma surface, (4) the extractor and (5) the ferroelectric cathode.

During the test, the plasma was run in dc mode and the ferroelectric cathode was pulsed at a repetition rate from 1 to 500 Hz. Due to their short lifetime, each ferroelectric cathode has been used for about 15 minutes before the performance degraded.

Figure 6 shows the Ar^{8+} current as a function of the RF heating power. Without electron injection, the ion current increases with the RF power but tends to saturate. The injection of

electrons seems to avoid such saturation and 30% higher ion currents are produced at the RF power of 400 W (which is the optimum power for Ar^{8+}). Such behaviour is physically reasonable: the higher is the RF power level, the higher are the velocities to which the electrons are accelerated by the RF field and the more electrons are lost from the outer plasma shell to the walls of the plasma chamber. Restoring the charge equilibrium of the plasma must inevitably increase the ion current yield. At lower power levels the electron loss from the plasma seems to be negligible and the amount of injected electrons is too small to significantly increase the ECR yield.

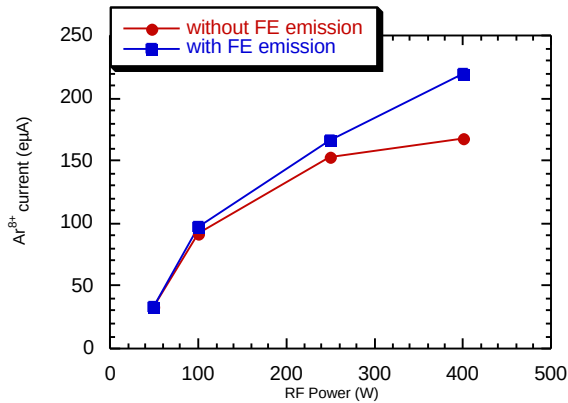


Fig. 6: Ar^{8+} ion current as function of RF power with and without pulsing of the PBZT cathode at 250 Hz driven with bipolar HV pulses of 1.6 kV amplitude.

A second significant result was the increase of the stability of the ECR source. The electron injection also improved the magneto-hydrodynamic stability of the ECR source; as observed on the oscilloscope signal of the Faraday cup, the beam ripple decreased by a factor two or three.

More measurements have been also taken, by measuring the Ar^{8+} current as a function of the distance cathode-plasma surface (20 cm, 10 cm, 4 cm) and of the cathode repetition rate (50, 100, 250 and 500 Hz). The optimum distance is a compromise between the solid angle maximization and the need to be away from the plasma. The distance of 100 mm appeared to be the most convenient. The dependence on the cathode repetition rate is evidently linked to the build-up time of the Ar^{8+} inside the plasma. The optimum occurred for 250 Hz, which means that

4 ms is the average build-up time for such a charge state. [7]

5 ACKNOWLEDGMENTS

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PLASMA PRODUCTION BY LASER ION SOURCE AT THE INFN-LNS OF CATANIA

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Abstract

A Nd:Yag pulsed laser is employed to produce ablation of metallic targets in vacuum. The laser pulse is 9 ns duration and the power density is of the order of 10^{10} W/cm². The ablation produces an intense plasma at the target surface with a temperature of the order of 10^7 K, a fractional ionization up to about 50% and a maximum charge state of about 10. Results are presented mainly for irradiation of heavy metals, which are the most interesting for the ECLISSE project.

1 Introduction

A hybrid ion source consisting of a Laser Ion Source (LIS) and of an ECR ion source is under study at the INFN-LNS, in the framework of the ECLISSE experiment founded by the INFN Fifth Committee [1]. LIS gives intense currents of electrons and of multiply charged ions ($q/m = 1/10$ or lower). The optimum energy of ions from the LIS, which is a crucial parameter for the coupling to the ECR, was estimated on the base of calculations by Shirkov to be of the order of hundreds of eV [2]. This work presents results of studies performed at LNS on the ion composition of different plasmas produced by IR laser. The main goal was to measure the charge-energy distribution of emitted ions from the plasma of heavy metals, such as Ta, W, Au and Pb.

2 Experimental section

The Nd:Yag laser Spectra Physics Quanta Ray LAB-190 was used in the performed experiments. Main nominal parameters are 0.9 mJ/9 ns in a single pulse regime. The maximum laser energy was about 300 mJ and it was measured by a high sensible calorimeter (NOVA laser power/energy monitor and 3A-P-CAL head). This instrument detects the light fraction (10%) reflected from a beam splitter placed along the laser path. A lens with focus length 50 cm was used in all presented experiments.

Minimum spot diameter was estimated to be about 0.5 mm.

The metal targets were irradiated in a vacuum chamber with many input/output windows. The output windows were chosen at angles of 17° , 30° , 43° and 56° (IC₁₋₄) with regards to the input window. The system was pumped by a 300 l/s turbo-molecular pump to the standard vacuum lower than 7×10^{-7} torr.

Three ion collectors (ICs) and a cylindrical electrostatic ion energy analyzer (IEA) were used, with a time of flight (TOF) configuration, for ion diagnostics during experiments. A grid placed in front of the ICs permits to suppress the secondary electron emission. The grid transmission is 58%. IEA has a bending radius of $R_0 = 10$ cm, the deflection angle $\psi = 90^\circ$ and the gap between the cylindrical electrodes of the analyzing capacitor is $\Delta R = 1$ cm. A windowless electron multiplier (WEM), EM 226 from Thorn EMI, was used as an ion detector behind the IEA. The path of ion flight was 155 cm for IEA in all experiments, and varied from 43 cm for IC₃ up to 95 cm for IC₁. Quadruple mass analyzer Quadstar 421 served for registration of the gas composition in the target chamber during the experiment and to detect the ejected atoms from the irradiated target. More details about the experimental set-up are given in previous papers [3, 4]. Fig. 1a shows a scheme of the experimental apparatus and Fig. 1b a scheme of the ion energy analyzer (IEA).

3 Results

Measurements of fluence threshold and of metal etching for different Z-targets, as a function of the laser fluence, have been given in a previously paper [5]. Also measurements of angular distribution of emitted ions and emitted neutrals, as a function of the laser fluence and of the Z-target, have been reported in a previously paper [6]. The emission is strongly peaked along the normal to the target surface.

The ion energy analyzer IEA was mounted to the chamber at the angle of 43° . Considering the target tilt angle was 43° , the ion composition measurements were performed in the direction of the normal to the target. The ion composition of laser plasma produced on Ta, W, Au and Pb targets was measured at the threshold laser energy $E_L \sim 40$ mJ (low fluence) and at the maximum laser energy $E_L \sim 300$ mJ (high fluence) at the 57 cm in front of the target. The voltage used on IEA ($\pm U/2$) varied from a few volts to several hundreds volts, which made possible to register ions with the kinetic energy-to-charge ratio from several tens of eV up to about $E_i/q \sim 10$ keV.

3.1 Ta ions

Ions up to Ta^{5+} were registered at low fluence (30 mJ) and up to Ta^{8+} at the highest fluence (310 mJ).

Approximate mean ion velocities $\langle v \rangle$ and mean ion energies $\langle E_i \rangle$, calculated from maximum of IC signals, were about 2.0×10^6 cm/s and 0.40 keV at low fluence (normal direction), about 3.6×10^6 cm/s and 1.2 keV at highest fluence. The ion composition of Ta laser plasma is presented in Fig. 2, charge energy distribution in Fig. 3a (low fluence) and Fig. 4a (high fluence). An abundance of about 45% and 25% of ions with charge state $1+$ was measured at low and high fluence, respectively. With increasing E_L the amount of the ions at high charge state increases from $5+$ (low fluence) up to $8+$ (high fluence).

The maximum plasma temperature associated to the mean ion velocity is 9.3×10^6 iK.

3.2 W ions

Ions up to W^{6+} were detected at low fluence (40 mJ) and up to W^{9+} at the high fluence (310 mJ).

Approximate mean ion velocities $\langle v \rangle$ and mean ion energies $\langle E_i \rangle$ calculated from maximum of IC signals were about 2.2×10^6 cm/s and 1.0 keV in the first case (low fluence), and about 4.1×10^6 cm/s and 1.6 keV at high fluence. Ion composition of W laser plasma is seen in Fig. 2, charge energy distribution in Fig. 3b and Fig. 4b). An abundance of about 50% and 24% of ions with charge state $1+$ was measured at low and high fluence, respectively. With increasing E_L the amount of the ions at high charge state increases from $6+$ (low fluence) up to $9+$ (high fluence).

The maximum plasma temperature associated to the mean ion velocity is 1.2×10^7 iK.

3.3 Au ions

Ions up to Au^{6+} were registered at low fluence (40 mJ) and up to Au^{10+} at the highest fluence (280 mJ).

Approximate mean ion velocities $\langle v \rangle$ and mean ion energies $\langle E_i \rangle$, calculated from maximum of IC signals, were about 1.9×10^6 cm/s and 0.37 keV at low fluence, and about 3.3×10^6 cm/s and 1.1 keV at highest fluence (both in normal direction). Ion composition of Au laser plasma is presented in Fig. 2, charge energy distribution in Fig. 3c and Fig. 4c. An abundance of about 55% and 50% of ions with charge state $1+$ was measured at low and high fluence, respectively. With increasing E_L the amount of the ions at high charge state increases from $6+$ (low fluence) up to $10+$ (high fluence).

The maximum plasma temperature associated to the mean ion velocity is 8.5×10^6 iK.

3.4 Pb ions

Ions up to Pb^{4+} were registered at threshold energies (40 mJ) and up to Pb^{9+} at the highest energies (290 mJ).

Approximate mean ion velocities $\langle v \rangle$ and mean ion energies $\langle E_i \rangle$ calculated from maximum of IC signals were about 1.8×10^6 cm/s and 0.33 keV in the first case, about 2.6×10^6 cm/s and 0.75 keV in the second one. Ion composition of Pb laser plasma is shown in Fig. 2, charge energy distribution in Fig. 3d and Fig. 4d. An abundance of about 52% and 24% of ions with charge state $1+$ was measured at low and high fluence, respectively. With increasing E_L the amount of the ions at high charge state increases from $4+$ (low fluence) up to $9+$ (high fluence). The maximum plasma temperature associated to the mean ion velocity is 5.8×10^6 K.

4 Discussion and Conclusions

Ions with maximum charge state between $8+$ and $10+$ were registered among those emitted from the Nd:Yag laser produced plasma of different heavy elements (Ta, W, Au and Pb) at laser power densities $\sim 1 \times 10^{10}$ W/cm² or lower. More than 70 % of ions are of the charge state lower than $4+$ for all tested elements. The ICs ion current density at the distance of 20 cm from the target depends on the kind of target, as well as on the experimental conditions used (laser energy, laser power density, diameter of the focal spot). Its value is above ~ 100 mA/cm², higher for lower-Z elements (measurements have performed also on Al, Ti, Ni, Cu, Nb and Sn targets) and lower for high-Z elements. For heavy elements the mean velocity of ions, emitted perpendicularly to the target at energies ~ 300 mJ, ranged from 1.8×10^6 cm/s (Pb) to 4.1×10^6 cm/s (W), corresponding mean ion energies from ~ 330 eV (Pb) to 1.6 keV (W). Angular distribution of emitted ions is not isotropic but direct mainly along the normal to the target surface [6].

Generally, three ion groups (thermal, fast, slow), besides that of impurities, may be emitted from the laser produced plasma [7]. The main one corresponds to the thermal ions, the second (slow) one appears due to reabsorbed x-rays outside the laser focus, the third one (fast) is ascribed to the presence of over-thermal (hot) electrons. The IC

signals from them may overlap each other and create more or less pronounced maximum, the position of which and their amplitude may reflect the mechanism of the ion production, depending on the laser power density and beam quality. Increasing the laser power density, the higher ion energy and charge state are produced. The highest power density supposes the smallest size of the focal spot at a given laser power, which, in turn, does not mean the highest number of produced ions. This is due to the nonlinear effect of laser beam focus position on ion generation. Depending on the laser power density it is possible to generate a smaller amount of higher energy ions or a larger amount of low energy ions.

At high laser energy the plasma temperature is of the order of 10^7 K, as presented in a previously paper [8]. Comparing the neutral emission with the ionic emission, the fractional ionization of the plasma has been calculated. It increases with the laser pulse energy and, at high laser fluence, it may reach about 50 % [4].

In order to inject ions in ECR ion source a ion deceleration at about 200-300 eV is need [2]. In this direction work is in progress.

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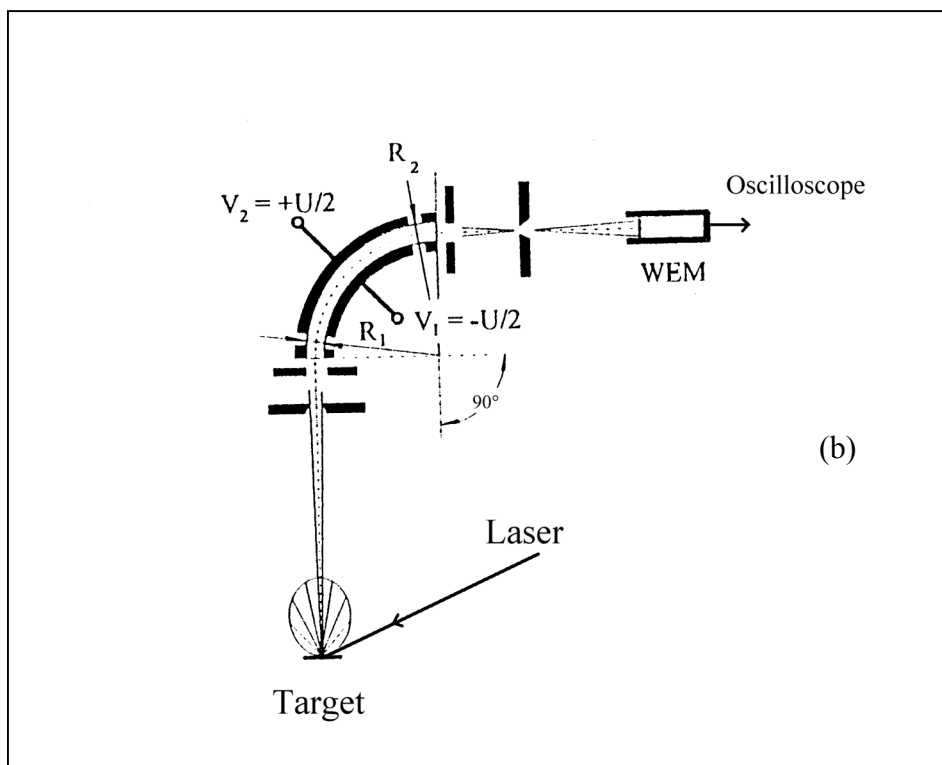
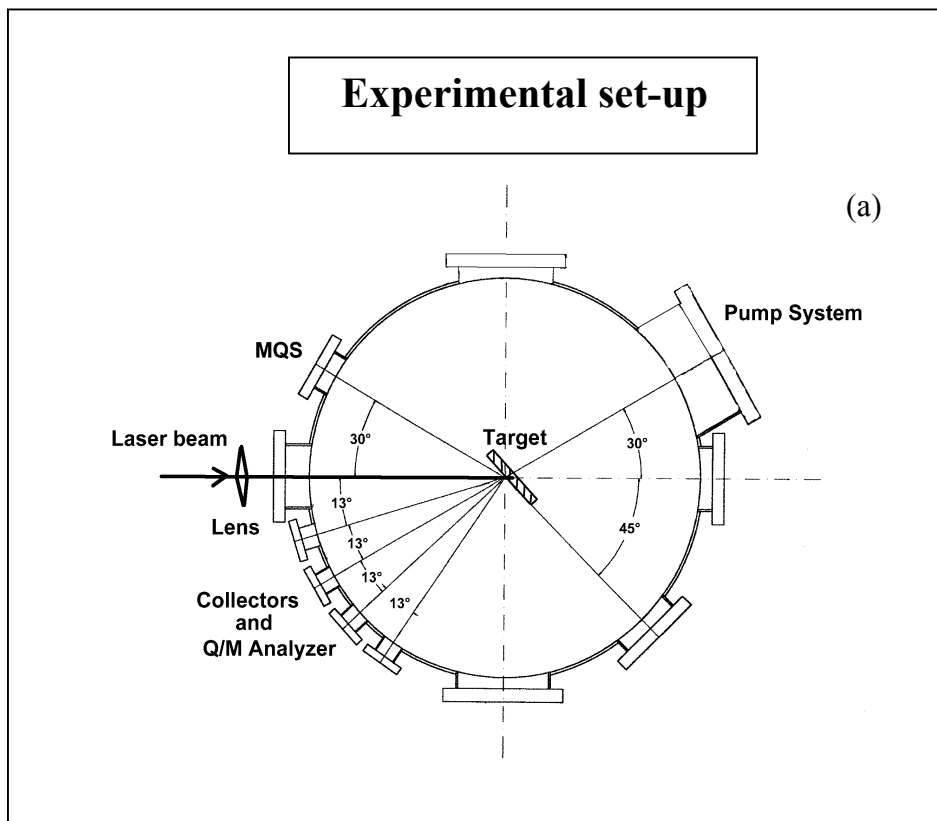


Fig. 1: Scheme of the experimental apparatus at the INFN-LNS of Catania (a) and of the ion energy analyzer (IEA) (b).

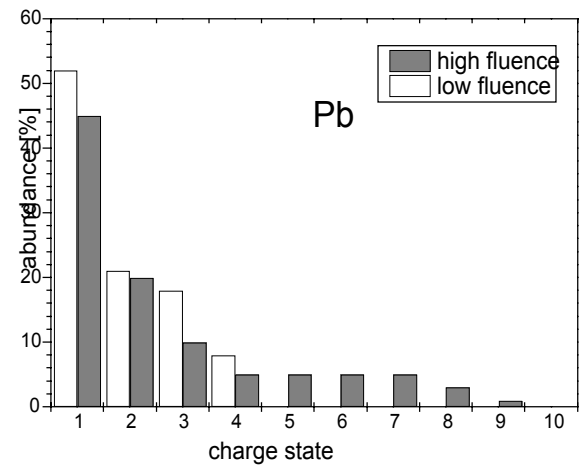
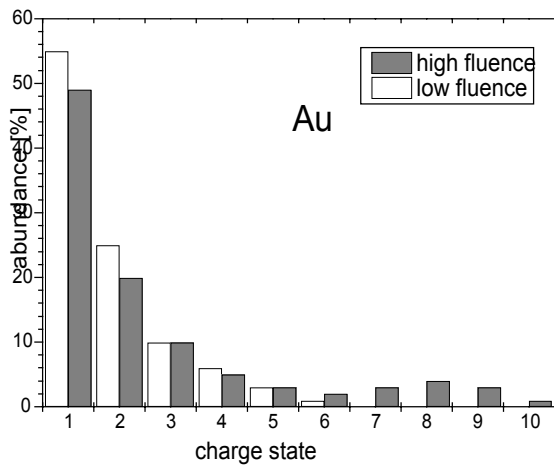
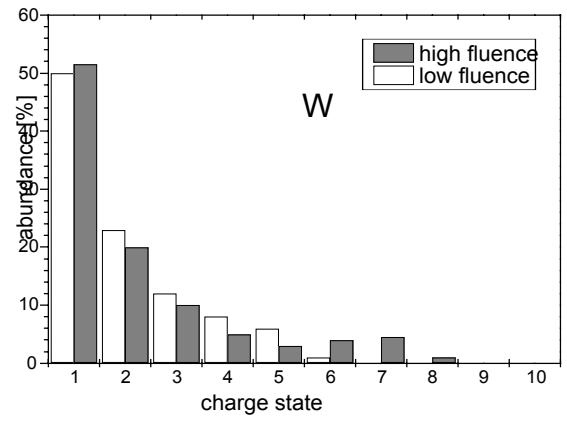
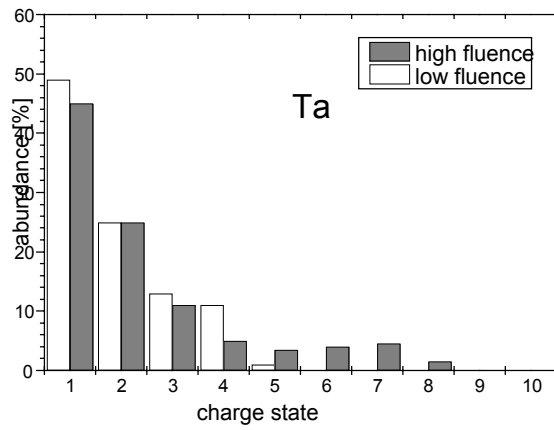


Fig. 2: Charge state and ion production at low and at high laser fluence for Ta, W, Au and Pb.

Low fluence

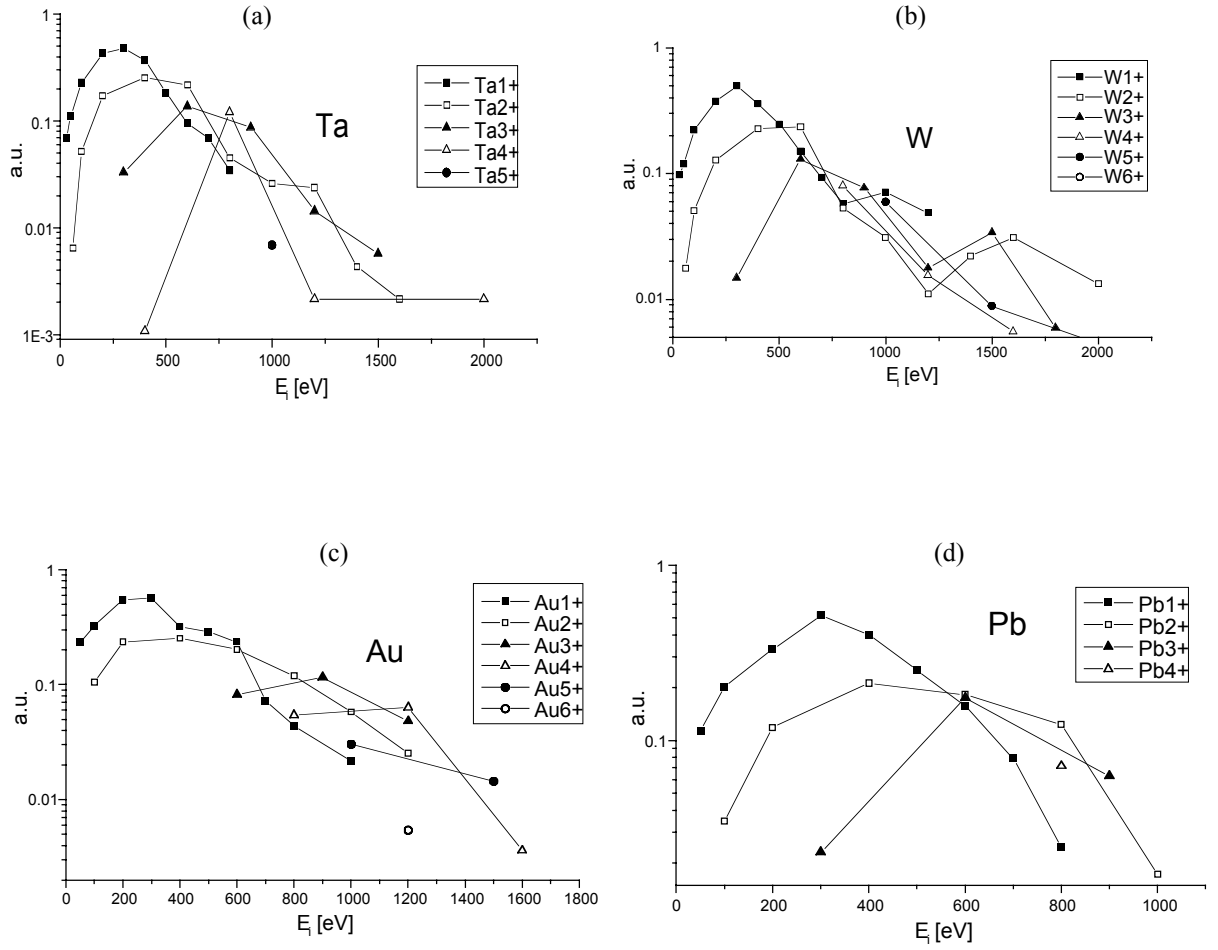


Fig. 3: Ion energy distribution for Ta (a), W (b), Au (c) and Pb (d) at low laser fluence.

High fluence

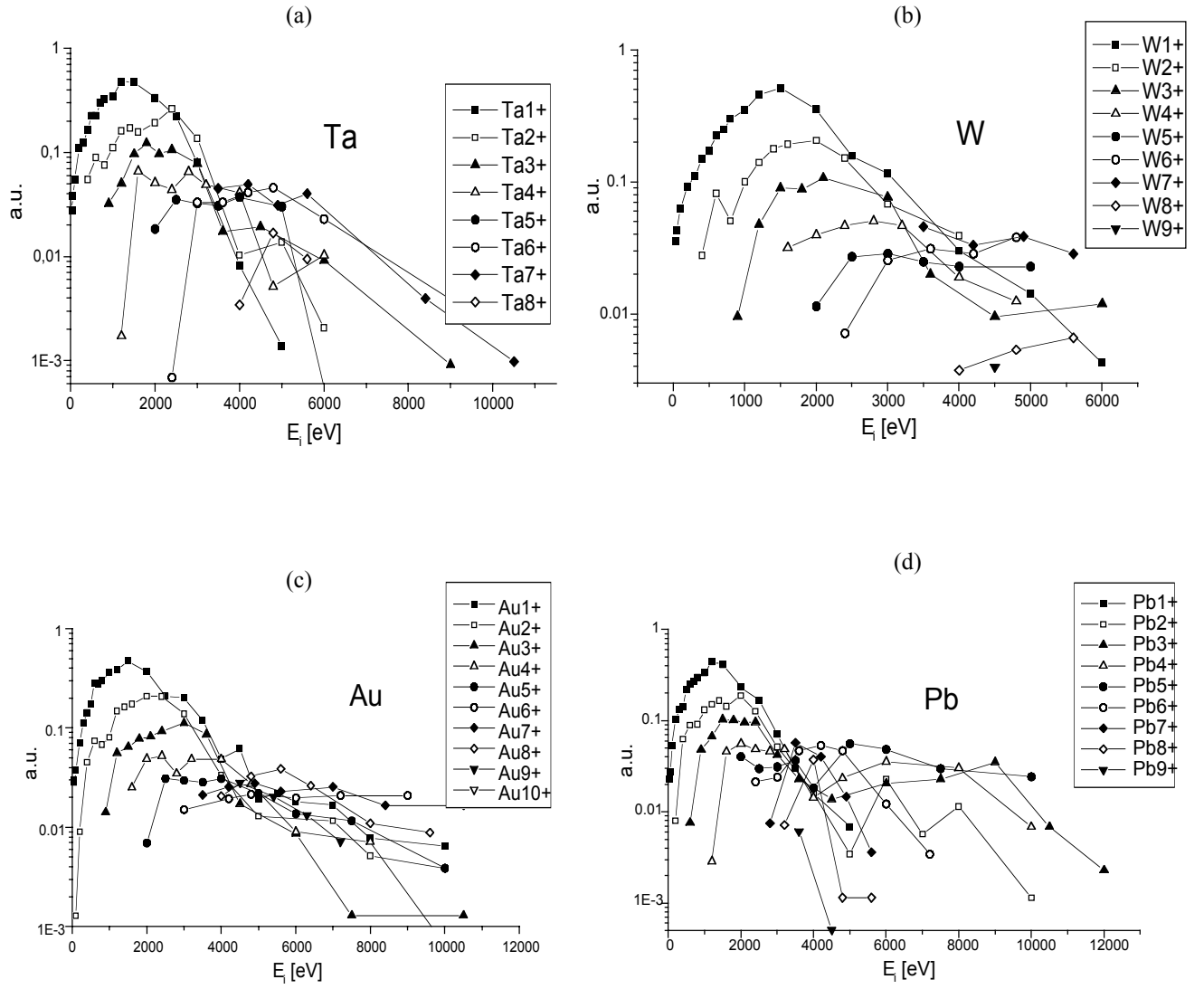


Fig. 4: Ion energy distribution for Ta (a), W(b), Au (c) and Pb (d) at high laser fluence.

CATANA

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Abstract

The CATANA project (Centro di AdroTerapia e Applicazioni Nucleari Avanzate) is developed at Laboratori Nazionali del Sud-INFN in collaboration with Physics Department, Ophtalmology Institute and Radiology Institute of the Catania University. The main goal of CATANA is the development of a facility for the treatment of ocular tumors with 62 AMeV proton beams.

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 MeV proton beams from a Superconducting Cyclotron [1]. 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 exits 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 (25 mm is our goal), minimizing the energy loose.

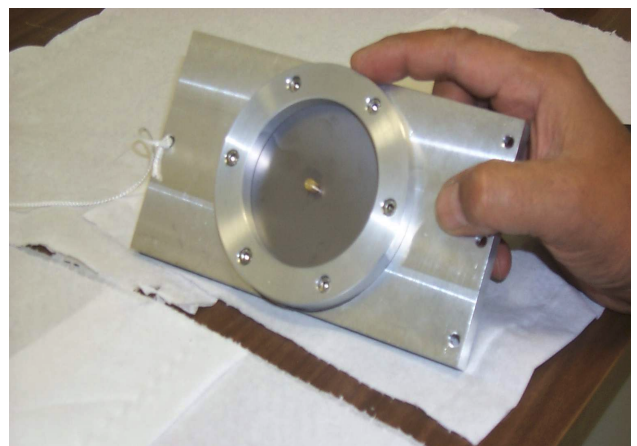


Figure 2. The second tantalum scattering foil with the central stopper.

Range shifter and *range modulator* are placed downstream the scattering system and mounted on two different boxes. 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* [2], implemented to have an on-line control of the dose furnished to the patients and an information on beam symmetry respectively.

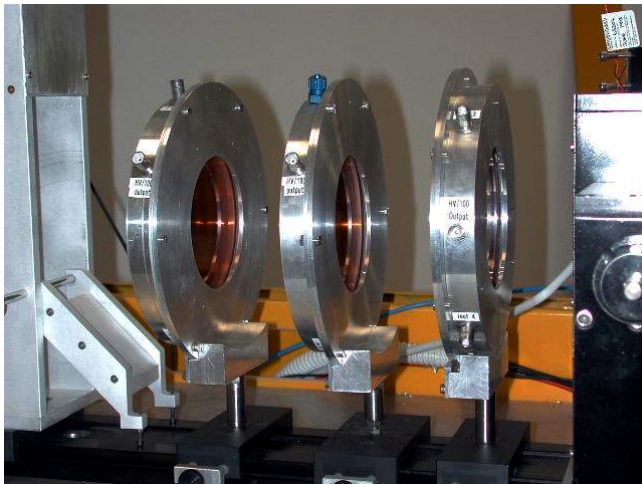


Figure 3. A view of the two monitor chambers and four sectors chambers.

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. 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 [3]. 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 4 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 MeV.

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.

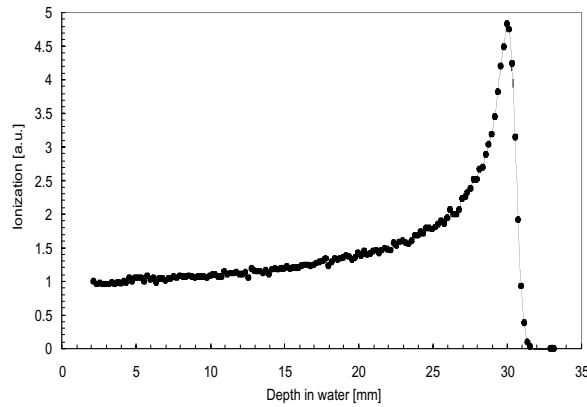


Figure 4. Bragg peak of 62 MeV proton Beam acquired with a water-tank system and a Markus chamber ionization chamber at CATANA facility.

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 MeV to 10 MeV, were acquired with the Markus chamber in a water phantom (Figure 5).

Finally Figure 6 shows the Spread Out Bragg Peak obtained with the first prototypes of the modulator wheel realized.

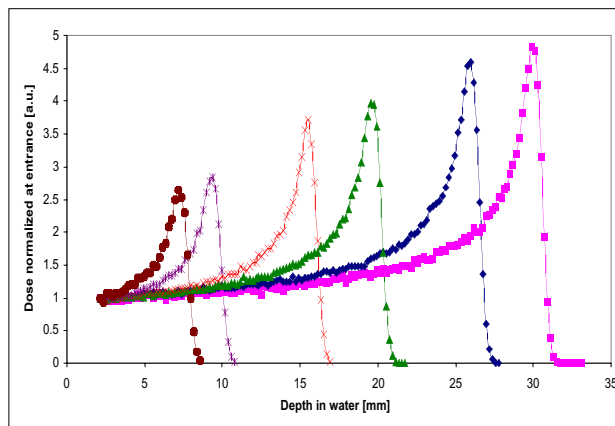


Figure 5. Various Bragg peaks for different energies of the proton acquired in water with the Markus chamber.

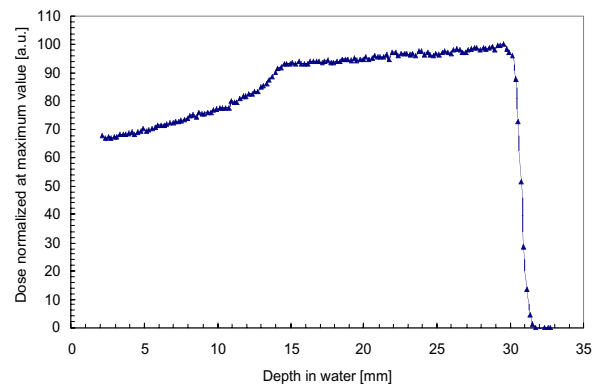


Figure 6. Spread Out Bragg Peak obtained with a modulator wheel, in water and with the Markus chamber.

In this condition we were able to carry out the first dosimetric characterizations of the therapeutic proton beam with different dosimeter systems.

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ELECTRON SCREENING STUDIED BY MEANS OF THE TROJAN HORSE METHOD

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Abstract

The ${}^6\text{Li}(d,\alpha){}^4\text{He}$ and the ${}^7\text{Li}(p,\alpha){}^4\text{He}$ reaction have been studied by means of the Trojan Horse Method (THM). The bare nucleus astrophysical factor was thus extracted using a new theoretical description, based on the DWBA approach. This allows us to have an independent measure of the electron screening U_e for both reactions. The results are compared with direct experimental data and with the adiabatic calculation.

1 INTRODUCTION

The experimental measurement of cross sections of astrophysical interest has allowed a better understanding of many astrophysical processes. The energies which characterize the nuclear processes in the astrophysical context are so low that the presence of atomic electrons must be taken into account. Their effect is usually referred to as *electron screening* [1].

However the different physical conditions make electron shielding in the stellar plasma and in the laboratory completely different. Nevertheless a complete understanding of the screening in the laboratory can help to describe the effect of electron shielding in stellar plasma. In both cases such effect leads to an exponential increase of $\sigma(E)$ (or equivalently of $S(E)$) with decreasing energy when compared to the case of bare nuclides. This can be described, for the laboratory case, by an enhancement factor

$$f_{\text{lab}}(E) = \sigma(E) / \sigma_b(E) = \exp(\pi\eta U_e / E) \quad (1)$$

where $\sigma(E)$ and $\sigma_b(E)$ refer to the cross sections of electron-shielded and bare nuclei respectively, and U_e is the electron screening potential energy.

In order to give useful inputs to astrophysics a precise knowledge of the bare nucleus cross section must be available. Due to the impossibility of directly measuring the bare nucleus factor, extrapolations are generally used in order to obtain the bare cross section.

The THM [2] was suggested as a complementary and independent method to evaluate the bare nucleus cross section and therefore the electron screening potential. This method has been now applied to the ${}^6\text{Li}(d,\alpha){}^4\text{He}$ and the ${}^7\text{Li}(p,\alpha){}^4\text{He}$ reactions which are important for the so-called “Lithium problem”.

The basic assumptions of the THM have already been discussed extensively elsewhere [2,3] and in the previous contribution to this report.

2 THE ${}^6\text{Li}(d,\alpha){}^4\text{He}$ REACTION

The bare nucleus cross section of the ${}^6\text{Li}(d,\alpha){}^4\text{He}$ reaction has been studied via the ${}^6\text{Li}({}^6\text{Li},\alpha\alpha){}^4\text{He}$. The symmetry of the entrance channel allows to consider alternatively either the α -cluster in the target or in the projectile as spectator of the two-body reaction. So in principle two similar quasi-free processes may occur.

The experiment [3] was performed using the EN Tandem Van de Graaff accelerator at the Institut Rudjer Boskovic in Zagreb. A ${}^6\text{Li}$ beam ($E=6$ MeV) was used to bombard an isotopically enriched lithium oxide target, ($125 \mu\text{g}/\text{cm}^2$ thick). The outgoing α particles were detected in coincidence by three position sensitive detectors (PSD) mounted in co-planar geometry. They were centered at the quasi-free angles ($\theta_1=60^\circ$, $\theta_2=73^\circ$ $\theta_3=-103^\circ$ with respect to the beam axis) and covered an angular range $\Delta\theta=14^\circ$. Each PSD had a geometrical acceptance of about $50\times 10 \text{ mm}^2$ and offered an angular resolution of 0.2° . During all measurements, the target thickness was continuously monitored by observing the elastic scattering peak with a Si-detector, positioned at $\theta=40^\circ$.

In figure 1 we plot the kinematical locus of the ${}^6\text{Li} + {}^6\text{Li} \rightarrow \alpha + \alpha + \alpha$ reaction together with the appropriate graphical cut. The picture shows how this locus can be easily discriminated from other reaction channels.

After identifying the quasi-free contribution to the α - α final channel [3], we have extracted the triple differential cross section for events corresponding to spectator momentum $p_s < 35 \text{ MeV}/c$.

In the framework of the distorted-wave impulse approximation (DWIA) the three-body cross section can be written in the form [3,4]

$$\frac{d^3\sigma}{dE_{\alpha 1} d\Omega_{\alpha 1} d\Omega_{\alpha 2}} \propto \text{KF} |W(Q_{(\alpha\alpha)\alpha})|^2 \frac{v_{12}}{v_{\text{Li-d}}} \frac{\exp(-2\pi\eta)}{E P_0(k_{\text{Li-d}}R)} \left(\frac{d\sigma}{d\Omega} \right)_{\text{Li+d}}^{\alpha} \quad (2)$$

where KF is a kinematic factor, $|W(Q_{(\alpha\alpha)\alpha})|^2$ is the relative momentum distribution, P_0 is the penetration factor for $l=0$, v_{12} and $v_{\text{Li-d}}$ the α - α and ${}^6\text{Li}$ -d relative velocities respectively. $d\sigma/d\Omega$ is the cross section of the virtual reaction

${}^6\text{Li}(d,\alpha){}^4\text{He}$. As regards the momentum distribution we adopted the function

$$|\Phi_{\text{Li}}(p_s)|^2 = \frac{e^{-x}}{1+x}$$

with $x=p_s^2/3555 \text{ fm}^{-2}$, p_s being the α spectator momentum in ${}^6\text{Li}$ [5].

In this way it is possible to extract the two-body cross section by inverting formula (2) thus obtaining the bare nucleus cross section for the two body reaction.

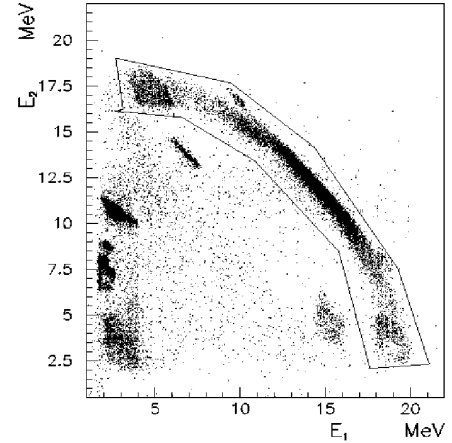


Figure 1 Scatter plot of the coincidence events. The graphical cut selects the α - α exit channel of interest.

Our data were then expressed in terms of the astrophysical factor by using its definition:

$$S(E) = \sigma(E) E \exp(2\pi\eta) \quad (3)$$

where η is the Sommerfeld parameter.

In figure 2 the comparison between the normalized $S(E)$ -factors extracted from the target and projectile break-up is made. The fair agreement shown by the two data sets is to be interpreted as a positive test of the method. Moreover it has also allowed an improved confidence in the final result for the $S(E)$ -factor which has been obtained after averaging over the two data sets.

This is shown in figure 3 where the full dots represent the THM data where the direct measurement data [6] are reported as open dots. A second order polynomial fit is also shown as a dashed line. The normalization procedure, which is required by the THM was performed at the highest available energy range, i.e. for $E_{\text{c.m.}}=600-700 \text{ keV}$. The zero order parameter, $S(0)$, is in this case $16.9 \pm 0.5 \text{ MeV b}$, which has

to be compared to the directly measured value of 17.4 MeV b.

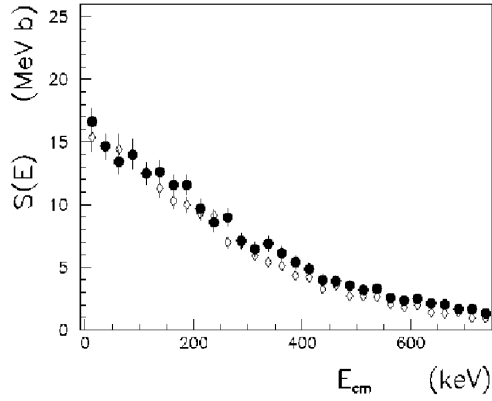


Figure 2 Comparison between the astrophysical factor for the ${}^6\text{Li}(d,\alpha){}^4\text{He}$ extracted from the projectile and target break-up.

The large discrepancy at $E_{\text{c.m.}} < 100$ keV can be related to the electron screening effect in the direct data. Then from the comparison of THM and direct data, and applying equation (1) a screening potential $U_e = 320$ eV is obtained.

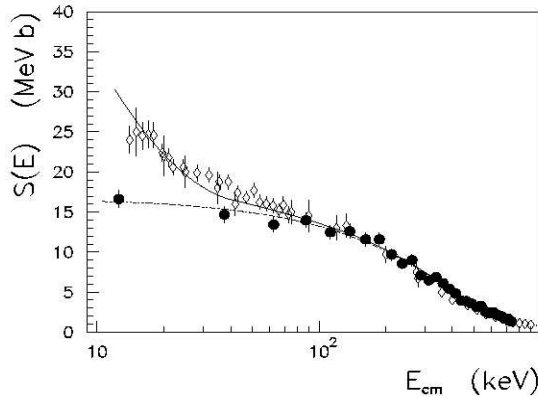


Figure 3 The average astrophysical $S(E)$ -factor (full dots) compared with direct data (diamonds) from [6]. The dashed line represents a second order polynomial fit while the solid line represents the fit used to determine U_e .

This value agrees with the evaluation from direct experiment, $U_e = 380$ eV [6] but is significantly higher than the calculations for the adiabatic case ($U_e = 175$ eV).

3 THE ${}^7\text{Li}(p,\alpha){}^4\text{He}$ REACTION

The reaction ${}^7\text{Li}(p,\alpha){}^4\text{He}$ has been studied using the indirect approach based the THM, through the three-body reaction ${}^2\text{H}({}^7\text{Li}, 2\alpha)n$.

The experiment [7] was performed using the SMP Tandem Van de Graaff accelerator at the LNS, Catania. ${}^7\text{Li}$ ion beams were used to bombard a deuterated polyethylene target. The outgoing α particles were detected in coincidence by six PSD. Beam energies of 19, 19.5, 20, 21 MeV were used. The detectors were mounted in a co-planar geometry and were centered at the quasi-free angles ($\theta_1 = 45^\circ$, $\theta_2 = 34^\circ$, $\theta_3 = 23^\circ$, $\theta_4 = -45^\circ$, $\theta_5 = -55^\circ$, $\theta_6 = -65^\circ$) with respect to the beam axis. Each telescope had a geometrical acceptance of $50 \times 10 \text{ cm}^2$ and their angular resolution turned out to be around 0.1° . During all measurements, the target thickness was continuously monitored by observing the elastic scattering peak with a Si-detector, positioned at $\theta = 65^\circ$.

Measurements of the α - α coincidence events were carried out at each incident energy. Using suitable kinematical cuts, spectra of relative energy between the two α 's were built up. In figure 4 we plot the relative energy spectra with and without the cut on the spectator momentum ($p_s < 40 \text{ MeV}/c$); it was verified that for events fulfilling this condition the sequential contribution from ${}^8\text{Be}$ states at 16.6 and 16.9 MeV is reduced to few percent.

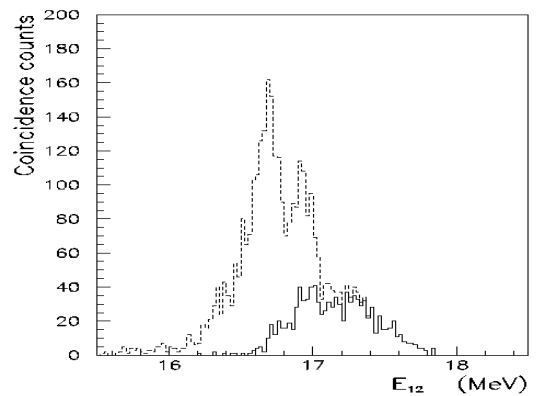


Figure 4 Relative energy spectra of the two detected α 's for $E = 20$ MeV. The solid histogram show events with $p_s < 40 \text{ MeV}/c$, corresponding to the quasi-free conditions while the dotted line represents the case of no restrictions.

By using equation (2) the bare nucleus cross section and hence the bare $S(E)$ -factor were obtained. In figure 5 we plot the final result which is averaged over all the energies and angles. The resulting $S(E)$ -factor was again fitted using a second order polynomial expression, so that a $S(0)$ mean value of 55 ± 3 keV b was found which can be compared with the directly measured value of 58 keV b [8].

From the comparison between the direct measurement [6] and the present one, the electron screening potential is evaluated fitting the data with the expression in eq. (1). For the present reaction we obtain a value of $U_e = 330 \pm 40$ eV to be compared with $U_e = 300 \pm 280$ deduced by direct experiments [6]. Again the discrepancy between the experimental result and the adiabatic calculation ($U_e = 175$ eV) for the electron screening potential shows a systematicity which was found for the ${}^6\text{Li}(d,\alpha){}^4\text{He}$ case as well.

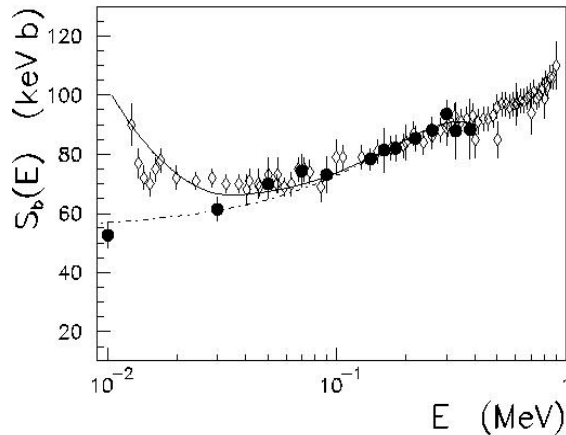


Figure 5 The average astrophysical $S(E)$ -factor (full dots) compared with direct data (diamonds) from [6]. The dashed line represents a second order polynomial fit while the solid line represents the fit used for determining U_e .

4 CONCLUDING REMARKS

The present systematic discrepancy between the theoretically calculated U_e (adiabatic limit) and the experimentally deduced one is confirmed by a completely independent method, the THM for both the ${}^7\text{Li}(p,\alpha){}^4\text{He}$ and ${}^6\text{Li}(d,\alpha){}^4\text{He}$ reactions. Moreover the isotopic independence of the electron screening effect, which was already observed [6] is here confirmed.

As regards the lithium problem the THM results are in agreement with the NACRE [9] compilation of nuclear reaction rates; present astrophysical predictions are therefore confirmed.

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THE α - ^{12}C ELASTIC SCATTERING STUDIED VIA THE $^6\text{Li}(^{12}\text{C}, \alpha ^{12}\text{C})^2\text{H}$ REACTION

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Abstract

In order to derive information on the astrophysical relevant $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ reaction, the α - ^{12}C elastic scattering has been studied via the Trojan Horse Method. In particular the $^6\text{Li}(^{12}\text{C}, \alpha ^{12}\text{C})^2\text{H}$ three-body reaction was studied in a kinematically complete experiment at an incident energy of 15 MeV. The excitation function of the three-body reaction has been calculated by a Monte-Carlo under the assumption that the mechanism giving rise to the reaction is purely quasi free. This simulation has been compared with the experimental data at 15 MeV and 18 MeV [1].

1 INTRODUCTION

The $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ cross section has strong implications both in nucleosynthesis and in the evolution of massive stars [2].

A large number of measurements has been devoted to the determination of this cross section at the Gamow energy ($E_0 \sim 300$ keV); information can also be extracted from ^{12}C - α elastic scattering data [3,4] in order to add further constraints on the nuclear parameters of the ^{16}O sub-threshold states which dominate the $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ reaction cross section at the Gamow peak.

Extreme difficulties have been encountered in direct measurements of the $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ cross section at sub-Coulomb energies and indirect methods have also been applied.

The Trojan Horse Method (THM) [5-9] is an indirect method which can overcome the problem of low cross sections due to the Coulomb barrier at energies near the Gamow Peak. It was applied here to the elastic scattering ^{12}C - α by using the $^6\text{Li}(^{12}\text{C}, \alpha ^{12}\text{C})^2\text{H}$

reaction, where ^6Li behaves like a Trojan Horse.

A previous experiment was performed at a beam energy of 18 MeV [1], and the extracted two-body excitation function was compared with the results of direct α - ^{12}C elastic scattering measurements [3] in the energy range 2.5-3.5 MeV. In order to reach lower energies ($E_{\alpha-^{12}\text{C}} = 1.7 \div 2.5$), the study of the elastic scattering ^{12}C - α at $E_{^{12}\text{C}} = 15$ MeV has been carried out [9] and will be discussed in the following. A sketch of the theory will be also given.

2 THEORETICAL BACKGROUND

In order to study an astrophysically relevant reaction $x(A, C)c$ through the THM, it is necessary to use an appropriate three-body reaction $a(A, Cc)b$ where a is highly clustered into $b+x$.

The THM is based on the quasi-free break-up mechanism which implies that the incident cluster b does not take part in the $A+x$ interaction behaving as a spectator to the process.

If the incident beam energy is larger than the Coulomb barrier of $A+a$, the cluster x can be brought into the nuclear interaction region to induce the reaction. The inter-cluster motion of x in a can partly compensate the initial projectile velocity and let the two-body reaction $A+x$ be induced at very low energy.

A general formulation of the THM in the framework of direct reaction theory has been given in ref. [9].

If a plane wave approximation for the relative motion of both the initial $A+a$ and the final $B+b$ $B \equiv Cc$ channels is used, one obtains the three-body cross section as:

$$\frac{d^3\sigma}{dE_C d\Omega_C d\Omega_c} = KF \left| W(\vec{Q}_{Bb}) \right|^2 \frac{16\pi^2}{(k_{Ax} Q_{Aa})^2} \frac{v_{Cc}}{v_{Ax}} \frac{d\sigma^{TH}}{d\Omega_{Ax}} \quad (1)$$

where KF is a kinematical factor. $\vec{Q}_{Aa}$ and $\vec{Q}_{Bb}$ are defined as functions of the relative wave numbers $\vec{k}_{Ax}$ and $\vec{k}_{Bx}$:

$$\begin{aligned} \vec{Q}_{Aa} &= \vec{k}_{Aa} - \frac{m_A}{m_A + m_x} \vec{k}_{Bb} \\ \vec{Q}_{Bb} &= \vec{k}_{Bb} - \frac{m_b}{m_b + m_x} \vec{k}_{Aa} \end{aligned} \quad (2)$$

and $W(\vec{Q}_{Bb})$ is essentially the inter-cluster momentum distribution in the Trojan Horse nucleus $a=b+x$.

In this approximation the three-body cross section is factorized, as in [9], into a structure factor and the desired two-body cross section.

The last one can be explicitly expressed as:

$$\begin{aligned} \frac{d\sigma^{TH}}{d\Omega_{Ax}}(Cc \rightarrow Ax) &= \frac{1}{4k_{Cc}^2} \cdot \\ &\cdot \left| \sum_l (2l+1) P_l(\hat{Q}_{Aa} \cdot \hat{k}_{Cc}) [S_l J_l^{(+)} - \delta_{(Ax)(Cc)} J_l^{(-)}] \right|^2 \end{aligned} \quad (3)$$

where the S_l are the total (nuclear-plus-Coulomb) S-matrix elements for the reaction $C+c \rightarrow A+x$.

Eq.(3) has the form of a usual two-body cross section except for the functions $J_l^{(\pm)}(k_{Ax}, Q_{Aa})$ which are a consequence of the off-shell nature of the two-body process and are given explicitly in [9].

The additional energy dependence introduced by the $J_l^{(\pm)}$ functions is the essential feature of the THM. For inelastic 2-body processes, where the diagonal term is absent, the modification for the low energy behaviour due to $J_0^{(+)}$ leads to a term $e^{\pi\eta_{Ax}}$ which counteracts the exponential decrease of the S-matrix and leads to a finite TH cross section.

For elastic processes, as in the present case, it is important to evaluate in eq. (3) the relative weight of the $J_l^{(+)}$ and the $J_l^{(-)}$ integrals as well as their energy dependence. Qualitatively one can see [4] that the Coulomb amplitude alone at low energies is suppressed by a factor $e^{-\pi\eta_{Ax}}$. Since for elastic processes at low energies the Coulomb amplitude dominates, we have adopted here the simple approximation of multiplying the usual two-body nuclear-plus-Coulomb cross section by a factor $e^{-2\pi\eta_{Ax}}$.

3 THE α - ^{12}C ELASTIC SCATTERING VIA THE THM

Elastic scattering measurements have been performed in order to obtain information on α -widths of the ^{16}O subthreshold states. It is possible to find direct elastic scattering measurements and analysis in [2,3,11] and more recently in [12].

In order to study the α - ^{12}C elastic scattering by the THM, we have used the reaction $^{12}\text{C} + ^6\text{Li} \rightarrow ^{12}\text{C} + \alpha + d$ as in [1].

The reason of this choice is merely that the ^6Li nucleus can be considered as being strongly clustered into $\alpha + d$.

A ^{12}C beam at 15 MeV, provided by the SMP Tandem Van De Graaf accelerator of the Laboratori Nazionali del Sud (LNS) Catania,

was used on LiF and LiH targets (enriched in ${}^6\text{Li}$ to 95%).

The reaction products were detected in coincidence by means of two ΔE -E telescopes, each one consisting of an ionization chamber and a position sensitive detector (1000 μm thick). The two ΔE -E telescopes were centered at $\theta_\alpha=17.4^\circ$ and $\theta_c=12.4^\circ$ on opposite sides of the beam direction, covering angular ranges of 10° and 9.2° respectively.

Front-end standard electronics was used for both position and energy signal processing.

The detection geometry was chosen in order to accept coincidences corresponding to small momenta of the spectator, for which the quasi-free process should be dominant. This is a consequence of the zero angular momentum of the cluster relative motion in ${}^6\text{Li}$.

To determine completely the kinematics of the final state, the kinetic energies of the two outgoing particles were measured together with their emission angles.

After identification of the He and C ions in the ΔE -E matrix, the locus of the events due to the ${}^6\text{Li}({}^{12}\text{C}, \alpha {}^{12}\text{C})\text{H}$ reaction in the E_α - E_c plane was defined by the corresponding three-body kinematics.

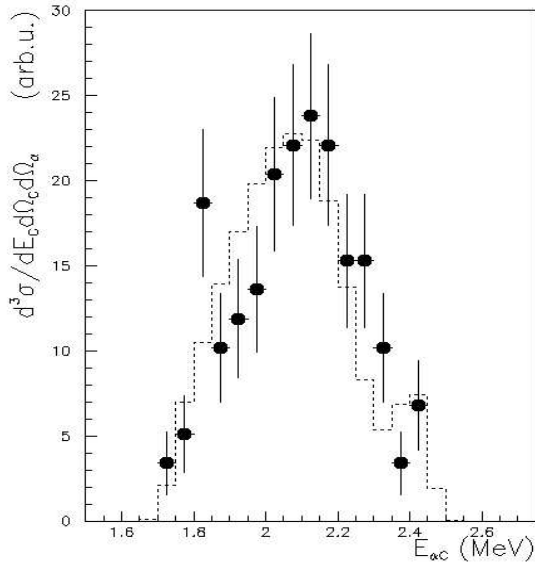


Figure 1 Comparison between the experimental and the simulated three-body cross section as a function of the relative energy $E_{\alpha c}$ at 15 MeV beam energy; the selected events correspond to deuteron momenta lower than 10 MeV/c and to ${}^{12}\text{C}$ angular range, in the α - ${}^{12}\text{C}$ system, is between 120 and 150 degrees.

The experimental spectra were simulated for the two beam energies of 15 and 18 MeV by Monte-Carlo methods on the basis of the eq.(1).

The momentum distribution has been obtained from the Fourier transform of a simple potential model of the ${}^6\text{Li}$ ground-state wave function, while the two-body α - ${}^{12}\text{C}$ cross section comes from a multilevel R-matrix parametrization of the direct elastic data [4]. As in [1], we can assume the quasi-free mechanism dominant when the deuteron momentum is lower than 10 MeV/c.

As discussed above the modification of the two body cross section in the THM was approximated by a suppression factor $e^{-2\pi\eta Ax}$ for the two incident beam energies (see also [10]). From the results, shown in the Figure 1 and Figure 2, one can see that the three-body process is described reasonably well.

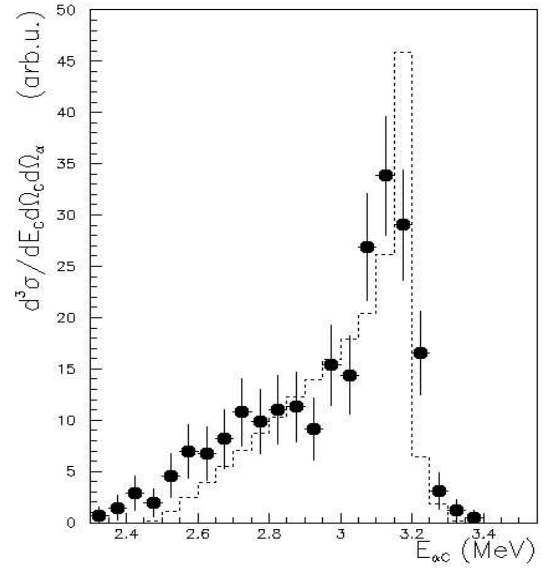


Figure 2 Comparison between the experimental dots and the simulated three-body cross section as a function of the relative energy $E_{\alpha c}$ at 18 MeV beam energy; the deuteron momentum is lower than 10 MeV/c and the ${}^{12}\text{C}$ angular range, in the α - ${}^{12}\text{C}$ system, is between 120 and 150 degrees.

5 SUMMARY

A more detailed experimental and theoretical investigation is, however, under way in order to

use the THM to extract elastic cross-sections at lower energies.

A new measurement in the α - ^{12}C relative energy range between the two data sets at 15 and 18 MeV would be useful in order to extract information in a region where the interplay between Coulomb and nuclear scattering amplitudes is supposed to be strong. To go down in α - ^{12}C relative energy, a magnetic spectrometer can be used in order to separate the elastic contribution from the reaction products at small angles. Work is in progress to get a complete evaluation of the J_l factors since they are key elements of the phase shift analysis that will be performed directly on the three-body cross section.

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BLACK GLOSS CHARACTERISATION OF GREEK ATTIC POTTERY CARRIED OUT BY MEANS OF THE NEW NON DESTRUCTIVE PIXE - ALPHA PORTABLE SYSTEM

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Abstract

In the present work we demonstrate that the new portable system PIXE – ALPHA recently designed and realised through a collaboration between the DAMRI-SACLAY (France) and the LNS laboratory (Italy) gives the possibility of a non destructive and careful analysis of pigments and it is particularly suited in the characterization of the black gloss present in Attic pottery. This because PIXE analysis is sensitive to light elements and concerns only the surface layers; as it is known the major elements present in the black gloss range from Na to Fe.

1 INTRODUCTION

The characterization of pigments covering the ancient pottery holds an important role in what enables:

i) to deeply understand the pictorial technique, giving also the possibility to put in evidence recent restorations;

ii) to establish, through the study of the similarities in the pigment composition, the provenance of the artefacts.

Unfortunately, a complete chemical analysis of the pigments cannot be performed without destroying a not negligible part of the material. In the cases in which chemical methods deal with very small quantities it could be emphasized that the obtained results often risk a severe loss of significance.

Non destructive methods and portable instruments have been proposed to overcome these problems. One of the most diffused to carry out elemental analysis is XRF (X-ray Fluorescence) method.

However, in the pigment characterization this method presents the following disadvantages:

i) due to the incoming X-ray energy and to the exponential absorption, atoms of the substrate can be excited and their characteristic X-rays can interfere with those of the pigment so giving often a doubtful interpretation of the energy

spectra;

ii) light elements like Na, Mg, Al, Si, P and S are not evidenced due to the low excitation X-ray cross section.

These difficulties are overcome by using charge particles (mainly protons or alpha particles) as excitation source: in fact they are completely stopped in the first few microns (typically 10-15 μm) and the fluorescence cross-section is high for light elements. The above method is the well known PIXE (Particle Induced X-ray Emission) one [1].

Unfortunately the charge particle beams are produced by accelerators so the PIXE method is expensive and the artefacts must be brought near the beam line: it is well known that a charged particle accelerator is installed at the Louvre museum to perform PIXE analysis.

Recently a portable PIXE system, made up by an alpha source coupled to a detector and electronic system (PIXE-ALPHA system), has been designed and realized by the LANDIS-LNS Laboratory in collaboration with the CEA/DAMRI[2].

The main problems to be solved were the safety ones and the compactness of the system enabling low activity sources to be used.

Up to date some applications have been performed [3].

In the present work we illustrate a further application of the PIXE-ALPHA system in the characterization of the black gloss covering a vase (Skyphos) coming from Caltagirone (Sicily).

As it is known the black gloss of Greek pottery is obtained by preparing a clay rich of iron oxide, aluminum oxide and potassium oxide who successively is fired in a reducing atmosphere[4].

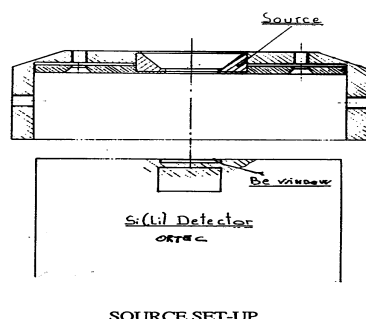
2 THE PIXE-ALPHA SOURCE

Fig.1 the source realised by the Laboratorio Nazionale del Sud in collaboration with the DAMRI [2].

1mCi ^{210}Po is electroplated on a silver backing which was been evaporated on a Mylar support displaying a conical shape.

A 0.2 μm layer of aromatic epoxy resin was deposited over the ^{210}Po layer to further ensure the confinement.

Fig. 1 – The PIXE-alpha source



Two 2 μm thin Kapton foils are glued on the faces of the source.

Alpha particles, emitted from the ^{210}Po impinge on the sample and the characteristic X-rays are emitted and detected by a Si(Li) detector.

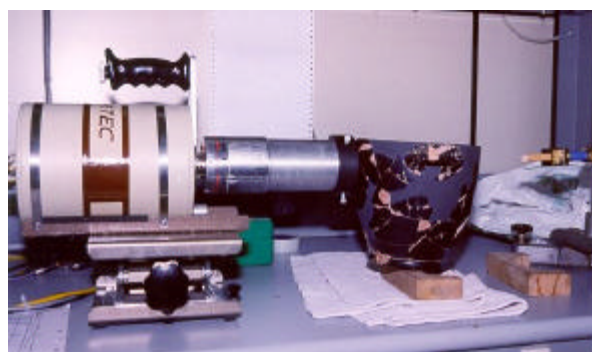
After accurate leakage tests the source has been certified as non contaminant.

The performances of the system in quantitative analysis has been tested using geological standards [3].

Fig.2 shows the portable PIXE-alpha system put near the black part of the Skyphos. The measurement time was 1800 sec. The X-ray detector was a 80 mm² Si(Li) and the data are acquired by means of the NOMAD PLUS ORTEC MCA system.

The alpha particle beam spot is 2.5 cm² large enough to ensure sufficient significance to the data.

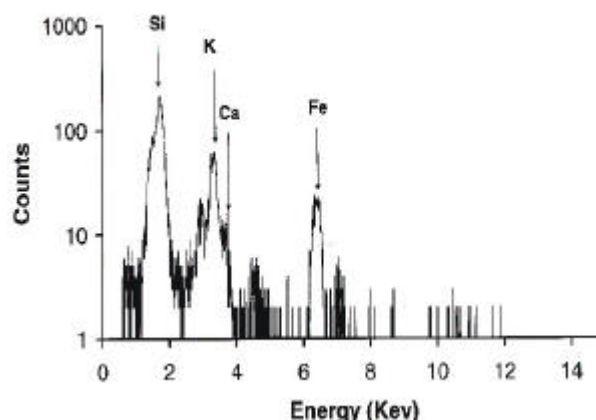
Fig. 2 - A view of the portable PIXE-a system during a "in situ" characterisation of the black glass of an attic pottery (Skyphos from Caltagirone - Sicily).



3 RESULTS

In fig. 3 the X-ray spectrum of the black pigment covering the attic Skyphos of fig. 2 is shown.

Fig. 3 – The X-ray spectrum obtained by using the portable PIXE-alpha system to measure the black pigments of the attic vase.



We emphasise that the PIXE-alpha system represents the unique way to simultaneously evidence elements from Al to Fe present in thin layer without contribution from the substrate.

The quantitative analysis has been performed by using the GUPIX 96 [5] code, in the “matrix” option and in the following assumptions:

- i) the alpha particle are equivalent to protons of 1,250 MeV;
- ii) the black gloss components are present as oxides;
- iii) only Na is not seen and considered as unique unknown component.

The obtained concentration values are shown in table 1.

Table 1. Concentrations of the components of the black gloss covering the Skyphos. The average accuracy is about 15%.

Component	Concentration in percent
Al ₂ O ₃	24
SiO ₂	47
K ₂ O	7
CaO	1.2
TiO ₂	0.9
FeO tot	17

4 CONCLUSIONS

The obtained data are consistent with those known from the few existing measurements carried out on attic black gloss by destructive methods [6] with the exception of the Potassium content that is 25% higher.

We emphasise that the PIXE-alpha system represents the unique way to simultaneously evidence elements from Al to Fe present in thin layers avoiding any contribution from the substrate and it is up to day the only that gives the above opportunity with a portable instrument.

5 ACKNOWLEDGEMENTS

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UNDERSTANDING OF THE ELECTRIC TRANSPORT CHARACTERISTICS OF CABLES UNDER 4 GeV Au-ION IMPLANTATION

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Abstract

A review of some main issues concerning type II superconductors is presented. It is aimed at framing the effects of columnar tracks produced by heavy ion implantation on high temperature superconductors inside the related scenario. In this framework recent results concerning high-energy irradiation of single crystals, multifilamentary and multilayered BSCCO cables, with particular emphasis on electric transport properties, are shown and briefly discussed.

1 INTRODUCTION

Superconductivity is a remarkable quantum phenomenon which can be characterized by the coherence of the charge condensate over a macroscopic length scale. The quantum coherence of the condensate as well as the vanishing resistance make superconductors extremely promising materials for various applications in electrotechnics, micro-electronics ultra-sensitive devices (field, current and voltage sensors, particle detectors, etc...). The possibility of practical applications of superconducting materials are determined by their critical parameters: temperature (T_c), field (H_c , H_{c1} , H_{c2}) and current density (J_c). Therefore, besides the fundamental interest in superconductivity, there exists a strong demand from the modern technology to improve these parameters. In type II superconductors and high temperature superconductors (HTSC) the destructive action of the applied field on single Cooper pairs, formed by electrons with opposite spins, results in the appearance of quantized states between the Meissner state ($H < H_{c1}$) and the upper critical field (H_{c2}) (Fig. 1a). In the mixed (critical) state the magnetic field penetrates the superconductor in the form of flux lines or vortices. Each flux line carries one flux quantum Φ_0 and in a homogeneous superconductor these topological excitations

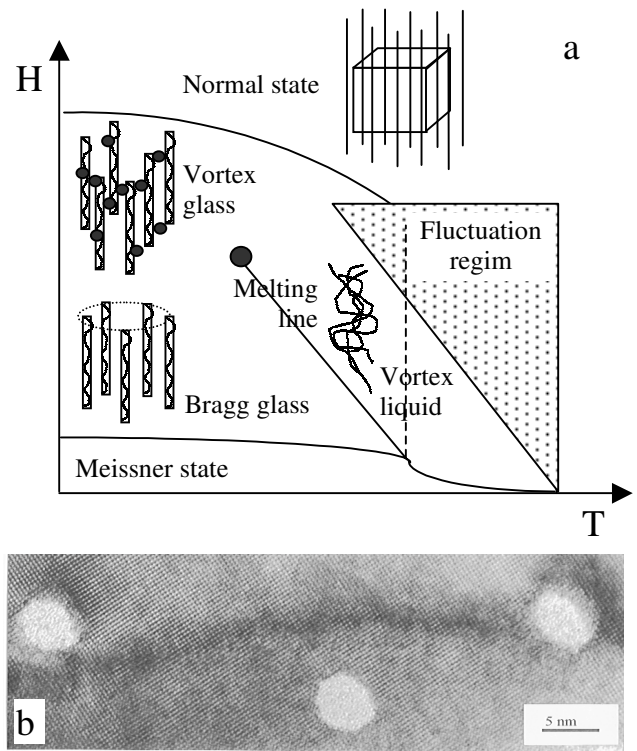


Fig. 1 – (a) Temperature-magnetic field diagram of an HTSC superconductor. *Columnar defects deeply affect the vortex liquid region shifting the melting line toward higher fields and temperatures (dashed line).* The shape and the shift of the melting line depend on the material ion energy and fluence. (b) High-resolution TEM image in [001] zone axis of a plan-view of an irradiated specimen (dose equivalent field, $B_0 = 2T$ [1]). The white spots are the cross-sections of three damaged columns of nanometric size, due to the impact of the Au ions (INFN LNS, 1999).

arrange themselves into a triangular Abrikosov vortex lattice. In low T_c materials this lattice can be viewed as a lattice of rigid rods. In high T_c cuprates and other quasi two-dimensional layered superconductors, due to strongly enhanced fluctuations, the vortices should be considered as a system of flexible interacting line-objects generating a non trivial statistical mechanics [2]. A recent phase-diagram is shown in Fig 1a.

Since the vortex has a normal core with a size comparable to the superconducting coherence length, it is energetically favorable to superimpose the vortex core spatially with normal state defects (pinning). Knowing that, intense efforts to optimize the vortex confinement by various defects have been made. *Columnar defects (Fig. 1b) with a morphology reproducing the size and the shape of HTSC vortices are the best confining objects (best pinning centers). If the ion energy overcomes a threshold value, columnar tracks can be created across the superconducting material. Nano-engineered pinning arrays with pseudo-regular distribution (at a given dose the average distance between columnar defects can be tailored [1]) provide a unique opportunity to stabilize different types of flux line [3, 4].*

The scenario has been recently complicated, at least for what concerns the HTSC cuprates, by the realization that there is a competition between Josephson vortices (without normal core) and the before mentioned Abrikosov vortices. With a different approach we can say that weak links of different length scales, ranging from "hidden weak-links" [5] in strong coupled junctions up to larger junctions, deeply affect the performances of the material. The interaction between these new Abrikosov-Josephson vortices [6] and intrinsic or extrinsic defects is the most relevant issue in order to understand the nature of new thermodynamic vortex phases. This knowledge stimulates the efforts to control the interaction itself because it determines the limits of the new applications.

Recent spectacular efforts in the fabrication of nanostructures and their array have strongly implemented the experimental and theoretical studies of nanostructured systems, including nanostructured superconductors. *The modern approach rely upon modifying the bulk*

properties through nanostructuring. It implies optimization of the confinement potential and topology (concept of quantum design).

In this sense the Superconducting Cyclotron (CS) of the "Laboratori Nazionali del Sud" (INFN-LNS) provides a powerful tool to nanotailor HTSC and perhaps to promote the knowledge of the particular characteristics of the recently discovered superconductor MgB_2 .

The aim of this paper is to show the vortex confinement induced by pseudo-ordered pinning arrays as those provided by columnar tracks in heavy ion irradiated samples (CS accelerator). The effect of the implantation of heavy ion tracks on i) BSCCO single crystals with suitable different size defects, ii) multifilamentary cables, iii) multilayered cables, is shown. The role of columnar defect implantation as a tool to push the HTSC cable performances toward levels competitive with conventional technologies is stressed out.

2 EXPERIMENTAL RESULTS

2.1 Single crystals

BSCCO-2212 single crystals are ideal systems to study the columnar defect implantation effects on the HTSC magnetic granularity because they allow zooming on elementary domains. In cables these domains are repeated in an infinite variety of length scales and inter-domains coupling strength. The single crystals under study have planar defects of different size, known as lamellae [7], which act as "weak-links" of different strength. In Fig. 2a a magneto-optical image of a single crystal is shown. The flux penetrates through the lamellae (bright lines) where the superconducting order is depressed due to oxygen and calcium deficiency, creating weak links [7]. In the intrinsic crystal these defects can break the current paths and create two or more separated single crystals.

After irradiation the lamellae exhibit a dramatically different in-field behavior. The narrowest lamellae (Fig. 2b) appear to be "healed", while the largest lamella is still existing, though the flux entering inside is confined in a narrower region. The flux enters with less success inside the weak links (with respect to the non-irradiated samples), due to the

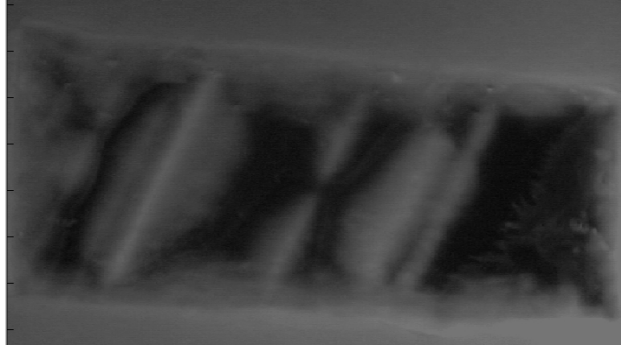


Fig. 2a - Magneto-optical images of a BSCCO single crystals evaluated before irradiation and in zero field cooling condition at $T = 15$ K and $\mu_0 H = 45$ mT.

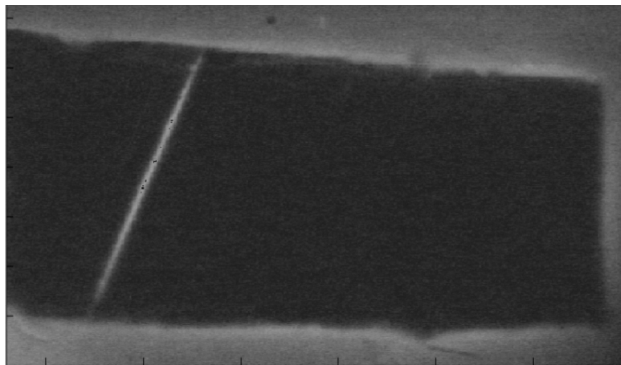


Fig. 2b - Magneto-optical images of a BSCCO single crystals evaluated after irradiation in zero field cooling condition at $T = 15$ K and $\mu_0 H = 45$ mT (0.25 GeV Au-ions, fluence: $2.5 \cdot 10^{10}$ ion/cm² corresponding to $B_\phi = 0.5$ T)

reinforcement of the pinning in the "banks" of the weak-link itself. Either canceling or persistence of the weak-links is the signature of "strong" or "weak" coupling strength between the grains, respectively.

2.2 Cables

To outline the role of columnar defect implantation into enhancing the HTSC cable performances, we irradiated BSCCO-2223 55-filament tapes [8], about 10 cm long. The irradiation was made perpendicularly to the tape surface with 4 GeV Au-ions. At this energy the irradiation affects only 70% of the whole sample thickness. The samples were irradiated, at room temperature, in a vacuum chamber equipped with multisample holder, Faraday cup, charge suppressor and electronics for charge integration suitably set up at the "Laboratori Nazionali del Sud" [9]. The samples were

characterized by means of electric transport measurements performed at Cesi-Enel. The magnetic field was applied perpendicularly to the surface tape (i.e. parallel to the ion tracks).

In Fig. 3 the value of the critical currents evaluated for two twin 55-filament tapes are reported before and after irradiation at two different doses, respectively. The ratios between the critical current density values obtained after and before irradiation are reported in Fig. 4. As emerges from the figures, at 77 K the irradiation effect becomes significant when the magnetic field is higher than 200 mT.

These results are particularly significant because a lessening of the critical current

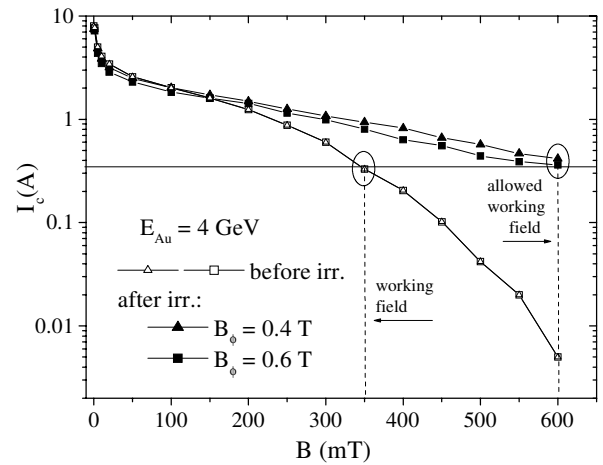


Fig. 3 - Critical currents evaluated before and after irradiation in 55-filament tapes by transport measurements ($1\mu\text{V}/\text{cm}$ criterion) in different external fields. (Irradiation fluences: $2 \cdot 10^{10}$ ion/cm² and $3 \cdot 10^{10}$ ion/cm² corresponding to a dose equivalent fields $B_\phi = 0.4$ T and 0.6 T, respectively [1]).

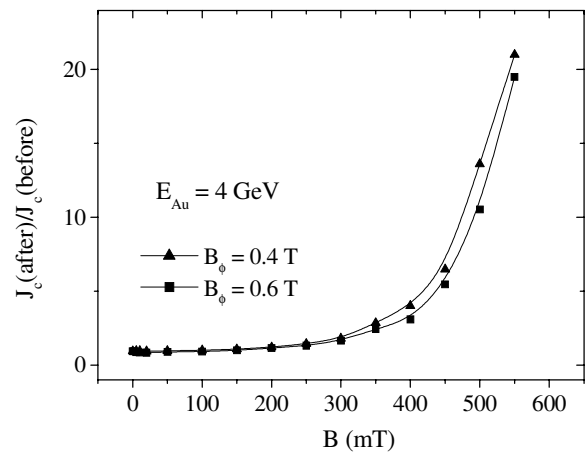


Fig. 4 - Ratios between the critical current density values measured after and before irradiation for the tapes referred to in Fig. 3.

decrease with field means that a single cable is allowed transporting more dc current. Namely, BSCCO-2223 multifilamentary and multilayered tapes are packed together to form a cable or a current lead, respectively. Because of the carried current, both cables and current leads work in a self-field regime whose value depends on the total current. In particular these cables are designed to carry currents up to a maximum allowed self-field, otherwise the single-filament current decreases down threshold limits. The maximum allowed self-field is just about 300 mT in most applications. In Fig. 3 it is shown that, after irradiation, the same critical current values as before irradiation are kept when the field is twofold. *Because of that the packing of more filaments in a single cable is allowed.* This is a results the scientific community is looking for.

Similar preliminary results were obtained by the columnar defect implantation on BSCCO-2223 multilayered samples fabricated by the "Accordion Folder Methods (AFM)" (Fig. 5) [10]. The samples, about 20 cm long were irradiated with 3 GeV Au-ions at a fluence of $5 \cdot 10^{10}$ ion/cm², corresponding to a dose equivalent field $B_\phi = 1$ T [1]. With this energy, the irradiation affects only 10% of the whole thickness. Also in this case, notwithstanding the irradiation affects a very limited part of the whole sample, when the applied magnetic fields is larger then a temperature-dependent threshold

the critical current significantly increases.

In order to extend our analysis on samples having sizes useful for applications a new irradiation chamber was designed to allow the easy implantation of quite large surfaces. It consists in a vacuum chamber with a moving target holder and an automatic control on the beam intensity and uniformity. It was designed to irradiate tapes and cables with a maximum surface size of 50 cm x 1 cm.

3 CONCLUSIONS

Columnar defect implantation is a powerful tool:

i) to correlate structural and magnetic granularity of HTSC cuprates. The magnetic granularity is the major drawback of HTSC cuprates. The issue is also a major open question in MgB₂

ii) to enhance the cable performances toward levels competitive with conventional technologies. Namely, in BSCCO cables the irradiation can be tailored to keep the same critical current as in a non-irradiated cable in a twofold working field.

Finally the new chamber could open the way toward an up-scaling of the irradiation tools in order to modify the in-field properties at least in strategically relevant cable-plant locations.

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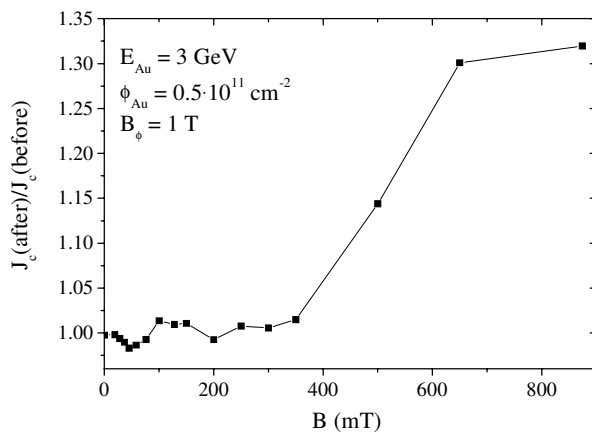


Fig. 5 Ratio between the critical current density values measured after and before irradiation in a AFM conductor by transport measurements (1μV/cm criterion) in different external fields. (Irradiation fluences: $5 \cdot 10^{10}$ ion/cm² corresponding to a dose equivalent fields $B_\phi=1$ T).

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X-ray imaging with thin CsI scintillating plates

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Abstract

At LNS-Catania, in the framework of digital radiography, the use of thin monocrystal scintillating plates made from CsI(Tl), has allowed to obtain promising results in terms of high sensitivity, compactness and handiness. A CCD camera is used to observe the light produced in the crystal when it is crossed by X-rays. Spatial resolution has been measured with X-rays as a function of the plate thickness (100 μm to 2 mm).

1 INTRODUCTION

In the last years the CsI(Tl) scintillator has gained significant popularity, because of its considerable light yield and low hygroscopicity. Within the framework of LANDIS (Laboratorio Analisi Non DIstruttive) [1] at Laboratori Nazionali del Sud (LNS), the technique for X-ray imaging makes use of thin monocrystal CsI(Tl) plates as sensors. The advantages, as compared to the traditional technique with radiographs, are mainly the possibility of acquiring X-ray pictures in real time and of handling them with a computer. The operating principle consists of irradiating the plate with a X-ray flux, that is modulated in intensity by the sample placed in front of it; the scintillation light thus produced in the scintillator gives rise to the radiographic image. This is finally acquired by a PC by means of a CCD (Charge Coupled Device) camera. The performance of such a kind of system is primarily measured in terms of the Modulation Transfer Function (MTF).

2 DIGITAL RADIOGRAPHY

In the framework of non-destructive analysis in the LANDIS activity, which includes applications for antique paintings, we have developed a simple technique in order to perform digital radiography. It is based on the scintillation light produced when a scintillator plate is crossed by X-rays. The overall luminosity depends on the energy lost by each X photon and on the intensity (number of photons per second). In order to explain the formation of

the radiographic image, let us suppose to have a X-ray tube which produces a stable X-ray beam. A plate is used as a screen, in order to have a rather homogeneous luminosity produced on the surface. When a sample is placed between the tube and the plate, the resulting X-ray intensity is modulated as a function of the sample density. The corresponding luminosity modulation in the scintillating plate gives rise to the radiographic image. From the analytical point of view, the image can be described by the following exponential relation:

$$I(x, y) = I_0(x, y) \cdot e^{-\mu(x, y) \cdot d(x, y)} \quad (1)$$

where (x, y) are the spatial coordinates on the plate surface, I is the intensity on the plate surface when the sample is put in, I_0 when the sample is removed, d and μ are respectively the crossed thickness and the attenuation coefficient of the sample. In case a digital image is acquired, a suitable software can subtract the systematic noise pixel by pixel, due to the non-uniformity of the impinging radiation and to the CCD background noise, provided that their mean values are stable. The final picture can be represented by the expression

$$e^{-\mu(x, y) \cdot d(x, y)} \quad (2).$$

2.1 Experimental Set-up and Results

The choice of a monocrystal CsI(Tl) scintillator comes from its high luminous efficiency, in order to keep low the statistical fluctuations of the scintillation photons and to reduce the needed dose. The experimental scheme is shown in Fig. 1. The set-up consists

of a light-tight box, containing the CCD camera (COHU 4910 with 16 mm optics), closed on a side by the blackened scintillating plate. The tube is placed at a suitable distance, so that the plate surface is irradiated rather uniformly. The typical operating voltage is 40 kV, the current 1 mA.

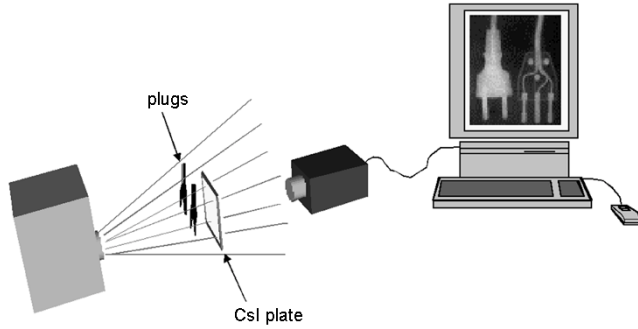


Fig. 1. Scheme of the experimental set-up for the radiographic system.

The performance of this X-ray imaging system has been measured in terms of spatial frequency, with particular care for the spatial resolution. This is affected by contributions coming from the interactions between X-rays and the sample (mainly the Compton scattering), and from the experimental set-up, i.e. the CCD pixel size ($8.5 \times 8.5 \mu\text{m}^2$), the plate thickness which affects the light spread inside the plate, the distance between plate and CCD. In order to reduce the light spread inside the plate, we use thin plates with thickness from $100 \mu\text{m}$ to a few millimetres. Plates thinner than $100 \mu\text{m}$ would be desirable, but they are quite difficult to manufacture.

An analysis in the spatial frequency domain has been carried out, by measuring the Line Spread Function (LSF) and calculating its Fourier Transform, in order to obtain the Modulation Transfer Function (MTF) [2], [3]. The LSF measurement has been performed by irradiating a thin metallic wire ($100 \mu\text{m}$ diameter), and then extracting the corresponding transversal profile from its X-ray picture. We reported the pixel grey level as a function of x , being x perpendicular to the wire, and fitted the data with the following exponential function according to ref.[4]:

$$LSF(x) = a + b \cdot e^{-\frac{|x-c|}{d}} \quad (3)$$

where a and b are normalization constants, c is the mean position, while d is related to the width of the curve. The MTF is obtained by the modulus of the Fourier Transform of eq. (3):

$$MTF(f) = \frac{1}{4\pi^2 d^2 f^2} \quad (4)$$

with f the spatial frequency expressed in line pairs/mm (lp/mm).

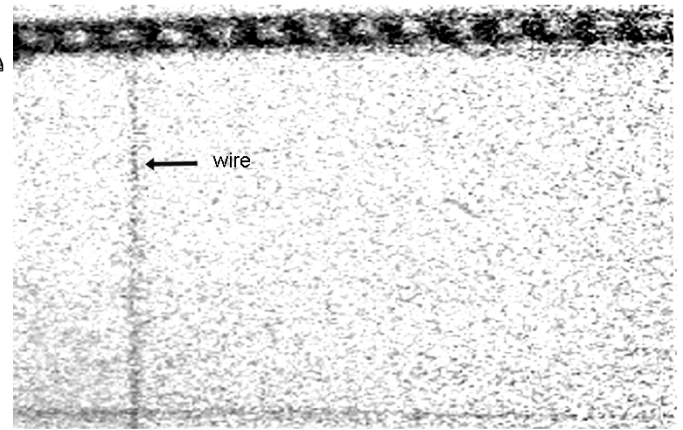


Fig. 2. Radiographic picture of a $100 \mu\text{m}$ metallic wire. The grid for horizontal calibration is visible in the upper part.

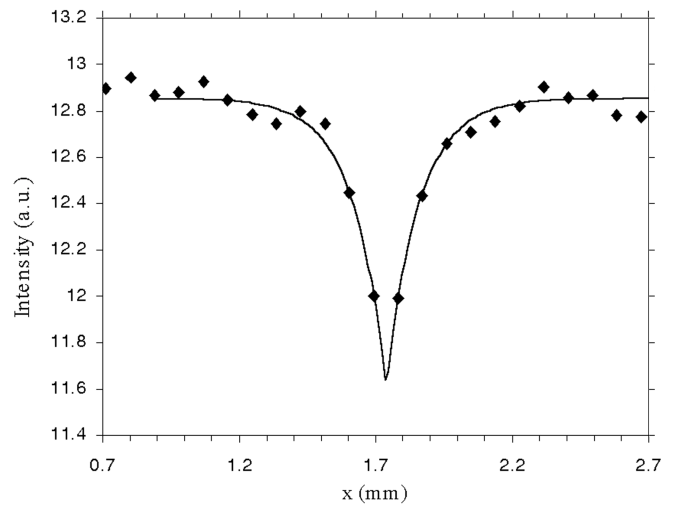


Fig. 3. Line spread function (LSF) extracted from the upper picture as the wire transversal profile. Exponential fit is also plotted.

Experimental measurements of LSF were carried out for different thickness of the plates, $100 \mu\text{m}$, $200 \mu\text{m}$ and 2 mm . In Fig. 2 and Fig. 3 a X-ray picture of the wire and its corresponding LSF are shown respectively; a grid was used in

order to perform the x - y calibration of the system.

The MTF's obtained for the three plates are shown in Fig.4. In order to compare the different performance of the plates, the noise equivalent passband (Ne), defined as the spatial frequency for 30% of modulation transfer, is extracted from the plots. We measure $Ne = 2.2$ lp/mm for the 100 μ m plate and 1 lp/mm for the 2 mm one. It is evident that, for a given value of frequency, the MTF becomes lower when increasing the plate thickness. This means that spatial resolution worsens in thicker plates, since the light spread increases. In Fig. 5 we show a radiograph obtained using two ordinary plugs as samples.

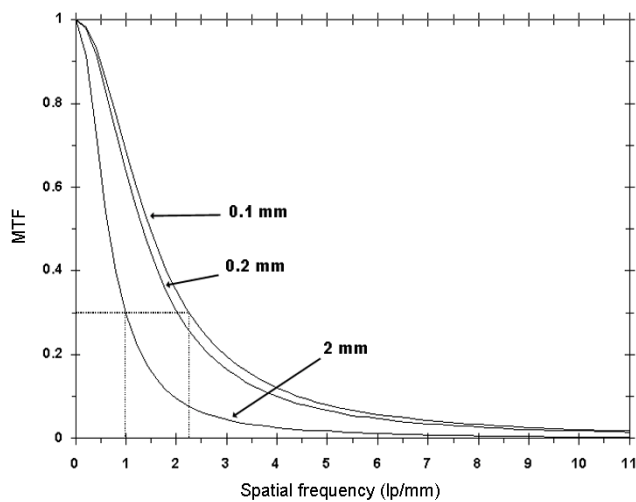


Fig. 4. MTF curves calculated for three CsI(Tl) plates with different thickness. Noise equivalent passband Ne was extracted from the 100 μ m and 2 mm curves.

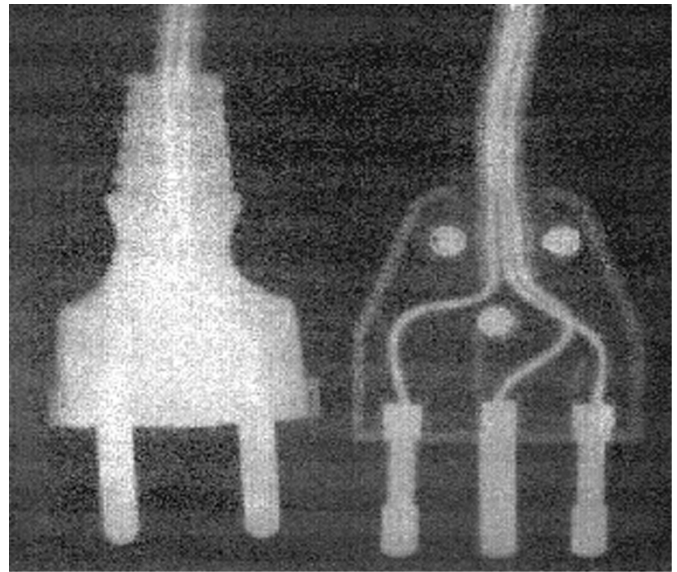


Fig. 5. Radiographic picture acquired with the X-ray camera. The samples are common commercial plugs.

3 CONCLUSIONS

CsI(Tl) was known to be a powerful scintillator, being able to satisfy a wide range of requirements. We have shown that, in form of thin monocrystal plates, it can be fruitfully exploited for imaging, achieving good quality and sensitivity at low cost with a simple set-up. In particular, the application of X-ray imaging look very promising in view of future developments.

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