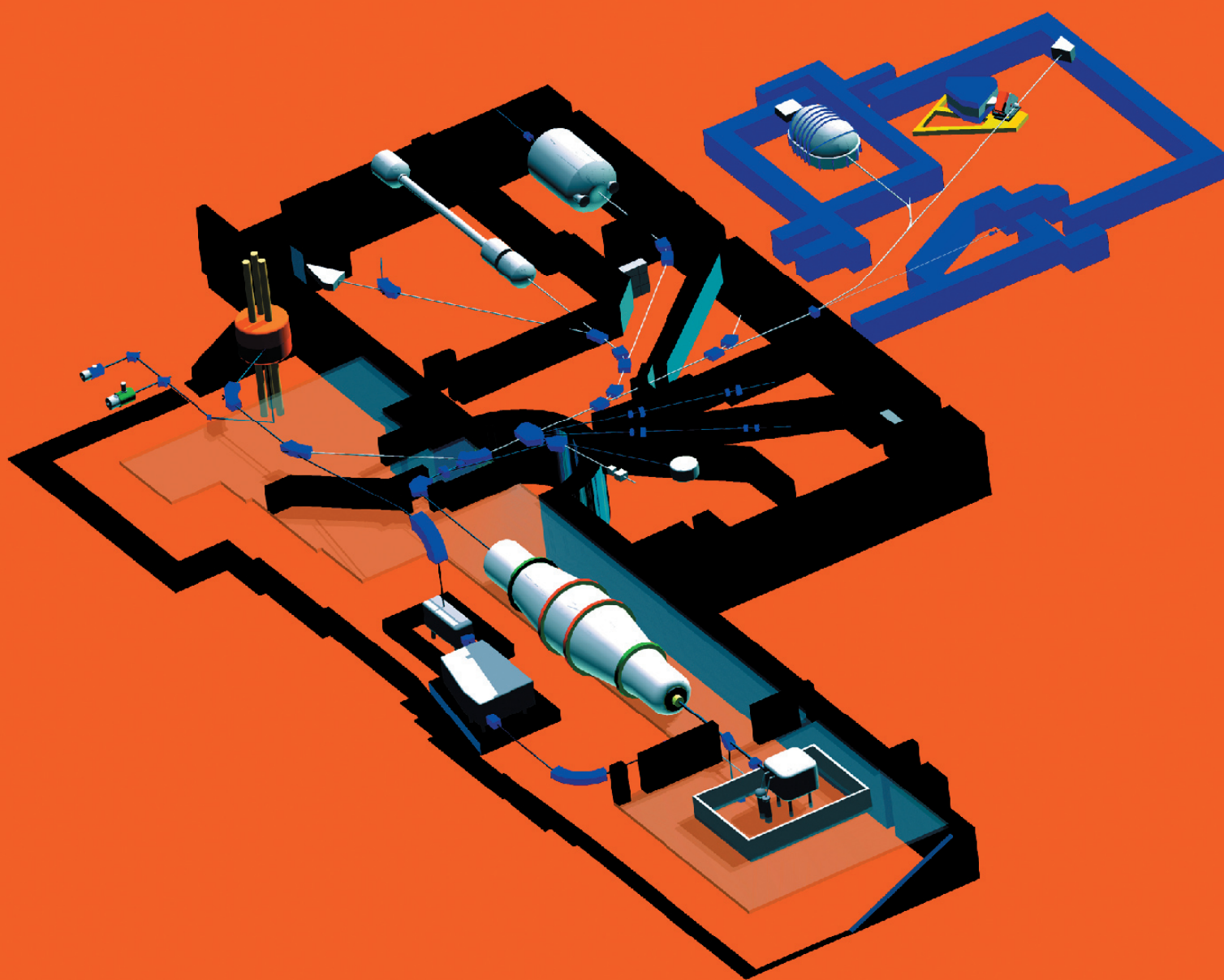




LABORATORI NAZIONALI DEL SUD



ACTIVITY REPORT 2004

Foreword

Catania, June 2005

An intense experimental activity with the two accelerators was performed, as usually, in 2004, together with a hard work aimed at the completion of the radioactive beam facility EXCYT and the development of the other research projects of LNS.

The main achievements concerning EXCYT consist in the successful test of the charge exchange channel at ORNL and in the full mounting of the beam line up to the entrance of Tandem, fully equipped with pumping and vacuum control systems. Also low intensity diagnostics devices were mounted in the low energy part of the line and others started to be installed in the high energy section.

New nuclear physics experiments, pointing at a better understanding of the projectile multifragmentation mechanism, have been carried out with the Cyclotron beams, by means of the multidetector CHIMERA. Moreover intermediate energy beams of protons and ^{12}C have also been widely employed in applied studies, mainly dealing with the behavior of the biological matter following ion beam irradiation.

At half of 2004 a relevant result was achieved by the Cyclotron staff that improved the performance of the accelerator. A $^4\text{He}^{2+}$ beam was successfully accelerated for the first time to 80 A MeV and extracted from the Cyclotron. This energy is 30% higher than the former maximum operating energy, the previous value being 62 A MeV, and gets much closer to the limit design value of 100 A MeV.

On the side of applications, irradiation sessions with the proton therapy facility CATANA went on during 2004, leading to a total number of 77 patients suffering of ocular pathologies that were treated so far by means of the Cyclotron proton beam.

Nuclear structure experiments and indirect astrophysical measurements performed with the low energy, high performance Tandem beams demonstrated that this accelerator can still play a role in the fundamental research on the atomic nucleus. The Tandem beams were also used in a number of interdisciplinary experiments ranging from characterisation studies of new materials for particle detectors to the investigation of the behavior of superconducting materials after irradiation, from particle irradiation tests of power devices in view of aerospace missions to the realisation of micro opto-mechanical devices by means of a sophisticated ion beam lithographic technique.

The beam line going to the spectrometer MAGNEX was completed and tested as well as the vacuum, cooling and power distribution systems. At the end of the year, both start and focal plane detectors were ready for the overall commissioning of the spectrometer.

Technological developments concerning the NEMO project are fruitfully going along, with the definition of the mechanical structure and realisation of a small scale prototype of the detector tower and with the design of the electrical power distribution and related control systems. At the same time computer simulations allowed to test the sensitivity of the proposed geometry of the neutrino telescope.

It is to be mentioned that all these achievements were made possible only thanks to the competence and the enthusiasm of the whole research, technical and administrative LNS staff.

Prof. Emilio Migneco
LNS Director

DYNAMICAL FISSION IN $^{124}\text{Sn} + ^{64}\text{Ni}$ COLLISION AT 35 A·MEV

P. Russotto^{a,*}, E. De Filippo^b, A. Pagano^b, E. Piasecki^c, F. Amorini^a, A. Anzalone^a, L. Auditore^d, V. Baran^a, I. Berceanu^e, J. Blicharska^f, J. Brzychczyk^g, A. Bonasera^a, B. Borderie^h, R. Bougaultⁱ, M. Bruno^j, G. Cardella^b, S. Cavallaro^a, M.B. Chatterjee^k, A. Chbihi^l, M. Colonna^a, M. D'Agostino^j, R. Dayras^m, M. Di Toro^a, J. Frankland^l, E. Galichet^h, W. Gawlikowicz^g, E. Geraci^j, F. Giustolisi^a, A. Grzeszczuk^f, P. Guazzoniⁿ, D. Guinet^o, M. Iacono-Manno^a, S. Kowalski^f, E. La Guidara^a, G. Lanzano^b, G. Lanzaone^a, N. Le Neindre^h, S. Li^p, S. Lo Nigro^a, C. Maiolino^a, Z. Majka^g, M. Papa^b, M. Petrovici^e, S. Pirrone^b, R. Planeta^g, G. Politi^b, A. Pop^e, F. Porto^a, M.F. Rivet^h, E. Rosato^q, F. Rizzo^a, S. Russoⁿ, M. Sassiⁿ, K. Schmidt^f, K. Siwek-Wilczynska^c, I. Skwira^c, M.L. Sperduto^a, J.C. Steckmeyer^j, L. Swiderski^c, A. Trifirò^d, M. Trimarchi^d, G. Vannini^j, M. Vigilante^q, J.P. Wieleczko^l, J. Wilczynski^r, H. Wu^p, Z. Xiao^p, L. Zettaⁿ, and W. Zipper^f

- a) *INFN, Laboratori Nazionali del Sud and Dipartimento di Fisica e Astronomia, Università di Catania, Italy*
- b) *INFN, Sezione di Catania and Dipartimento di Fisica e Astronomia, Università di Catania, Italy*
- c) *Institute of Experimental Physics, Warsaw University, Warsaw, Poland*
- d) *INFN, Gruppo Collegato di Messina and Dipartimento di Fisica, Università di Messina, Italy*
- e) *Institute for Physics and Nuclear Engineering, Bucharest, Romania*
- f) *Institute of Physics, University of Silesia, Katowice, Poland*
- g) *M. Smoluchowski Institute of Physics, Jagellonian University, Cracow, Poland*
- h) *Institute de Physique Nucléaire, IN2P3 and Université Paris-Sud, Orsay, France*
- i) *LPC, Ensi Caen and Université de Caen, France*
- j) *INFN, Sezione di Bologna and Dipartimento di Fisica, Università di Bologna, Italy*
- k) *Saha Institute Of Nuclear Physics, Kolkata, India*
- l) *GANIL, CEA, IN2P3-CNRS, Caen, France*
- m) *DAPNIA/SPHN, CEA-Saclay, France*
- n) *INFN, Sezione di Milano and Dipartimento di Fisica, Università di Milano, Italy*
- o) *IPN, IN2P3-CNRS and Université Claude Bernard, Lyon, France*
- p) *Institute of Modern Physics, Lanzhou, China*
- q) *INFN, Sezione di Napoli and Dipartimento di Fisica, Università di Napoli, Italy*
- r) *A. Soltan Institute for Nuclear Studies, Swierk/Warsaw, Poland*

* Corresponding author, e-mail: russotto@lns.infn.it

Abstract

Some properties of fast, non-equilibrium splitting of projectile in the 35 A·MeV $^{124}\text{Sn} + ^{64}\text{Ni}$ reaction were determined using the 4 π Chimera detector system. In particular the angular distributions and relative velocities of PLF fragments were measured. The time scale of the process was estimated and it turned out that the process is sequential but much faster than the ordinary, equilibrated fission.

1. INTRODUCTION

The phenomenon of fast, non-equilibrium fission of projectile-like fragments (PLF) was first observed at rather low energies [1,2], in heavy-ion deep-inelastic collisions, but later it was observed also at higher energies [3,4]. It is not clear, however, whether the physics in both cases is the same.

In the case of the equilibrium PLF fission, the angular distribution should be forward/backward symmetric in the PLF reference system. Main signature of non-equilibrium fission is that the heavier of the fission fragments is usually the faster one, i.e. it is forward directed. Thus, the lighter of two fragments is situated preferentially between its heavier partner and the target like nucleus. In the case of the lightest fragments, we usually characterize this process as mid-velocity emission [5] or neck fragmentation [6,7]. Since we do

not know whether the reaction mechanism is the same for all heavy/light fragment mass ratios (A_H/A_L) we provisionally reserve the name “dynamical fission” (DF) for more mass symmetric PLF splitting, when $A_H/A_L < 4.6$. In our system, for the PLFs of $Z \approx 50$, this corresponds to the charge of the lighter DF fragment $Z_L > 9$.

II. DATA ANALYSIS

The experimental data (REVERSE campaign) were obtained in the $^{124}\text{Sn} + ^{64}\text{Ni}$ reaction at 35A MeV by using the forward part of the multidetector CHIMERA [8].

Since we are interested in fission of projectile like fragments in semi-peripheral collisions, we concentrate our attention on the two heaviest fragments accompanied by at most 4 other charged fragments, so the total charge particle multiplicity condition set in off-line analysis was $M_{\text{tot}} < 7$. The forward part of CHIMERA, having close to 100% registration efficiency of PLFs, has much lower efficiency for target-like fragments (TLFs). Consequently, we did not to apply the usual condition of the (almost) complete fragment charge and momentum registration. Instead, we have selected events fulfilling the condition of total registered charge $30 < Z_{\text{tot}} < 80$ and of the sum of charges of two heaviest fragments $Z_{2F} > 15$.

III. RESULTS

A. Sources

Because of our interest in dynamical fission of PLF, we selected here the events corresponding to the heaviest two fragments mass ratio $A_H/A_L < 4.6$. The distribution (in the logarithmic scale) of number of counts in function of Z_{2F} and the parallel velocity (in the laboratory reference frame) of lighter of the two, V_{par}^L , is presented in Fig.1 for three mass asymmetries A_H/A_L and for three ranges of the total kinetic energy of two heaviest fragments, E_{2F} . This latter quantity is related to the total kinetic energy loss (and centrality of collision).

For the lighter (of two heaviest) fragments we see that velocities have broad distributions consisting basically of two main components: of very low velocity (about 1 cm/ns) and the second one, close to the beam velocity. Low velocity fragments can be interpreted as the target remnants, as suggested by simple kinematical calculations and in agreement with model calculations.

The fact that the high energy group has Z_{2F} close of about 45 – 50 suggests that for $V_{\text{par}}^L > 4\text{cm/ns}$ we observe essentially splitting of the PLF into two main fragments. This is also born out by refs. [7,9,10].

This information is important for interpretation of V_{par}^L vs. (perpendicular) V_{per}^L plots, shown in Fig. 2, after putting an additional condition on Z_{2F} , corresponding to PLF. In this figure we see the

structures reminding the Coulomb rings, centered somewhat below the beam velocity, $V_{\text{beam}} = 8.2\text{ cm/s}$

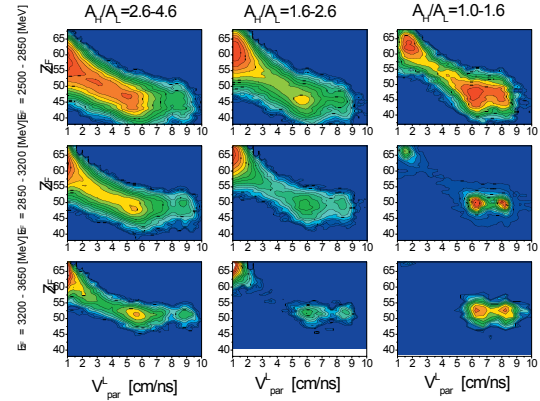


Fig. 1. The sum of charges of two heaviest fragments (Z_{2F}) vs. the lighter fragment parallel velocity (in the lab reference frame) for different mass asymmetries and different ranges of kinetic energy of these two fragments. The distributions are shown in logarithmic scale.

The rings point to a well-defined PLF source and make probable the scenario of two separate (sequential) reaction steps: scattering of the PLF followed by its splitting into two fragments. Moreover, we see that the light fragments are most frequently occupying the low-velocity sides of the rings.

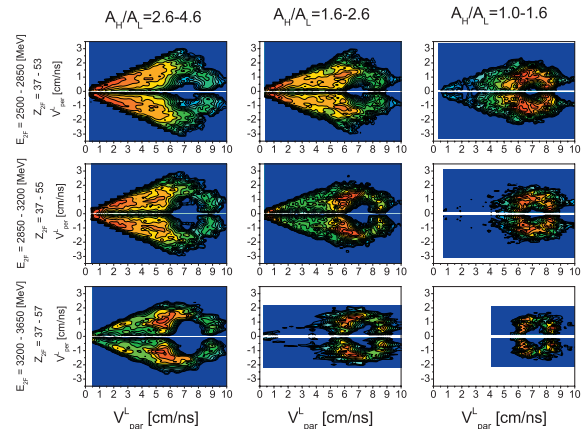


Fig. 2. V_{par}^L vs. V_{per}^L plots for the lighter fragment (of the two heaviest) for different values of mass asymmetry and kinetic energy of these fragments. The sharp cuts in the region of $V_{\text{par}}^L < 5\text{ cm/ns}$ are due to the angular range of the forward part of CHIMERA limited to 30° . The distributions are shown in logarithmic scale.

This is the signature of the “dynamical fission”, namely the fact that the lighter fragments are emitted preferentially backwards in the PLF reference system, i.e., towards the target nucleus. The lack of the forward/backward symmetry of the rings shows that the

second split is a very fast process, with the time interval between the two steps much shorter than the PLF rotation time, otherwise the averaging over the emission directions would result in the forward/backward symmetry. This is why we consider this process as being the “fast sequential” one.

In addition, at somewhat lower (intermediate) velocity, outside of the rings, we see also light fragments not forming any ring-like structures. They are described in ref. [7] as the “neck emission”. It is seen that for the near-symmetric splits the fragments sequentially emitted from PLF dominate over the mid-velocity particles, even if this dominance gradually decreases with increased mass asymmetry and with kinetic energy loss in the collision step.

To get rid of the TLF we should put a condition on V_{par}^L . The choice of this condition depends on decision how large contribution of the Intermediate Velocity Fragments we are ready to tolerate in the study of DF. We have chosen the compromise condition $V_{\text{par}}^L > 4$ cm/ns, realizing, however, that for asymmetric splits any such a crude condition would result in some distortion of results.

B. Angular distributions

We can define the reaction plane by the beam and velocity vector of the scattered PLF. The latter one is reconstructed from velocity vectors of two heaviest fragments for events fulfilling the given above selection conditions. Next, we can calculate the in-plane and out-of-plane angular distributions [2]. The in-plane angular distribution for various kinetic energy losses and mass asymmetries is presented in Fig. 4. The meaning of the in- and out of plane angles is illustrated on the Fig. 3.

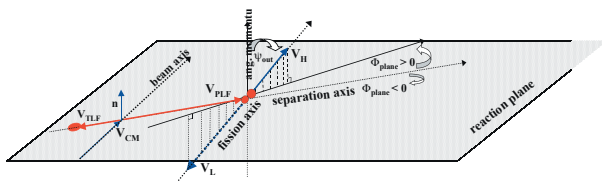


Fig.3. Diagram indicating the definition of the in-plane (ϕ_{plane}) and out-of-plane (ϕ_{out}) angles.

The direction $\phi_{\text{plane}} = 0^\circ$ in Figs. 3, 4 corresponds to the heavier fragment moving forward, strictly along the PLF flight direction; according to the sign convention chosen in ref. [2], positive ϕ_{plane} value mean that the fragment is deflected towards the beam direction.

The slow (equilibrated) fission, because of losing memory after many PLF rotations, should result in the flat in-plane distribution [2]. We see, however, distinct maxima in the distributions, located close to 0° , being a manifestation of dynamical fission. For moderately mass asymmetric divisions ($A_H/A_L = 2.6 - 4.6$) the maximum dominates the flat equilibrated component, seen at angles around $\phi_{\text{plane}} = 120^\circ$ and -120° . For

smaller mass asymmetries the maximum, even if weaker, is still distinct. This clearly points to non-equilibrium dynamical fission processes: the existence of the maximum means that the process is fast, otherwise one would observe the averaged-out, flat angular distribution.

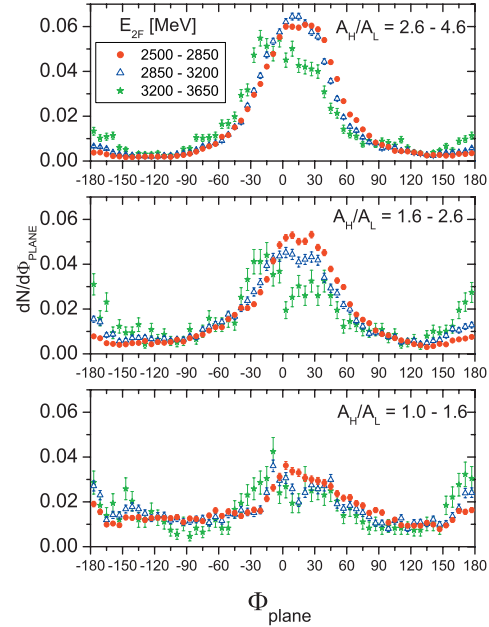


Fig. 4. Normalized to unity in-plane angular distributions of the heavier fragment from the PLF splitting.

The dips in the in-plane distribution close to $\pm 15^\circ$ and $\pm 165^\circ$, are caused by the beam evacuation hole of the detector system.

Since statistical fission should result in the flat in-plane distribution, its contribution is easy to calculate and in this way we could estimate *lower limits* of DF probability (see Table I) in function of E_{2F} and splitting asymmetries.

Table I: Lower limits of DF percentage defined as $DF/(DF + \text{statistical})$

		A_H/A_L		
		1.0-1.6	1.6-2.6	2.6-4.6
E_{2F} [MeV]	3200-3650	0.57	0.60	0.83
	2850-3200	0.36	0.70	0.87
	2500-2850	0.40	0.76	0.87

C. Relative velocities

Next information on the properties of the DF phenomenon can be obtained from analysis of relative velocities of two heaviest fragments. It turns out that the ring-like structures in the V_{par}^L vs. V_{per}^L plots are not circular but rather remind ellipses. In Fig. 5 we present angular distributions of the relative velocity normalized to the velocity due to the Coulomb repulsion, taken

event-by-event according to the Viola systematics for asymmetric systems [11]. It is seen that the predictions based on this systematics, established for equilibrium fission, agree with our data only for fragments emitted at large angles (greater than $\pm 70^\circ$), while for the DF the relative velocities become larger by some 10 - 40% even for A_H/A_L close to 1.0.

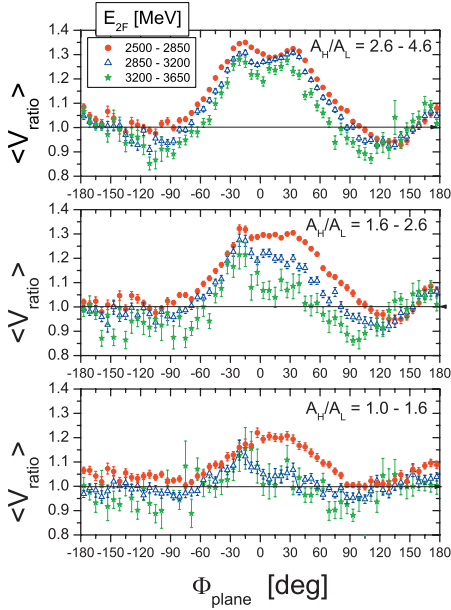


Fig. 5. Mean values of the relative velocity of the PLF fragments normalized by Viola systematics (V_{ratio}) in function of the in-plane angle for different centralities of collision and asymmetries of the PLF splits.

This means that in dynamical fission, even if it appears to be a definitely sequential process, the velocity field of various parts of the PLF did not attain equilibrium. This effect is weakest for more symmetric splitting, what points to the longer time scale in this case.

D. Time scale estimation

According to the method and discussion reported in [10] and applied in [12] we can estimate that the time interval between collision and PLF splitting is in the limits of 100 - 300 fm/c. This is much shorter time scale than that necessary for the equilibrated fission which, according to many experiments, is at least 10 - 100 times longer [13,14]; the fragments emitted on the shortest time scale ($t < 100 - 150$ fm/c) are visible outside the Coulomb rings [10].

IV. DYNAMICAL FISSION AND BNV CALCULATIONS

Some light on the dynamics of these splitting processes could be shed by theoretical predictions within the Boltzmann–Nordheim–Vlasov transport

model [7]. The simulations based on this model describe well the “neck emission”, but have problems with predicting existence of the experimentally observed fragments, having larger velocities and forming the ring-like structures, demonstrating sequential decay of some well defined sources.

One should stress that the model does predict production of the strongly deformed PLFs, which might be candidates to undergo dynamical fission, having the time scale slowed down with respect to the neck fragmentation, among others due to the more symmetric splitting. There exist some arguments supporting the idea that DF, i.e. the fast sequential PLF splitting, is essentially of the same nature as that described as “neck fragmentation”.

V. SUMMARY

We studied the $^{124}\text{Sn} + ^{64}\text{Ni}$ reaction at 35 A·MeV energy. The selected events fulfilled the condition of observing the PLF splitting into 2 main fragments after mid-peripheral collision. The more asymmetric splittings, giving rise to very light fragments, are described well as the neck fragmentation, occurring almost immediately after collision [7,10]. However, the PLF splitting in comparable fragments ($A_H/A_L < 4.6$) has been also observed in quite a large portion. This class of events is dominated by clearly sequential process: fission after collision. In at least 35 - 90% of cases, depending on kinetic energy loss in the collision and on the splitting asymmetry, in relatively short time after collision ($t < 600$ fm/c) PLFs undergone dynamical fission into two aligned fragments; in the rest of cases we observe the typical, equilibrium fission, known to be slower by one or two orders of magnitude [12].

REFERENCES

- [1] P.Glassel et al., Z.Phys. A 310(1983)189.
- [2] A.A.Stefanini et al., Z.Phys. A 351(1995)167.
- [3] F.Bocage et al., Nucl.Phys. A 61(2000)391.
- [4] J.Colin et al., PRC 67(2003)064603.
- [5] G.Poggi et al., Nucl.Phys. A 685(2001)296c.
- [6] J.Łukasik et al., Phys.Rev. C55(1997)1906.
- [7] V.Baran et al., Nucl. Phys. A730(2004)329.
- [8] A.Pagano et al., Nucl.Phys. A 681(2001)331c and reference therein.
- [9] A.Pagano et al., Nucl.Phys. A734(2004)504.
- [10] J.Wilczynski et al., Intl. J. Mod. Phys. 14, 353 (2005);
- [11] E.De Filippo et al., PRC 71, 044602 (2005).
- [12] D.J.Hinde et al., Nucl.Phys. A472(1987)318.
- [13] E.De Filippo et al., PRC, in press.
- [14] D.Hilscher and H.Rossner, Ann.Phys. Fr. 17(1992)471.
- [15] F.Goldenbaum et al., PRL 25(1999)5012.

SEARCH FOR TOROIDAL AND BUBBLE LIKE NUCLEI FORMED IN THE AU + AU COLLISIONS

R.Planeta^g, C.Agodi^a, R.Alba^a, F.Amorini^a, A.Anzalone^a, L.Auditorè^d, V.Baran^e, I.Berceanu^e, J.Blicharska^f, J.Brzychczyk^g, B.Borderie^h, R.Bougaultⁱ, M.Bruno^j, G.Cardella^b, S.Cavallaro^a, R.Coniglione^a, M.B.Chatterjee^k, A.Chbihi^l, J.Cibor^m, M.Colonna^a, M.D'Agostino^j, E.DeFilippo^b, R. Dayras^o, A.DelZoppo^a, M.DiToro^a, J.Frankland^l, E.Galichet^h, W. Gawlikowicz^g, E.Geraci^j, F.Giustolisi^a, A.Grzeszczuk^f, P.Guazzoni^p, D.Guinet^q, P.Hachaj^u, M.Iacono-Manno^a, S.Kowalski^f, E. La Guidara^a, G.Lanzanò^b, G.Lanzalone^a, C.Maiolino^a, N.LeNeindre^h, N.G.Nicolisⁱ, Z.Majka^g, A.Pagano^b, M.Papa^b, M.Petrovici^e, E.Piasecki^r, S.Pirrone^b, R.Planeta^g, G.Politi^b, A.Pop^e, F.Porto^a, M.F.Rivet^h, E.Rosato^s, F.Rizzo^a, S.Russo^p, P.Russotto^l, D.Santonocito^a, M.Sassi^p, K.Schmidt^f, K.Siwiek-Wilczyńska^r, I.Skwira^r, M.L.Sperduto^b, A.Sochocka^g, L.Świderski^r, A.Trifirò^d, M.Trimarchi^d, G.Vanniniⁱ, G.Verde^b, M.Vigilante^s, J.P.Wielecško^l, J.Wilczyński^c, L.Zetta^p, and W.Zipper^f

(CHIMERA-ISOSPIN Collaboration)

- a) INFN, Laboratori Nazionali del Sud and Dipartimento di Fisica e Astronomia, Università di Catania, Italy
 - b) INFN, Sezione di Catania and Dipartimento di Fisica e Astronomia, Università di Catania, Italy
 - c) A. Soltan Institute for Nuclear Studies, Swierk/Warsaw, Poland
 - d) INFN, Gruppo Collegato di Messina and Dipartimento di Fisica, Università di Messina, Italy
 - e) Institute for Physics and Nuclear Engineering, Bucharest, Romania
 - f) Institute of Physics, University of Silesia, Katowice, Poland
 - g) M. Smoluchowski Institute of Physics, Jagellonian University, Cracow, Poland
 - h) Institute de Physique Nucléaire, IN2P3-CNRS, Orsay, France
 - i) LPC, ENSI Caen and Université de Caen, France
 - j) INFN, Sezione di Bologna and Dipartimento di Fisica, Università di Bologna, Italy
 - k) Saha Institute of Nuclear Physics, Kolkata, India
 - l) GANIL, CEA, IN2P3 – CNRS, Caen, France
 - m) H. Niewodniczanski Institute of Nuclear Physics, Cracow, Poland
 - o) DAPNIA / SPHn, CEA – Saclay, France
 - p) INFN, Sezione di Milano and Dipartimento di Fisica, Università di Milano, Italy
 - q) IPN, IN2P3 – CNRS and Université Claude Bernard, Lyon, France
 - r) Institute for Experimental Physics, Warsaw University, Warsaw, Poland
 - s) INFN, Sezione Napoli and Dipartimento di Fisica, Università di Napoli, Italy
 - t) Department of Physics, University of Ioannina, Ioannina, Greece
 - u) Cracow University of Technology, Cracow, Poland
- * Corresponding author, e-mail: ufplanet@cyf-kr.edu.pl

Abstract

We study the feasibility for an experimental observation of toroidal and bubble like nuclei in the Au + Au collisions. The current status of reaction simulations, developed for this purpose, is presented.

It was suggested 55 years ago by Wheeler that nuclear objects formed in heavy ion collisions can assume nonspherical shapes [1,2]. This idea was investigated in following years by many authors [3-15]. In these works both stability of exotic systems and dynamics leading to formation of such objects were tested. A number of observables were suggested as the signatures of noncompact nuclear system breakup configurations, e.g. enhanced similarity in the charges of large fragments.

The experimental evidence for the decay of noncompact geometries up to now is limited to results obtained by Stone et al. [16]. The authors noticed a 5% enhancement of the intermediate mass fragments emission and similarity of these fragment charges for the $^{86}\text{Kr} + ^{93}\text{Nb}$ reaction measured at energies ranging from 35 to 95 MeV/nucleon.

In this contribution, we present the feasibility study for the experimental observation of toroidal and bubble like nuclei. This search is based on data collected by the CHIMERA collaboration for the Au

+ Au and Au + C reactions at 15 MeV/nucleon. The experiment was performed at INFN – LNS in Catania using the 4 π CHIMERA multidetector [17].

In the first step of our analysis, we have established an identification method of heavy fragments using raw (uncalibrated) experimental data [18]. The multiplicity distributions of heavy fragments for both reactions are presented in Fig. 1. For the Au + C system this distribution is limited to multiplicities smaller than 4 and has a maximum at multiplicity 2 corresponding to a fission of Au nucleus. The distribution for the Au + Au reaction is much broader indicating that processes other than fission of Au nuclei are involved.

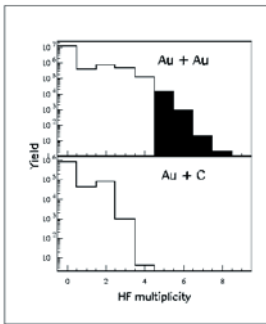


Fig. 1. The multiplicity distributions of heavy fragments for Au + Au and Au + C reactions (black area correspond to events with at least five heavy fragments).

In order to test the applicability of CHIMERA multidetector for recognition of noncompact nuclear geometries the Monte Carlo simulation program ETNA (Expecting Toroidal Nuclear Agglomerations) was constructed. This code allows us to simulate the decay of the nuclear system assuming ball, disc, toroidal, bubble and rod-like break-up geometries.

For the Au + Au collisions at 15 MeV/nucleon all nucleons from projectile and target nuclei are assumed to form a composite system which breaks up into pieces. The number of resulting primary fragments, N_f , is an input to the simulation program. The fragments can be set in two alternative procedures: (i) the composite system divides into two with a Gaussian curve probability of charge distribution between them. The fragment to break next is selected with a probability equal to the portion of total system charge it carries. The process is repeated until the desired number of fragments is obtained (I method); (ii) fragment charges are drawn according to the Gaussian curve probability centered at Z_{tot}/N_f , where Z_{tot} is the total charge of the composite system (II method).

All the fragments are then placed within a freezout volume of density given by an input parameter. The shape of the freezout volume in the current version of the ETNA code can be: a sphere, a bubble, a disc, a toroid or a rod. The fragments are placed randomly inside the freezout volume. Then an overlap check is performed. If two or more fragments are to occupy the same location in space the placing procedure is repeated.

Energy conservation is then applied. The energy of the entrance channel (kinetic energy in the CM minus binding energy of the substrates) must not be less than the energy of the output channel (Coulomb energy minus binding energy of the products). If this does not happen – the event is discarded and the procedure starts from the beginning. The remaining energy is distributed between excitation energy of fragments and their thermal motion assuming the common temperature. In the next step of the procedure fragments are accelerated in the mutual Coulomb field. Finally simulation results are “filtered” by a software replica of the CHIMERA multidetector [19]. In the present calculations only granularity of the CHIMERA was taken into account.

Basic characteristics of the simulation results for the Au + Au reaction at 15 MeV/nucleon are presented in Fig. 2 for the case when 5 primary fragments are formed. Here distributions of charge, total detected charge and mass, multiplicity, angle of detected fragments, and total kinetic energy of detected

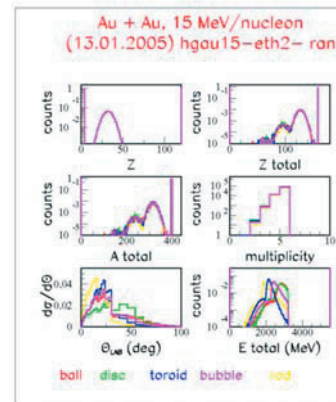


Fig. 2. Distributions of charge, total detected charge and mass, multiplicity, angle of detected fragments, and total kinetic energy of detected fragments for the Au + Au reaction.

fragments are shown. Different color curves correspond to different decaying objects. These results were obtained for fragment charges and masses

selected by the II method (see the charge distribution shown in the upper left panel).

Distributions of total detected charge and mass are showing characteristic structure corresponding to events with one or two undetected particles. The differences between breakup geometries are visible in angular distributions of detected fragments. Here also the geometrical structure of the CHIMERA detector is noticeable. Differences between total kinetic energy distributions for different breakup geometries are related to differences in Coulomb energy of fragment interaction in the freeze out volume.

In order to be able to disentangle between different break up geometries six observables were tested:

- θ_{12} – relative angle between two heaviest fragments;
- θ_{ij} – relative angle between all pairs of fragments;
- $\Delta\phi_{12}$ – azimuthal angle difference between two heaviest fragment;
- $\Delta\phi_{ij}$ – azimuthal angle difference between all pairs of fragments;
- planarity – measure of system flatness;
- $1 + R(v_{red})$ – two particle correlation function;

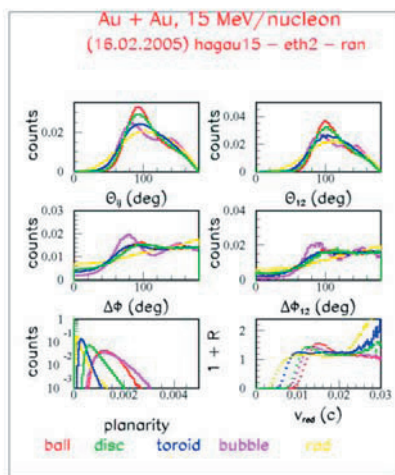


Fig. 3. Distributions of tested observables.

Distributions of the above observables are shown in Fig. 3 for tested breakup geometries. One can see that the distributions for the first four observables corresponding to different geometries are very similar. Noticeable differences are observed for planarity and $1+R$ correlation function. Presented in Fig. 3 results were obtained for fragment charges and masses

selected by the II method. Inspection of the same distributions generated using method I for fragment selection gives similar differences for planarity and $1+R$.

These simulations will be further refined with the inclusion of mass, charge and recoil corrections due to evaporation from the excited fragments. The relevant subroutines have been prepared [20].

In this contribution the feasibility study of experimental observation of toroidal and bubble nuclei in the Au + Au reaction is presented. Present status of the Monte Carlo simulation predictions is shortly discussed. Further simulations should be extensively compared with experimental data in order to drawn any conclusions about existence of exotic nuclear objects.

REFERENCES

- [1] J.A.Wheeler, "Nucleonic Notebook", 1950 (unpublished).
- [2] R.E.Euwema and J.A.Wheeler, unpublished.
- [3] P.J.Siemens and H.Bethe, Phys. Rev. Lett. 18 (1967) 704.
- [4] C.Y.Wong, Phys. Rev. Lett. 55 (1985) 1937.
- [5] L.G.Moretto et al., Phys. Rev. Lett. 78 (1997) 824.
- [6] C.Fauchard and G.Royer, Nucl. Phys. A598 (1996) 125.
- [7] W.Bauer et al., Phys. Rev. Lett. 69 (1992) 1888.
- [8] L.G.Moretto et al., Phys. Rev. Lett. 69 (1992) 1884.
- [9] S.R.Souza and C.Ngo, Phys. Rev. C48 (1993) R2555.
- [10] B.Borderie et al., Phys. Lett. B302 (1993) 15.
- [11] H.M.Xu et al., Phys. Rev. C49 (1994) R1778.
- [12] D.O.Handzy et al., Phys. Rev. C51 (1995) 2237.
- [13] L.Phair et al., Phys. Lett. 314 (1993) 271.
- [14] C.Y.Wong, Ann.Phys. (N.Y.) 77 (1973) 279.
- [15] T.Glasmacher et al., Phys. Lett. B314 (1993) 265.
- [16] N.T.B.Stone et al., Phys. Rev. Lett. 78 (1997) 2084.
- [17] A.Aiello et al., Nucl. Phys. A583 (1995) 461.
- [18] R.Planeta et al., Activiti Report 2003, LNS-INFN, Catania, 2003.
- [19] W.Gawlikowicz, The software replica of the Chimera multidetector, (<http://zeffr.if.uj.edu.pl/catania>).
- [20] N.G.Nicolis (private communication).

ISOSPIN EFFECTS IN NEUTRON-RICH AND NEUTRON-POOR Sn+Ni SYSTEMS

R. Płaneta^g, C. Agodi^a, R. Alba^a, F. Amorini^a, A. Anzalone^a, L. Auditore^d, V. Baran^e, I. Berceanu^e, J. Blicharska^f, J. Brzychczyk^g, B. Borderie^h, R. Bougaultⁱ, M. Bruno^j, G. Cardella^b, S. Cavallaro^a, R. Coniglione^a, M. B. Chatterjee^k, A. Chbihi^l, J. Cibor^m, M. Colonna^a, M. D'Agostino^j, E. De Filippo^b, R. Dayras^o, A. Del Zoppo^a, M. Di Toro^a, J. Frankland^l, E. Galichet^h, W. Gawlikowicz^g, E. Geraci^j, F. Giustolisi^a, A. Grzeszczuk^f, P. Guazzoni^p, D. Guinet^q, M. Iacono-Manno^a, S. Kowalski^f, E. La Guidara^a, G. Lanzaⁿ, G. Lanzalone^a, C. Maiolino^a, N. Le Neindre^h, N. G. Nicolis^t, Z. Majka^g, A. Pagano^b, M. Papa^b, M. Petrovici^e, E. Piasecki^r, S. Pirrone^b, R. Płaneta^g, G. Politi^b, A. Pop^e, F. Porto^a, M. F. Rivet^h, E. Rosato^s, F. Rizzo^a, S. Russo^p, P. Russotto^l, D. Santonocito^a, M. Sassi^p, K. Schmidt^f, K. Siwek-Wilczyńska^r, I. Skwira^f, M. L. Sperduto^b, A. Sochocka^g, L. Świdorski^r, A. Trifirò^d, M. Trimarchi^d, G. Vannini^j, G. Verde^b, M. Vigilante^s, J. P. Wieleczko^l, J. Wilczyński^c, L. Zetta^p, and W. Zipper^f

(CHIMERA-ISOSPIN Collaboration)

- a) INFN, Laboratori Nazionali del Sud and Dipartimento di Fisica e Astronomia, Università di Catania, Italy
 - b) INFN, Sezione di Catania and Dipartimento di Fisica e Astronomia, Università di Catania, Italy
 - c) A. Soltan Institute for Nuclear Studies, Swierk/Warsaw, Poland
 - d) INFN, Gruppo Collegato di Messina and Dipartimento di Fisica, Università di Messina, Italy
 - e) Institute for Physics and Nuclear Engineering, Bucharest, Romania
 - f) Institute of Physics, University of Silesia, Katowice, Poland
 - g) M. Smoluchowski Institute of Physics, Jagellonian University, Cracow, Poland
 - h) Institut de Physique Nucléaire, IN2P3-CNRS, Orsay, France
 - i) LPC, ENSI Caen and Université de Caen, France
 - j) INFN, Sezione di Bologna and Dipartimento di Fisica, Università di Bologna, Italy
 - k) Saha Institute of Nuclear Physics, Kolkata, India
 - l) GANIL, CEA, IN2P3 – CNRS, Caen, France
 - m) H. Niewodniczanski Institute of Nuclear Physics, Cracow, Poland
 - o) DAPNIA / SPhN, CEA – Saclay, France
 - p) INFN, Sezione di Milano and Dipartimento di Fisica, Università di Milano, Italy
 - q) IPN, IN2P3 – CNRS and Université Claude Bernard, Lyon, France
 - r) Institute for Experimental Physics, Warsaw University, Warsaw, Poland
 - s) INFN, Sezione Napoli and Dipartimento di Fisica, Università di Napoli, Italy
 - t) Department of Physics, University of Ioannina, Ioannina, Greece
- * Corresponding author, e-mail: ufplanet@cyf-kr.edu.pl

Abstract

Isospin effects are studied for neutron-rich, $^{124}\text{Sn} + ^{64}\text{Ni}$, and neutron-poor, $^{112}\text{Sn} + ^{58}\text{Ni}$, systems at 35 A MeV. The experimental data were compared with quantum molecular dynamics calculations for peripheral collisions. It was found that in the $^{124}\text{Sn} + ^{64}\text{Ni}$ reaction the neutron richness of emitted clusters is enhanced, and the number of emitted protons is reduced.

The isospin dependence of nuclear equation of state, EOS, is among the most important but poorly known properties of nuclear matter [1], [2], [3]. Knowledge of the density dependence of symmetry energy term in EOS is important for: (i) studies of structure of nucleus (neutron skin [4], determination of the stability boundaries of neutron rich nuclei), (ii) nuclear reactions models, and (iii) mechanism of nuclear

multifragmentation. Interest on properties of neutron rich matter has also an astrophysical aspect, e.g. mechanism of type II supernova explosions, formation and structure of neutron stars.

Several approaches were proposed to obtain information on symmetry energy term, $E_{\text{sym}}(\rho)$, of the EOS. For the case of low densities of nuclear matter

they comprise: (i) n/p ratio of fast pre-equilibrium nucleons [5], (ii) $t^3\text{He}$ ratios, (iii) isospin diffusion [6], [7], (iv) isospin fractionation (distillation) and isoscaling in nuclear multifragmentation [8], (v) neutron-proton differential flow [9], and (vi) neutron-proton and proton-proton correlation functions at low relative momenta [10].

Simulations of reaction dynamics have shown [11], that collisions of asymmetric nuclei (N/Z) could lead to a unique information on the symmetry energy term of NEOS. It was shown that the main reaction mechanisms, from fusion to deep inelastic and fragmentation, appear quite sensitive to the form of the symmetry term of the effective force used. The calculations of Baran et al. [3] evidence a characteristic behavior of the N/Z of the intermediate mass fragments as a function of the centrality of reaction. For peripheral collisions IMF will be emitted in a statistical way from the excited PLF and TLF sources close to the stability line. For semiperipheral events the neck-fragmentation mechanism will form more neutron-rich fragments. For central collisions the neutron distillation will take place and fragments will be again much more symmetric. The relevance of such behavior is related to the stiffness of the symmetry term at subnuclear densities.

For a class of central collisions for the $^{112,124}\text{Sn} + ^{112,124}\text{Sn}$ systems at 50 MeV/nucleon it was found that: (i) gas phase is more enriched in neutrons than the liquid phase represented by fragments, consistent with the predicted partial fractionation of nucleon components in the liquid-gas phase transition; (ii) the observed effects are significantly enhanced in neutron-rich systems relative to the neutron-deficient systems [12]. The same conclusions were drawn from data analysis for central collisions of $^{124}\text{Sn} + ^{64}\text{Ni}$ and $^{112}\text{Sn} + ^{58}\text{Ni}$ at 35 MeV/nucleon. The isoscaling analysis using the ratios of the isotopic yields has been performed. The results are consistent with the effect of isospin distillation [13].

The experiment was performed at LNS in Catania using the forward part of the CHIMERA 4π multidetector array [14]. There were a total of 688 Si-CsI(Tl) detectors used, covering the polar angle range between 1° and 30° with full azimuthal symmetry around the beam axis. Reverse kinematics of $^{124,112}\text{Sn} + ^{64,58}\text{Ni}$ reactions at 35 MeV/nucleon allowed the use of this set-up as an effective 4π device.

In this contribution we will focus our attention on noncentral collisions for $^{124}\text{Sn} + ^{64}\text{Ni}$ and $^{112}\text{Sn} + ^{58}\text{Ni}$ reactions at 35 MeV/nucleon. Due to properties of CHIMERA detector and the reverse kinematics of studied reactions we can expect particles originating from projectile-like fragment source, PLF, intermediate velocity source, IVS, and partly from target-like fragments, TLF. Class of events corresponding to noncentral interaction was selected using conditions: (i) the large amount of total charge and projectile momentum is detected, and (ii) the PLF

remnant is visible. The analysis presented in this report was performed only for a class of events selected by the above described conditions.

In our analysis the experimental data were compared with the model calculations performed using the CHIMERA code [15]. This code is representing a Quantum-Molecular Dynamics (QMD) approach with features of Quasi-Particle Dynamics (QPD) [16]. The code uses, partially, the QMD approach from [17]. Values of the potential parameters correspond to a soft EOS ($K \approx 200$ MeV). The symmetry energy strength coefficient was chosen as: $C = 31.4$ MeV (ASY-STIFF).

Calculations with the CHIMERA code were executed up to 300 fm/c. After that time, all nucleons separated in configuration space by less than 3 fm were assumed to form a cluster. The hot fragments decay afterwards via sequential decay which is simulated by the GEMINI code [18]. In the present calculations, the dynamical version of the GEMINI code was used [19]. Here, excited fragments were decayed in flight with proper time constants. The equations of motion of all

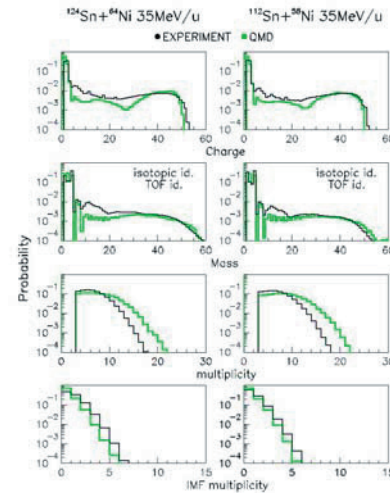


Fig. 1. Charge, mass, total and IMF multiplicity distributions for $^{124}\text{Sn} + ^{64}\text{Ni}$ and $^{112}\text{Sn} + ^{58}\text{Ni}$ systems.

charged fragments moving in the mutual Coulomb field were integrated numerically. All simulation results were "filtered" by an exact software replica of the CHIMERA multidetector [20].

For a class of events corresponding to noncentral collisions a comparison between experimental data and CHIMERA/GEMINI predictions for selected observables is presented in Fig. 1.

In order to study evolution of heavy-ion reactions with respect of centrality of the collision it is necessary to use impact parameter related variables. Such variables allow to analyze reaction evolution with respect to excitation energy, energy dissipation, entrance channel angular momentum, etc [21]. In the present analysis we have tested several variables as

impact parameter estimators for a class of peripheral-like collisions. The Fig. 2 shows a correlation between impact parameter, b , and velocity of the heaviest fragment normalized to the projectile velocity in CM system, $V_{Z\max}^{CM} / V_p^{CM}$. This variable was used in the further analysis as impact parameter estimators.

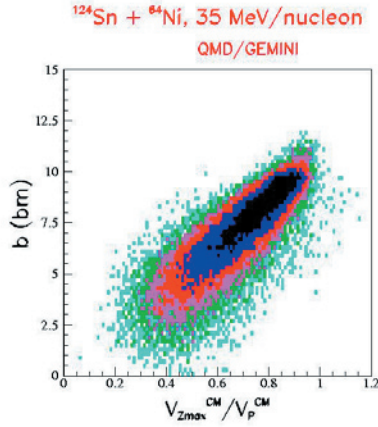


Fig. 2 Impact parameter estimators for $^{124}\text{Sn} + ^{64}\text{Ni}$ system (CHIMERA/GEMINI predictions)

The left column of Fig. 3 presents the yield of different isotopes per event as a function of velocity of the heaviest fragment normalized to the projectile velocity in CM system, $V_{Z\max}^{CM} / V_p^{CM}$, while the right

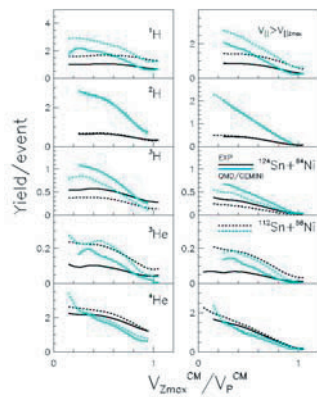


Fig. 3 Yield of light particles per event as a function of velocity of the heaviest fragment normalized to the projectile velocity $V_{Z\max}^{CM} / V_p^{CM}$.

column shows particle yield per event for selected PLF region. Here particles with parallel velocity higher

than $V_{||, Z\max}$ were attributed to the PLF region. Generally, emission of light charged-particles increases with decreasing impact parameter. The predictions of the QMD/GEMINI simulations are close to experimentally observed yields for very peripheral collisions (large $V_{Z\max}^{CM} / V_p^{CM}$). With an increase of collision centrality (decrease of $V_{Z\max}^{CM} / V_p^{CM}$) the model overestimates the emission rates, especially for hydrogen isotopes. As one can see, the change of cluster production rates, as a function of isospin, is different for hydrogen and helium isotopes. Neutron richness leads to increased triton production, while reducing the number of emitted ^3He clusters.

The influence of the entrance channel on particle production can be also seen in Fig. 4 where the ratio of tritons to ^3He yield per event is shown. One observes that for neutron-rich system the number of tritons is about six times larger than the number of ^3He particles. For neutron-poor system this ratio is much lower at the level of two. The behavior of the curves for particles observed in the PLF region is similar, however the ratios are somewhat lower and one can see some impact parameter dependence.

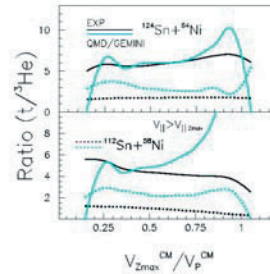


Fig. 4. Ratio of tritons to ^3He yield as a function of $V_{Z\max}^{CM} / V_p^{CM}$.

In order to get insight into the mechanism of fragment formation Fig. 5 present the spectra of observed IMF fragments for both reactions as a function of parallel velocity in CM system. One observes that when the mass of the fragment increase (starting from ^7Be) more of them is located close to the midrapidity region. Practically no fragments are observed in the PLF region.

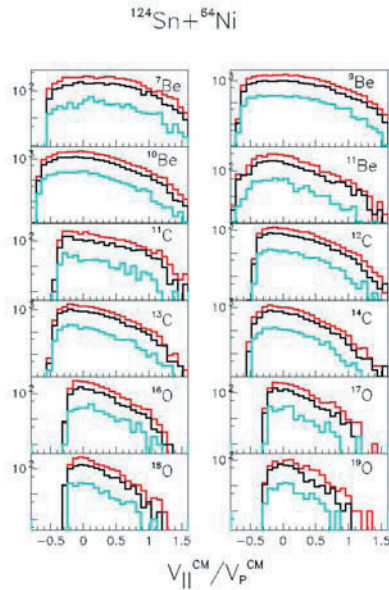


Fig. 5. The IMF fragments spectra projected on the beam axis for $^{124}\text{Sn} + ^{64}\text{Ni}$ reaction for consecutive windows of $V_{Z\text{max}}^{\text{CM}} / V_P^{\text{CM}}$ (0.4-0.6 – blue, 0.6-0.8 – black, 0.8-1.0 – red). Fragment velocities are normalized to the projectile velocity.

Isospin effects for neutron-rich and neutron-poor Sn+Ni systems were studied at 35 MeV/nucleon. The QMD calculations, presented in this contribution, were made for ASY-STIFF parametrization of symmetry energy strength coefficient ($C = 31.4$ MeV). Calculations performed for ASY-SOFT parametrization ($C = 76.5-45.1\rho/\rho_0$ MeV) gave nearly the same result.

In the $^{124}\text{Sn} + ^{64}\text{Ni}$ reaction the neutron richness of emitted clusters is enhanced, and the number of emitted protons is reduced. One observes a large difference of the triton to ^3He particles ratio. These observations are interpreted as spin-isospin effect. Inspection of IMF spectra shows that the main source of their emission is the midrapidity region.

REFERENCES

- [1] Bao-An Li et al., Int. J. Mod. Phys. E7 (1998)147;
- [2] Bao-An Li et al., Nucl. Phys. A699 (2002) 493;
- [3] V. Baran et al., Nucl. Phys. A703 (2002) 603;
- [4] B. Alex Brown, Phys. Rev. Lett. 85 (2000) 5296;
- [5] W.U.Schröder and J.Töke, Nucl. Phys. A681 (2001) 418c;
- [6] M.B. Tsang et al., Phys. Rev. Lett. 92 (2004) 062701;
- [7] Lie-Wen Chen et al., Phys. Rev. Lett. 94 (2005) 032701;
- [8] A.Ono et al., Phys. Rev. C68 (2003) 051601;

- [9] Bao-An Li, Phys. Rev. Lett. 85 (2000) 4221;
- [10] R.Ghetti et al., Phys. Rev. C69 (2004) 031605;
- [11] M.Colonna et al., Phys. Rev. C57 (1998)1410;
- [12] H.S.Xu et al., Phys. Rev. Lett. 85 (2000) 716;
- [13] E.Geraci et al., Nucl. Phys. A732 (2004) 173;
- [14] S.Aiello et al., Nucl.Phys. A583 (1995) 461;
- Nucl. Instr. and Meth. A369 (1996) 50;
- Nucl. Instr. and Meth. A400 (1997) 469;
- IEEE Trans. on Nucl. Sci. 47, No.2 (2000) 114;
- [15] J.Łukasik and Z.Majka, Acta Phys. Pol. B24 (1993)1993;
- [16] D.H.Boal and J.N.Glosi, Phys. Rev. C38 (1988)1870; Phys. Rev. C38 (1988)2621;
- [17] J.Aichelin and H.Stöcker, Phys. Lett. B176 (1986)14;
- J.Aichelin, Phys. Rep. 202 (1991) 233;
- [18] R.J.Charity et al., Nucl. Phys. A483(1988)391;
- [19] W.Gawlikowicz, Acta Phys. Pol. 28 (1997) 1687;
- [20] W.Gawlikowicz, REPORT ZFGM-03-02, Kraków, 2003;
- The software replica of the Chimera multidetector, (<http://zeffr.if.uj.edu.pl/catania>).
- [21] J.D.Frankland et al., Nucl. Phys. A689 (2001) 905;

Thermodynamical coordinates of excited nuclear systems. Status of the THERMO experiment.

U. Abbondando^{a)}, S. Barlini^{b)}, C. Birattari^{c)}, R. Bougault^{d)}, M. Bruno^{e,*)}, G. Casini^{f)}, A. Clivio^{b)}, M.D'Agostino^{e)},
J. De Sanctis^{e)}, E. Gadioli^{c)}, E. Geraci^{e)}, F. Gramegna^{b)}, A. Giussani^{c)}, B. Guiot^{e)}, V. Kravchuk^{b)}, A. Nannini^{f)},
N. Le Neindre^{g)}, G. V. Margagliotti^{a)}, A. Moroni^{c)}, A. Olmi^{f)}, S. Piantelli^{f)}, G. Poggi^{f)}, G. Vannini^{e)}, L. Vannucci^{b)}
NUCL-EX Collaboration

F. Amorini^{h,i)}, L. Audatore^{j)}, G. Cardella^{i,k)}, Salv. Cavallaro^{h,i)}, E. De Filippo^{i,k)}, E. Galichet^{h,i)}, E. La Guidara^{h,i)},
G. Lanzalone^{h,i)}, C. Maiolino^{h,i)}, A. Pagano^{i,k)}, M. Papa^{i,k)}, S. Pirrone^{i,k)}, G. Politi^{i,k)}, A. Pop^{l)}, F. Porto^{h,i)},
F. Rizzo^{h,i)}, P. Russotto^{h,i)}, A. Trifirò^{j)}, M. Trimarchi^{j)}
for CHIMERA/ISOSPIN collaboration

a) Dipartimento di Fisica and INFN, Trieste, Italy

b) INFN, Laboratori Nazionali di Legnaro, Italy

c) Dipartimento di Fisica and INFN, Milano, Italy

d) LPC, Caen, France

e) Dipartimento di Fisica and INFN, Bologna, Italy

f) Dipartimento di Fisica and INFN, Firenze, Italy

g) IPN Orsay, France

h) INFN, Laboratori Nazionali del Sud, Catania, Italy

i) Dipartimento di Fisica ed Astrofisica, Università' di Catania, Italy

j) INFN, Gruppo Collegato, Messina, Italy

k) INFN, Sezione di Catania, Italy

l) Institute for Physics and Nuclear Engineering, Bucharest, Romania

** Corresponding author, e-mail: mauro.bruno@bo.infn.it*

Abstract

We report on the analysis of the Thermo experiment performed during the 2003 CHIMERA experimental campaign. ΔE -E and Fast-Slow analyses are in progress. The status of energy calibration is shown. A short description of the experiment is given and some results on the detector behavior are reported. A new measurement at higher energy will be performed in 2005. A very preliminary analysis of the first few detectors calibrated in mass and charge has been presented in 2004 report.

1 INTRODUCTION

The main interest of the NUCL-EX collaboration [1] is the investigation of dynamical and thermodynamical aspects of heavy ion reactions, through experiments to be performed at the INFN "Laboratori Nazionali di Fisica Nucleare" in Catania and in Legnaro. In particular in the Legnaro Laboratories we plan to use the Garfield apparatus, whereas in Catania we are using the Chimera [2] apparatus in its full configuration (1192 detectors).

The THERMO experiment has been proposed in 2002 and the measurements have been performed in July 2003. The main aim of this experimental line is to investigate the signals of the existence of different phases for finite nuclear matter, predicted by theoretical

calculations since the 60's, and to deduce from several experimental signals obtained within the same experimental program a circumstantial evidence of the occurrence of a liquid-gas phase transition [3].

In the recent years the signals for the phase coexistence and phase transition [4] have been extracted from experimental data through long and cumbersome procedures which backtrace the asymptotic data to the initial stage information. However, to better clarify this picture, many new and more precise measurements are needed.

The plan of the measurements with the Garfield and Chimera devices are in the framework of a systematic study of the coexistence region, starting from the liquid side, up to some A MeV of available energy. Indeed, from first measurements performed at the ALPI

accelerator (LNL) with the Garfield apparatus at relatively low excitation energies (~ 3 AMeV) it resulted that nuclear systems of $A \approx 100$, formed in central collisions, already manifest a critical behavior, with the opening of the multifragmentation channel [5].

The measurements performed in 2003 in LNS are $^{58,62}\text{Ni} + ^{40,48}\text{Ca}$ at 25 AMeV. A further measurement of the same reactions at 35 AMeV has been approved by the PAC and will be performed in the fall of 2005.

These reactions are expected to give rise to a fused system with $Z \approx 40$, $N/Z \approx 1.02$ and 1.28 and excitation energies about 5 and about 7 AMeV, respectively. The expected cross section for this process is estimated of the order of 100-200 mb.

Due to the different N/Z values, the limiting temperature, i.e. the maximal temperature for a nucleus in a liquid phase at normal density [6], results 6.5 MeV and 8.4 MeV for the neutron-poor and for neutron-rich system [7], respectively. Different temperatures correspond to different liquid drop level density parameters (8 and 12, respectively) and this should give less *liquid (asymmetric)* partitions for the decay of the neutron-poor system with respect to the neutron-rich one at the phase coexistence. Also multifragmentation statistical models [8] predict microcanonical temperatures for the neutron-poor systems lower than those of neutron-rich over a wide range of excitation energies.

These theoretical predictions can be experimentally checked by measuring, together with the charge partition of the systems, also the isotopic composition of the emitted products.

The isotope double ratio temperatures can be calculated from data and the corrections to extract the microcanonical temperature of the system can be deduced not only via model comparisons, but also by estimating the excitation energy of primary fragments from the correlation functions between asymptotically detected fragments and light particles.

By evaluating the average volume of the system from Coulomb trajectory calculations and its isospin from the N/Z ratio of the decay products, the thermodynamical coordinates ($T - \rho$ and isospin) of the finite and equilibrated source at the phase coexistence can provide experimental information to the nuclear phase diagram.

2 ΔE -E ANALYSIS

The ΔE -E scatter plot for the different telescopes given by the silicon and CsI(Tl) stages of the CHIMERA telescopes have been analyzed to extract the charge and, when possible, the mass of the detected particles. For each channel only one signal has been obtained by matching the low and high gain chains by means of specific pulser runs. The method described in ref. [9] was used to parametrize the ΔE and E signals obtaining charge and mass identification starting from converted un-calibrated signals. The analysis for all the detectors

is close to the end. Only a final check on a small numbers of the detectors is needed to complete it. Good charge identification can be obtained in 908 detectors, mass identification can be obtained at least for charges up to 8-9 for 590 detectors. These percentages are also due to

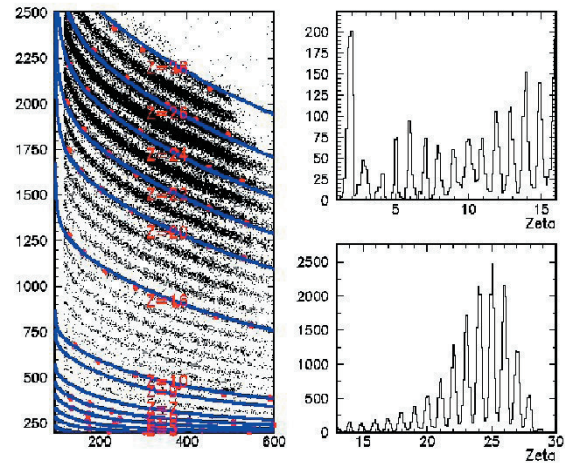


Fig. 1 Left panel: ΔE -E scatter plot for detector #12 of the first ring. Right panels: charge distribution for the same detector.

the fact that the Thermo experiment was the last experiment performed during the 2003 campaign.

The results of the calibration procedure are also suited to calibrate data of other experiments of the same campaign with the same amplifications. Only a shift in the centroids of some mass spectra are observed. A small change (around 4-6 channels) on the high gain silicon pedestal in general gives a very good mass determination. This has been checked for Limiting and Bose experiments [10].

Fig.1 shows the results for charge identification up to $Z = 28$ of the elastically scattered beam and the Z distribution for one of the detectors of the first ring. In Fig. 2 a matrix showing the very good mass resolution which can be obtained is presented. Fig. 2 shows also the corresponding mass distributions for $Z = 1 - 8$ for the same detector.

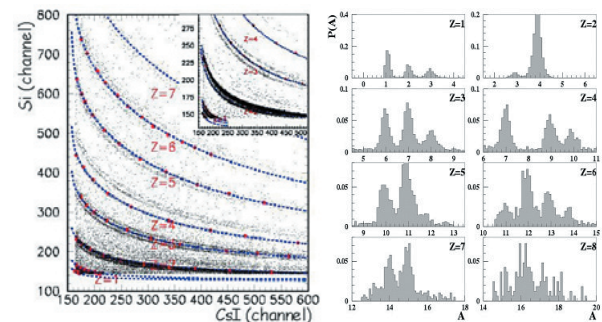


Fig. 2 Left panel: ΔE -E scatter plot. The very good mass identification appears. The insert shows a zoom for the lightest isotopes. Right panel: mass distribution for the same detector.

3 ENERGY CALIBRATIONS

Starting from the calibration in millivolt of the Silicon signals obtained by pulser runs, we have used 3 or 4 calibration or normalization points for each silicon detector in order to obtain the MeV to channels relation [11].

From the pulser we have obtained

$$\begin{aligned} V_{LG} &= a_{LG} x_{LG} + b_{LG} \\ V_{HG} &= a_{HG} x_{HG} + b_{HG} \end{aligned}$$

where V are the millivolt for low and high gain, the coefficients a and b give the mV/ch relation and the offset. The energy-millivolt relation $E(x) = \beta V(x)$ obtained with the calibration points of elastically scattered ^{12}C beams at 40 and 90 MeV and ^{16}O beams at 60 and 100 MeV on Au targets, allowed to obtain mean values of the β coefficient for low and high gains. Fig. 3 shows the obtained energy calibrations.

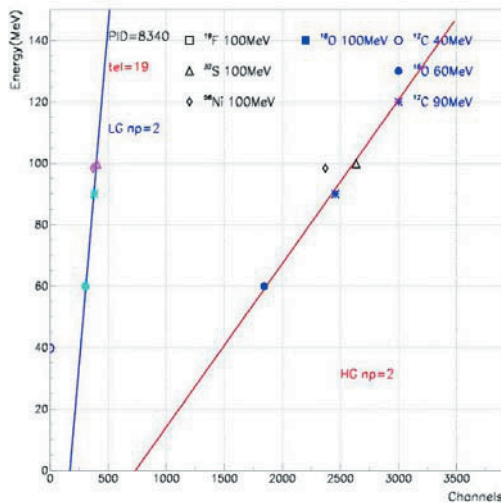


Fig. 3 Energy calibrations. Points not used for the calibrations and to be used for pulse height defect determination are also shown.

4 FAST-SLOW ANALYSIS

An analysis of Fast-Slow CsI(Tl) signals is able to identify charge and mass for light particles stopped in CsI detectors. This analysis is important for high energy particles which lose a small amount in the silicon detectors and cannot be identified with the method outlined in § 2. The Fast-slow analysis has been performed using a method used by INDRA collaboration [12]. The analysis is in progress. In Fig. 5 a sketch of the procedure of selecting points belonging to a given A,Z fragment and drawing a curve, is presented. Fig. 6 shows preliminary results of the mass distributions obtained through this procedure for 30 detectors of a given ring (4e). The very good superposition shows the very good behaviour of several CsI detectors at a time and the power of this kind of analysis.

5 PERSPECTIVES

Within this year we expect to have all the particles identified through ΔE -E and Fast-slow methods in charge (and mass when possible) for the reactions of the neutron poor and neutron rich systems. We will start to characterize the events which are due to the most central collisions. When also the particles identified by the E/ ΔE TOF method will be available, we will perform more careful and complete analyses of the central events.

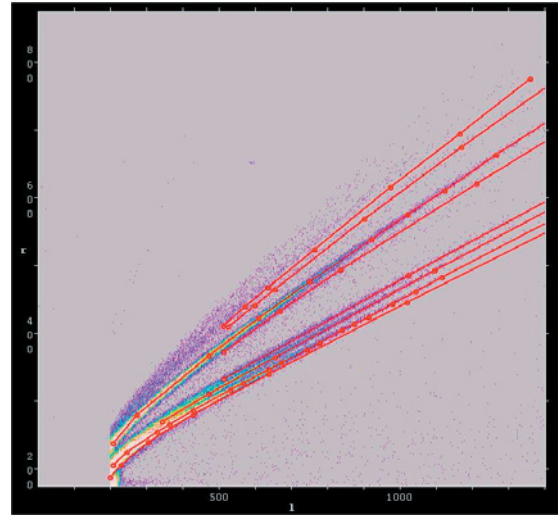


Fig.5 The fast slow components for a CsI detector.

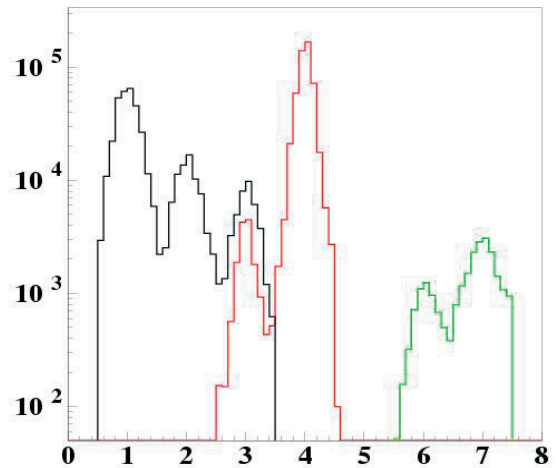


Fig.6 The isotopic identification obtained for 30 of the CsI telescopes (ring 4e, $\theta = 9^\circ$)

6 ACKNOWLEDGEMENTS

The NUCL-EX Collaboration would like to thank the technical staff of INFN Catania and LNS, for skillful operating of the whole apparatus and in particular the Laboratori Nazionali del Sud Tandem and

Cyclotron staff and D. Rifuggiato for having provided beams of very good quality for stability and timing. Special thanks to M. Loriggiola and G. Manente of LNL for making very good quality ^{40}Ca and ^{48}Ca targets.

We would like to thank in particular the work of Mr. Luca Morelli, who has learned very fastly and made with a very high efficiency part of the calibrations while doing his diploma thesis.

This work has been supported in part by grants of Alma Mater Studiorum (Bologna University).

REFERENCES

- [1] web-page www.bo.infn.it/nucl-ex/
- [2] S. Ajello *et al.* Nucl. Phys. A 583 (1995) 461.
- [3] Ph. Chomaz: The Nuclear Liquid Gas Phase transition and Phase Coexistence Int. Nucl. Phys. Conference INPC 2001, AIP Proceedings Vol.No.610 2002.
- [4] J. Pochodzalla *et al.* Phys. Rev. Lett 75, 1040 (1995); M. D'Agostino *et al.* Nucl. Phys. A650, 329 (1999); J. B. Elliott *et al.* Phys. Rev. Lett. 85, 1194 (2000); B. Borderie *et al.*, nucl-ex/0102015 and Phys. Rev. Lett. 86, 3252 (2001); V. Viola for ISIS collaboration, Nucl. Phys. A681, 199c(2001); M. F. Rivet, nucl-ex/0205010; M. D'Agostino *et al.* Phys. Lett. B473, 219(2000) and Nucl. Phys. A699, 795 (2002).
- [5] F. Gramegna *et al.* – Proc. of the Int. Conf. on Nucl. Phys. at Border Lines, Lipari, May 2001.
- [6] P. Bonche, S. Levit, H. Vautherin, Nucl. Phys. A427, 278 (1984); A436, 265 (1986); J. Besprosvany and S. Levit, Phys. Lett. B 217, 1 (1989).
- [7] J. B. Natowitz *et al.* Phys. Rev. C 65, 034618 (2002).
- [8] J. P. Bondorf, A. S. Botvina, A. S. Iljinov, I. N. Mishustin, K. Sneppen, Phys. Rep. 257, 133 (1995).
- [9] N. Leneindre, *et al.* Nucl. Instr. Meth. A490 (2002) 251.
- [10] see contributions to this issue.
- [11] see other contribution of the NUCL-EX coll. in this issue.
- [12] L. Tassan-Got, private communication

FRAGMENT-FRAGMENT CORRELATION IN $^{124}\text{Sn}+^{64}\text{Ni}$ AT 35A.MEV

C. Maiolino^{a,*}, C. Agodi^a, R. Alba^a, F. Amorini^a, A. Anzalone^a, L. Audatore^d, V. Baran^e, I. Berceanu^e, J. Blicharska^f, J. Brzychczyk^g, B. Borderie^h, R. Bougaultⁱ, M. Bruno^j, G. Cardella^b, S. Cavallaro^a, R. Coniglione^a, M. B. Chatterjee^k, A. Chbihi^l, J. Cibor^m, M. Colonna^a, M. D'Agostino^j, E. De Filippo^b, R. Dayras^o, A. DelZoppo^a, M. Di Toro^a, J. Frankland^l, E. Galichet^h, W. Gawlikowicz^g, E. Geraci^j, F. Giustolisi^a, A. Grzeszczuk^f, P. Guazzoni^p, D. Guinet^q, M. Iacono-Manno^a, S. Kowalski^l, E. La Guidara^a, G. Lanza^d, G. Lanzalone^a, N. Le Neindre^h, Z. Majka^g, A. Pagano^b, M. Papa^b, M. Petrovici^e, E. Piasecki^r, S. Pirrone^b, R. Płaneta^g, G. Politi^b, A. Pop^e, F. Porto^a, M. F. Rivet^h, E. Rosato^s, F. Rizzo^a, S. Russo^p, P. Russotto^l, D. Santonocito^a, M. Sassi^p, K. Schmidt^f, K. Siwek-Wilczyńska^r, I. Skwira^r, M. L. Sperduto^b, Ł. Swiderski^r, A. Trifirò^d, M. Trimarchi^d, G. Vannini^j, G. Verde^b, M. Vigilante^s, J. P. Wieleczko^l, J. Wilczyński^c, L. Zetta^p and W. Zipper⁶

a) INFN, Laboratori Nazionali del Sud and Dipartimento di Fisica e Astronomia, Università di Catania, Italy

b) INFN, Sezione di Catania and Dipartimento di Fisica e Astronomia, Università di Catania, Italy

c) A. Sołtan Institute for Nuclear Studies, Swierk/Warsaw, Poland

d) INFN, Gruppo Collegato di Messina and Dipartimento di Fisica, Università di Messina, Italy

e) Institute for Physics and Nuclear Engineering, Bucharest, Romania

f) Institute of Physics, University of Silesia, Katowice, Poland

g) M. Smoluchowski Institute of Physics, Jagellonian University, Cracow, Poland

h) Institut de Physique Nucleaire, IN2P3-CNRS, Orsay, France

i) LPC, ENSI Caen and Université de Caen, France

j) INFN, Sezione di Bologna and Dipartimento di Fisica, Università di Bologna, Italy

k) Saha Institute of Nuclear Physics, Kolkata, India

l) GANIL, CEA, IN2P3-CNRS, Caen, France

m) H. Niewodniczański Institute of Nuclear Physics, Cracow, Poland

o) DAPNIA/SPHN, CEA-Saclay, France

p) INFN, Sezione di Milano and Dipartimento di Fisica, Università di Milano, Italy

q) IPN, IN2P3-CNRS and Université Claude Bernard, Lyon, France

r) Institute of Experimental Physics, Warsaw University, Warsaw, Poland

s) INFN, Sezione Napoli and Dipartimento di Fisica, Università di Napoli, Italy

* Corresponding author, e-mail: Maiolino@lns.infn.it

Abstract

Particle-particle correlation method has been applied to ternary event in $^{124}\text{Sn}+^{64}\text{Ni}$ in inverse kinematics at 35A MeV using the forward part of CHIMERA detector at LNS. The results indicate the good performance of the apparatus for such correlation studies, opening new possibilities in the data analysis.

1 INTRODUCTION

The production of Intermediate Mass Fragment (IMF) is a phenomenon that takes places at intermediate energy, where both one body and two body dissipation play a role in reactions with heavy ions. The coexistence of both statistical and dynamical production mechanisms of IMF's, in the same class of events has been assessed in the study of $^{58}\text{Ni}+^{58}\text{Ni}$ collisions at 30A MeV [1]. Consequently, disentangling between different origins in IMF's production at intermediate energy is very important in order to identify the reaction mechanism. The particle-particle correlation functions are suitable tools to do that, because they give access to a quantitative measure of the space-time extension of the sources. An application of the particle-particle correlation functions to ternary events, collected by the

CHIMERA detector [2], in the inverse reaction $^{124}\text{Sn}+^{64}\text{Ni}$ at 35A MeV will be presented.

2 EVENT SELECTION

For each event, the contemporaneous presence of three fragments, the first having atomic number (Z) greater than 28 and beam parallel velocity greater than 6.0 cm/ns (PLF), the second with atomic number between 3 and 15 and a parallel velocity smaller than 2.0 cm/ns (TLF) and the third having atomic number between 3 and 10 and parallel velocity in the range 2.0÷8.0 cm/ns (IMF) has been required. In addition the condition that $Z_{\text{PLF}}+Z_{\text{TLF}}+Z_{\text{IMF}}\geq 60$ has been selected. In order to select semiperipheral and peripheral collisions, events have been sorted with a further cut of 8 in the particle multiplicity, that corresponds, according to the Cavata method [3], to impact parameters larger than 6.0

im. Moreover the constraint that the total linear momentum should be greater than 60% of the projectile linear momentum has been imposed.

3 REDUCED VELOCITY CORRELATION FUNCTIONS

Fragment-fragment correlation functions [4] have been studied as function of v_{red} [5]

$$1 + R(v_{red}) = \frac{\sum_{12} Y_{12}(v_{red})}{\sum_{mix} Y_{mix}(v_{red})} \quad (1)$$

where

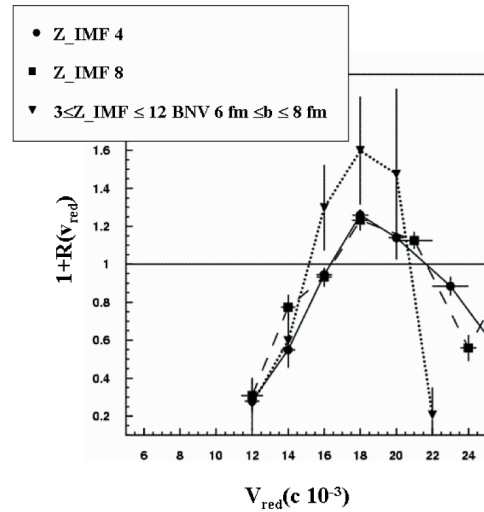
$$v_{red} = \frac{v_{rel}}{\sqrt{Z_1 + Z_2}}$$

In the equation 1) $Y_{12}(v_{red})$ is the coincidence yield between the fragments with charge Z_1 and Z_2 , normalized to its integral and $Y_{mix}(v_{red})$ is the background yield (normalized to its integral) constructed by event mixing, i.e., by randomly selecting each of the fragment pair from different events of the same class [4]. v_{rel} is the relative velocity between the pair fragment. The use of v_{red} has the advantage that different pairs of fragments, with different charges, can be compared. The particle-particle correlation function is dominated by final state interactions. Therefore the correlation function is expected to be strongly suppressed in the case of simultaneous emission of fragments due to their mutual Coulomb repulsion.

4 RESULTS

A previous analysis has shown that constraining the IMF velocity between 3.0 cm/ns and 5.0 cm/ns corresponds to select IMF's that are candidate to be emitted in a close configuration between projectile and target [6]. The correlation function has been applied to the pair PLF IMF satisfying the previous constraint. In the figure the correlation functions for the pair PLF-IMF with $Z_{IMF}=4$ (full circles) and $Z_{IMF}=8$ (full squares) are shown. The lines only guide the eyes. There is no substantial difference in the correlation functions for the two different charges, indicating that the selected IMF's are emitted at the same time. These results have been compared with the ternary events of a microscopic stochastic Boltzmann-Nordheim-Vlasov (BNV) simulation (filtered with the acceptance of the detector) for initial impact parameter configuration ranging between $b=6$ fm and $b=8$ fm [7]. The simulation shows that for these impact parameters a large fraction of events has essentially binary character. Ternary events are present with a maximum probability of about 25% around 6-7 fm. For such events the IMF's are dynamically originated by the break of a neck-like structure formed in the region of contact between

projectile and target, break due to the development of volume and surface instabilities [5]. The qualitative agreement between data and simulation seems promising, indicating that BNV simulations are able to predict the observed trend in the experimental data. The inclusion of the non considered velocity resolution (up to 5% depending on the charge state) in the theoretical output, could widen the distribution increasing the agreement with the data. Moreover IMF's of not dynamical origin, present in the experimental data could blur the distribution. Further analysis is in progress.



v_{red} correlation function and comparison with theoretical calculation; see text for more details.

4 CONCLUSIONS

Particle-particle correlation function has been built for pairs PLF-IMF in ternary events for $^{124}\text{Sn}+^{64}\text{Ni}$ at 35A MeV. In particular the comparison with correlation function built for pair PLF dynamical IMF selected in the output of BNV calculations seems to confirm the presence of IMF's dynamically originated in the break of the neck.

5 REFERENCES

- [1] P.M.Milazzo et al. Physics Letter B 509 (2001) 204.
- [2] A.Pagano et al. Nuclear Physics A734 (2004) 504-511 and references therein.
- [3] C.Cavata et al. PRC 42 (1990) 1760
- [4] R.Trockel et al. PRL 59 (1987) 2844
- [5] Y.D.Kim et al PRC 45 (1992) 45, E.Geraci et al NPA 732 (2004) 173
- [6] E.DeFilippo et al. PRC 71 (2005) 044602, C.Maiolino proc of XLIII Int. Winter meeting on Nucl. Phys., Bormio 13-20 march 2005
- [7] V.Baran et al. NPA 730 (2004) 329

THE DIPROTON EXPERIMENT AT LNS

E.Rapisarda^{b,c}, G.Cardella^{a,*}, R.Alba^b, F.Amorini^{b,c}, L.Calabretta^b, S.Cavallaro^{b,c}, G.Cosentino^b, E.De Filippo^a, P. Del Carmine^d, M.De Napoli^{b,c}, A.Di Pietro^b, P.Figuera^b, G.Immè^{a,b}, G.Lanzanò^a, E.La Guidara^{b,c}, G.Lanzalone^{b,c}, A.Pagano^a, M.Papa^a, S.Pirrone^a, G.Raciti^{a,c}, F.Rizzo^{b,c}, D.Santonocito^b, C.Sfienti^{b,c}, A.A.Stefanini^d, G.Verde^a

a) INFN Sezione di Catania, Italy

b) INFN Laboratori Nazionali del Sud, Catania, Italy

c) Dipartimento di Fisica e Astronomia Università di Catania, Italy

d) Dipartimento di Fisica Università di Firenze e INFN Sezione di Firenze, Italy

** Corresponding author, e-mail: giuseppe.cardella@ct.infn.it*

Abstract

We report on the tests performed on 2004 for the DIPROTON experiment. The tests were devoted to the production of a ^{18}Ne beam, to its transport on the scattering chamber, and to preliminary physics investigations on the two proton decay of ^{18}Ne excited levels.

1 INTRODUCTION

The DIPROTON experiment at LNS wants to investigate on the decay of the 6.15 MeV excited level of ^{18}Ne . This level (see fig.1) is over the threshold for two proton decay of ^{18}Ne . There is not evidence of

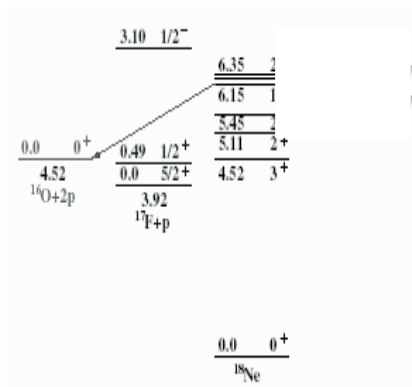


fig.1 Level scheme of ^{18}Ne

existence of levels of ^{17}F to allow a simple sequential decay, as follows: $^{18}\text{Ne}^{6.15} \rightarrow ^{17}\text{F}^* + p \rightarrow ^{16}\text{O} + p + p$. Consequently, the direct two proton emission is not excluded, although a two step sequential like decay process is possible due to the energy width of the available ^{17}F excited levels. In case of direct 2p decay, the two protons can be emitted as an ^2He cluster that decays after its emission. Angular correlations between the decay products can disentangle between such different decay modes. In particular the very exciting ^2He decay can be evidenced by the fact that the two protons must be emitted at 180° in their center of mass, whereas independent decay, sequential or direct, leads to a flatter angular distribution. This decay was first

investigated in ref.[1] by producing the ^{18}Ne in fusion reactions using a ^{17}F beam impinging on a plastic target. However in ref.[1] authors were unable to discriminate between the different decay scenarios due to a limited angular acceptance of the detection system. Direct two proton emission has been also found in nuclei near the proton drip line[2]. Encouraged by these experimental results we studied a method to measure such decay using a ^{18}Ne beam impinging on a heavy target. The 6.15 MeV level can be excited via E1 Coulomb excitation (the level is $j^\pi = 1^-$). Simple calculations of Coulomb excitation predict a cross section for the excitation of such level of about 80 mb[3]. With our method we will excite at the same time other levels at higher energy for which sequential emission is possible. We can use the angular correlations between protons emitted from such higher energy levels to better evidence the behavior of the searched ^2He emission.

In the following sections we describe the production method of the ^{18}Ne beam and some preliminary results obtained detecting the fragments with the CHIMERA apparatus completed with detectors from the TRASMA and HODO arrays to cover the 0° region.

2 BEAM PRODUCTION

For the beam production we used the FRIBS method described in detail in refs.[4,5], see fig.2. A primary beam of ^{20}Ne 45 MeV/A was used impinging on a ^9Be target 500 μm thick. The magnetic field of the selecting magnets was set to accept the ^{18}Ne ions produced via fragmentation on the target. The production rate and the beam selection was checked detecting and identifying the fragments at the so-called FRIBS point before the switching magnet (see fig.2). The produced ions can be seen in fig.3, where an identification scatter plot is reported. It was obtained combining the signals of a

silicon detector (used as ΔE signal), and of a plastic detector (E stage) used to stop the particles. The lines relative to charges from 6 to 11 are evidenced in the plot.

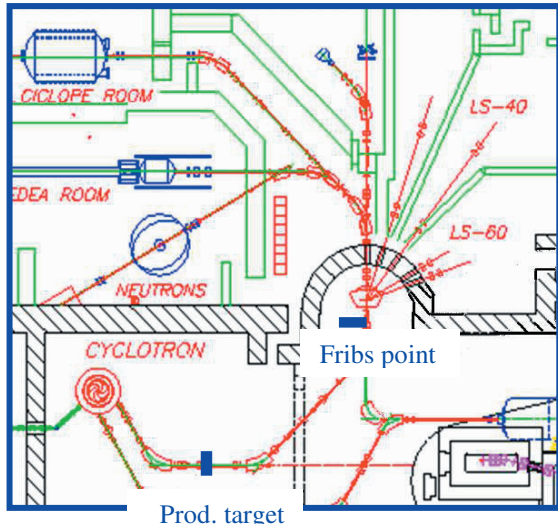


Fig.2 Layout of the FRIBS line at LNS

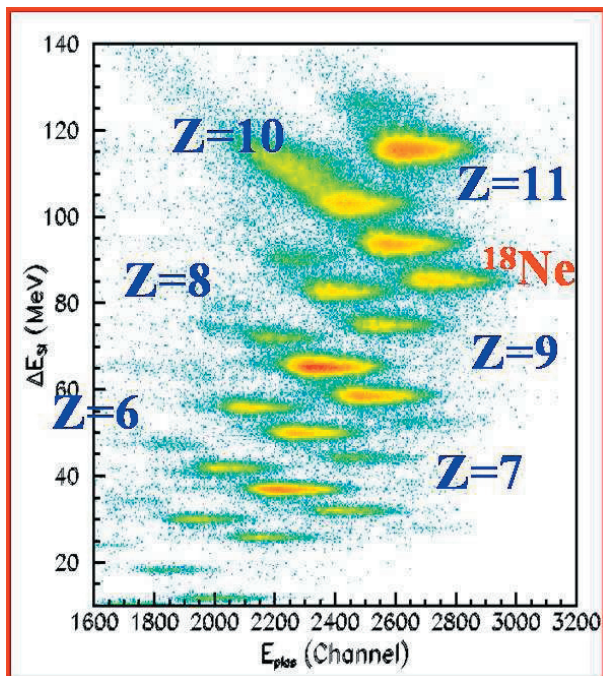


Fig.3 Identification scatter plot of the produced ions at FRIBS point

Different masses can be seen along the charge identification lines. Typically, fragments of different

mass must have different kinetic energy in order to match the bp of the transport beam line.. ^{18}Ne is evidenced in the figure. In this first run the transport efficiency up to the CICLOPE room, where the detection system was mounted, was quite low. Only about 5% of the yield observed at the FRIBS point was seen. However about $6 \cdot 10^5$ ^{18}Ne ions were detected during the experiment in the tagging silicon detector put before the CICLOPE scattering chamber.

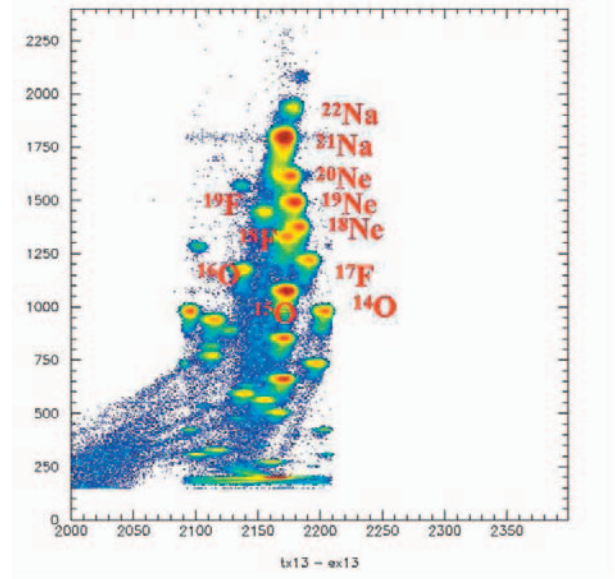


Fig.4. Identification scatter plot of the tagging detector

In fig. 4 it is shown the identification scatter plot obtained plotting the ΔE signal, measured with the tagging detector, against the time of flight measured respect the radio-frequency of the cyclotron. Due to the low beam transported, only 4 coincidences $2p+O$ were observed in events triggered by a ^{18}Ne ion with excitation energy from 8 to 15 MeV, higher than the level we want to see. The fact that we have not observed the two proton decay of the level is due to the low beam intensity. In the region of 4-6 MeV excitation energy we see only a small number of $p-F$ coincidences compatible with the predicted cross section and with the strong competition of the $1p$ decay channel respect to the $2p$ one.

4 2005 MEASUREMENTS AND PERSPECTIVES

A new transmission test has been performed at the beginning of 2005. A first measurement for the DIPROTON experiment is planned for June 2005 at the 20° beam line where an higher transmission can be obtained. To improve the transmission on all other experimental rooms a new position for the production target will be studied (after the switching magnet).

Another implementation to reduce the problems of the primary beam intensity, will be the use of a beam switch controlled by the acquisition dead time. During the dead time of acquisition the beam is not necessary and

produces only noise and detector damage. Using the beam switch we can stop the beam before injection on the cyclotron. In this way we will reduce the power loss on the electrostatic deflector at the extraction of the cyclotron (this dissipated power is the main limit to the high beam intensity). The stop of the beam during dead time will be also good for the production target, that will decrease its temperature. Under appropriate conditions this method could allow to increase the beam peak current.

5 REFERENCES

- [1] J. Gomez del Campo et al; PRL 86(2001)43
- [2] B.Blank et al; Nucl.Phys.A 746(2004)236c
- [3] C.Bertulani private communication
- [4] G.Raciti et al; Report lns 2001,p59
- [5] G.Raciti et al; proceedings of the 10th int. conf. on Nuclear Reaction Mechanisms Varenna 2003,p11.

FIRST RESULTS FOR THE ANALYSIS OF THE LIMITING EXPERIMENT

P.Russotto^{b,c}, G.Cardella^{a,*}, C.Agodi^b, R.Alba^b, F.Amorini^{b,c}, A.Anzalone^b, I.Berceanu^f, M.B.Chatterjee^d, R.Coniglione^b, S.Cavallaro^{b,c}, M.D'Agostino^e, E.De Filippo^a, A.Di Pietro^b, E.Geraci^e, A.Grzeszczuk^g, P.Figuera^b, E.La Guidara^{b,c}, G.Lanzalone^{b,c}, N.Le Neindre^f, C.Maiolino^b, A.Pagano^a, M.Papa^a, S.Pirrone^a, A.Pop^h, G.Politi^{a,c}, F.Porto^{b,c}, F.Rizzo^{b,c}, P.Sapienza^b, W.Tian^{b+}

a) INFN Sezione di Catania, Italy

b) INFN Laboratori Nazionali del Sud, Catania, Italy

c) Dipartimento di Fisica e Astronomia Università di Catania, Italy

d) Saha Institute of Nuclear Physics, Kolkata, India

e) Dipartimento di Fisica e Astronomia Università di Bologna e INFN Bologna, Italy

f) Institut de Physique Nucleaire d'Orsay, CNRS-IN2P3, 91406 orsay cedex France

g) Institute of Physics, University of Silesia, Katowice, Poland

h) Institute for Physics and Nuclear Engineering, Bucharest, Romania

** Corresponding author, e-mail: giuseppe.cardella@ct.infn.it*

+present address : Shanghai Institute of Applied Physics, China

Abstract

We report on the analysis of the Limiting experiment performed during the 2003 CHIMERA experimental campaign. Work on particle identification both for ΔE -E and Fast-Slow analysis has been done. A short description of the experiment is given and some results on the detector behavior are reported. First results are expected during 2005.

1 INTRODUCTION

The Limiting experiment is devoted to investigate on the maximum excitation energy that a nucleus can sustain, and on the dependence of this maximum excitation energy on the isospin of the excited system. It follows a previous experiment where the γ -decay of systems around mass 60 was investigated with particular attention to the GDR γ -decay[1]. In such experiment evidence was found of a limiting excitation energy of about 5 MeV*A at which the GDR can be still excited in mass $\approx$ 60 nuclei. Comparing the observed limiting excitation energy with older measurements[2], performed for system around mass 110, a difference was found. For mass 110 in fact the limiting excitation energy is around 2-3 MeV*A. This difference is similar to the mass dependence of the caloric curve recently observed[3]. Two systems were studied in ref.[1] using a ^{40}Ca beam impinging on ^{48}Ca and ^{46}Ti targets, some small differences were observed in the limiting excitation energies of the two systems characterized by a different isospin. The Limiting experiment was therefore performed with the intent to better investigate the source characteristics of the systems excited in ref.[1] and on the isospin effect of the colliding system. The reactions investigated where $^{40}\text{Ca} + ^{40,48}\text{Ca}, ^{46}\text{Ti}$ at 25 MeV/A.

2 ΔE -E ANALYSIS

The ΔE -E scatter plots for the different telescopes given by the silicon and CsI(Tl) stages of the CHIMERA detectors have been analyzed to extract the charge and, when possible, the mass of the detected particles. The method described in ref.[4] was used to parameterize the ΔE and E signals obtaining a semiautomatic charge and mass identification starting from converted un-calibrated signals. The analysis for rings 2-5 (3° - 12°), 8-26 (21° - 170°) is now done for most of the runs of the experiment. Good charge identification can be obtained in 722 of the 968 analyzed detectors and starting from ring 5(12°) in most of the running detectors, mass identification can be achieved at least for some charges (up to charge 9 in the best detectors of the rings 5-8 (12° - 21°)). No ΔE -E analysis was obviously possible for the telescopes where one or both signals (silicon or fast) were missing. However such telescopes are not completely lost. In fact in the largest part of such telescopes one can get information about the mass of heavy fragments, via time of flight analysis, or on light particles, depending from which stage of the telescope (Silicon or CsI(Tl)) was working.

The analysis of the complete event is still not possible and we are looking only to data without selections. In Fig.1 some representative mass identification spectra, collected at different angles, are plotted. It is interesting to note how the heaviest mass of each selected charge disappears going to more backward angles. Comparing the yields of different carbon isotopes measured at ring 10(34°) and ring 12(40°) one observes a similar yield ratio between ^{11}C and ^{12}C whereas ^{13}C is practically absent at 40°. ^9Be disappears at 66° (ring 14) whereas ^7Be is still present. Looking at ring 16(82°) also ^7Li is missing and only ^6Li can be observed. Moreover going from forward to backward angles one sees that the ratio $^3\text{He}/^4\text{He}$ increases and already at ring 22 (130°) ^3He and ^4He are nearly equally produced. This kinematical effect must be further investigated including the event selection. The mixing of different reaction mechanisms could explain such apparent kinematical suppression. We must however study the influence of kinematics on the measure of the double isotopic ratios[5] used to evaluate the temperature of excited systems.

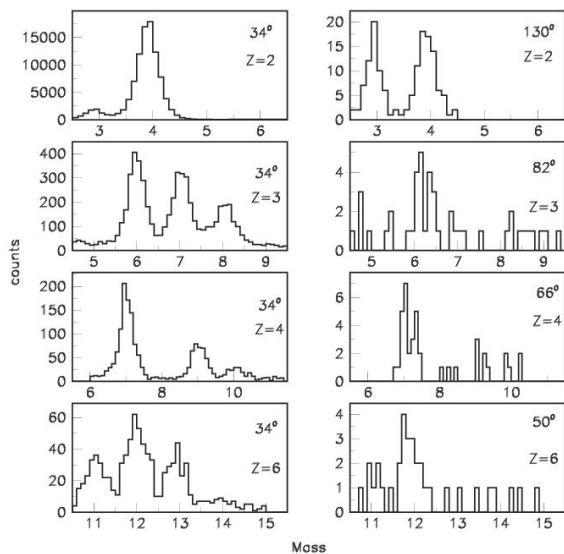


Fig 1 Isotopic identification obtained at different detection angles.

3 FAST-SLOW ANALYSIS

Fast-Slow analysis of CsI(Tl) signals, obtained as described in ref [6], is necessary to charge and mass identify high energy light particles stopped in CsI(Tl) detectors. The Fast-Slow analysis has been performed by using the Tassan-Got method used also by the INDRA collaboration[7]. Rings from 7 to 15 (17°-74°) have been analyzed up to now. Unfortunately about 25% of the CsI(Tl) detectors of the forward rings (<30°) show some saturation effects of CsI(Tl) preamplifiers, as due to a too low effective preamplifier bias. The particle identification in such detectors was difficult and sometime impossible. This problem is now solved in the apparatus, however it reduced the number of well

working detectors for some experiments performed in the 2003 experimental campaign. Apart from these detectors a good behavior is found in all other telescopes. In Fig.2 a typical mass-charge identification spectrum is reported. Isotopes for particles from hydrogen to lithium are well resolved. In many detectors stable beryllium isotopes cannot be resolved and the generic mass 9 is attributed to them. However in the Fast-Slow scatter plot one see a line obtained as a sum of two α -particle signals detected together in the same detector. Such events are attributed to ^8Be in flight decay and they can be seen in Fig.2. This ^8Be identification is very important, in fact such two- α events strongly contaminate the ΔE -E scatter plot in the region of ^8Li . Due to the multiple identification capabilities of CHIMERA detectors this bad identification can be corrected using the CsI(Tl) information.

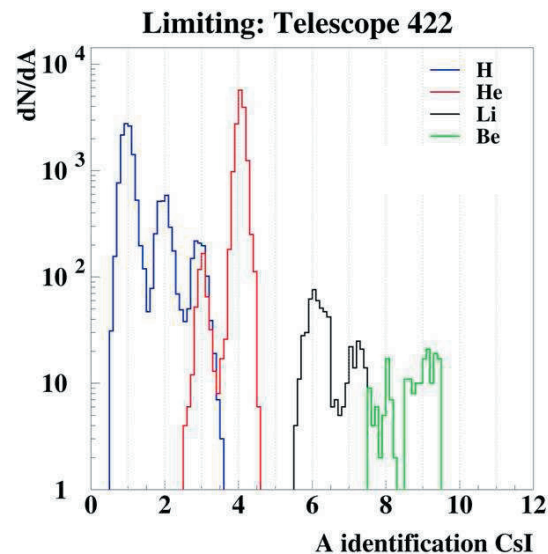


Fig.2 The isotopic identification obtained for a CsI(Tl) telescope (ring 7, $\theta=17^\circ$). In the Be line the events with mass 8 are due to the detection of two alpha particles. At mass 9 are grouped all the other Be isotopes not mass identified.

4 TOF ANALYSIS AND PERSPECTIVES

The complete TOF analysis must still be performed and only a preliminary analysis has been done. The first analysis of RF stability is important to correct the particles time of flight. This analysis was done looking to the peak position of the time spectrum of a telescope used as monitor in the experiment. Subtracting few jumps, due to beam adjustments, one can see a quite stable RF behavior during the whole experiment, see Fig.3. The maximum displacement is about 8 channels i.e. about 1.5 nsec (from run 1128 to run 1258 the experiment BOSE was performed and data are not reported).

During 2005 we expect to have the first results from the analysis. Test with the COMD model[8] will be performed looking mainly to the isospin of the emitted fragments.

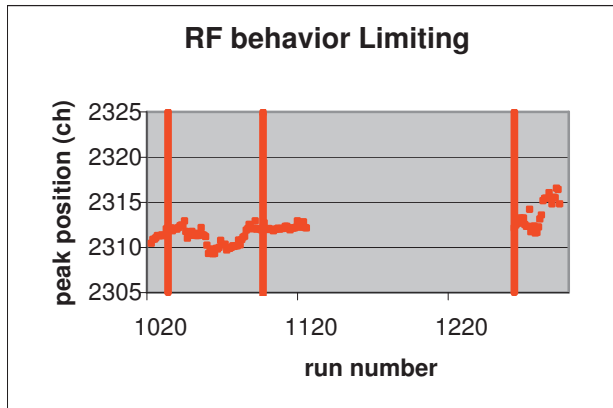


Fig.3 Position of the monitor elastic time peak as a function of the run number. Lines evidence runs where a beam adjustment was done. Data after these runs are normalized to better evidence the RF stability.

REFERENCES

- [1] F. Amorini et al., Phys.Rev. C 69 (2004)014608
- [2] J.H. Le Faou et al, PRL 72(1994)3321
- [3] J. B. Natowitz et al., Phys.Rev.C 65(2002)034618
- [4] N. Le Neindre, et al NIM A 490(2002)251
- [5] S. Albergo et al, Nuovo Cimento A **89**, 1 (1985).
- [6] M. Alderighi et al, NIM A 489(2002)257
- [7] L. Tassan-Got, private communication
- [8] M. Papa et al, Phys.Rev.C 64(2001)024612 ; M. Papa et al, Phys.Rev.C68(2003)034606

INVERSE KINEMATICS RESONANCE SCATTERING ON THICK TARGET

A. Di Pietro^a, P. Figuera^a, M. Lattuada^{a,b}, F. Pansini^{a,b}, M. Papa^c, D. Vinciguerra^{a,b}, M. Zadro^d,
O.Yu. Goryunov^e, A. Khouaja^a, V. Lyapin^f, C. Nociforo^a, V.V. Ostashko^e

a) INFN Laboratori Nazionali del Sud, Catania, Italy

b) Dipartimento di Fisica ed Astronomia, Università di Catania, Catania, Italy

c) INFN Sezione di Catania, Catania, Italy

d) Rudjer Boskovic Institute, Zagreb, Croatia

e) Institute for Nuclear Research, Kiev, Ukraine

f) Institute of Physics, Helsinki, Finland

Abstract

The method of the inverse kinematics resonance scattering on infinite target has been applied to two systems, $^{18}\text{O}+\alpha$ and $^9\text{Be}+\alpha$, with the aim of testing and optimizing the experimental apparatus, in view of similar experiments to be performed with the ^8Li and ^9Li radioactive beams of the forthcoming facility EXCYT. The results of these experiments are compared with previous results reported in the literature.

1 INTRODUCTION

Resonances in scattering excitation function can be the signature of special structures in the intermediate nuclear system. In the pioneering experiments on the $^{12}\text{C}-^{12}\text{C}$ system the resonances in the elastic and inelastic channels around the Coulomb barrier, and the corresponding ones found in other exit channels, were interpreted in terms of excitation of states associated with a dinuclear rotating configuration of ^{24}Mg .

Without entering into the details of the history of scattering resonances, we remind that in the last years scattering experiments induced by exotic beams were used to study the formation of cluster states in nuclei far from stability.

These experiments made use of inverse kinematics, which focuses the scattering products into a forward cone whose opening depends on the projectile-target mass ratio, thus allowing to cover the entire angular range even without using 4π detectors.

Moreover the so called *thick target* condition allows the measurement of a scattering excitation function in a wide excitation energy region with a single beam energy. The method is more efficient when the target can be used in form of a gas. In this case a scattering chamber is filled with gas (Hydrogen or Helium, typically) that acts at the same time as target and as beam degrader. Usually the pressure of the gas inside the chamber is chosen in order to stop the beam before reaching the end of the chamber, where detectors are placed. Thanks to the different specific energy losses of the (heavy) projectile and the (light) recoil, the latter can reach the detectors, making it possible to measure the excitation function even at 180° in the center of mass system with a detector placed at 0° in the lab system. This is a very favourable condition to enhance the

visibility of resonances due to excitation of the intermediate nuclear system, since the potential scattering cross section is comparable or even smaller than the resonant cross section.

The relationship between the energy of detected recoil target nucleus and the energy of the projectile inducing the scattering event is unique, if the elastic scattering events are identified and separated from the inelastic contribution. The separation of elastic and inelastic events can be achieved by measuring the time between the entrance of the projectile into the chamber and the detection of the recoil. The time resolution needed to get a good separation depends, of course, on the energy of the first excited level of the projectile, since, at the typical energies of these experiments, levels in the target cannot be excited.

The reconstruction of the excitation function of the process from the energy spectra of the recoil α -particles is, of course, very much dependent on the calculation of energy losses of the projectile before the interaction and of the recoil after the interaction.

2 THE EXPERIMENT

In order to investigate on the presence of possible α - ^8Li and α - ^9Li cluster states in ^{12}B and ^{13}B , a set of resonance scattering experiments on *infinite* ^4He target are planned with the first radioactive beams (^8Li and ^9Li) of the forthcoming RIB facility EXCYT at LNS.

A preliminary experiment was then performed with stable tandem beams, in order to test and optimise the experimental set up.

Two beams were used in this test, ^9Be at 30 MeV and ^{18}O at 56 MeV which were delivered on an *infinite* ^4He gas target. The first beam was chosen because of its

mass, close or equal to the masses of the exotic beams of interest, since it is well known that the resolution obtained in this kind of experiments strongly depends on the projectile-target mass ratio. Moreover the excitation function of the $^9\text{Be}-\alpha$ system has been measured with a standard thin target experiment and the strong resonance at around 3.5 MeV c.m. energy can represent a good reference for comparison. The second system was chosen with the aim of comparing the quality of our spectra with the data taken by Goldberg et al. [1] on the same system with the same method.

The beam was delivered in the CT2000 reaction chamber having a diameter of 2 m. A 13 μm thick Kapton window was mounted at the entrance of the scattering chamber and the beam line, allowing to fill the chamber with Helium gas (purity up to 99.9 %). The gas pressure was controlled via a pre-calibrated capacitor manometer, able to measure pressures of hundreds mbar with an accuracy of 0.2%.

A MCP detector was mounted just before the entrance window in order to count the number of projectiles delivered to the target and to produce a fast signal for the time of flight measurement. Thus the maximum beam intensity during the experiment was kept below the level of few 10^5 pps.

Two large area Silicon telescopes (65 μm + 500 μm) were placed on the forward part of the chamber to detect and identify recoil α -particles. Each thin detector was segmented into four equal quadrants, whereas each E detector consisted of an array of 12 horizontal position sensitive strips.

Another Silicon detector, 300 μm thick, was placed at the center of the chamber on a support mobile along the vertical axis, that allowed to put it on the beam direction when needed.

3 RESULTS AND DISCUSSION

As a preliminary step, the chamber was first filled with Helium and, keeping the beam intensity below 10^3 pps, the energy of the ^9Be and ^{18}O ions after crossing a distance equal to the radius of the chamber was measured directly in the 300 μm detector, for several values of the gas pressure.

The measured energy losses were compared with the ones calculated by means of the SRIM code [2]. Taking into account the measured pressure changes due to air inlet during the measurements, the energy losses measured for ^{18}O ions were found to be in fair agreement with the SRIM calculations.

The excitation function of the $^{18}\text{O}-\alpha$ elastic scattering process deduced from our experiment using the SRIM code for energy loss calculations is shown in fig. 1. It compares rather well with the data measured in a similar experiment and reported in fig. 2 [1]. A slight discrepancy is observed in the position of the peaks, that increases with increasing energy. It needs to be better

understood and might be related to the use of different energy loss codes in the two data analysis.

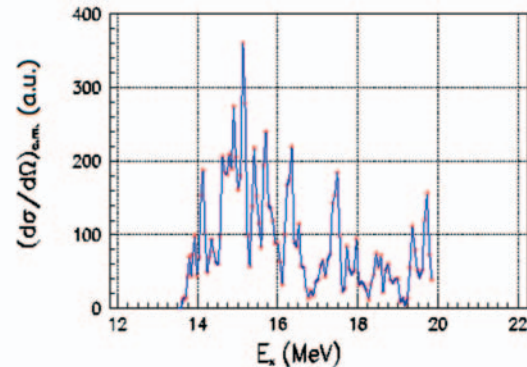


Fig.1 $^{18}\text{O} + \alpha$ elastic scattering excitation function deduced from our experiment for the detector at 0° .

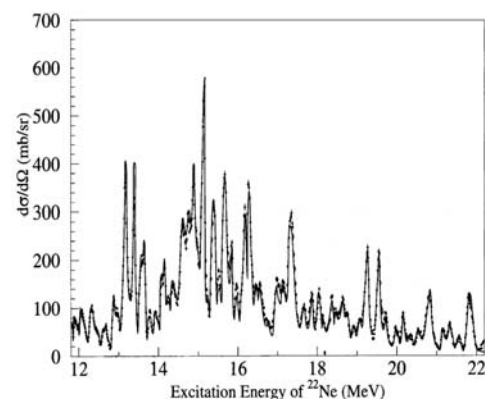


Fig.2 $^{18}\text{O} + \alpha$ scattering excitation function measured with a similar experiment [1].

On the other hand a large discrepancy around 12 % was found in the comparison of the energy losses of ^9Be measured with the 300 μm detector and the ones calculated by means of the SRIM code. This discrepancy was also observed in the analysis of the $^9\text{Be}-\alpha$ scattering, since only with this correction our data overlap the data of ref. [3] and ref. [4] obtained in standard experiments using thin targets and different α -beam energies. Figs.3 and 4 show the comparison of the published data with our excitation function deduced with and without the 12 % correction in ^9Be energy losses, respectively. The comparison is made for the lowest region of the excitation function, corresponding to recoil α -particles stopped in the ΔE detector, where a pronounced resonance at 3.5 MeV is present. It is evident that a correction of the calculated ^9Be specific energy losses is needed as confirmed by these data.

We underline that no relative normalisation was performed on these two sets of data, since for the $^9\text{Be}+\alpha$

process we could deduce the absolute value of the cross section. Thus the comparison appears more significant and the smaller absolute value of our excitation function with respect to the published ones can be explained by angular distribution effects. In fact the data of ref. [3] and [4] were obtained at 167.2° and 171.6° c.m. angles respectively, whereas the c.m. scattering angle calculated in correspondence of the resonance energy for the present experiment was 175.2° , as can be seen in the upper scale of Figs. 3 and 4.

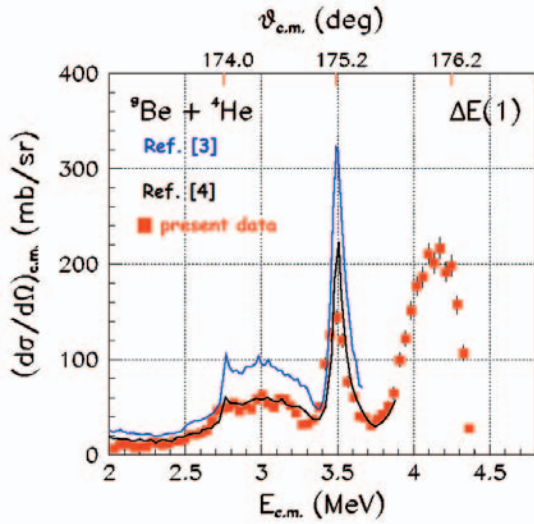


Fig. 3 $^9\text{Be} + \alpha$ excitation function compared with published data. ^9Be specific energy losses calculated by SRIM have been corrected by a factor 1.12.

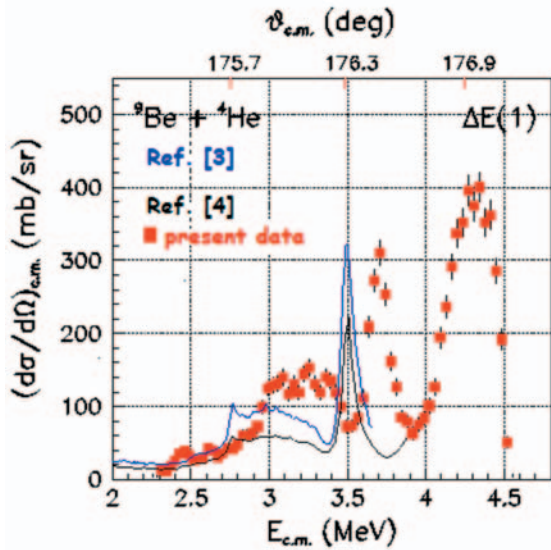


Fig. 4 $^9\text{Be} + \alpha$ excitation function compared with published data. Energy losses are calculated by SRIM without any correction.

It is to be stressed that, for both systems, the reported data refer only to the elastic scattering events, since the inelastic contribution was excluded thanks to the time of flight measurement. In the measurement of the time

difference between the entrance of the projectile in the chamber and the detection of the α particle in the ΔE detectors, a time resolution of less than 1 ns was achieved, enough to separate elastic from inelastic events. Fig. 5 shows the TOF- ΔE scatter plot of one of

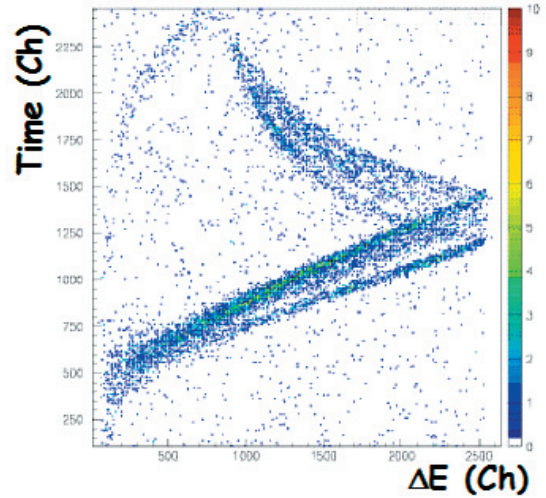


Fig.5 – Example of TOF vs ΔE scatter plot for the $^9\text{Be} + \alpha$ system. The time scale conversion is about 25 ps/ch.

the four quadrants of the thin detector at 0° , for the $^9\text{Be} + \alpha$ experiment. As it can be seen, the separation of the ground state events (bottom locus) from the excited state ones (upper loci) is fully accomplished.

4 REFERENCES

- [1] V.Z. Goldberg, et al, Phys. Rev. C 69 (2004)024602.
- [2] SRIM code by J. F. Ziegler (www.srim.org)
- [3] J.Liu et al., Nucl. Instr. And Meth., B108(1996)247..
- [4] J.D.Goss and S.L.Blatt, Phys. Rev. C 7(1973)1837.

HIGH EXCITATION IN ^{32}S BY ALPHA-PARTICLE TRANSFER

M. Brenner^{a,*}, M.Lattuada^b, M.Zadro^{b,c}

a) Department of Physics, Åbo Akademi University, FIN20500 Turku, Finland

b) INFN, Laboratori Nazionali del Sud, Catania, Italy

c) Ruder Boškovich Institut, Zagreb, Croatia

Abstract

In order to search for cluster structure in ^{32}S , states at high excitation were looked for by the $^6\text{Li,d}$ transfer reaction on silicon targets followed by alpha-particle decay to the ^{28}Si ground state. The experimental results, as reported tentatively in the Activity Report 2003, have been analyzed in more detail. The improved calibration of the position sensitive alpha-particle detectors gives different results than reported before.

1 ENERGY CALIBRATION

The experiment was described in Activity Report 2003 [1]. From the de-detectors of five telescopes ($i=1,2..5$) the channel numbers dei were obtained to give the energy losses $deni$ in the de-detector in front of thick solid state detectors. The total energies displayed by the deuterons in the telescopes i.e. the energy of the deuterons, eni , is obtained by adding $deni$ to the energy displayed in the thick e-detector. The energies displayed in that detectors are obtained from the channel numbers ei . The calibration, that gives the relation between channel numbers and the energies was described in [1].

To detect alpha-particles two $5\times 2\text{ cm}^2$ position sensitive alpha-particle detectors, PSDj ($j=1,2$) were used. For their calibration a large enough energy range was not spun by the use of an alpha-particle source, as mentioned in [1]. More over the relation between the channel number $epsdj$ and energy displayed $enpsdj$ i.e. the alpha-particle energy value depends on the position, $thpsdj$, as given in angle of

emission. The latter is obtained from the channel number of position, $ppsdj$. The energy and position calibration is brought above by keeping a grid of slots of known positions in front of the PSD:s during a calibration run. When events of a calibration run are plotted in a $epsdj$ versus $ppsdj$ diagram lines are displayed, one line per slot. The lines diverge from a point which can be taken as the offset for the energy and the angle. Two more calibration points were obtained from curves, which were observed to cross the lines. One curve is due to deuterons emitted in the transfer to ^{16}O of the oxygene impurity in the target, by which the 1.634 state in ^{20}Ne is populated. The other curve was due to proton recoils of ^6Li striking hydrogen in the target. The beam energy was 22 MeV and the centres of the PSD-detectors were at -36 and -51 degree in the calibration run. In the experiment the beam energy, enp , was 47 MeV. The angles spun by the depletion layer of the detectors were -146.9 to -157.2 and -161.9 to -170.9 degrees. These limits were red from plots of alpha-particles due the

population of the ground state and two first excited states of ^{28}Si .

The offset and the points where the ^{20}Ne and proton recoil curves cross the lines of different angles give three points of linear calibration for different positions of impact of particles. In the linear relation

$$\text{enpsdj} = A + B \times \text{epsdj} \quad (1)$$

the dependence of the coefficients A and B on the position thpsdj was fitted by a line ($j=1$) and a second degree polynomial ($j=2$).

This procedure of calibration enabled the identification of the alpha-particle transfer reaction by the d- α coincidences recorded in the first part of the experiment. Most coincidence events were however recorded in the second part of the experiment. The calibration was, however, made only in the beginning of the experiment. In the second part a small shift in the calibration of the PSD2 caused an error in the reaction identification, resulting in the misinterpretation of the preliminary data [1]. A re-calibration, of the detector based on known $q3$ -values, given by

$$q3 = \text{eni} + \text{enpsdj} + \text{en3ij} - \text{enp} \quad (2),$$

for the ground state and two first excited states in ^{28}Si , gave a linear relation used to correct the erroneous enpsd2 values.

2 EXPERIMENTAL RESULTS

For the identification of the appropriate reaction channels two plots were used. When the excitation energy ex of ^{32}S , as calculated from en1 , was plotted versus $q3$, vertical lines $q3 = 1.47, 3.25, 6.09$ were displayed corresponding to the ground state, and the $2+$ and $4+$ excited states. The energy en3ij of the third particle, ^{28}Si , was calculated from the kinematical relation for the alpha particle transfer from ^6Li to ^{28}Si . Another plot due to Costanzo *et al.* [2] is shown in Fig.1. In it $\text{en3ij}-q3$ is

plotted versus $(p3)^2/2mp$, where mp is the unit mass i.e. the mass of ^{12}C divided by 12. The momentum of the third particle is $p3$. The slope of three weak lines is $1/A$. The value of A is 28, which indicates that the lines are due ^{28}Si . A strong line on the left is due ^{16}O . It was in [1] erroneously supposed to be of ^{28}Si .

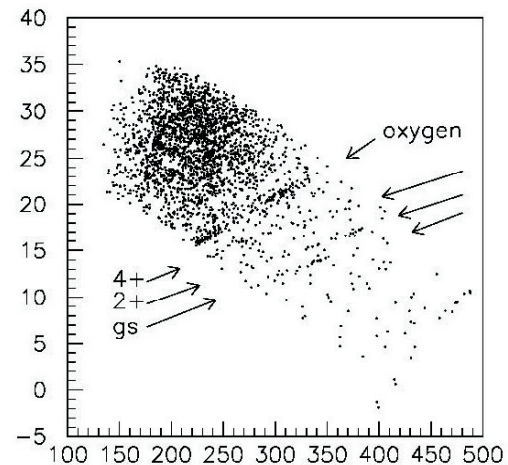


Fig.1 $\text{en3}-q3$ versus $(p3)^2/2mp$. Note the three lines of populating ^{28}Si . C.f. text

The ground state line displays the abrupt drop in the yield of events above 31 MeV excitation in ^{32}S , as expected by alpha-particle scattering. The assumed onset of the decay in four alpha particles above this energy is accordingly in agreement with the results of ref. [3]. Excitation functions and angular correlations are being evaluated.

3 REFERENCES

- [1] M. Brenner *et al.*, LNS Act.Rep. 2003
- [2] E. Costanzo *et al.*, NIMA 295(1990) 373
- [3] M. Brenner *et al.*, Proc. Symp. Nuclear Clusters: From Light Exotic to Superheavy Nuclei, edd R. Jolos and W. Scheid (EP Systema, Debrecen, Hungary, 2003)

VALIDITY TEST OF THE TROJAN HORSE METHOD APPLIED TO THE ${}^7\text{Li}(p,\alpha){}^4\text{He}$ REACTION VIA THE ${}^3\text{He}$ BREAK-UP

A. Tumino^{a,b,*}, M.L. Sergi^{a,b}, C. Spitaleri^{a,b}, V. Kroha^c, V. Burjan^c, S. Cherubini^{a,b}, V. Crucillà^d, S. Fulop^d, M. La Cognata^{a,b}, L. Lamia^{a,b}, A. Musumarra^{a,b}, J. Novák^c, R.G. Pizzone^{a,b}, S. Romano^{a,b}, E. Somorjai^d, S. Typel^e, S. Tudisco^{a,b}, J. Vincour^c

a) Dipartimento di Metodologie Fisiche e Chimiche per l'Ingegneria, Università di Catania, Catania, Italy

b) INFN Laboratori Nazionali del Sud, Catania, Italy

c) Nuclear Physics Institute of ASCR, Rez near Prague, Czech Republic

d) Institute of Nuclear Research of Hungarian Academy of Sciences (ATOMKI), Debrecen

e) Gesellschaft für Schwerionenforschung mbH, Theorie, Darmstadt, Germany

** Corresponding author, e-mail: tumino@lns.infn.it*

Abstract

The Trojan Horse Method (THM) was applied to the ${}^3\text{He}+{}^7\text{Li}$ interaction in order to investigate the quasi-free ${}^7\text{Li}(p,\alpha){}^4\text{He}$ reaction. The three-body experiment was performed at 33 MeV corresponding to a $p-{}^7\text{Li}$ relative energy ranging from 0.2 to 7 MeV. The extracted ${}^7\text{Li}(p,\alpha){}^4\text{He}$ quasi-free cross-section was compared with the behaviour of direct data, already reproduced in a previous THM investigation on the ${}^7\text{Li}(p,\alpha){}^4\text{He}$ reaction off the neutron in ${}^2\text{H}$. A very good agreement between the two trends shows up throughout the energy range investigated, providing a very important validity test of the pole approximation for the THM.

1 INTRODUCTION

In the last years, the Trojan Horse Method (THM) [1-5] has proven to be a successful indirect approach for studying charged particle two-body reactions relevant for astrophysics. The Trojan Horse Method selects the quasi-free contribution of an appropriate three-body $A+a \rightarrow c+C+s$ reaction performed at energies well above the Coulomb barrier to extract the relevant two-body $A+x \rightarrow c+C$ reaction cross-section at astrophysical energies free of Coulomb suppression as well as electron screening effects. The method is based on previous studies on quasi-free (QF) scattering and reactions [6-9], where evidence for a QF mechanism at energies of few tens of MeV was observed and justified by the high momentum transferred to the outgoing particles, due to the high Q-value of the reactions involved. When applying the method, kinematical conditions are appropriately chosen in order to be s spectator to the process and the $x-s$ binding energy “enough” to compensate for the $A+a$ relative motion.

In the selected phase space region the Impulse Approximation [10,11] can be applied, which describes the quasi free $A+a \rightarrow c+C+s$ reaction by a Pseudo Feynman diagram where only the first term of the Feynman series is retained. A pole of the diagram describes the break-up of the target nucleus a into the clusters x and s , and the other one contains the information on the virtual $A+x \rightarrow c+C$ two-body process.

A key role is played by the “Trojan Horse nucleus” a , whose wave function is required to have a large amplitude for a $x\oplus s$ cluster configuration. However, a general view of the influence of its bound structure on the validity of the pole approximation for the THM is still missing.

Recently this problem was addressed within an experimental program to indirectly study relevant reactions destroying Li isotopes in stellar environments. In particular the ${}^7\text{Li}(p,\alpha){}^4\text{He}$ reaction, key reaction in the so called “Li problem”, was first investigated via ${}^2\text{H}$ break-up and then by picking the proton up from ${}^3\text{He}$. From the first investigation via the ${}^2\text{H}({}^7\text{Li},\alpha\alpha)n$ break-up process, very interesting results were obtained [2,12,13,14]. Two resonances, associated with the group of ${}^8\text{Be}$ states between 19.9 and 20.2 MeV and that around 22.2 MeV of excitation energy, contributing to the ${}^7\text{Li}-p$ direct cross section, could be observed also in the indirect ${}^7\text{Li}-p$ excitation function [12]

Moreover, the behaviour of the THM $S(E)$ -factor at low energy was found to be in very good agreement with that of standard measurements in the region where screening effects are negligible. Estimates of the bare nucleus S_0 factor and electron screening potential U_e were obtained in PWIA [13] as well as applying the more sophisticated MPWBA [14,15], confirming the values from direct measurement, but with smaller errors. Direct values are indeed affected by larger uncertainties due to the extrapolation procedure employed to get them [16]. In the present paper the THM results of the ${}^7\text{Li}(p,\alpha){}^4\text{He}$ reaction via the

${}^7\text{Li}({}^3\text{He}, \alpha\alpha)\text{d}$ three-body experiment analysed in PWIA are presented. A ${}^7\text{Li}$ -p relative energy range (0.2 – 7 MeV) including the mentioned resonances, was populated.

Results may be eventually different due to the presence of a different “Trojan Horse nucleus” (${}^3\text{He}$ instead of ${}^2\text{H}$). Moreover a charged spectator, as in the present case, may introduced some distortions in the exit channel. A good agreement between direct and indirect two-body excitation functions also in this case would provide a very important validity test of the pole approximation.

2 THE EXPERIMENT

The ${}^7\text{Li}({}^3\text{He}, \alpha\alpha){}^2\text{H}$ experiment was performed at the at the Nuclear Physics Institute of ASCR in Rez (near Prague). A 33 MeV ${}^3\text{He}$ cyclotron beam was delivered onto an isotopically enriched lithium fluoride target (${}^7\text{Li} \approx 95\%$) of about 200 $\mu\text{g}/\text{cm}^2$. Two silicon ΔE -E telescopes for α 's identification, consisting of 20 μm ΔE - and 1000 μm position sensitive E-detector, were placed on opposite sides with respect to the beam direction covering the laboratory angles 94.6° to 109.4° and 44.3° to 59.7° . The angular ranges were chosen in order to cover momentum values P_s of the undetected proton ranging from about -100 MeV/c to about 100 MeV/c. This assures that the bulk of the quasi-free contributions for the break-up process of interest falls inside the investigated regions, allowing also to cross check the method outside the relevant phase-space regions. The trigger for the event acquisition was given by the coincidences between the two telescopes. Energy and positions signals for the detected particles were processed by standard electronics together with the coincidence relative times.

3 DATA ANALYSIS AND RESULTS

The energy and position calibration of the telescopes was performed using data acquired in preliminary runs of the ${}^3\text{He}+{}^{197}\text{Au}$ elastic scattering. A standard three-peak α source was also used. In order to identify the channel of interest and to choose the kinematical conditions where the quasi-free process is dominant, α and loci were selected in the ΔE -E two-dimensional plots. An example of the ΔE -E plot with the graphical cut to select α 's, is shown in fig. 1.

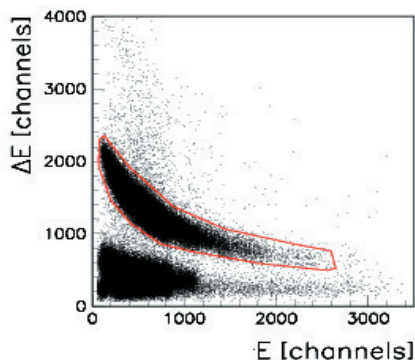


Fig.1: Example of ΔE -E plot referring to the telescope where the ${}^3\text{H}$ locus was selected

The kinematics were reconstructed under the assumption of a deuteron as third particle, leading to the locus of events in the E_α vs. E_α plane shown in fig.2. It reproduces very well the one calculated by using a three-body kinematical calculation. At least three correlated groups of events can be recognized in the figure, corresponding to excited states of ${}^8\text{Be}$ which decay into the two α 's in the exit channel. The first group from the left is fed by the 16.6 and 19.2 MeV states, the second one is due to the states between 19.9 and 20.2 MeV, while the third one corresponds to the 22.2-22.9 MeV levels. These states have all isospin $T=0$ and natural parity, with $J=2^+$. The Q-value spectrum for these events shows a peak at about 12 MeV, which refers to the $\alpha+\alpha+\text{d}$ channel of interest whose calculated Q-value is 11.85 MeV.

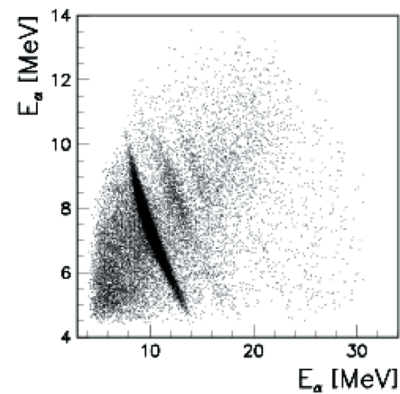


Fig.2: Locus of events in the E_α vs. E_α plane. The correlated group of events correspond to ${}^8\text{Be}$ excited states, feeding the two α 's in the exit channel

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

Another representation of the coincidence events is given by projecting them onto the 2D-plot of relative energies for any two of the three final particles.

The 2D-plot for α - α vs. α -d relative energies is shown in fig.3. In this representation very clear horizontal loci show up, corresponding to the groups of ${}^8\text{Be}$ states recognized in fig.2. Neither vertical nor diagonal loci associated to the excitation of ${}^6\text{Li}$, seem to be present. The ${}^8\text{Be}$ excited states can be populated via quasi-free mechanism or via sequential decay.

A way to investigate the reaction mechanism involved and to disentangle quasi-free coincidence events from other, is to examine the shape of the experimental momentum distribution for the deuteron.

The experimental momentum distribution was reconstructed by applying the energy sharing method [17] to our coincidence data selecting ${}^7\text{Li}$ -p relative energy windows of 100 keV. The ${}^7\text{Li}$ -p relative energy was calculated in

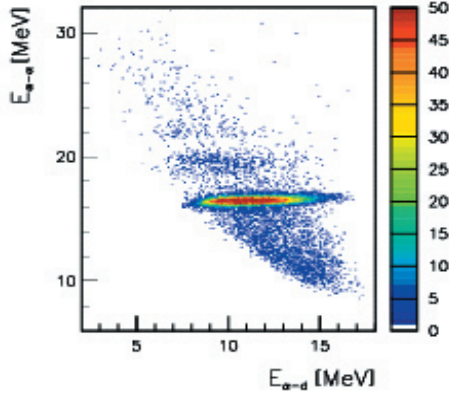


Fig.3: Coincidence events in the α - α vs. α -d relative energy plane

post collision prescription in the standard way (for details see ref.[2-5]). The plane wave impulse approximation (PWIA) was employed, which factorizes the three-body cross-section into two terms corresponding to the two poles mentioned in the introduction:

$$\frac{d^3\sigma}{dE_c d\vec{U}_c d\vec{U}_c} \propto \text{KF} \frac{d\sigma}{d\vec{U}} \left| \vec{O}(\vec{p}_s) \right|^2 \quad (1)$$

where $d\sigma/d\Omega$ is the off-shell differential cross-section for the two-body ${}^7\text{Li}(p,\alpha){}^4\text{He}$ reaction of interest, KF is a kinematical factor depending on masses, momenta and angles of the outgoing particles and containing the final

phase-space factor [1-4], and $\vec{\Phi}(\vec{p}_s)$ is the Fourier transform of the radial wave function for the p-d intercluster motion inside ${}^3\text{He}$, described in terms of a Hulthén function [12].

Dividing the three-body coincidence yield by the kinematical factor, we are left with a quantity proportional to the product of the momentum distribution with the differential ${}^7\text{Li}$ -p two-body cross-section. Since in the restricted relative energy ranges of 100 keV, the differential two-body cross-section can be considered constant, the quantity above reflects the behaviour of the experimental momentum distribution in arbitrary units. The result is reported in fig.4. The dashed line superimposed on the data gives the shape of the theoretical Hulthén function in momentum space, which is normalized to the experimental maximum. A quite good agreement shows up, making us confident

that in the experimentally selected kinematical region, the quasi-free mechanism gives the main contribution to the ${}^3\text{He}+{}^7\text{Li}$ reaction and it can be selected without significant interference with contaminant sequential decay processes.

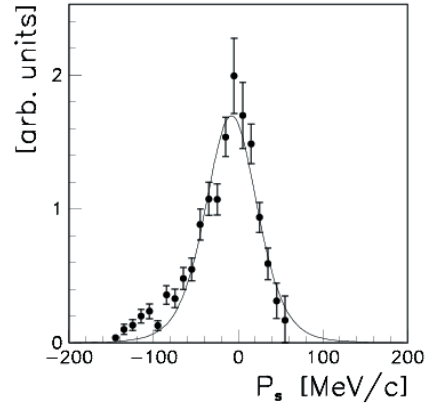


Fig.4: Experimental deuteron momentum distribution. The dashed line represents the shape of the theoretical Hulthén function in momentum space

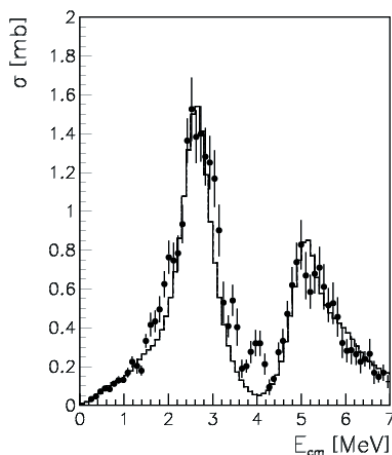
The further analysis was performed by considering coincidence events with a neutron momentum ranging between -30 and 30 MeV/c. Following the PWIA approach the two-body cross-section was derived dividing the selected three-body coincidence yield by the result of a Monte Carlo calculation reproducing the

behaviour of the $\text{KF} \left| \vec{\Phi}(\vec{p}_s) \right|^2$ product (see eq.(1)). The geometrical efficiency of the experimental setup as well as the detection thresholds were accounted for in the calculation. An error calculation for the ${}^7\text{Li}$ -p relative energy was also performed giving a value ranging from 80 to 120 keV, the minimum estimate corresponding to the phase space region where the lens effect is more efficient [18].

In the extracted off-energy shell ${}^7\text{Li}$ -p two-body cross-section, penetrability effects were included before the comparison with direct data [16,19,20]. Both s and p waves in the entrance channel had to be considered, the s wave describing the non-resonant behaviour, while the p wave being responsible of the resonant contributions. Thus Coulomb as well as $l=1$ centrifugal barrier were accounted for in the procedure.

In order to perform the comparison, direct data were integrated over the same $\theta_{\text{c.m.}}$ angular region covered in the present experiment ($50^\circ - 70^\circ$), $\theta_{\text{c.m.}}$ being the emission angle for one outgoing α particle in the α - α center-of-mass system [2-5]. The comparison is shown in fig. 5, where full dots represent our data while the behaviour of direct data from [16,19,20] is shown as full line, both sets averaged out at the same energy bin of 100 keV comparable with the uncertainty. The two data sets agree quite well throughout the investigated range,

including the resonant regions. The good agreement validates the pole approximation for this experiment together with the PWIA approach and, importantly, the present results with ^3He as “Trojan Horse nucleus” confirm the previous investigation of the $^7\text{Li}(p,\alpha)^4\text{He}$



reaction via the $^7\text{Li}+d$ interaction.

Fig.5: Comparison between quasi-free data (full dots) and direct cross-section (full line) from ref. [16,19,20]

4 CONCLUSIONS

The $^7\text{Li}(p,\alpha)^4\text{He}$ reaction was investigated by selecting the quasi-free contribution to the $^3\text{He}(^7\text{Li},\alpha\alpha)d$ three-body reaction performed at 33 MeV. The two-body cross-section was deduced in PWIA approach and compared with the direct behaviour.

The good agreement between the two sets of data confirms the previous results of ref. [15], suggesting that ^3He is a good “Trojan Horse nucleus”, in spite of its quite high binding energy (5.85 MeV) and the validity of the pole approximation, at least for the $^7\text{Li}+p$ interaction, is not “Trojan Horse nucleus” dependent. Although the present analysis in PWIA does not include Coulomb distortions due to the charged spectator, these effects seems not so important. However further investigation with a more sophisticated theoretical approach based on the DWBA formalism is needed in order to better understand these important aspects.

5 REFERENCES

- [1] G. Baur, Phys. Lett B 178 (1986) 135.
- [2] C. Spitaleri et al., Phys. Rev. C 60 (1999) 055802.
- [3] C. Spitaleri et al., Phys. Rev. C 63 (2001) 055801.
- [4] M. Lattuada et al., ApJ 562 (2001) 1076.
- [5] A. Tumino et al., Phys. Rev. C 67 (2003) 065803.
- [6] Dj. Miljanić et al., Nucl. Phys. A215 (1973) 221.

- [7] J. Kasagi et al., Nucl. Phys. A239 (1975) 233.
- [8] M. Lattuada et al., Nucl. Phys. A458 (1986) 493.
- [9] M. Zadro et al., Nucl. Phys. A474 (1987) 373.
- [10] G.F. Chew, Phys. Rev. 80 (1950) 196.
- [11] N.S. Chant and P.G. Roos, Phys. Rev. C15 (1977) 57 and references therein.
- [12] M. Zadro et al., Phys. Rev. C40 (1989) 181.
- [13] M. Aliotta et al., Eur. Phys. Journ. A9 (2000) 435.
- [14] M. Lattuada et al., Astr. Phys. Journ. 562 (2001) 1076.
- [15] S. Typel and H. Wolter, Few-Body Syst. 29 (2000) 7
- [16] S. Engstler et al., Z. Phys. 342 (1992) 471.
- [17] N. Arena et al., Nuovo Cimento 45 (1978) 40.
- [18] G. Baur and H. Rebel, Ann. Rev. Nucl. Part. Sci. 46 (1996) 321.
- [19] G.S. Mani et al., Nucl. Phys. 60 (1964) 588.
- [20] Y. Cassagnou et al., Nucl. Phys. 33 (1962) 449.

Recent investigation for the $^{11}\text{B}(\text{p},\alpha)^8\text{Be}$ reaction via the Trojan Horse Method

L. Lamia^{*1,2}, C. Spitaleri^{1,2}, S. Cherubini^{1,3}, V. Crucillà, P. Figuera¹, M. Gulino^{1,2},
M. La Cognata^{1,2}, A. Musumarra^{1,2}, R.G. Pizzone¹, C. Rolfs³, S. Romano^{1,2}, S. Typel⁴, S. Tudisco^{1,2},
A. Tumino^{1,2}

¹*Istituto Nazionale di Fisica Nucleare -Laboratori Nazionali del Sud, Catania, Italy.*

²*Dipartimento di Metodologie Fisiche e Chimiche per l'Ingegneria- Università di Catania, Italy.*

³*Ruhr-Universität Bochum, Germany.*

⁴*GSI, Darmstadt, Germany*

* Corresponding author, e-mail: llamia@lns.infn.it

Abstract

The study of the light elements lithium, beryllium and boron could be important in different field of astrophysics. In particular the $^{11}\text{B}(\text{p},\alpha)^8\text{Be}$ represent the main channel for the boron destruction in stellar sites and then more accurate determination of its astrophysical $S(E)$ -factor are needed in the energy range $0 < E_{\text{CM}} < 1$ MeV. In this work we present a very recent investigation for this reaction involving the MPWBA theory applied to the THM.

1 INTRODUCTION

In the last twenty years particular interest was devoted to the “light element problem” in astrophysics. Different studies of lithium, beryllium and boron (LiBeB) showed their importance in the field of galactic chemical evolution and, in particular, in the field of stellar structure. As reported in [1], the study of boron abundances in young stars, together with lithium and beryllium, can provide a strong test for understanding stellar structure and discriminate between possible non-standard mixing processes in stellar interiors.

In this environments LiBeB are mainly destroyed by proton-capture reactions via the (p,α) channel with a Gamow energy E_G of few keV. These energies are low if compared with the Coulomb barrier E_C , usually of the order of MeV's, thus implying the reactions take place via tunnel effect with an exponential decrease of the cross section,

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

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

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

which varies smoothly with energies. Nevertheless this extrapolation procedure can

introduce some uncertainties due, for example, to the presence of unexpected sub-threshold resonances. However, for nuclear reaction studied in laboratory, the electron clouds surrounding the interacting nuclei lead to a screened cross section $\sigma_S(E)$ larger than the “bare” nucleus one $\sigma_B(E)$ [2]. The enhancement factor is defined by the relation

$$f_{\text{lab}}(E) = \frac{\sigma_S(E)}{\sigma_B(E)} \approx \exp(\pi\eta U_e / E) \quad (2)$$

where U_e represents the electron screening potential measured in the laboratory. To extract the $S(E)$ -factor without extrapolations problem, however, many indirect methods have been developed in recent years. In particular the THM [4,5] is a powerful tool which selects, under appropriate kinematical conditions, the quasi-free (QF) contribution of a suitable three-body reaction performed at energies well above the Coulomb barrier to extract a charged particle two-body cross section at astrophysical energies, free of Coulomb suppression.

In the present paper, we present the recent results of the “re-analysis” of two-body $^{11}\text{B}(\text{p},\alpha)^8\text{Be}$ reaction, obtained through the application of the THM to the three-body $^2\text{H}(^{11}\text{B},^8\text{Be}\alpha)\text{n}$ reaction using the MPWBA approach [3].

2 EXPERIMENTAL SETUP

The aim of the experiment was to extract the information about the $^{11}\text{B}+\text{p} \rightarrow ^8\text{Be}+\alpha$ reaction after selecting the QF-contribution of $^{11}\text{B}+\text{d} \rightarrow ^8\text{Be}+\alpha+\text{n}$

reaction. The deuteron was used like “trojan horse nucleus”, having a $p\oplus n$ structure[6]; in this framework the proton acts like *participant* while the neutron is the *spectator* to the virtual two-body reaction.

The experiment was performed at the LNS in Catania. The SMP Tandem Van de Graaf accelerator provided a 27 MeV ^{11}B beam with a spot size on target of about 2 mm and intensities up 2-5 pA. A deuterated polyethylene target (CD_2) of about $170 \mu\text{g}/\text{cm}^2$ was placed at 90° with respect to the beam axis direction. Due to its instability against alpha-decay, the detection of ^8Be ions was performed with a DPSD (Dual Position Sensitive Detector) centered at 20° , while the alpha particles were detected by using three usual PSD centered at 17° , 37° and 57° on opposite side with respect to the beam.

The displacement of the experimental setup was chosen in order to cover the whole QF-angular range, known “a priori” from a Montecarlo simulation. Energy and position signals for the detected particles were processed by standard electronics and sent to the acquisition system for on-line monitoring of the experiment and data storage on magnetic tape for the off-line analysis. More details for experimental setup and analysis can be found in [4].

3 RESULT AND CONCLUSION

After the identification of the three-body reaction channel and the selection of the events corresponding to the QF mechanism on our data, was possible, like widely discuss in [4], to extract the $S(E)$ -factor for the $^{11}\text{B}(p,\alpha)^8\text{Be}$ by using the PWIA approach. In order to do this, a normalization procedure on the direct data was needed and the final results is showed in Figure 1. The presence of a resonant state at $E_{\text{CM}} \sim 150\text{keV}$, due to the 16.106 MeV level of ^{12}C , represents a further validity test of the method well below the Coulomb barrier.

By an empirical fit of the experimental-indirect data was possible to extract the value $S_B(0) = 0.41 \pm 0.09$ MeV barn, with an evaluated normalization error of about 20%. The value obtained was compared with the $S(0) = 2.1$ MeV barn extracted by different authors ([5]) on direct data. The discrepancy between the two values can be due to uncertainties deriving from the extrapolation procedure on the direct data or from some uncertainties due to the theoretical approach.

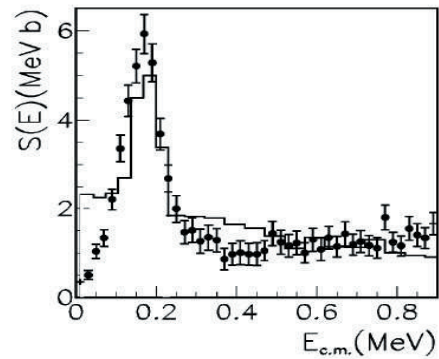


Figure 1: Comparison between THM data (full dots) and direct data (histogram). A normalization procedure was done in the energy window 500-750 keV ([4]).

In order to evaluate this difference, a new analysis of the same set of indirect data was performed using the MPWBA approach and a comparison with the previous ones is reported in figure 2. From an empirical fit we obtained a new value of $S_B(0) = 1.1 \pm 0.2$ MeV barn. The reduced discrepancy from the extrapolated direct value of $S_B(0)$ is still under investigation. In particular we stress that the THM data are not affected by the electron screening effects present in the direct ones. According to the “enhancement” described by the relation (2), further analysis could describe the role of the electron screening on the difference between the direct data and the new set of THM data showed in this brief report.

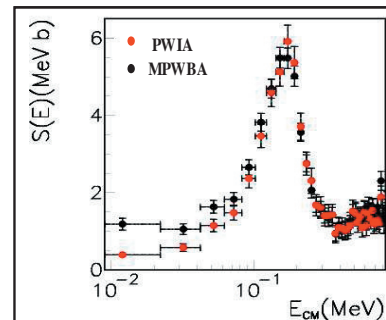


Figure 2: Comparison between the THM data extracted with the PWIA approach (red points [5]) and the data extracted with the DWBA (black points).

REFERENCES

- [1] Boesgaard A.M., “*The Light Elements: Lithium, Beryllium and Boron*”, Origin and Evolution of the Elements, 2004.
- [2] Rolfs C. and Rodney W.S. “*Cauldrons in the cosmos*”, University of Chicago Press, Chicago, 1988.
- [3] Typel S. and Wolter H., Few-Body Syst., **29**, 2000.
- [4] Spitaleri C. et al., PRC, **69**, 055806, 2004.
- [5] Becker H.W. et al., Z. Phys., **327**, 341-355, 1987.

Trojan Horse estimate of bare nucleus astrophysical $S(E)$ -factor for the ${}^6\text{Li}(p,\alpha){}^3\text{He}$ reaction and its astrophysical implications

R.G. Pizzone^{1,2}, A. Tumino^{1,2}, S. Degl'Innocenti³, C. Spitaleri^{1,2}, S. Cherubini^{1,2}, V. Crucillà^{1,2},
M. Gulino^{1,2}, M.La Cognata^{1,2}, L. Lamia^{1,2}, A. Musumarra^{1,2}, S. Romano^{1,2}, S. Tudisco^{1,2}

¹Laboratori Nazionali del Sud-INFN, Catania, Italy

²Dipartimento di Metodologie Fisiche e Chimiche per l'Ingegneria,
Università di Catania, Catania, Italy

³Dipartimento di Fisica, Università di Pisa, Pisa, Italy

Low-energy cross sections for reactions producing or destroying lithium isotopes are fundamental for a number of still not completely solved astrophysical problems, e.g. understanding Big Bang nucleosynthesis and the “Lithium depletion” in the Sun or in other galactic stars. In particular, not only the more abundant ${}^7\text{Li}$ has a relevant astrophysical importance but also ${}^6\text{Li}$ whose abundance has been extensively studied only recently. Since ${}^6\text{Li}$ is more fragile than ${}^7\text{Li}$ its abundance can give hints of the ${}^7\text{Li}$ depletion mechanism. Both production and destruction mechanisms must be studied and their cross sections should be measured in the astrophysically relevant energy window. In the recent decades, destruction mechanisms for lithium have been studied; in particular, great effort has been devoted to the study of relevant reactions such as ${}^7\text{Li}(p,\alpha){}^4\text{He}$, ${}^6\text{Li}(d,\alpha){}^4\text{He}$, ${}^6\text{Li}(p,\alpha){}^3\text{He}$, at astrophysically important energies ([19]). Due to the difficulties encountered in charged-particle experimental studies at sub-Coulomb energies (e.g. electron screening effect), indirect methods, e.g. Coulomb dissociation ([4, 5]) and ANC (Asymptotic Normalization Coefficients) ([21, 38]) have been applied to transfer reactions. Among these methods, the Trojan-horse Method (THM) ([3, 25, 44–47, 52]) is particularly well suited for investigating low-energy charged-particle two-body reactions using appropriate three-body processes. This method overcomes both Coulomb barrier and electron screening effects in the off-shell cross section of the two-body reactions. An experimental program is presently underway applying the THM to the study of relevant reactions destroying lithium in cosmic environments. The ${}^7\text{Li}(p,\alpha){}^4\text{He}$ and the ${}^6\text{Li}(d,\alpha){}^4\text{He}$ reactions have been studied through the $d({}^7\text{Li},\alpha)n$ and the ${}^6\text{Li}({}^6\text{Li},\alpha){}^4\text{He}$ three-body reactions respectively ([25, 29, 36, 45, 47]).

I. EXPERIMENTAL RESULTS ON THE ${}^6\text{Li}(p,\alpha){}^3\text{He}$

Leaving the details of the THM to the references ([45, 47, 52]), we stress that in order to get the two-body cross section from the three-body reaction for the process of interest, the Plain Wave Impulse approximation or the Modified Plane-Wave Born (MPWBA) description are adopted, as extensively treated in [48, 52].

After the standard THM analysis, the bare nucleus

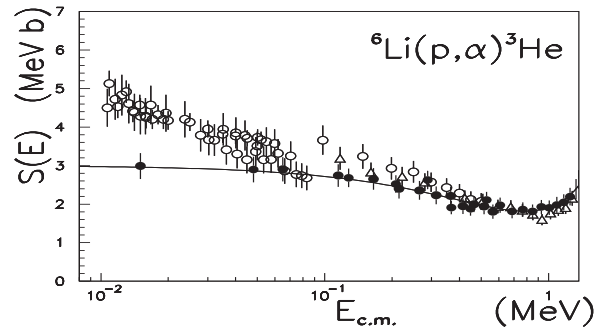


FIG. 1: Bare nucleus astrophysical $S(E)$ -factor extracted according to the THM prescriptions (full dots). The direct data from [19] and [18] are shown as open circles and open triangles respectively.

$S(E)$ -factor was extracted in the energy range $E_{cm} = 10 - 1200$ keV and normalized to direct data taken from [19] in the energy range $E_{cm} = 800 \div 1200$ keV. The normalized THM data are shown in Figure 1 as full circles, and compared with the direct behaviour (open circles) in the ${}^6\text{Li}$ - p energy range from 0 to 1 MeV. The solid line in the figure represents a second order polynomial fit to the THM data giving a bare nucleus $S(0)$ value of $S(0)=3.0\pm0.3$ MeV.b, including systematic errors arising from normalization (Table I). The derived electron screening potential is $U_e=450\pm100$ eV, in agreement with direct determination by [19]; thus the systematic discrepancy between the experimental data and the adiabatic approximation (which represents a theoretical upper limit for U_e) is evident. Moreover the isotopic independence of the electron screening effect is confirmed as seen from the comparison with the U_e estimates from the ${}^7\text{Li}(p,\alpha){}^4\text{He}$ and the ${}^6\text{Li}(d,\alpha){}^4\text{He}$ reactions (see [19, 25]). The bare nucleus $S(E)$ -factor is the relevant quantity for astrophysical application and that the THM allows its measurement without any extrapolation.

The reaction rates for the ${}^6\text{Li}(p,\alpha){}^3\text{He}$ and ${}^7\text{Li}(p,\alpha){}^4\text{He}$ processes were therefore calculated assuming the bare nucleus cross section from the THM measurement. The reaction rate $R=N_A \langle \sigma v \rangle$ (measured in $\text{cm}^3\text{sec}^{-1}\text{mol}^{-1}$) can be written following [20]

TABLE I: Bare nucleus $S(0)$ and screening potential estimates for the direct ([19]) and indirect ${}^6\text{Li}(p, \alpha){}^3\text{He}$ and ${}^7\text{Li}(p, \alpha){}^4\text{He}$ measurements.

Reaction	Method	$S(0)$ MeV·b	U_e^{exp} eV
${}^6\text{Li}(p, \alpha){}^3\text{He}$	THM	3.00 ± 0.3	450 ± 100
	Direct	2.86 ± 0.80	470 ± 150
${}^7\text{Li}(p, \alpha){}^4\text{He}$	THM	55 ± 3	330 ± 30
	Direct	58	300 ± 160

TABLE II: Coefficients for the reaction rate expansion for the ${}^6\text{Li}(p, \alpha){}^3\text{He}$ and ${}^7\text{Li}(p, \alpha){}^4\text{He}$ reactions obtained from THM measurements.

Coefficient	${}^7\text{Li}(p, \alpha){}^4\text{He}$	${}^6\text{Li}(p, \alpha){}^3\text{He}$
a_1	0.0493	0.0496
a_2	0.927	-0.243
a_3	0.320	-0.084
a_4	-0.332	0.037
a_5	-0.292	0.033

as:

$$R = (7.83 \times 10^9 (Z_1 Z_2 / \mu)^{1/3} S_{eff}) T_9^{-2/3} \exp(-\tau) \quad (1)$$

where $S_{eff} = S(0)[1 + a_1 T_9^{1/3} + a_2 T_9^{2/3} + a_3 T_9 + a_4 T_9^{4/3} + a_5 T_9^{5/3}]$, $\tau = 4.25 (Z_1^2 Z_2^2 / \mu T_9)^{1/3}$, T_9 is the temperature in billions of K, Z_1 and Z_2 charges of the interacting particles and μ the reduced mass. The a_i coefficients are reported in Table II for both reactions.

II. ASTROPHYSICAL IMPLICATIONS

To study the origin and evolution of the light element abundances in the Galaxy one should take into account several competing processes: the Big Bang, cosmic rays production, stellar depletion and nucleosynthesis, all of which are linked to the cosmic and chemical evolution (see e.g. [28], [7, 22] for reviews).

In general, theoretical analyses of light element abundances in stars are still limited by the lack of precise information on the efficiency of envelope convection, microscopic diffusion, radiative acceleration and on the possible presence of additional mixing mechanisms (e.g. induced by the stellar rotation) see [27, 35]). Moreover, the predicted light element depletion strongly depends on the adopted physical inputs, such as the nuclear reaction rates, the equation of state, the opacity of the stellar matter, still affected by relevant uncertainties (see e.g. [17, 51] for some results of evolutionary models). It is therefore not surprising that discrepancies persist

between the predicted and observed light element abundances e.g. solar ${}^7\text{Li}$ abundance (see e.g. the discussion in [33, 39]) or light element abundance in open clusters and disk stars (see e.g. Boesgaard et al. 2004, Boesgaard, Armengaud & King 2004, Piau, Randich, & Palla 2003, Sestito et al. 2003, Sills & Deliyannis 2000).

For ${}^6\text{Li}$ the most relevant mechanisms of production of this isotope are spallation and fusion processes normally due to the interaction of galactic cosmic rays with the interstellar medium ([54] for a review). Many studies have followed the evolution of ${}^6\text{Li}$ in our Galaxy (see e.g. [54, 55]). The original abundance of Galactic ${}^6\text{Li}$ is still an open question (see e.g. [24]).

Detection of ${}^6\text{Li}$ in stellar atmospheres constrains the possible destruction of the less fragile ${}^7\text{Li}$ ([16]). Since the depth of the convective zone increases with metallicity or with decreasing mass, ${}^6\text{Li}$ is almost completely depleted in high metallicity disk stars, as it is in the Sun ([2]) and it is below the detection level in all but the hottest main sequence thick disk and halo stars.

The detection of ${}^6\text{Li}$ in stellar spectra is very difficult since high resolution, high signal to noise spectra are required (see e.g. [43]). Recent measurements of halo stars ([2, 22, 30, 31, 43]) frequently have yielded only upper limits to the ${}^6\text{Li}$ abundance; for halo stars in which ${}^6\text{Li}$ has been observed, the abundances show a "plateau" as a function of $[\text{Fe}/\text{H}]$ (e.g. [24]) and whether in these stars ${}^6\text{Li}$ is burned or not is uncertain. ${}^6\text{Li}$ was observed in two metal-poor field disk stars: HD68284 and HD130551 ([30]) with an abundance ratio $N({}^6\text{Li})/N({}^7\text{Li}) \approx 0.05 \pm 0.01$.

We are interested in stars in which ${}^6\text{Li}$ burning has already started but where depletion is not complete, that is, metal-poor disk stars.

We adopt the two observed disk stars as representative examples to study the surface ${}^6\text{Li}$ abundance and we assume as an estimate of the uncertainty on the ${}^6\text{Li}(p, \alpha){}^3\text{He}$ cross section the 10% error arising from THM data obtained by the present work.

The present models are computed with an updated version of the FRANEC evolutionary code (see e.g. [15]). The input physics adopted in our code has been described in detail in [12]. Our models account for atomic diffusion, including the effects of gravitational settling and thermal diffusion, with diffusion coefficients given by [50]. We adopt the Schwarzschild criterion to define convective regions where convection is treated using the mixing length formalism (see the description in [10]). Rotation is not included in our models. With respect to [12] we updated the equation of state (The OPAL EOS₂₀₀₁ tables at the URL: <http://www-phys.llnl.gov/Research/OPAL>, see also [23]), the conductive opacity ([37]) and the heavy element mixture ([2]) adopted for the model abundances and the opacity tables. Initial values for ${}^6\text{Li}$ and ${}^7\text{Li}$ in low metallicity disk stars which, as discussed before, are not observationally known, are taken from the chemical galactic model calculations by [55].

Table III summarizes recent observational physical pa-

TABLE III: Observational physical parameters for HD68284 and HD130551 are from [6, 30, 32, 49]. The table shows: star identification, absolute visual magnitude, effective temperature (in Kelvin degrees), logarithm of surface gravity (c.g.s. units), [Fe/H] see text.

Star	M_V	T_{eff}	$\log g$	[Fe/H]
HD68284	3.42 ± 0.19	5883 ± 100	3.96 ± 0.1	-0.59 ± 0.06
HD130551	3.76 ± 0.09	6237 ± 100	4.18 ± 0.1	-0.62 ± 0.06

rameters for the two selected stars ([30, 32, 49]). The T_e evaluation by different authors can vary by $\pm \approx 100$ K and that absolute visual magnitudes are calculated from the observed visual ones. The parallaxes are taken from the Hipparcos catalogue (ESA 1997) and thus are affected by both photometric and parallax errors. The estimated $[\alpha/\text{Fe}]$ is about 0.15. An observational evaluation of the Helium abundance is not possible for these stars, and the primordial helium abundance as well as the ratio between metal and helium enrichment of the galactic medium (dY/dZ) are not precisely defined yet (Luridiana & Peimbert 2003). The observational quantities reported in Table III with their uncertainties can be fitted by several plausible combinations of the adopted values for masses, chemical compositions, efficiency of the envelope convection (different values of the mixing length parameter), which lead to different lithium depletions. We note that the fit of the absolute visual magnitude requires the adoption of a bolometric correction value whose uncertainty is as about 0.05 mag. (Bensby et al. 2003).

We find that the change in the lithium abundance due to the uncertainty on stellar physical parameters largely dominates over the variation of ${}^6\text{Li}$ and ${}^7\text{Li}$ values due to the uncertainties of the burning cross sections measured via THM. We are interested in exploring a relatively broad range of plausible physical parameters so that we can better analyze the sensitivity of the lithium isotopes depletions. We selected a mass range from $0.89 M_\odot$ to $0.99 M_\odot$, metallicity from $Z=0.004$ to 0.006 , original helium abundance from $Y=0.24$ to 0.27 and mixing length values from 1.5 to 2.2 and we accepted as representative of the two observed stars only the models that reproduce all the observational quantities shown in Table III within the quoted errors. The physical parameters adopted for these models are shown in Table 4. The comparison between the predicted and observed positions in the HR diagram indicates that the selected stars have evolved just after central H exhaustion (Turn-Off, TO). Theoretical models indicate that for these stars lithium burning seems to be active only in the Pre-Main Sequence (PMS) phase, while in the MS the surface lithium abundance should decrease by about 10% due to microscopic diffusion. Since the burning occurs in the PMS we will take only this phase into account.

TABLE IV: Physical parameters of selected evolutionary models that reproduce the observational values for HD68284 and HD130551 reported in Table III. α indicates the adopted mixing length value.

$M (M_\odot)$	Z	Y	α
0.89	0.004	0.27	2.2
0.92	0.004	0.27	1.8
0.97	0.004	0.24	1.8
0.99	0.004	0.27	1.5
0.99	0.006	0.24	1.9

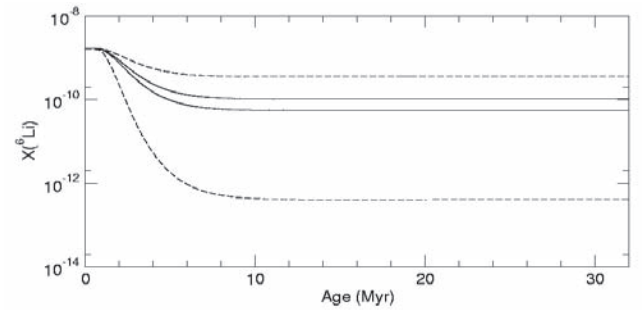


FIG. 2: The behaviour of ${}^6\text{Li}$ abundance during the PMS phase. Solid lines refer to the same model ($M=0.97$ $Z=0.004$ $Y=0.24$ $\alpha=1.76$) calculated with the THM upper and lower limits on ${}^6\text{Li}$ burning cross sections respectively. The region between the long-dashed lines represents the range of variation allowed by different choices of stellar masses, chemical compositions and efficiency of the external convection for the selected stars shown in Table IV

We can thus calculate the variation of ${}^6\text{Li}$ and ${}^7\text{Li}$ abundances in PMS for the models with different physical parameters, reported in Table IV with respect to the uncertainty on these abundances due to the errors on THM measurement.

The variation of lithium abundances due to the present uncertainties in the physical inputs other than nuclear cross sections are not taken into account because they are not relevant for the present analysis.

Figures 2 and 3 shows the behaviour of ${}^6\text{Li}$ and ${}^7\text{Li}$ abundances as a function of time during the PMS phase. The solid lines represent the results for the upper and lower limit of THM cross section (error from normalization is included)

for a given combination of stellar parameters ($M=0.97 M_\odot$ $Z=0.004$ $Y=0.24$ $\alpha=1.76$). The region between the long-dashed lines represents the range of variation allowed by the different choices of the stellar parameters shown in Table IV. Figure 3 shows the ${}^7\text{Li}$ behaviour with the same meaning for the represented lines. As expected, ${}^7\text{Li}$ is quite undepleted as indicated by the survival of a detectable amount of ${}^6\text{Li}$. It is evident that the variability range of ${}^6\text{Li}$ and ${}^7\text{Li}$ abundances due to

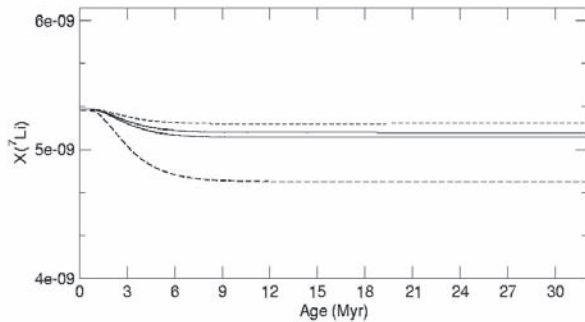


FIG. 3: ${}^7\text{Li}$ abundance during the PMS phase. Same description as in Fig.2.

different stellar parameters is very much wider than that due to the cross section uncertainties. This means that the problem of the surface lithium abundances is not at the nuclear physics level but is an astrophysical problem that requires improvements in our knowledge of the mixing mechanisms, the reduction of the uncertainties on the other (non-nuclear) physical inputs, and more precise observational data. The bare nucleus cross section, at least for lithium burning reactions at stellar energies, are now well determined.

- [1] Angulo C., Arnould M., Rayet M. et al., Nucl. Phys. A 656, 3 (1999)
- [2] Asplund, M., Grevesse, N., & Sauval, A. 2004, astro-ph/0410214
- [3] Baur, G., Phys. Lett. B **178** (1986) 135
- [4] Baur, G., & Rebel, H., J. Phys. G 20 (1994) 1 and references therein
- [5] Baur, G., & Rebel, H., Annu. Rev. Nucl. Part. Sci. 46 (1996) 321
- [6] Bensby, T., Feltzing, S., Lundstrom, I., 2003, A&A, 410, 527
- [7] Boesgaard, A.M., 2004, astro-ph/0412198
- [8] Boesgaard A. M., McGrath E. J., Lambert D. L., Cunha K. ApJ 606 (2004) 306
- [9] Boesgaard A. M., Armengaud E., King J. R. ApJ 605 (2004) 864
- [10] Brocato E. & Castellani V., 1993, ApJ, 410, 99
- [11] Calvi, G., Cherubini, S., Lattuada, M., et al., Nucl. Phys. A621 (1997) 139c
- [12] Cariulo, P.; Degl'Innocenti, S.; Castellani V. 2004 A&A, 424, 927
- [13] Castellani V., Degl'Innocenti S., Marconi M., A&A 349 (1999) 834
- [14] Chaboyer, B., Astrophys. J. 432, (1994) L47
- [15] Chieffi A., & Straniero O. 1989, ApJS, 71, 47
- [16] Copi, C.J, Schramm, D.N, Turner, M.S., Phys. Rev. D 55, (1997), 3397
- [17] D'Antona, F., Mazzitelli, I., Mem. SAIT 68 (1997) 807
- [18] Elwyn, E., et al. Phys.Rev.C 28 (1997) 1984
- [19] Engstler, S., et al., Z. Phys. A (1992)
- [20] Fowler, W.A., Caughlan, G.R., Zimmermann, B.A., 1967, Ann. Rev. Astron. Ap., 5
- [21] Gagliardi, et al., Phys. Rev. C 59 (1999) 1149
- [22] Hobbs, L.M. 2000, Phys. Reports, 333-334, 449
- [23] Iglesias, C. A. & Rogers, F. J, 1996, ApJ 464, 943
- [24] Lambert D.L., 2004, astro-ph/0410418
- [25] Lattuada, M., Pizzone, R.G., Typel S., et al., Astrophys. J. 562 (2001) 1076
- [26] Luridiana, V.; Peimbert, A.; Peimbert, M.; Cervino, M., 2003, ApJ...592..846
- [27] Montalbán, J., Schatzman, A., A&A 354 (2000) 943
- [28] Michaud, G. & Charbonneau, P. 1991, Space Sci. Rev., 57,1
- [29] Musumarra, A., Pizzone, R.G., Blagus S., et al., Phys. Rev., **C64**, 068801, (2001).
- [30] Nissen, P.E., Lambert, D.L., Primas, F., Smith, V.V., A. & A. 348 (1999), 211
- [31] Nissen P.E., Asplund, M., Hill, V. & D Odorico, S. 2000, A & A 357, L49
- [32] Nordström, B., Mayor, M., Andersen, J., et al., 2004, A&A, 418, 989
- [33] Piau, L., Turck-Chize, S., 2002, ApJ, 566, 419
- [34] Piau L., Randich S., Palla F., A&A 408 (2003) 1037
- [35] Pinsonneault, M.H., Walker, T.P., Steigman, G. & Narayanan, V.K., 1999, ApJ 527, 180
- [36] Pizzone, R.G., et al. A&A., **398**, 423, (2003)
- [37] Potekhin, A. Y., 1999 A&A, 351, 787
- [38] Ross, J.C., Görres, C., Iliadis, G., et al. Phys. Rev. C 52 (1995) 1681
- [39] Schlattl, H., Weiss, A., A&A 347 (1999) 272
- [40] Sestito P., Randich S., Mermilliod J.-C., Pallavicini R. A&A 407 (2003) 289
- [41] Sills A. & Deliyannis C. P. ApJ 544 (2000) 944
- [42] Smith, V.V., Lambert, D.L., Nissen, P.E. Astrophys. J. 408 (1993) 262
- [43] Smith, V.V., Lambert, D.L., Nissen, P.E., Astrophys. J. 506 (1998) 405
- [44] Spitaleri, C., Problems of fundamental Physics, II, World Scientific, ed. by R. Cherubini, P. Dal Piaz, B. Minetti (1990).
- [45] Spitaleri, C., et al., Phys. Rev. C 60 (1999) 055802
- [46] Spitaleri, C., et al., Eur. Phys. J A 7 (2000) 181
- [47] Spitaleri, C., et al., Phys. Rev. C **63**, 005801 (2001)
- [48] Spitaleri, C., Lamia, L., Tumino, A., et al., Phys. Rev. C **69**, 055806 (2004)
- [49] Taylor, B.J., 2003, A&A, 398, 731
- [50] Thoul, A., Bahcall J., Loeb, A., 1994, ApJ, 421, 828
- [51] Turcotte, S. & Christensen-Dalsgaard, J., 1998, Space Sci. Rev. 85, 133
- [52] Tumino A., et al., Phys. Rev. C **67**, 065803 (2003)
- [53] Tumino A., et al., Progr. Theor. Phys. Suppl., 154, 341 (2004)
- [54] Vangioni-Flam, E., Cassé, M., Cayrel, R., New Astron. 4, (2000), 245
- [55] Valle, G., et al. 2002, ApJ., 566, 252

The $^{15}\text{N}(p,\alpha)^{12}\text{C}$ reaction studied via the Trojan Horse Method

M. La Cognata^{1,2}, S. Romano^{1,2}, C. Spitaleri^{1,2}, R. Tribble³, L. Trache³, Changbo Fu³, S. Cherubini^{1,2}, V. Crucillà^{1,2}, M. Gulino^{1,2}, L. Lamia^{1,2}, A. Mukhamedzhanov³, A. Musumarra^{1,2}, R.G. Pizzone^{1,2}, C. Rolfs⁴, G. Tabacaru³, A. Tumino^{1,2}

¹*Dipartimento di Metodologie Fisiche e Chimiche per l'Ingegneria - Università di Catania, Catania, Italy*

²*Laboratori Nazionali del Sud - INFN, Catania, Italy*

³*Cyclotron Institute, Texas A&M University,
College Station, USA*

⁴*Ruhr-Universität, Bochum, Germany*

I. INTRODUCTION

The importance of ^{19}F in astrophysics is two-fold: in red giant the fluorine abundance is enhanced by large factors with respect to the solar one. On the other hand, the fluorine abundances observed in giants can constrain AGB star models. The reaction rate for the $^{15}\text{N}(p,\alpha)^{12}\text{C}$ can affect the production of fluorine since it removes protons and ^{15}N nuclei from ^{19}F production chain [1].

In Fig. 1 the comparison of ^{19}F abundance observed by [2] and the predictions from AGB star models [1] is reported. Though for some masses and metallicities even the highest experimentally observed fluorine abundances are achieved, this occurs for C/O values much larger than what experimental data suggest. In fact ^{12}C and ^{19}F are correlated since they are both dredged up to the stellar surface in correspondence of the third dredge-up. The $^{15}\text{N}(p,\alpha)^{12}\text{C}$ rate introduce at least a 8% uncertainty in the fluorine surface abundance [1], since NACRE and CF88 rates show up a factor 2 difference. As $^{15}\text{N}(p,\alpha)^{12}\text{C}$ experimental cross section is measured down to 80 keV

[3], much larger than 8 keV, the Gamow peak energy, then only extrapolations are available in that energy region.

The measurement of nuclear cross sections at ultra-low energies is a very difficult task because of the presence of the Coulomb barrier exponentially dumping the cross section. Therefore extrapolation is necessary when data at astrophysical energies are unavailable. A possible way to avoid extrapolation from high energy data is the application of the Trojan Horse Method.

The Trojan Horse Method (THM) [4] is an indirect method that allows to extract the bare nucleus cross section of a two body reaction of astrophysical interest

$$A + x \rightarrow c + C \quad (1)$$

from the cross section measurement of a suitable three-body process

$$A + a \rightarrow c + C + s, \quad (2)$$

where x acts as participant and s as a spectator to the two-body process. If the energy of the projectile a is higher than the Coulomb barrier then the reaction is induced within the nuclear interaction field. Therefore the Coulomb barrier and electron screening effect are negligible and a measurement of the cross section at ultra-low energies is possible.

In the DWBA post-form [4] approach the two-body bare nucleus cross section is extracted from the measured three-body cross section using the equation:

$$\frac{d^3\sigma}{dE_c d\Omega_c d\Omega_s} = KF \left| W(\vec{Q}_{Bs}) \right|^2 \frac{v_{Cc}}{v_{Ax}} \sum_l P_l C_l \frac{d\sigma_l}{d\Omega} (Cc \rightarrow Ax) \quad (3)$$

where KF is a kinematical factor, C_l a normalization constant, P_l the penetration probability and $|G(p_s)|^2$ the momentum distribution of spectator particle s inside a .

II. THE EXPERIMENT

A 60 MeV, 5 nA ^{15}N (from Texas A&M Cyclotron) was impinging on a 200 $\mu\text{g}/\text{cm}^2$ thick CD_2 target. The experimental setup is very simple: a telescope (A) made up of

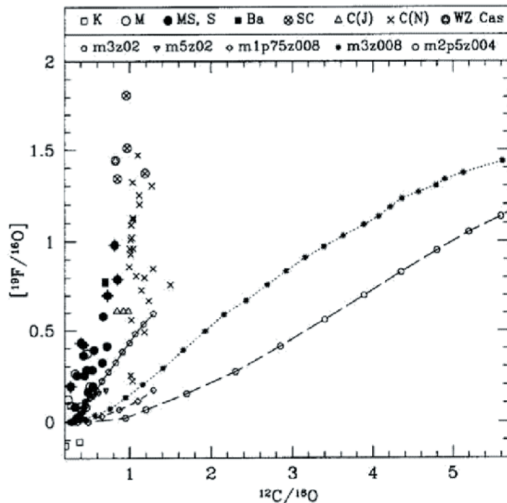


FIG. 1: Comparison of ^{19}F abundance observed by [2] and the predictions from AGB star models [1].

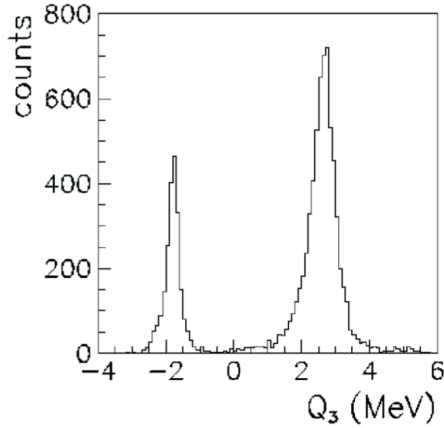


FIG. 2: Three-body Q-value spectrum. Two peaks corresponding to the ground state and first excited state of ^{12}C are clearly visible

a silicon PSD and a ionization chamber to discriminate carbon nuclei, and a couple of silicon PSD (B, C) on the opposite side with respect to the beam direction. Two events are recorded: coincidences between A and B and A and C. Alpha particles are discriminated by selecting the kinematical locus of the three body reaction.

The angular condition were selected in order to maximize the quasi-free contribution. The spectator particle momentum range spanned in the experiment is such that a comparison of the coincidence yield for small p_s (≤ 20 MeV/c) and large p_s can be performed, in order to check that the resonances occurring in the 2-body reaction are fed through a quasi free channel and not through sequential decay of intermediate nuclei.

After detector calibration, the first step of the analysis is the selection of the events corresponding to the three body reaction. This is accomplished through a selection of the coincidence events and of the kinematical locus of the reaction. For the selected events the Q value is calculated by imposing the energy balance of the three body reaction. In the picture the Q-value spectrum is reported, showing two peaks corresponding to the ground state and first excited state of ^{12}C (Q-values 2.74 MeV and -1.70 MeV respectively). The nice agreement between the calculated and the theoretical Q-values confirms the accuracy of the performed calibration.

The second step of THM data analysis is the study of the reaction mechanisms feeding the exit channel. This is a necessary step to disentangle the QF from SD mechanisms. Such a selection is fulfilled investigating the correlation between the $E_{c.m.}$ relative energy, defined as

$$E_{c.m.} = E_{^{12}\text{C}-\alpha} - B_{n-p} \quad (4)$$

and the momentum p_s for all coincidence events. In order to explore the behaviour of the coincidence yield depending on the momentum p_s , relative energy $E_{c.m.}$ spec-

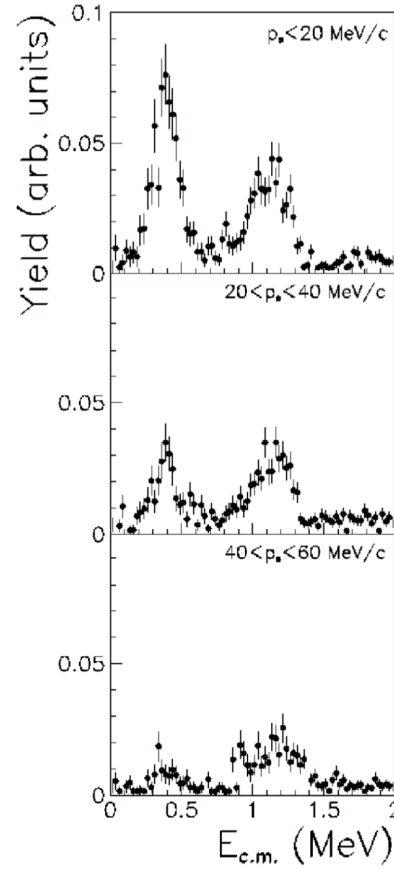


FIG. 3: Correlation spectra between $E_{c.m.}$ and neutron momentum p_s .

tra divided by the phase-space contribution were reconstructed for different ranges of the neutron momentum p_s . Within 0 MeV/c up to 20 MeV/c (Fig. 5(a)) the coincidence yield appears to be dominated by the decay of the three levels of ^{16}O at 12.44 MeV, 13.09 MeV and 13.26 MeV. For larger p_s , the coincidence yield decreases as shown in Fig. 5(b) and Fig. 5(c), and such resonances become barely visible with respect to the background. These experimental data provide clear evidence for a strong correlation between coincidence yield and neutron momentum p_s , a necessary condition for the dominance of the quasi-free mechanism in the region approaching zero spectator momentum. In fact this is what should occur when the relative motion inside the Trojan Horse nucleus take place in s -wave, as in the case of the deuteron.

Once the quasi-free contribution has been selected, the bare astrophysical $S(E)$ factor is extracted by means of the equation (3). A p_s window of 20 MeV/c around zero spectator momentum is adopted in accordance with the previous result.

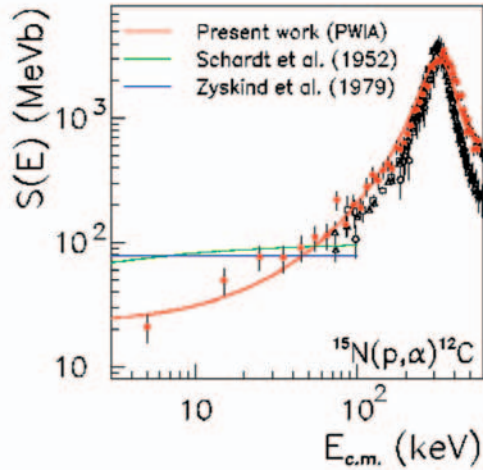


FIG. 4: THM astrophysical $S(E)$ factor together with direct data [3,5,6] in the low energy region.

The extracted THM astrophysical $S(E)$ factor is reported together with direct data [3,5,6] in the low energy region. THM $S(E)$ -factor is normalized to direct data (equating the peak value for the 320 keV resonance) for getting $S(E)$ in absolute units. By fitting indirect data with the sum of a 2nd order polynomial and a Breit-Wigner, $S(8 \text{ keV})$ is determined: $S(8 \text{ keV}) \sim 38 \text{ MeVb}$, in clear disagreement with direct data extrapolation [3,5,6], giving a much higher value $S(8 \text{ keV}) \sim 81 \text{ MeVb}$ [3,5]. Such a result tend to reduce the rate for the $^{15}\text{N}(p,\alpha)^{12}\text{C}$ in the astrophysically relevant energy region, confirming the value reported in CF88 in contrast with the one cited in NACRE compilation.

- [1] M. Lugaro et al., Ap. J. 615, 934 (2004)
- [2] A. Jorissen et al., A&A 261, 164 (1992)
- [3] A. Redder et al., Z. Phys. A 305, 325 (1982)
- [4] C. Spitaleri et al., Phys. Rev. C 63, 055801 (2001)
- [5] A. Schardt et al., Phys. Rev. 86, 527 (1952)
- [6] J.L. Zyskind et al., Nucl. Phys. A 320, 404 (1979)

THE REACTION ${}^6\text{He}+{}^{64}\text{Zn}$ AT ENERGIES ABOVE THE COULOMB BARRIER

A. Amorini^{a,b}, G. Cardella^a, A. Di Pietro^a, P. Figuera^a, A. Musumarra^{a,b}, M. Papa^a, F. Rizzo^{a,b}, V. Scuderi^{a,b},
C. Angulo^c, E. Caserejos^c, M. Pellegriti^d, R. Raabe^e

a) INFN- Laboratori Nazionali del Sud and Sezione di Catania, Catania, Italy

b) Dipartimento di Fisica ed Astronomia, Catania, Italy

c) CRC, Louvain la Neuve, Belgium

d) GANIL, Caen, France

e) Instituut voor Kern- en Stralingsfysica Katholieke Universiteit Leuven, Leuven, Belgium

Abstract

The reaction ${}^6\text{He}+{}^{64}\text{Zn}$ was measured in order to study fusion, elastic scattering and transfer+break-up cross-sections at energies above the Coulomb barrier. As comparison the reaction ${}^4\text{He}+{}^{64}\text{Zn}$ was also measured.

1 INTRODUCTION

The possibility to study collisions induced by post accelerated radioactive ion beams allows to investigate new effects on the reaction mechanisms due to the peculiar structure of the bombarding nuclei. Controversial effects on the fusion cross-section have been predicted by different theoretical models in reactions induced by halo nuclei at energies around and below the Coulomb barrier. These models agree that the larger spatial extent of halo nuclei and the coupling with possible low lying resonant states would increase the fusion cross section. However, they disagree about the role played by the break-up of the loosely bound halo nucleons on the fusion cross section. In fact, break-up can be considered either as a loss of flux for fusion thus decreasing the cross-section, or as an additional open channel which enhances the fusion cross-section [1,2 and references therein].

The experimental investigation is quite difficult owing to the very low intensity of the available radioactive beams coupled to the difficulty of measuring fusion cross-sections at low energies for reactions induced by light projectiles. For this reason only four systems have been studied: ${}^6\text{He}+{}^{209}\text{Bi}$ [3-6], ${}^6\text{He}+{}^{238}\text{U}$ [7], ${}^{11}\text{Be}+{}^{209}\text{Bi}$ [8] and ${}^6\text{He}+{}^{64}\text{Zn}$ [9,10]. With the exception of the results for the ${}^6\text{He}+{}^{209}\text{Bi}$ reaction, where an enhancement of the fusion cross-section is found below the barrier, all other results do not show such an enhancement.

In the experiment, performed in October 2004, we studied the reaction ${}^6\text{He}+{}^{64}\text{Zn}$ to extend the fusion excitation function, we had already measured at energies below the Coulomb barrier, to energies above the barrier. Moreover we measured the elastic

scattering angular distribution and the transfer+break-up angular distribution at two beam energies ($E_{\text{beam}}=15$ and 18 MeV) in order to complement the previous results obtained at lower energy and to perform an excitation function for the total reaction cross-section and transfer+break-up as well. As comparison the reaction ${}^4\text{He}+{}^{64}\text{Zn}$ was also measured.

Using the ${}^6\text{He}$ beam available at Louvain la Neuve, we have measured the fusion excitation function in the energy range $7.5 \text{ MeV} \leq E_{\text{cm}} \leq 17 \text{ MeV}$. To perform this experiment we used an activation technique, which allows to measure the fusion cross-section by detecting the atomic X-rays emitted from the radioactive evaporation residues (E.R.) after decaying by Electron Capture (E.C.).

2 THE EXPERIMENT

The experimental set-up is sketched in fig.1. An array of Si strip detectors surrounding a thin ($\sim 500 \mu\text{g}/\text{cm}^2$) ${}^{64}\text{Zn}$ target was used to detect the light particles (${}^6\text{He}$, α and p) produced in the reaction. The thin ${}^{64}\text{Zn}$ target was angled at 45° in order to allow detection of particles emitted at 90° . The angular range covered was $5^\circ \leq \theta \leq 120^\circ$. In the experiment, He isotopes were discriminated from H using the time of flight (TOF) information.

To limit the beam time request we activated the target stack while measuring at the same time the elastic and transfer+break-up processes. This was done also in the previous experiment. Short and long activation runs were performed to optimise the production of E.R. with different half-lives. Downstream the thin ${}^{64}\text{Zn}$ target a stack of thick ${}^{64}\text{Zn}$

targets ($\sim 2\text{mg}/\text{cm}^2$), each followed by a Nb catcher ($\sim 3.5\text{mg}/\text{cm}^2$), was irradiated by the same beam.

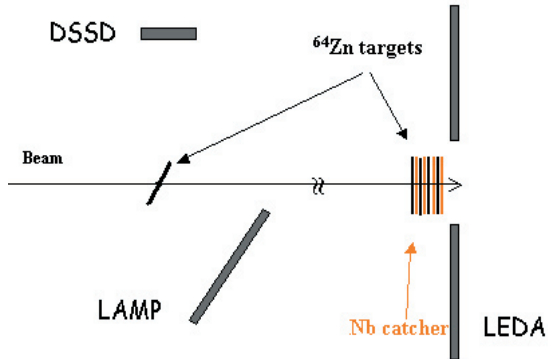


Fig. 1 Experimental set-up.

The catcher thickness was chosen in order to stop the E.R. produced in the previous ^{64}Zn target and to degrade the beam energy. The activity of the irradiated targets was measured off-line using Pb shielded large area Si(Li) detectors whose intrinsic efficiency is 100% for X-ray energies of our interest (6-11 keV). The advantage of measuring X-ray is the very low background that can be obtained with proper shields. In the previous experiment we could measure counting rates as low as 0.3 counts/h for about 1 month, collecting enough statistics even for the E.R. with the lowest cross section.

To extract the activity of the long lived residues the activated targets were measured at LNS for few months. In figs. 2a and 2b the X-ray spectra obtained short after the end of the activation and about three weeks after the end of the activation are shown. For each element two peaks are present corresponding to the $K\alpha$ and $K\beta$ X-ray emission. In figure 2a two dominant peaks are observed which correspond to the $K\alpha$ and $K\beta$ lines of the Ga isotopes. This spectrum

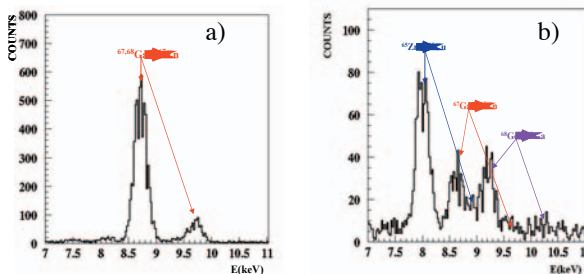


Fig. 2 a) X-ray spectrum collected for few hours, starting one hour after the activation run ended. b) X-ray spectrum collected for few

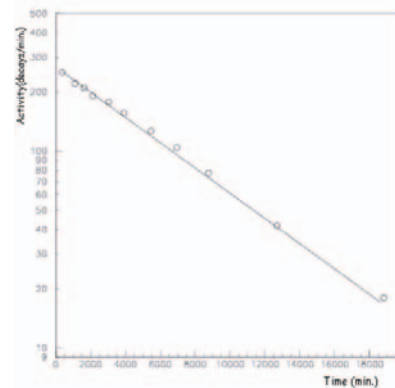
days, starting three weeks after the end of the activation run. See text for details.

was collected for about 10 hours. In figure 2b a spectrum collected for about 10 days, starting few weeks after the end of the activation is shown. The peaks corresponding to Ga isotopes are strongly reduced, since the half-life of the longest lived Ga isotope produced in the reaction is 3.2 days. Instead in this spectrum, due to the long collection time, the peaks

E.R.	$T_{1/2}$	decay chain
^{68}Ge	270 d	2n
^{67}Ge	18.9 m	3n
^{68}Ga	67.6 m	1n1p
^{67}Ga	3.26 d	2n1p
^{65}Zn	244.26 d	1n1 α
^{64}Cu	12.7 h	1n1p1 α

corresponding to the long-lived ^{65}Zn and ^{68}Ge can be observed.

Table 1 CASCADE prediction of radioactive E.R. produced in $^4\text{He}+^{64}\text{Zn}$ and experimentally observed.



In table 1 are listed the radioactive E.R. produced in the experiment. The activity of the different isotopes was measured at different time periods.

Fig. 3 Activity curve for the Ga peak obtained for a target irradiated with the ^4He beam at $E_{\text{beam}} \approx 15\text{ MeV}$ (see text).

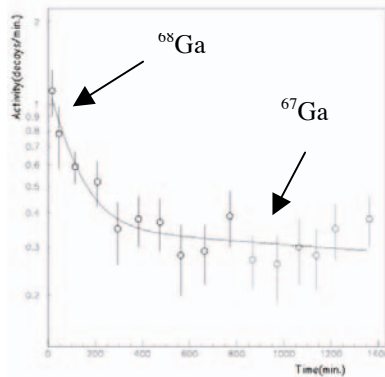


Fig.4 Activity curve for the Ga peak obtained for a target irradiated with the ${}^6\text{He}$ beam at $E_{\text{beam}} \approx 15$ MeV (see text).

In figs. 3 and 4 are shown the activity curve for the Ga isotopes extracted in the activation run with ${}^4\text{He}$ beam (fig. 3) and with the ${}^6\text{He}$ beam (fig. 4) both at $E_{\text{beam}} \approx 15$ MeV. The time $T=0$ corresponds to the end of the irradiation. In fig. 3 only the contribution of one Gallium isotope, ${}^{67}\text{Ga}$, is evident, whereas in the run with ${}^6\text{He}$ beam the activity curve shows two different slopes corresponding to the two Gallium isotopes ${}^{68}\text{Ga}$ and ${}^{67}\text{Ga}$. Analysis is still in progress to extract from the activity the fusion cross sections.

4 REFERENCES

- [1] C. Signorini et al. Nucl.Phys. A 693(2001)190
- [2] C. Signorini et al. Nucl.Phys. A 616(1997)262c
- [3] E.F. Aguilera et al. Phys.Rev. C 63(2001)061603
- [4] E.F. Aguilera et al. Phys. Rev. Lett. 84(2000)5058
- [5] P.A. De Young et al. Phys.Rev. C 58(1998)3342
- [6] J.J. Kolata et al. Phys.Rev.Lett. 81(1998)4500
- [7] R. Raabe et al. Nature 431(2004)823
- [8] C. Signorini et al. Nucl.Phys. A 735(2004)329
- [9] A. Di Pietro et al. Eur.Phys.Lett. 64(2003)309
- [10] A. Di Pietro et al. Phys.Rev. C 69(2004)044613

EXCLUSIVE CHANNEL IDENTIFICATION IN PP COLLISIONS IN HADES

S.Spataro^{a,b,*} for the HADES collaboration

a) Istituto Nazionale di Fisica Nucleare - Laboratori Nazionali del Sud, 95125 Catania, Italy

b) Dipartimento di Fisica e Astronomia, Università di Catania, 95125, Catania, Italy

** Corresponding author, e-mail: spataro@lns.infn.it*

Abstract

During the first pp production run the HADES spectrometer was equipped with an almost complete outer tracking system. The main goal of this experiment was to collect data to identify the $pp \rightarrow pp\eta$ reaction channel via exclusive reconstruction of the hadronic and dielectron decay channel, in order to provide a reference for dielectrons measured by HADES in C+C collisions at similar energies. Furthermore, pp elastic scattering channel was selected for systematic studies of the high resolution tracking system recently installed in the spectrometer. We present the status of HADES high resolution tracking reconstruction on example of pp elastic scattering reconstruction. We show the particle identification capability of the spectrometer, and exclusive channel reconstruction for four charged particle events.

1 INTRODUCTION

HADES [1] is a second generation experiment designed to study dielectron production in proton, pion and heavy ion induced reactions at the GSI accelerator facility in Darmstadt.

A first HADES physics run was conducted in 2002 with C+C at 2AGeV [2], to reinvestigate the enhancement of dileptons measured by the DLS collaboration [3]. In order to provide absolute measurement of dielectron reconstruction efficiency needed for the final interpretation of C+C data, an independent measurement is needed; the $pp \rightarrow pp\eta$ reaction channel.

The η production cross sections can be measured both through the hadronic ($\eta \rightarrow \pi^+ \pi^- \pi^0$) and the dielectron ($\eta \rightarrow e^+ e^- \gamma$) Dalitz decays, whose branching ratios are known. This fact allows to use the $pp \rightarrow pp\eta$ channel as calibration reaction for the dielectron identification of the spectrometer, in order to normalize the dielectron yields in the heavy ions experiments. Moreover an accurate measurement could help improving our evaluation of the electromagnetic form factor of the meson.

A proton-proton run was done on January 2004 at 2.2GeV, with the full coverage of outer chambers in 4 over 6 sectors, so with the high resolution tracking for the first time. The main aim of this experiment was to identify the $pp \rightarrow pp\eta$ reaction channel, and moreover to collect elastic pairs, in order to evaluate and improve the alignment of the tracking system.

The following chapters will deal with some preliminary results from a proton beam experiment, mainly focusing on the hadronic decay and on the strategy for particle identification.

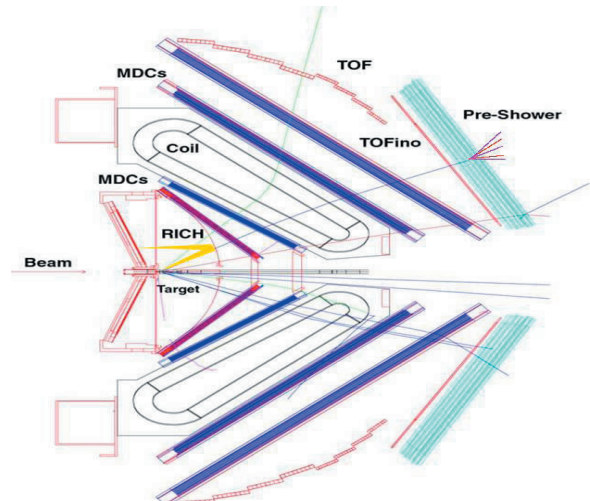


Figure 1 – Schematic view of the spectrometer

2 THE EXPERIMENT

HADES (High Acceptance DiElectron Spectrometer [1]) is a second generation experiment for high resolution electron pair spectroscopy (figure 1). It consists of 6 identical sectors covering a polar angle region between 18° and 85° , and almost the full azimuthal acceptance. A hadron-blind Ring Imaging Cherenkov detector (RICH) [4] is used for electron identification, enhanced by an electromagnetic Pre-Shower detector [5] and a set of plastic scintillators as time-of-flight wall (TOF [6] and TOFINO). Tracking is performed by 4 planes of Multi-wire Drift Chambers (MDC) [7], placed before and after a magnetic field region (a toroidal magnet, $B_{\max} \approx 0.7$ T); the expected invariant mass resolution is 1-2% in the ρ/ω region. The first-level trigger identification is obtained by means of a fast multiplicity signal coming from the TOF/TOFINO wall, while the second level decision is the combination of RICH, Pre-Shower and TOF

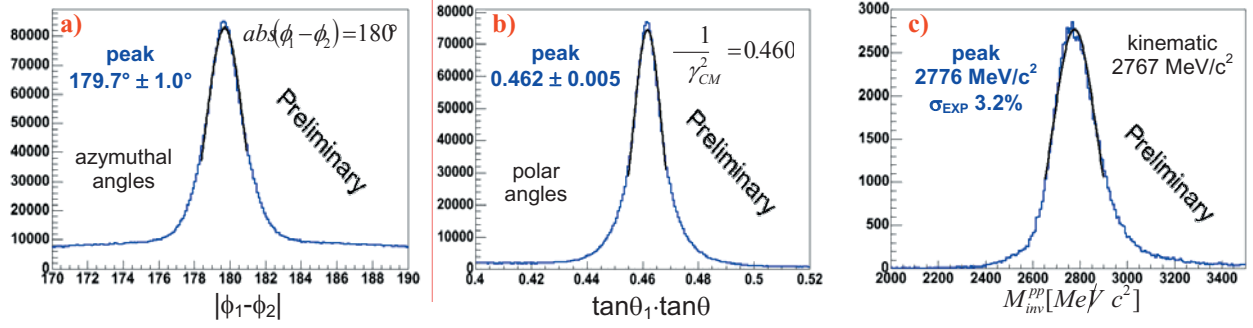


Figure 2 – Proton-proton pairs: a) absolute value of the difference between the azimuthal angles of opposite pairs; b) product of tangents of polar angles; c) invariant mass distribution for elastic pairs.

detectors in fast image-processing units [8], for an enrichment of the event stream with lepton-pair candidates.

In the January 2004 experiment we had protons at 2.2 GeV kinetic energy, with an intensity of about 10^7 particles/second, hitting a target chamber 5 cm long filled with liquid hydrogen.

The data acquisition was performed with two types of first level trigger. The first one was used to detect elastic pairs, so we acquired events with at least two hits in opposite sectors. The second one was optimised, after a simulation study, in order to detect η reactions while keeping low the background from other uninteresting reactions; we required at least four hits in the multiplicity detector, two of them in opposite sectors, and at least two hits in the lower polar angle region (TOFINO wall). The second level trigger enhances by at least one order of magnitude the events due to reactions containing at least one high-energy electron.

In two weeks of beam time we collected about 420 million events. In the following chapters some very preliminary results will be shown, after a first iteration of analysis, where we studied a sample of 270 million events.

3 PROTON-PROTON PAIRS

The pp elastic channel is a wonderful tool to study the detector alignment and its tracking capability. Presently we have developed some alignment procedure based on straight trajectories in runs without magnetic field; the elastic scattering provides additional information quite useful for a further improvement of the tracking resolution.

In an elastic scattering the kinematics of the reaction is fixed, and so is the relationship between the angular variables of the proton pairs. First of all the two protons lay on the same reaction plane, and this fact imposes a condition on the azimuthal angles (ϕ_1 and ϕ_2):

$$\text{abs}(\phi_1 - \phi_2) = 180^\circ \quad (1)$$

Furthermore, from relativistic calculations, the two polar angles (θ_1 and θ_2) follow the law:

$$\tan \theta_1 \cdot \tan \theta_2 = \frac{1}{\gamma_{CM}^2} \quad (2)$$

Figure 2 shows the plots for azimuthal and polar angles selecting pairs of positive charged tracks (from the deviation inside the magnetic field) and belonging to opposite sectors, after a first iteration alignment. It is possible to see that the peaks are very close to the expected values.

Placing a window-cut around the elastic peaks we can select the proton pairs due to elastic scattering; the 3rd plot of figure 2 shows the invariant mass of the pairs inside this cut, for a couple of sectors equipped with all the four MDC planes. The position of the peak is well centred around the theoretical value, without any normalization factors, while the resolution is 3.2%.

The second step of the analysis is to study inelastic channels, whose main contribution should come from π^0 meson decay. If we assume that the two positive charged tracks are protons, knowing the initial total energy and momentum, we can calculate the missing mass of the system from the relativistic equation:

$$M^2 = (E_{ini} - E_{p^1} - E_{p^2})^2 - (\vec{p}_{ini} - \vec{p}_{p^1} - \vec{p}_{p^2})^2 \quad (3)$$

where M is the missing mass of the system, E and p stand for the energies and momenta of the initial state and of the two outgoing protons.

In the upper frame of figure 3 the distribution of squared missing mass is shown (a), for all the pairs belonging to opposite sectors. The main peak at zero is due to elastic pairs, as it appears after applying the cut on the angular variables (b); it is also possible to distinguish a structure at positive values in missing mass. If we remove the elastic pairs from the distribution (c), the peak at positive missing mass becomes evident. The lower frame of figure 3 shows the distribution for “inelastic” pairs in linear scale; the centroid value of a gaussian fit corresponds to the mass of a missing π^0 meson, so that it is possible to separate it and calculate yields and distributions.

For further analysis a particle identification procedure is needed, to study other inelastic channels which involve more particles, such as reactions where η 's are produced.

4 PARTICLE IDENTIFICATION

In HADES the main algorithm for particle identification requires a combination of momentum and

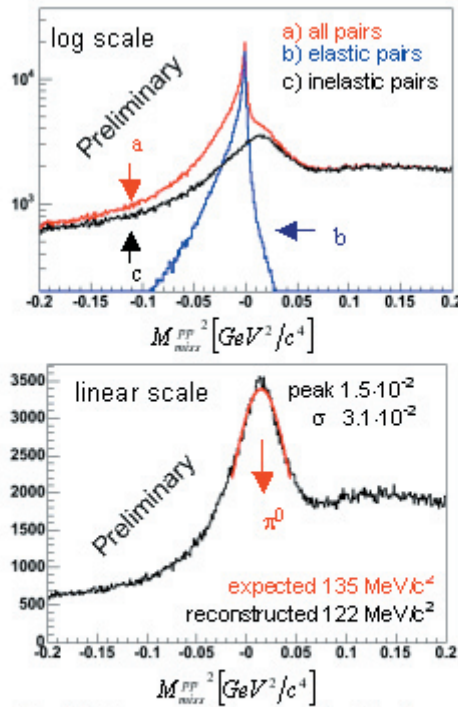


Figure 3 – Missing mass (squared) plots for positive charged pairs. Upper plot: the spectrum for all the pairs, and separately the contribution from elastic and inelastic ones. Lower plot: distribution only for the inelastic pairs (in linear scale).

time-of-flight measurements [2]. But in the p+p experiment it was not possible to use the START detector as a time reference, unlike C+C experiments, because of the high number of secondaries produced. This means that there is not a common start time reference for tracks in the same event, but in general the data acquisition is started by the fastest particle which crosses the TOF wall and produces a signal. In this case we measure the difference in time-of-flight with respect to the fastest particle, instead of the real time-of-flight. What we need is a procedure which reconstructs the start time of the reaction to make particle identification possible.

The algorithm relies on using a different method to identify one particle inside the event. The first kind of identification comes from RICH Cherenkov detector, which can select electron/positron tracks; if a lepton candidate is not found, we can try to find inside the event a negative charged track (from the deviation of the trajectory inside the magnetic field) and assume it is a negative pion.

From the assumed mass and the measured momentum it is possible to calculate the time-of-flight of the particle, and so the offset to the real start time of the reaction. Finally, we can recalculate the time-of-flight of the other particles inside the same event using the reaction time.

The events where we are not able to apply these kinds of identification are not used, but it is important to stress that the reactions of interest are the decay

channels of η , so $pp \rightarrow pp\pi^+\pi^-\pi^0$ and $pp \rightarrow ppe^+e^-\gamma$. Events with only positive tracks are not interesting, or we can use other kinds of identification as seen in chapter 4. Once a track is identified, its time-of-flight is calculated and the start time is extracted, the time of the other particles is recalculated.

Figure 4 shows momentum versus velocity plots when a track is identified as due to an electron/positron (left) or a negative pion (right). Now we can see that protons and pions are well resolved, therefore it is possible to use this new time-of-flight to identify particles.

By applying this method to data from a dedicated commissioning beam time, we were able to measure time-of-flight directly and to evaluate the performance of the method itself. We obtained a time resolution of 339 ps and an efficiency of about 92% for events with a lepton, and a resolution of 440 ps and an efficiency of about 93% for events with a negative pion. We expect that by improving the alignment, and consequently the momentum resolution, these values will improve as well.

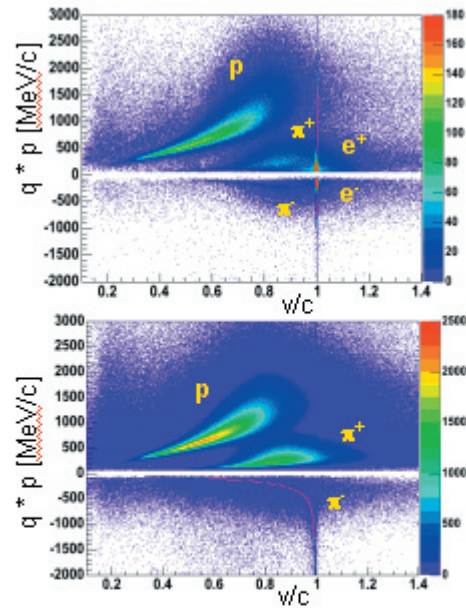


Figure 4 – Plots of momentum times polarity versus reconstructed velocity, for events with an identified e^+/e^- (upper), and with an identified π^- (lower).

5 SEARCH FOR η HADRONIC DECAY

In this chapter we will explain the procedure to identify the η mesons decaying into hadrons; the dielectron decay channel is still under analysis, therefore it will not be shown in this paper.

Using the momentum-versus-velocity plots of figure 4 it is possible to identify the particles and to select 4-prong events where two protons, a negative pion and a positive pion are detected; by looking at the missing mass distribution it is then possible to select events with the hadronic decay of the η meson. The reaction of interest is $pp \rightarrow pp\eta \rightarrow pp\pi^+\pi^-\pi^0$, so if we plot the missing

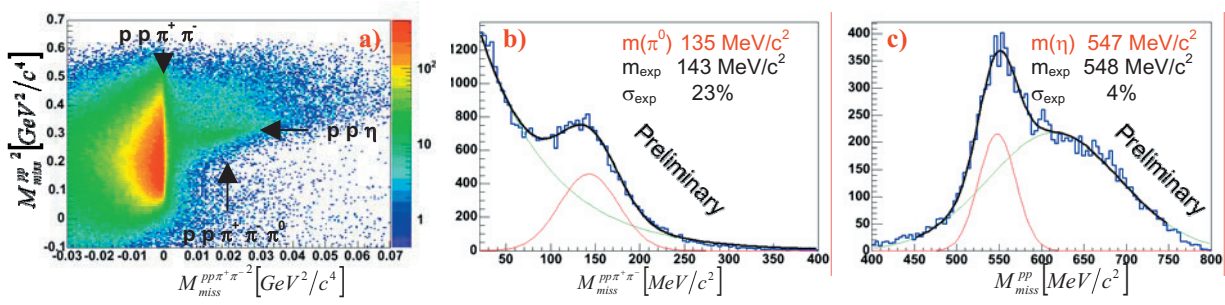


Figure 5 – Missing mass plots for 4-particle events (two protons, two pions) plots: a) 2-dimensional missing mass plot; b) missing mass of $pp\pi^+\pi^-$; c) two-proton missing mass, after applying a cut on the four-particle missing mass ($100 < M(pp\pi^+\pi^-) < 180$ [MeV/c²]). The η peak is evident, with a mass resolution of 4%

mass distribution of the 4-particle final state we should observe a peak in the region of the missing neutral pion; moreover, by plotting the missing mass of the two-proton final state, the peak of the missing η meson should appear.

The left frame of figure 5 shows the pp squared missing mass (y axis) versus $pp\pi^+\pi^-$ squared missing mass (x axis) for experimental data. Looking at the plot one observes that the main part of the distribution stays around the zero of the 4-particle missing mass, and this corresponds to the $pp \rightarrow pp\pi^+\pi^-$ channel. In the positive region of the x axis there is a bump corresponding to events where the π^0 is missing. In this region the η meson appears as a peak in the two-proton missing mass, in form of a horizontal trace in the plot.

In order to identify η mesons the first step is to find events with a missing π^0 . The $pp\pi^+\pi^-$ missing mass distribution (figure 5 - central frame) shows the background coming from the $pp\pi^+\pi^-$ channel plus a peak. It is possible to fit the distribution by a gaussian plus an exponential background function, and to obtain the mass of π^0 meson (within the error bars).

By imposing a cut around the π^0 region we now look at the plot of the two-proton missing mass (figure 5 - right frame). The spectrum is composed of a background, coming from $pp\pi^+\pi^-\pi^0$ non-resonating channels, plus a well defined peak; fitting the distribution by means of two gaussian functions we can find the value of the η mass, with an invariant mass resolution of 4%. Therefore we can state that, even though the analysis is at a preliminary stage, we were able to identify η mesons and to study them.

6 CONCLUSIONS

In this work some preliminary plots were presented from the p+p experiment at 2.2GeV done in January 2004.

A study of the elastic scattering channel allowed us to estimate a 3.2% value of the invariant mass resolution for the high resolution tracking, with the currently imperfect alignment parameters; as soon as the alignment parameters will be better tuned, the angular resolution of the proton pairs will improve, as well as the overall resolution of the tracking system.

In order to solve the problem of the missing START detector for time-of-flight measurements, an algorithm for the reaction time reconstruction was developed, and it was demonstrated as capable of providing a good proton/pion identification and separation.

The particle identification was used to select reactions where an η meson decays into hadrons (two protons and two charged pions in the exit channel). The results are well promising even at this preliminary stage, the missing η is identified as well the missing π^0 , so that the analysis can now proceed and cross sections will be evaluated.

In the next future the analysis of the dilepton decay channel will be performed; this study will allow to evaluate branching ratios and, by comparison with the hadronic channel yields, to determine the efficiency of the HADES spectrometer, in order to check normalization of the dilepton spectra produced in heavy-ion collisions.

This work has been supported by GA CR 202/00/1668 and GA AS CR IAA1048304 (Czech Republic), KBN 5P03B 140 20 (Poland), BMBF (Germany), INFN (Italy), CNRS/IN2P3 (France), MCYT FPA2000-2041-C02-02 and XUGA PGIDT02PXIC20605PN (Spain) and INTAS ref. Nr. 03-51-3208.

8 REFERENCES

- [1] The HADES Collaboration, proposal for a High Acceptance Spectrometer, GSI 1994 - R. Schicker et al., Nucl. Instr. Meth. A 380 (1996) 586
- [2] T. Wojcik, XLIII International Winter Meeting on Nuclear Physics
- [3] E. L. Bratkovskaya et al., Nucl. Phys. A 634 (1998) 168
- [4] K. Zeitelhack et al., Nucl. Instr. Meth. A 433 (1999) 201
- [5] A. Balanda et al., Nucl. Instr. Meth. A 531 (2004) 445
- [6] C. Agodi et al., Nucl. Instr. Meth. A 492 (2002) 14
- [7] H. Bokemeyer et al., Nucl. Instr. Meth. A 477 (2002) 397
- [8] J. Lehnert et al., Nucl. Instr. Meth. A 502 (2003) 261

Isospin Dynamics in Relativistic Heavy Ion Collisions

V. Baran^{1,2}, M. Colonna¹, M. Di Toro¹, A. Drago³, G. Ferini¹,
T. Gaitanos⁴, V. Greco¹, A. Lavagno⁵, E. Santini^{1,6}, H. H. Wolter⁴
¹*Laboratori Nazionali del Sud, INFN, Via S. Sofia 44, I-95123 Catania, Italy*
and Dipartimento di Fisica e Astronomia, Università di Catania
²*Theory Division, NIPNE-HH and Univ. of Bucharest, Romania*
³*Dipartimento di Fisica, Università di Ferrara*
and INFN, Sezione di Ferrara, 44100 Ferrara, Italy
⁴*Sektion Physik, Universität München,*
Am Coulombwall 1, D-85748 Garching, Germany
⁵*Dipartimento di Fisica, Politecnico di Torino*
and INFN, Sezione di Torino, 10129 Torino, Italy and
⁶*Institute für Theoretische Physik, Universität Tübingen, Germany*
(Dated: June 1, 2005)

Aim of the project is to select observables in Relativistic Heavy Ion Collisions (*HIC*) particularly sensitive to the elusive symmetry energy at high baryon density. Using relativistic transport approaches we actually show the possibility of direct observation of the microscopic field structure of the effective isovector interaction. We present here predictions of isospin effects on collective flows, fragment formation, particle production, iso-transparency and finally on the possibility of a high density transition to deconfined matter.

I. COLLECTIVE FLOWS AS PROBES OF THE HIGH DENSITY SYMMETRY ENERGY

Intermediate energy heavy ion collisions open the unique possibility to explore the Equation of State (*EOS*) of nuclear matter far from saturation, in particular the density dependence of the symmetry energy [1].

The elliptic flows of nucleons and light isobars appear to be quite sensitive to microscopic structure of the symmetry term, in particular for particles with large transverse momenta, since they represent an earlier emission from a compressed source. Thus future, more exclusive, experiments with relativistic radioactive beams should be able to set stringent constraints on the density dependence of the symmetry energy far from ground state nuclear matter.

In recent years some efforts have been devoted to the effects of the scalar-isovector channel in finite nuclei. Such investigations have not shown a clear evidence for the δ -field and this can be understood considering that in finite nuclei one can test the interaction properties mainly below the normal density, where the effect of the δ -channel on symmetry energy and on the effective masses is indeed small [2] and eventually could be absorbed into non linear terms of the ρ field. Moreover even studies of the asymmetric nuclear matter by means of the Fermi Liquid Theory [2] and a linear response analysis have concluded that some properties, like the borderline and the dynamical response inside the spinodal instability region, are not affected by the δ field [3].

Here we show that heavy-ion collisions around 1 AGeV with radioactive beams can provide instead a unique opportunity to spot the presence of the scalar isovector channel [4]. In fact, due to the large counterstreaming nuclear currents one may exploit the different Lorentz nature of a scalar and a vector field.

Oversimplifying the *HIC* dynamics we consider locally neutrons and protons with the same γ factor (i.e. with the same speed). Then nucleon equations of motion can be expressed approximately by the following transparent form ($\rho_{S3} = \frac{M}{E^*} \rho_3$), [4]:

$$\frac{d\vec{p}_p^*}{d\tau} - \frac{d\vec{p}_n^*}{d\tau} \simeq 2 \left[\gamma f_\rho - \frac{f_\delta}{\gamma} \right] \vec{\nabla} \rho_3 \quad (1)$$

where γ is the Lorentz factor for the collective motion of a given ideal cell.

Keeping in mind that $NL\rho\delta$ has a three times larger ρ field, [2], it is clear that dynamically the vector-isovector mean field acting during the *HIC* is much greater than the one of the $NL\rho, NLD\rho$ cases ($NLD\rho$ is built with the same density dependence of the $NL\rho\delta$ symmetry energy, but without the δ coupling). Then the isospin effect is mostly caused by the different Lorentz structure of the “interaction” which results in a dynamical breaking of the balance between the ρ vector and δ scalar fields, present in nuclear matter at equilibrium.

We have performed a set of simulations for the realistic $^{132}\text{Sn} + ^{124}\text{Sn}$ reaction at 1.5 AGeV ($b=6\text{fm}$), that likely could be studied with the new planned radioactive beam facilities at intermediate energies. The transverse and elliptic differential flows are shown in Fig.1. The effect of the different structure of the isovector channel is quite clear. Particularly evident is the splitting in the high p_t region of the elliptic flow.

From Fig.1 we see that, in spite of the statistical errors, in the $(\rho + \delta)$ dynamics the high- p_t neutrons show a much larger *squeeze-out*. This is fully consistent with an early emission (more spectator shadowing) due to the larger repulsive ρ -field. We can expect this appreciable effect since the relativistic enhancement discussed above is relevant just at the first stage of the collision. The v_2 observable, which is a good *chronometer* of the reac-

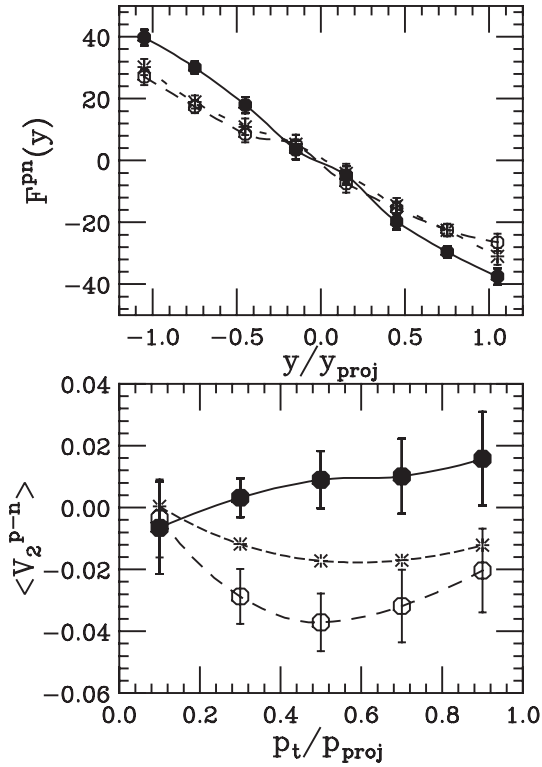


FIG. 1: Differential neutron-proton flows for the $^{132}\text{Sn} + ^{124}\text{Sn}$ reaction at 1.5 AGeV ($b=6\text{fm}$) from the three different models for the isovector mean fields. Top: Transverse Flows. Bottom: Elliptic Flows. Full circles and solid line: $NL\rho\delta$. Open circles and dashed line: $NL\rho$. Stars and short dashed line: $NL - D\rho$. Error bars: see the text and the previous caption.

tion dynamics, appears to be particularly sensitive to the Lorentz structure of the effective interaction.

We expect similar effects, even enhanced, from the measurements of differential flows for light isobars, like ^3H vs. ^3He .

II. FRAGMENT FORMATION IN CENTRAL HEAVY ION COLLISIONS AT RELATIVISTIC ENERGIES

We perform a systematic study of the fragmentation path of excited nuclear matter in central heavy ion collisions at the intermediate energy of 0.4 AGeV. The theoretical calculations are based on a Relativistic Boltzmann-Uehling-Uhlenbeck ($RBUU$) transport equation including stochastic effects. A Relativistic Mean Field (RMF) approach is used, based on a non-linear Lagrangian, with coupling constants tuned to reproduce the high density results of calculations with correlations.

At variance with the case at Fermi energies, a new fast clusterization mechanism is revealed in the early compression stage of the reaction dynamics. Fragments ap-

pear directly produced from phase-space fluctuations due to two-body correlations. In-medium effects of the elastic nucleon-nucleon cross sections on the fragmentation dynamics are particularly discussed. The subsequent evolution of the primordial clusters is treated using a simple phenomenological phase space coalescence algorithm [5].

The reliability of the approach, formation and recognition, is investigated in detail by comparing fragment momentum space distributions and simultaneously their yields with recent experimental data of the *FOPI* collaboration by varying the system size of the colliding system, i.e. its compressional energy (pressure, radial flow). We find an excellent agreement between theory and experiment in almost all the cases and, on the other hand, some limitations of the simple coalescence model. Furthermore, the temporal evolution of the fragment structure is explored with a clear evidence of an earlier formation of the heavier clusters, that will appear as interesting *relics* of the high density phase of the nuclear Equation of State (*EoS*).

Fig. 2 shows the charge particle distributions at mid rapidity for three different colliding systems ($Au + Au$, $Zr + Zr$ and $Ni + Ni$ at 0.4 AGeV incident energy). It can be seen that the theoretical results fit the experimental data very well. The extracted coalescence parameters have been chosen as 4.5 fm and 1.5 1/fm in coordinate and momentum space, respectively. One should note that these parameters are unique for all the systems considered here. The moderate discrepancies between theory and experiment for the heavier clusters ($Z > 5 - 6$) will not influence most of the results shown below, due to their low multiplicity with respect to that of protons and light ions. We will see later that in fact these heavier fragments are associated to a very interesting physics and so the lack of statistics, in simulations as well as in experiments, represents a serious drawback.

We note how well the simulations are reproducing the increasing slope of the $N(Z)$ exponential behavior with decreasing system size. This doesn't mean that lighter systems become "hotter" but just that we have less stopping while the fragments, in particular the heavier ones, are produced in the dense phase. This "non-equilibrium" interpretation will be clear in the following and in fact it has been already suggested from the analysis of experimental data in ref. [8].

The multiplicity of heavy clusters $Z > 2$, M_{hc} (relative to that of a 100 proton system), linearly increases with system size, independent of the phase space selections (apart the absolute values). The comparison between the theoretical calculations and the data is almost perfect, see Fig.3. In particular, the multiplicity of heavier clusters is well reproduced quantitatively, including the deviation in the system size systematics for $Z \approx 80$. This refers to the Ru, Zr systems (same mass number A , but different isospin content) and may be due to isospin effects. However, it is a very moderate effect and will not be discussed in the following. As already noted in the data, ref.[8], the good linear fits mean that the system-

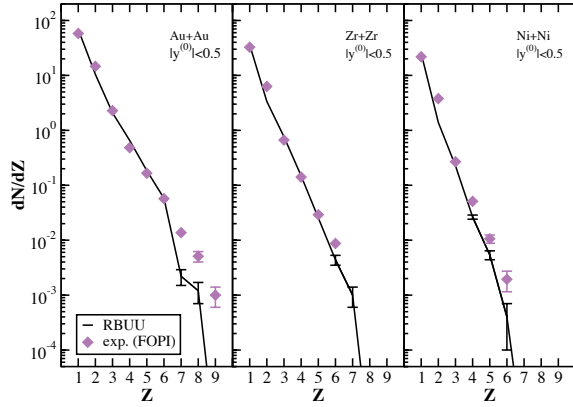


FIG. 2: Charge distributions at mid-rapidity ($|y^0| < 0.5$, [6]) for central ($b^{(0)} \leq 0.15$, [7]) collisions for different systems (as indicated) at 0.4 AGeV incident energy. The theoretical curves (solid lines) performed within the *RBUU* transport model are compared with experimental data (diamonds) from the *FOPI* collaboration [8].

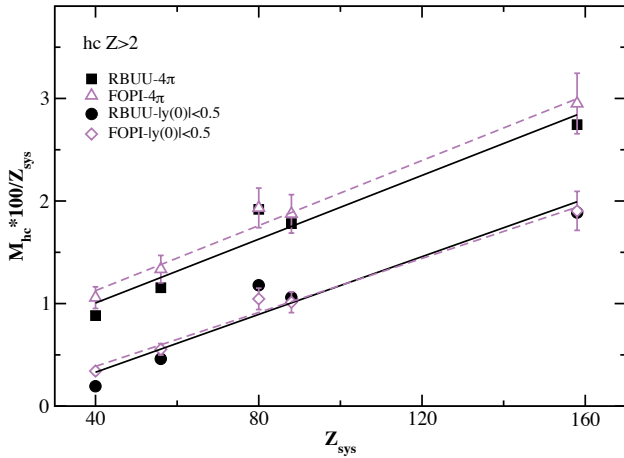


FIG. 3: Average multiplicities of heavy ($Z > 2$) clusters, normalized to those of a system with 100 protons (i.e., $M_{hc} \times 100/Z_{sys}$), as function of the system charge Z . Calculations (full symbols) and experimental data (empty) for all the phase space (4π) and confined to the midrapidity interval $|y_z^{(0)}| < 0.5$ are shown. All straight lines are linear least square fits to the symbols. The *FOPI* data are taken from Ref. [8].

size dependence of M_{hc} follows a quadratic behavior vs. the system charge (mass). This further supports the two-body dominant mechanism for fragment formation.

The simulation and experimental results are confirming the expectations that in central *HIC* at intermediate energies fragments are originally formed in the high density phase of the reaction dynamics from fluctuations due to two-body correlations. This interpretation is mostly supported by two clear evidences: i) The correlation between fragment multiplicity and stopping, see Figs.2, 3; ii) The linear Z_{sys} behavior of the normalized heavy clus-

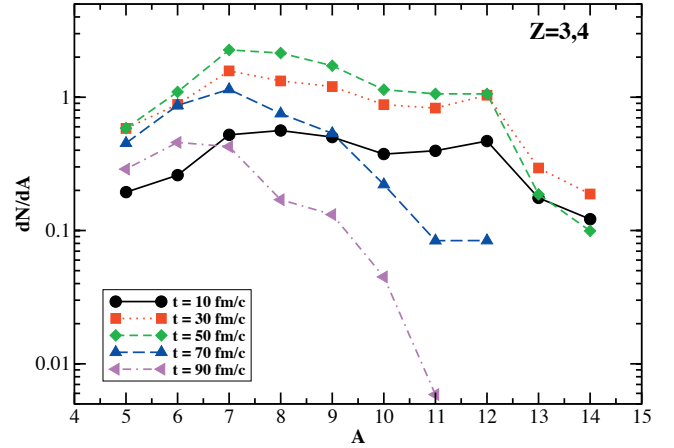


FIG. 4: Mass distributions of clusters with charges in the interval $Z = 3, 4$ at different times, as indicated, of a *Au + Au* central collision at 0.4 AGeV incident energy.

ter multiplicity of Fig.3. Such fast clusterization mechanism is completely different from the one observed at the Fermi energies, the growth of spinodal instabilities in dilute matter leading to a first order liquid-gas phase transition.

This new fragmentation dynamics opens the exciting possibility of directly probing the high density features of nuclear matter from the study of the cluster properties. However, the high density formed clusters would be largely modified during the expansion phase up to the freeze-out time. So it appears very important to follow the dynamical evolution of the clusterization in order to select the fragments that are expected to better keep the memory of the primordial high density source.

We have applied the phase space coalescence at several stages of a central *Au + Au* collision. Fig.4 shows the mass distributions of $Z = 3, 4$ fragments at different times as indicated. It is seen that heavy clusters are identified at a very early phase of the reaction dynamics ($t \approx 10 - 30$ fm/c). In this time interval the system is in a high density phase, of around $2.5\rho_0$ and locally equilibrated, so we can speak in terms of the nuclear *EoS* [4, 10]. After that time-step the system enters a fast expansion phase and the multiplicity of heavy clusters starts to decrease with a corresponding enhancement of the number of light (stable) *Li* and *Be* isotopes. We note that no sequential decay has been applied so far.

It turns out that heavy clusters are formed very early during the high density phase whereas the evaporation of single nucleons and light fragments appear at stages after freeze-out. This picture seems not obvious since at that early stage the colliding system is still hot and highly excited. A possible answer for this surprising result could be the onset of a collective motion responsible for a fast cooling of the fireball region. In fact, in theoretical as well as in experimental studies, a strong (isotropic) radial collective flow pattern is found in inter-

mediate energy collisions of heavy nuclei such as Au . The radial flow sets in very early during the expansion phase and then rapidly governs the dynamics. Thus much of thermal energy is transferred into collective motion making the existence of heavy primary fragments possible. However, the radial flow pattern does not “freeze” the multiplicity of the early formed heavy clusters. In fact the momentum distribution of nucleons inside those clusters is still rapidly changing because of the strong radial flow component (apart the relatively small thermal and Fermi momentum components). Thus, due to the coalescence requirement in momentum space, the radial flow will imply an effective break-up of primary heavy fragments. This mechanism finally leads to the formation of light clusters.

This scenario seems to be not unrealistic: radial flow is ultimately connected with pressure gradients and thus with the achieved maximal densities. With respect to the system size the maximal density is (almost) proportional to the number of *participant* nucleons as the degree of stopping does, [9]. Similar behavior will show up in the NN collision frequency. Therefore, heavy clusters are preferentially formed in the fireball region between heavy colliding systems relative to that of the lighter ones. As already noted, this interpretation can explain the rapidity distributions and the fragment multiplicities of the previous section (in particular the quadratic Z_{sys} dependence of Fig.3).

We conclude that the phase space coalescence model can successfully characterize the non-trivial reaction dynamics of heavy ion collisions at intermediate energies. Furthermore, the interesting evidence of an early heavy-cluster formation offers the possibility to study compressional and isospin effects at the level of fragmentation measurements.

III. ASPECTS OF PARTICLE PRODUCTION IN CHARGE ASYMMETRIC MATTER

The production/absorption rate of particles in compressed and heated asymmetric matter is studied using a Relativistic Mean Field (RMF) transport model with an isospin dependent collision term. Just from energy conservation in the elementary production/absorption processes we expect to see a strong dependence of the yields on the basic Lorentz structure of the isovector effective interaction, due to isospin effects on the scalar and vector self-energies of the hadrons. This will be particularly evident for the ratio of the rates of particles produced with different charges: results are shown for π^+/π^- , K^+/K^0 yields.

In order to simplify the analysis we perform first RMF cascade simulations in a box with periodic boundary conditions. In this way we can better pin down all such fine relativistic effects in particle production, that could likely show up even in realistic heavy ion collisions.

We show that both π^+/π^- and K^+/K^0 yields present

interesting isospin effects. This is particularly evident for the K^+/K^0 ratio just because of the large sensitivity around the threshold [11].

Particle production is of particular interest as a high-density probe since it mainly takes place in the first binary collisions during the compression phase, where the energy densities are still high above resonance thresholds. Moreover, it exists a wide field of experimental studies, in particular with respect to pion and subthreshold kaon production [12, 13]. However, the investigation of particle production represents a non-trivial task due to the following reasons:

- (a) At intermediate energies ($< 1.6 AGeV$) some of the pions created during the high density phase are directly emitted, but many of them undergo secondary re-scattering with isospin exchange before emission, [10].
- (b) Production and re-absorption processes must be consistently implemented in relativistic transport models with isospin effects. In fact within an isospin dependent mean field, isospin exchange processes such as $R' \leftrightarrow \pi N$, $\pi\pi R$ (N, R, R' stand for protons/neutrons and the $\Delta^{\pm,0,++}$ isospin resonance states, respectively, and $\pi^{\pm,0}$ for the pions) modify the scalar and vector content of the available energy between the in- and outgoing channels. This has to be taken into account in the energy conservation, and it is particularly relevant around the thresholds.
- (c) The situation in the production of particles with strangeness such as kaons ($K^{\pm,0}$) is similar, but even more complicated due to the availability of more than 50 isospin channels for the creation of K^+ and K^0 , only from BB and $B\pi$ processes (B stands for a resonance or a nucleon).

Kaons are produced very early during the high density stage of the collision, see the compressibility dependence in refs. [14, 15]. Moreover, the production of $K^{+,0}$ is expected to be directly related to the high density behaviour of the symmetry energy, since the mean free path of these low energy kaons is rather large ($\lambda(K^{+,0}) \sim 7$ fm, [14, 15]). These two facts make the subthreshold kaon production a very promising probe for the high density symmetry energy. Anti-kaons (K^-) does not fulfill the desired criteria due to their relatively small mean free path value (strong re-absorption effects).

We first investigate *hadronic matter* properties in a finite box with periodic boundary conditions performing cascade calculations by an extended isospin dependent collision integral. The description of the mean field is important, since nucleons and resonances are *dressed* by the mean field self-energies. This will directly affect the threshold energies, in particular for inelastic channels.

For elastic/inelastic nucleon-nucleon cross sections we use free parametrizations, in order to reduce the computing. From a in-medium (reduced) parametrization

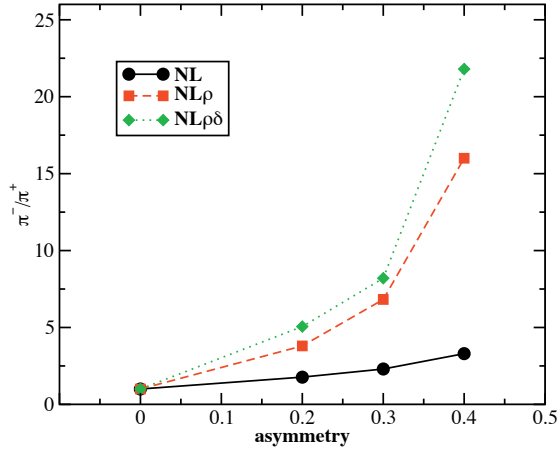


FIG. 5: Asymmetry dependence of the π^-/π^+ ratio for the same models as before, without the inclusion of reabsorption. The NM box is prepared at fixed baryon density $\rho_B = 2.5 \rho_0$ and temperature $T = 60 \text{ MeV}$, conditions that reproduce the high compression phase of a 1 AGeV collision.

we would have just a scaling of the particle multiplicities without affecting the relative yields of interest here. Kaon production is treated perturbatively, so that it does not affect the overall dynamics. It occurs according to two different creation mechanisms, i.e. baryon induced processes such as $BB \rightarrow BYK$, and pion induced processes such as $\pi B \rightarrow YK$. In both cases, kaons are created together with Y hyperons (Λ and Σ) to ensure strangeness conservation and are not reabsorbed by nucleons. They can anyway undergo elastic rescattering with nucleons, and thus modify their momentum distribution. However, since we are just interested in kaon yields and their possible dependence on the symmetry energy, we neglect this effect here and do not propagate kaons after production. To treat all these scattering processes in infinite hadronic asymmetric matter we have modified the original version of the collision term of the Tübingen $RQMD$ simulation code [15], taking explicitly into account the isospin dependence of scalar and vector self energies Σ_s, Σ^μ . This turns into an isospin dependence of the threshold of all isospin channels and thus affects particle yields.

This behaviour can be understood, to some extent, by comparing with the trend observed when forbidding pion reabsorption processes, ($\pi N \rightarrow \Delta$). In this case, as shown in Fig. 5, the π^-/π^+ ratio rises both in the $NL\rho$ (with respect to the NL) model and in the $NL\rho\delta$ (with respect to the $NL\rho$) model, for any value of the asymmetry parameter. This means that, as a result of the higher (lower) energy available in the “parent” nn (pp) collisions, the addition of each isovector meson (ρ and δ) favours π^- over π^+ production.

For the *Kaon* production the $BB \rightarrow BYK$, $B\pi \rightarrow YK$ channels can be schematically divided as follows:

1. $NN \rightarrow BYK$
2. $N\Delta \rightarrow BYK$

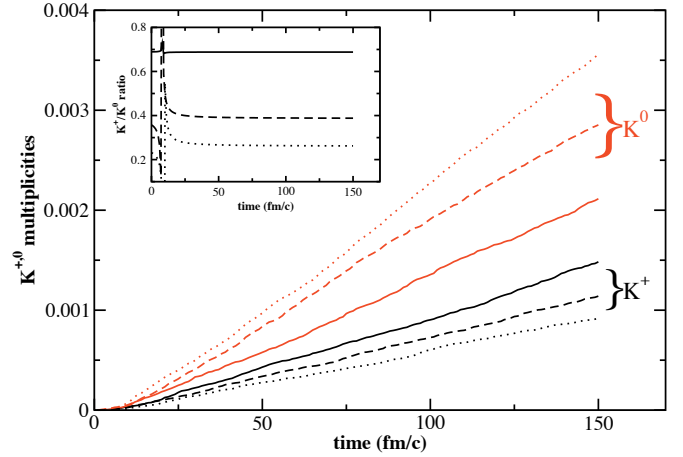


FIG. 6: Time evolution of $K^{+,0}$ yields and their ratio (in the inserted panel) for asymmetric ($\alpha = 0.2$) hadronic matter for the same iso-vector models as in Fig. 5.

3. $\Delta\Delta \rightarrow BYK$

4. $\pi N \rightarrow YK$

5. $\pi\Delta \rightarrow YK$

where N stands for a nucleon and B for a non-strange baryon.

At low energy densities, such as those achieved in the present calculations and/or in heavy ion collisions at energies below 1.5 AGeV, the pionic channels πN , (iv), give the main contribution [16], together with the $N\Delta$ ones, (ii). $\pi\Delta$ and NN collisions contribute just for a few percent to the total K^+ and/or K^0 yield, while the $\Delta\Delta$ channel is negligible.

In the case of asymmetric matter we note the different behavior of the important πN channel when we add the isovector mesons: the weight is decreasing for the K^+ production while it is increasing for the K^0 . This is very promising for our search for fine relativistic effects of the isovector interaction on kaon production.

Fig. 6 shows the temporal evolution of kaon multiplicities for asymmetric ($\alpha = 0.2$ or $N/Z=1.5$ corresponding to the asymmetry of ^{197}Au) hadronic matter and their ratio for the NL , $NL\rho$ and $NL\rho\delta$ models. First of all, we observe an almost linear time dependence of the kaon yields, perturbative production without rescattering. The isospin effect on the kaon yields essentially turns out in a change of the slope, i.e. of the production rate. In particular, for K^0 (K^+) the formation rate increases (decreases) as the symmetry energy becomes stiffer, i.e. passing from the $NL\rho$ to the $NL\rho\delta$ case.

Generally the isospin effects on kaon yields originate from at least two different mechanisms: the isospin dependencies of the $\pi^\pm$ yields and of the threshold energies. We will now discuss in detail these two effects.

Since kaon production from pionic channels (which give the main contribution) is competitive with pion reabsorption, it occurs before secondary $\pi N \rightarrow \Delta$ processes set

in. Therefore, K^0 and K^+ kaon yields are mainly affected by the π^- and π^+ abundances before reabsorption, see Fig. 5. In particular, as K^0 (K^+) mainly come from $\pi^- N$ ($\pi^+ N$) processes, the enhancement (reduction) of the π^- (π^+) multiplicities in the $NL\rho\delta$ model is partially responsible for a corresponding increase (decrease) of the K^0 (K^+) yields.

The isospin effect on the kaon production threshold is more complicated, due to the many isospin channels that may affect the threshold (and hence the yields) differently. However, effects in opposite direction originating from different channels do not exactly cancel each other. In order to clarify the observed influences of the models on the yields in a transparent way, it is appropriate to focus on some demonstrative channels, with larger cross sections. Such examples are the isospin channels $n\pi^- \rightarrow \Sigma^- K^0$ and $p\pi^+ \rightarrow \Sigma^+ K^+$ for $K^{0,+}$ production, respectively.

πN channels offer the advantage of two particles in the final state (instead of the three that we have in the BB case); moreover, since also kaons (and not only pions) are, in the present calculations, unaffected by nuclear mean field,

The corresponding threshold conditions read

$$s_{in}(n\pi^-) \geq (M_{\Sigma^-} + M_{K^0} + \Sigma_{s\Sigma^-} + \Sigma_{\Sigma^-}^0)^2 + \Sigma_{\Sigma^-}^2 \quad (2)$$

$$s_{in}(p\pi^+) \geq (M_{\Sigma^+} + M_{K^+} + \Sigma_{s\Sigma^+} + \Sigma_{\Sigma^+}^0)^2 + \Sigma_{\Sigma^+}^2 \quad (3)$$

where s_{in} are the *cm* available energies in the initial channel; $M_{\Sigma^-} + M_{K^0} = 1695 \text{ GeV}$ and $M_{\Sigma^+} + M_{K^+} = 1683 \text{ GeV}$.

Due to the different vector contributions to the self energies, for collisions involving neutrons (protons) s_{in} increases (decreases) when going from NL to $NL\rho$ and then to $NL\rho\delta$ model. Therefore, the available energy for K^0 production increases as the symmetry energy becomes stiffer, leading to an enhanced K^0 yield. Obviously the trend for the isospin behavior of the K^+ yield will be opposite.

A. Isospin effects on sub-threshold kaon production at SIS/GSI energies

Once understood the main production mechanisms and channels in a *NM* box we can pass to the study of the full production dynamics in a *open* system, i.e. for a realistic *HIC*. We have considered a central $^{197}\text{Au} + ^{197}\text{Au}$ collision at 1 AGeV incident energy.

We start the discussion with the temporal evolution of the $\Delta^{\pm,0,++}$ resonances and that of the pions ($\pi^{\pm,0}$), see Fig. 7. The pion multiplicity depends only weakly on the isospin part of the nuclear mean field, since the results in the NL , $NL\rho$ and $NL\rho\delta$ cases are very similar. This finding is consistent with other studies [10, 11], where isospin effects on the (π^-/π^+) -ratio have been investigated. Only if one uses extreme choices of the symmetry energy at high densities visible isospin effects on pion production can be

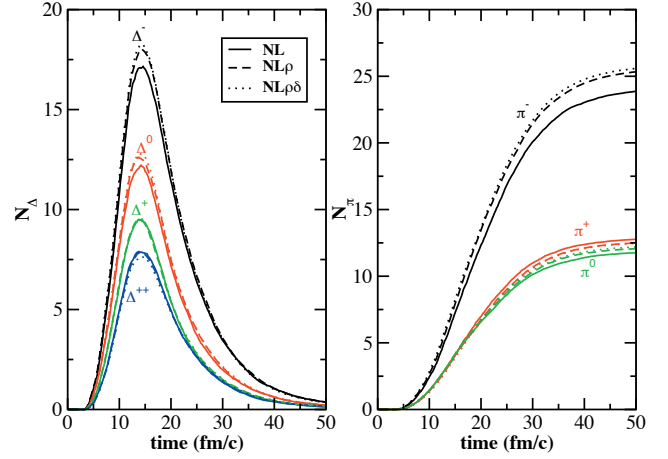


FIG. 7: Time evolution of the $\Delta^{\pm,0,++}$ resonances (left) and the pions $\pi^{\pm,0}$ (right) for a central ($b=0$ fm impact parameter) Au+Au collision at 1 AGeV incident energy. Transport calculation using the NL , $NL\rho$ and $NL\rho\delta$ models for the iso-vector part of the nuclear *EoS* are shown.

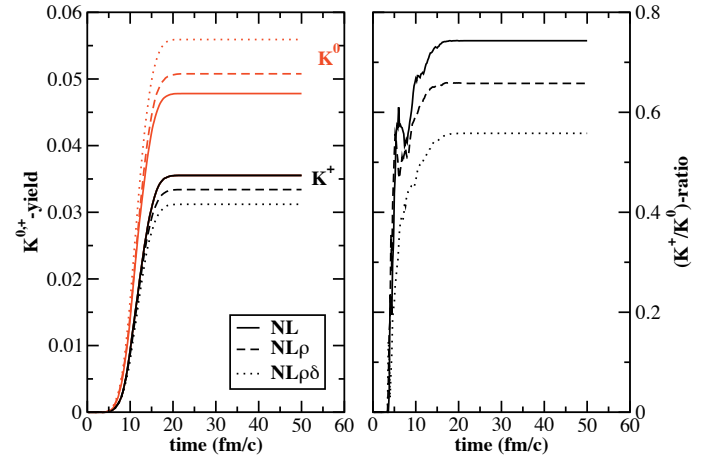


FIG. 8: Time evolution of the $K^{0,+}$ yields (left) and their (K^+/K^0) -ratio (right) for same reaction and models of Fig. 7.

observed [17, 18]. This moderate isospin dependence on pion production is attributed to a compensation between the increase shown in Fig. 5 and the decrease expected for larger fast neutron emission in a *open* system [10]. Moreover we expect to see a larger π^- reabsorption for low energy pions when we pass from NL , $NL\rho$ and to $NL\rho\delta$ models, due to the corresponding increase of the incident available energy for the process $\pi^- n \rightarrow \Delta^-$.

If one wants to see important isospin effects from the high density phase of the reaction dynamics the produced particles should (a) not interact with the hadronic medium (secondary re-scattering effects with isospin exchange) (b) and the threshold condition should mainly contribute to the isospin effect. At intermediate relativistic energies around 1 AGeV the positive charged (K^+) and neutral (K^0) kaons fulfill the desired condi-

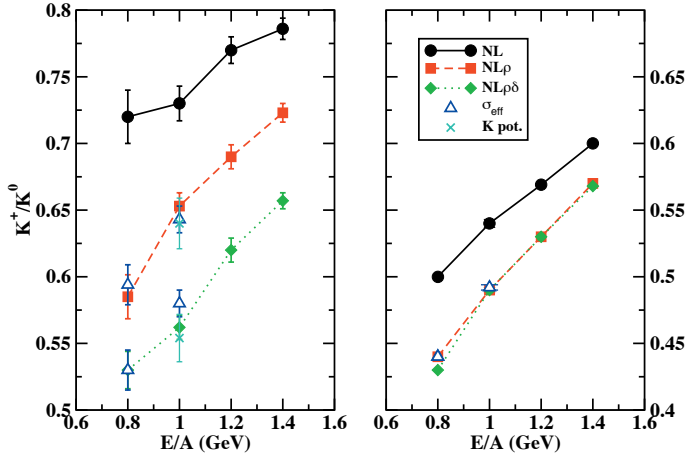


FIG. 9: (K^+/K^0) and (π^+/π^-) ratios (left and right panels, respectively) as a function of the incident energy for central Au+Au collisions with the same models for the iso-vector part of the mean field as in Fig. 7.

tions, but not the negative charged (K^-) kaons due to strong secondary effects [19].

Fig. 8 shows the time dependence of the kaons ($K^{+,0}$) and their ratio K^+/K^0 for a central Au+Au collision at 1 AGeV incident energy. First it is nicely seen that kaons are produced very early, during the pre-equilibrium high density phase ($t < 15 fm/c$), in contrast to the temporal behavior of pions (compare with Fig. 7). We stress again that we have included all the isospin dependent channels with the corresponding isospin dependent cross sections for the production of $K^{+,0}$, and the isospin dependent threshold energy. Among them the most important channels of kaon production are $\pi N \rightarrow YK$ and $N\Delta \rightarrow NYK$, in particular if the hyperon is a Λ , due to its lower mass relative to that of the Σ hyperon.

For Au+Au collisions the initial asymmetry parameter is $\alpha = \frac{N-Z}{N+Z} = 0.2$. Thus $nn \rightarrow nn, n\Delta^{0,-}$ processes with the sequential decay $\Delta^{0,-} \rightarrow \pi^- n, p$ mainly dominate relative to $pp, p\Delta^{+,++}$ channels. Consequently we obtain a higher K^0 yield with respect to that of K^+ , for all the considered models.

Comparing with the pion production (Fig. 7) the isospin effects on the kaon multiplicities are essential. The general trend is an enhancement (reduction) of the K^0 (K^+) yield going from NL, NL ρ to the NL $\rho\delta$ model, i.e. by increasing the stiffness of the symmetry energy. This observation has important consequences for the K^+/K^0 ratio: the introduction of the δ -mesonic field in the iso-vector sector of the nuclear EoS (NL $\rho\delta$ model) strongly reduces the K^+/K^0 ratio by a factor of 23%, 14% (relative to NL, NL ρ models, respectively).

Similar dependencies on the kaon yields have been found for other incident energies below the threshold, as can be seen in Fig. III A. Important isospin effects are visible for the K^+/K^0 ratio as function of the beam energy as compared to the corresponding energy depen-

dence of the π^+/π^- ratio.

It would be of major importance to measure the K^+/K^0 ratio for Au+Au collisions at intermediate relativistic energies. From the theoretical side, however, one needs to account particularly for the kaon potential when comparing with experimental data. Preliminary studies for Au+Au collisions at 1 AGeV incident energy show that the isospin effect on the K^+/K^0 ratio is robust against any modification of the kaon effective mass and coulomb potential. The results are very promising for the possibility of a direct link between particle production data in exotic Heavy Ion Collisions (HIC) and the isovector Equation of State (EoS) at high baryon densities.

IV. STOPPING AND ISOSPIN EQUILIBRATION IN HEAVY ION COLLISIONS

We investigate the density behaviour of the symmetry energy with respect to isospin equilibration in the combined systems $Ru(Zr) + Zr(Ru)$ at relativistic energies of 0.4 and 1.528 AGeV. The study is performed within a relativistic framework and the contribution of the isovector, scalar δ field to the symmetry energy and the isospin dynamics is particularly explored. We find that the isospin mixing depends on the symmetry energy and a stiffer behaviour leads to more transparency. The results are also nicely sensitive to the “fine structure” of the symmetry energy, i.e. to the covariant properties of the isovector meson fields.

The isospin tracing appears much less dependent on the in medium neutron-proton cross sections (σ_{np}) and this makes such observable very peculiar for the study of the isovector part of the nuclear equation of state. Within such a framework, comparisons with experiments support the introduction of the δ meson in the description of the iso-vector equation of state.

In order to reach definitive conclusions on the high density behavior of the symmetry energy one should first select the key signals and then simultaneously compare with experimental data. As shown before, Collective isospin flows and particle production, i.e. pion and kaon yields, seem to be good candidates. Here we continue the previous studies by considering another interesting aspect, which has been extensively investigated by experiments of the FOPI collaboration: the correlation between the degree of stopping and the isospin equilibration (or transparency).

The idea is to study colliding systems with the same mass number but different N/Z ratio, in particular a combination of $^{96}_{44}Ru$, $N/Z = 1.18$ and $^{96}_{40}Zr$, $N/Z = 1.4$ has been used as projectile/target in experiments at intermediate energies of 0.4 and 1.528 AGeV [21, 22]. The degree of stopping or transparency has been determined by studying the rapidity dependence of the *imbalance ratio* for the mixed reactions $Ru(Zr) + Zr(Ru)$: $R(y^{(0)}) = N^{RuZr}(y^{(0)})/N^{ZrRu}(y^{(0)})$, where $N^i(y^{(0)})$ is

the particle emission yield inside the detector acceptance at a given rapidity for $Ru + Zr$, $Zr + Ru$ with $i = RuZr$, $ZrRu$. The observable R can be measured for different particle species, like protons, neutrons, light fragments such as t and 3He and produced particles such as pions ($\pi^{0,\pm}$), etc. It characterizes different stopping scenarios [20].

In the proton case, moving from target to cm rapidity, $R(p)$ rises (positive slope) for partial transparency, falls (negative slope) for full stopping/rebound scenarios and it is flat when total isospin mixing is achieved in the collision. An opposite behavior will appear for neutrons. Indeed we remind that in the full transparency limit R should approach the initial value of $R(p) = Z^{Zr}/Z^{Ru} = 40/44 = 0.91$ and $R(n) = N^{Zr}/N^{Ru} = 56/52 = 1.077$ for protons and neutrons at target rapidity, respectively. Therefore, $R(p)$ can be regarded as a sensitive observable with respect to isospin diffusion, i.e. to properties of the symmetry term as we will show later.

In order to proceed to a direct comparison with experiments, in our kinetic equation simulations we have used a coalescence method to select nucleon and light ion emissions. The algorithm is quite standard, see before. For the investigation of isospin equilibration we have analyzed the transport results in the same way as carried out in the *FOPI* experiment, in particular selecting central events through the observable *ERAT* which measures the ratio of the mean transverse to the mean longitudinal kinetic energy. To do so, we first apply the coalescence method for fragment production in the final state and then we calculate the observable *ERAT*. At this point we can use the same centrality cuts as in the *FOPI* expts. [22].

In Fig. 10, we report the rapidity dependence of the imbalance ratio in central collisions of the mixed system $Ru(Zr) + Zr(Ru)$ for free protons ($R(p)$) and free neutrons ($R(n)$) at the two energies 0.4 and 1.528 AGeV.

First of all, the imbalance ratio correctly approaches unity at mid-rapidity for all particle types considered. This is a obvious check of the calculation since the symmetry of the two collisions naturally implies a full isospin mixing in the cm rapidity region.

Going from target- to mid-rapidity it nicely rises for protons, and decreases for neutrons, a good isospin transparency signature. The effect is much more evident for the $NL\rho\delta$ interaction. The observed difference between the two models is obvious since within the $NL\rho\delta$ picture neutrons experience a more repulsive iso-vector mean field, particularly at high densities, than protons, with a consequent much less nucleon stopping in the colliding system. It can be also considered as a high density effect since the particle emission takes mainly place during and just after the compression phase.

The observed effect of the *EOS* on the imbalance ratio of protons and neutrons is not very large. At low intermediate energies (0.4 AGeV) one has to deal with moderate compressions of $\rho_B < 2 \cdot \rho_{sat}$ where the differences in the iso-vector *EOS* arising from the δ meson and

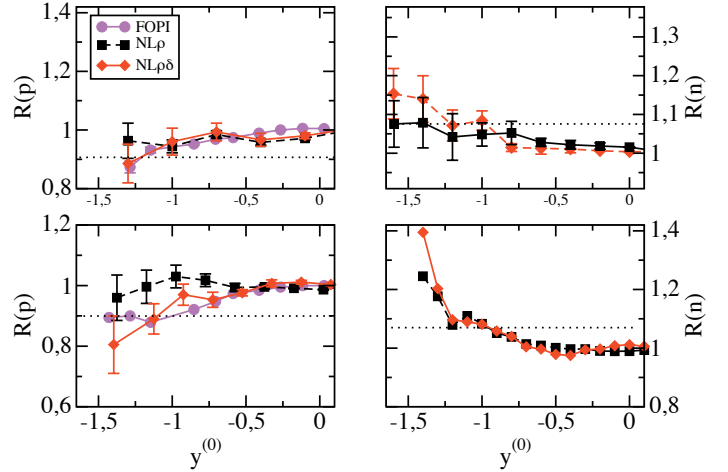


FIG. 10: The imbalance ratio $R(y^{(0)}) = \frac{N^{RuZr}(y^{(0)})}{N^{ZrRu}(y^{(0)})}$ as function of the normalized rapidity $y^{(0)} = y/y_{proj}$ of free protons (left columns) and free neutrons (right columns) for the various isovector models, for central ($b \leq 2$ fm) $Ru(Zr) + Zr(Ru)$ -collisions at 0.4 (top) and 1.528 AGeV beam energies. The experimental data are taken from the *FOPI* collaboration [22].

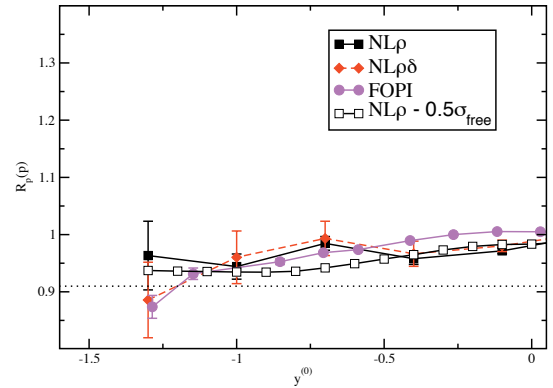


FIG. 11: Proton imbalance ratio as function of the normalized rapidity for central ($b \leq 2$ fm) $Ru(Zr) + Zr(Ru)$ -collisions at 0.4 AGeV like the top-left part of Fig.10. A curve is added (empty squares) corresponding to a $NL\rho$ calculation with reduced nucleon-nucleon cross sections (half the free values, $\sigma_{NN}(E) = \frac{1}{2}\sigma_{free}$).

thus from the different treatment of the Lorentz structure are small. On the other hand, at higher incident energies (1.528 AGeV) a larger difference is observed between the two models.

Reduced in medium Nucleon-Nucleon (NN) cross sections, in particular the σ_{np} , will also increase the isospin transparency in the direction shown by the data. We have tested this possibility considering a factor two reduction, $\sigma = \frac{1}{2}\sigma_{free}$, of the free NN -cross section values used before. We note that such a reduction represents a rather strong in-medium effects as compared to recent

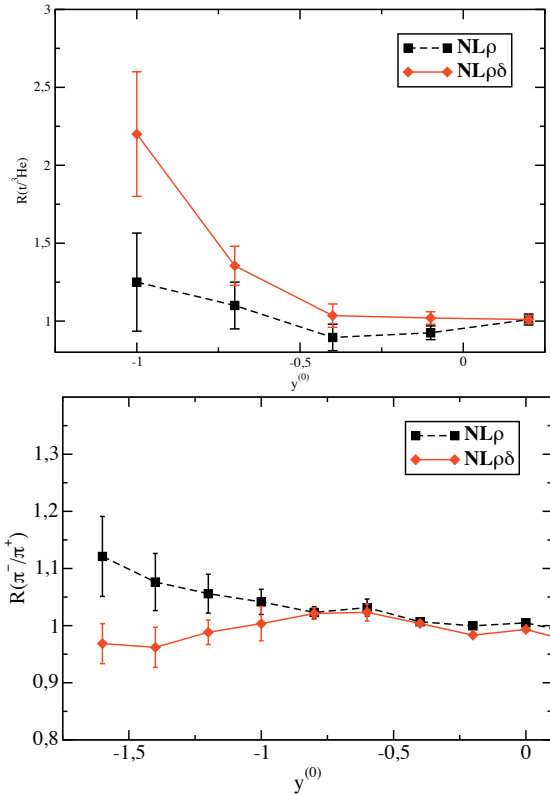


FIG. 12: Same as in Fig. 10 for 0.4 AGeV beam energy, but for the ratio of t to ${}^3\text{He}$ (top) and the ratio of negative to positive charged pions (bottom).

microscopic Dirac-Brueckner estimations [23].

In Fig.11 we report the results, open squares, for the proton imbalance ratios at 0.4 AGeV + $0.5\sigma_{free}$ in the $NL\rho$ case. We see a overall slightly increasing transparency but not enough to reproduce the trend of the experimental values in the target rapidity region. On the other hand the reduction of the NN cross sections, and in particular of the $\sigma_{(np)}$, implies a too large transparency in the proton rapidity distributions for central collisions of the charge symmetric $Ru + Ru$ case; effect clearly seen in our simulations and already remarked in previous *IQMD* calculations, see ref.[22]. So we can exclude such and further reductions of the NN cross sections.

Since the calculations are performed with the same *EOS* for the symmetric nuclear matter, same compressibility and momentum dependence, the observed transparency appears to be uniquely related to *isovector* – *EOS* effects, i.e. to the isospin dependence of the nucleon self-energies at high baryon densities.

In Fig.12 we report the rapidity dependence of the imbalance ratio for other particle emissions in central collisions of the mixed system $Ru(Zr) + Zr(Ru)$ at 0.4 AGeV beam energy: (top) for the ratio of triton to He -fragments ($R(t/{}^3\text{He})$) and (bottom) for the ratio of negative π^- to positive π^+ charged pions ($R(\pi^-/\pi^+)$).

The fact that protons *and* neutrons exhibit an *opposite*

behavior for the corresponding imbalance ratios at target rapidity, clearly suggests that the detection of the imbalance observable $R(t/{}^3\text{He})$ for the $t/{}^3\text{He}$ ratio should reveal a larger sensitivity. We thus have determined the observable $R(t/{}^3\text{He})$, using the above discussed phase space coalescence procedure to extract the light ion emissions.

Fig. 12 (on the left) shows the $R(t/{}^3\text{He})$ results. The isospin effect originating from the appearance of the isovector, scalar δ meson in the $NL\rho\delta$ model turns out to be here crucial near target rapidities. We note that the effect indeed can be hardly seen from the separate imbalance ratios for protons and neutrons at the same rapidity, see Fig. 10 top panels, apart the difficulties of neutron emission detections. It would be therefore of great interest to experimentally measure directly this quantity.

Finally, another sensitive observable appears to be the imbalance ratio of charged pions $R(\pi^-/\pi^+)$ (Fig. 12, right panel). At variance with the previous results for neutrons and light isobars, this ratio is reduced at target rapidity with the $NL\rho\delta$ model. Such effect strongly supports our understanding of the transport properties of the various effective interactions. Pions are produced from the decay of Δ resonances formed during the high density phase. The π^- abundance is then linked to the neutron-excess of the high density matter, that can form negative charged resonances, as detailed described in [10]. We remind that the contribution of the δ meson leads to a more repulsive field for neutrons at supra-normal densities and consequently to less neutron collisions and finally to a smaller π^-/π^+ ratio.

We have analyzed the stopping and isospin transparency in relativistic collisions in terms of the imbalance ratio of different particle types in projectile/target rapidity regions in mixed collisions. We show that this observable is even sensitive to the microscopic Lorentz structure of the symmetry term. Effective interactions with symmetry energies not much different at 2–3 *times* the normal density ρ_{sat} are predicting large differences in the *isospin* – *transparencies*, depending on the relative contribution of the various charged vector and scalar fields. The interest is also in the fact that this appears to be a genuine relativistic effect. Such result, combined to a weak dependence on the in-medium NN cross sections for hard nucleon collisions, indicates the importance of imbalance ratio measurements for a better knowledge of the nuclear *EOS*, and its *fine* – *structure*, at high baryon density.

V. TESTING DECONFINEMENT AT HIGH ISOSPIN DENSITY

At high baryon density and low temperature we can expect a transition from hadronic matter to deconfined quark matter. The procedure is straightforward:

- Start from two "reasonable" model Equations of State (*EOS*), one for the hadronic phase, which can

reproduce saturation properties, one for the quark phase, which can reproduce the hadron spectrum.

- Construct the phase separation boundary surface from the Gibbs phase rule [24–26].

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

The new feature we would like to focus on in this report is the isospin dependence of such boundary location. We can foresee an interesting asymmetry effect, in the appealing direction of a decrease of ρ_{cr} , since the hadronic *EOS* becomes more repulsive. This has been actually seen in the calculations of ref.[26] (see the Fig.7): for a proton fraction $Z/A = 0.3$ the boundary density is shifted to the left of about a 10%, from the $4.0\rho_0$ of symmetric matter to a $3.5\rho_0$. The point we like to note is that this evaluation has been obtained in quite "adverse" conditions. The interaction symmetry part of the hadronic *EOS* is only coming from the charged vector ρ -meson coupling. The *EOS* of the quark phase is obtained within the MIT bag model with a very high pressure-of-vacuum parameter $B^{1/4} = 190$ MeV, i.e. it is very repulsive.

We have revisited the study with new *EOS*'s in the two phases, with modifications, inspired by sensible physics arguments, which lead to a stiffer asymmetric matter and to a softer quark matter and therefore to an earlier transition [27, 28].

For the hadronic phase we have enhanced the symmetry repulsion at high baryon density introducing also the coupling to the charged scalar δ -meson. In the quark phase we use various values of the bag constant, even in the range $B^{1/4} \simeq 150$ -170 MeV, consistent with the Witten-Bodmer hypothesis [29, 30]. It is important to notice that the hadronic *EOS* depends more strongly on isospin than the quark *EOS*, this would imply an isospin distillation effect, as we will see later.

For a fixed value of the *Bag* constant the quark *EOS* has a minimum below the hadronic *EOS* for very neutron rich matter, $Z/A \simeq 0.3$, while symmetric matter the minimum of the hadronic *EOS* is still the absolute one. In this situation, the critical density separating hadronic matter from the mixed phase of quarks and hadrons drops dramatically when the value of Z/A is reduced.

This effect is shown in Fig. 13 where we compare the predictions on the isospin dependence of the transition density (at zero temperature) to a deconfined phase for two effective hadronic Lagrangians *GM3* [31] and our *NL $\rho\delta$* , for various *Bag* constants. The isoscalar part is very similar and in fact rather suitable at high densities where it appears closer to various Dirac-Brueckner predictions, as already noted. The isovector part is quite different, in *GM3* we have only the coupling to the vector ρ -field, in *NL $\rho\delta$* we have also the contribution of the

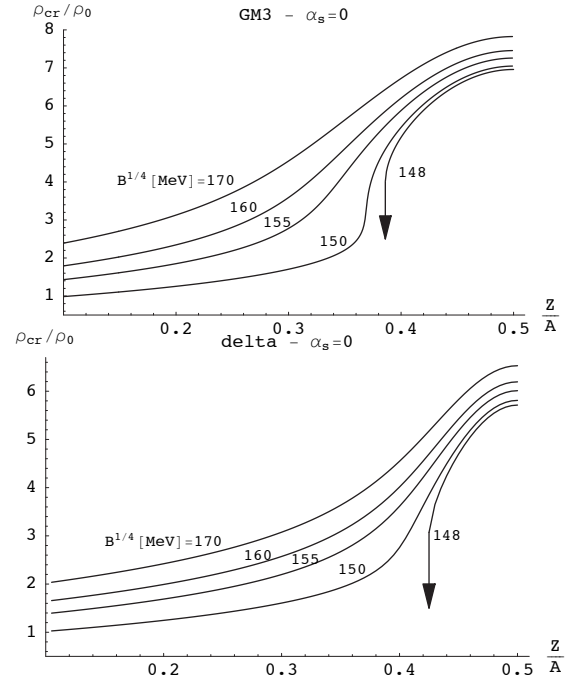


FIG. 13: Transition densities separating hadronic matter from mixed quark-hadron phase at zero temperature. In the upper panel the *GM3* parametrisation has been used for the hadronic *EOS*, in the lower panel, *NL $\rho\delta$* parametrisation, see before. The *MIT* bag model without gluon exchange has been used for the quark *EOS*. The arrows indicate that the transition density drops to very small values and the parameter $B^{1/4}$ cannot be further reduced.

δ -field, which leads to a stiffer symmetry term and to a neutron/proton effective mass splitting.

Since in a realistic heavy ion collision we cannot have compression without heating, we have studied also the temperature dependence of the *crossing densities*. This is shown in the Fig. 14 obtained with the hadronic *NL $\rho\delta$* and a rather realistic $B^{1/4} = 170$ MeV.

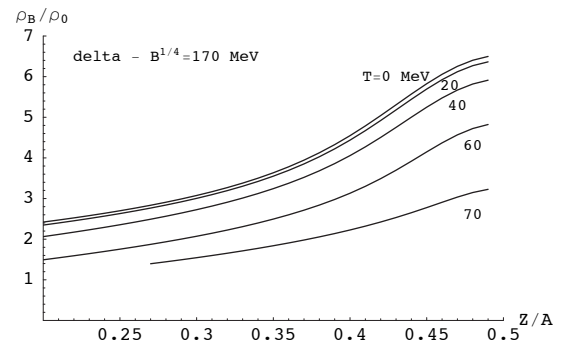


FIG. 14: Temperature variation of the crossing density vs. proton fraction, for the hadron/quark *EOS* see text

We see that for a $\rho_B, T, Z/A$ combination *not too exotic* we can have matter well inside the

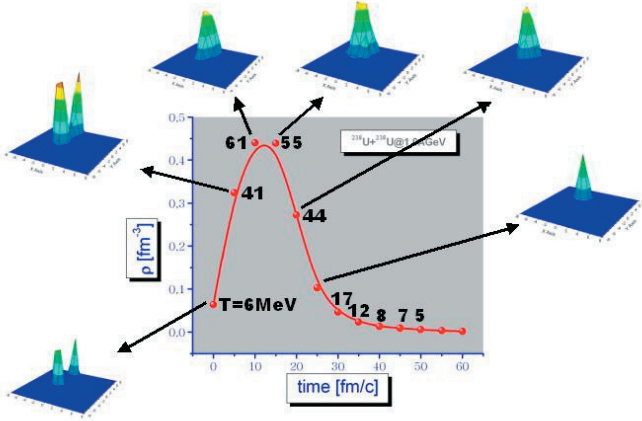


FIG. 15: Time evolution of baryon density and momentum distribution in a cell around the *center of mass* for the $^{238}\text{U} + ^{238}\text{U}$ collision at 1 AGeV beam energy, semicentral $b = 7\text{ fm}$. The numbers correspond to the evaluated local temperatures.

mixed phase. We will see if such conditions could be reached in a transient state of a relativistic *HIC*.

A. Realistic Collision Simulation and Precursor Signals

Using our Relativistic Transport Code, with the same effective interaction of the $NLH(\rho + \delta)$ EOS, we have performed some simulations of the $^{238}\text{U} + ^{238}\text{U}$ (average $Z/A = 0.387$) collision at 1 AGeV beam energy, for a semicentral impact parameter, $b = 7\text{ fm}$, just to optimize the neutron skin effect in order to get a large asymmetry in the interacting zone. The direct use of equilibrium EOS concepts is supported by the results shown in Fig. 15, where the time evolution of quadrupole moment, in momentum space, and density, in a cell of "2.5 fm" lateral size around the Centre of Mass, is reported. At the time of maximum density of interest here the system appears quite well locally equilibrated. Then with a Fermi-Dirac fit we can extract a reliable "local" temperature.

The corresponding *physics* parameters are shown in Fig. 16.

We clearly see that for a time interval of the order of 10 – 15 fm/c the system is well inside the mixed phase conditions of Fig. 14.

What could be a signature of such transition? As already said we expect a reduced symmetry repulsion in the quark clusters and so an interesting isospin distillation with the neutrons more migrating to the quark phase. This is in fact the meaning of the Fig. 17 where we report the proton fraction in the quark clusters inside the mixed phase, for a fixed total proton fraction of the matter $Z/A = 0.4$.

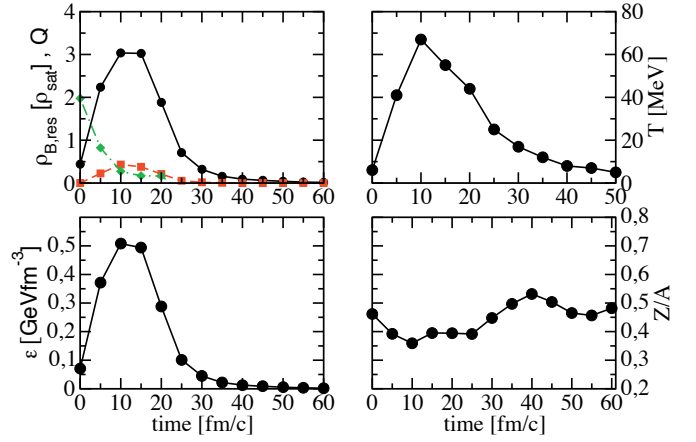


FIG. 16: *UU* collision simulation, see previous figure: time evolution of the physics parameters inside a cubic cell 2.5 fm wide, located in the center of mass of the system. Top-Left Panel: quadrupole moment in momentum space (diamonds), resonance density (squares) and baryon density (circles). Top-right panel: local temperature. Bottom-left panel: energy density. Bottom-right panel: proton fraction.

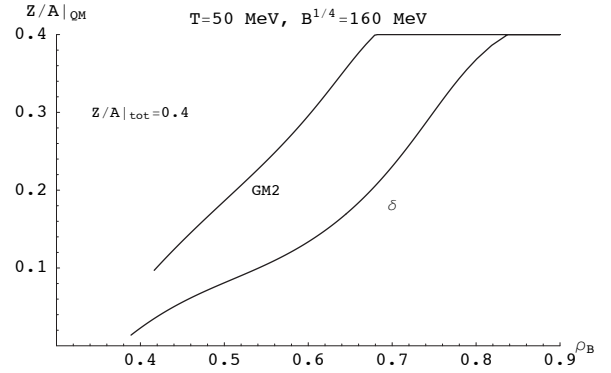


FIG. 17: Proton fraction in the quark clusters inside the mixed phase. The calculation is for $T = 50\text{ MeV}$ and $B^{1/4} = 160\text{ MeV}$ for two hadron EOS, GM2 and $NL\rho\delta$.

We clearly see that at the lower border of the mixed phase the quark clusters are extremely neutron rich. Since at such high densities we actually expect a strong neutron expulsion due to the large symmetry repulsion, the migration to the quark phase will keep the neutrons in the interacting matter with observable effects on the subsequent hadron emissions, e.g. very neutron rich fragments and/or larger π^-/π^+ , K^0/K^+ yields could be observed.

In conclusion we support the possibility of observing precursor signals of the phase transition to a deconfined matter in violent collisions (central and semicentral) of

exotic (radioactive) heavy ions in the energy range of few GeV per nucleon.

-
- [1] V.Baran, M.Colonna, V.Greco, M.Di Toro, Phys.Rep. **410**, 335-466 (2005).
 - [2] B.Liu, V.Greco, V.Baran, M.Colonna, M.Di Toro, Phys.Rev. **C65**, 045201 (2002).
 - [3] V.Greco, M.Colonna, M.Di Toro, F.Matera, Phys.Rev. **C67**, 015203 (2003).
 - [4] V.Greco et al., Phys.Lett. **B562**, 215 (2003).
 - [5] E.Santini, T.Gaitanos, M.Colonna, M.Di Toro, arXiv:nucl-th/0501021, Nucl.Phys. **A** (2005) in press.
 - [6] $y_{z,x}^{(0)}$ are the *reduced* (longitudinal/transverse) rapidities normalized to the Projectile ones.
 - [7] $b^{(0)}$ is the *reduced* impact parameter, normalized to a $b_{max} = 1.15(A_p^{1/3} + A_t^{1/3})$.
 - [8] W.Reisdorf and the FOPI collaboration, Phys.Lett. **B595** (2004) 118.
 - [9] W.Reisdorf and the FOPI collaboration, Phys.Rev.Lett. **92** (2004) 232301.
 - [10] T.Gaitanos et al., Nucl.Phys. **A732** (2004) 24.
 - [11] G.Ferini, M.Colonna, T.Gaitanos, M.Di Toro, arXiv:nucl-th/0504032.
 - [12] B.Hong and FOPI Collab., Phys.Rev. **C71** (2005) 034902.
 - [13] C. Sturm *et al.* (KaoS Collaboration), Phys.Rev.Lett. **86**, 39 (2001);
F. Laue *et al.* (KaoS Collaboration), Phys.Rev.Lett. **82**, 1640 (1999).
 - [14] J. Aichelin, C.M. Ko, Phys.Rev.Lett. **55**, (1985) 2661;
X.S. Fang, C.M. Ko, G.Q. Li, Y.M. Zheng, Nucl.Phys. **A575** (1994) 766;
G.Q. Li, C.M. Ko, Phys.Lett. **B349** (1995) 405.
 - [15] C. Fuchs et al., Phys.Rev.Lett. **86**, (2001) 1974.
 - [16] C. Fuchs *et al.*, Phys.Rev. **C56** (1997) R606.
 - [17] Bao-An Li, Nucl.Phys. **A708**, (2002), 365.
 - [18] B.-A. Li, G.-C. Yong, W. Zuo, Phys.Rev. **C71** (2005) 014608.
 - [19] Guo-Qiang Li, C.H. Lee, G.E. Brown, Nucl.Phys. **A625** (1997) 372.
 - [20] T.Gaitanos, M.Colonna, M.Di Toro, H.H.Wolter, Phys.Lett. **B595**, (2004) 209.
 - [21] F.Rami, Y.Leifels, B. De Schauenburg, et al. (FOPI Coll.), Phys.Rev.Lett. **84** (2000) 1120.
 - [22] B. Hong, Y.J. Kim, D.H. Kang, et al. (FOPI collaboration), Phys.Rev. **C66** (2002) 034901;
Very preliminary data taken from B. Hong, Y.J. Kim, Y. Leifels, et al. (FOPI collaboration), GSI-Report 2002.
 - [23] C. Fuchs, A. Faessler, N. El-Shabshiri, Phys. Rev. **C64** (2001) 024003.
 - [24] L.D.Landau, L.Lifshitz, *Statistical Physics*, Pergamon Press, Oxford 1969.
 - [25] N.K.Glendenning, Phys.Rev. **D46**, 1274 (1992).
 - [26] H.Mueller, Nucl. Phys. **A618**, 349 (1997).
 - [27] M.Di Toro, A.Drago, V.Greco and A.Lavagno, *Isospin dependence of the critical quark-deconfinement densities*, arXiv:nucl-th/0210052.
 - [28] M.Di Toro et al., Nucl.Phys. **A722**, 129c (2003).
 - [29] A.R.Bodmer, Phys. Rev. **D4**, 1601 (1971).
 - [30] E.Witten, Phys. Rev. **D30**, 272 (1984).
 - [31] N.K.Glendenning and S.A.Moskowsky, Phys. Rev. Lett., **67**, 2414 (1991).

Isospin effects on fragmentation mechanisms

M.Colonna¹, V.Baran^{1,2}, M.Di Toro¹, R.Lionti¹, F.Matera³, M.Zielinska-Pfabe⁴, J.Rizzo¹ and H.H.Wolter⁵

¹ *Laboratori Nazionali del Sud, Via S. Sofia 44, I-95123 Catania, Italy
and Physics-Astronomy Dept., University of Catania,*

² *NIPNE-HH, Bucharest and Bucharest University, Romania,*

³ *Istituto Nazionale di Fisica Nucleare, Sezione di Firenze,
Via G. Sansone 1, I-50019, Sesto F.no (Firenze), Italy,*

⁴ *Smith College, Northampton, USA, and*

⁵ *Sektion Physik, University of Munich, Germany*

We discuss fragmentation mechanisms, in neutron-rich systems, occurring in central and mid-peripheral collisions at Fermi energies. The most relevant isospin effects are the distillation mechanism, that leads to the formation of more symmetric fragments, surrounded by a neutron-rich gaseous phase, in central collisions, and isospin transport mechanisms that are responsible for the neutron enrichment of the overlap (neck) region in mid-peripheral collisions, where fragments are formed. The origin of fluctuations in the isotopic composition of fragments and the link to the low density properties of the symmetry energy are discussed.

I. INTRODUCTION

Heavy ion collisions at Fermi energies offer the possibility to learn about properties of the nuclear effective interaction in situations of density and temperature different from normal ones. In particular, considering charge asymmetric systems, one can access information on the behaviour of the symmetry energy, that is poorly known at low and high densities. In this way one can also put some constraints on the effective interactions used in the astrophysical context [1, 2], where such information is essential for the understanding of the life of supernovae and neutron stars [3–8]. Moreover we like to remark that the same symmetry energy is of relevant importance for structure properties, being clearly linked to the thickness of the neutron skin in n-rich (stable and/or unstable) nuclei (see [9] and the discussion in refs. [10, 11]).

Fragmentation mechanisms at Fermi energies can be used to study the symmetry energy at densities below and around the normal value. In violent central collisions, where the full disassembly of the system into many fragments is observed, one can study new properties of liquid-gas phase transitions occurring in asymmetric matter. In neutron-rich matter, phase co-existence leads to a different asymmetry in the liquid and gaseous phase: fragments (liquid) appear more symmetric with respect to the initial matter, while light particles (gas) are more neutron-rich [12–15]. This effect, that is simple related to the fact that the symmetry energy decreases when the density gets lower, depends on the isovector part of the nuclear EOS, namely on the derivative of the symmetry energy. Hence fragmentation studies in central collisions can allow to get information on this low-density properties of the symmetry energy.

In mid-peripheral collisions intermediate mass fragments (IMF) are formed in the overlap (neck) region between projectile and target. This region may reach den-

sity values larger than normal one, during the first stage of the reaction, and then expand, before the system re-separates. IMF's form during this expansion phase, in some analogy with what happens, for the full system, in central collisions. However, in this case, the low density region (neck) is in contact with regions of larger density (the spectators), hence one observes an “isospin migration” from projectile and target towards the participant zone, leading to a neutron enrichment of the neck. Also this effect is nicely connected to the derivative of the symmetry energy, but around density closer to normal one [16, 17].

Hence the two fragmentation mechanisms, from central to peripheral collisions, nicely allow to explore the behaviour of the symmetry energy from low to normal values of the density.

We will describe the reaction dynamics using a stochastic mean-field approach. We follow semi-classical transport theories, that describe the time evolution of the one-body distribution function according to the nuclear mean-field (plus the Coulomb repulsion for protons) and including the effects of two-body nucleon-nucleon collisions, with some degree of stochasticity. This description allows the treatment of physical situations where bifurcations and larger fluctuations occur. This is certainly the case of phase separation and multi-fragment formation. In our scenario, fragmentation is due to the development of volume (spinodal) instabilities during the expansion phase that follows the initial collisional shock. The thermal agitation of the system generates density fluctuations, that are amplified by the unstable mean-field. Fragment properties will be related to the features of the most important unstable iso-scalar oscillations [16, 18]. In particular, we will discuss how these properties evolve with the charge asymmetry of the considered matter and how they depend on the symmetry energy of the nuclear EOS.

II. DESCRIPTION OF FRAGMENTATION MECHANISMS

A. Stochastic mean-field approaches

Theoretically the evolution of complex systems under the influence of fluctuations can be described by a transport equation with a stochastic fluctuating term, the so-called Boltzmann-Langevin equation (BLE):

$$\frac{df}{dt} = \frac{\partial f}{\partial t} + \{f, H\} = I_{coll}[f] + \delta I[f], \quad (1)$$

where $f(\mathbf{r}, \mathbf{p}, t)$ is the one-body distribution function, $H(\mathbf{r}, \mathbf{p}, t)$ is the one-body Hamiltonian and $\delta I[f]$ represents the stochastic part of the two-body collision integral [19, 20]. Exact numerical solutions of the BLE are very difficult to be obtained and they have only been calculated for schematic models in two dimensions [21]. Therefore various approximate treatments of the BLE have been introduced [22–24].

Here we will follow the method presented in Ref.[24].

Within the assumption of local thermal equilibrium, the stochastic term of Eq.(1) essentially builds the kinetic equilibrium fluctuations typical of a Fermi gas: $\sigma_f^2 = f(1-f)$, where $f(\mathbf{r}, \mathbf{p}, t)$ can be approximated by a Fermi-Dirac distribution, $f(\mathbf{r}, \mathbf{p}, t) = 1/(1+e^{(\epsilon-\mu)/T})$ with local chemical potential and temperature, $\mu(\mathbf{r}, t)$, $T(\mathbf{r}, t)$. We project on density fluctuations obtaining:

$$\sigma_{\rho,eq}^2(\mathbf{r}, t) = \frac{1}{V} \int \frac{d\mathbf{p}}{h^3/4} \sigma_f^2(\mathbf{r}, \mathbf{p}, t) = \frac{T}{V} \frac{3\rho}{2\epsilon_F} \left(1 - \frac{\pi^2}{12} \left(\frac{T}{\epsilon_F}\right)^2 + \dots\right), \quad (2)$$

where we have used the Sommerfeld expansion around $\epsilon = \mu$ for small T/ϵ_F (ϵ_F denotes the Fermi energy).

Actually this kinetic equilibrium value is reached asymptotically for an ideal gas of fermions. After a small time step Δt , the value reached for the density fluctuations can be approximated by:

$$\sigma_{\rho}^2(\mathbf{r}, t, \Delta t) = \sigma_{\rho,eq}^2(\mathbf{r}, t) \frac{2\Delta t}{\tau_{coll}(\mathbf{r}, t)}, \quad (3)$$

where τ_{coll} is the damping time associated with the two-body collision process. At temperatures around 4 MeV, that are typically reached in fragmentation processes, τ_{coll} is of the order of 50 fm/c [25]. In our calculations fluctuations are injected each $\Delta t = 5$ fm/c and their amplitude is scaled accordingly (see Eq.(3)). In the cell of $\mathbf{r}$ space being considered, the density fluctuation $\delta\rho$ is selected randomly according to the gaussian distribution $\exp(-\delta\rho^2/2\sigma_{\rho}^2)$. This determines the variation of the number of particles contained in the cell. A few left-over particles are randomly distributed again to ensure the conservation of mass. Momenta of all particles are finally slightly shifted to ensure momentum and energy conservation.

The fluctuations introduced are then amplified by the unstable mean-field. It is important to notice that the

characteristic growth time for the unstable modes is smaller ($\tau \approx 30$ fm/c) [26] than the collisional damping time, so two-body collisions act just as a seed to perturb the density profile of the system, but the dynamics is essentially driven by the propagation of the mean-field instabilities.

B. Reaction mechanisms

Calculations have been performed using the TWINGO code, where the test particle method is adopted to solve Eq.(1) [27]. A typical example of the dynamical evolution of a central collision is represented in Fig.1 (left), where we consider the reaction $^{124}\text{Sn} + ^{124}\text{Sn}$ at 50 MeV/A. After the initial collisional shock, the system expands and reaches a low-density unstable phase, where fragments start to form. Hence, according to stochastic-mean field calculations fragmentation happens through the development of volume (spinodal) instabilities. The

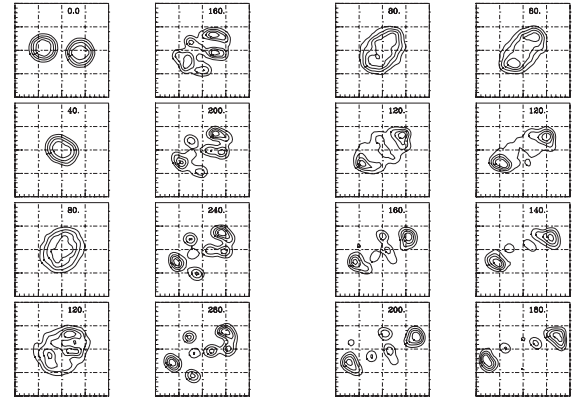


FIG. 1: Left: $^{124}\text{Sn} + ^{124}\text{Sn}$ collision at 50 MeV: time evolution of the nucleon density projected on the reaction plane. Semi-central $b = 2$ fm collision: approaching, compression, separation, and fragmentation phases. The times in fm/c are written in each panel. The iso-density lines are plotted every 0.02 fm^{-3} starting from 0.02 fm^{-3} . Right: First column: $b = 4$ fm, second column: $b = 6$ fm, separation phase up to the freeze-out.

same scenario applies, but in a reduced region, the overlap (neck) zone, in mid-peripheral collisions, as shown in Fig.1 (right) for the same system at $b = 4.6$ fm. The fact that also in neck fragmentation spinodal instabilities are encountered is confirmed by the role of the nuclear matter compressibility K in the observed fragmentation path. Changing K from 200 MeV to 380 MeV, in fact, nuclear matter becomes stiffer, density oscillations are reduced and the neck fragmentation mechanism is quenched [17].

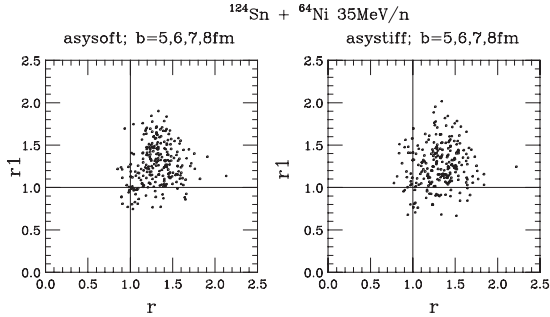


FIG. 2: Wilczynski-2 Plot: correlation between deviations from Viola systematics (see the text for definitions and ref.[28]). Results are shown for two *asy* – EOS (see text).

III. KINEMATICAL PROPERTIES OF NECK FRAGMENTS

Before discussing isospin effects in fragmentation mechanisms it is worth to mention some important properties of these fragments originated through instabilities. Properties of neck fragments have been recently investigated in the context of the reactions $^{124}\text{Sn} + ^{64}\text{Ni}$ and $^{112}\text{Sn} + ^{58}\text{Ni}$ at 35 MeV/A, for which nice experimental data exist [28]. It can be shown unambiguously that neck fragments are not related to the statistical emission of Projectile-like (PLF) or Target-like (TLF) residues, but they appear produced by a low density source that develops in between PLF and TLF. This can be seen by performing an analysis in terms of the deviation of the fragment velocity with respect to the Viola systematics. A scatter plot in the $r-r_1$ plane is shown in Fig.2. r (r_1) represents the ratio between the IMF-PLF(TLF) relative velocity and the velocity given by the Viola systematics. One can see that the points are mostly located far from the axes $r = 1$, $r_1 = 1$.

In Fig.3 we represent the velocity of fragments (including PLF and TLF) in the plane determined by the beam parallel and perpendicular velocities, in the center of mass frame. It is possible to easily recognize the points associated with PLF and TLF. Neck fragments (points with velocity closer to the center of mass velocity) have mostly a negative velocity along the direction perpendicular to the beam. In fact, due to the mass asymmetry of the reaction considered, the projectile contributes by a larger proportion to the matter that forms in the overlap neck zone. This appears as a nice memory effect of the entrance channel. Hence this neck source will present a given degree of alignment with respect to the PLF-TLF direction.

IV. ISOSPIN PROPERTIES OF FRAGMENTS

Calculations have been performed adopting two different prescriptions for the behaviour of the symmetry en-

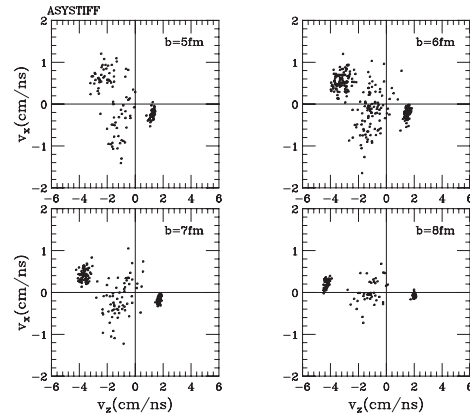


FIG. 3: Center of mass z, x -velocity component distributions.

ergy, namely an “asy-soft” dependence, where the symmetry energy tends to saturate and eventually decreases at high density, and an “asy-stiff” dependence, where the symmetry energy increases linearly with density [16].

A. Central collisions

The properties of fragments obtained in a central collision, $^{124}\text{Sn} + ^{124}\text{Sn}$ at 50 MeV/A, are summarized in Fig.4. Let us look in particular at the dynamical evolution of the isospin properties of the considered system (panels (b)). By looking at the asymmetry of the liquid (fragment) phase, one can see a first decrease, to pre-equilibrium particle emission, that is neutron-rich in neutron-rich systems. Then, when the system expands and enters the low-density region, fragments are formed and the asymmetry continues to decrease. This second phase can be associated with the isospin-distillation mechanism: while fragments are formed, the neutron excess is transferred to the low density gaseous phase, while the liquid (fragment) phase results more symmetric. This effect depends on the EOS used, and in particular on the derivative of the symmetry energy, resulting more important in the asy-soft case, where the derivative is larger at low density. In fact the fragment asymmetry results smaller in the asy-soft case (panels (e)). We notice that properties of fragments are given at the time when they do not interact anymore, apart from the Coulomb repulsion (freeze-out time).

B. Mid-peripheral collisions

In neck fragmentation the isospin dynamics appears quite different, with respect to central collisions. Indeed now the formation of a low-density region in between projectile and target induces isospin migration towards the neck. So finally neck IMF's appear more neutron rich

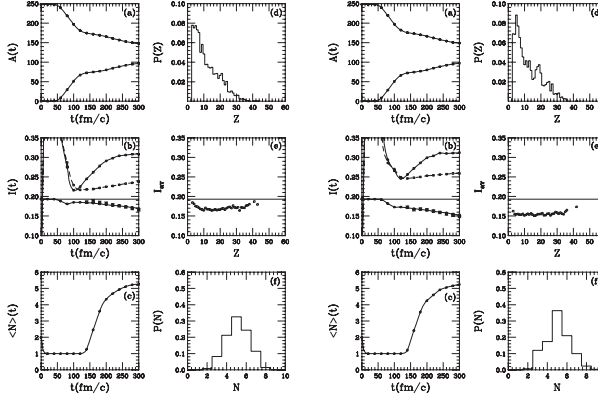


FIG. 4: Left: $^{124}\text{Sn} + ^{124}\text{Sn}$ $b = 2\text{ fm}$ collision: Time evolution of total mass of the liquid (top curve) and gas (bottom curve) phases (panel (a)), asymmetry of liquid (bottom curve) and gas (top curves) phases (panel (b)), average IMF multiplicity (panel (c)). IMF charge distribution (panel (d)), average asymmetry (panel (e)) and multiplicity distribution (panel (f)), calculated at the freeze-out time. Results correspond to the asy-stiff EOS. Right: the same as in the left panels, but for the asy-soft EOS.

with respect to fragments emitted by the projectile or the target. So, after the pre-equilibrium emission, the asymmetry of the central liquid phase rises again, due to the formation of neutron-rich IMF's (see Fig.5). Of course also this effect depends on the adopted EOS and is more pronounced in the case of the asy-stiff interaction, since now we are testing the derivative of the symmetry energy close to normal density. So the asymmetry of neck fragments increases with the stiffness of the symmetry energy.

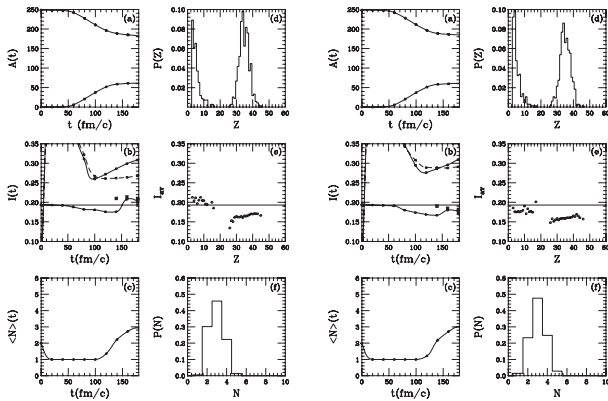


FIG. 5: The same as in Fig.4, but for $b = 6\text{ fm}$

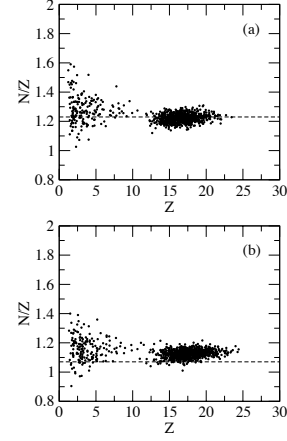


FIG. 6: Asymmetry vs. charge of each nuclei arising from the simulation of the reaction $^{58}\text{Fe} + ^{58}\text{Fe}$ (a) and $^{58}\text{Ni} + ^{58}\text{Ni}$ (b) with an asy-stiff EOS. Horizontal dashed lines are the initial asymmetries of the colliding systems.

C. Effects in symmetric and charge-symmetric reactions

We will discuss the reactions $^{58}\text{Fe} + ^{58}\text{Fe}$ (charge asymmetric $N/Z = 1.23$) and $^{58}\text{Ni} + ^{58}\text{Ni}$ (charge symmetric $N/Z = 1.07$) at 47 MeV/A [29]. The interest of these reactions is that, due to the uniform N/Z distribution, we do not have isospin gradients initially. So the study of the full dynamics and of the possible occurrence of density gradients is essential also to understand the isospin dynamics. Fig. 6 reports the N/Z ratio of each fragment vs. the charge Z at the freeze-out time, obtained at the impact parameter $b = 4\text{ fm}$, using the asy-stiff EOS.

Residual nuclei, i.e. PLF and TLF (large Z range), show a different behaviour in the two reactions: we note, in fact, that the points of Fe system are along the dashed line, that represents the initial system asymmetry, while for Ni reaction points lie above that line. The IMF behaviour is similar for the two reactions: the points, for both reactions, lie above the dashed line, although for the reaction $^{58}\text{Ni} + ^{58}\text{Ni}$ the difference between the N/Z of IMF's and large nuclei seems to be less pronounced.

We can conclude that: i) In the neutron rich reaction, neutron evaporation due to pre-equilibrium goes in the same direction of the neck neutron enrichment, caused by the isospin-migration. So finally we observe slightly more symmetric residues accompanied by neutron-richer IMF's; ii) In the neutron-poor collision, pre-equilibrium proton emission enhances the N/Z of large fragments. The acquired asymmetry is then transferred to the neck region.

To better disentangle between the two mechanisms, pre-equilibrium and isospin migration effects, one can study the charge composition of residues distinguishing between binary and ternary events.

For both reactions, we note that the N/Z ratio of

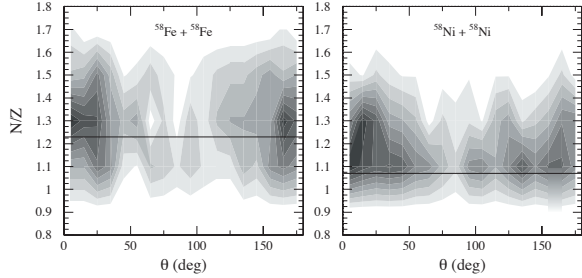


FIG. 7: Contour plots of the N/Z distribution versus the emission angle

residual nuclei in ternary events is lower than the value for binary events, since in the second case the isospin-migration effect does not apply. The isospin dynamics effect is rather evident from the comparison with the asymmetry values at the time corresponding to the end of the pre-equilibrium phase ($t \approx 100 fm/c$). For the Fe + Fe system the N/Z of residues changes from 1.22 to 1.19, in ternary events; for the Ni + Ni reaction this difference is not so evident (from 1.12 to 1.125) because the isospin-migration competes with proton evaporation. On the other hand, in binary events, we observe a neutron enrichment of residues ($N/Z = 1.17$) in the Ni reaction, due to a favorite proton pre-equilibrium emission.

It is interesting to look also for some correlations between asymmetry, mass, velocity and direction of outgoing fragments. Small masses are emitted at all angles, while large fragments appear closer to PLF and TLF emission angles. The analysis of the N/Z distribution versus the emission angle reveals that larger fluctuations are present close to forward and backward angles, suggesting that IMF's that are more correlated to the spectator matter may become more neutron-rich, since they interact for a longer time with the system and the distillation mechanism becomes more effective (see Fig.7).

We stress again that the *neck - IMF's* always present a neutron enrichment, *even in the case of a n-poor system*. The latter paradox is due to the pre-equilibrium isospin dynamics. In fact, as explained above, due to pre-equilibrium, the system will loose some protons and acquire a N/Z larger than the initial one. Then, before the di-nuclear system reseparates, the neutron excess is transferred to the neck region that is at low density. Some evidence has been found in recent data on ^{58}Ni induced fragmentation [30–32].

In Fig. 8, the average asymmetry of products arising from the two reactions ($b = 4 fm$) is shown for the two choices, *asy - stiff* and *asy - soft* EOS.

We note that both fragments and residual nuclei are more symmetric in the *asy-soft* case. The fact that the N/Z of large fragments is smaller in the *asy-soft* case is due to pre-equilibrium effects, i.e. with the soft EOS more neutrons are emitted. On the other hand, the more pronounced difference between IMF and large fragment

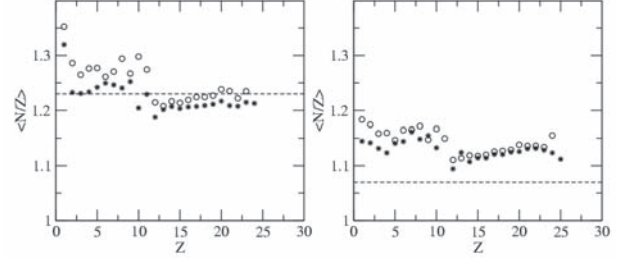


FIG. 8: Average asymmetry vs. Z for nuclei from the reactions $^{58}Fe + ^{58}Fe$ (left panel) and $^{58}Ni + ^{58}Ni$ (right panel) for an *asy - stiff* (circles) and *asy - soft* (stars) EOS. Horizontal dashed lines represent initial asymmetry of colliding systems [16].

asymmetries with the stiff parameterization is a consequence of a more effective isospin migration in this case.

V. FLUCTUATIONS OF FRAGMENT ISOTOPIC CONTENT

Until now we have described mechanisms that are mainly responsible of the average fragment asymmetry. What is the origin of the fluctuations observed in the isotopic composition of fragments? Fragment formation is driven by the development of instabilities, and so by unstable isoscalar-like mode, however isovector oscillations also contribute to the width of the isotopic distributions.

In asymmetric matter isoscalar and isovector modes are coupled, and some times isovector-like oscillations are even suppressed. The isospin distillation mechanism, that is a feature of isoscalar-like oscillations, creates a given dispersion in the N/Z of fragments. In fact the amplitude of the effect depends on the considered unstable modes and, since fragments come up from the beating of several modes, this leads to a given width in the isotopic distributions. The more effective the distillation is (as in the *asy-soft* case), the smaller the width, since all unstable modes will behave in a similar way. However, also the contribution of the isovector-like vibrations has to be considered [33].

To illustrate their role in spinodal decomposition we have performed very schematic calculations for unstable low-density matter inside a box with periodic boundary conditions, with $\rho_{in} = \rho_0/6$ and temperature $T = 2.5 MeV$. For the sake of simplicity, we consider here symmetric matter, for which isoscalar and isovector vibrations are de-coupled. In this case N/Z fluctuations are only due to iso-vector vibrations. We study the temporal evolution of fluctuations, inside a given cell, of volume V , of the densities $\rho = \rho_n + \rho_p$ and $\rho_i = \rho_n - \rho_p$, where ρ_n and ρ_p are neutron and proton densities. Some fluctuations are present at the initial time, due to the fact that particles are randomly distributed inside the box. As it can be seen from Fig.9, isoscalar fluctuations

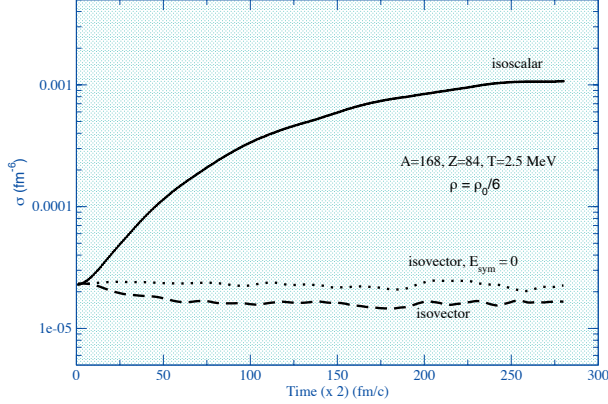


FIG. 9: Time evolution of isoscalar (full line) and isovector (dashed line) fluctuations, in a given cell of volume V , for unstable matter inside a box with periodic boundary conditions. The dotted line refers to calculations with zero symmetry energy.

grow since fragments are formed, while iso-vector fluctuations rapidly converge to an “equilibrium” value, that depends on the initial density, temperature and on the value of the symmetry energy. If the symmetry potential is removed, iso-vector fluctuations keep their initial value. While the density grows inside a fragment, isovector fluctuations do not grow anymore. This is because the fragment is constructed according to isoscalar vibrations, where neutrons and protons move in phase, with the same amplitude, while isovector fluctuations maintain their equilibrium value, that is associated with the initial density ρ_{in} .

The variance associated with equilibrium isovector fluctuations in a given volume V can be written as:

$$\sigma_{\rho_i} = \langle \delta \rho_i \delta \rho_i \rangle = \frac{\mathcal{F}}{2} \frac{\rho_{in}}{V},$$

where the function $\mathcal{F}$ depends on the temperature and on the symmetry energy at the considered density.

Now the probability to observe a given fluctuation $\delta \rho_i$ can be expressed as:

$$P \approx \exp(-\delta \rho_i^2 / 2\sigma_{\rho_i}) \quad (4)$$

and then, for a fragment of given mass A , the distribution $P(N - Z)$ can be written as:

$$P(N - Z) \approx \exp(-[N - Z - (\bar{N} - \bar{Z})]^2 / (\mathcal{F} \rho_{in} V)), \quad (5)$$

where $\bar{N}$ and $\bar{Z}$ are the average neutron and proton numbers. Indicating by $\rho_{fin} = A/V$ the actual density of the fragment and introducing the parameter $\alpha = \rho_{in} / \rho_{fin}$, the formula can be recast as follows

$$P(N - Z) \approx \exp(-A [I - \bar{I}]^2 / (\mathcal{F} \alpha)), \quad (6)$$

where $I = (N - Z)/A$. Hence one can see that, in the spinodal decomposition process, the variance of the fragment isotopic distribution is reduced by a factor α with respect to the equilibrium value $\mathcal{F}$.

It is easy to realize that, in log scale, the ratio of the yields of a given isotope with charge Z , obtained in two different systems having asymmetries $\bar{I}_1$ and $\bar{I}_2$ depends linearly on the neutron number N . Hence this property, that is named isoscaling [34], and has been observed in several experimental data, is present also in spinodal decomposition processes.

VI. CONCLUSIONS

We have discussed some properties of fragmentation mechanisms in charge-asymmetric systems. The isospin effects can be related to the behaviour of the symmetry energy below and around normal density, thus allowing to extract important information on fundamental quantities of the nuclear interaction. It appears that the isospin dynamics is strictly linked to the presence of density gradients. Indeed, even in symmetric reactions, one can observe isospin transport phenomena, due to pre-equilibrium emission and to the fact that the neutron excess is transferred to the low density regions, since this situation is energetically favourable for the system. This effect appears connected to the derivative of the symmetry energy at density lower than normal one, in the case of violent multifragmentation phenomena, up to around normal density, for more peripheral reactions. The results observed are compatible with the occurrence of spinodal instabilities and phase co-existence in charge-asymmetric nuclei. Comparison of the fragment isotopic distributions with experimental data can allow to extract information on the value of the symmetry energy at the moment when fragmentation occurs.

REFERENCES

- [1] I. Bombaci, T.T.S. Kuo and U. Lombardo, Phys. Reports. 242 (1994) 165 .
I. Bombaci, Phys. Rev. C55 (1997) 1
- [2] M.Prakash et al., Phys.Rep.280 (1997) 1
- [3] I.M.Irvine, "Neutron Stars" Oxford Univ. Press 1978
- [4] J.M.Lattimer et al., Phys.Rev.Lett. 66 (1991) 2701
- [5] D.Pines, R.Tamagaki and S.Tsuruta Ed.s, "Neutron Stars", Addison-Wesley N.Y.1992
- [6] K.Sumiyashi and H.Toki, Astro.Phys.Jour. 422 (1994) 700
- [7] C.J.Pethick and D.G.Ravenhall in "The Lives of Neutron Stars" Ed.s M.A.Alpar et al., NATO ASI Series C Vol.450 (1995) pp.59-70
- [8] C.H.Lee, Phys.Rep. 275 (1996) 255
- [9] "It is important to put the properties of *neutron* matter at *subnuclear* densities on as firm a footing as possible, not only for astrophysical applications, but also for interpreting terrestrial experiments with coming radioactive beam facilities" C.J. Pethick and D.G. Ravenhall, in ref.[7].
- [10] B.A.Brown, Phys.Rev.Lett. 85 (2000) 5296

- [11] C.J.Horowitz and J.Piekarevicz, *Phys.Rev.Lett.* **86** (2001) 5647.
- [12] H.Mueller and B.D.Serot, *Phys.Rev.* **C52** (1995) 2072
- [13] Bao-An Li and C.M.Ko, *Nucl.Phys.* **A618** (1997) 498
- [14] M.Colonna, M.Di Toro and A.Larionov, *Phys.Lett.* **B428** (1998) 1
- [15] V.Baran, M. Colonna, M. DiToro and V.Greco, *Phys.Rev.Lett.* **86** (2001) 4492
- [16] V. Baran *et al.*, *Nucl. Phys.* **A 703**, 603-632 (2002).
- [17] V. Baran, M.Colonna, M.Di Toro, *Nucl. Phys.* **A 730**, 329-354 (2004).
- [18] M.Colonna, Ph.Chomaz, S.Ayik, *Phys.Rev.Lett.* **88** (2002) 122701; M.Colonna *et al.*, *Nucl. Phys.***A742** (2004) 337-347.
- [19] S.Ayik, C.Gregoire, *Phys. Lett.* **B212** (1998) 269
- [20] J.Randrup and B.Remaud, *Nucl. Phys.* **A514** (1990) 339
- [21] G.F.Burgio, Ph.Chomaz, J.Randrup, *Nucl. Phys.* **A529** (1991) 157.
- [22] S.Ayik, E.Suraud, M.Belkacem, D.Boilley, *Nucl. Phys.* **A545** (1992) 35c
- [23] Ph.Chomaz *et al.*, *Phys. Rev. Lett.* **73** (1994) 3512; A.Guarnera *et al.*, *Phys. Lett.* **B403** (1997) 191
- [24] M.Colonna *et al.*, *Nucl. Phys.* **A642** (1998) 449
- [25] J.Randrup and S.Ayik, *Nucl. Phys.* **A572** (1994) 489
- [26] Ph. Chomaz, M. Colonna and J.Randrup, *Phys. Rep.* **389** (2004) 263-440.
- [27] A.Guarnera, M.Colonna, Ph.Chomaz, *Phys. Lett.* **B373** (1996) 297
- [28] A. Pagano *et al.*: *Nucl. Phys.* **A 681**, 331c (2001); E. De Filippo *et al.*, *Phys. Rev. C*, in press.
- [29] D. V. Shetty *et al.*, *Phys. Rev.* **C68**, 021602 (R)(2003), D. V. Shetty *et al.*, arXiv:nucl-ex/0406008.
- [30] P. Milazzo *et al.*, *Phys. Lett.* **B509**, 204 (2001).
- [31] L.Gingros *et al.*, *Phys. Rev.* **C65**, 061604 (2002).
- [32] R.Moustbchir *et al.*, *Nucl. Phys.* **A 739**, 15 (2004).
- [33] M.Colonna and F.Matera, arXiv:nucl-th/0503018, to appear in *Phys. Rev. C*
- [34] H.Xu *et al.*, *Phys.Rev.Lett.* **85** (2000) 1908

Signatures of Hadronization via Quark Coalescence at RHIC

Vincenzo Greco and Che Ming Ko

Cyclotron Institute, Texas A&M University, College Station, Texas 77843-3366, USA

We study hadronization mechanism in ultra-relativistic heavy-ion collision in relation to the formation of a quark-gluon plasma. We show how a quark-coalescence model plus fragmentation model can explain the observed large baryon to meson ratio at intermediate transverse momentum and scaling of the elliptic flows of identified hadrons. We further show its predictions on J/Ψ and D meson production in heavy ion collisions and on higher-order anisotropic flows, and discuss how quark coalescence applied to open- and hidden-charm mesons can give insight to charm quark interactions in the quark-gluon plasma.

PACS numbers:

I. INTRODUCTION

Experimental data from relativistic heavy ion collisions at the Relativistic Heavy Ion Collider (RHIC) during past few years have shown convincing evidence that the quark-gluon plasma has already been produced in these collisions. Besides studying the properties of the quark-gluon plasma, it is also important to understand how quarks and gluons are converted to hadrons during hadronization. Because of its non-perturbative nature, hadronization has so far been treated only phenomenologically. One of such approaches is the quark coalescence model, in which colored partons are combined into color singlet hadrons. We show that a model that includes quark coalescence and mini-jet fragmentation provides a natural explanation for the large baryon to pion ratio at intermediate transverse momentum and the quark number scaling of identified hadrons that are observed in heavy ion collisions at RHIC [1–5]. We also discuss the relevance of coalescence to study the properties of the plasma in the heavy quark sector [10] and the possibility to further test hadronization models by mean of higher-order anisotropic flows [11].

II. THE QUARK COALESCENCE MODEL

In the quark coalescence model, the transverse momentum spectrum of hadrons that consist of n quarks is given by the overlap of the product of n quark phase-space distribution function $f_q(x_i, p_i)$ with the Wigner distribution function $f_H(x_1..x_n; p_1..p_n)$ of the hadron, multiplied by the probability g_H of forming from n colored quarks a color neutral object with the spin and isospin of the hadron, i.e.,

$$\frac{dN_H}{d^2P_T} = g_H \int \prod_{i=1}^n \frac{p_i \cdot d\sigma_i d^3\mathbf{p}_i}{(2\pi)^3 E_i} f_q(x_i, p_i) \times f_H(x_1..x_n; p_1..p_n) \delta^{(2)}\left(P_T - \sum_{i=1}^n p_{T,i}\right), \quad (1)$$

where $d\sigma$ denotes an element of a space-like hypersurface.

The n quark phase space distribution is usually approximated by the product of n single quark distribution functions. In Refs. [2, 3], the quark transverse momentum spectra below $p_0 \sim 2$ GeV are taken to be thermal with a temperature $T = 170$ MeV and a radial flow velocity $\beta_{max} = 0.5$, which are consistent with both experimental data at RHIC and predictions from hydrodynamic calculations. The masses of these quarks are taken to be those of constituent quarks, i.e., $m_{u,d} = 300$ MeV and $m_s = 475$ MeV. Above p_0 , the quark transverse momentum spectra are power-like as given by the quenched pQCD minijets [6], and their masses are those of current quarks. Both soft thermal and hard minijet partons are assumed to distribute uniformly in a fireball of transverse radius of 8.15 fm and longitudinal length of 4.35 fm, corresponding to a volume of 900 fm³. Including also gluons of masses similar to those of light quarks to take into account nonperturbative effects in the quark-gluon plasma, the quark and gluon numbers are then fixed by the measured transverse energy of about 750 GeV for Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. For the Wigner distribution functions of hadrons, they are taken to be spheres in both space and momentum with radii Δ_r and $\Delta_p = \Delta_r^{-1}$, respectively. A good description of both pion and proton spectra can be obtained with a radius parameter of $\Delta_p = 0.24$ GeV for mesons and 0.36 GeV for baryons.

III. PARTICLE SPECTRA

A. Light and strange hadrons

In the coalescence model, baryons with momentum p_T are mainly produced from quarks with momenta $\sim p_T/3$, while mesons with same momentum are mainly from quarks with momenta $\sim p_T/2$. Since the quark transverse momentum spectra decrease with p_T , production of high momentum baryons from quark coalescence is more favored than mesons. This is opposite to the fragmentation process where baryon production is suppressed with respect to mesons as more quarks are needed from the vacuum, leading to a typical p/π ratio of ~ 0.2 . As shown in the upper panel of Fig.1, the $\bar{p}$ and π^- spec-

tra obtained from the quark coalescence model indeed become comparable at intermediate transverse momenta as in the experimental data from PHENIX collaboration [7, 8]. These intermediate transverse momentum hadrons receive significant contributions from coalescence of minijet partons with thermal partons as seen in the inset of the left panel of Fig.1, where the ratio of hadron spectra with and without this contribution is shown.

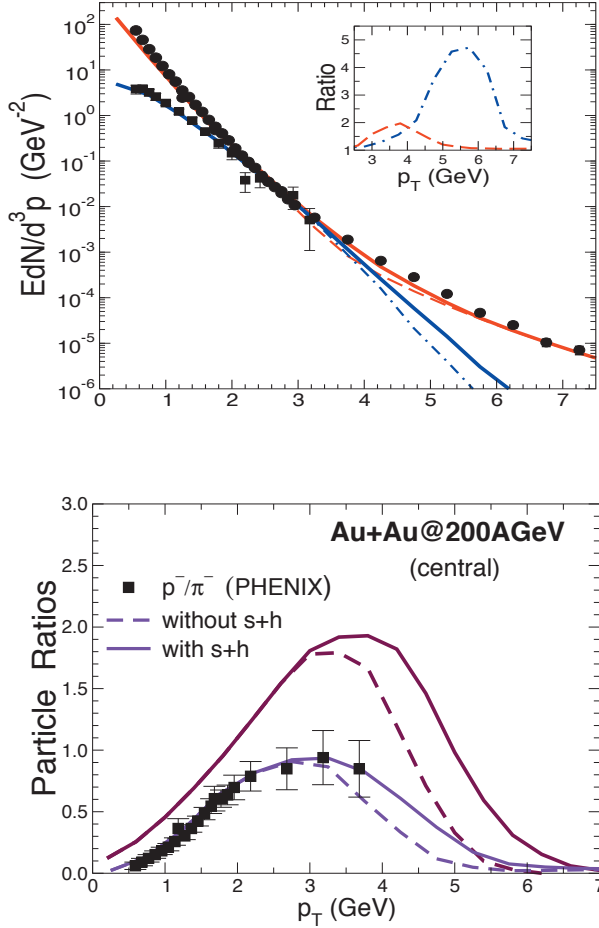


FIG. 1: Upper panel: Pion and antiproton transverse momentum spectra from Au+Au collisions at $\sqrt{s} = 200$ AGeV with (solid curve) and without (dashed and dash-dotted curves for pion and antiproton, respectively) contributions from coalescence of minijet partons with thermal partons (s+h). Ratio of the two cases is given in the inset with the dash-dotted curve for antiprotons and the dashed curve for pions. Experimental data at 200 AGeV [8] are shown by filled circles for π^0 and by squares for $\bar{p}$. Lower panel: $\bar{p}/\pi$ (lower curves) and Λ/K_s^0 (upper curves) ratios with and without contributions from s+h coalescence. Filled squares are experimental data [7].

The resulting $\bar{p}/\pi$ ratio is shown in the lower panel of Fig.1 by lower lines and reproduces well the experimental data [7]. A similar effect is seen also for the Λ/K_s^0 ratio (upper lines). Similar conclusions are reached in other studies based on quark coalescence [1, 4], except that we also obtain a good description of $\bar{p}$ and pion spectra

as well as their ratio $\bar{p}/\pi$ at $p_T < 2$ GeV as a result of including resonance decays and avoiding the collinear approximation in our approach. Because the dominance of resonance production, the total entropy before and after hadronization only decreases by about 15%, largely due to a similar decrease in the total energy.

At lower RHIC energy, $\sqrt{s_{NN}} = 62$ GeV, an increase of about 20 % is expected for the p/π peak. This arises from a balance between an increased chemical potential, a reduced jet quenching and a steeper pQCD contribution to the π spectrum [9].

B. Charmed hadrons

Coalescence model has also been used to study open and hidden charmed hadron production in relativistic heavy ion collisions based on the same fireball parameters as for light quarks [10]. With Gaussian wave functions for the charmonium states and taking the charm quark number to be $dN_{c\bar{c}}/dy = 2.5$ from the PYTHIA routines, the quark coalescence model gives a J/ψ yield of $dN_{J/\psi}/dy = 2.7 \cdot 10^{-3}$ for a charm quark spectrum that is thermalized in the quark-gluon plasma but only $0.9 \cdot 10^{-3}$ for the spectrum obtained from the pQCD. The slopes of the transverse mass spectra from the two scenarios also differ significantly as shown in Fig.2. The uncertainty

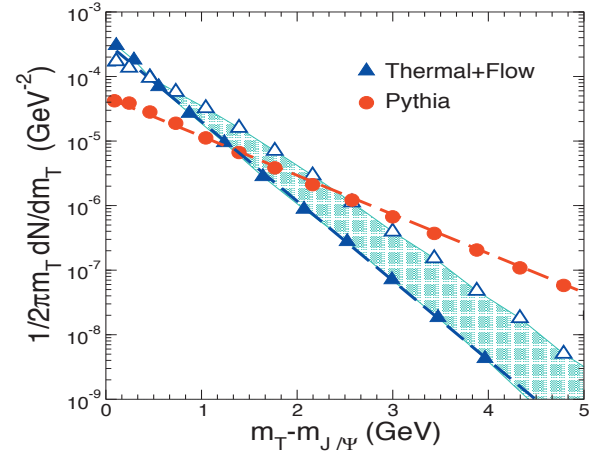


FIG. 2: Spectra of J/ψ at midrapidity from the quark coalescence model for central 200 AGeV Au+Au collisions. Results using thermal and pQCD c -quark distributions are shown, respectively, by circles and triangles. The dashed areas show theoretical uncertainties due to that of radial flow in the thermal c -quark spectrum.

in the charmonium spectrum for a thermalized charm quark spectrum, shown by the dashed area, is due to the estimated uncertainty in the radial flow velocity of the fireball $\beta_{\max} = 0.5-0.65$. For D mesons transverse momentum spectra has been calculated together with their decay into single electrons. We find that the single electron spectrum from present data cannot clearly distinguish between a scenario in which charm meson do not

rescatter (pQCD) and one in which they thermalize with the medium.

IV. MOMENTUM ANISOTROPIES

A. Elliptic flow of light and strange hadrons

In Heavy Ion collisions the anisotropy of the particle momentum distributions in the plane perpendicular to the beam directions offers the possibility to understand the dynamics of the collisions and the properties of the initial hot and dense matter. At RHIC energies it has been shown that it is built in very early in the dynamical evolution, thus being a probe of the interaction during the partonic stage. Recently, we have realized that elliptic flow provide also a way to understand the hadronization mechanism in itself. If hadronization go through coalescence of constituent quarks the anisotropy at partonic level propagates at hadronic level according to [5, 18] :

$$v_{2,M}(p_T) \approx 2v_{2,q}(p_T/2), \quad v_{2,B}(p_T) \approx 3v_{2,q}(p_T/3) \quad (2)$$

this effect allows to see the characteristic feature of coalescence that is a larger elliptic flow for baryons, by a factor 3/2, and a similar shift of the p_T at which the v_2 reaches the maximum value. This features are clearly seen in the experimental data. In Ref.[3], we have extracted the quark elliptic flow fitting the measured pion elliptic flow according to the coalescence model. Then the elliptic flows of other hadrons comes as a prediction. In Fig.3, the elliptic flows of π , K , p , and Λ from such study are shown, and they are seen to agree with available experimental data [13, 14].

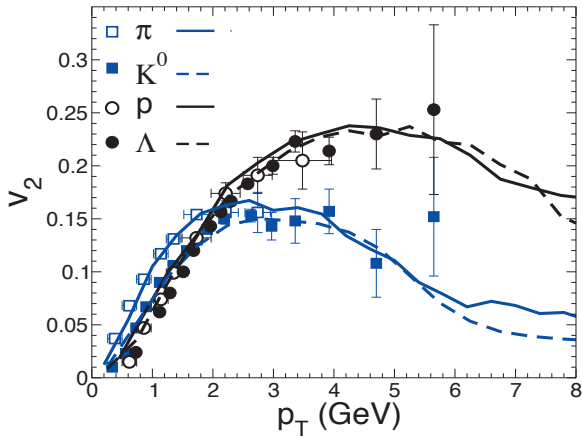


FIG. 3: Elliptic flow of different hadron species vs p_T , data are from STAR [15] and PHENIX [14].

Except for pions, the measured elliptic flows of identified hadrons follow approximately the quark number scaling, i.e., the dependence of hadron elliptic flows on hadron transverse momentum becomes similar if both are divided by the number of constituent quarks in hadrons.

Such scaling follows naturally if only comoving constituent quarks with equal transverse momenta can coalesce into hadrons. Allowing coalescence of quarks with different momenta and also taking into account the finite momentum distribution of quarks inside hadrons as in more realistic coalescence model described leads to a small breaking of quark number scaling of about 10% for mesons and about 5% for baryons [16]. Including resonance decays can also break quark number scaling. However, for p , Λ , and K from resonance decays elliptic flows are very similar to the directly produced ones. Only the elliptic flow of pions from the decay of ω , K^* , and Δ is significantly larger than that of directly produced pions. Since pions in the coalescence model are mainly from resonance decays due to their larger degeneracy, the elliptic flow of pions is thus enhanced compared to those of other stable hadrons, leading to a deviation from the quark number scaling.

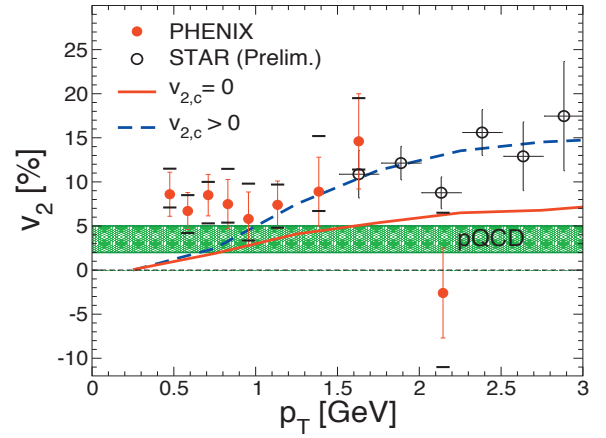


FIG. 4: Elliptic flows of “non-photon” single $e^\pm$ in minimum bias Au+Au collisions at $\sqrt{s} = 200$ AGeV, compared to coalescence model prediction, using c-quark distribution from p-p collisions ($v_{2,c} = 0$, solid line) and assuming a flow profile as determined for light quarks ($v_{2,c} > 0$, dashed line). The band indicates prediction from jet-quenching [17].

B. Elliptic flow of charmed hadrons

With the light quark elliptic flows known from those of light hadrons, the lower limit for the elliptic flow of charmed hadrons can be determined in the coalescence model by using the charm quark spectrum from PYTHIA for $p-p$ collisions. This is a scenario in which charm interaction in the plasma can be discarded, $v_{2,c} = 0$. Notice that even in such a case D mesons acquire an elliptic flow from the light quark in a coalescence model, at variance with a fragmentation model. An upper limit is obtained assuming that charm quarks are flowing together with the light quarks. This means an elliptic flow similar to that of light quarks except for the mass effect due to radial flow.

In Fig.4 the elliptic flow of the single $e^\pm$, coming from the D mesons formed by coalescence of c quarks with (u,d), is shown together with the “non-photonic” single $e^\pm$ from STAR and PHENIX Collaborations. The scenario with charm quark strongly interacting with the medium (dashed line) seems to be favored respect to the case with vanishing charm elliptic flow (solid line). These results do not include charmed mesons produced from direct fragmentation of charmed quarks, whose elliptic flow has been shown to be small due to small charm quark energy loss in the quark-gluon plasma [17].

A stronger dependence on the charm in-medium interaction is expected for the J/ψ [10], for a strong interacting plasma a non-vanishing J/ψ elliptic flow is expected at $p_T > 1.5$ GeV. Therefore with upcoming experiments ALICE at CERN and RHIC-II at BNL, it will be possible to have a better insight into the properties of charm quarks in the plasma.

C. Higher-order momentum anisotropy

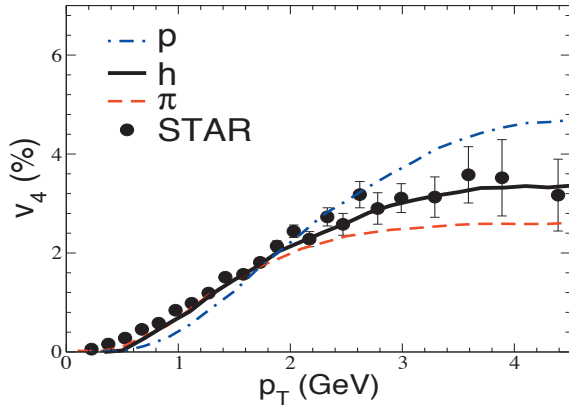


FIG. 5: v_4 for charged hadrons from quark coalescence together with the experimental data for charged hadrons [19].

Recently, a sizeable fourth order momentum anisotropy v_4 has been observed in experiments [15]. In the naive coalescence model that only allows quarks of equal momentum to form a hadron, the meson $v_{4,M}$ and baryon $v_{4,B}$ are related to quark $v_{2,q}$ and $v_{4,q}$ by [18]:

$$v_{4,M}(2p_T) \simeq 2v_{4,q} + v_{2,q}^2, \quad v_{4,B}(3p_T) \simeq 3v_{4,q} + 3v_{2,q}^2, \quad (3)$$

with $v_{n,q}$'s evaluated at p_T . The ratio of baryon to meson v_4 is thus 3 if there is no quark $v_{4,q}$. A fit to the charged hadron v_4 data using the quark coalescence model requires, however, that $v_{4,q} \simeq 1.8v_{2,q}^2$. With non-zero $v_{4,q}$, the ratio $v_{4,B}/v_{4,M}$ is thus expected to be about 2. These results are shown in Fig.5 for the meson (dashed line) and baryon (dot-dashed line) v_4 predicted by quark coalescence, using a $v_{4,q}$ extracted from a fit to the measured charged hadron $v_{4,h}$ (solid circles) [19].

V. CONCLUSIONS

For heavy ion collisions at RHIC, quark coalescence leads to a natural explanation for the observed large baryon to pion ratio at intermediate transverse momenta and the quark number scaling of the elliptic flows of identified hadrons. The violation of pion elliptic flow from this scaling is largely due to the effect of resonance decays. For charmonia and charmed mesons that consist of heavy charm quarks, the coalescence model gives significant different predictions for the spectra and elliptic flows based on two extreme scenarios. One where charm quarks do not rescatter with the bulk of the plasma and the other with charm flowing with the plasma. Experimental test of these predictions would give valuable information on charm quark interactions in the quark-gluon plasma. Furthermore, the coalescence model allows us to infer from the measured hadron higher-order momentum anisotropy that the parton higher-order momentum anisotropy before hadronization is appreciable.

-
- [1] Hwa R C and Yang C B 2003 Phys. Rev. C **67** 034902.
 - [2] Greco V Ko C M and Lévai P 2003 Phys. Rev. Lett. **90** 202302.
 - [3] Greco V Ko C M and Lévai P 2003 Phys. Rev. C **68** 034904.
 - [4] Fries R J Müller B Nonaka C and Bass S A 2003 Phys. Rev. Lett. **90** 202303; 2003 Phys. Rev. C **68** 044902.
 - [5] Molnar D and Voloshin S A 2003 Phys. Rev. Lett. **91** 092301.
 - [6] Gyulassy M, Lévai P and Vitev I 2000 Phys. Rev. Lett. **85** 5535.
 - [7] Adler S S *et al.* [PHENIX Collaboration] 2003 Phys. Rev. Lett. **91** 172301.
 - [8] Adler S S *et al.* [PHENIX Collaboration] 2003 Phys. Rev. Lett. **91** 072301; 2004 Phys. Rev. C **69** 034909.
 - [9] Greco V, Ko C M Vitev I 2005 Phys. Rev. C **71** 041901.
 - [10] Greco V Ko C M and Rapp R 2004 Phys. Lett. B **595** 202.
 - [11] Greco V Ko C M, nucl-th/0405040.
 - [12] Adcox K *et al.* [PHENIX Collaboration] 2002 Phys. Rev. Lett. **88** 192303.
 - [13] Sorensen P 2004 J. Phys. G. **30** S217; J. Adams *et al.* [STAR Collaboration], nucl-ex/0409033.
 - [14] Adler S *et al.* [PHENIX Collaboration], 2002 Phys. Rev. Lett. **91** 182301.
 - [15] Adams J *et al.* [STAR Collaboration] 2003 Phys. Rev. Lett. **92** 052302.
 - [16] Greco V and Ko C M, 2004 Phys. Rev. C **70** 024901.
 - [17] Djordjevic M and Gyulassy M 2003 Phys. Lett. B **560** 37.
 - [18] Kolb P F Chen L W Greco V and Ko C M 2004 Phys. Rev. C **69** 051901 (R).
 - [19] Adams J *et al.* [STAR Collaboration] 2004 Phys. Rev. Lett. **92** 062301.

Fast nucleon emission as a probe of the isospin momentum dependence

M. Colonna, M. Di Toro, and J. Rizzo

*Laboratori Nazionali del Sud INFN, via S.Sofia 62, I-95123 Catania, Italy
Dipartimento di Fisica e Astronomia, Università di Catania*

I. INTRODUCTION

Effective interactions have been extensively used in transport codes to gain knowledge about nuclear matter properties in conditions far from equilibrium. They predict very different behaviours for some physical properties, such as the momentum dependence of the mean field in the iso-scalar and iso-vector channel (see [1] for a recent review).

In general, the momentum dependence of the potential is strictly related to the concept of in-medium reduction of the nucleon mass. In particular, the non-local part of the symmetry potential has become an interesting subject of investigation, because it leads to a splitting of the masses of different nucleonic species in asymmetric matter, and the sign of this splitting already is an open and controversial problem ([2],[3]). This property of the interaction affects the dynamical evolution of heavy ion collisions, so we can get informations about it by looking at some suitable physical observables.

II. DETAILS OF THE INTERACTION

In order to directly test the influence of the S -effective mass splitting we will present results from reaction dynamics at intermediate energies analysed in a non-relativistic transport approach, of BNV type, see [1]. The $Iso - MD$ effective interaction is derived via an asymmetric extension of the GBD force [4, 5].

The energy density can be parametrized as follows (see also [6],[7]):

$$\varepsilon = \varepsilon + \varepsilon_{kin} + \varepsilon(A', A'') + \varepsilon(B', B'') + \varepsilon(C', C'') \quad (1)$$

where ε_{kin} is the usual kinetic energy density and

$$\begin{aligned} \varepsilon(A', A'') &= (A' + A''\beta^2) \frac{\rho^2}{\rho_0} \\ \varepsilon(B', B'') &= (B' + B''\beta^2) \left(\frac{\rho}{\rho_0} \right)^\sigma \rho \\ \varepsilon(C', C'') &= C'(\mathcal{I}_{NN} + \mathcal{I}_{PP}) + C''\mathcal{I}_{NP} \end{aligned} \quad (2)$$

The variable $\beta = (N - Z)/(A)$ defines the isospin content of the system, given the number of neutrons (N), protons (Z), and the total mass $A = N + Z$. The momentum dependence is contained in the $\mathcal{I}_{\tau\tau'}$ terms, which indicate integrals of the form:

$$\mathcal{I}_{\tau\tau'} = \int d\vec{p} d\vec{p}' f_\tau(\vec{r}, \vec{p}) f_{\tau'}(\vec{r}, \vec{p}') g(\vec{p}, \vec{p}')$$

with $g(\vec{p}, \vec{p}') = (\vec{p} - \vec{p}')^2$. This choice of the function $g(\vec{p}, \vec{p}')$ corresponds to a Skyrme-like behaviour and it is suitable for BNV simulations. In this frame we can easily adjust the parameters in order to have the same density dependence of the symmetry energy *but with two opposite n/p effective mass splittings*, as predicted by the early Skyrme forces [8] and the later Skyrme-Lyon parametrizations [9]. So we can separately study the correspondent dynamical effects, [2].

A good way to visualize the physical meaning of the mass splitting is to look at the kinetic energy dependence of the so-called Lane potential $U_{Lane} = (U_N - U_P)/2\beta$, [10]. Its slope depends on the value and sign of the mass splitting (see [11] for details).

In Fig. 1 we plot this E -dependence with the parametrizations corresponding to the two choices of the sign of the n/p mass splitting (shown in the insert for the $\beta = 0.2$ asymmetry). The value of the splitting is exactly the same, only the sign is opposite. The upper curve well reproduces the Skyrme-Lyon (in particular $SLy4, Sly7$) results. The lower (dashed) the $SIII, SKM^*$ ones.

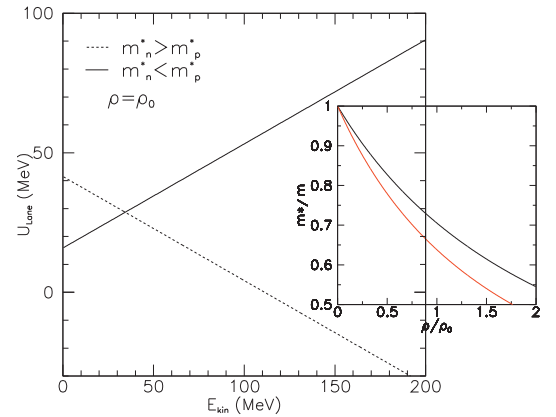


FIG. 1: Lane potential for the used parametrizations; small panel: the effective mass splitting, related to the slope of the Lane potential.

From the figure we can immediately derive the expectation of very different symmetry effects for nucleons around $100 MeV$ kinetic energy, enhancement (with larger neutron repulsion) in the $m_n^* < m_p^*$ case vs. a disappearing (and even larger proton repulsion) in the $m_n^* > m_p^*$ choice.

We can see a crossing of the two prescriptions at low energy: this means that low momentum nucleons feel almost the same Lane potential, so it is important to

choose the appropriate dynamical observables in order to clearly see the effect of mass splitting, e.g. to look at observables where neutron/proton mean fields at high momentum are playing an important role.

III. ISOTOPIC CONTENT OF THE FAST NUCLEON EMISSION

We performed realistic “ab initio” simulations of collisions at intermediate energies of n-rich systems, in particular $^{132}\text{Sn} + ^{124}\text{Sn}$ at 50 and 100 AMeV, central selection. We used either an asy-stiff or an asy-soft density dependence of the symmetry energy. Performing a local low density selection of the test particles ($\rho < \rho_0/8$) we can follow the time evolution of nucleon emissions (gas phase) and the corresponding asymmetry. In Fig. 2 we show the evolution of the gas asymmetry ($I(t) \equiv (N - Z)/A$) for the 50 AMeV reaction (the solid line gives the initial asymmetry).

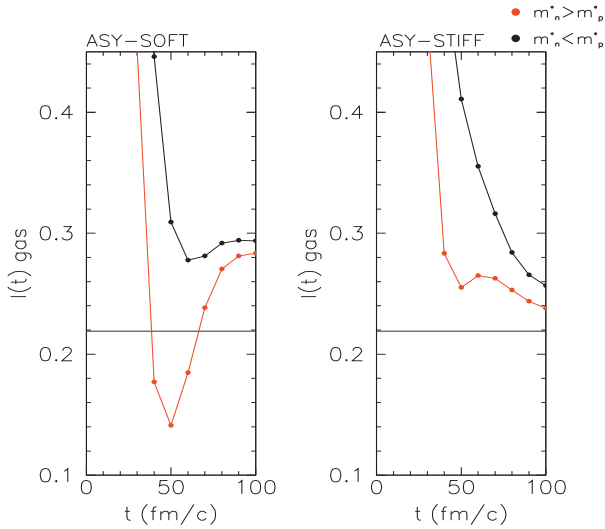


FIG. 2: Isospin gas content as a function of time in a central collision $^{132}\text{Sn} + ^{124}\text{Sn}$ at 50 AMeV for two opposite choices of mass splitting. Left: asy-soft EOS; right: asy-stiff EOS.

For both choices of the density stiffness of the symmetry term we clearly see the effects of the mass splitting, resulting in a reduced fast neutron emission when $m_n^* > m_p^*$. Moreover, for a given sign of the splitting, we find an interesting behaviour for the isospin content of the nucleonic gas: at early times (up to about 60 fm/c), during the (high density) compression phase, the asy-stiff choice leads to higher isospin asymmetry than the asy-soft one; later, we can see an inversion of this trend, due to big contributions to the gas phase coming from low density regions (see also [12]). These effects, the former related to the momentum dependence, the latter to the density dependence of the symmetry potential, can be singled out in the transverse momentum distribution of the N/Z content of the gas phase.

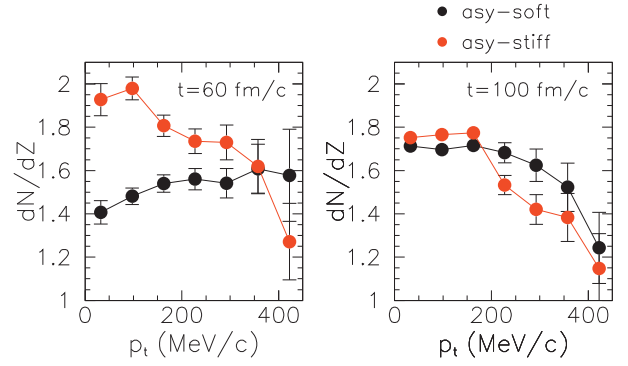


FIG. 3: Transverse momentum dependence of the neutron/proton ratio in the rapidity range $|y^{(0)}| \leq 0.3$ for a central reaction $^{132}\text{Sn} + ^{124}\text{Sn}$ at 50 AMeV. Comparison between two choices of symmetry energy stiffness at different times.

In order to better disentangle the mass splitting effect and to select the corresponding observables, in Figs. 3, 4 we report the N/Z of the “gas” at two different times, $t = 60 \text{ fm/c}$ (end of the pre-equilibrium emission), and $t = 100 \text{ fm/c}$ (roughly freeze out time). We have followed the transverse momentum dependence, for a fixed central rapidity $y^{(0)}$ (normalized to projectile rapidity). In Fig. 3 we show the results *without the mass splitting effect*, i.e. only taking into account the different repulsion of the symmetry term (the initial average asymmetry is $N/Z = 1.56$).

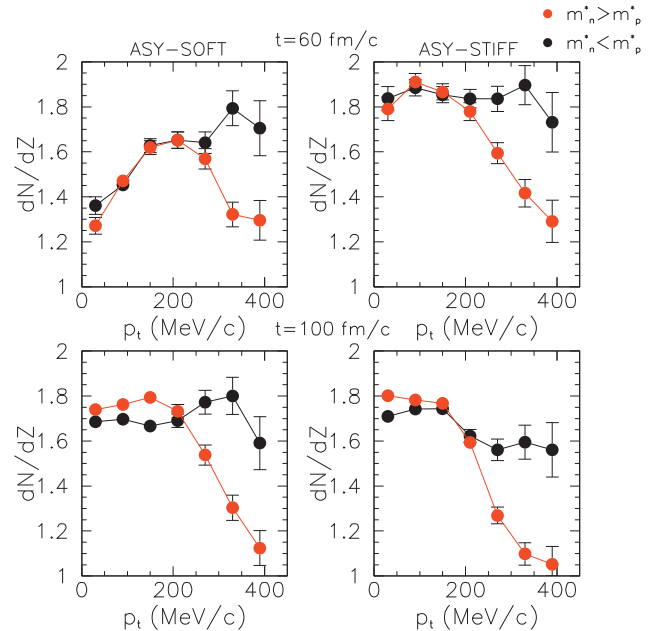


FIG. 4: Same as Fig. 3, for two opposite choices of mass splitting.

At early times (left panel of Fig. 3), when the emission from high density regions is dominant, we see a dif-

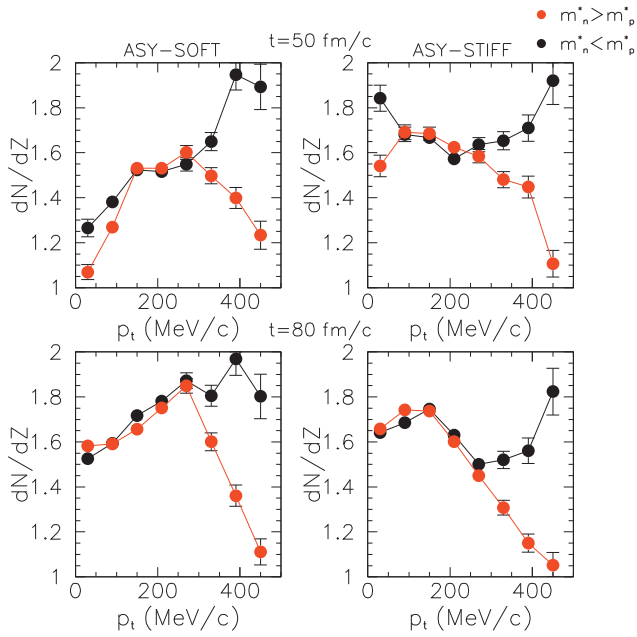


FIG. 5: Same as Fig. 4, but for an incident energy of 100 A MeV.

ference due to the larger neutron repulsion of the asy-stiff choice. The effect is reduced at higher p_t s due to the overall repulsion of the isoscalar momentum dependence. Finally at freeze out (right panel) the difference is almost disappearing, due also to the more efficient *Isospin Distillation* of the asy-soft choice during the expansion phase, [1] and refs. therein.

When we introduce the mass splitting the difference in the isotopic content of the gas, for the larger transverse momenta, is very evident at all times, in particular at the freeze-out of experimental interest, see Fig. 4. As expected the $m_n^* > m_p^*$ sharply reduces the neutron emission at high p_t s. On the other hand, low momentum nucleons show a behaviour which is consistent with Fig. 3, related to the local part of the symmetry potential.

We have repeated the analysis at higher energy, 100 A MeV, and the effect appears nicely enhanced, see Fig. 5. The observed differences for nucleons at high p_t s already appear at early times, when the momentum dependence is more effective. Since these momentum regions are populated mostly during the early stages of the reaction (cfr. [13]), we finally get a permanent signal of a dynamical feature of the interaction.

Similar results have been obtained in ref. [14] at 400 A MeV in a different *Iso - MD* model, restricted to the $m_n^* > m_p^*$ choice.

IV. CONCLUSIONS

Our aim was to find an observable effect of the nucleon effective mass splitting, which is determined by the momentum dependence of the symmetry potential. We performed some BNV simulations for reactions of interest at the new radioactive beam facilities. From our results it appears that the isospin content of pre-equilibrium emitted nucleons at high transverse momentum can be a good observable in order to solve the mass-splitting puzzle.

- [1] V.Baran, M.Colonna, V.Greco, M.Di Toro, Physics Reports 410 (2005) 335-466.
- [2] J.Rizzo, M.Colonna, M.Di Toro, V.Greco, Nucl.Phys. A732 (2004) 202.
- [3] B.-A. Li, Phys.Rev. C69 (2004) 064602.
- [4] C.Gale, G.F.Bertsch, S.Das Gupta, Phys.Rev. C41 (1990) 1545.
- [5] V.Greco, Diploma Thesis (1997);
V.Greco, A.Guarnera, M.Colonna, M.Di Toro, Phys.Rev. C59 (1999) 810.
Nuovo Cimento A111 (1998) 865.
- [6] *Isospin Physics in Heavy-ion Collisions at Intermediate Energies*, Eds. Bao-An Li and W. Udo Schröder, Nova Science Publishers (2001, New York).
- [7] I.Bombaci, "EOS for isospin-asymmetric nuclear matter

- for astrophysical applications", in [6] pp. 35-81 and refs. therein.
- [8] E.Chabanat, P.Bonche, P.Haensel, J.Meyer, R.Schaeffer, Nucl.Phys. A627 (1997) 710.
- [9] E.Chabanat, P.Bonche, P.Haensel, J.Meyer, R.Schaeffer, Nucl.Phys. A635 (1998) 231.
- [10] A.M.Lane, Nucl.Phys. 35 (1962) 676.
- [11] M.Di Toro, M.Colonna, J.Rizzo, arXiv: nucl-th/0505013
- [12] V.Baran, M.Colonna, M.Di Toro, V.Greco, M.Zielinska-Pfabé, H.H.Wolter, Nucl.Phys. A703 (2002) 603.
- [13] L.-W.Chen, V.Greco, C.M.Ko, B.-A.Li, Phys.Rev. C68 (2003) 014605.
- [14] B.-A.Li, C.B.Das, S.Das Gupta, C.Gale, Nucl.Phys. A735 (2004) 563.

Isospin splitting of the nucleon mean field

L.G. Cao^a, B.A. Li^b, U. Lombardo^a, C.W. Shen^a, W. Zuo^c

a) INFN Laboratori Nazionali del Sud, Catania, Italy

b) Department of Chemistry and Physics (AR), USA

c) Institute of Modern Physics (Lanzhou), China

Abstract

The isospin splitting of the nucleon mean field is derived from the Brueckner theory extended to asymmetric nuclear matter. The Argonne V18 has been adopted as bare interaction in combination with a microscopic three body force. The isospin splitting of the effective mass is determined from the Brueckner-Hartree-Fock self-energy: It is linear according to the Lane ansatz and such that $m_n^* > m_p^*$ for neutron-rich matter. The symmetry potential is also determined and a comparison is made with the predictions of the Dirac-Brueckner approach and the phenomenological interactions. The theoretical predictions are also compared with the empirical parametrizations of neutron and proton optical-model potentials based on the experimental nucleon-nucleus scattering and the phenomenological ones adopted in transport-model simulations of heavy-ion collisions. The direct contribution of the rearrangement term due to three-body forces to the single particle potential and symmetry potential is discussed.

The purpose of this study is to determine the isospin properties of the optical potential in the framework of the Brueckner theory. This enables us to range the density domain of optical potential from the saturation density for application to nucleon-nucleus scattering up to high density for application in HIC. The theoretical quantity which incorporates all single particle properties, including the nuclear potential, is the self-energy.

In the BHF approximation it is given by three terms:

$$\Sigma(k, \varepsilon) = \Sigma_{bhf} + \Sigma_{cpol} + \Sigma_{tbf} \quad (1)$$

where the first term is the HF potential with the G-matrix as the effective interaction, the second term is due to the core polarization [1] and the third term stems from the density dependence of the effective force $\tilde{v}$, i.e., the TBF rearrangement term $\tilde{v}$ [2]. The first two terms in the BHF approximation in asymmetric nuclear matter have been discussed elsewhere [3]. In general, the TBF effect on the selfenergy within the BHF framework is twofold. First, it affects the selfenergy via the modification of the G-matrix. This effect has been embodied in the BHF selfenergy, i.e., the first two terms in Eq. (1). Second, the density dependence of $\tilde{v}$ will induce an additional contribution, i.e., a rearrangement contribution to the selfenergy (third term in Eq.(1)). The main contribution of the TBF rearrangement can be formally written in the BHF approximation

$$\Sigma_{tbf} = \frac{1}{2} \sum_{ij} \left\langle ij \left| \frac{\delta \tilde{v}}{\delta n_k} \right| ij \right\rangle_A n_i n_j \quad (2)$$

where n_i is the Fermi step function.

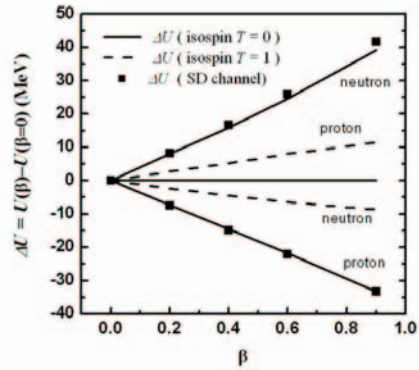


Fig.1 Isospin splitting the proton and neutron s.p. potentials at $k=0$: isospin $T=0$ (solid curves) channels, $T=1$ (dashed curves) channels, SD tensor channel (squares).

Fig.1 displays the main features of the on-shell self-energy, whose physical meaning is that of nuclear potential U . The isospin shift of U is plotted at zero momentum. The results show that the isospin $T=0$ component gives the largest contribution and it comes mostly from the tensor SD force.

The effective mass is also an important quantity extracted by the self-energy, since it governs the transport properties in nuclear dynamics. The isospin splitting of the effective mass is a matter of controversy, since some Skyrme forces and also some Dirac-Brueckner calculations predict that the proton effective mass is increasing with isospin and the neutron one is decreasing at variance with the Brueckner calculations [3] and other Dirac-Brueckner calculations [6,7]. In Fig. 2 we plot the new Brueckner results including the

effects of the three body force. The latter confirm the previous isospin trend. A discussion of the physical justification for such trend is reported in Ref. [8]

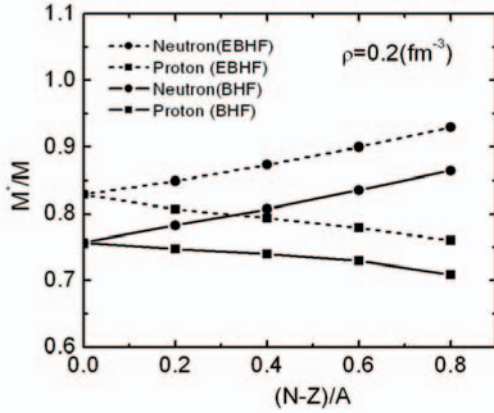


Fig.2 Isospin splitting of the effective mass from a Brueckner calculation with three-body force.

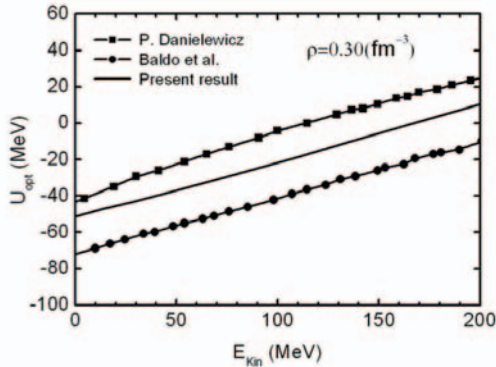


Fig.3 Optical potential in nuclear matter as a function of nucleon energy at density $\rho = 0.3 \text{ fm}^{-3}$ from the BHF calculation including all the three terms of Eq.(1) with the Argonne V_{18} interaction plus TBF (solid line). The squares are from Ref.[4]. The circles are from the earlier BHF calculation without three-body force[5].

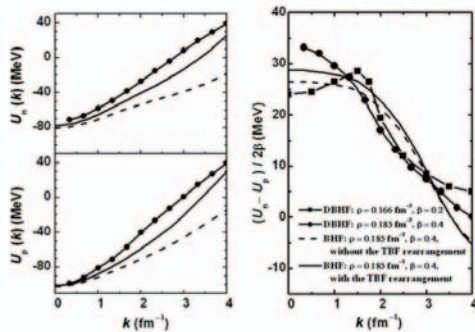


Fig.4 Comparison of the BHF symmetry potential with and without the Σ_{tbf} contribution with Dirac-Brueckner predictions. The curve with full circles is from Ref.[6], the one with full squares is from Ref.[7], where also the optical-model potential for nucleon-nucleus scattering is discussed. Here we just report the effects of three body force (third term of Eq.(1)) which seem to give a sizeable contribution to the optical potential and to have some relevance for the collective flows of HIC.

The results are depicted in Fig.3 and Fig.4, along with other predictions.

REFERENCES

- [1] J.P. Jeukenne, A. Lejeune and C. Mahaux, Phys. Rep.25, 83 (1976).
- [2] P. Ring, and P. Schuck, The Nuclear Many-Body Problem,(Springer-Verlag, New York, 1980).
- [3] W. Zuo, I. Bombaci, and U. Lombardo, Phys. Rev. C60, 024605 (1999).
- [4] P. Danielewicz, Nucl. Phys. A 673, 375 (2000).
- [5] M. Baldo, I. Bombaci, G. Giansiracusa, and U. Lombardo, Phys. Rev. C 40, R491 (1989).
- [6] E.N.E. van Dalen, C. Fuchs and A. Faessler, Nucl. Phys. A 744, 227 (2004).
- [7] D. Alonso and F. Sammarruca Phys. Rev. C67, 054301 (2003).
- [8] W. Zuo, L.G. Cao, B.A. Li, U. Lombardo and C.W. Shen, Phys. Rev. C, in press.

NUCLEAR MATTER PHASE TRANSITION IN INFINITE AND FINITE SYSTEMS

S.Terranova^{a,*}, A.Bonaserà^{a,*}

a) INFN Laboratori Nazionali del Sud, Catania, Italy

* Corresponding author, e-mail: terranova@lns.infn.it, bonaserà@lns.infn.it

Abstract

A new "semiclassical" approach (CoMD) based on the molecular dynamics simulation of the quarks is proposed. With a suitable choice of the quark masses, some possible Equation of State (EOS) of the nuclear matter, at temperature equal to zero and finite baryon density, are obtained. These EOS, not only present the Quark-Gluon Plasma (QGP) phase transition, but also the existence of a new state, the Exotic Color Clustering (ECC) state, in which cluster of quarks with the same color are formed. The phase transition is studied through the definition of some new quantities: three order parameters, M_{c2}, M_{c3}, M_{c4} and the lifetime of the J/Ψ particle. The behavior of the J/Ψ particle is studied also in the "finite" systems, obtained by expanding the corresponding "infinite" systems. It seems that the dynamics and the finite size effects do not wash completely the phase transition occurred in infinite systems, and the J/Ψ particle is still a good signature.

This is the *Constrained Molecular Dynamics (CoMD)* [3].

1 CONSTRAINED MOLECULAR DYNAMICS (COMD)

In the phase space, the dynamics of the quarks is solved classically through the evolution of the distribution function $f(r,p,t)$:

$$\partial_t f + \frac{\vec{p}}{E} \cdot \vec{\nabla}_r f - \vec{\nabla}_r U \cdot \vec{\nabla}_p f = 0 \quad (1)$$

where E is the total energy of each quark and m_q is the (u,d) quark mass. The colored quarks interact through the Richardson potential [1].

Numerically the Eq.1 is solved by writing the one body distribution function for each particle i through the delta function [2].

At the initial condition, the quarks are randomly distributed in a box of side L in coordinate space and in a sphere of radius p_f (Fermi momentum) in the momentum space. The Fermi momentum is related to the density of the colored quarks ρ_{qc} by the following expression:

$$\rho_{qc} = \frac{g_q}{3\pi^2} p_f^3, \quad (2)$$

$g_q = n_f \cdot n_c \cdot n_s$ is the degeneracy number. The Pauli blocking implies that each cell in the phase space of size $h=2\pi$, can accommodate at most g_q identical quarks.

To simulate an "infinite system", periodic boundary condition are imposed and many events are generated.

The Pauli blocking implies that the *Occupation Average*, which is the probability that a cell in the phase space is occupied, must be less or equal to 1. In order to verify this condition the momenta of the particles are multiplied for a quantity ξ , i.e. $\mathbf{p}_i = \mathbf{p}_i \cdot \xi$, in particular if $\bar{f}_i$ is greater than 1, then ξ will be greater than 1; if $\bar{f}_i$ is less than 1, then ξ will be less than 1.

2 THE ORDER PARAMETERS

The study of the nuclear matter phase transition from confined hadronic matter to Quark-Gluon Plasma needs some unambiguous quantity able to check if the transition is happened or not. One of this quantity is the order parameter M_c which relates the colors of closest interacting quarks. In particular three different order parameters are defined: M_{c2}, M_{c3}, M_{c4} , the first is related to the color of two closest quark, the second to the color of three closest quarks and the last to the color of four closest quarks. The color matrices $\lambda^{3,8}$ allow to define the order parameters [2,4] normalized in this way:

$$\begin{aligned} \tilde{M}_{c2} &= \frac{2}{3} [M_{c2} + 1]; \quad \tilde{M}_{c3} = \frac{2}{9} [M_{c3} + 3]; \\ \tilde{M}_{c4} &= \frac{2}{15} [M_{c4} + 6] \end{aligned} \quad (3)$$

The order parameters can assume different values which characterize different states of the nuclear matter.

If the three closest quarks have different colors (nucleonic state) then $\tilde{M}_{c2} = \tilde{M}_{c3} = \tilde{M}_{c4} = 1$. This case is recovered in the calculation at small densities, where the system is "locally" invariant for rotation in color space.

If the four closest quarks have the same color $\tilde{M}_{c2} = \tilde{M}_{c3} = \tilde{M}_{c4} = 0$, a new state of the nuclear matter, dubbed *Exotic Color Clustering* materializes. The system is "locally" invariant for rotation in color space.

If the three closest quarks have two different colors, the Quark Gluon Plasma state is reached, $\tilde{M}_{c2} = \tilde{M}_{c3} = 2/3$, $\tilde{M}_{c4}$ can assume three different values: 4/5; 1; 3/5, according to the colors of the four closest quarks and to the number of pairs of different color

which are created. In the Quark-Gluon Plasma case the system is "globally" invariant for rotation in color space.

3 J/Ψ LIFETIME

In the high-energy nucleus-nucleus collisions, some J/Ψ particles are produced. Many experimental results seem to suggest that if the Quark-Gluon Plasma state is formed the multiplicity of the revealed J/Ψ particles reduces. Hence the lifetime of the J/Ψ particle in a quark system can give information on the occurrence or not of the QGP phase transition.

Practically, in the code, when the system of quarks reaches the equilibrium condition, a pair of bound $c\bar{c}$ quarks, with mass equal to 1.37 GeV, is embedded in the system. The presence of other light quarks in the system weakens and consequently breaks the bond between $c\bar{c}$ quarks.

The lifetime of the J/Ψ particle in the medium is calculated through its survival probability in the system. The survival probability, P_{sur} is calculated by counting the total number of pairs $c\bar{c}$ that stay bound after they are inserted in the system of u and d quarks. The obtained distribution is fitted by the following expression, similar to the fission [5]:

$$P_{sur}(t) = \exp[-(t-t_D)/\tau] \quad (4)$$

where t_D is the delay time, i.e. the time after which the exponential decrease starts happening, and τ is the lifetime of the J/Ψ in the system. Hence the survival time t_{sur} of the J/Ψ particle in the quark matter will be:

$$t_{sur} = t_D + \tau \quad (5)$$

4 RESULTS FOR INFINITE SYSTEMS

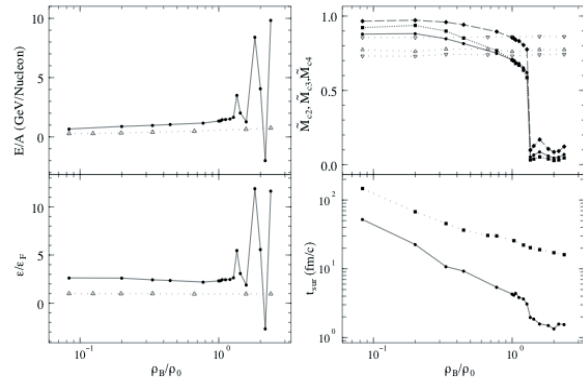
When quarks of different colors, are embedded in a dense medium, such as in the nuclear matter, the interaction between them becomes screened, *Debye Screening*.

The screening in a quarks system can be obtained "directly", as the potential includes the color charges (Gell-Mann matrices). Moreover, because the considered system is not really an infinite system, as instead the nuclear matter is, the screening is not worth enough to avoid the divergence of the linear potential for $r \rightarrow \infty$. A cut-off is introduced: when quark distances are greater than the cut-off, the interaction is equal to zero. The cut-off is a free parameter, which is fixed, with the other free parameters (Λ , and the quark

masses). The Λ value is fixed at 0.25 GeV for all cases.

Fig. 1 shows the results obtained by choosing: $m_u = 0.005$ GeV, $m_d = 0.01$ GeV and the cut-off equal to 3fm.

The energy per nucleon and the corresponding energy density in units of the ϵ_F (energy density for a Fermi gas) (panels in the left) have a very irregular behavior already at small density. The three order parameters (top panel in the right) allow to better explain it: for small densities the quarks are condensed in clusters of three different colors, the system is locally white (isolated white nucleon): $M_{c2}(\text{circles}) \approx M_{c3}(\text{squares}) \approx$



$M_{c4}(\text{diamonds}) \approx 1$. At higher densities, the quarks are not in clusters but randomly distributed, $M_{c2} \approx M_{c3} \approx 2/3$ and $M_{c4} \approx 4/5$.

Figure 1: Energy per nucleon (top panel in the left), energy density (bottom panel in the left), normalized order parameters (top panel in the right) and time survival of J/Ψ (bottom panel in the right) versus density divided by the normal density ρ_0 , for $m_u = 5$ MeV, $m_d = 10$ MeV and cut-off = 3 fm.

The system reaches the QGP phase at $\rho_B/\rho_0 \approx 1.2$ but it does not remain in this state as it prefers the ECC state, where at least the four closest quarks have the same color. In fact, at density about $1.4 \div 2.4\rho_0$ $M_{c2} \approx M_{c3} \approx M_{c4} \approx 0$. The system reaches this state through a first order phase transition at about $1.3\rho_0$.

In the energy per nucleon figure, the transition is demonstrated by a discontinuity at the same density. The other discontinuities, at larger densities $\rho_B/\rho_0 > 1.5$, are probably due to the clusterization of more than four quarks of the same color. The definition of further order parameters, which relate more than four closest quarks, could explain these irregularities.

The calculations have been repeated with the Coulomb term only, (triangles in Fig.1); a constant contribution has been obtained, not only to the energy,

but also to the order parameters. This means that the Coulomb term produces a permanent clusterization among quarks which prevents them to reach the ideal QGP state. When the linear term is included, it prevails over the Coulomb term and the system stays in ECC state.

The lifetime t_{sur} of the J/Ψ particle versus baryon density is plotted in the bottom part (right) of the Fig.1, where dotted line represents the time distribution obtained by the code and full line is obtained through Eq. 5.

When the density increases, the J/Ψ lifetime decreases because it is more probable that a light quark u, d gets in between a $c\bar{c}$ pair and breaks the bond. t_{sur} behaves like an order parameter, in fact it has a jump just where there is the phase transition $\rho_B/\rho_0 \approx 1.3$ and after there is a saturation of the surviving probability. In the same figure, the behavior of J/Ψ particle in the medium is analyzed by turning off the interaction (squares). Here one observes only a monotonic decrease with the density. The survival time of the J/Ψ in the medium without the interaction is always larger than the survival time calculated with the interaction; in fact, the forces between quarks lead to the Debye screening and break more easily the bonds between particles ($c\bar{c}$ quarks).

It is clear that the cut-off value changes the transition point as a consequence. In Fig.2 the reduced order parameters versus cut-off are plotted (left panel). The quark masses are $m_u = 0.005$ GeV, $m_d = 0.01$ GeV and $\rho_B = \rho_0$.

The system is in a nucleonic state for small cut-off values, crosses a Quark-Gluon Plasma region and finally reaches the Exotic Color Clustering state. The phase transition from QGP to ECC state happens at $\rho_B = \rho_0$ if the cut-off values is larger or equal to 3.1 fm; while in Fig.1 the transition was at $\rho_B = 1.3\rho_0$. This means that the critical density of the ECC phase transition increases for decreasing cut-off values.

Nevertheless, it is interesting to verify if quark system moves to the Exotic Color Clustering state also for higher quark masses.

Fig.2 (right panel) shows the three reduced order parameters versus quark masses when the cut-off is equal to 1.26 fm. The reduced order parameters are almost constant; hence the cut-off is the main responsible of the nuclear matter phase transition.

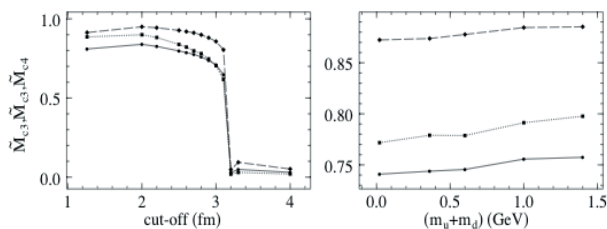


Figure 2: Reduced order parameters vs cut-off(left panel) and vs quark masses(right panel).

In order to study the sensitivity of the results to the input parameters, other calculations have been repeated changing not only the cut-off values, but also the quark masses.

The results are presented in [2]. The results show that the first order phase transition to Exotic Color Clustering can disappear or that also a QGP phase transition can appear.

4 RESULTS FOR FINITE SYSTEMS

A finite system of quarks can be considered as an infinite system without periodic boundary conditions. When boundary conditions are excluded, the systems expands and cause of the confinement, (kr term in the Richardson potential), the quarks clusterize in nucleons. During the expansion the total energy per particle is preserved. The dynamic and the finite size effects might wash out completely or hide the phase transition present in the corresponding infinite system.

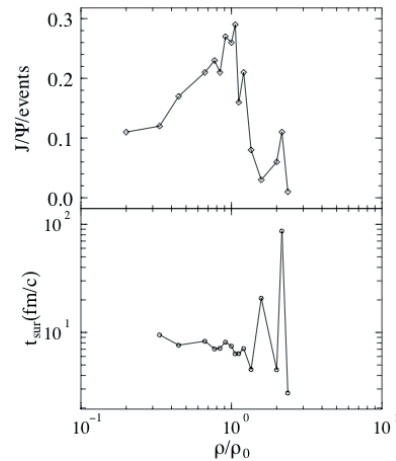


Figure 3: Number of survival J/Ψ (left panel) and J/Ψ lifetime(right panel) vs density.

The behavior of the J/Ψ particle in an expanding system can offer many information on the phase transition. While in an infinite quark system the J/Ψ particle sooner or later will dissolve, in a rapidly expanding system the dissolution might not occur. Fig.3 shows the results of a finite system. They have been obtained by expanding the infinite systems previously discussed ($m_u=0.005$ GeV, $m_d=0.01$ GeV).

The number of survival J/Ψ (left panel) increases with the density up to $\rho \approx \rho_0$, after it seems to have a jump, at the same density in which a first order phase transition has been obtained for the corresponding infinite system, Fig.1.

At low density, the Fermi momentum of the light quarks is small, each J/Ψ particle stays "imprisoned" in a piece of nuclear matter and it will disappear. Instead when the density increases the system of light quarks expands faster and the slow $c\bar{c}$ quarks stay bond.

The lifetime of J/Ψ versus the baryon density, obtained through the Eq.5 is shown in the right panel, it has a plateau up to the critical density, and after shows some discontinuities.

4 CONCLUSION

In conclusion, the Constrained Molecular Dynamics simulation is able to describe some aspects of the nuclear matter system, at zero temperature and finite baryon density. In particular a new state of the nuclear matter appears, the Exotic Color Clustering state, where at least the four closest quarks have the same color. The three reduced order parameters and the J/Ψ lifetime can be considered a "good indicators" of the phase transition. The J/Ψ particle, also in finite system, seems to be a suitable physical observable. Hence, finite size effects and the dynamic of the expansion do not cancel the phase transition.

5 REFERENCES

- [1] J. L. Richardson, Phys.Lett. 82B (1979)272.
- [2] S.Terranova, A. Bonasera, Phys. Rev.C 70 (2004).
- [3] M. Papa et al., Phys. Rev.C64 (2001).
- [4] A. Bonasera, Phys. Rev.C62 (2000).
- [5] T. Maruyama et al., Eur. Phys. A 14 (2002) 191.

RELATIVISTIC BOLTZMANN METHOD FOR p-p AND Au-Au COLLISIONS

D.Zhou^{a,*}, S.Terranova^{b,+}, A.Bonasera^{b,+}

a) Institute of Particle Physics, Huazhong Normal University, Wuhan, 430079 China

b) INFN Laboratori Nazionali del Sud, Catania, Italy

** Corresponding author, e-mail: zdm@iopp.ccnu.edu.cn*

+ Corresponding author, e-mail: Terranova@lns.infn.it , Bonasera@lns.infn.it

Abstract

A new method of solution of the semiclassical transport equation for ultra-relativistic nucleus-nucleus collisions is proposed. The method (ReB) is based on the mean free path approach and on a collision probability; it is manifestly Lorentz invariant. The results which are depending on a “hadronization time”, for p-p and Au-Au collisions will be discussed and compared to data.

1 INTRODUCTION

Relativistic heavy ion collisions (RHIC) offer the possibility to explore the different states of the Nuclear Matter (NM), in particular Quark-Gluon Plasma (QGP) phase transition. The purpose of this paper is to propose a new method of solution the semiclassical transport equation which should describe the many body part of the process. The method, “*Relativistic Boltzmann method (ReB)*” [1], is based on the concept of the *mean free path approach* and on a *collision probability*. The same method has been applied to low energy heavy ion collisions [2], to solve the Boltzmann equation in the case where an analytical solution is known. Here relativistic effects are kept into account.

The hadronic interactions and the space-time evolution of the collisions are described through the Parton Cascade Model (PCM). Three different phases of the collision can be distinguished: 1- Initial state; 2- Parton cascade development; 3- Hadronization [3].

The parton initial state is generated by using the JPCIAE multiple mini-jet generator [4], it is based on PYTHIA event generator for hadron-hadron collision. The partonic system is hadronized by JETSET.

An important ingredient of the approach is the *hadronization time (ht)*, which is the time it takes for partons, created after a collision, to coalesce and form the new hadrons. Any finite *ht* value will reduce secondary hadron-hadron collisions. This is a very important effect because it suggests that it is possible to have a finite hot region of quarks and gluons (QGP) which will not coalesce into hadrons for a *ht* time boosted to the nucleus-nucleus CM frame.

It is important to stress here that collisions at the parton level do not occur.

2 REB METHOD

The mean free path method [1] consists to search for each event, for each ion *i*, at each time step *dt*, the closest ion *j(i)* in the phase space, this is obtained by defining the quantity:

$$\Xi_{ij} = \frac{r_{ij}}{v_{ij} dt} \quad (1)$$

where r_{ij} is the relative distance and v_{ij} is the relative velocity (relativistic) of two closest particles and *dt* is the time step used in the calculations. This means that two particles have to be close in the coordinate space and far away in the momentum space (opposite momenta).

Consequently the collision probability is defined:

$$\Pi = \frac{v_{ij} dt}{\lambda} = \sigma \rho(r_i) v_{ij} dt \quad (2)$$

where $\rho(r_i)$ is the local density calculated at each time step and σ is the elementary cross section of two colliding particles.

Note that the quantities defined above are scalars and it is quite easy to show that they are Lorentz invariant.

A random number is taken and if it is smaller than the calculated probability, a collision occurs and it is modeled by Pythia, if $\sqrt{s} > 4\text{GeV}$.

Because of the probabilistic nature of the process discussed above it can happen that particles which are very close in the phase space do not collide, and for small densities a collision can occur with a small probability.

The time step is chosen such that the probability is always small compared to 1 and to minimize the CPU time. Once these conditions are fulfilled a further decrease of the time step *dt* will not change the results but will increase linearly the CPU time.

3 P-P COLLISIONS

In p-p collisions the essential parameters which enter the calculations will be fixed to fit experimental data and after they will be used in Au-Au collisions. The colliding partners are chosen as discussed in the previous section (collision probability).

Depending on their relative energy the collision can be elastic or inelastic. If it is inelastic, the number of produced partons and their energies and momenta are decided using PYTHIA. The partons are randomly distributed in a sphere whose diameter is given by the original positions of the colliding hadrons. The partons are evolved on straight line trajectories and they cannot collide before the ht . In this time the partons hadronize and then the formed hadrons can collide again.

In Fig.1 the pseudorapidity distribution of particles multiplicity in p-p collisions at 200 GeV is plotted, results from ReB calculations are compared to data (full circles) [5] for various set parameters entering PYTHIA. The results are obtained at zero impact parameter, at zero hadronization time, this means that at each collision the produced particles are hadronized instantaneously.

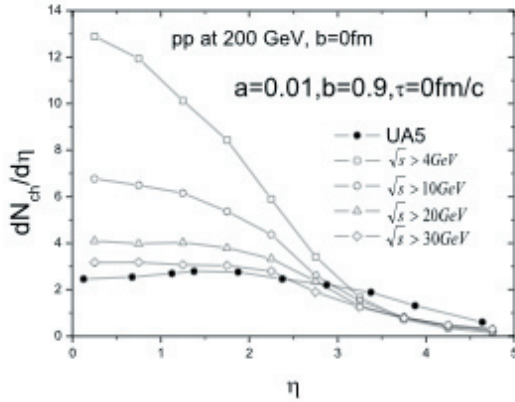


Figure 1: Particles production versus pseudorapidity in p-p collisions at 200 GeV C.M. energy, zero impact parameter and zero hadronization time.

In order to improve the agreement to data the low energy cutoff for PYTHIA has to be increased up to 30 GeV. Notice however that to increase the energy cutoffs means to suppress the inelastic secondary collisions occurring at later times. Moreover it is possible to obtain the same effect by increasing the hadronization time how it is shown in Fig.2

Different ht values are displayed in the figure together with the set of PYTHIA adjusted parameters. Only finite values of ht fit the p-p data.

Notice also that the results of the fits are not so dependent on the ht if it is larger than 0.1 fm/c. In fact because of the Lorentz time dilatation the hadronization does not occur before the system has expanded thus suppressing secondary collisions.

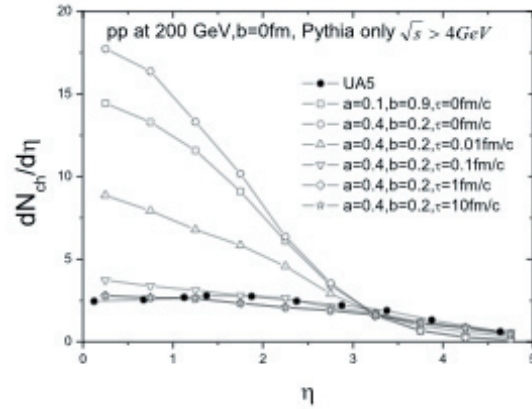


Figure 2: Particles production versus pseudorapidity in p-p collisions at 200 GeV C.M. energy for different hadronization times.

4 NUCLEUS-NUCLEUS COLLISIONS

If, with the same PYTHIA parameters and zero ht , Au-Au collisions at $\sqrt{s} = 200 \text{ GeV}$ are considered, the results are not so good, how it is shown in Fig.3.

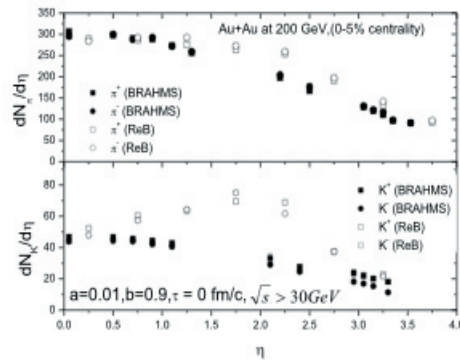


Figure 3: Particles production versus pseudorapidity in Au-Au collisions at 200 GeV CM energy for central collisions. Data for charged pions (top panel) and charged kaons (bottom panel), experimental data (full symbols) are included.

The results of calculations (open symbols), compared with experimental data (full symbols) [6] are largely overestimated especially for kaons.

The calculations have been repeated with different values of the hadronization time Fig.4, in particular in the first panel ht is equal to $\hbar/2m$ fm/c, where m is the masses of the forming hadron. In the second panel ht is equal to 1 fm/c and in the last panel ht is equal to 100 fm/c. The discrepancy with the data is striking at low pseudorapidity values especially for kaons.

However a finite ht or a large cutoff in the energy in Au-Au collision does not have the same effect that they have in p-p collision.

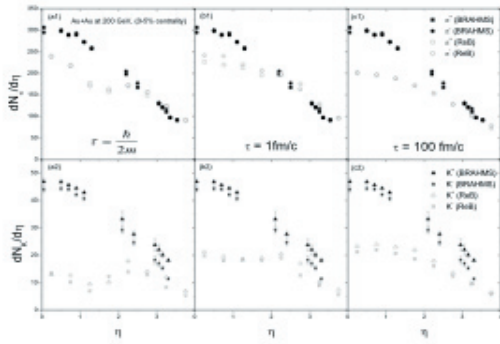


Figure 4: Particles production versus pseudorapidity in Au-Au collisions at 200 GeV C.M. energy for different hadronization times.

Therefore, as in the zero ht case the low energy cutoff was responsible for decreasing the low η yield, it could be that the 4 GeV cutoff in PYTHIA is responsible as well for the bad reproduction of the data for lower η .

By implementing a new subroutine with a parametrization of elementary collisions data for energies below 4 GeV and above the energy for pion production new results for finite ht have been obtained.

They are plotted in Fig.5 for ht equal to $\hbar/2m$ fm/c and in Fig.6 for ht equal to 1 fm/c.

Obviously the PYTHIA parameters have been fixed before to fit p-p data.

The agreement to data is now better both for pions and kaons production, even though the data are overestimated at small η .

The way these results have been obtained suggests that low η particles are produced from hadron-hadron collisions at lower energies and later times, i.e. at the final stages of the reaction.

It is obvious to think now that if these particles are created at such late times, they might not carry any relevant information about the QGP.

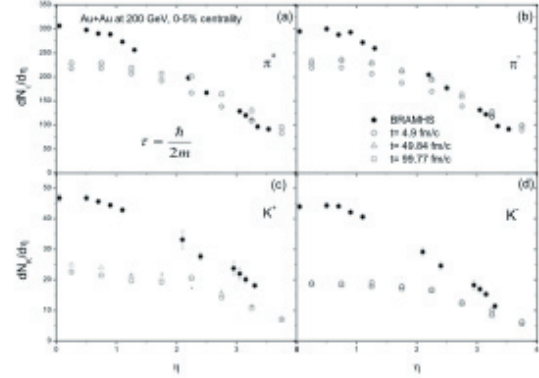


Figure 5: Particles production versus pseudorapidity in Au-Au collisions at 200 GeV C.M. energy at different times for proper formation time equal to $\hbar/2m$ fm/c.

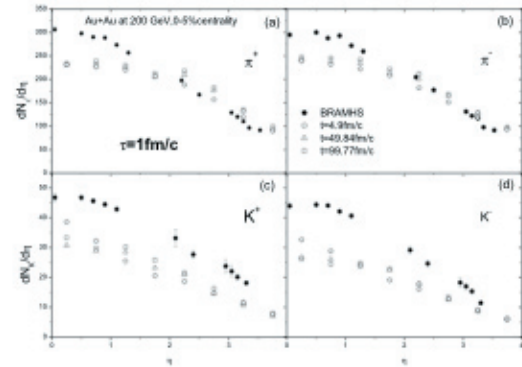


Figure 6: Particles production versus pseudorapidity in Au-Au collisions at 200 GeV C.M. energy at different times for formation time equal to 1 fm/c.

5 CONCLUSIONS

In this work a new transport approach to relativistic heavy ion collisions has been introduced. Elementary collisions are chosen following a mean free path method already developed at low energies. The elementary processes are dealt within the PYTHIA approach. The low energies (below 4 GeV C.M.) elementary collisions have been implemented as well. Within this model we have shown that a purely hadronic approach fails in

reproducing nucleus-nucleus data and can reproduce the p-p data with a large energy cutoff in the elementary inelastic collisions or a finite hadronization time. Further a careful inclusion of all possible inelastic channels down to the pion threshold production gives a good description of pseudorapidity distributions both in p-p and Au-Au data. The possibility of a finite hadronization time hints to the formation of a mixed QGP and hadronic state after kinetic equilibrium has been reached. The comparison with experimental data in this paper has been restricted to the highest available energy at RHIC. The future plan is to extend the calculations with the present model to other observables and different energies. Collective flow calculations are also of interest. One of the main interests is to find new physical observables able to indicate a phase transition to the QGP. For this reason the code could be accomplished with a Constrained Molecular Model (CoMD) for quarks degree of freedom recently developed [7].

6 REFERENCES

- [1] ArXiv :nucl-th/0501083 v1 (31 Jan-2005) .
- [2] A. Bonasera et al., Phys. Rep. (1994) 243.
- [3] K. Geiger, Phys. Rep. (1995) 258, 237.
- [4] Ben-Hao Sa et al., Phys. Rev. C 59 (1999) 2728.
- [5] G. J. Alner, et al., UA5 Collaboration, Z. Phys. C - Particles and Field 33, (1986) 1-6.
- [6] I. G. Bearden, et al., BRAHMS Collaboration, nucl-ex/040350.
- [7] S.Terranova, A. Bonasera, Phys. Rev.C 70 (2004).

CONSTRAINED MOLECULAR DYNAMICS SIMULATIONS OF ATOMIC GROUND-STATES

S.Kimura*, and A.Bonasera

INFN Laboratori Nazionali del Sud, Catania, Italy

* Corresponding author, e-mail: kimura@lns.infn.it

Abstract

The Constrained molecular dynamics (CoMD) model, previously introduced for nuclear dynamics, has been extended to the atomic structure and collision calculations. Quantum effects, corresponding to the Pauli and Heisenberg principles, are enforced by constraints, following the idea of the Lagrange multiplier method. Our calculations for small atomic system, H, He, Li, Be, F reproduce the ground state binding energies reasonably, compared with the experimental data. We discuss also the shell splitting due to e-e correlation.

1 INTRODUCTION

Molecular dynamics is a powerful tool to simulate nuclear heavy ion collisions and atomic collisions, due to its simplicity and ability to take into account the influence of correlations and fluctuations. However, as it is seen in the case of the classical trajectory Monte Carlo method, truly classical atoms, without constraints due to the Heisenberg and Pauli principles, are unstable. To describe the ground-state properties of the systems with molecular dynamics, the pseudo potential is often introduced to simulate the effects of the Heisenberg uncertainty and the Pauli exclusion principles. The method with pseudo potential is known as Fermionic molecular dynamics (FMD) and it is applied to the studies of various atomic processes, in which a fully quantum mechanical dynamical simulation encounters numerical problems difficult to overcome.

Meanwhile, a constrained molecular dynamics (CoMD) approach has been proposed to treat fermionic properties of the nucleons in nuclei [1]. The approach has been successfully applied to study the Equation of State of the quark system as well [2]. In this approach, the Pauli exclusion principle is accomplished by restricting the phase space occupancy f_i to values less or equal to 1. Here, the equation of motion with the constraints for each electron is derived using the Lagrange multiplier method. The constraint of the CoMD approach is proposed as an alternative to the pseudo potential and can be easily extended to the case of the Heisenberg principle as well. The constraints play the role of a “dissipative term” in the classical equation of motion and lead the system to its ground-state. But in the CoMD, at variance with the FMD approach, the “dissipative term” can increase or decrease the energy of the system depending on the phase space occupation.

In this brief report, we apply the CoMD to atomic systems for the purpose of determining their ground-states configurations. Particularly, we discuss some

properties of ground-states atoms, i.e., binding energies (the total electronic energies) of the bound electrons. We discuss also the energy spread (variance of the binding energy) as well. In our approach, we prepare ensembles of initial configurations. The binding energies of the electrons in the systems are calculated as average values over the ensembles. Our approach is sufficient to obtain stable atomic ground-states providing their atomic energies fairly accurately. Using the obtained ensembles of initial states which occupy different points in the phase space, molecular dynamics simulations with constraints for the atomic collision has been performed and applied to nuclear fusion enhancement factor calculations of the reactions $D+d$, $D+D$, ${}^3\text{He}+d$, ${}^3\text{He}+D$, ${}^6\text{Li}+d$, ${}^6\text{Li}+D$ for astrophysical interests [3].

2 FORMARISM

We describe the essence of the CoMD briefly. In classical molecular dynamics (CMD) one solves the Hamilton equations, i.e:

$$\frac{dr_i}{dt} = \frac{p_i c^2}{\varepsilon_i}; \quad \frac{dp_i}{dt} = -\nabla_r U(r) \quad (1)$$

Where we use relativistic kinematics:

$\varepsilon_i = \sqrt{p_i^2 c^2 + m_e^2 c^4}$, m_e and $U(r_i)$ are the energy, the mass and the potential of the i -th electron, respectively. The total Hamiltonian is written down as

$$H(r; p) = \sum_{i=1}^N (\varepsilon_i + U(r_i) - m_e c^2)$$

The shortcoming of the CMD approach is the lack of the Pauli exclusion principle. In quantum mechanics the Pauli principle requires that the overall wave function of electrons in an atom should be antisymmetric for the exchange of two identical electrons. If two electrons

have the same spin quantum number, the spatial part of the overall wave function should be antisymmetric and vanishes in case where the two electrons occupy the same position in the phase space. Semiclassically, this implies that the occupation probability f_i of two identical electrons should be always less equal 1. It can be expressed in terms of the distance of two particles in the phase space, i.e., $r_{ij} p_{ij}$ where $r_{ij} = |r_i - r_j|$ and $p_{ij} = |p_i - p_j|$. The relation $f_i \leq 1$ is fulfilled, if $r_{ij} p_{ij} \geq \xi_P \hbar \delta_{S_i S_j}$. Here $\xi_P = 2\pi \left(\frac{3}{4\pi}\right)^{2/3} 2^{1/3}$, i, j refer only to electrons and $S_i, S_j (= \pm 1/2)$ are their spin projection [11, 13]. We cast the relation $r_{ij} p_{ij} \geq \xi_P \hbar \delta_{S_i S_j}$ into the constraint of the Lagrange multiplier method. We can easily extend the approach to the Heisenberg principle where the constraint is expressed as $r_{ij} p_{ij} \geq \hbar$, where i, j refer to the electron and the nucleus, respectively. Note that the path integral of the relation $r_{ij} p_{ij} = \hbar$ is known as the semi classical quantization condition [2].

The Variational calculus of Lagrangian with these constraints leads to

$$\frac{dr_i}{dt} = \frac{p_i c^2}{\varepsilon_i} + \frac{1}{\hbar} \sum_{j(i)} \left(\frac{\lambda_i^H}{\xi_H} + \frac{\lambda_i^P}{\xi_P} \delta_{S_i S_j} \right) r_{ij} \nabla_{p_i} p_{ij} \quad (2)$$

$$\frac{dp_i}{dt} = -\nabla_r U(r) - \frac{1}{\hbar} \sum_{j(i)} \left(\frac{\lambda_i^H}{\xi_H} + \frac{\lambda_i^P}{\xi_P} \delta_{S_i S_j} \right) p_{ij} \nabla_{r_i} r_{ij} \quad (3)$$

In order to obtain the atomic ground-state configuration, we perform the time integration of the eqs. (2) and (3). If $r_{ij} p_{ij}$ is smaller (larger) than $\xi \hbar$, λ has positive (negative) sign, changing the phase space occupancy of the system. The constraints work as the “dissipative term” in the case of the pseudo potential approach and lead automatically to the minimum energy.

3 RESULTS

	CoMD	experimental
H	13.3±1.8	13.6
He	79.1±6.9	79.1
Li	196.8±15.	203.6
Be	371.2±27.	399.4
F	2560.3±192.	2717.4

TABLE I: Summary of the binding energies (in eV) of calculated systems. The binding energies with the CoMD including error bars with experimental values [5] are shown for each atom.

In Table I together with the ground-state energies from our method, experimental values [5] are shown. Since we determine the binding energies as an average of many events, our results have a variance. It is also included in the tables. We obtain ground-state binding energies in good agreement with experimental data within the variances [4].

4 SUMMARY

We have presented results of the Constrained molecular dynamics approach to describe the atomic ground states configurations. We calculated the binding energies and the radial coordinates of the electrons in atoms. The total electronic energies for the ground-state atoms are given rather accurately. At last we stress that the intent of the CoMD simulation of the atomic systems is to applying it to the collision calculations and determining the Equation of State of matter at very low temperatures where quantum effects play a decisive role.

REFERENCES

- [1] M. Papa, *et al.* Phys. Rev. C 64, 024612 (2001).
- [2] S. Terranova, and A. Bonasera, Phys. Rev. C 70, 024906(2004).
- [3] S. Kimura, and A. Bonasera, Phys. Rev. Lett. 93, 262502 (2004); S. Kimura, and A. Bonasera, Nucl. Phys. A in press (2005), nucl-th/0504005.
- [4] S. Kimura, and A. Bonasera, submitted to Phys. Rev. A, physics/0409008;
- [5] These binding energies are obtained from the measured ionization energies of atoms given in the web site: <http://www.webelements.com/>

INFLUENCE OF THE ELECTRONIC CHAOTIC MOTION ON THE FUSION DYNAMICS AT ASTROPHYSICAL ENERGIES

S.Kimura*, and A.Bonasera

INFN Laboratori Nazionali del Sud, Catania, Italy

* Corresponding author, e-mail: kimura@lns.infn.it

Abstract

We have performed semi-classical molecular dynamics simulations of screening by bound target electrons in low energy nuclear reactions. In our approach quantum effects corresponding to the Pauli and Heisenberg principle are enforced by constraints [1]. We show that the enhancement of the average cross section and of its variance is due to the perturbations induced by the electrons. This gives a correlation between the maximum amplitudes of the inter-nuclear oscillational motion and the enhancement factor. It suggests that the chaotic behavior of the electronic motion affects the magnitude of the enhancement factor. We investigate tunneling process under the chaotic environment. We discuss also numerical experiments using polarized targets. The derived enhancement factors in our simulation are in agreement with those extracted within the *R*-matrix approach.

1 INTRODUCTION

The knowledge of the bare nuclear reaction rates at low energies is essential not only for the understanding of various astrophysical nuclear problems, but also for assessing the effects of host material in low energy nuclear fusion reactions in matter. This is currently a subject of great interest in nuclear physics, since Bochum group has reported that the experimental cross sections of the reactions ${}^3\text{He}(d,p){}^4\text{He}$ and of $\text{D}({}^3\text{He},p){}^3\text{He}$ with gas target show an increasing enhancement with decreasing bombarding energy with respect to the values obtained by extrapolating from the data at high energies. Many studies attempted to attribute the enhancement of the reaction rate to the screening effects by bound target electrons. In this context one often estimates the screening potential as a constant decrease of the barrier height in the tunneling region through a fit to the data. A puzzle has been that the screening potential obtained by this procedure exceeds the value of the so called adiabatic limit, which is given by the difference of the binding energies of the united atoms and of the target atom and it is theoretically thought to provide the maximum screening potential. Over these several years, the redetermination of the bare cross sections has been proposed theoretically [2] and experimentally [3], using the Trojan Horse Method [4]. The comparison between newly obtained bare cross sections, i.e., astrophysical *S*-factors, and the cross sections by the direct measurements gives a variety of values for the screening potential. There are already some theoretical studies performed using the time-dependent Hartree-Fock(TDHF) scheme[5,6].

2 FORMALISM

In this study we examine the subject within the

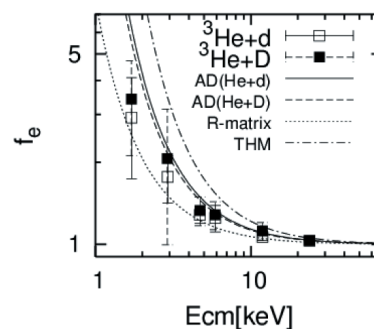
constrained molecular dynamics (CoMD) model [7], even in the very low incident energy region not reached experimentally yet. At such very low energies fluctuations are anticipated to play a substantial role. So as to study the sources of such fluctuations, the TDHF scheme which gives averaged values is insufficient. Molecular dynamics contains all possible correlations and fluctuations due to the initial conditions (events). For the purpose of treating quantum-mechanical system like target atoms and molecules, we use classical equations of motion with constraints to take into account the Heisenberg uncertainty and the Pauli exclusion principles.

In extending the study to the lower incident energies, we would like to stress the connection between the motion of bound electrons and chaos. In fact, depending on the dynamics, the behavior of the electron(s) is unstable and influences the relative motion of the projectile and the target. The tunneling probability can be modified by the existence of such a chaotic environment.

3 PARTICULAR REACTIONS AND RESULTS

We investigate the reactions $\text{D}+d$, $\text{D}+\text{D}$, ${}^3\text{He}+d$, ${}^3\text{He}+\text{D}$, ${}^6\text{Li}+d$ and ${}^6\text{Li}+\text{D}$.

Fig. 1 Enhancement factor for the reactions ${}^3\text{He}+d$ and ${}^3\text{He}+\text{D}$ as a function of the incident energy.



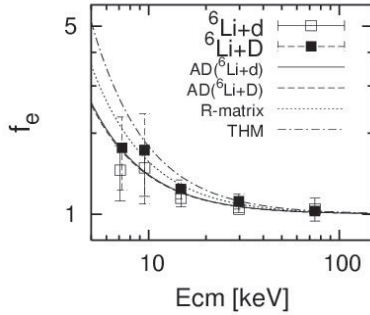


Fig. 2 Enhancement factor for the reactions ${}^6\text{Li}+d$ and ${}^6\text{Li}+D$ as a function of the incident energy

Fig. 1 shows the incident energy dependence of the average enhancement factor for the reaction ${}^3\text{He}+d$ (open squares) and its variances over all the events in the ensemble. In the same figure, the average enhancement factors for the reaction ${}^3\text{He}+D$, with a bound electron on the projectile are shown with closed squares.

Fig. 2 is same with Fig. 1 but for the reactions ${}^6\text{Li}+d$ and ${}^6\text{Li}+D$.

We showed that the enhancement of the average cross section and of its variance is due to the perturbations induced by the electrons. It suggests that the chaotic behavior of the electronic motion affects the magnitude of the enhancement factor.

As a result, we obtained smaller enhancement factor compared with one from TDHF scheme. For all the reactions it is shown that both the average enhancement factors and their variances increase as the incident energy becomes lower. Using bare projectiles we obtained the average screening potential smaller than the value in the adiabatic limit for all reactions. It is because of the excitation or emission of several bound electrons during the reactions. The comparison between bare and atomic projectile cases for each reactions revealed that the electron capture of the projectile guides to larger enhancements. The derived enhancement factors in our simulation are in agreement with those extracted within the *R*-matrix approach including the variances over all the events [2].

We performed numerical experiments using polarized targets for the reaction $D+d$.

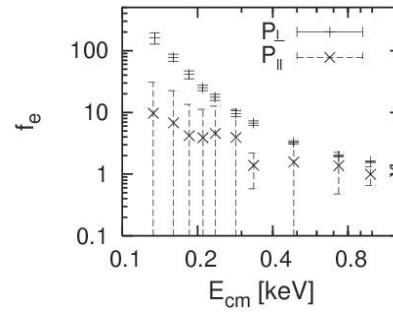


Fig. 3 Enhancement factor for the reactions $D+d$ using polarized targets as a function of the incident energy.

Using $P_{\perp}$ targets (Polarized target perpendicular to the beam axis) we obtained relatively large enhancements with small variances, instead $P_{\parallel}$ target (Polarized target parallel to the beam axis) gives large variances of the enhancement factors and relatively small averaged enhancement factors. It is because with the $P_{\parallel}$ targets the force exerted from the electron to the relative motion of the nuclei is oscillational, in the direction of the beam axis, and the motion of the electron becomes often excited or unstable. It is the case where the chaoticity of the electron motion affects the tunneling probability and at the same time the enhancement factor of the cross section.

REFERENCES

- [1] S. Kimura, and A. Bonasera, Phys. Rev. Lett. 93, 262502 (2004);
S. Kimura, and A. Bonasera, submitted to Phys. Rev. A, physics/0409008;
S. Kimura, and A. Bonasera, Nucl. Phys. A in press (2005), nucl-th/0504005.
- [2] F. C. Barker, Nucl. Phys. A 707, 277 (2002).
- [3] M. Junker, *et al.* Phys. Rev. C 57, 2700 (1998).
- [4] A. Musumarra, *et al.* Phys. Rev. C 64, 068801 (2001).
- [5] T. D. Shoppa, *et al.* Phys. Rev. C 48, 837 (1993).
- [6] S. Kimura, *et al.*, Phys. Rev. C 67, 022801(R) (2003).
- [7] M. Papa, *et al.* Phys. Rev. C 64, 024612 (2001).

STATUS OF THE MAGNEX SPECTROMETER

A.Cunsolo^{a,b,*}, F.Cappuzzello^a, A.Foti^{b,c}, A.Khouaja^a, G.Longo^{a,b},
 C.Nociforo^a, S.E.A.Orrigo^{a,b}, J.S.Winfield^a, H.Petrascu^d,
 C.Cali^a, V.Campagna^a, A.Distefano^a, P.Litrico^a, S.Lo Faro, E.LoVecchio^a,
 A.Mirabella^a, M.Piscopo^a, S.Salamone^a, A.Santonocito^a, G.Schillaci^a

a) INFN Laboratori Nazionali del Sud, Catania, Italy

b) Dipartimento di Fisica e Astronomia, Università di Catania, Italy

c) INFN Sezione di Catania, Catania, Italy

d) NIPNE, Bucharest, Romania

** Corresponding author, e-mail: cunsolo@lns.infn.it*

Abstract

The status of the MAGNEX large-acceptance spectrometer at the LNS is described. The spectrometer itself is essentially complete and under commissioning. First ^{16}O Tandem beam at 80 MeV have been successfully sent to the “Cameretta” scattering chamber and the elastically scattered ions have been detected at the focal plane. The data have been stored and analyzed with the MAGNEX acquisition system. New runs with beam are on the way. The principal remaining work (in progress) concerns the completion of the final scattering chamber and the test of the new Position Sensitive Start Detector with the beam.



Fig. 1. View from the top of the shielding walls of MAGNEX with the recently-installed FPD on the right. The beam will come from roughly the top-left of the picture.

1 INTRODUCTION

Considerable work has been done for MAGNEX over the last year, as will be found in the following sections of this report. A photograph of the spectrometer in the new experimental area is shown in Fig. 1.

2 INFRASTRUCTURE

With the completion of the radiation shielding, it was possible to complete the installation of the electric power, the cooling water systems and other important facilities.

As regards the electric power it has been tested in all the services supplied. In particular the main line, distributing up to 600 kW from the Dipole and Quadrupole power supplies to the relative magnets has been tested at the maximum power. In addition a ground loop has been built in the experimental room in order to safely release the energy from the magnets in case of short and to reduce the noise in the electronic chains due to the current flowing to the earth.

The water cooling system for the magnets and the power supplies has been successfully tested at the maximum power. The power supplies input flowmeters have been upgraded in order to work at 5 bar 30 l/m de-

mineralized water, instead of previous values of 3 bar, 36 l/m. The test also included the full rotation of the MAGNEX platform while water flowing.

A rotating crane has been mounted for the purpose of detectors and vacuum chamber lifting. Its position on one side of the spectrometer allows in particular to move the focal plane detector to the new service room on the side of the experimental hall, where all the necessary set-up can be easily done.

3 MECHANICAL AND VACUUM

The vacuum system has been completely mounted and tested. The test included the full functionality of the control system. All the procedures for guaranteeing the safety under normal or particular operation conditions have been produced, coded and tested. In this step some upgrading have been obtained in the focal plane gas handling system and in the dipole vacuum chamber, such as the inclusion of a new vacuum line with an electromagnetic valve to prevent the explosion of the internal chamber, or the increased control of the dipole Cryopump.

A new scattering chamber of reduced size called “Cameretta” has been projected, built, installed and tested. It is intended to work at a fixed angle of 25° compare to the beam line. All the necessary equipments to adapt this chamber to the existing quadrupole chamber and beam line and to adapt it to the vacuum system have been included in this job.

3 DETECTORS

The Focal Plane Detector has been tested with an α -source and for some hours with ^{16}O ejectiles elastically scattered in the $^{58}\text{Ni}(^{16}\text{O}, ^{16}\text{O})^{58}\text{Ni}$ reaction at 80 MeV and $25^\circ \pm 5^\circ$. In both cases the gas drift and proportional sections of the detector have been put in coincidence with the silicon hodoscope signals. The tests with the α -source indicate a need to work at high voltage (about 800 V or more) on the drift and proportional wires, which at present has limited a full exploration of the wire multiplication gain as a function of the voltage and the pressure. This parameter will be more deeply studied during the new tests with beam scheduled for late May and early June 2005.

The new Position Sensitive Detector for the entrance to the spectrometer (as mentioned in last year’s Report) has been completed and tested with an α -source in coincidence with a silicon detector. An important activity has regarded the minimization of the noise due to the Gassiplex control board on the time signal. This has lead to an upgrading of such a board, completely restyled, such as to a change of the time signal extraction from the copper plate anode to the micro-channel itself. More information are in another contribution included in this annual report. Moreover all the pieces to adapt this detector to the “Cameretta” have

been built and the next step in the immediate future will be to use it with elastically scattered heavy ions.

4 DATA ACQUISITION SYSTEM

Further development has been made to the MAGNEX data acquisition system following the replacement of the VP7 single board CPU by a VME Optical Link Controller purchased from CAEN. A large part of the VME-Linux software already developed for the VP7 was reused for the Optical Link Controller. The auxiliary programs to determine the thresholds for the C-RAMS ADCs and control the CFD boards have also been ported from the VP7 to the Optical Link Controller.

Meanwhile, the MAGDAQ front-end software has been upgraded to provide a run-time log file with start/stop time stamps of runs, event and buffer count information as well as an error log. These log files are saved to a particular directory as a permanent record of the data acquisition history.

As regards the back-end acquisition system, (two 1750 PowerEdge rack-mounted workstations) substantial progress has been made on the ray reconstruction software needed for both online and offline analysis. An intermediate program NTUPLES has been written which incorporates the application of the inverse matrices created by COSY INFINITY. The output of this program, the reconstructed initial energies and angles, are passed to the end-user analysis and display program such as CERN’s PAW or ROOT.

The back-end CHIMERA-based program (XCHIMERA FDL) has been modified to output pulser-calibration data from the GASSIPLEX-readout of strips. These data are mapped from the C-RAMS FIFO order into contiguous strip-order. The data are then analysed by a ROOT analysis procedure to give the calibration coefficients for each strip. These coefficients are then read back by the normal data-taking version of XCHIMERA FDL and the properly-normalised signals from the strips are then used in the calculation of the position centroids, which is crucial for MAGNEX.

“ β ” VERSION OF THE POSITION START DETECTOR FOR THE MAGNEX SPECTROMETER

A.Cunsolo^{a,b,*}, F.Cappuzzello^a, A.Foti^{b,c}, C.Nociforo^a, S.E.A.Orrigo^{a,b}, J.S.Winfield^a, H.Petrascu^d, G.Longo^a,
C.Cali^a, P.Litrico^a, S.Marino^a, G.Passaro^a, B.Trovato^a

a) INFN Laboratori Nazionali del Sud, Catania, Italy

b) Dipartimento di Fisica e Astronomia, Università di Catania, Italy

c) INFN Sezione di Catania, Catania, Italy

d) NIPNE-HH, Bucharest, Romania

* Corresponding author, e-mail: cunsolo@lns.infn.it

Abstract

A new PS detector was designed for MAGNEX spectrometer, considering the results and conclusions following the previous version. The magnetic field homogeneity was increased, enlarging the magnetic poles, the height of the detector was reduced and the electric field homogeneity was optimized too, adding a grid. The total voltage applied on the detector was reduced by $\sim 40\%$ for the new design.

1 INTRODUCTION

The Position Start Detector of MAGNEX spectrometer is a “zero time detector” type and it is the first analyzer of the incoming beam, from the composition and heavy ions position point of view, giving the start signal for the rest of the analyzing chain.

2 DESCRIPTION

In this version the PSD has a shape of a parallelepiped having a total volume of $24.6 \times 12.8 \times 87 \text{ cm}^3$. It is based on the electron detection, using two micro channel plates in chevron configuration. The electrons released by an aluminum foil are deflected away from the main beam, by the aid of a magnetic field perpendicular on the applied electric field. In fig. 1 is represented a scheme that shows the concept of this type of detector. The electric field E has a value of 1560 V/cm and the magnetic field B is ~ 90 gauss in the center of the detector. The detector’s electric cavity has a number of 3 equipotential wires made by Cu-Be with $\phi 100 \text{ }\mu\text{m}$. The upper and lower electrodes are realized using 1.6 mm printed circuit foils. The Cu layer is covered by $0.2 \text{ }\mu\text{m}$ of gold. The heavy ions beam pass through the grid of the anode, toward the cathode.

Following the interaction with the aluminized mylar window, back scattered electrons with zero velocity are released in the chamber. Because the applied electric field they will be accelerated and the magnetic field will bend their trajectories on an ellipsoidal path, out of the main beam. The maximum height of the electron’s path, from simulations using SuperFish Poisson code, is $\sim 2.5 \text{ cm}$ and the path’s length is $\sim 7.6 \text{ cm}$. At the end of their movement, the electrons will fall on the first surface of the chevron’s first micro channel plate having a residual energy around 62 eV , enough to excite the chevron. The

value of the electron’s residual energy is “mechanically adjusted”, depending directly by the level of the chevron inside detector, relative to the aluminized mylar window. In our case this level difference is 4 mm .

The chevron was made using a pair of micro-channel plates provided by Photonis, having a total area of $66 \times 54 \text{ cm}^2$, and a thickness of 1 mm . The active area used in our configuration is $62 \times 50 \text{ cm}^2$. The pores of the micro-channel plates are $12 \text{ }\mu\text{m}$ in diameter, having an inclination of 11° . The two micro-channel plates are mounted having a 0.3 mm gap in between.

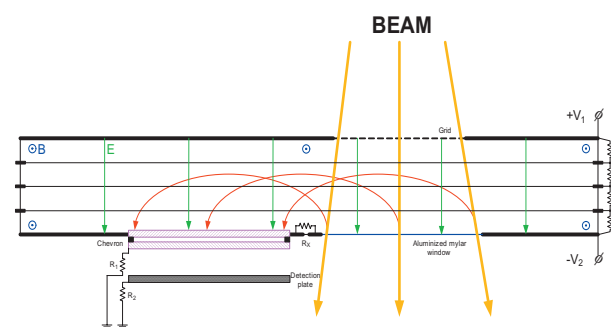


Fig. 1: The “zero time detector” concept

In fig. 2 one can see an image of the PS Detector. The view is from emerging beam side. In the upper side the two HV connectors, able to work in high vacuum, can be seen. The third connector is an ordinary BNC and here the signal directly from the chevron can be find. The short cable terminated with LEMO connector is

provisory, being used in present only for tuning and calibration.

Below the connector support is the position assembly, mounted behind the chevron. It has three main parts:

- a) The Cu plate, that collects the electronic shower released by the chevron and transfers it further to the position matrix. The charge transfer is capacitive.
- b) The XY matrix, composed by 192 rectangles.
- c) The gassiplex preamplifier with 192 channels.

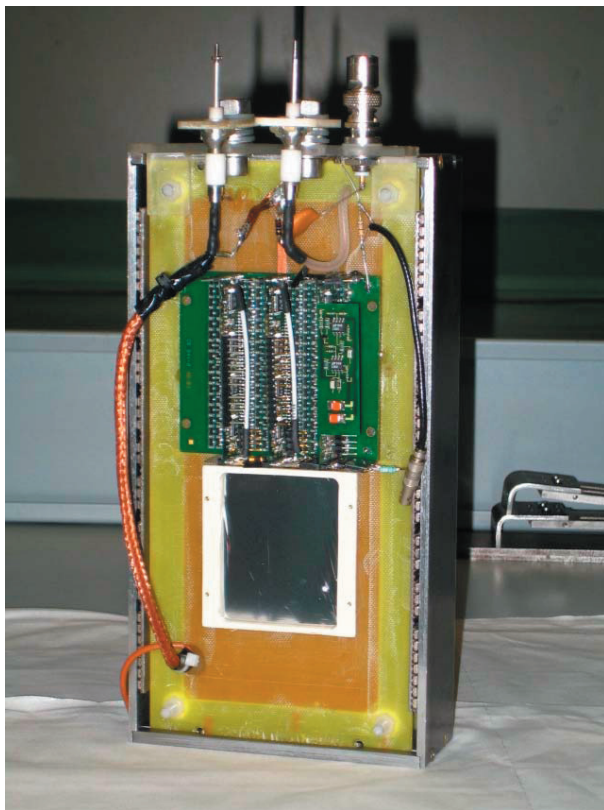


Fig. 2: PSD view

Below the position determination assembly is the mylar + Al window, having a thickness of 6 μm .

Around the electric cavity is the magnetic circuit, realized using 320 small but powerful permanent magnets, each one having a 12 x 4 x 2 mm³ volume. We preferred this design because the requested magnetic field value can be tuned very precisely in this way. In the final version of PSD the number of permanent magnets will be 448 pieces.

3 ELECTRIC DIAGRAM

The scheme of the electric connections used for the actual version of PS detector is presented in fig. 3. To apply around 4700 V on the detector, two different high voltage, low ripple power supplies are used, having common ground. The timing signal is extracted directly

from the lower surface of the chevron using a fast transimpedance preamplifier designed special for micro-channel plates [2]. This preamplifier adapts the micro-channel output to the 50 Ω of the oscilloscope input and protects the equipment from accidental discharges.

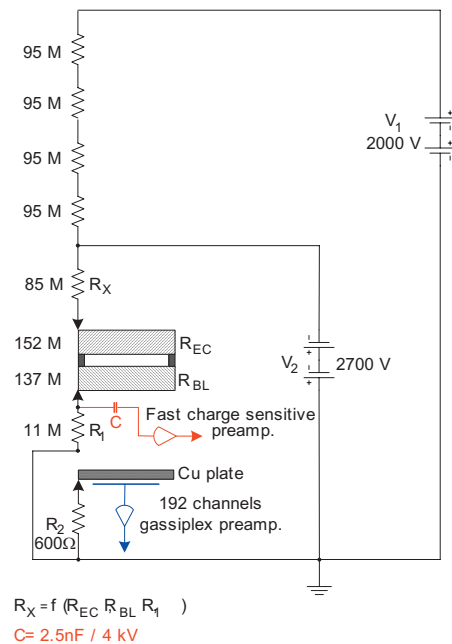


Fig. 3: Electric diagram

The electron bursts that are emerging from chevron are accelerated using 100 V electric field and are captured by the copper plate. The electric charge released here by the electrons is transferred by capacitive effect to the gassiplex preamplifiers and, after coding, further to the data acquisition system.

The preliminary tests of this detector are made at present using one α source and a Si detector for measurements in coincidence.

4 REFERENCES

- [1] Los Alamos Accelerator Code Group, *Computer codes for particle accelerator design and analysis: a compendium*. Tech. Rep. LA-UR-90-1766, Los Alamos National Lab., Los Alamos, NM, USA (May 1990), second edition, revised and expanded.
- [2] P.Schwartz, H.Baumgärtel, and C.G.Eisenhardt, *Rev. Sci. Instrum.*, Vol. 72, No. 7 (July 2001) 3125.

DEAD THICKNESSES MEASUREMENT IN CHIMERA SILICON DETECTOR.

G.Lanzalone^{a,*}, P.Russotto^{a,†}, S.Cavallaro^a, M.Alderighi^d, F.Amorini^a, L.Auditore^c, G.Cardella^b, M.D'Andrea^b, E.De Filippo^b, N.Giudice^b, A.Grimaldi^b, P. Guazzoni^d, E.La Guidara^a, C.Maiolino^a, A.Pagano^b, M.Papa^b, S.Pirrone^b, G.Politi^b, F.Porto^a, F.Rizzo^a, S.Russo^d, G.Saccà^b, M.Sassi^d, A. Trifirò^c, M. Trimarchi^c, S.Urso^b, L. Zetta^d.

a) INFN -LNS, Catania, Italy and Dipartimento di Fisica e Astronomia, University of Catania

b) INFN Sezione di Catania and Dipartimento di Fisica e Astronomia, University of Catania

c) INFN Gruppo collegato di Messina and University of Messina

d) INFN Sezione di Milano and Dipartimento di Fisica, University of Milano

* Corresponding author, e-mail: lanzalone@ct.infn.it

† Corresponding author, e-mail: russotto@lns.infn.it

Abstract

A dead zone thicknesses measurement has been performed on two different Silicon detectors of 4 π CHIMERA multi-detector system.

1 INTRODUCTION

The knowledge of Silicon detector dead zones is very important for energy calibration [1]. In front side of a CHIMERA n-type silicon detector [2,3] an Al thin layer (electric contact) and a P⁺-Si layer (junction) are present. Conversely a similar Al layer and a N⁺ Si layer (blocking contact) are in the rear side. These zones are inefficient for charge collection and can be considered as dead thicknesses.

The results of a measurement of these dead thicknesses are presented here.

2 EXPERIMENT

The measurements have been performed in the vacuum chamber "3000" at the detector laboratory in Department of Physics and Astronomy in Catania. A common three peaks α source has been used with energy 5155 (²³⁹Pu), 5484 (²⁴¹Am) and 5806 (²⁴⁴Cm) KeV. The source has been collimated by a cylindrical collimator with radius r equal to 1.75 mm and length l equal to 15 mm ($r/l = 11.7\%$).

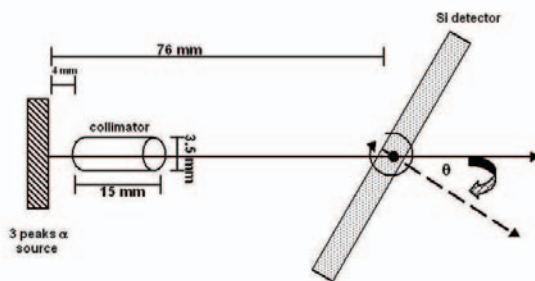


Figure 1.a : schematical view of experimental setup, non in scale.

The collimator has been set at 0.4 mm from the surface of the source and the distance between the source and the detector has been equal to 7.6 mm a sketch of experimental setup is given in figures 1.a and 1.b.

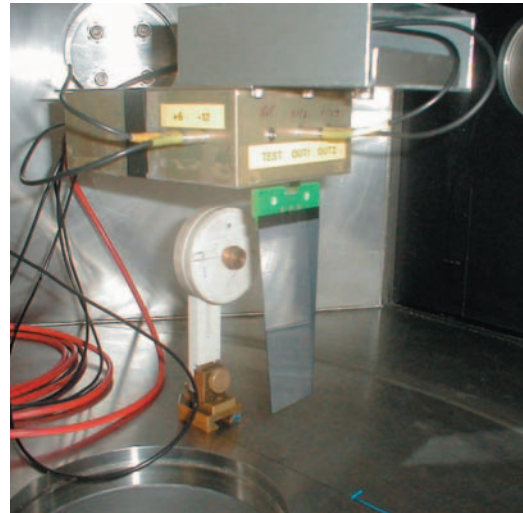


Figure 1.b: a photo of experimental setup.

A simple simulation program has been used to evaluate the geometrical efficiency of the apparatus ($N_{\text{particles on detector}}/N_{\text{particles emitted}} = 0.7\%$) and the angular width of the beam impinging on the detector $\Delta\theta = \pm 5^\circ$.

In figure 2 is possible to see the simulation of radial distribution of α particles impinging on the detector. The energy signal of Silicon detector has been processed by a preamplifier, then shaped by an amplified (Ortec 572) and codified by an ADC (7423 UHS). A mechanical system has allowed the rotation of the Silicon detector with respect to the collimator axis.

The measurements have been performed on two Silicon detectors of the 4π CHIMERA multi-detector. One is an old detector (called in this report number 1) used in the REVERSE (2000) and ISOSPIN (2003) experiments. The other is a new detector (number 2) not used before.

The characteristics of these detectors are given in table n. 1. The irradiation has been performed alternatively in front and rear sides of the detector and at various angles θ , in particular from -60° to 60° with step of 15° .

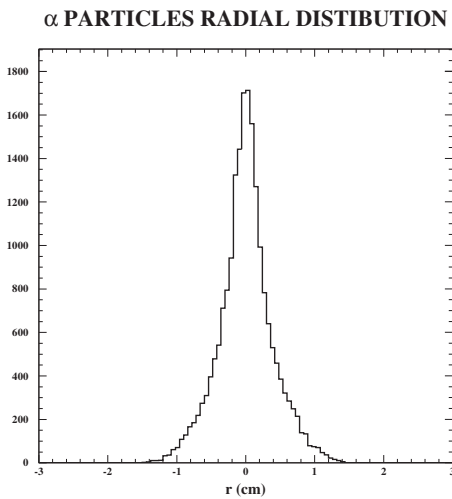


Figure 2: simulation of α particles spreading on the detector.

In this way it has been possible to use the left-right symmetry to find the better alignment ($\theta = 0^\circ$) between the collimator axis and the detector surface.

Both the detectors have been over-depleted with a bias V_{op} , and inverse current I_{inv} has been monitored during the acquisition as can be seen in table n. 1; this current is very high in the detector number 1, indicating a worsening of performance due to the high usage.

Table 1: detectors operations condition

Detec tor	Thickness (μm)	V_d (V)	V_{op} (V)	I_{inv} (μA)
1	296	35	38.4	2.35
2	206	26	28	0.01

2 ANALYSIS

The spectra at various angles have been analyzed and for each of them the centroid of the peaks and the FWHM have been determined with a Gaussian fit. In figure 3 is shown as example the spectra obtained for detector 1 (front) at $\theta = 0^\circ$ and 45° .

The position of the centroid of each peak has been renormalized calculating the difference $DE(\theta) = E(\theta=0^\circ) - E(\theta)$, and this difference DE has been plotted in function of θ . For each one of the three alpha peaks the points obtained have been fitted with a function [4]

$$F(\theta) = par * \left(\frac{1}{\cos(\theta)} - 1 \right)$$

A first fit has been performed shifting all the angles θ between -5° and $+5^\circ$ with a step of 0.5° ; the chi-square values of these fits have been compared and the minimum has been assumed as the real alignment configuration. In all the cases, the correction has been lower than 3° , inside the experimental error on θ .

So the three peak at $\theta = 0^\circ$ have been also used for energy calibration.

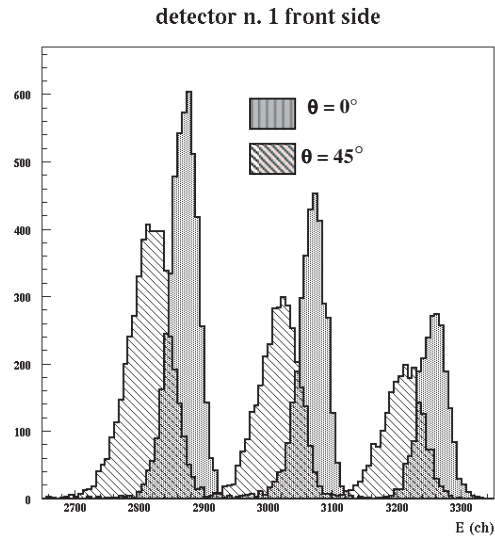


Figure 3: Energy spectra of α particles on front side of detector 1.

Once obtained the value of par and its error [4] for each alpha peak, this value has been transformed in KeV by calibration coefficient.

The dead zone thickness t and its error Δt have been then calculated by the formula

$$t = \frac{par}{dE/dx} \quad \Delta t = \frac{\Delta par}{dE/dx}$$

where the dE/dx of α in Silicon medium has been accurately calculated at the energy of the three alpha peaks by the TRIM program stopping range calculator.

In this case we are not distinguishing between Al and Si dead zone, and the t value obtained is only Silicon equivalent (dead zone made up only by Silicon)

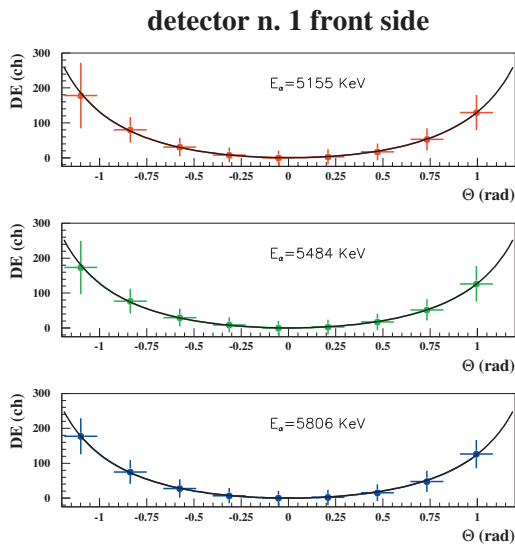


Figure 4: DE vs θ and best-fit results for the three α peaks for detector 1 in front case.

The three values of t obtained for the three peaks measurement have been averaged by their weights [5] and the final values obtained are given in table n. 2.

Table 2: detector dead zone

Detector	t (μm)	Δt (μm)
1-front	1.25	0.23
1-rear	0.41	0.11
2-front	0.64	0.13
2 rear	0.43	0.13

So while in the rear zone the dead thickness is almost the same for both the detectors, the entrance dead zone for old detector is bigger by a factor 2 than the new one. This could be related to a surface damage due to the use of the detector or to the formation of a spurious layer; the presence of a such effects need to be investigated in more properly ways.

It has been also measured the time performance of both detectors and the results are given in table n. 3 ; when injected in the front face there is no difference in time performance between the two detectors.

Table 3: rise time

Detector	Rise time (ns)
1-front	60 ± 5
1-rear	200 ± 40
2-front	60 ± 5
2 rear	170 ± 30

For the measurement in back side the rise time of the detector 1 is slightly longer (+17 %) than the one of the new detector. A big difference in rise times for back side injection could indicate the presence of internal damage

due to the usage; however a more detailed analysis and further measurements are required.

3 ACKNOWLEDGEMENTS

The technical support of Salvatore Urso and Antonio Grimaldi is gratefully acknowledged for the operative availability during the measurements procedure.

4 REFERENCES

- [1] G.F.Knoll, "Radiation Detection and Measurement", chapter 11, third Edition, John Wiley & Sons, Inc.
- [2] S.Aiello et al., Nuclear Instruments and Methods in Physics Research A 385 (1997), p. 306, and reference therein.
- [3] A.Pagano et al., Nuclear Physics A 681 (2001), p. 331c, and references therein.
- [4] Paw Reference Manual.
- [5] J.R. Taylor, "Introduzione all'analisi degli errori", Zanichelli.

OPERATIONS OF CLEANING AND RESPONSE FUNCTION RESTORATION OF THE CHIMERA SILICON DETECTORS

F.Amorini^{a,*}, M.D'Andrea^b, E.La Guidara^a, S.Pirrone^b, G.Saccà^b, L.Auditore^c, G.Cardella^b, S.Cavallaro^a, E. Costa^a, E.De Filippo^b, N.Giudice^b, A.Grimaldi^b, P. Guazzoni^d, G. Lanzalone^a, C.Maiolino^a, C.Marchetta^a, A.Pagano^b, M.Papa^b, G.Politi^b, F.Porto^a, F.Rizzo^a, S.Russo^d, P.Russotto^a, M.Sassi^d, A. Trifirò^c, M. Trimarchi^c, S.Urso^b, L.Zetta^d.

a) INFN -LNS, Catania, Italy and Dipartimento di Fisica e Astronomia, University of Catania

b) INFN Sezione di Catania and Dipartimento di Fisica e Astronomia, University of Catania

c) INFN Gruppo collegato di Messina and University of Messina

d) INFN Sezione di Milano and Dipartimento di Fisica, University of Milano

** Corresponding author, e-mail: amorini@lns.infn.it*

Abstract

In this work are reported some operations of cleaning and response function restoration executed on the CHIMERA device. In particular it is described the protocol adopted to preserve the high standard efficiency and resolution of the silicon detectors that set up the first stadium of the 1192 telescope modules of CHIMERA.

1 INTRODUCTION

Since January 2003, the 4Π multidetector CHIMERA is operational at LNS in Catania in its complete configuration.

CHIMERA is formed by 1192 modules, each consisting of a 300 μm silicon detector followed by a CsI(Tl) scintillator whose thickness ranging from 3 cm at backward angles to 12 cm at the most forward ones. The whole apparatus is organized in two sections: a forward part, in which 688 modules are arranged on 9 rings, covering the angular range between 1°÷30°, and a sphere formed by the other 504 modules, on 17 rings, covering the angular range from 30° to 176°[1].

The detector was installed inside the reaction chamber CICLOPE at LNS, to study the multifragmentation reaction mechanism at Fermi energy [2].

During 2003 and 2004 two very long experimental campaigns were performed in the framework of the ISOSPIN experiment.

2 STATUS AND RECOVERY OF THE CHIMERA SILICON DETECTORS

Following the long 2003/2004 ISOSPIN campaign, the CHIMERA apparatus underwent a severe effort that conditioned the behaviour of the detectors.

With the aim of restoring and preserving the usual high-standard performances, several intervention were planned, and many of them fulfilled during the 2004.

One of the most serious problems dealt with an uncontrolled increase of the leakage current in the silicon detectors (Fig. 1) that make the first stage of

each CHIMERA detection module. This phenomenon can have different origins.



Fig.1 - CHIMERA silicon detector from one telescope of ring 7.

First of all it is necessary to take into account the radiation damage of the detector itself, due to the continuous exposition to the beams and to the particles produced in the reactions. This kind of inconvenient was partially taken under control by covering, during some runs, the most forward part of the apparatus with two thick aluminium shields.

A second cause can be attributed to the raising of the temperature of the detectors and the associated

electronic chain; the heating of a semi conductor could generate parasitic currents, consequences of the increased mobility of the minority carriers in the crystal lattice, so worsening the performances of the device. To overcome the problem, the apparatus is provided with a cooling system to prevent the devices and electronic components to reach unbearable temperature.

A careful examination of the detectors revealed a third problem related to the deposition of dust and grease on the silicon active surface. This inconvenient happens mainly during the venting operation in the CICLOPE scattering chamber. This suggested to try if an accurate cleaning could better the detector conditions.

2.1 Silicon detector cleaning

Before starting any operation, all the apparatus was tested in air to have a reference point for the leakage current values. All the detector were biased with the operative value of the high voltage, usually a 30% higher than the factory indication, to get the over depletion of the active detector thickness.

The corresponding leakage current values are reported in the following Table 1 for the ring 7 detectors, that were the ones among the most affected from the dirt.

Table 1 – Results of the cleaning procedure for the silicon detectors of ring 7 of the CHIMERA apparatus.

Silicon Detector Group	Operating Voltage	Leakage current before cleaning	Leakage current after cleaning	Relative variation
00-03	70 V	3.50 μ A	1.95 μ A	44 %
04-07	70 V	0.95 μ A	0.94 μ A	1 %
08-11	70 V	1.50 μ A	1.18 μ A	21 %
12-15	70 V	15.0 μ A	4.00 μ A	73 %
16-19	70 V	6.50 μ A	1.42 μ A	78 %
20-23	70 V	5.00 μ A	0.78 μ A	84 %
24-27	70 V	22.0 μ A	19.9 μ A	1 %
28-31	70 V	1.40 μ A	0.76 μ A	46 %
32-35	70 V	9.50 μ A	5.62 μ A	41 %
36-39	70 V	2.00 μ A	1.53 μ A	24 %
40-43	70 V	5.00 μ A	2.20 μ A	56 %
44-47	70 V	2.60 μ A	1.04 μ A	60 %

Actually, the numbers given by the high voltage supply modules are related to groups of four detectors that are biased together; even though they're not directly comparable to those checked under vacuum during the experiments, they are reliable to quote the effects of the maintenance operations.

After the leakage current first monitoring, the detector were dismantled. Their fragility requires the handling

to be done with extreme care, to avoid direct contact with its active parts and the very thin wires that realize the electrical contacts (bondings). For this reason, each detector was sealed to be moved safely to the LNS Chemical Laboratory, that offers the possibility to work in controlled atmosphere. The detectors were washed, under an extractor fan, in a bath of 99% pure ethanol, that doesn't leave any trace after its evaporation, then they were rapidly dried by means of a controlled blow of pure Nitrogen.

The measurement performed after the detector were mounted again in the reaction chamber are reported in Table 1. As it can be seen from the leakage current comparison, the effects of cleaning were highly remarkable. If we look, for example, to the worst cases as the groups from 12-15 to 32-35, the decrease of the inverse current after the washing operations ranges from 41% to 84%. This result witnesses the extreme importance of keeping the detectors' surface perfectly clean to preserve their performances and extend their operating life.

2.2 Electrical contacts recovering

Some of the detectors didn't get any advantage from the cleaning operations, maintaining an inverse current far from the standards of a good quality device as, for example, group 24-27 on tab.1. For the elements of this group, further investigation were performed to seek for possible mechanical damages in the electrical connection. An examination with the help of a microscope showed up the crimping and/or breaking of the bondings. The bondings were subsequently reconnected using a special machine able to solder thin aluminium wires ($\phi=0.25 \mu\text{m}$) on the surface of the silicon detector. In Fig. 2 is shown a good soldered bonding.

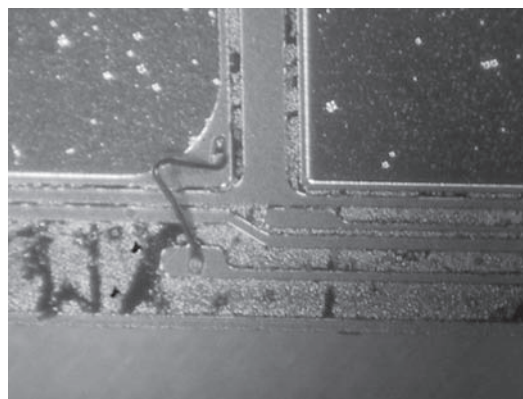


Fig.2 - Microscopic view of the bonding of a silicon detector after its recovering.

These operations were made in the Detector Laboratory at the INFN Sezione di Catania.

In most of the cases this soldering operation allowed to restore the good response function of the detector.

3 CONCLUSIONS

A careful serie of maintenance operations was performed on the CHIMERA silicon detector. The results showed up the fundamental importance of performing continuous and accurate intervention to keep an high efficiency and optimum resolution of the CHIMERA device.

5 REFERENCES

- [1] A.Pagano et al., Nuclear Physics A681(2001)331.
- [2] A.Pagano et al., Nuclear Physics A734(2004)504.

A COMPUTATIONAL AND STORAGE UNIT FOR CHIMERA DAQ

F.Amorini^a, A.Anzalone^a, G.Cardella^b, S.Cavallaro^a, E.DeFilippo^b, D.Ghilardi^c, P.Guazzoni^{c,*}, E.LaGuidara^a,
G.Lanzanò^b, G.Lanzalone^a, C.Maiolino^a, A.Pagano^b, S.Pirrone^b, G.Politi^b, F.Porto^a, F.Rizzo^a, S.Russo^c, P.Russotto^b,
M.Sassi^c, L.Zetta^c

a) INFN Laboratori Nazionali del Sud, Catania, Italy

b) INFN Sezione di Catania, Italy

c) Dipartimento di Fisica dell'Università and INFN Milano, Italy

** Corresponding author, e-mail: paolo.guazzoni@mi.infn.it*

Abstract

We have designed, built and tested an on-line pre-analysis and data-storage unit for the CHIMERA data acquisition system. The unit uses special algorithms to perform particle identification and automatic peak detection. It tags in charge each event and stores the results on external unit, together with the raw data. It consists of two commercial 2GHz workstations connected together through 1Gb/s Ethernet boards and to the data acquisition system through a 100Mb/s Ethernet.

1 INTRODUCTION

Each of the 1192 detection cells of CHIMERA multidetector [1], generates up to four analog signals: the energy loss in the first transparent silicon detector (ΔE), the Time of Flight (ToF) from the ΔE detector, and the FAST and SLOW components from the CsI(Tl) scintillator [2]. In the off-line analysis of experimental data thousands of bidimensional matrices must be reconstructed. So if it is possible to identify on-line in charge each event and consequently to label each of them with a proper "charge tag", a great advantage will arise for the preliminary analysis. Moreover the on-line monitoring of the operation of the detector is an important tool to assure accurate data taking.

CHIMERA does not make use of any monitoring signal, except for the pulses coming from the pulse generator system. Therefore we decided to use the actual physical pulses coming from the multidetector during the experiment [3], [4]. We have exploited particle identification techniques, based on the power-law function [5], in order to obtain monodimensional frequency distributions of the charge identification function of the reaction products.

The original algorithm of the power-law for a telescope of silicon detectors can be directly derived from the range-energy relationship and written in the form:

$$PIF = (E + \Delta E)^X - E^X \quad (1)$$

where:

- PIF charge identification function
- ΔE energy lost in the first transparent detector
- E remainder of energy, lost in the second thick detector
- X real parameter, usually $1.5 < X < 1.8$

In accordance with our heuristic approach [6], in (1) we use *FAST*, the light-pulse height from CsI(Tl) scintillators in channels (i.e. without any preliminary calibration) instead of E , thus obtaining:

$$PIF = (FAST + \Delta E)^X - FAST^X \quad (2).$$

The algorithms are applied without any preliminary calibration [6] to the signals coming from the detectors. The resulting monodimensional plots are much easier to handle for automatic on-line data processing than the standard bidimensional scatter plots.

In a monitoring system, whose aim is to evaluate on-line the status of the detector array, analyzing a subset of data may be sufficient. On the contrary, a processing system must process the whole amount of produced data. Merging into the same system the functions of monitoring and of on-line computation is a non-trivial issue. In fact a new, pressing constraint arises: the need for not losing events. In general, for an on-line computational unit allocated in a data acquisition system, the most important timing constraints are due to complexity and high data rate. In the case of CHIMERA, because of the large number of detection cells and parameters to be collected, the data rate may be high even though the event rate is low.

The old Control System [7] is based on a small-scale parallel system. It consists of a heterogeneous architecture of VME-boards (equipped with six Digital Signal Processors - DSP), managed by an embedded CPU and an external PC used for data presentation.

We have established [7] that in a 10-DSP system all the packets generated by the Data Acquisition System [8], [9] find a free DSP to be processed by. We have also to remark that, if the processing time or the

injection frequency increase, ten DSPs would not suffice anymore. To restore the "zero dead-time increase" is necessary to provide an adequate number of DSP-boards. To date is no more adequate and too much expensive not only to think to possible developments using DSP-boards, but also to provide the standard maintenance in case of failure.

In this contribution we present a case study of a new on-line pre-analysis, monitoring and data-storage system for CHIMERA, designed on the basis of the results obtained with the previous Control System. The upgraded system uses new generation commercial dual-processor workstations that allow for more powerful computing capabilities than DSP boards.

2 THE COMPUTATIONAL AND DATA-STORAGE UNIT

As last generation PCs (about 2 GHz processors) are much more powerful and cheaper than commercial DSP-boards, we have decided to employ this kind of hardware to implement an improved monitoring system. This choice also granted us the possibility to set up a simple hierarchical architecture, easier to develop and upgrade. Our intent was to obtain a more complete system able to monitor the operation of CHIMERA, perform on-line pre-analysis of the data and store raw data and computed charge-tags for each event.

The hierarchical architecture of *PRESTO* (PRE-analysis, monitoring and data-STorage unit) uses two dual processor workstations connected through a 1Gb/s Ethernet as shown in Fig. 1. The first workstation works as supervisor, computational and data-storage unit, and performs the on-line pre-analysis on each datum collected by CHIMERA before data-storing, in order to monitor the operation of the multidetector and speed up the off-line analysis of collected data. The second workstation is mainly used as graphic station, to visualize the data. Furthermore, it is able to carry out additional calculations, if needed.

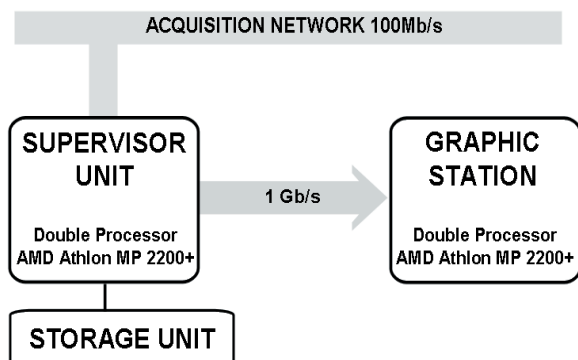


Fig. 1 - Hardware architecture of the pre-analysis, monitoring and data-storage unit.

Each workstation is equipped with two AMD-Athlon MP 2200+ processors (1.8 GHz), 2GB shared memory and an Intel Pro/1000 XT Ethernet board to perform the 1Gb/s Ethernet copper connection. The storage units used for the tests are a Quantum DLT8000 tape unit (DLT) [10] and a Hitachi Deskstar-180GXP [11] hard disk mounted in a USB2.0 external box (USB-Disk). The Operating System used is Linux Mandrake 9.2.

The supervisor code is written in C++ and developed using Borland Kylix 3.0 Enterprise Edition [12]. Its software architecture is subdivided in five threads strictly correlated, each one performing a specific task. The Main Thread initializes the whole system and starts the other threads. The Input Network Thread reads Data-packets of raw data from Ethernet. The Computational Thread unpacks the Data-packet, calculates the PIF spectrum, performs the automatic peak detection and the computation of the Figure of Merit (FoM) [13] to appreciate the goodness of separation between adjacent charge peaks. For each collected event, the Storage Thread stores the raw data in a new Data-packet together with the charge-tag on the storage unit. The Output Network Thread sends results (PIF spectrum, peak centroid positions and FoM values) to the graphic station through Ethernet. The graphic station reads and visualizes the results to allow for system monitoring and result evaluation. The visualization tool is written in C++ and implemented using ROOT [14].

The Input Network Thread waits for Data-packets from the Acquisition Network. When a Data-packet arrives, the thread reads it and writes it into a FIFO. Concurrently the Computational Thread receives a Data-packet from the FIFO queue and unpacks it to extract event-parameters and telescope-coordinates (crate, board and channel). Then, it calculates the PIF value for each ΔE and FAST pair contained in the Data-packet and properly updates the PIF spectrum of each telescope involved, on the basis of the read telescope coordinates. When all the events contained in the incoming Data-packet have been analyzed, the thread adds the proper charge-tag to the raw data, writes everything in a new Data-packet, and sends it to the Storage Thread. When a telescope has collected 1000 new events, the Computational Thread starts the automatic peak detection algorithm on the corresponding PIF spectrum. The automatic peak detection algorithm is based on the method for the automatic identification of peaks described in [15]. Before peak detection, each PIF spectrum is fed into a least square fit smoothing algorithm [16] in order to reduce the noise components, without any loss of information. As soon as the spectra are smoothed, the thread performs the automatic peak detection. Then it fits each peak with a Gaussian function, obtaining as results centroid position and full width at half maximum. These results are used by the Computational Thread to calculate FoM values and to

tag in charge each event. Peak centroid and FoM values are sent to the Output Network Thread together with the corresponding PIF spectrum.

3 RESULTS AND CONCLUSIONS

Extensive benchmarking tests have been carried out to determine performance and actual possibilities of the system, using data previously collected, by means of an ad hoc written code, employed to simulate the DAQ multicasting.

In the following the timings concerning the three different system phases (on-line computation, on-line storage and off-line computation) are separately considered. Regarding on-line storage, we performed two sets of tests, using both DLT and USB-Disk as storage unit.

The timing measurements have been made by using the C++ clock function and computing each processing block one million times in order to increase precision. In Table I the timing results obtained with PRESTO are compared with those of the old Control System.

Fig. 2-a) displays the (ΔE , FAST) raw data scatter plot for $^{124}\text{Sn}+^{58}\text{Ni}$ reaction at 35 MeV/u. The cluster corresponding to the elastically scattered ^{124}Sn ions is shown. The presence of the elastic scattering ($Z_{\text{Sn}} = 50$), or other easily recognizable charge cluster in the collected data, allows for absolute charge identification.

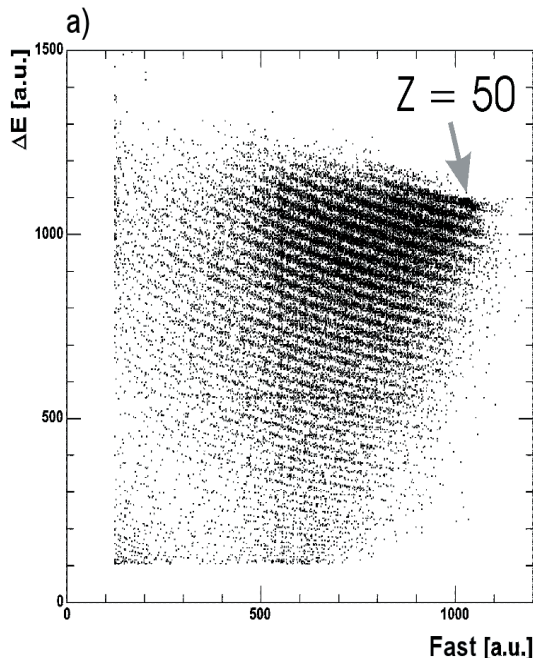


TABLE I
PERFORMANCE OF THE OLD CONTROL SYSTEM AND PRESTO

Operation	Control System	PRESTO
<i>On-line operation</i>		
Data-Packet unpacking and charge labeling ^a	~2ms/Data-Packet	~160μs/Data-Packet
on-line PIF calculation ^b	9.2μs/telescope	460ns/telescope
	4.6ms/Data-Packet	230μs/Data-Packet
storage on DLT	-	2.32ms/Data-Packet
storage on USB-Disk	-	1.01ms/Data-Packet
<i>Off-line operation^c</i>		
Initial peak position estimation	-	3ms
Peak detection, Gaussian peak fitting and Factor of Merit calculation	-	0.7 ms/peak

^a Adding charge label only in the PRESTO system.
^b The computational time depends on the number of telescopes contained in a Data-Packet (~500).
^c The off-line operations are executed when a telescope has collected 1000 new events.

Otherwise the different clusters can be labeled with a relative tag, but not unambiguously identified in charge. For the previous reaction, absolute charge identification has been performed in the range $15 \leq Z \leq 50$. In Fig. 2-b) a typical screen dump of the Graphic Station shows the results in the range $32 \leq Z \leq 50$. It has to be noted that Z-identification of the reaction products is performed only for ejectile peaks whose FoM is greater than 0.75, in order to assure acceptable charge identification. In Fig. 3 the FoM plots for the PIF spectra of $^{58}\text{Ni}+^{27}\text{Al}$ and $^{124}\text{Sn}+^{58}\text{Ni}$ reactions are shown.

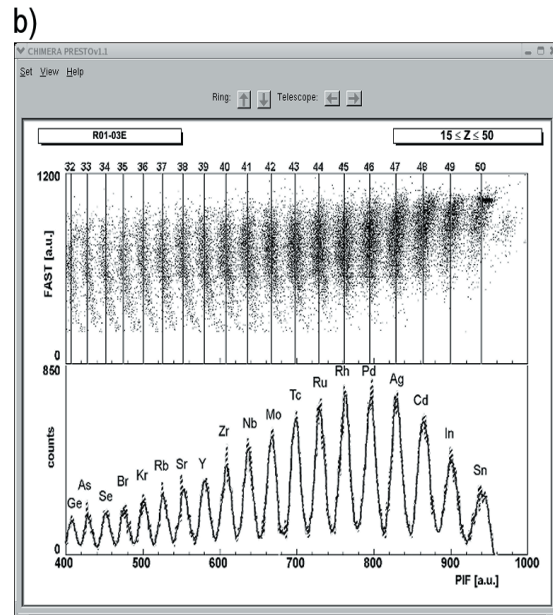


Fig.2 – a) The (ΔE , FAST) scatter plot for $^{124}\text{Sn}+^{58}\text{Ni}$ reaction at 35 MeV/u; the arrow indicates the cluster corresponding to the elastic scattering ($Z=50$). b) Screen dump of the Graphic Station for $^{124}\text{Sn}+^{58}\text{Ni}$ reaction at 35 MeV/u (see text). In the upper side a zoomed area of the (FAST, PIF) scatter plot, in the lower side the dashed curve indicates corresponding PIF spectrum and the solid curve the smoothed spectrum for identified peaks.

4 SUMMARY

In the present work we have verified the possibility to perform on-line computations in order not only to monitor the detector, but also to carry out real-time calculations on the collected data, having performed on-line charge tagging for different elements.

Indeed, the on-line processing time needed for labeling data with charge-tags does not considerably affect acquisition and storing frequency, and it is practically independent from the used algorithm, for not too complex calculations. Thus, other real-time computations can be performed on each collected event by PRESTO during measurements.

This approach can be valuably employed in many other cases. Using a multidetector allows for a variety of experiments to be performed, each one having its own peculiar characteristics, depending 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, event total charge or mass of the reaction products through the Mass Identification Function, given for the non-punching-through particles by the Time of Flight formula ($E \Delta T^2 \div A$).

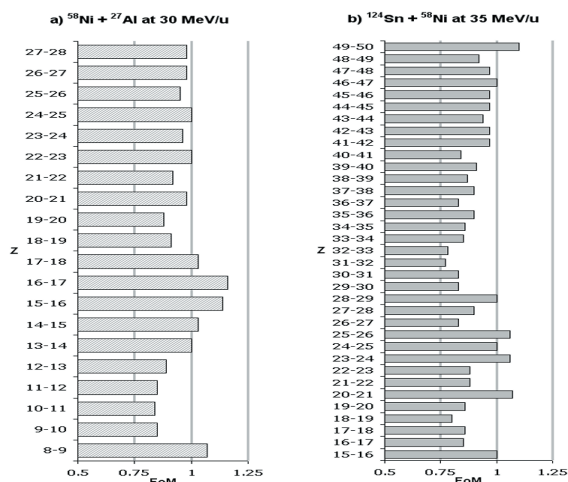


Fig.3 – a) The FoM plots of the PIF spectra for the $^{58}\text{Ni} + ^{27}\text{Al}$ reaction at 30 MeV/u. b) The FoM plots for the $^{124}\text{Sn} + ^{58}\text{Ni}$ reaction at 35 MeV/u.

5 REFERENCES

- [1] S. Aiello, et al., *Nucl. Phys.* A583 (1995) 461c.
A. Pagano, et al., *Nucl. Phys.* A681 (2001) 331c.
- [2] S. Aiello, et al., *Nucl. Instr. Methods*, A369 (1996) 50.
- [3] S. Aiello, et al., *IEEE Trans. Nucl. Sci.*, 45 (1998) 1798.
- [4] S. Aiello, et al., *IEEE Trans. Nucl. Sci.*, 47 (2000) 196.
- [5] F.S. Goulding and B.G. Harvey, *Ann. Rev. Nucl. Sci.*, 25 (1975) 167.
- [6] M. Alderighi, et al., *IEEE Trans. Nucl. Sci.*, 48 (2001) 385.
- [7] M. Alderighi, et al., *IEEE Trans. Nucl. Sci.*, 49 (2002) 432.
- [8] S. Aiello, et al., *IEEE Trans. Nucl. Sci.*, 45 (1998) 1877.
- [9] S. Aiello, et al., *IEEE Trans. Nucl. Sci.*, 47 (2000) 114.
- [10] Quantum Corp., <http://www.quantum.com/NR/rdonlyres/8101C3CA-9851-4792-9074-729A9CD1D2DA/0/dlt8000productmanual.pdf>
- [11] Hitachi Global Storage Technologies, [http://www.hitachigst.com/tech/techlib.nsf/techdocs/CF02BAB6EA8E3B7F87256C16006B1CFA/\\$file/HGSTDeskstar180GXP.PDF](http://www.hitachigst.com/tech/techlib.nsf/techdocs/CF02BAB6EA8E3B7F87256C16006B1CFA/$file/HGSTDeskstar180GXP.PDF)
- [12] Borland Software Corp., Borland Kylix 3.0 Enterprise Edition, <http://www.borland.com>
- [13] R.A. Winyard, et al., *Nucl. Instr. Methods*, 95 (1971) 141.
- [14] R. Brun and F. Rademakers, *Nucl. Instr. Methods*, A389 (1997) 81.
- [15] A. Mariscotti, *Nucl. Instr. Methods*, 50 (1967) 309.
- [16] R. Klopfenstein Jr, *ISA Trans.*, 37 (1998) 3.

TOF calibration of CHIMERA silicon detector.

G.Lanzalone^{a,b} for Isospin Collaboration.

a) INFN Laboratori Nazionali del Sud, Catania, Italy

b) Università degli Studi di Catania, Catania, Italy

** Corresponding author, e-mail: gaetano.lanzalone@ct.infn.it*

Abstract

A procedure for the time calibration for the 688 telescopes of the rings of the multidetector CHIMERA in the REVERSE 2000 campaign is described. The work was aimed to obtain reliable calibration procedures, by limiting the number of the parameters. It was found that the value of the time of flight depends on different causes, but the adopted procedure allows to calibrate in time every detector with a limited number of parameters. An extension of method is proposed for its application to recent experimental CHIMERA campaigns.

1 TOF MEANING IN REVERSE EXPERIMENT.

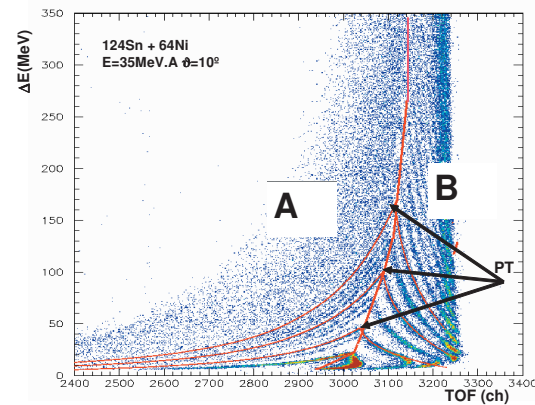
The time of flight (TOF) technique is a powerful tool to determine the velocity of the fragments produced in nuclear reactions[1]. In CHIMERA, this technique is the basic method to identify in mass the fragments stopped in the silicon detectors. The TOF measurement is thus practically performed by measuring the time difference between a reference signal (RF) delivered by the Super Conductor Cyclotron (SCC) and the signal generated by the silicon detector. This time difference is converted in a 12 bit integer - channel number- Tch, by a time to digital converter (TDC). This time difference includes the true TOF that the particle takes from the target to the detector, the time delays associated with cables and cyclotron phase, the pulse delay in the silicon detector. All this effects are included in a time constant t_0 dependent on the particular detector. Consequently, beside the TDC conversion factor α , the time calibration needs the accurate determination of this t_0 parameter. Basically, under the simple assumption of linear response function of the TDC (condition, fulfilled, in our case, with good approximation) the TOF is given by the linear expression, $\text{TOF} = \alpha(t_0 - t_{ch})$, where α (dispersion of the TDC) has a typical value of about 200ps/channel.

2 HOW TO DETERMINE T_0 PARAMETER.

In the determination of the parameter t_0 , we must distinguish two kind of detected particles:

i) particle stopped in the silicon detector are typically identified in mass (region A in Fig.1), according to the non relativistic kinetic energy formula $E \propto A(t - t_0)^{-2}$, where A is the particle mass number;

ii) which particles punching through (PT) the silicon detector are stopped in the CsI(Tl) and are identified in charge by the ΔE -E method (region B in Fig.1). In this case by combining both ΔE and TOF



information one obtain the relation: $\Delta E \propto Z^2(t - t_0)^2$, where Z is the atomic number.

In fig.1, as an example, the TOF- ΔE , matrix for a detector placed at $\theta=10^\circ$ for the reaction $^{124}\text{Sn} + ^{58}\text{Ni}$ at $E=35\text{MeV.A}$ is shown. The two different zones, A and B, are separated by a continuum curve connecting the punch through points (PT) of each atomic number Z.

2.1 A and B Zones.

The first step of procedure is aimed to determine possible dependences of the parameter t_0 on the energy and on the mass of the particles. Therefore, the classical kinetic energy formula (1):

$$E = \frac{1}{2}MV^2 = A \frac{D^2}{2\alpha^2} \frac{1}{(t_0 - t_{ch})^2} \quad (1)$$

where M is the mass of the particle and D is its flight distance from the target, is assumed to be valid. By inspecting Fig.1 we can identify three loci corresponding to the stopped particles with mass numbers $A = 7$, $A = 11$, and $A = 15$ (assumed as our standard), respectively. Assuming for each silicon detector an ideal, linear energy response function, independent on the charge and mass of the particle, it is easy to determine the dependence of the time parameter t_0 on the particle energy by inverting Formula (1).

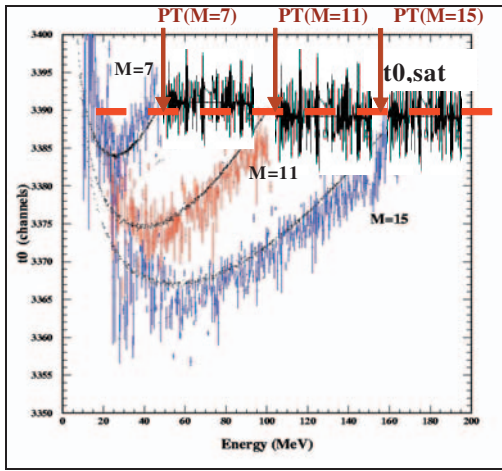


Figure 2. The t_0 parameter vs. particles kinetic Energy. The dependence from E and M is evident for stopped particles in the silicon detector. The $t_{0,sat}$ value (dashed line) is determinate for particles crossing the silicon detector, plotted on the right of the PT arrows.

In Fig. 2, the dependence of the parameter t_0 is shown for the three masses. Note that in the ideal case the parameter t_0 should be independent on the energy and the mass of the detected particle. Actually, such constancy is obtained within fit accuracy only for particles that punch through the active (depleted) layer of the silicon detector. The corresponding punch through energies have been indicated, for simplicity, by vertical arrows in Fig. 2 for the three different masses. Consequently, as results of our analysis, the desirable ideal behavior of the parameter t_0 , i.e., independence of particle mass and energy, has been obtained only for particle energies above ≈ 10 MeV/nucleon (Zone B, in fig. 1), where the universal value $t_{0,sat}$ has been indicated by a horizontal dashed red line.

By fitting the behaviour of t_0 , for stopped particles, it was possible to parameterize the experimental data by the semi empirical formula (2):

$$t_0 = t_{0,sat} + (S - R) * \left[0.1 * \sqrt{\frac{A_0}{E - c1}} - p * (1.0 - e^{-\frac{A_0}{c2}}) \right] \quad (2)$$

where R (calculated by an iterative procedure) represents the range in silicon for particles of atomic mass A_0 and kinetic energy E ; $c1$, $c2$, p are characteristic parameters of the detector.

The variation of t_0 with energy is simply interpreted in terms of a pulse shape dependence of the detector timing response due to variations in charge collection times. These effects are expected to be of the order of a few ns in the case of a front injection configuration [2]. Our analysis gives a maximum variation of t_0 of about 3ns.

2.2 Short $t_{0,sat}$ Procedure.

In order to shorten the time-consuming calibration procedures, it was necessary to establish a protocol, which is described in the following.

As a first simplification, the parameters of the fit $c1$, $c2$ p were set equal for groups of detectors within the accuracy of 0.8%. All adopted values have been tabulated and stored for time calibration. In order to evaluate t_0 saturation value of formula (2), we adopted an automatic fitting procedure, requiring an injection value of t_0 that was evaluated by the punching through for alpha particle. Then, velocity spectra as evaluated by the TOF method, $VelT = D/\alpha(t-t_0)$ and velocity spectra as evaluated by the Kinetic energy relation, $VelE = \sqrt{(2E/M)}$, were compared by a fitting procedure. The t_0 was extracted by requiring the condition $VelE = VelT$. The difference between the $VelT$ and $VelE$ spectra have been valuated with different procedures and Kolmogorof criteria [3]. In order to minimize for possible non linearity in the energy calibration and pulse defects (PHD), the time velocity spectra ($VelT$) have been constructed for particles of zone B and charge $Z=6$ (Carbon). Notice that the energy spectra for punching through particles have been obtained by the range-energy table once the ΔE value is measured in the silicon detector. This procedure has tendency to over-estimate the high energy part of the spectra. So, we further restrict the analysis for values $VelE < 7.0$ cm/ns. The automatic procedure is able to normalize all the spectra of the same ring. The high number of detectors suggested to carry out an automatic procedure.

The idea was to take advantage of the fact that in a bi-dimensional scatter plot, $VelT-VelE$, in the ideal case of perfect evaluation of t_0 , one must obtain a straight line, exactly at the bisector of the first quadrant.

Several fits has been performed shifting the $t_{0,sat}$ value between -15 and +15 channels in a step of 0.5 ch; the

chi-square values of these fits have been compared and the minimum has been assumed as the best $t_{0,sat}$.

A graphical example of the output procedure is illustrated in the Fig. 3.

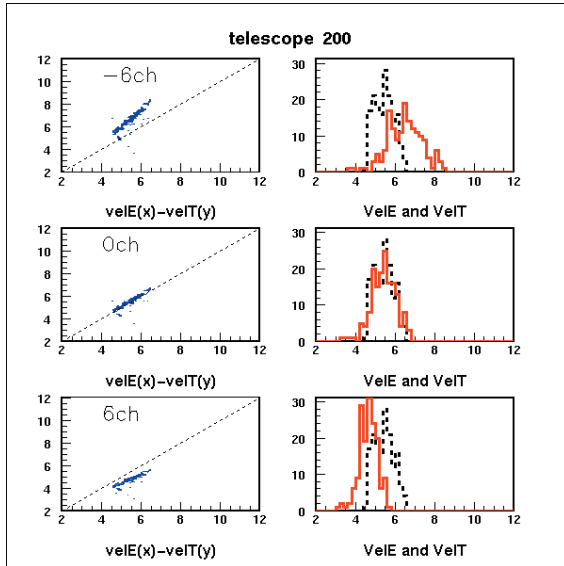


Figure 3 Graphical example of the program output. On the left the matrixes (VelE-VelT) for three different time shifts (it has been summed at $t_{0,sat}$ respectively the values -6, 0 and +6 channels). It is visible that, in this case, is not necessary time shift. On the right the three one-dimensional spectra correspondent with VelE (dash line) and VelT (continuous line).

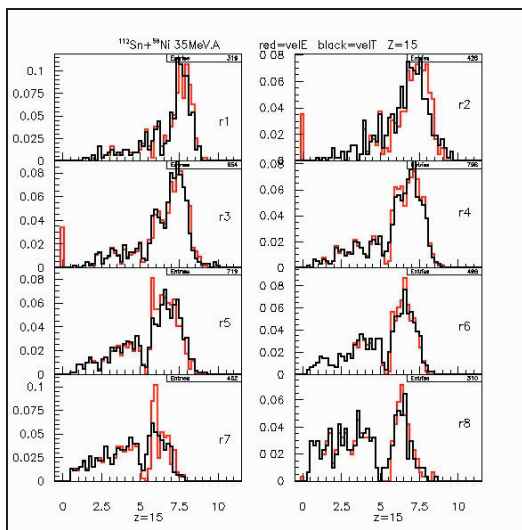


Figure 4. Comparison between VelE and VelT for different rings (1 up to 8) and charge=15.

2.3 Verifications.

Controls and verifications have been made for all the detectors and for the charge Z=6 up to Z=25.

A good agreement has been found for charges up to Z=25. The Fig. 4 shows the spectra for the charge Z=15. Note the good superimposition between the VelE and VelT spectra.

In the 18% of total number of detectors we found some problems not solvable by the fit. These detectors were classified by a time-code from 1 to 9, while also the good detectors were classified by time-code=0.

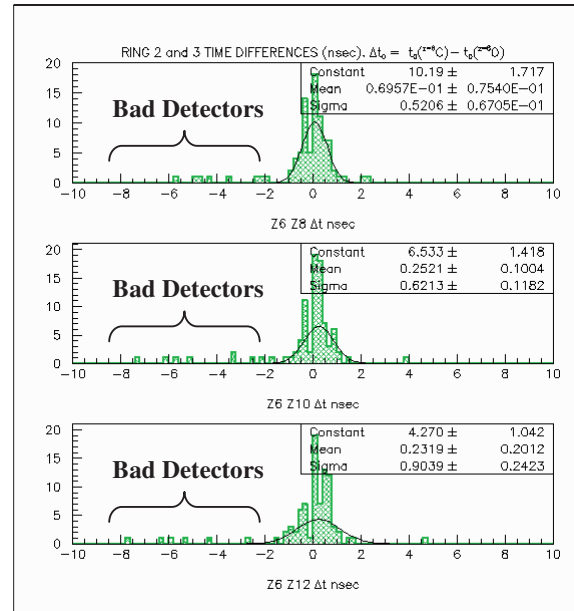


Figure 5. The distribution of differences ($t_{0,sat,Z=6}^{124Sn} - t_{0,sat,Z=8}^{124Sn}$, $t_{0,sat,Z=6}^{124Sn} - t_{0,sat,Z=10}^{124Sn}$, $t_{0,sat,Z=6}^{124Sn} - t_{0,sat,Z=12}^{124Sn}$) is shown. Also the bad detectors are indicated.

Other interesting information on the detectors performances were obtained by using different automatic procedures and the results were compared. As an example of such evaluation, the distributions of the difference between the $t_{0,sat}$ value for Z=6 (standard) and other values of $t_{0,sat}$ obtained selecting three different charge, Z=8, Z=10 and Z=12, have been plotted in figure 5 with a superimposed Gaussian fits. All the bad detectors are localized in a far zone external to Gaussian. In fact for these detectors the time differences are greater that 3 nsec.

2.4 Recursive work.

This method has applied first on the reaction $^{124}\text{Sn} + ^{64}\text{Ni}$ $E=35\text{MeV.A}$ and then by means the “short $t_{0,\text{sat}}$ procedure” on the reactions : $^{124}\text{Sn} + ^{27}\text{Al}$ $E=35\text{MeV.A}$ and $^{112}\text{Sn} + ^{58}\text{Ni}$ $E=35\text{MeV.A}$.

The $t_{0,\text{sat}}$ values have been obtained and compared for all the detectors.

In particular, it has been found that the distribution of the differences between the parameter $t_{0,\text{sat}}$ of the first reactions and those of other reactions follows a Gaussian behaviour. This Gaussian have a mean value

$\overline{\Delta t_{0,\text{sat}}}(\text{ch})$ and root mean square $\sigma_{\Delta t_{0,\text{sat}}}(\text{ch})$:

Reaction	$\overline{\Delta t_{0,\text{sat}}}(\text{ch})$	$\sigma_{\Delta t_{0,\text{sat}}}(\text{ch})$
$^{124}\text{Sn} + ^{27}\text{Al}$	0	5.4
$^{112}\text{Sn} + ^{58}\text{Ni}$	180	5.8

The differences found between the values of $t_{0,\text{sat}}$ in the three reactions evidenced the existence of a constant value shift is approximately equal to 180 channels. As expected, this value is consistent with the phase shift associated with the change of the particle beam and/or beam energy.

This result implies that for the next measures (2003 and 2004 campaign) it will be necessary to calibrate only few detectors by evaluating this constant shift respect to the previous t_0 evaluation. Consequently, the result will be extended to all the detectors. A preliminary work has been done on the new ISOSPIN 2003-2004 campaign data, and it seems to confirm this witty forecast [4].

REFERENCES

- [1] W. F. Schneider et al., Nucl. Instr. And Method. 87, **253** (1970)
- [2] LNS Activity Report INFN 2002, Catania, Italy <http://www.ct.infn.it/~webcom3/esperimenti2001/sommario/reverse.pdf>, M.Alderighi et al. NPA 734 (2004) E88-E91; J. B. A. England, G. M. Field and T. R. Ophel, Nucl. Instr. & Meth. **A280** (1989) 291.; G. Pausch, W. Bohne and D. Hilscher, Nucl. Instr. & Meth. A 337 (1994) 573.
- [3] Kolmogorov, W.T.Eadie et al., Statistical Methods in Experimental Physics. North.Holland,1971
- [4] I.Berceano, Private Communication, 2005 , A.Pagano, contribution to LNS Calibration meting –February 21th 2005.

DIGITAL SIGNAL PROCESSING FROM CHIMERA: PULSE SHAPE ACQUISITION FOR CHARGE DISCRIMINATION FROM FRONT MOUNTED SILICON DETECTORS

F.Amorini^a, A.Anzalone^a, R.Bassini^b, C.Boiano^b, G.Cardella^c, S.Cavallaro^a, E.DeFilippo^c, P.Guazzoni^{b,*},
E.LaGuidara^a, G.Lanzanò^c, G.Lanzalone^a, C.Maiolino^a, A.Pagano^c, S.Pirrone^c, G.Politi^c, F.Porto^a, F.Rizzo^a,
S.Russo^b, P.Russotto^c, G.Saccà^c, M.Sassi^b, L.Zetta^b

a) INFN Laboratori Nazionali del Sud, Catania, Italy

b) Dipartimento di Fisica dell'Università and INFN Milano, Italy

c) INFN Sezione di Catania, Italy

** Corresponding author, e-mail: paolo.guazzoni@mi.infn.it*

Abstract

Digital pulse shape technique has been applied to the charge discrimination of the products stopped in the CHIMERA large area totally depleted planar silicon detectors (5 cm x 5 cm area, 300 μ m thick), used in front side injection. Full charge identification for the reaction products up to $Z = 11$ has been obtained for products both crossing (ΔE -E technique) and stopping in the silicon detector, using a 21 AMeV ^{20}Ne beam. The quality of the obtained results clearly indicates that the digital signal processing approach is able to give excellent results in this application, too.

1 INTRODUCTION

In view of the new 4π -Detector Array projects [1] we present the results for charge identification obtained using the pulse shape discrimination via digital pulse shape acquisition technique. The results confirming the feasibility of (ΔE ,E) charge identification, (Fast,Slow) LCP isotopic identification for CHIMERA detection cells, and charge identification in reverse mounted silicon detectors by using digital pulse shape acquisition have been already presented [2]. This contribution shows the results obtained for the charge identification of the products stopping in the totally depleted CHIMERA silicon detectors, in realistic experimental conditions, using front side injection. We used a very simple analog front end and digital pulse processing of signals directly collected from the preamplifier [3].

2 EXPERIMENTAL SET-UP

The sampling analog to digital converters (SADC) used are SIS3301 [4] VME modules. SIS3301 is an 8-channel digitizer/transient recorder with a sampling rate of up to 100 MHz for the individual channel and a 14-bit resolution. It manages a dual memory bank, a multievent functionality and pre/post trigger capability.

For the present tests we have used a simple real-time architecture based (Fig.1) on two new generation PCs (2 GHz, Linux O.S.) and a PCI-VME bridge [4], the SIS1100/3100 PCI-to-VME interface, allowing for a transfer rate of 80 MB/s (2eVME protocol). The bridge permits to manage SADCs and to transfer the collected samples to the PC station. The first PC operates as supervisor to collect and reorganize samples. It is

connected through a 1 Gb/s Ethernet to the second PC, used as graphic and computational unit. The different SADCs (three in the present tests) are located in a VME crate together with SIS3100, the VME-side of the bridge module, used both as VME bus master and to monitor SADCs. It is optically connected to SIS1100, the PCI-side located in the supervisor.

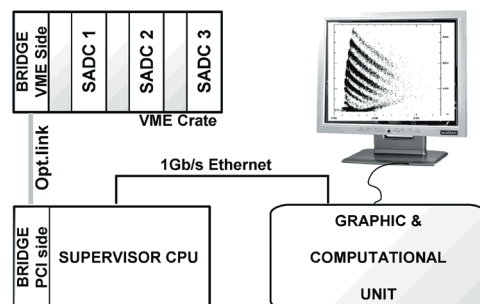


Fig. 1: The used simplified real-time H/W architecture.

The acquisition program is written in C++, runs under Mandrake Linux 9.2 and uses the Kylix 3.0 Graphic User Interface (GUI) Borland Component Libraries.

3 EXPERIMENTAL RESULTS

Charge identification has been obtained for the reaction products stopping in silicon detector (E_{Si} -RT technique). The measurement has been done as parasitic test during an Intermediate Energy experiment with the multidetector CHIMERA in its final 4π -configuration (1192 telescopes). Silicon detectors in the 3rd and in the 5th wheel have been used in front mount configuration.

In fact, in the standard CHIMERA mounting, silicon detectors are front mounted and slightly overbiased in order to obtain a fast timing signal for Time of Flight (ToF) measurements, allowing for mass identification, too.

With regards to the data processing, waveforms of 2048 consecutive samples are collected at 10 ns time intervals and stored in the SADC memory banks in wrap-around mode. For each event a post-trigger is used to stop the sample collection. The pulse-form for each event parameter is reconstructed and stored.

Each signal is filtered digitally by means of a simple triangular filter [5], using a symmetric triangle with a time baseline of 11 samples (110 ns at 100 MSamples/s) as kernel. The use of post-trigger allows for an accurate baseline restoring of each pulse, before the pulse height computation. The rise time of pulses is calculated as the time taken to traverse the region between 10% and 90% of the full pulse height relative to the baseline, thus obtaining a realistic rise time value. The algorithm is based on a linear interpolation around each crossing point, using a five-sample range.

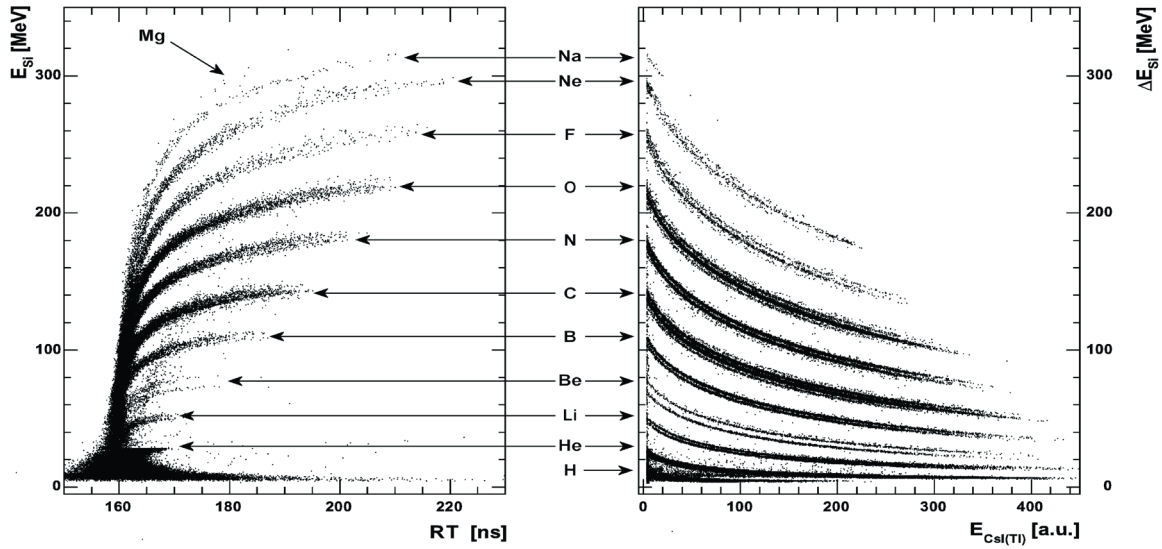


Fig. 2: Front side injection, $^{20}\text{Ne} + ^{12}\text{C}$ reaction at 21 MeV/u; (E_{Si} -RT) scatter plot (left) and (ΔE_{Si} - $E_{\text{Csl(Ti)}}$) scatter plot (right).

In Fig. 2 the results obtained for the reaction $^{20}\text{Ne} + ^{12}\text{C}$, at $E_{\text{inc}}(^{20}\text{Ne}) = 21$ AMeV are shown for a detector of the 5th wheel ($\theta_{\text{lab}} = 11.5^\circ$). The bias was $V = -55\text{V}$, the working bias normally used to obtain also a good timing signal for ToF measurements.

The obtained results are very good. In Fig. 3, the particle identification spectrum obtained by projecting the properly linearized (E_{Si} -RT) scatter plot of Fig. 2 is shown. It clearly appears that not only a good charge identification is obtained (the FoM value ranges from 0.97 up to 4.48 for all the $Z > 1$), but that isotopic identification in the range $2 \leq Z \leq 5$ is possible as well, for products stopping in silicon detector.

Finally we performed two other tests changing the bias voltage of the silicon detector; one with the detector overbiased (-66V) and the other with the detector underbiased (-44V).

As shown in the Fig. 4 in all the three cases charge identification is possible. As expected the overbiased spectrum is the worst, due to saturation of rise times to the highest values. However, it should be remarked that also with the detector at working bias (i.e. in conditions good for ToF measurements) good charge identification is achieved for the products stopping in the silicon detectors, as previously discussed.

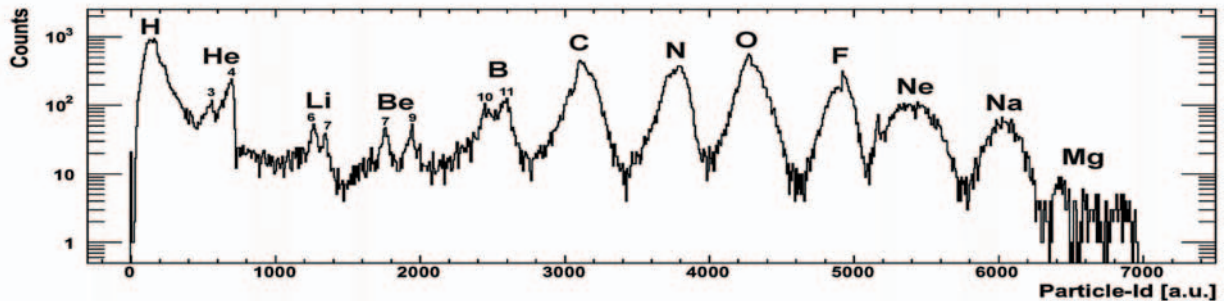


Fig.3: Particle identification spectrum obtained by projecting the properly linearized (E_{Si} -RT) scatter plot of Fig. 2 on the particle id-axis.

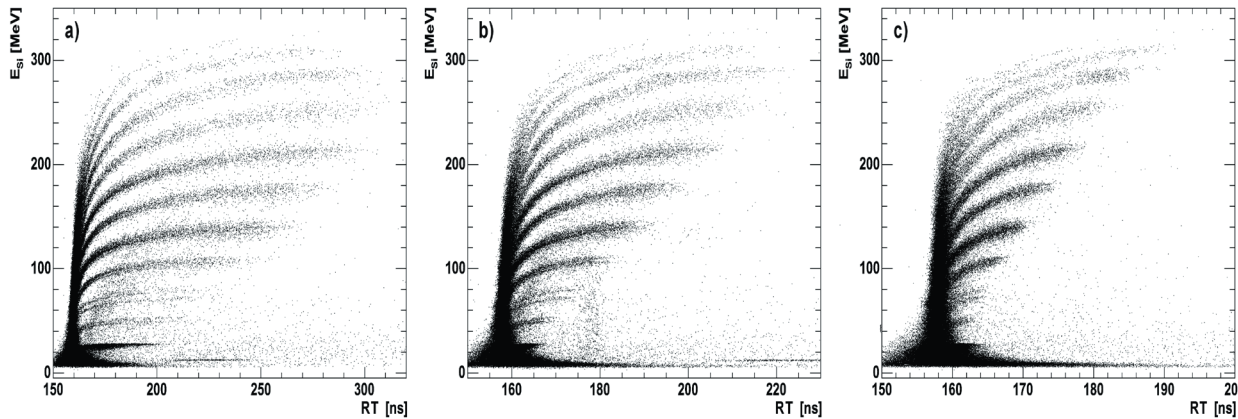


Fig. 4: (E_{Si} -RT) scatter plot for the $^{20}\text{Ne} + ^{12}\text{C}$ reaction. a) underbiased detector (-44V). b) working-mode-biased detector (-55V). c) overbiased detector (-66V).

4 SUMMARY

The quality of our on-beam results demonstrates that digital signal processing approach is able to give excellent results not only in the acquisition of “standard” scatter plots of a multidetector, such as (ΔE -E) and (Fast-Slow), but also in Z-identification of reaction products stopped in silicon detectors, both reverse and front mounted.

Employing the large area (5 cm x 5 cm), high capacitance (~ 1 nF), 300 μm thick CHIMERA planar silicon detectors, we have identified elements up to Na in a wide dynamic range.

It can be accordingly stated that the rise time technique can successfully supplement, even in the framework of digital pulse shape acquisition, Z-identification performed with (ΔE -E) technique.

Moreover the achieved Z-identification, using silicon detectors with front side injection and slightly overbiased to allow for Time of Flight measurement,

clearly shows that this method is an ideal complement to the time of flight method in order to perform full mass and charge identification for the products stopped in silicon detectors.

5 REFERENCES

- [1] www.ganil.fr/eurisol/instrumentationgroup/meetings/reaction-subgroup/Reactions_Legnaro_06-04-01.pdf.
www.finuphy.org/doc/new_joint_research_projects_I3NS.pdf.
- [2] M. Alderighi, et al, Conf. Record Archive, N13-1, 2004 IEEE NSS-MIC, Roma, 2004;
 LNS Activity Report 2003, p. 110, 113, 116.
- [3] M. Alderighi, et al, IEEE-TNS, 51 (2004)1475.
- [4] SIS GmbH, Hamburg, Germany.
- [5] V.T. Jordanov and G.F. Knoll, Nucl. Instrum. Methods, A345(1994)337.

Energy and time calibration and particle identification for the MIDVELOCITY experiment

S.Piantelli^a, P.Marini^a, A.A.Stefanini^a, M.Calviani^a, L.Bardelli^a, M.Bini^a, M.Bruno^b, G.Casini^a, B.Guiot^b,
P.R.Maurenzig^a, P.Milazzo^f, A.Olmi^a, G.Pasquali^a, G.Poggi^a, G.Vannini^b for the NUCL-EX collaboration*

^a *Sezione INFN di Firenze and Dipartimento di Fisica Università di Firenze,*

Via G. Sansone 1, I-50019 Sesto Fiorentino, Italy

^b *Dipartimento di Fisica and INFN, Bologna, Italy and*

^f *INFN Trieste, Italy*

G.Lanzalone^c, G.Cardella^d, C.Maiolino^c, F.Amorini^c, E.La Guidara^c, S.Pirrone^d,
A.Pagano^d, G.Politi^d, F.Rizzo^c, M.Papa^d, E.De Filippo^d, A.Trifirò^e, L.Auditore^e,
M.Trimarchi^e, Salv.Cavallaro^c, F.Porto^c, P.Russotto^c, E.Galichet^c, A.Pop^c

^c *INFN-LNS and Dip. di Fisica e Astr. Univ. di Catania*

^d *INFN-Sezione and Dip. di Fisica e Astr. Univ. di Catania and*

^e *INFN Gr. Coll. Messina*

The energy and time-of-flight calibration for the Silicon detectors and the particle identification for the Silicon-CsI(Tl) telescopes for the MIDVELOCITY experiment performed with the CHIMERA detector in March-April 2004 are presented.

PACS numbers:

I. THE EXPERIMENT

The MIDVELOCITY experiment was proposed by the NUCL-EX-DYNA collaboration with two main aims. The first one is the investigation of the dependence of the midvelocity emission (see for example [1][2][3][4] and references therein) on the size of the system. The second one is to determine the reference frame where the midvelocity emission takes place i.e. the center of mass of either the nucleus-nucleus or the nucleon-nucleon system. A measurement in March-April 2004 for the systems $^{58}\text{Ni} + ^{112}\text{Sn}$, ^{58}Ni at 45.4 MeV and 35.4 MeV and $^{112}\text{Sn} + ^{112}\text{Sn}$, ^{58}Ni at 35.4 MeV was performed at LNS by means of the CHIMERA[5] detector in its complete configuration (1192 detectors). Particular care was taken in reducing the detection thresholds to enhance the detection efficiency of heavy fragments in peripheral and semiperipheral collisions, where midvelocity emission is particularly evident.

At present the calibration work is in progress; this report shows preliminary results on this topic.

II. ENERGY CALIBRATION FOR THE SILICON DETECTORS

The energy calibration procedure for the Silicon detectors consists of the following steps:

1. pulser calibration in order to determine the

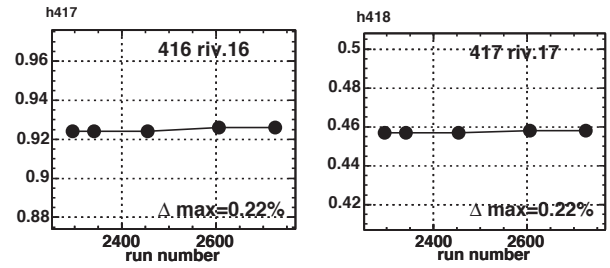


FIG. 1: Slope parameters extracted from 5 different pulser runs for two typical Silicon detectors (Low Gain) of RI7; the maximum percentage variation of the parameter is indicated on each panel

mV/chan factor and the offset in mV for both the Low and the High Gains;

2. centroid determination of the elastic peaks (in channels) for low energy reactions and for a three-peak alpha source;
3. after applying the conversion factor from channel to mV, fitting all the available low energy peaks for a given detector in order to extract the MeV/mV factor;
4. checking of the obtained value by means of punching through alpha particles and/or elastic ions in high energy reactions.

Details of the outlined procedure now follow:

During the measurement we performed about 20 pulser runs in order to check the electronic stability. At present,

*Corresponding author; S.Piantelli, piantelli@fi.infn.it

of all the available pulser data, we analyzed 5 runs. The pulser spectra are in general quite good for more than 80% of the detectors, with two well-identified reference peaks (100mV for the High Gain and 1000mV for the Low Gain).

Linear fits to extract the slope (mV/chan) and the offset (mV) for each detector (Low and High Gains) have been performed. In this way the matching between the Low and the High Gain scale is (in principle) automatic. In general the stability of the extracted parameters during the measurement campaign is quite good, as put in evidence by the example reported in figure 1 for two typical detectors (maximum variation of the slope parameter smaller than 0.5%). The calibration parameters are quite similar (except for the gain changes) to those extracted for the 2003 campaign.

Concerning point 2, we identified the elastic peak associated to some low energy beams (${}^7\text{Li}$ at 38.6MeV, ${}^{16}\text{O}$ at 60MeV, ${}^{19}\text{F}$ at 100.06MeV) and the three peaks of an alpha source.

In figure 2 (top four panels) the elastic peaks for the detector #714 are presented; the peak channel-centroid was extracted by means of a Gaussian fit (dashed curve). All the six peaks were available for this detector, but in general this is not the case. After identifying the channel-centroid of all the available peaks for a given detector, the proper calibration factor (depending on the used gain) mV/chan and the offset are applied to obtain the mV-centroids. Finally a linear fit with the constant term fixed to 0 is performed in order to evaluate the MeV/mV factor, which is now unique for both Low and High Gains. An example of the fit is presented in figure 2 (bottom panel).

On the basis of the known or measured detector thickness the obtained energy calibration was checked by means of punching through alpha particles, identified on energy-time-of-flight spectra, and (where possible) by punching through high energy elastic ions (in particular for the ${}^{58}\text{Ni}$ at 35.4MeV beam). For the largest part of the detectors there generally is a reasonable agreement between the experimental value of the energy of the punching through alpha particles and the expected value. Some detectors (mainly located in the first ring, internal and external) show, on the contrary, experimental values significantly smaller than the expected ones, probably due to radiation damage (as suggested also by the rounded shape of the cusp in the energy vs. time-of-flight spectra).

For about 100 detectors, mainly located in the Sphere (S14-S19), neither low energy beams nor the alpha source points are available; for these detectors the calibration parameter MeV/mV was directly extracted from punching through alpha particles taking into account the detector thickness; in this case no independent check of the energy calibration was possible.

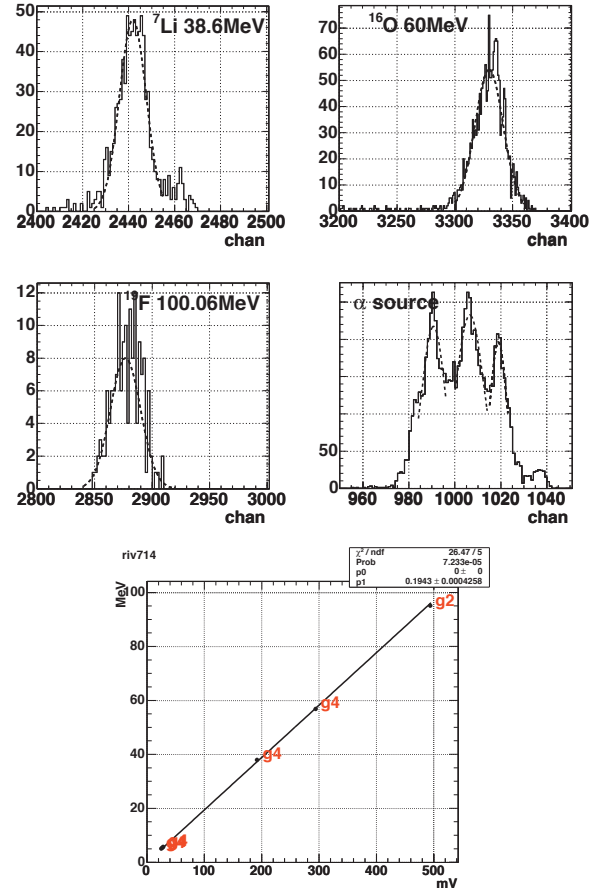


FIG. 2: Four top panels: Energy spectra for low energy beams for the detector #714. The superimposed dashed curves are the result of a Gaussian fit to identify the elastic peak position (the scale is in channel). Bottom panel: Linear fit to obtain the MeV/mV conversion factor. g2(4) indicates that the low energy spectrum was produced with gain 2(4).

III. CHARGE AND MASS IDENTIFICATION FOR THE SILICON -CSI(TL) TELESCOPES

The charge and mass identification was performed on the Silicon vs. CsI(Tl)Fast spectra with both scales in mV. The technique used to extract the calibration parameters (slope mV/chan and offset mV) for the CsI(Tl)Fast is the same used for the Silicon detectors. However, at variance with respect to the Silicon detector case, larger non-linearities are observed. As a consequence it was necessary to tune the calculated offset in order to obtain a satisfactory matching between the Low and the High Gains. The particle identification took advantage of the technique described in [6]. An example of the obtained mass spectra for different charges is presented in figure 3 for the detector #692. In general, mainly for the detectors of the Sphere, a very good isotopic separation for $Z \leq 5 \sim 6$ is obtained.

Up to now we performed the Si-CsIFast particle iden-

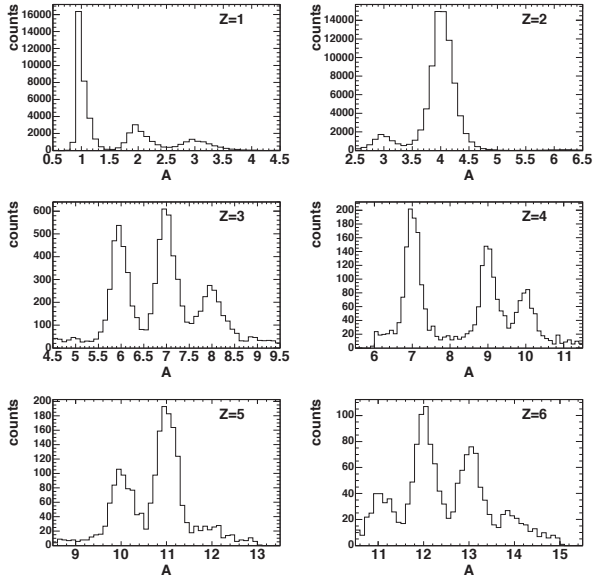


FIG. 3: Preliminary results: mass spectra for detector #692. Each panel corresponds to ions of different charge from $Z=1$ to $Z=6$

tification for the system $^{58}\text{Ni} + ^{112}\text{Sn}$ at 35A MeV . At present the charge identification and energy calibration has been obtained for about 65% of the detectors; for most of them also the mass identification was possible.

We are going to export the traced lines also to the other measured systems. In principle the exporting procedure is straightforward, because the spectra are in mV and the pulser should correctly keep trace of all the changes and instabilities.

IV. TIME CALIBRATION

The first step in time calibration was the determination of the conversion factor f_{ns} between TDC channels and nanoseconds. Profiting of dedicated timing pulser runs, the f_{ns} factor has been measured for almost all detectors by linearly fitting the time dependence of the pulser peaks.

A similar procedure was applied in the 2003 Chimera campaign. A comparison between the two sets of factors has been performed and is shown in fig. 4. Good long term stability has been found (within 2% for almost all TDCs).

As an internal check of the measured f_{ns} factors, the time distance between main and spurious peaks in elastically fired detectors has been measured. Depending on the TDC channel region where the data were collected, the linear time calibration underestimated more or less the known beam repetition period (0-0.5 ns underestimate out of ~ 130 ns). Better agreement has been found by using quadratic calibration (see fig. 5).

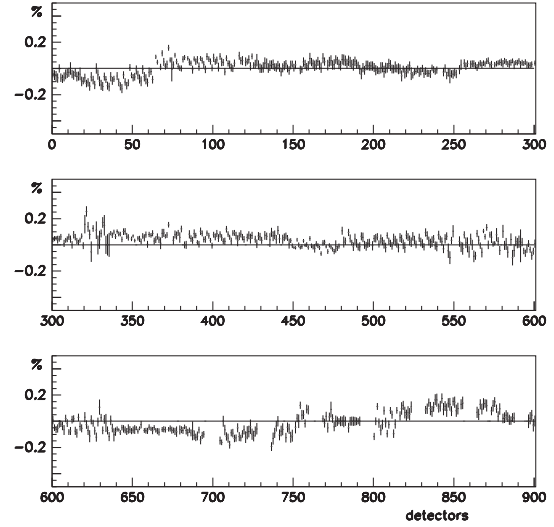


FIG. 4: Relative difference between the f_{ns} TDC factors in 2004 and 2003 CHIMERA campaigns

The second step in the time calibration has been the determination of the relative time offset for all detectors. This task is easily performed for the detectors where elastically scattered projectiles are measured. For all the other detectors and for all the other particles the offset determination necessarily passes through the energy measurement, allowing the determination of the energy

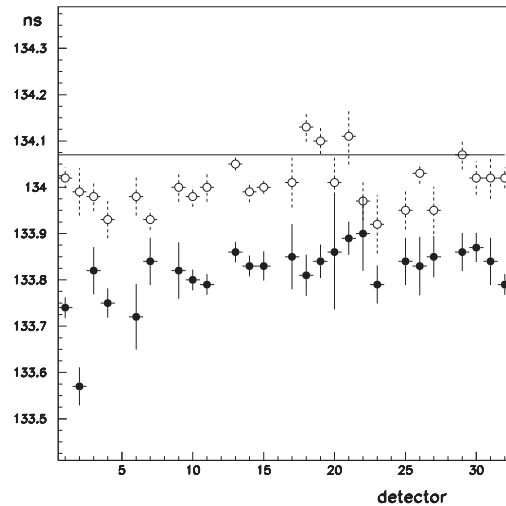


FIG. 5: Distance between main and spurious peaks in time spectra of elastically fired detectors: full symbols correspond to linear time calibration, while the empty ones crosses are for the quadratic fit. The horizontal line corresponds to the known radiofrequency period.

and mass dependence of the relative offset[7]. This task is at present in progress.

V. ACKNOWLEDGMENTS

The NUCL-EX DINA collaboration would like to thank the technical staff of INFN Catania and LNS, for

skillful operating of the whole apparatus and for continuous support during the analysis.

Special thanks are due to the Tandem and Cyclotron staff of the Laboratori Nazionali del Sud and particularly to Dr. D.Rifuggiato for having provided beams of very good timing and stability (time resolution $\lesssim 1$ ns FWHM).

-
- | | |
|---|--|
| [1] C.P.Montoya <i>et al.</i> , <i>Physical Review Letters</i> 73 (1994) 3070 | [5] S.Aiello <i>et al.</i> , <i>Nucl. Phys. A</i> 583 (1995) 461 |
| [2] J.Lukasik <i>et al.</i> , <i>Physical Review C</i> 55 (1997) 1906 | [6] N.LeNeindre <i>et al.</i> , <i>NIMA</i> 490 (2002) 251 |
| [3] E.Plagnol <i>et al.</i> , <i>Physical Review C</i> 61 (2000) 014606 | [7] G.Lanzalone, <i>Private communication</i> |
| [4] S.Piantelli <i>et al.</i> , <i>Physical Review Letters</i> 88 (2002) 052701 | |

DIELECTRON SPECTROMETRY WITH HADES

P.Finocchiaro^a and P.Salabura^{b,c} for the HADES collaboration

- a) INFN Laboratori Nazionali del Sud, Catania, Italy*
- b) Smoluchowski Institute of Physics, Jagiellonian University of Cracow, 30059 Cracow, Poland*
- c) Gesellschaft für Schwerionenforschung mbH, 64291 Darmstadt, Germany*
- d) Institute of Physics, Slovak Academy of Sciences, 84228 Bratislava, Slovakia*
- e) Dipartimento di Fisica e Astronomia, Università di Catania, 95125, Catania, Italy*
- f) Joint Institute of Nuclear Research, 141980 Dubna, Russia*
- g) Institut für Kernphysik, Johann Wolfgang Goethe-Universität, 60486 Frankfurt, Germany*
- h) II.Physikalisches Institut, Justus Liebig Universität Giessen, 35392 Giessen, Germany*
- i) Istituto Nazionale di Fisica Nucleare, Sezione di Milano, 20133 Milano, Italy*
- j) Dipartimento di Fisica, Università di Milano, 20133 Milano, Italy*
- k) Institute for Nuclear Research, Russian Academy of Science, Moscow, 117259 Moscow, Russia*
- l) Institute of Theoretical and Experimental Physics, 117218 Moscow, Russia*
- m) Moscow Engineering Physics Institute (State University), 115409 Moscow, Russia*
- n) Physik Department E12, Technische Universität München, 85748 Garching, Germany*
- o) Department of Physics, University of Cyprus, 1678 Nicosia, Cyprus*
- p) Institut de Physique Nucléaire d'Orsay, CNRS/IN2P3, 91406 Orsay Cedex, France*
- q) Nuclear Physics Institute, Academy of Sciences of Czech Republic, 25068 Rez, Czech Republic*
- r) Institut für Kern- und Hadronenphysik, Forschungszentrum Rossendorf, PF 510119, 01314 Dresden, Germany*
- s) Departamento de Física de Partículas. University of Santiago de Compostela. 15782 Santiago de Compostela, Spain*
- t) Instituto de Física Corpuscular, Universidad de Valencia-CSIC, 46100-Burjassot, Valencia, Spain*

Abstract

The High Acceptance DiElectron Spectrometer (HADES) has been recently commissioned at GSI Darmstadt. It has been designed to study hadron properties inside nuclear matter via measurements of dielectron decays in proton, pion and heavy ion induced reactions in 1 - 2 AGeV energy range. We report preliminary results on invariant masses of e^+e^- pairs measured in $^{12}\text{C} + ^{12}\text{C}$ collisions at $E = 2$ AGeV and compare them to simulations based on UrQMD transport model.

1 INTRODUCTION

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

Within such a scenario we try to understand the nuclear matter behavior in terms of an equation of state that, connecting variables such as pressure, temperature and density could provide an explanation to the multi-fragmentation of the colliding nuclei as a liquid-gas phase transition.

At even higher energies, above 1 A GeV, a large fraction of the beam energy is transferred into the excitation of nucleon resonances and meson production.

This exotic phase of nuclear matter is called hadronic matter [1]. At even higher densities and temperatures, of the order of $T=170$ MeV, a new nuclear matter phase characterized by the melting of hadrons into a plasma of quarks and gluons is expected to occur[2].

The investigation of the nuclear matter phase diagram in such a broad range of temperatures and/or densities offers a unique way to study the strong interaction and its theory, Quantum Chromodynamics (QCD), in a region of transition from hadronic to partonic degrees of freedom.

In this context, fundamental symmetries, spontaneous symmetry breakdown and the mass generation mechanism are of particular importance. One of the most important symmetries of QCD is the chiral symmetry. The QCD Lagrangian exhibits this symmetry in the limit of massless quarks. As a consequence, left and right handed quarks decouple and "handedness" is conserved in strong interactions. In spite

of the small current mass of the (u,d) quarks this symmetry is considered to be approximately valid. It is commonly believed that chiral symmetry is spontaneously broken by a non-trivial feature of the QCD vacuum, namely the existence of long-range quark-quark correlations resulting in the appearance of a quark condensate [3]. “Dressing” of quarks by the quark condensate is responsible for the generation of constituent quark and hence hadron masses. Moreover, the quark constituent masses appear in this picture as dynamical quantities depending on the temperature and/or density of the surrounding nuclear matter.

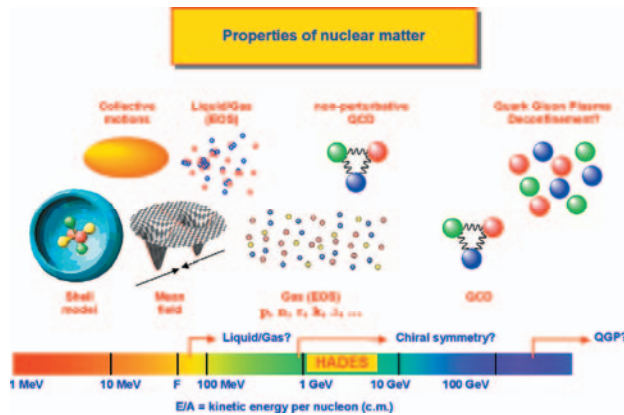


Figure 1 - Properties of nuclear matter as a function of the collision energy.

Several authors have predicted that partial chiral symmetry restoration occurs even at moderate temperatures and nuclear matter densities [4]. For example, in Fig.2 we show the result of calculations based on the Nambu-Jona-Lasino (NJL) model [5]. It shows a reduction of the “up/down” constituent quark mass as a function of temperature and/or density. The underlying mechanism responsible for this remarkable phenomenon is the melting of the quark condensate in hot and/or dense nuclear matter. This situation is somehow similar to the formation of Cooper pairs in a superconductor below the critical temperature and its disappearance at higher temperatures. Catalysts of this process are long-range interactions of electron pairs via phonon exchange in a crystal lattice.

The connection between the quark condensate and hadron properties cannot be derived in a model independent way. However, there are models (i.e NJL) that illustrate possible mechanisms of chiral symmetry breakdown. The most popular hypothesis is the so-called linear sigma model, which implies that the hadron masses (i.e nucleon) are generated by the coupling to pion and sigma meson fields, appearing as a consequence of spontaneous symmetry breakdown and signaling a new vacuum ground state [3]. The scalar sigma field, representing the vacuum expectation value, appears to have a much larger mass than its chiral partner, the pion, and this breaks chiral symmetry. The latter feature, the absence of parity doublets in hadron spectra, can be

observed for all hadrons species and is a clear manifestation of chiral symmetry breakdown.

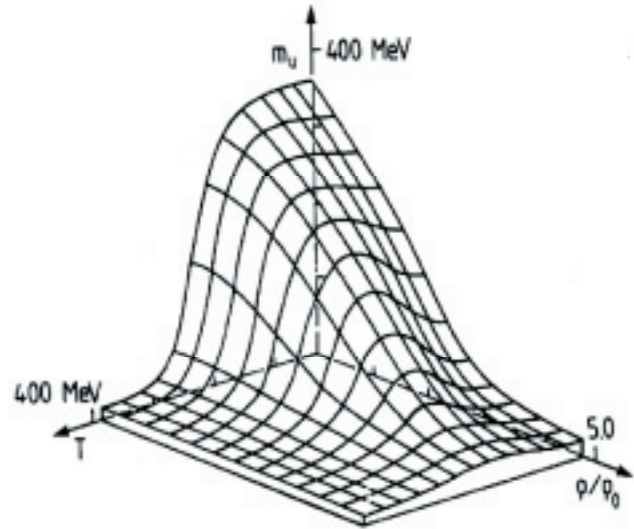


Figure 2 - Typical behaviour of the constituent up quark mass, which at high temperature and/or density approaches zero according to the Nambu-Jona-Lasino model [5].

2 MODELS AND EXPECTATIONS

Several models have been proposed and developed throughout the last years, in order to try to predict the behaviour of hadron masses at higher temperature and density. The most frequently faced problem concerns the mass of mesons, mainly because their structure is intrinsically simpler than that of baryons (two valence quarks instead of three). In this context the most relevant mesons have been the vector mesons ρ , ω and ϕ , on which we shall concentrate hereafter, which are spin 1 states with negative parity.

The ρ meson is a broad resonance centered around 770 MeV/c², with a width of $\Gamma=150$ MeV; its extremely short life time, $\hbar/2\pi\Gamma$, is of the order of $4 \cdot 10^{-24}$ s. The ω meson mass is 782 MeV/c², its width 8.4 MeV and the corresponding life time is $7.8 \cdot 10^{-23}$ s. The ϕ meson has a mass of 1020 MeV/c² and a width of 4.4 MeV/c², with a corresponding life time of $1.5 \cdot 10^{-22}$ s. Obviously the very short life times of these particles exclude any possibility of direct measurement, and therefore any experimental method in order to study these mesons has to be indirect. On the other hand, we should note that these life times are comparable with the life time of a fireball, $\tau \approx 3 \cdot 10^{-23}$ s, formed in heavy ion collisions at a few AGeV.

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 predict a different behavior for each different vector meson. Sometimes a broadening of the resonance, sometimes a shift toward lower or higher energy, sometimes both [6-10] are obtained. In this context one should mention that hadronic models are also predicting significant meson mass changes due to strong meson-hadron couplings. There is no established

clear connection of this mechanism to the picture based on the chiral symmetry breakdown.

The very few available experimental data seem to indicate a shift toward lower mass, namely the dropping mass of vector mesons [12,13]. As a consequence it is important to measure the vector mesons' masses as a function of the medium density, but unfortunately both mass and density are difficult to control. Density can however be deduced from theoretical transport model calculations assuming given 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 vector meson masses is straightforward in vacuum, but very difficult in medium.

3 MASS MEASUREMENT

Since direct observations of vector mesons are not possible due to their short life time, one has to measure their decay products, in order to reconstruct the original mass by exploiting the invariant mass method. Unfortunately, this is not realistic for the preferential hadronic decay channels of mesons i.e. $\pi\pi$, $\pi\pi\pi$, ...) since the decay products strongly interact with the nuclear matter itself. As a consequence, the initial information about the vector meson is distorted by the final state interaction, prohibiting the reconstruction of the vector meson properties. Fortunately, there are electromagnetic decays of vector mesons into lepton pairs (e^+e^-) which can provide an unperturbed view into the hot and dense medium.

Even though the branching ratio of such a decay is 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

Even though the possible solution just examined seems to be ideal, as it allows a clean measurement with unperturbed probes from the decay, there are also disadvantages. Many different processes can lead to an e^+e^- pair in the final state, and these will represent a considerable background in the mass spectrum we plan to look at: these processes have therefore to be taken into account, if we want to extract significant information from the measured data. The most difficult part of this background appears due to fake pairs, called combinatorial background, formed in the event reconstruction from electrons originating from different decays of abundantly produced π^0 . These decay processes include external pair conversion of γ -rays from $\pi^0 \rightarrow \gamma\gamma$ or/and (since few pions can be produced in one event) $\pi^0 \rightarrow e^+e^-\gamma$ Dalitz decays.

Furthermore, there are other physical processes that lead to the production of di-electrons. The most relevant

among such processes are: 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 baryonic resonances (i.e. Delta baryon $\Delta^0 \rightarrow ne^+e^-$, $\Delta^+ \rightarrow pe^+e^-$), even though there are other possible channels, some of them not well known yet.

The detectors built so far for di-electron measurements in heavy ion reactions are mainly two: CERES and DLS [11-13]. The former, in operation at SPS-CERN, has produced interesting data showing an excess of di-electrons in the mass region just below the ρ meson, but only occurring in the 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 was at very high energy, up to 160 AGeV, thus considerably above the production threshold for the vector mesons under examination. This implies that the number of open reaction channels is large and the production of vector mesons is not only restricted to a high-density zone of the fireball. Consequently the data interpretation can be manifold. DLS, which operated at the BEVALAC for several years around 1-2A GeV, was ideal from the energy point of view since it operated just above the mentioned threshold, but its geometrical acceptance and momentum resolution was rather poor. DLS has produced indications for an excess of e^+e^- pairs as well, and in the same mass region below the ρ meson.

In order to be able to appreciate slight variations in the mass spectrum, i.e. the ω resonance (8 MeV wide), one needs a mass resolution of 1-2%. The study of vector meson properties as a function of transverse momentum and rapidity requires considerably more statistics than available so far. This situation calls for a new e^+e^- spectrometer with large geometrical acceptance and the capability to operate 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, ranging from p+p up to Au+Au. 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 in the energy domain between 1 and 2 AGeV, as well as the fundamental hadronic processes in proton and pion induced reactions. A dedicated spectrometer was built for this purpose, and after a series of commissioning runs, production runs started in November 2002.

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. At the same time, it can serve as a high performance hadron

spectrometer with superior resolution, particle identification and rate capabilities. Additional important entrance channels are represented by proton-proton, proton-nucleus, pion-nucleon and pion-nucleus collisions. For the latter case a special pion beam facility has been recently developed at GSI. The HADES experimental programme combines systematic studies of di-electron production in elementary reactions with di-electron spectroscopy in heavy ion collisions, with special emphasis on the vector meson properties in nuclear matter.

As it has been mentioned above, the dielectron decay channels of the vector mesons are suppressed by a factor of 10^{-4} as compared to the hadronic decays. Thus, in a typical A-A reactions at GSI energies, the expected total yield of di-electrons from vector meson decays is about 10^{-6} per central event: the experimental challenge is to find one dielectron in one million of these central collisions, each containing background of charged hadrons and photons from π^0 decays. This requires a system with large geometrical acceptance, high rate capabilities, sufficient granularity and a highly selective multi-stage trigger scheme with real time electron recognition. For fast electron recognition, detectors with good electron/hadron separation power and dedicated trigger schemes, involving image processing, are necessary. Moreover, an excellent invariant mass resolution $\Delta M/M \sim 1\%$ is required for vector meson identification.

The spectrometer, shown in figs.3 and 4, consists 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 ultra-light carbon mirror reflecting the produced Cherenkov photons back to a gas-based photon detector with solid CsI photo-cathode, placed behind the target position; this system allows to uniquely identify the electrons and accurately measure their emission direction;
- two layers of mini-drift chambers (MDC) with small cell size for high counting rate capabilities, followed by a superconducting magnet, 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 in the magnetic field within a position accuracy of $<100\mu\text{m}$;
- a time of flight wall (TOF), made of 320 rods of plastic scintillators, covering the polar angles between 44° and 88° , to measure the event-by-event multiplicity which 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 layers of gas detectors intermixed with two lead converter layers, allowing electron/hadron discrimination; in front of the SHOWER a 24-slab low-granularity tof wall (TOFINO) further helps in electron/hadron discrimination. The low granularity TOFINO system

presently limits HADES capabilities to low and medium size systems. However, its up-grade with a high-resolution segmented Resistive Plate Chamber (RPC) tof wall is planned in the up-coming years.

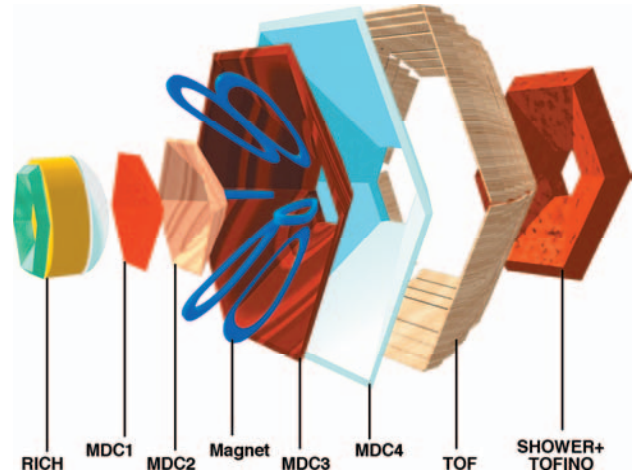


Figure 3 - 3D sketch of the HADES spectrometer, split along the longitudinal direction for clarity. In operating conditions all the shown elements fit into each other, making the whole structure much more compact.

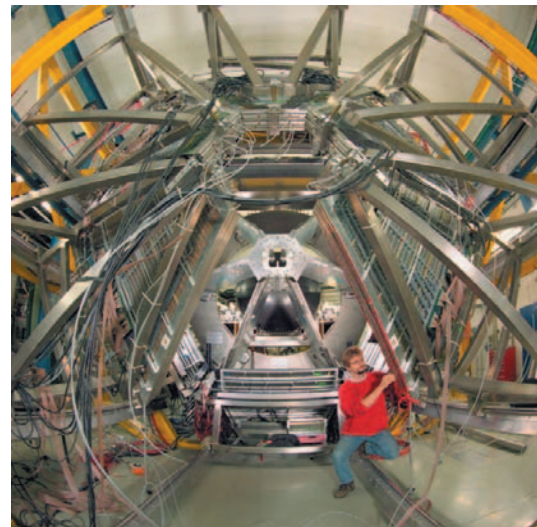


Figure 4 - A picture of the HADES spectrometer as seen from the beam dump.

The data acquisition is started by a positive first level trigger (LVL1) decision. The first level trigger is obtained by a fast ($t < 100$ ns) hardware analysis of the multiplicity measurement performed by the TOF/TOFINO walls. The second level trigger (LVL2) machine consists of 60 dedicated electronic modules. It performs a three-step process with a typical latency of $100\mu\text{s}$. In the first step a search for electron ring images on the RICH pad plane is made. In parallel, charge clusters with the signature of an electromagnetic shower in the Pre-Shower detector, as well as particles with an appropriate time of flight in the scintillator TOF wall, are searched. The resulting position coordinates of electron candidates in the inner RICH and the outer

TOF/Pre-Shower detectors are compared in the Matching Unit (MU) in an appropriate matching window that takes into account the track deflection due to the magnetic field. The matched hits define valid electron candidate tracks. In the third step the selected electron tracks with opposite charges can be combined into dielectron pairs, and their invariant mass can be calculated based on a look-up table which contains a mapping of the polar electron track deflection angles to momenta.

In the presently investigated 2AGeV C+C collisions a conservative LVL2 trigger condition was imposed requiring at least one electron track, which provided 92% background event rejection and a high single electron identification efficiency $\varepsilon > 70\%$.

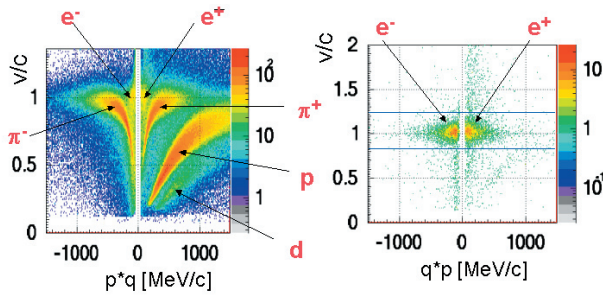


Figure 5 - Left: Velocity versus sign(charge)*momentum correlation for all reconstructed tracks from C+C at 2 AGeV collisions. Pion and proton branches are clearly resolved. Right: same as on the left but with additional condition on electron identification. The intensity scale is logarithmic.

The performance of the spectrometer was studied in several commissioning beam times by means of the C+C reaction. In the recent two experimental runs in 2001 and 2002 we collected around $50 \cdot 10^6$ and $200 \cdot 10^6$ events, respectively. In the second run we used for the first time the LVL2 trigger to select only LVL1 events with electron tracks, and collected around 50k di-electron signal pairs. The principle of the electron identification is illustrated in Figure 5 (left). Particles with different mass fill different regions in the velocity vs. momentum distribution. The pronounced maxima correspond to positive/negative pions, protons and deuterons. Only a slight indication of electrons can be visible. The situation changes dramatically when the electron identification in RICH is switched on, as shown on the right hand side. A clear electron signal, that can be further improved by imposing TOF/TOFINO ($\beta \approx 1$) and Pre-Shower conditions, is visible. The detailed investigation of electron distributions reveals that the residual contamination of hadronic background is less than 2%.

From the identified electrons we have constructed unlike e^+e^- and like sign (e^+e^+ , e^-e^-) pairs. Most of pairs are due to combinatorial background arising from multiple photon conversions ($\sim 65\%$) and Dalitz decay of π^0 mesons ($\sim 20\%$). However, this background can be effectively reduced by a powerful Close Pair Rejection (CPR) method. The CPR uses information from the inner MDC system, such as cluster size and number of

contributing wires, and allows for efficient rejection of pairs with very small opening angle which are the main source of combinatorial background.

The expected most dominant sources of dielectron signal pairs are mentioned above: π^0 , and to a much smaller extent, η Dalitz decays. We observe indeed that the dominant signal, with the S/B ~ 5 , is in the invariant mass region up to $M_{e^+e^-} < 150 \text{ MeV}/c^2$. In the higher mass region we also observe a systematic excess of dielectron yield over the combinatorial background with an average S/B $\sim 1:3$.

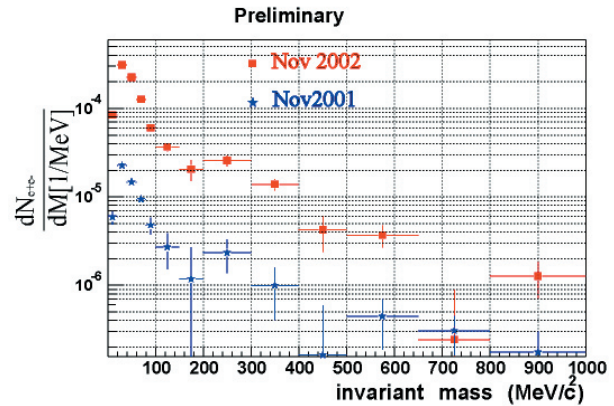


Fig6: Comparison of dielectron invariant mass distributions (combinatorial background subtracted) normalized to the number of the LVL1 (blue stars) and the LVL2 events (red squares) as measured in 2001 and 2002, respectively. Both distributions are preliminary and are not corrected for the detector acceptance and tracking efficiencies.

Figure 6, shows a comparison of the signal resulting after the combinatorial background subtraction plotted together for data obtained with LVL1 (2001 data) and LVL2 (2002 data) trigger. Both distributions were obtained with the same analysis and are for pair opening angle $\theta_{e^+e^-} > 4^\circ$. The spectra have been normalized with the number of collected LVL1 and LVL2 events, respectively, and are not yet corrected for spectrometer acceptance and tracking efficiencies. The impact of the LVL2 clearly results in a strong dielectron statistics enhancement (a factor 10 over the run with LVL1 trigger) and allows for investigations of dielectron production over a wider invariant mass range. The analysis is in progress and final results are expected soon.

6 CONCLUSIONS

The HADES spectrometer offers a unique possibility for systematic studies of the light vector meson mass distributions inside nuclear matter by means of dielectron spectroscopy. Recent results from commissioning runs confirmed the expected superior on-line and off-line electron identification capabilities. In particular, a high-statistics run with LVL2 trigger provided the first pair data from C+C reactions at 2 AGeV. High resolution di-electron spectroscopy

becomes now also possible, after the completion of the outer MDC tracking system.

The full experimental programme is planned for several years, and the first experiments aiming at the exclusive meson reconstruction in proton-proton reactions have been started this year. High resolution studies of the vector meson production in pion induced reactions and light nucleus-nucleus system are planned in next 2-3 years. After this, when the construction of the inner RPC wall is completed, the heaviest collision systems, i.e Au+Au, will be investigated.

7 REFERENCES

- [1] V.Metag, Prog. Part.Nucl. Phys. 30 (1993) 75.
- [2] J.Engels, F.Karsch, K.Redlich, Nucl. Phys. B435 (1995) 295.
- [3] B.W. Lee, Chiral Dynamics, Gordon and Breach, London (1972), V.Koch, Introduction to Chiral Symmetry, nucl-th/9512029, LBNL-39463 UC-413;
- [4] G.E.Brown and M. Rho, Phys. Rev. Lett. 66 (1991) 2720
- [5] M.Lutz, S. Klimt and W. Weise, Nucl. Phys. A542 (1992) 521.
- [6] W.Cassing, E.L.Bratkovskaya, Phys. Rep. 308 (1999) 65.
- [7] T.Hatsuda and S.H.Lee, Phys. Rev. C 46 (1992) R34.
- [8] F.Klingl and W.Weise, Nucl. Phys. A606 (1996) 329.
- [9] R.Rapp, G.Chanfray and J.Wambach, Nucl. Phys. A617 (1997) 472.
- [10] M.Herrmann, B.Friman and W.Nörenberg, Nucl. Phys. A560 (1993) 411.
- [11] R.J.Porter et al., Phys. Rev. Lett. 79 (1997) 1229.
- [12] J.Stachel, proc. Nuclear Physics Conference, Paris, August 1998, Nucl. Phys. A
- [13] CERES coll., G.Agakichiev et al., Phys.Rev.Lett 75(1995)1272

SINPHOS - A SINGLE PHOTON SPECTROMETER

S. Tudisco^{a,b,*}, P. Finocchiaro^a, L. Cosentino^a, F. Musumeci^{a,b}, S. Privitera^{a,b}, A. Scordino^{a,b},
A. Pappalardo^{a,b}, G. Fallica^c, D. Sanfilippo^c, M. Vervaeke^d, B. Volckaerts^d, P. Vynck^d,
A. Hermanne^d, H. Thienpont^d

a) INFN-LNS, Via Santa Sofia 65 95125 Catania Italy

b) DMFCI - Università di Catania, Viale A. Doria 6, 95125 Catania, Italy

c) ST-Microelectronics, Stradale Primrose 50, I95100 Catania Italy

d) Vrije Universiteit Brussel, Pleinlaan 2, 1050 Brussels, Belgium

** Corresponding author, e-mail: tudisco@lns.infn.it*

Abstract

SINPHOS a monolithic micro-device, able to measure simultaneously time distribution and spectrum of photons coming from a weak source like Delayed Luminescence of biological systems.

1. INTRODUCTION

Substantial efforts are currently being made towards the development of innovative methods for early diagnosis, in particular those employing non-invasive techniques. The most promising techniques, especially for skin melanoma, are based on the use of optical diagnostic tools and on the information provided by the light emitted (i.e. Delayed Luminescence emitted from mammalian cells), elastically or inelastically, by cells and tissues after suitable illumination [1-7], which is an important physical parameter to select cell state. In this respect in figure 1 the Delayed Luminescence emission spectra for normal fibroblasts and melanoma's human cells are reported. It appears that the spectral components up to the near-infrared region become relevant in the possibility of discriminating the two cell types. Devices with single photon detection capability are necessary, in order to measure emission at longer wavelength up to $\lambda \approx 1000$ nm, like that from cells [8, 9]. Such devices should be able to resolve the few detected photons both in time and in wavelength. This could be the first step toward a matrix for imaging purpose. In this report the results of first year of activity on the SINPHOS (SINgle PHOton Spectrometer) project are discussed.

SINPHOS aims combining different technologies in order to build a monolithic device capable of measuring simultaneously the decay time distribution and the wavelength spectrum of photons coming from a weak source.

2. THE PRISM SPECTROGRAPH IN DLP TECHNIQUE

One of our research topics is the development of micro-optical components made from Poly-Methyl-Methacrylate (PMMA), by exploiting a promising technique, named Deep Lithography with Ions (DLI). Presently it is considered as a unique and powerful rapid prototyping tool for the fabrication of monolithic

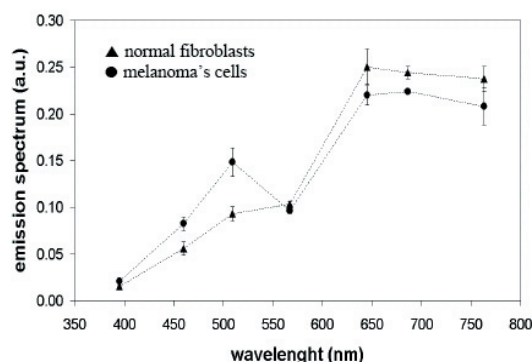


Figure 1. Emission spectrum for normal fibroblasts and melanoma's cells.

refractive micro-optical elements and micro-mechanical structures [10].

Deep Lithography with Ions (DLI) for the fabrication of micro-mechanical and micro-optical components, perfectly suited to be coupled to the silicon sensors that we proposed. The fabrication process consists of the irradiation of a PMMA sample, by means of a particle accelerator, followed by a chemical treatment. The typical size scale of the proposed high-aspect-ratio

components ranges from 10 μm to 3 cm across and from 50 μm to 3 cm depth, depending on the combination of beam types and energies employed.

The first prototype spectrum analyzer was designed and optimized for operation around 600 nm, consists of three groove-shaped holders (140 μm wide) for the input fiber, an aspherical lens (300 μm wide) to compensate the beam divergence due to the numerical aperture of the fiber itself, and finally a prism.

In figure 2 we report the real picture of first iteration prototype produced by means of DLI.

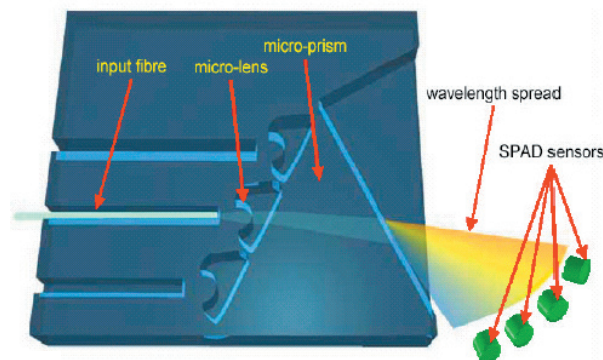


Figure. 2: SINPHOS prototype sketch.

The obtained results on the characterization of our prototype are very promising. For the entire region the RMS value of roughness R_q was 186 nm with a standard deviation of 35 nm while, for selected areas of 50 μm by 50 μm , R_q was 62 nm with a standard deviation of 12 nm. However, such values do not fit our requirement in order to achieve a good resolving power. In fact, by the characterization, using different laser lights, we observe a relevant light diffusion.

It is remarkable that, although the light diffusion on the surfaces produces broad distributions, it is possible to appreciate a measurable shift between the two distributions. These shifts are quite small but, with an improvement of the experimental set up currently in progress, we will improve the surface quality, thus remarkably reducing the light peak width.

2. THE SINGLE PHOTON AVALANCHE DETECTOR (SPAD)

SPADs are p-n junctions biased at a voltage above the breakdown, operating in Geiger mode. At this bias, because the high electric field, a single charge carrier can trigger a self-sustaining avalanche.

The current swiftly rises with subnanosecond rise time to a macroscopic steady level in the milliamperage range. Their typical quantum efficiency is far better than a usual photocathode employed in a photomultiplier tube, as showed in fig 3. The proposed devices have a pretty good time resolution, below 100 ps, that is independent of the number of impinging photons, because whenever

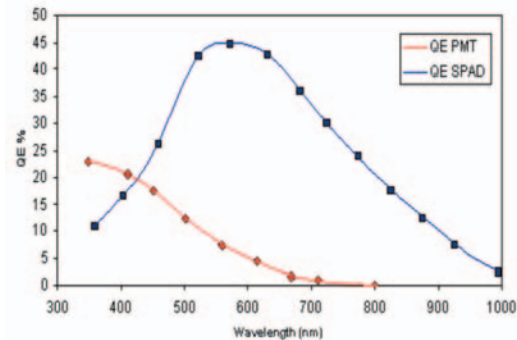


Figure 3. Comparison between quantum efficiency of PMT-multialkali and SPAD

a photon is detected the avalanche discharge is totally independent of the number of interacting photons.

Then, to quench the avalanche we need to lower the bias voltage to breakdown or below. We can do that with a passive or active quenching circuit.

2.1 Passive-Quenching Circuit

In PQC a resistive mechanism quench the avalanche current by increasing a voltage drop on a high impedance load. The SPAD is reverse biased through a high ballast resistor of 100 K Ω , like a good compromise between quenching the avalanche and restoring a fast quiescent state. The consequence of these features is that each SPAD channel provides an output signal that is very fast and contains the same charge, within <1%, whatever the number of photons detected. In that situation, the overall dead time is of $\approx 1\mu\text{s}$.

The aim of our experimental work is to prove the feasibility of SPAD sensors as photodetectors for various applications (timing, photon counting etc). For these measurements we have chosen to test both the multi- and few- photons regimes. The light source was a UV pulsed laser (337 nm wavelength, 2 ns FWHM) coupled, in order to remove fluorescence decay contributions, with a dye laser system for the wavelength shift up to 395 nm. Two identical SPADs, with 50 μm active diameter, were coupled to the two opposite and biased at 32 V; as a reference readout detector, a PMT was also coupled. To operate in the single photon regime we used also some grey filters with the following transmission coefficients: 0.32-2-10%. The geometrical efficiency of each SPAD with respect to the PMT was of the order of 10^{-5} . In figures below we report the time spectra of one of the SPADs in the different regimes selected by using different filters.

The timing trend in the few photons regime, perfectly reproduced by gaussian plus exponential fit, reflect the time structure of laser pulse due to dye excitation. This is also an evidence that we were running with few photons, as the SPAD was triggered by photons

generated at any instant within the light pulse whose time structure we reproduced. In the many photons regime the obtained resolution is the sum of two main contributions coming from the SPAD and from the laser start jitter.

We also performed a series of measurements with an optical pulse from a ps laser ($\lambda=408$ nm, 50 ps FWHM, 1 MHz max. rep. rate). The pulse was sent to the two SPADs. The transition between the multi-photons and few photons regime was achieved, as done previously, using a grey filter (0.01%).

time resolution of the SPADs appears very good. The time spectra of the SPADs measured working in multi-photons regime are well fitted, as in the previous measurements, by a gaussian plus an exponential function and, due to the very low FWHM of the laser, we are able, in this condition, to evaluate the real timing of SPAD detectors (see fig. 5a and b).

In the few photon regime we expect, as previously mentioned, that the FWHM of the SPADs signals are larger with respect to the many photons regime. This evidence, as shown in figure 4, is confirmed in the few photon regime too.

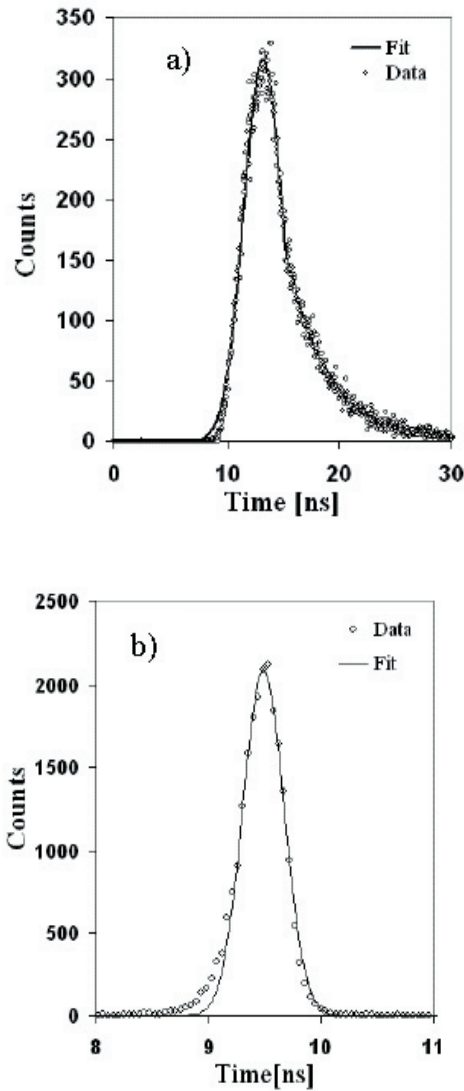


Figure 4. a) SPAD time spectrum in a few photons regime, FWHM $\approx$ 4ns, b) SPAD time spectrum in many photons regime with a FWHM $\approx$ 0.42 ns.

The trigger signal was taken from the laser trigger out and, as in the previous measurement, we checked that there were no coincidences between the two SPADs signals to be confident that the SPADs were operating in few photons regime. The obtained results show that

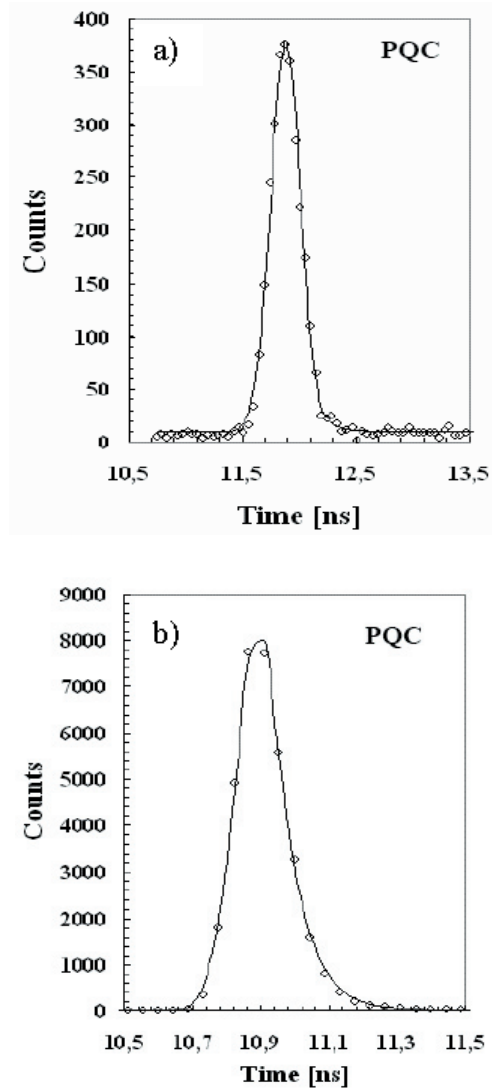


Figure 5. a) time spectrum of SPAD in many photons regime with a FWHM $\approx$ 0.161 ns, b) time spectrum of SPAD in a few photons regime with a FWHM $\approx$ 0.31 ns.

3. CONCLUSIONS

The tests performed on the various SINPHOS elements are quite promising. In the near future we are going to produce a new spectrometer prototype

characterized by a more controlled surface roughness and then a more prominent resolving power. SPADs tests showed that such a device have a relevant timing performance also in single photon counting regime. It is also suitable for others use like a component of high-sensitivity high-resolution solid state photomultipliers used in the most common applications of bio-photonics in medical research.

5 REFERENCES

- [1] M. Meurens et al., *Vibrational Spectroscopy* 10-2 (1996) 341.
- [2] M. Panjehpour et al., *Lasers In Surgery And Medicine* 31 – 5 (2002) 367.
- [3] B. Mayinger et al., *J Photoche. Photobio. B* 70 1 (2003) 13.
- [4] A. Gibson et al., *Appl. Optics* 42 (2003) 3109.
- [5] BW Chwirot , et al., *Lasers in Surgery and Medicine* 21-2 (1997) 149.
- [6] K. Izuishi et al., *Hepato-Gastroenterology* 50 (2003) 366.
- [7] A. Pradhan et al., *J Photochem Photobiol B* 31 (1995) 101.
- [8] S. Tudisco et al., *Nucl. Inst. and Metho. A* 518 (2004) 463.
- [9] F. Musumeci et al., *J Photochem Photobiol B* 79 (2005) 93
- [10] H. Thienpont et al., *Proceedings of the IEEE*, Vol. 88, No. 2, June 2000.

PULSE HEIGHT DEFECT FOR HEAVY IONS IN CVD DIAMOND DETECTORS

Cristina Tuvè^a, R. Potenza^a, A. Giusa^a, G. Russo^a, C. Sutura^a

V. Bellini^b, A. Bonanno^b, F. Mammoliti^b

G. Pucella^c, M. Marinelli^c, E. Milani^c, M.E. Morgada^c, A. Paoletti^c, A. Tucciarone^c, G. Verona-Rinati^c

a) Università di Catania, Via Santa Sofia 64, I-95123 Catania, Italy

INFN – Sezione di Catania, Via Santa Sofia 64, I-95123 Catania, Italy

b) Università di Catania, Via Santa Sofia 64, I-95123 Catania, Italy

INFN – LNS, Via Santa Sofia 62, I-95123 Catania, Italy

c) Università di Roma "Tor Vergata", Via di Tor Vergata 110, I-00133 Roma, Italy

INFN – Sezione di Roma2, Via di Tor Vergata 110, I-00133 Roma, Italy

Abstract

We compared the responses of CVD diamond detectors grown in Roma Tor Vergata Laboratory to α -particles of ^{241}Am source and to ^7Li , ^{12}C and ^{14}N ions of various energies produced in the 15 MV Tandem accelerator of LNS. It was clear that the signals obtained from heavier particles were lower than those measured or expected for the lighter α -particles, showing the so called pulse height defect, already known in other types of detectors [1]. Preliminary results are here shown concerning the dependence of this defect on particle charge, energy and angle of incidence.

1 INTRODUCTION

Diamond was shown to be a suitable material for applications in high energy particle detection [2] due to its striking electrical and thermal properties and its radiation hardness and high quality diamond films have been obtained by microwave plasma enhanced chemical vapor deposition (CVD) [3].

The main macroscopic parameter which relates to diamond quality as nuclear detector is its mean charge collection efficiency $\langle\eta\rangle = \langle Q_c \rangle / Q_0$, that is the ratio between the mean collected charge and the total charge generated by a single incident ionizing particle; Q_c is proportional to the individual pulse height and can vary much from one particle to another of the same monoenergetic beam due to the different paths inside the specimen, giving rise to bad energy resolution. If we assume that in silicon detectors $\eta \approx 1$ for ions of small and intermediate mass we can measure $\langle\eta\rangle$ for diamond comparing the signals produced by this latter in a charge amplifying circuit to those produced by a silicon detector bombarded with the same particles. Assuming that light ($M \leq 4$) particles produce equal largest signals, any pulse height defect is proportional to the difference $\langle\eta_l\rangle - \langle\eta\rangle$, where the subscript l indicates light particles.

2 EXPERIMENT

Detector grade CVD diamond films were grown on single crystal (100) p-type silicon substrates using a optimized [4] 1%CH₄-99%H₂ gas mixture in Roma Tor Vergata Laboratories [4,5]. Details of the production of the detectors in fully pumped state can be found in [6]. Each diamond detector was allowed to detect α -particles

from ^{241}Am standard source and ^6Li , ^{12}C and ^{14}N ions of various energies scattered at 20 degrees with respect to the incident beam by a gold target 300 $\mu\text{g}/\text{cm}^2$ thick. The particles impinged on the growth side of the diamond. This side was in turn placed at equal positive and negative values of the HV suitable for generating electric fields $E = \pm 1 \text{ V}/\mu\text{m} = \pm 10 \text{ kV}/\text{cm}$. Only data taken at positive values of HV will be discussed here.

The energy of α -particles was varied between 1.5 and 5.5 MeV using air as absorber. The energy of ^{12}C ions was varied in steps between 22.0 MeV and 91.2 MeV and that of ^6Li ions from 23.1 to 47.4 MeV; that of ^{14}N ions was 82.5 MeV. The intensity of the beam varied between 2 and 10 pA [6]. During all the measurements the pulses produced in the diamonds were amplified by conventional electronics, digitalized through ADC's and stored. Diamonds could be rotated around an axis orthogonal to the beam, so that this latter could hit diamonds at an angle of incidence θ measured with respect to the applied field, which was normal to the surface of the diamond.

3 RESULTS

The main observable feature in the samples, apart from the known the asymmetric behavior under the opposite polarities due to the different mean free paths of electrons and holes [4], was the much higher efficiency for α -particles than for ^{12}C at the same penetrations, as it is clearly seen in fig. 1 for positive as well as negative values of the field. This efficiency is about constant for sufficiently low penetration depths. It seems reasonable to define a pulse height defect of diamond for a given incident ion as the difference

$$\begin{aligned}\Delta E &= E_{\text{exp}} - E_{\text{meas}} = KQ_0 - K\langle Qc \rangle / \langle \eta_\alpha \rangle = KQ_0(1 - \langle \eta \rangle / \langle \eta_\alpha \rangle) \\ &= E_{\text{exp}}(\langle \eta_\alpha \rangle - \langle \eta \rangle) / \langle \eta_\alpha \rangle\end{aligned}\quad (1)$$

where E_{exp} is the energy released by the particle into the detector, which can be easily computed from the known Bethe-Bloch law and related corrections, and E_{meas} is the measured value normalized to the (supposedly constant) efficiency of the detector for α -particles.

Fig. 2 reports ΔE vs. E_{exp} for ^{12}C ions at different angles of incidence. A striking feature of these data reported is the decrease of ΔE with increasing θ . Fig. 3 reports ΔE vs. θ for different released energies. The decreasing of ΔE with θ is again clearly shown.

4 DISCUSSION

To interpret these results we observe that the main contribution to the pulse height defect should come from the recombination of charge carriers [1,7] in regions where, due to the high stopping cross sections of the heavier ions, the presence of defects in the crystal lattice favors the formation of a plasma which inhibits the electric field from penetrating inside for a time sufficient to allow charge recombination. The inhibition is maximum when the electric field is just parallel to the plasma column, which develops essentially along particle trajectory, that is at $\theta=0^\circ$. It decreases with θ and eventually vanishes when the electric field become perpendicular to the plasma column, that is at $\theta=90^\circ$. The recombination is always proportional to the ratio between the characteristic recombination time t_r and the plasma lifetime t_p , following:

$$\Delta N/N = \Delta E/E = t_p/t_r \quad (2)$$

where ΔE is the pulse height defect, N is the total number of carriers produced by the impinging ion in releasing the energy E and ΔN are those which subsequently recombine. As for other solid as silicon we can suppose that t_r is a constant property of the material, t_p is much more reduced by the applied field F for $\theta \approx 90^\circ$ ($t_p \sim F^{-2}$) than for $\theta \approx 0^\circ$ ($t_p \sim F^{-1}$), giving the requested dependence on angle. The carrier density n_c can be obtained roughly from

$$n_c = (E/\epsilon)/\pi r_0^2 G \quad (3)$$

being ϵ the energy necessary to produce a pair of carriers (13.6 eV in diamond), r_0 the radius of the cylindrical plasma column (of the order of 1 μm) and G the penetration depth of the particle. Taking into account eq. (2) and the fact that $G \sim E^{1+2}$ and the dependence of t_p on E through n_c we obtain that

$$\Delta E \sim E^{1+(4/3)} \quad (4)$$

All the data were well fitted by a power law $\Delta E \sim E^{1.2}$ (see fig.2) and the most reliable complete function of energy and angle to fit the data is finally:

$$\Delta E = AE^{1.2}(1 - e^{\cos\theta}) \quad (5)$$

Fig. 2 and 3 show the good fit to the data and table 1 reports the values of A and C .

5 CONCLUSION

^7Li , ^{12}C and ^{14}N ions of various energies produced by Tandem of LNS, Catania (Italy) have been used as probes as well as α -particles from ^{241}Am to measure pulse height defects for massive particles detected in samples of diamond grown with CVD technique in Roma Tor Vergata laboratories. The results obtained clearly show (fig. 2 and 3) that the pulse height defect is depending on charge carrier recombination in the sample. The function in eq. (5) is a simple product of an energy and an angular function so showing that energy and angle dependences arise from independent processes. The former one depends on n_c , to be referred to incident particle, while the latter depends on t_p , to be referred to the lattice defects in the actual detector, which do not influence n_c appreciably. So we see that the power law in energy is common to all data, while the saturating angular function depends on the actual detector and particle. We must however say now that further analysis is necessary to give more precise conclusions particularly for the fact that we have used here three approximations: i) the charge collection efficiency for α -particles has been taken constant at all penetrations; ii) the modified Hecht curve[4] for charge collection in the case of massive ions has been also approximated with a constant and iii) the Bragg curve is approximated to a constant in deducing eq. (3).

5 REFERENCES

- [1] E. C. Finch, Nucl. Instr. and Meth. **113**, 41 (1973).
- [2] W. Adam et al., Electrochem. Soc. 5th Symposium on Diamond Materials Proc. (1998) 491
- [3] D. R. Kania in "The Physics of Diamond", A. Paoletti and A. Tucciarone Editors, IOS Press, Amsterdam, 1997
- [4] M. Marinelli, E. Milani, A. Paoletti, A. Tucciarone, G. Verona Rinati, G. Messina, M. Angelone, M. Pillon, Proc. Of Applied Diamond Conference/Frontier Carbon Technology Joint Conference, Tsukuba, Japan, August 31-September 3, (1999) 154
- [5] M. Marinelli, E. Milani, A. Paoletti, A. Tucciarone, G. Verona Rinati, M. Angelone, M. Pillon, Appl.Phys.Lett. **75** (1999) 3216
- [6] C. Tuvè, R. Paoletti, C. Sutura, V. Bellini, A. Bonanno, F. Mammoliti, G. Pucella, M. Marinelli, E. Milani, A. Paoletti, A. Tucciarone, G. Verona-Rinati, LNS Activity Report 2003, (2004) ...;
- [7] E. C. Finch, M. Asghar, M. Forte, Nucl. Instr. and Meth. **163**, 467 (1979).

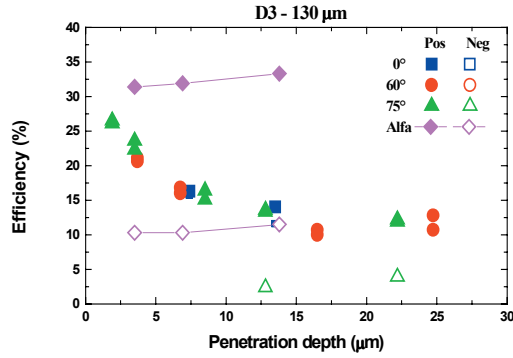


Table 1 – Fitting coefficients in eq. (5)

	${}^6\text{Li}$			${}^{12}\text{C}$			${}^{14}\text{N}$		
	D1	D2	D3	D1	D2	D3	D1	D2	D3
A	0.52 ± 0.02			0.39 ± 0.03			0.4	–	–
C	3.4 ± 0.4	3.1 ± 0.2	$2. \pm 0.2$	5.4 ± 0.8	5.2 ± 0.5	3.7 ± 0.3	5.0	–	–

Fig. 1: Mean efficiency of a diamond detector hit by ${}^{12}\text{C}$ ions and α -particles vs. particle penetration for low values of this. Note that the lowest value of penetration depth is around 3 μm .

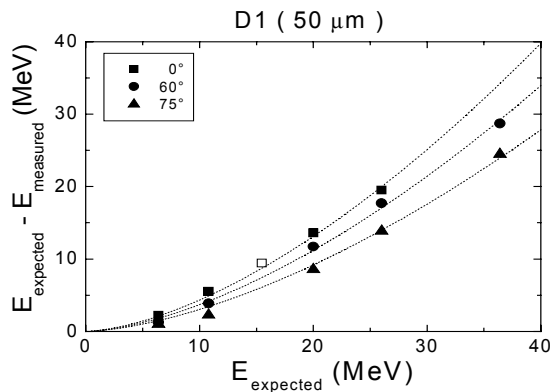


Fig. 2: Pulse height defects shown by a diamond detector hit by ${}^{12}\text{C}$ as a function of the released energy for various angles of incidence. The hollow square refers to a case in which the released energy E_{exp} is lower than incident particle energy because the particle has energy sufficient to pass over the diamond detector. Curves are computed using eq. (5), see text.

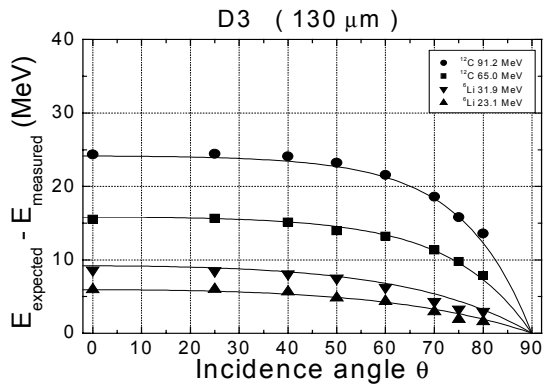


Fig. 3: Pulse height defects shown by a diamond detector hit by ${}^{12}\text{C}$ as a function of the angle of incidence for various particles and released energies. Curves are computed using eq. (5), see text.

SIMULATIONS OF THE RESPONSE OF A NEMOkm³ UNDERWATER TELESCOPE TO MUON NEUTRINO FLUXES

P. Sapienza ^{a,*}, R. Coniglione^a, C. Distefano^a and E. Migneco ^{a,b} for the NEMO Collaboration

a) INFN Laboratori Nazionali del Sud, Catania, Italy

b) Dipartimento di Fisica dell'Università di Catania, Catania, Italy

* Corresponding author, e-mail: sapienza@lns.infn.it

Abstract

The simulated performances of a km³ underwater neutrino telescope made of 81 (9 × 9) NEMO towers to E² neutrino fluxes are reported. In particular, effective areas and angular resolutions as a function of the neutrino energy and incident direction are shown. The related muon effective areas and angular resolutions are also reported.

1 INTRODUCTION

The study of the response of a km³-scale underwater telescope to astrophysical neutrino sources is a fundamental task for the high energy neutrino astronomy. The neutrino fluxes from astrophysical beam dump scenarios are expected to have a flavor ratio of $\phi_{\nu_e} : \phi_{\nu_\mu} : \phi_{\nu_\tau} \sim 1:1:1$ due to the flavor mixing occurring in the propagation from the source to the Earth. Moreover, the Earth becomes opaque to very energetic ν_e and ν_μ ($E_\nu \geq 100$ TeV) due to the increasing ν interaction cross section, while the very energetic tau neutrinos due to a regeneration process which allows them to reach the detector volume with a reduced energy. For these reasons a km³ neutrino telescope should be able to detect neutrinos of all flavors and, for the most energetic ones, both horizontal and down-going neutrinos have to be efficiently detected with the best possible angular accuracy.

Due to the expectations on neutrino fluxes, mainly based on the measured cosmic ray fluxes and the estimated fluxes for several high energy sources (GRB, AGN, GZK, ...) from theoretical models [1], the “opening” of the high energy neutrino astronomy era can only be afforded with detector in the km³ scale.

Following the success of the under-ice AMANDA detector [2], which is presently the largest detector operating in the field of high energy neutrino astronomy, the IceCube km³ detector [3] is under construction at the South Pole. On the other hand, many arguments — as the full sky coverage, with particular reference to the Galactic Center (as demanded by the impressive HESS results [4]), and the complementarity in the detection properties — strongly support the construction of a km³-scale detector in Mediterranean Sea at large depth.

The NEMO Collaboration [5], which was formed in the 1998, aims at carrying out the necessary R&D for

the construction of a km³-scale underwater neutrino telescope. The activity has been mainly focused on the search and characterization of an optimal site for the detector installation and on the development of key technologies for the km³ underwater telescope via the realization of a technological demonstrator to face the most critical items such as mechanics, deployment and sea operations, power distribution, electronics, data acquisition, calibration, etc.

In the following, we report on the muon neutrino simulations of an underwater detector placed at about 3400 m depth in the Capo Passero (36° 16' N, 16° 06' E) site which is one of the three candidate sites for the Mediterranean high energy neutrino telescope. The study of the detector response to cascade-like events with particular reference to the ν_e detection has been recently undertaken and will be presented in a forthcoming paper.

The simulations have been performed using the software [6] developed by the ANTARES Collaboration, which is building an under-water detector demonstrator of about 0.1 km² to be installed at about 2400 m depth 40 km off-shore Toulon [7].

2 DETECTOR LAY-OUT AND SIMULATION

In this report, we present the expected performances, for muon neutrino detection, of NEMO140dh, which is one of the detector configurations based on NEMO towers [8], understudy in the NEMO Collaboration for the construction of a deep underwater km³-scale Cherenkov detector to be deployed in the Mediterranean Sea [9]. The energy range investigated in this report is $100 \text{ GeV} \leq E_\nu \leq 100 \text{ PeV}$. The extension of the energy range at higher energies, up to the GZK energies [10], is of great interest, but not possible with the actual version of the code. An upgrading in this direction is one of the most important improvement for the design of a deep underwater km³-scale neutrino telescope and should be undertaken as soon as possible.

The simulations reported in this report are only a part of the simulation work done in the NEMO Collaboration and the NEMO140dh, described in the following, represents a reference detector which is just a starting point for the optimisation of the telescope. Indeed, further simulations have been undertaken in order to investigate the specific features of various detector configurations with particular reference to detectors made of NEMO towers.

The definition of the detector lay-out has been mainly constrained to the feasibility in terms of available technology within a reasonable budget and time construction schedule.

The NEMO140dh detector is made of 81 (9×9) towers with an instrumented height of 680 m, arranged in a square pattern. Each NEMO-tower consists of 18 horizontal bars (storeys) 40 m vertically spaced and consecutive storeys are orthogonal to each other. The bar length is one of the parameter which has been investigated in previous simulations and no significant differences were observed for values in the interval 15-20m. Each bar is equipped with two 10" PMTs at each edge, each PMT pair consists of a down looking PMT and a horizontal one looking outside with respect to the tower center. This PMT arrangement was chosen to assure a good angular coverage not only for up-going neutrinos, but also for down-going atmospheric muons, which obviously represent a source of background to get rid off, but are an important calibration source for the detector. The distance between towers is 140 m and each tower hosts 72 PMTs, namely 5832 PMTs for the whole detector.

The simulations on NEMO140dh has been a starting point for a km^3 -scale detector design based on NEMO towers.

In the ANTARES Monte Carlo the simulation of the detector response to high energy neutrino fluxes consists of several different steps which are undertaken by different codes [6]:

1. interaction of neutrinos in the media surrounding the instrumented volume;
2. propagation of the resulting particles until the detector horizon;
3. detector response to the Cherenkov light produced by the particles passing through the instrumented volume delimited by the detector horizon;
4. optical background and electronic simulation;
5. reconstruction track algorithms.

In the simulations presented in the following, we have used a modified version of the reconstruction code which allows to simulate large detectors of km^3 scale with several thousands of PMTs.

The site properties, such as depth, optical background, absorption and scattering length, have a severe impact on the detector performances as already shown in previous simulations [11]. In this report, the NEMO140dh has been placed in the Capo Passero site at about 3400m depth and the absorption and scattering length were chosen accordingly to the values measured in the several campaigns carried on by the NEMO

Collaboration in situ. An optical background of 20 kHz was considered in the simulations, namely only slightly lower than the measured in Capo Passero for a 10" PMT (about 30 kHz).

3 SIMULATION RESULTS

In this section, we present the simulation results on the response of NEMO140dh to muon neutrinos with an energy spectrum E^{-2} in an energy range between 100 GeV and 100 PeV. Muon neutrinos are generated inside a generation volume whose dimensions are defined accordingly to the corresponding expected maximum muon range. The detector horizon, where the muon light is simulated and propagated to the PMTs, is made of a cylindrical can which surrounds the detector. The can dimensions are chosen accordingly to distances where the Cherenkov light can be "seen" by the PMT, namely usually 2-3 attenuation lengths around to the instrumented volume. After the muon neutrino generation in the generation volume step 1 and step 2 are executed, then, if the muon reaches the can or it is generated inside the can volume, all the simulation the steps from 3 to 5 are executed.

In the following we report the results of simulations

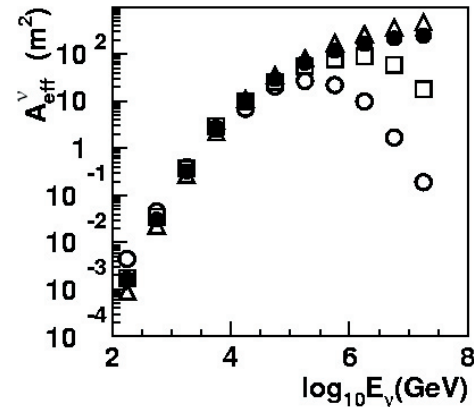


Fig. 1 – Effective areas for up-going neutrinos as a function of neutrino energy for different zenith angular ranges. Full circles $0^\circ \pm 90^\circ$, open circles $0^\circ \pm 30^\circ$, open squares $30^\circ \pm 60^\circ$ and open triangles $60^\circ \pm 90^\circ$.

where a quality cut $\Lambda \geq -9$ ($\Lambda = -\log(L)/N_{\text{DOF}}$, where L is the likelihood and N_{DOF} are the number of degrees of freedom) was applied. This cut selects events with $\Delta\Omega$ between the incident and reconstructed muon track comparable to the intrinsic angle $\theta_{\nu\mu}$ between the neutrino and the out-coming muon. In fig. 1, the neutrino effective area $A_{\text{eff}}^\nu(E_\nu, \theta_\nu)$ for up-going muon neutrinos is shown as a function of the neutrino energy for different angular ranges. The neutrino effective area is defined as follows:

$$A_{\text{eff}}^\nu(E_\nu, \theta_\nu) = V_{\text{eff}}(E_\nu, \theta_\nu) \cdot \rho \cdot N_A \cdot \sigma(E_\nu, \theta_\nu) \cdot P_{\text{earth}}(E_\nu, \theta_\nu)$$

where $V_{\text{eff}} = \frac{N_{\text{sel}}}{N_{\text{gen}}} \cdot V_{\text{gen}}$ is the neutrino effective volume (N_{sel} and N_{gen} are the number of events selected and generated respectively and V_{gen} is the generation volume), $\rho \cdot N_A$ is the nucleon density, σ is the neutrino cross section and P_{earth} is the transmission probability through the Earth.

The detector has been designed to provide full angular coverage. However, for neutrino energies up to few tens of TeV, the down-going neutrino fluxes is much lower than the atmospheric muon background. For this reason, in this energy range, only up-going neutrinos, for which the whole Earth acts as a screen, can be detected.

In fig. 1, the full circles refer to all the up-going neutrinos, the open circles refer to events with neutrino incident direction in the $0^\circ \div 30^\circ$ angular range, the open squares refer to the $30^\circ \div 60^\circ$ angular range and the open triangles refer to the $60^\circ \div 90^\circ$ angular range. At high energy ($E_\nu > 100$ TeV), due to the increased interaction cross section, the Earth becomes opaque to muon neutrinos and therefore the effective neutrino area A_{eff}^ν drops, while for almost horizontal neutrinos ($60^\circ \div 90^\circ$) A_{eff}^ν increases with increasing energy. For this reason at high energy ($E_\nu > 100$ TeV) the detection of horizontal and down-going neutrinos becomes of paramount importance as well as the electron neutrino and tau neutrino detection.

In fig. 2 the neutrino effective area A_{eff}^ν is plotted as a function of the cosine of the zenith angle for different energy ranges: namely full circles $10^3 \div 10^4$ GeV, open circles $10^4 \div 10^5$ GeV, open squares $10^5 \div 10^6$ GeV, and open triangles $10^6 \div 10^7$ GeV.

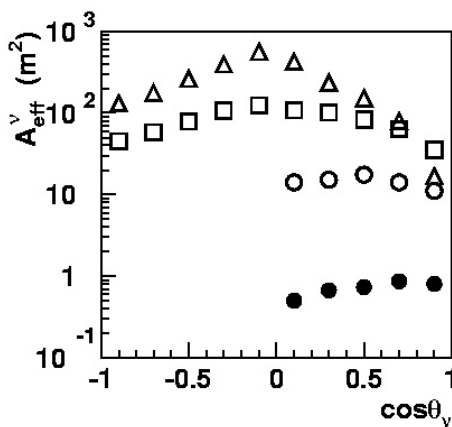


Fig. 2 – Effective neutrino areas as a function of neutrino zenith angles for different neutrino energy range. Full circles $10^3 \div 10^4$ GeV, open circles $10^4 \div 10^5$ GeV, open squares $10^5 \div 10^6$ GeV, and open triangles $10^6 \div 10^7$ GeV.

For the higher energy bins also the down-going ($-1 < \cos\theta < 0$) neutrino areas have been simulated: above 10^5 GeV the atmospheric muon background tends to vanish and the down-going neutrinos can be detected. In the highest simulated energy bin, namely $10^6 \div 10^7$ GeV (open triangles), the decrease of the effective area for up-going muon neutrinos due to the Earth absorption clearly shows up.

In order to better evaluate the detector performance dependence on the event direction, we have also simulated the muon effective area, which is independent of the neutrino interaction and cross section, as a function of the zenith angle for several muon energy bins.

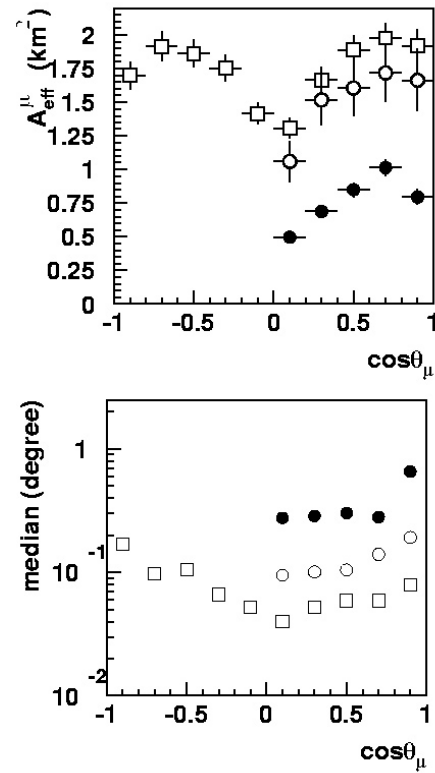


Fig. 3 - Muon effective areas (top) and median (down) between true and reconstructed muon direction as a function of zenith muon angles for different muon energy ranges. Full circles $10^3 \div 10^4$ GeV, open circles $10^4 \div 10^5$ GeV, open squares $10^5 \div 10^6$ GeV.

In previous simulations [11], where the muons were directly generated with a flat distribution in $\log_{10}(E_\mu)$ at the surface of the cylindrical can surrounding the detector horizon, in this work the muons are produced in the neutrino interactions and, as a consequence, the muon energy can be defined at different points (vertex, can, closer distance from detector center, ...) since it decreases as far as the propagation proceeds. We have used the same definition used in IceCube, where the

muon energy E_μ is defined as the energy at the point of closest approach to the detector center. The results are shown in fig. 3 for the different muon energy bins. In the top panel the muon effective area as a function of the cosine of the incident muon are reported for muon energy decades from 10^3 GeV to 10^7 GeV. The increase of the effective area going from horizontal to vertical tracks reflects the detector geometry. Rather larger effective area, up to almost 2 km^2 , are reached for the most energetic muons. Moreover, for the highest energy bin ($10^6 \div 10^7$ GeV) where also the down-going muons are reported, an almost symmetric trend is found for up-going and down-going tracks. This last result confirms that the chosen arrangement of the PMTs at the edges of the storeys, namely, one down-looking and one horizontal looking in the opposite direction with respect to the tower center, is a good compromise. The median, reported in the bottom panel of fig. 3, exhibits rather good angular resolution, comparable with the intrinsic spread in the θ_{vis} angle, in the whole angular range for all the energy bins, making a detector based on NEMO towers like NEMO140dh a very promising telescope for high energy neutrino astronomy.

However, for the detection of extraterrestrial neutrino fluxes above the background, specific cuts has to be imposed for diffuse and point-like source fluxes respectively in order to increase the detector sensitivity. The sensitivity, which is the most appropriate figure of merit for a neutrino telescope, has been calculated for the NEMO140dh detector for both diffuse and point-like source fluxes and the results are presented in this volume [12].

5 REFERENCES

- [1] F. Halzen and Dan Hooper, Rept. Prog. Phys. 65 (2002) 1025-1078.
- [2] Documentation in <http://amanda.uci.edu>
- [3] J. Ahrens et al, Astrpart. Phys. 20(2004)507 and documentation in <http://icecube.wisc.edu>.
- [4] F. Aharonian et al., Astronomy & Astrophysics 425, 213 (2004)
- [5] Documentation in <http://nemoweb.lns.infn.it>
- [6] D. Bailey, Monte Carlo tools and analysis methods for understanding the ANTARES experiment. Ph.D. thesis, University of Oxford, England (2002) <http://antares.in2p3.fr>
- [7] Documentation in <http://antares.in2p3.fr>
- [8] "Mechanical structures and sea operations for the NEMO experiment", M. Musumeci et al, in this volume
- [9] E. Migneco et al., Nucl. Phys. B (P.S.) 136 (2004) 61-68
- [10] T. Stanev, Nucl. Phys. B (P.S.) 136 (2004)103-110 and reference therein.
- [11] P. Sapienza et al., VLVNT Workshop, Amsterdam (2003) in <http://www.vlvnt.nl/proceedings> and P. Sapienza et al., Nucl. Phys. B (P.S.) 145 (2005) 331-334.
- [12] "The sensitivity of an underwater km3 telescope to muon neutrino fluxes from astrophysical sources", C. Distefano et al. in this report

THE SENSITIVITY OF AN UNDERWATER km^3 TELESCOPE TO MUON NEUTRINO FLUXES FROM ASTROPHYSICAL SOURCES

C. Distefano^{a,*}, R. Coniglione^a, E. Migneco^{a,b}, G. Riccobene^a, P. Piattelli^a, P. Sapienza^a,
for the NEMO Collaboration

a) INFN Laboratori Nazionali del Sud, Catania, Italy

b) Dipartimento di Fisica e Astronomia, Università di Catania, Catania, Italy

** Corresponding author, e-mail: distefano_c@lns.infn.it*

Abstract

In this work we report on the preliminary results of the sensitivity of the proposed NEMO neutrino telescope. The contribution of atmospheric neutrino and muon backgrounds is considered. In the calculation of the sensitivity, we consider both the cases of a diffuse neutrino flux and the case of a neutrino flux emitted by a point-like source.

1 INTRODUCTION

The realization of a km^3 scale detector for astrophysical neutrinos is considered today one of the most important goals of the next decade. Indeed, due to their small interaction cross section, high energy neutrinos are expected to allow us, for instance, to observe into dense environments in our Universe and to extend our knowledge beyond the distances that can be explored with gamma-rays and cosmic ray observations [1,2]. Many candidate sources of high energy neutrinos either galactic (SuperNova Remnants, Microquasars, interaction of cosmic rays with interstellar medium, ...) and extragalactic (Active Galactic Nuclei, Gamma Ray Bursts, ...) have to be investigated. At present IceCube, a cubic kilometer-scale under-ice neutrino detector, is under construction near the geographic South Pole [3]. Many arguments, mainly the full sky observation, with particular reference to the Galactic Center, strongly support the construction of a second km^3 detector in the Mediterranean Sea. The NEMO Collaboration is conducting and R&D activity towards the construction of a Mediterranean km^3 neutrino telescope [4].

Aim of this work is to carry out a preliminary study of the sensitivity of a km^3 detector made of NEMO towers [5] to muon neutrino fluxes coming from astrophysical sources. In section 2, we describe the generation of the background due to atmospheric neutrinos and muons. In section 3, we define the detector sensitivity and illustrate the criteria adopted to select the detected events in order to minimize the sensitivity itself. Eventually, we determine the detector sensitivity, assuming a diffuse muon neutrino flux and a muon neutrino spectrum coming from a point-like source.

2 DETECTOR LAY-OUT

The geometry of the NEMO- km^3 telescope simulated in this work, NEMO140dh, is a squared array of 9×9

towers *a là* NEMO [5] equipped with 5832 optical modules (10" diameter PMTs). The towers, moored at a seabed of 3400 m depth, have an instrumented height of 680 m, with a storey-storey distance of 40 m, and are spaced of 140 m. The detector response is simulated using the simulation codes developed by the ANTARES Collaboration [6]. In the simulation codes, the light absorption length, measured in the site of Capo Passero ($L_a \approx 68$ m at 440 nm [7]), is taken into account. Once the sample of PMT hits is generated, spurious PMT hits, due to the underwater optical noise (^{40}K decay), are introduced, with an average rate of 20 kHz for 10" PMTs. This value is close to the measured one in Capo Passero site [7].

3 SIMULATION OF THE ATMOSPHERIC MUON AND NEUTRINO BACKGROUND

3.1 Generation of the atmospheric neutrino background

Since the neutrino interaction cross section is very low we have adopted the approach of generating only the neutrinos that interact in the proximity of the detector, i.e. that may produce muons detectable by the telescope. Interacting neutrinos are generated with a generic power law spectrum and then weighted to the expected atmospheric neutrino flux (for details see [8]). We simulated a total number $1.2 \cdot 10^{11}$ interacting atmospheric neutrinos, with a generation spectral index $X = 1$. Neutrinos are generated in the energy range between 100 GeV and 1 PeV and with a 4π isotropic angular distribution. The total number of neutrino-induced muons, reaching the detector sensitive volume, is about 10^7 . The analytical parameterization adopted to fit the generated events to the atmospheric neutrino spectrum is the same reported in ref. [1]. The contribution of prompt neutrinos is also considered, simulating $2.6 \cdot 10^8$ neutrinos with energy greater than $3 \cdot 10^5$ GeV. Also in this case, neutrinos are generated

with $X = 1$ and with a 4π isotropic angular distribution. The prompt neutrino flux is normalized according to the rqp model [9].

3.2 Generation of the atmospheric muon background

The atmospheric muon sample is generated according to the formula given by Okada [10], which parameterizes the integral muon energy spectrum of muons, reaching a given depth D in seawater ($D=3400$ m in the Capo Passero site), as a function of the muon energy and direction (see [11] for details). We generated a sample of atmospheric muons of $\approx 1.9 \cdot 10^8$, corresponding to a detection time of 5 days. The total number of reconstructed muon events is about $3.4 \cdot 10^6$ and the number of mis-reconstructed up-going events is $1.2 \cdot 10^5$.

4 CALCULATION OF THE SENSITIVITY

4.1 Definition of the sensitivity

The calculation of the NEMO140dh-km³ detector sensitivity is here performed following the Feldman & Cousins approach. They define the sensitivity of an experiment as the average upper limit that would be obtained by an ensemble of experiments with the expected background and no true signal [12]. The average upper limit is the maximum number of events that can be excluded at a given confidence level (c.l.). The 90% c.l. sensitivity to a hypothetical source flux will therefore be given by:

$$\left(\frac{d\varphi_v}{d\varepsilon_v} \right)_{90} = \frac{\mu_{90}(b)}{n_s} \left(\frac{d\varphi_v}{d\varepsilon_v} \right)_0, \quad (1)$$

where $\mu_{90}(b)$ is the 90% c.l. average upper limit for an expected background with *known* mean b and $(d\varphi_v/d\varepsilon_v)_0$ is an arbitrary source spectrum predicting a mean signal n_s .

4.2 Criteria for the rejection of the atmospheric events

The used muon reconstruction procedure is based on the sequential use of several fitting algorithms: linear pre-fit, L1-L2 M-estimator, Maximum likelihood [13]. In this work, we use, as *goodness of fit* criterion, the variable:

$$\Lambda \equiv -\frac{\log(L)}{N_{DOF}} + 0.1(N_{comp} - 1), \quad (2)$$

where $\log(L)/N_{DOF}$ is the log-likelihood per degree of freedom and N_{comp} is the total number of compatible solutions found by the reconstruction program (see ref. [13] for details). This quality cut is here applied together with other selection criteria, taking into account the result of the fit procedure [13]. The complete list of the used selection criteria is the following:

- the energy of the event must be reconstructed;
- the estimate of the error on the muon direction must be smaller than 1° ;

- the variable Λ must be greater than a given value Λ_{cut} ;
- the number of hits N_{fit} , forming the reconstructed event must be greater than a given value N_{fit}^{cut} ;
- only events reconstructed in a circular sky region centered in the source position and having a radius of r_{bin} are considered (only in the case of point-like neutrino sources).

We checked different possible combinations of values Λ_{cut} , N_{fit}^{cut} , r_{bin} and we chose the set of parameters that minimize Eq.1. In the following we examine in details the case of a diffuse neutrino fluxes or coming from point-like source.

4.3 Sensitivity to a diffuse neutrino flux

We simulated neutrino-induced muons, generated by a diffuse neutrino spectrum $(d\varphi_v/d\varepsilon_v)_0 = 10^{-7} \varepsilon_{\nu, \text{GeV}}^{-\alpha}$ ($\text{GeV}^{-1} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$), where α is the spectral index. We simulated $3 \cdot 10^8$ interacting neutrinos in the energy range $10^2 \div 10^8$ GeV and with a generation spectral index of $X=1$ and a 4π isotropic angular distribution. These events are, then, weighted in order to fit the neutrino-induced event rate expected from the neutrino spectrum $(d\varphi_v/d\varepsilon_v)_0$. At this point, Eq.(1) is calculated from the reconstructed events, after the events selection described above. Since the angular distribution of atmospheric muons doesn't reach the detector horizon, we divided the detected events into two angular ranges: one angular range considers up-going reconstructed directions, where the main background is due to mis-reconstructed atmospheric muons and atmospheric neutrinos, while the second considers down-going events, where the main background is due to well reconstructed muons events. For each angular range, Eq.(1) is calculated for Λ_{cut} ranging between 7.1 and 8.0 with a step of 0.1, and N_{fit}^{cut} ranging between 0 and 300 with a step of 1. The case of no application of Λ and/or N_{fit} selection is also considered. In this analysis we consider only cases with no atmospheric muons surviving the selection. The event selection will be revised when the statistics of the atmospheric muon sample will be larger. In tables 1 and 2, we report the results for up-going and down-going angular ranges, taking into account different neutrino spectral indexes and considering 3 years of data taking.

Table 1: Values of quality cuts that minimize the sensitivity to an up-going diffuse flux for different values of the neutrino spectral index α .

α	Λ_{cut}	N_{fit}^{cut}	n_s	B	μ_{90}
1.0	-	289	4.25E8	1.58	3.67
1.5	-	197	2.09E5	6.75	5.77
2.0	-	129	250.4	30.92	10.87
2.5	-	80	0.98	189.54	25.12

Table 2: Values of quality cuts that minimize the sensitivity to an down-going diffuse flux for different values of the neutrino spectral index α .

α	Λ_{cut}	N_{fit}^{cut}	n_s	B	μ_{90}
1.0	-	280	5.07E8	0.00	2.43
1.5	-	280	1.43E5	0.00	2.43
2.0	-	280	55.63	0.00	2.43
2.5	-	280	0.03	0.00	2.43

Figure 1 shows, for the spectral index $\alpha=2$, the neutrino energy spectra of the reconstructed and selected events, in the two considered angular ranges.

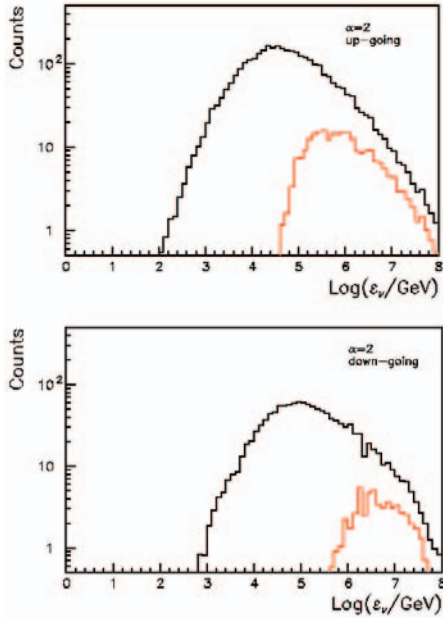


Figure 1: Neutrino energy spectra of reconstructed events, before (black) and after (red) the event selection.

The values of n_s and b , that minimizes Eq.1 in the two angular ranges, are then summed and the final sensitivity is calculated in the 4π solid angle and reported in table 3.

Table 3: Sensitivity to a diffuse neutrino flux, for different spectral indexes α and for 3 years of data taking.

α	$\epsilon_v^\alpha (d\phi_v/d\epsilon_v)_{90}$ (GeV $^{\alpha-1}$ /cm 2 s sr)
1.0	3.94E-16
1.5	1.64E-12
2.0	3.55E-9
2.5	2.49E-6

Eventually, we calculate the sensitivity to a diffuse muon neutrino flux as a function of years of data taking.

In fig. 2, as an example, we report the result for a spectral index $\alpha=2$. In the same figure, as a comparison, the same sensitivity for the IceCube detector [3] is shown.

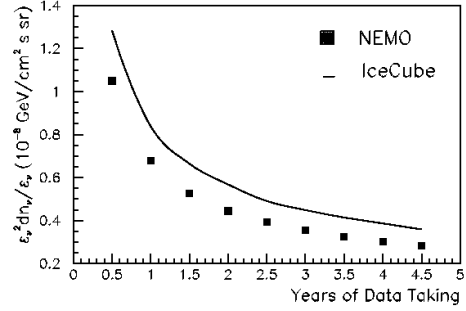


Figure 2: Sensitivity to a diffuse neutrino spectrum with $\alpha=2$ as a function of years of data taking and comparison with the IceCube detector [3].

4.4 Sensitivity to a neutrino flux coming from a point-like source

We simulated neutrino-induced muons, generated by a neutrino spectrum equal to $(d\phi_v/d\epsilon_v)_0 = 10^{-7} \epsilon_{v, \text{GeV}}^{-\alpha}$ (GeV $^{-1}$ cm $^{-2}$ s $^{-1}$), simulating also in this case, the energy range $10^2 \div 10^8$ GeV with a generation spectral index of $X=1$. These events are, then, weighted in order to fit the neutrino-induced event rate expected from the neutrino spectrum $(d\phi_v/d\epsilon_v)_0$. As a representative case, the source position is chosen at a declination of $\delta=-60^\circ$. Such a source, in fact, has a diurnal visibility of 24 hours (only up-going neutrinos come from it) and it covers a large angular range in the detector rest frame. The generated neutrino-induced muons were, then, propagated inside the detector.

We also estimated the atmospheric muon background for a point-like source corresponding to 3 years of data acquisition. As shown in [11], in fact, the mis-reconstructed atmospheric muons have, a given declination, an isotropic distribution in Right Ascension (RA). This consideration allows us to project the sample of simulated events (having the same declination δ) in a single bin of RA.

At this point, Eq.(1) is calculated for Λ_{cut} ranging between 7.1 and 8.0 with a step of 0.1, and N_{fit}^{cut} ranging between 0 and 300 with a step of 1. The case of no application of Λ and/or N_{fit} selection is also considered. We also checked a search bin r_{bin} , ranging between 0.1 and 1 degree, with a step of 0.1. In table 4, we report the results of the event selection for different spectral indexes, considering 3 years of data taking. In figure 3, we show how the energy spectrum of reconstructed events is modified after the event selection, considering the particular case of $\alpha=2$.

In table 5 we report the values of the sensitivity at different neutrino spectral indexes and for a time of 3 years. Figure 4 shows the sensitivity for $\alpha=2$, as a

function of years of data taking. In the same figure, we report, as a comparison, the sensitivity of the IceCube detector to a neutrino flux from a point-like source, obtained for a search bin of 1° [3].

Table 4: Results of the event selection for neutrinos coming from a point-like source at $\delta=-60^\circ$, considering different spectral indexes α and 3 years of data taking.

α	Λ_{cut}	$N_{\text{fit}}^{\text{cut}}$	r_{bin}	n_s	b	μ_{90}
1.0	-	33	0.4	1.19E8	0.05	2.48
1.5	-	33	0.4	8.10E4	0.05	2.48
2.0	-7.8	0	0.3	184.2	0.28	2.68
2.5	-7.8	0	0.3	0.86	0.28	2.68

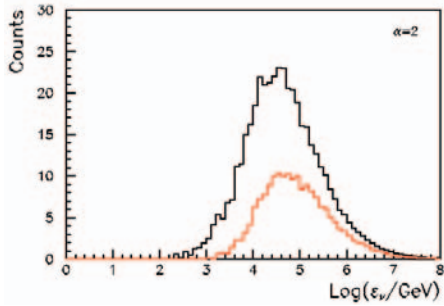


Figure 3: Neutrino energy spectrum of reconstructed (black) and selected (red) events, for the spectral index $\alpha=2$ and 3 years of data taking.

Table 5: Sensitivity to a neutrino flux coming from a point-like source at a declination $\delta=-60^\circ$.

α	$\epsilon_\nu^\alpha (d\Phi_\nu/d\epsilon_\nu)_{90}$ (GeV $^{\alpha-1}$ /cm 2 s)
1.0	2.08E-15
1.5	3.06E-12
2.0	1.46E-9
2.5	3.13E-7

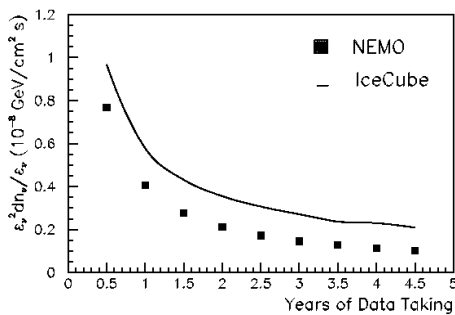


Figure 4: Sensitivity to a neutrino spectrum with $\alpha=2$, coming from a $\delta=-60^\circ$ declination point-like source, as a function of years of data taking, and comparison with the IceCube detector [3].

5 CONCLUSIONS

In this work, we report preliminary results of the sensitivity of the NEMO140dh-km3 detector, taking into account both the case of diffuse muon neutrino flux and a muon neutrino flux coming from a point-like source. We also compare the NEMO and the IceCube response, showing that the NEMO detector has a better sensitivity to muon neutrino fluxes. Moreover, in the case of a point-like source, the NEMO detector shows also a smaller search bin, and then a better angular resolution for point-like source search.

6 REFERENCES

- [1] J. Learned, K. Mannheim, Annu. Rev. Part. Sci 50 (2000) 679.
- [2] F. Halzen and D. Hopper, Rep. Prog. Phys. 65 (2002) 1025.
- [3] J. Ahrens et al., Astropart. Phys. 20 (2004) 507.
- [4] The NEMO Collaboration web site:
<http://nemoweb.lns.infn.it/>.
- [5] M. Musumeci, for the NEMO collaboration, 2003, Proc. of VLVnT Workshop, Amsterdam, October 5-8 2003, <http://www.vlvnt.nl/proceeding>.
- [6] D.J.L. Bailey, Monte Carlo tools and analysis methods for understanding the ANTARES experiment and predicting its sensitivity to Dark Matter, PhD dissertation, University of Oxford, United Kingdom, <http://antares.in2p3.fr/>.
- [7] The NEMO Collaboration, Study and characterization of a deep sea site for a km3 underwater neutrino telescope, report to ApPEC (2002).
- [8] C. Distefano et al., for the NEMO Collaboration, LNS Activity Report 2002.
- [9] E.V. Bugaev, Phys. Rev. D58 (1998) 054001.
- [10] A. Okada, 1994, Astrop. Phys. 2, 393.
- [11] C. Distefano, for the NEMO Collaboration, LNS Activity Report 2003.
- [12] G.J. Feldman & R.D. Cousins, Phys. Rev. D57(1998)3873.
- [13] A. Heijboer, 2004, Track reconstruction and point source searches with Antares, PhD dissertation, Universiteit van Amsterdam, Amsterdam, The Netherlands (<http://antares.in2p3.fr/>).

NEMO PHASE 1 – THE PROJECT AND REALIZATION OF THE JUNCTION BOX

G.Cacopardo^{a*}, R.Cocimano^a, A. D'Amico^a, C. D'Amato^a, V. D'Amato^a, M. Musumeci^a, R. Papaleo^a, G. Raia^a,

M.Taiuti^b for the NEMO Collaboration

a) INFN Laboratori Nazionali del Sud, Catania, Italy

b) Dipartimento di Fisica dell'Università di Genova and INFN Sezione di Genova, Genova, Italy

** Corresponding author, e-mail: cacopardo@lns.infn.it*

Abstract

The NEMO Collaboration is conducting an intense activity to develop technical solutions for an underwater neutrino telescope. One of the key elements is the Junction Box that distributes the power supply to every component of the telescope, collects all the digitized signals and provides the required links to the shore station. In this report we give a description of the Junction Box structure, of the adopted mechanical solutions and of the planned functional tests.

1 INTRODUCTION

The Junction Box (JB) is a key element in the stream-line between the shore station and an underwater neutrino telescope. It is normally located at the maximum depth close to the apparatus, and it is connected to one side to the electro-optical cable originating from the coast and to the other side to the elements of the telescope. Its functions are manifold and include:

- the electrical and data transmission;
- the control of the power feedings systems connected to the JB;
- the optical and electrical connections between the Remote Operated Vehicle (ROV) connectors frame;

It has been designed to host and protect from the effects of corrosion and pressure, the opto-electronic boards dedicated to the distribution and the control of the power supply and the digitized signals. In previous experiments the JB has been realized in titanium, that provide excellent protection against corrosion and pressure but it is very expensive. For the NEMO PHASE 1 a new conceptual design has been developed based on less expensive materials and an original layout of the electronics.

2 THE MECHANICAL STRUCTURE

The Junction Box is composed by:

- External components:
 - The glass-reinforced plastic container;
 - The external frame;
 - One pressure compensator for the external oil circuit;
 - One acoustic beacon for the positioning system;
- Internal components:

- Four Pressure Vessels: PV1, PV2, PV3, Trafo Box (TB);
- One Splitting Box (SB);
- One pressure compensator for the internal oil circuit;
- Electrical and mechanical components;
- The internal frame.

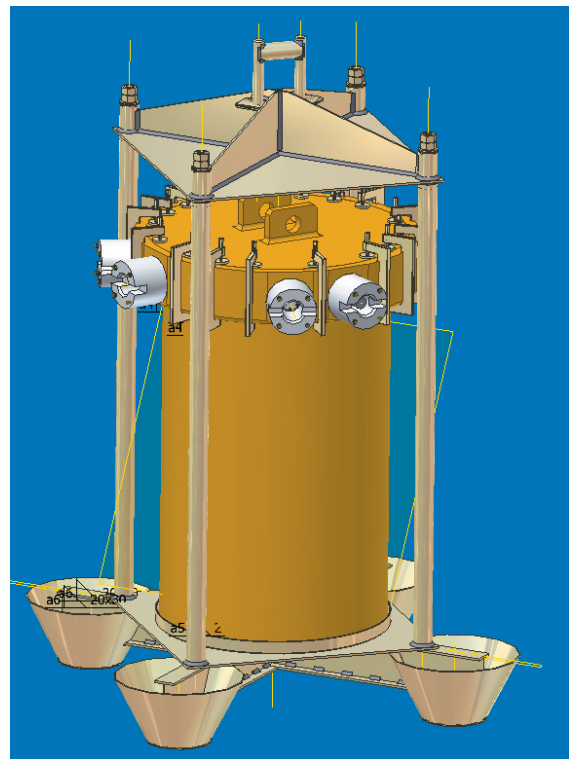


Fig.1 Drawing of the aluminum external frame and the glass-reinforced plastic container.

The external structure of the JB is reported in Fig. 1: the aluminum external frame has been designed to guarantee feasible and reliable sea operations and deployment [1] as well as good stability on the sea-ground; it hosts the glass-reinforced plastic container.

The glass-reinforced plastic container, of the volume of approximately 1.5 m³, will contain the previously listed internal items, it will also be a support for ROV connectors bulkheads, and will guarantee the perfect isolation between its content and the seawater. It is connected to a pressure compensator that can compensate a volume of approximately 100 liters and will be placed outside of the glass-reinforced plastic container, fixed on the external frame.

The glass-reinforced plastic container will be filled up with silicone oil in order to protect the steel internal structure from corrosion, and to increase the reliability of the system. In case of a water leakage, the water would flow down to the bottom of glass-reinforced plastic container, thus ensuring the integrity of the system.

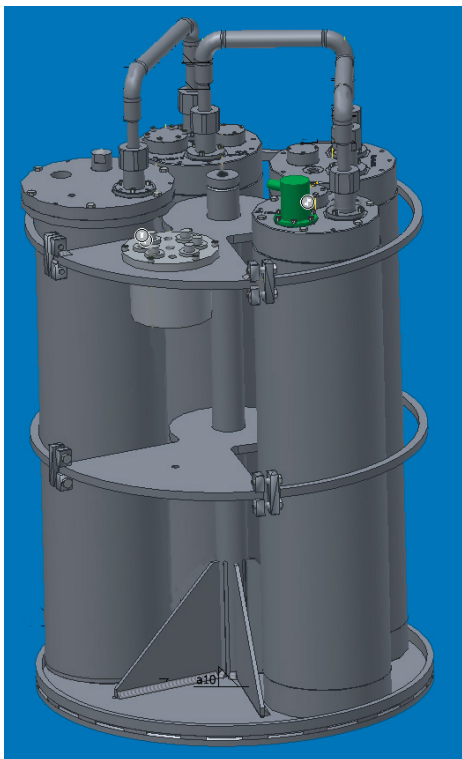


Fig.2 Internal structure of the Junction Box.

3 THE INTERNAL STRUCTURE

The internal structure is shown in Figg. 2,3. The three pressure vessels PV1, PV2 and PV3 contain the control boards of the power supply system and the data transmission system [2]. The pressure vessels have been designed to withstand the differential pressure of 350 bars. Therefore the electronics board contained in PV1,

PV2 and PV3 can operate when needed either in an oil bath or in air.

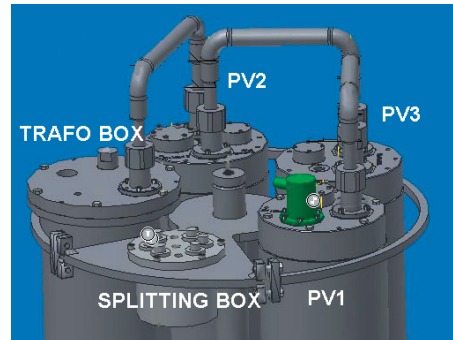


Fig.3 Detail of the top part of the internal structure with the name of individual items.

This choice also does not lead to a significant increase of the PV costs and it allows an absolute flexibility in the project choices about the control electronics. All the internal circuits (containers, branching pipes, splitting box) working at the external pressure are isolated from the outside and filled up of silicone oil. There is no contact between the internal oil and the outer oil.

The Trafo Box (TB) is a metallic container that will contain the three-phase transformer and the power supply.

These items are mounted on the internal frame together with the splitting box (SB), and the pressure compensator (PC1) for the internal oil circuit.

4 THE STATUS OF THE INTEGRATION

All the components of the internal structure have been realized and tested at the operating pressure in a hyperbaric pressure tank with positive results. The tests have been carried out at the pressure of 300 bars, first on the single containers, and then on all internal structure, complete of the interconnection pipes. The test procedure consisted in both cases of 10 cycles, in each cycle the pressure was raised up to 300 bars and kept for half an hour, and then was raised down to 1 bar. The tests have been carried out at Ring-O Valve facilities in Colico (Lecco-Italy), where a pressure tank of 2 m diameter and 6 m height can operate at the pressure of 300 bars.

All the components of the internal structure have been realized and tested. The integration of the internal structure is planned before this summer.

REFERENCES

- [1] M. Musumeci et al., *Mechanical structures and sea operations for the NEMO experiment*, in this report.
- [2] R. Cocimano et al., *The NEMO Phase-1 power control system and electronic devices pressure tests*, in this report.

NEMO PHASE 1 POWER CONTROL SYSTEM AND ELECTRONIC DEVICES PRESSURE TESTS

R.Cocimano^{a,*}, G. Cacopardo^a, A. D'Amico^a, C. D'Amato^a, V. D'Amato^a, M. Musumeci^a, R. Papaleo^a, G. Raia^a, M. Taiuti^b, for the NEMO Collaboration

a) INFN Laboratori Nazionali del Sud, Catania, Italy

b) INFN Sezione di Genova, Genova, Italy

** e-mail: cocimano@lns.infn.it*

Abstract

The NEMO Collaboration is conducting an intense activity to develop technical solutions for an underwater laboratory. In this framework the design of NEMO Phase 1 electrical power system and power control system have been carried out in order to feed the laboratory both in ordinary and in fault conditions. This report gives a brief description of the above mentioned electrical power system and power control systems. The paper is focused on the high pressure tests that have been carried out for a year on electric and electronics devices to improve on reliability and cost reduction of the Junction Boxes.

1 NEMO PHASE 1 LAYOUT

The NEMO PHASE 1 observatory layout is the result of a compromise between physics request and the technical feasibility within a reasonable budget. The aim of the NEMO PHASE 1 is to test all the elements that compose NEMO [1].

The main elements that compose the laboratory are the following:

- a *Shore Station* in which the feeding station, the on shore power control system, the data transmission and the storage system will be installed;
- the *main electro optical cable*, 25 km long, that brings power and communication to the submarine laboratory;
- one *Primary Junction Box* [2] that contains the electric and electronic devices for communication and power of two Secondary Junction Boxes;
- two *Secondary Junction Boxes* [2], each one containing the electric and electronic devices for communication and power of towers;
- two *Towers* [3] one of 16 floors and the other one of 4 floors, called mini-tower. A tower consist of 16 storey 20 m long and 40 meter spaced;
- *Floors* [3] were scientific instruments can be connected for communication and power. Each storey is equipped with two couples of Photomultipliers at the two ends.

2 NEMO PHASE 1 ELECTRICAL POWER SYSTEM

For the NEMO PHASE 1 electrical power system the same design choices proposed for NEMO were taken with the appropriate changes.

The electrical power system consists of a three-phase delivery and distribution system able to feed all the electrical loads located in the Junction Boxes and in the floors (see figure 1 and 2).

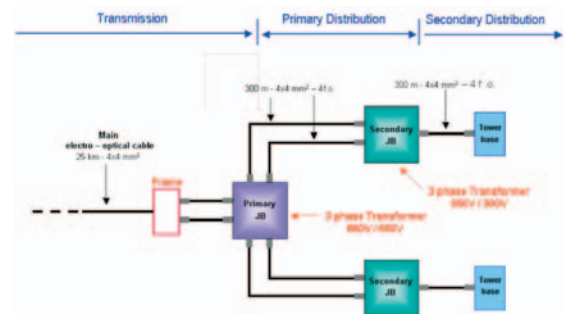


Fig. 1 NEMO PHASE 1 Electrical Transmission and Distribution System.

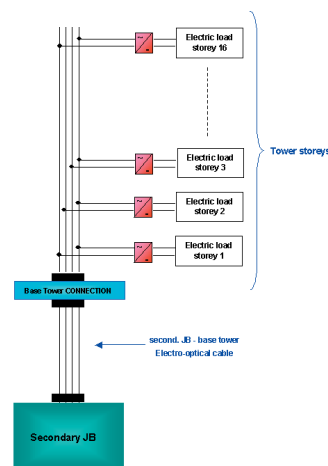


Fig. 2 NEMO PHASE 1 Tower Electrical Distribution System.

An ac three-phase distribution system seems to be more reliable and effective. It is used not only for the transmission system but also for the distribution one. In this way an improvement on reliability can be obtained by installing electrical transformers in critical points (such as the Primary JB and Secondary JB) and linear power converters near each load (for example in each floor). As a result, a fault occurring to an electronic power supply will cause only a localized loss of power.

In figure 1 a diagram of the electrical power system for the supply of two tower is visible. In it, the line-to-line nominal voltage levels in each node, the power delivered and power losses in the electro optical cables are pointed out. The total amount of power is 2 kW.

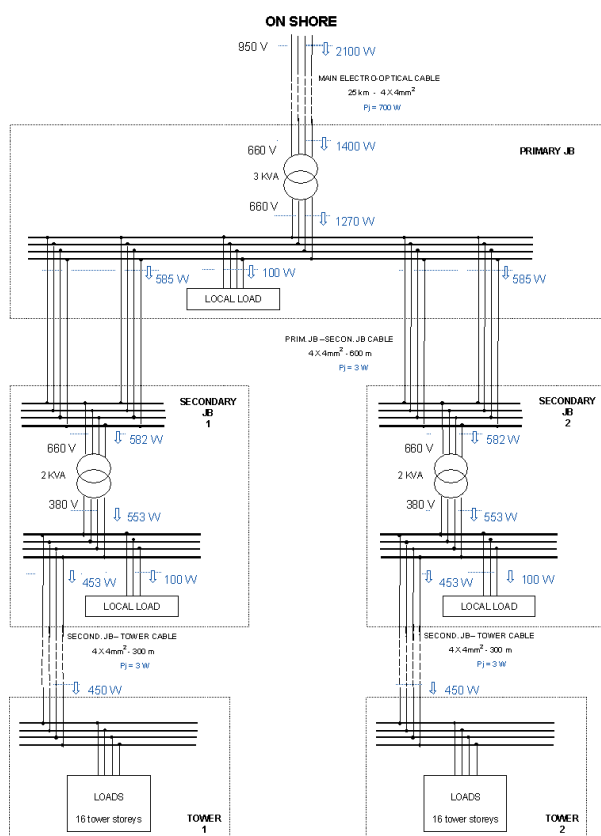


Fig. 3 NEMO PHASE 1 Electrical Power System

3 NEMO PHASE 1 POWER CONTROL SYSTEM

A design of the power control system was done in order to remotely monitor the submarine laboratory.

The NEMO PHASE 1 Power Control System has been designed to be able to:

- acquire environment parameters such as temperature, humidity, pressure inside the boxes,
- acquire electric parameters such as currents and voltages of all the feeding lines,
- switch the power on and off to each feeding line, both under ordinary and fault condition,

- reveal the electric fault and remotely control the breakers in order to continue feeding the JB interested by the fault by means of the redundancy lines

A controller is present in each box and, the communication between the field control system and the shore is realized by optical fibers while the communication among the field control levels is realized with a conveyed wave system (the transmission means is represented by the electrical wires) since optical fibers are not available (see figure 4).

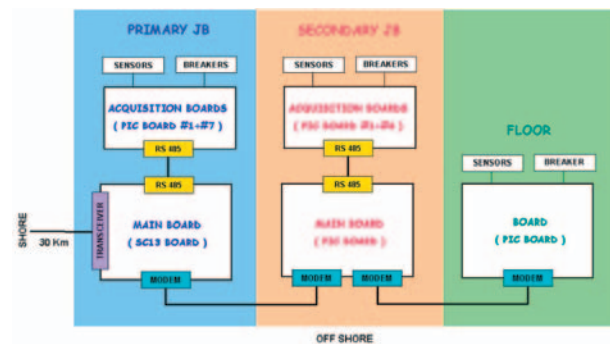


Fig. 4 NEMO PHASE 1 Power Control System

During design has been important:

- to use commercial devices already tested and used;
- to minimize the failure points to maximize reliability;
- to foresee the right redundancies;
- to foresee the storage of as much as possible devices in oil and high pressure environment.

The storage of as much as possible devices in pressure and oil environment is an important topic and is due to the JB design. The JB is made of a pressure resistant steel vessel contained in a fiberglass box to avoid direct contact between steel and sea water. The fiberglass box is filled with oil to compensate the external pressure and contains three other vessel for the transformer, power supplies, switches, sensors and electronics boards. The steel pressure vessel houses only the electronic devices that cannot stay under pressure. This solution will improve on reliability due to the reduced number of sealed connection that represent failure points. It will improve on costs reduction too, due to the reduction of its dimensions and to the use of low cost materials rather than expensive alloy such as standard titanium.

4 HIGH PRESSURE TESTS ON ELECTRIC AND ELECTRONIC DEVICES

To reach the goal of having the maximum number of electric and electronic devices working under pressure several pressure tests have been performed. These tests have been carried out on transformers, contactors and electronic components to investigate their behavior under pressure in an oil environment. For all the tests silicone oil have been used.

Initially a 400 bar water filled hyperbaric chamber was used, into which an oil-filled container with the devices to be tested was inserted. This uncomfortable procedure brought us to design another chamber. The new chamber is a 400 Bar oil-filled cylindrical hyperbaric chamber equipped with a 9 pin electrical connector and a manual pump (see figure 5).

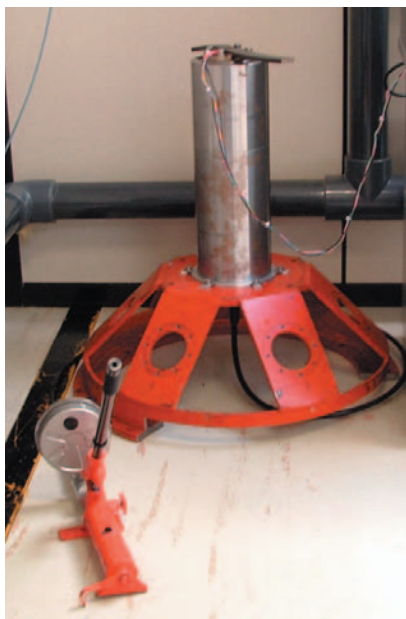


Fig. 5 Oil-filled 350 Bar hyperbaric chamber

Pressure tests have been performed on contactors, transformers, current and voltage sensors, temperature sensor, quartz crystals, capacitors, microcontrollers, integrated circuits and various electronic components.

The first component tested was a contactor that will be used in all the feeding lines. It was a 4-pole contactor (operating voltage of 690 V) with the reed relays able to pilot the 5 Vdc contactor operating coil (see figure 5). The test foresaw ten pressure cycles (0 bar - 350 bar - 0 bar), then the contactor was kept at 350 bar for a week. During the test it was forced to switch on and off every 10 seconds while an acquisition system registered the possible failures. No failures have been detected.

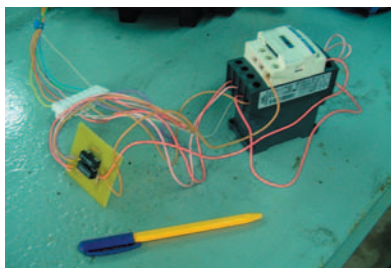


Fig. 6 Contactor and piloting relay reeds

Subsequently a voltage and a current hall effect transducers have been tested with a set of 10 cycles (0

bar - 350 bar - 0 bar) and left at 350 bar for 1 day. They worked properly.

The transformers tested under pressure were the ones that will be housed in the Junction Boxes. Each JB is equipped with a three-phase transformer (formed by 3 mono-phase toroidal transformers) with the following characteristics:

- nominal power: 7 KVA
- input nominal voltage: 660 V
- output nominal voltage: 660V or 380V
- frequency: 50 Hz
- efficiency: 0.98

These transformers have been tested by a set of 10 cycles (0 bar - 400 bar - 0 bar) at 400 bar. They worked properly.

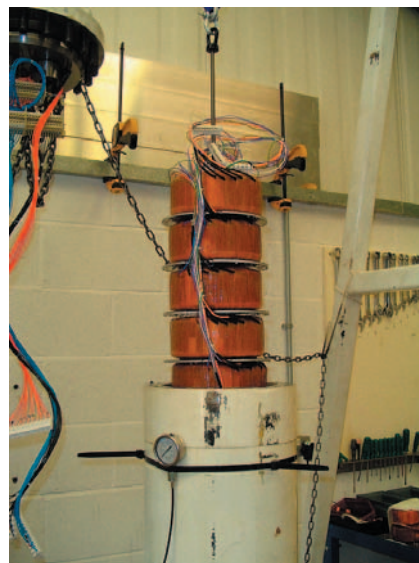


Fig. 7 Junction Box transformers during the test

Quartz crystals have been tested under pressure too. In particular were tested: a metal encased crystals, hermetically sealed in an inert atmosphere that failed under pressure, and a plastic encased SMD crystal that work properly.

Several kinds of capacitors have been subjected to a set of 10 cycles (0 bar - 300 bar - 0 bar), the results are listed below:

- electrolytic capacitors up to 200 μF worked properly under pressure, while capacitors from 200 μF to 470 μF even being squashed by pressure continued functioning;
- tantalum capacitors worked properly under pressure;
- ceramic capacitors showed a 10% capacitance variation due to oil impregnation, after the test the new capacitance value remained constant.

After the tests previously described a long term test was carried out. The LAMS board (see figure 8) was tested under a pressure of 300 Bar for six months, this board houses all the critical (from a pressure resistance

point of view) components of the NEMO PHASE 1 power control system:

- a wire-wound PT 100 temperature sensor;
- a voltage sensor (Hall effect transducer);
- a current sensor (Hall effect transducer);
- a reed relè to pilot the breaker;
- integrated circuit for sensors signal conditioning;
- analog-to-digital converter for sensors signals acquisition;
- a microcontroller (PIC 16F876);
- serial output RS485.

An acquisition system registered the possible failures. No failures have been detected.

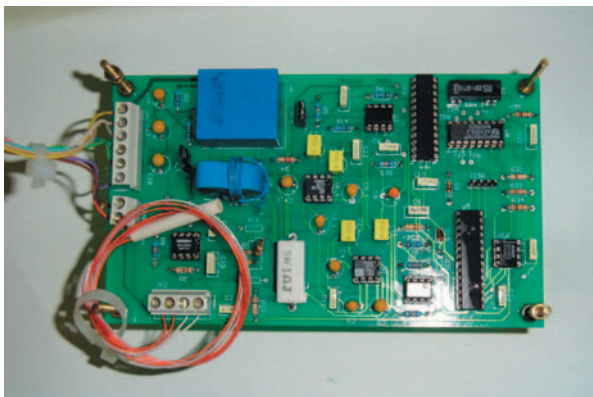


Fig. 8 LAMS board tested for 6 months

4 CONCLUSIONS

This paper reports a summary of the activity that has been in progress for a year on the realization of the power control system for the NEMO Phase-1 project. In particular, it is focused on the high pressure tests that have been carried out on electric and electronics devices to improve the reliability and cost reduction of the Junction Boxes. All the tests done up to today had successful results.

A pressure test of the completely assembled power control system will be performed in the near future.

5 REFERENCES

- [1] NEMO web page: <http://nemoweb.lns.infn.it/>
- [2] G. Cacopardo et al., in this report
- [3] M. Musumeci et al., in this report

MECHANICAL STRUCTURES AND SEA OPERATIONS FOR THE NEMO EXPERIMENT

M.S. Musumeci^{*a}, G.Cacopardo^a, R.Cocimano^a, C. D'Amato^a, V. D'Amato^a, A. Grmek^a, R.Papaleo^a, G.Raia^a

for the NEMO collaboration

a) INFN Laboratori Nazionali del Sud, Catania, Italy

** Corresponding author, e-mail: musumeci@lns.infn.it*

Abstract

The NEMO collaboration aims to install a km³ neutrino detector in ultra deep sea water. Due to the working environment, a big problem to solve is to maximize the reliability of the apparatus and to minimize the sea operations, in terms of number and duration. A good way to proceed is to minimize the number of the mooring lines required to realize the three dimensional matrix of optical sensors. An unfurling tower has been chosen by the NEMO collaboration in order to solve these problems. The mechanical characteristics of the structures and the ways to deploy and recover them will be presented in this paper. Devices useful to realize the submarine infrastructures that were deployed during the January '05 will also be described.

1 GENERAL DESCRIPTION OF THE NEMO DETECTOR

The first goal in developing the mechanical structures for the NEMO experiment was to obtain a semi rigid three dimensional support for the optical modules. In fact simulations show that 3D array of photo-multipliers (like the NEMO tower) improve tracks reconstruction capabilities compared with string [1] [2].

The tower is formed by a sequence of several (16÷18, depending on physics requirements) instrumented floors spaced vertically by 40 m. The floor structure is realized by means of a lattice girder having a length of 15 meters. On each end of the beam two glass spheres, housing the photo multipliers, are fastened. The structure supporting the optical modules has been thought in order to easily permit a change in the sensors orientation, depending on the physic requirements. Each floor is connected to the neighbors by means of four ropes. The ropes are fastened in a way that forces the beam to take an orientation rotated of 90 degrees one by each other.

Figure 1 shows a couple of floors together with the buoy used on the top of the structure to tension the ropes.

The first floor will have an elevation of 150 meters from the sea bed. This distance has been chosen to leave a sufficient volume of water for neutrino interactions occurring below the detector. The total height of the tower will be 750÷850 meters, depending on the number of floors.

Simulations show that to realize the whole km³ detector 64÷80 towers are needed. Each tower will be spaced of 180÷200 meter from its next neighbours [1] [2].

The instrumented tower has to be connected to the shore in order to receive power supply and to transmit

data. The link will be realized by means of Junction Boxes containing the power distribution system and the data transmission system. Each Junction Box will be used to connect a group towers by means of electro optical jumpers fitted with special wet mateable connectors.

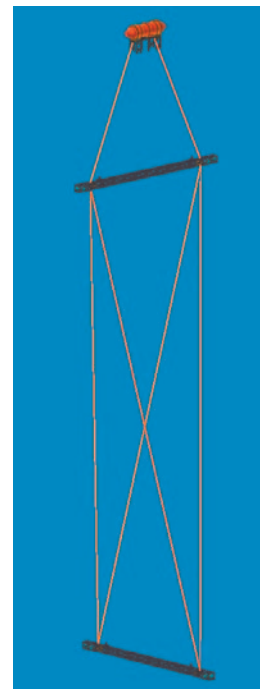


Figure 1

All Junction Boxes will be connected to shore by means of an electro-optical submarine cable equipped with wet mateable connectors. All the interconnections of the structure in deep sea water will be realized by means of a Remotely Operated Vehicle (ROV).

2 ENVIRONMENTAL CONSTRAINTS

The working environment (3500 meters sea water depth) of the detector is one of the most aggressive on the Earth. Both the corrosion, due the salt water, and the ultra high pressure, contribute to make the realization of a km³ scale neutrino detector very hard.

2.1 Corrosion resistance

The problem of corrosion resistance was solved in several different ways, depending on the device to be realized.

Following a lot of tests and costs evaluation, the floor lattice girder will be realized in marine aluminum (5000 series). This material optimizes the requirements of corrosion resistance and low cost of the raw material. Another big advantage of the aluminum, compared to the other metallic materials, is the light weight that permits to realize reliable structures reducing the risks of failure without a great influence on the costs.

All the electronic components (power distribution system, data transmission system, etc.) are fitted inside plastic boxes that will be described in the following paragraphs.

Commercially instruments are fastened to the floors through plastic material (HDPE) to avoid galvanic processes between different materials.

2.2 Pressure resistance

The problem of the pressure resistance is mainly related to the use of vessels to house electronic devices. It is possible to distinguish two groups of electronic components:

- ✓ pressure resistant;
- ✓ not pressure resistant.

Depending on that, two different choices were undertaken, with respect to the design of the vessel to accommodate the electronic device.

Devices able to resist to the pressure are hosted into plastic vessels filled with oil and pressure compensated by means of a lung. In this way instruments are not in contact with salt water and is easier to avoid leakages through the connectors holes. The sealing devices are in fact stressed by the same pressure on both sides and they should have a longer working life without any faults.

Figure 2 shows one of these elements: one half of the plastic box containing a 19" standard rack which host the power control electronic boards of the tower floor and power transformers [3].

The electronic devices not pressure resistant will be fitted inside aluminum cylindrical vessels. Each vessel, in order to avoid problems related to the galvanic corrosion is incorporated in a plastic vessel filled with oil and pressure compensated to avoid mechanical stress on the walls of the plastic box.

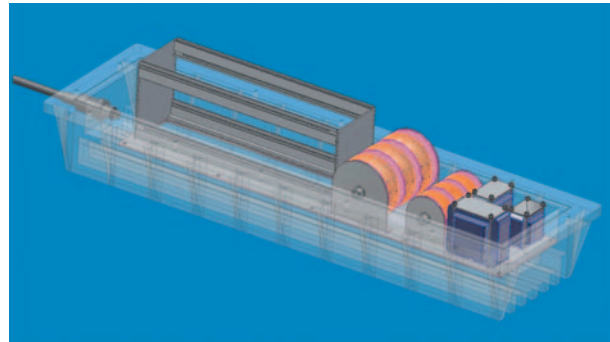


Figure 2

In Figure 3 an aluminum vessel fitted inside the plastic one is shown. This vessel will host the front end electronics for the floor.

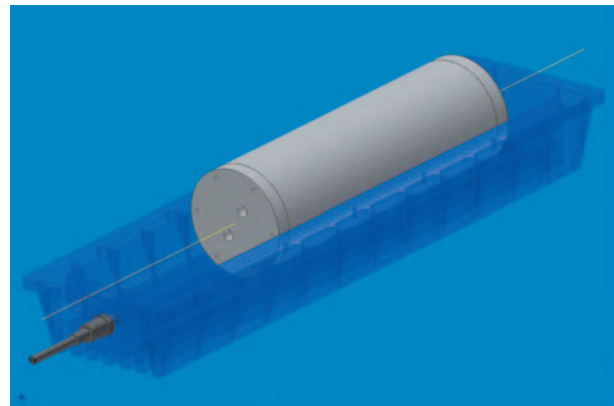


Figure 3

The power control electronic vessel and the front end electronics vessel will be fitted in the middle of the floors and connected with the backbone electro-optical cable used for the data and power transmission of the tower.

Similar conceptual way to face the problems of the corrosion and pressure resistance was used to design the Junction Boxes, extensively described elsewhere in this report [4].

3 SEA OPERATIONS

A big influence in the success of a deep sea water detector realization is related with the sea operations procedures. The sea operations requirements have a great influence also on the mechanical structures design principles. An excellent project thought to work statically on the sea bottom could be very bad from the point of view of the deployment and recovery procedures.

3.1 The deployment and recovery procedure of the tower

Due to its dimensions, the tower cannot be handled when it is completely extended. For this reason an “unfurling tower” has been designed. It will be in fact deployed in a packed configuration and, once it will have reached its final position on the sea bed, an unfurling mechanism will be actuated.

The opening phase will be carried out by releasing a buoy connected to the upper floor from its parking position on the anchor. The anchor is in fact designed both to maintain the bottom of the tower on a fixed position on the sea bed, and to group, park and hold the beams and the tensioning buoy out of the water and during the deployment.

In Figure 4 the whole packed system is shown. Only four beams are represented because during the first phase a mini tower will be deployed to test the technical feasibility of the project. The red cylinder represents the tensioning buoy, the cyan spheres represent the optical modules fastened at the ends of the lattice grinder. The green railings are meant to contain the beams during the transportation and the deployment phases.

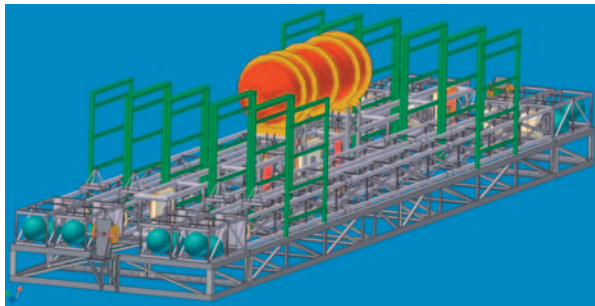


Figure 4

In order to carry out the recovery of the structure, at the end of its working life, a system of ropes able to realign again the beam on the anchor has been developed.

Once the floors will be aligned on the top of the lattice structure on the sea bottom, a second command will release the recoverable part from the anchor. Thanks to the pull force given by the buoy, the recoverable part of the structure will reach the sea surface and then it will be recovered on-board ship.

3.2 Simulations carried out on the tower behavior

Results of simulations carried out using two different multi-body numerical codes, ran by a LNS engineering team and a TECNOMARE [5] group respectively, are encouraging: the maximum deformation of the tower, estimated using the worst value of the current measured in Capo Passero site, is roughly 12 metres.

The movements of the beams during the unfurling phase were also simulated, the results obtained are fully compatible with the design expected values.

3.3 Tests carried out on the deployment procedure

A couple of scale model were realized in order to verify the simulation results and the deployment procedures.

The first one, scaled 1:10, was realized to test in air the furling and unfurling phases. A second model, scaled 1:5, was used for tests in shallow water (70 meters w.d.). The sea tests were conducted in April 2004 and provided very useful information on the behavior of the structure subjected to sea current during the deployment phase. The system in fact, during the test, worked in very bad current conditions (several tens of cm/sec) with respect to deep sea environment in Capo Passero site (average measured current ~3 cm/sec) [6].

A deployment and recovery test, using the final tower structure is presently scheduled to take place within the end of 2005.

3.3 Sea operations at the Test Site

The NEMO collaboration is presently installing a deep sea (2100 meters w.d.) laboratory 14 nautical miles off-shore the Catania harbour. An electro-optical deep sea cable, connecting the shore station with the underwater Test Site was deployed during summer 2001. The cable has an underwater branching unit that splits it into two parts: the North termination (TSN) and the South termination (TSS).

On January 2005 the two submarine termination of the electro-optical cable were recovered and, on each of them, a frame supporting a couple of wet mateable submarine connectors were installed. The ends of the cable were then re-deployed.

On TSS an acoustic station, designed and realized by the NEMO collaboration, was also installed and connected to monitor the environmental noise in deep sea [7] for further studies on acoustic neutrino detection.

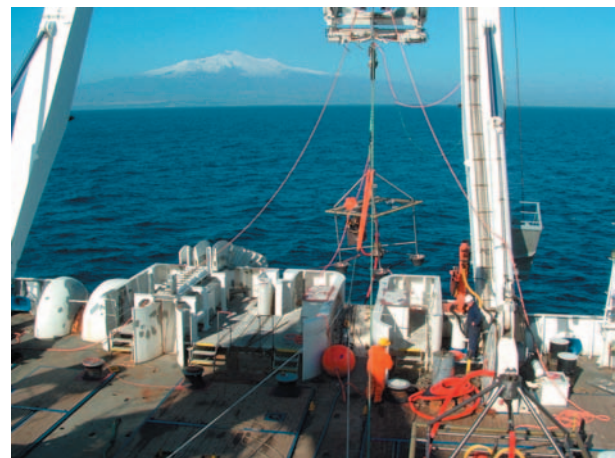


Figure 5

Figure 5 shows the deployment of TSS frame from the ship deck.

On TSN an on-line seismic monitoring station, developed by INGV (Istituto Nazionale di Geofisica e Vulcanologia) was installed. It is called SN1 and represents the first operational node of the European project ESONET [8], a network of sea environmental observatories to be deployed in several sites around the European coasts.

Both stations are working since the deployment date, providing a continuous stream of environmental data from 2000 meters w.d., extremely interesting for multidisciplinary sciences.

5 REFERENCES

- [1] C. Distefano et al. in this report;
- [2] P. Sapienza et al. in this report;
- [3] R. Cocimano et al. in this report;
- [4] G. Cacopardo et al. in this report;
- [5] Tecnomare, “Consulenza per osservatorio NEMO”.
- [6] G. Riccobene for the NEMO collaboration, proc. of the VLVvT Workshop, 5-8 October 2003, Amsterdam, pag. 93;
- [7] G. Riccobene for the for the NEMO collaboration, proc. of the ARENA Workshop, 17-19 May 2005, Zeuthen
- [8] <http://www.abdn.ac.uk/ecosystem/esonet/>

TANDEM AND SUPERCONDUCTING CYCLOTRON ACTIVITY

D. Rifuggiato on behalf of the LNS Accelerator staff

INFN Laboratori Nazionali del Sud, Catania, Italy

Abstract

The LNS accelerator activity in 2004 is described with details on the Cyclotron and Tandem beam time distribution. A status report on the Cyclotron upgrading is also given.

1 BEAM OPERATION

In 2004, beams accelerated with the Tandem and the Superconducting Cyclotron were delivered to users from February to July excluding May. As evident, a considerable amount of time and resources were dedicated to the EXCYT project: in this way the assembling phase of the whole facility was completed. However, all the experiments approved in the meeting of the Program Advisory Committee were accomplished, and only one experiment suffered from a significant beam loss due to a failure occurred at the Cyclotron. About 1500 Cyclotron beam hours and 1600 Tandem beam hours were delivered, corresponding to the numbers of the previous two years, taking account of the reduced time.

In 2004, a significant number of experiments were performed at the Cyclotron with the detector Chimera installed in the multi-purpose chamber Ciclope.

amount of 280 Cyclotron hours. After the last session, the protontherapy line began to be moved to its final location, in the new experimental hall.

The Tandem was mainly used for applicative experiments covering several inter-disciplinary fields: lithography, radiation hardness, archaeology, superconductivity and detectors, for a total of 1039 hours out of the 1574 delivered. The remaining beam time was distributed among experiments preparing the incoming investigation with radioactive beams.

In figures 1 and 2 the beam statistics for the years 2001 through 2004, scaled for a period of 8 months, are shown. As evident from figure 1, in the last 3 years the amount of delivered Cyclotron beam time is almost constant. A positive fact is the decreasing trend of the number of failures, while the big amount of setting hours demonstrates that the Cyclotron is really a complicated machine, which needs a careful and time

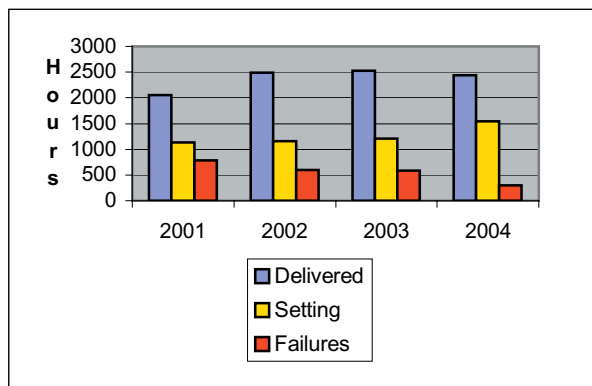


Figure 1: 2004 Cyclotron beam statistics scaled for 8 months

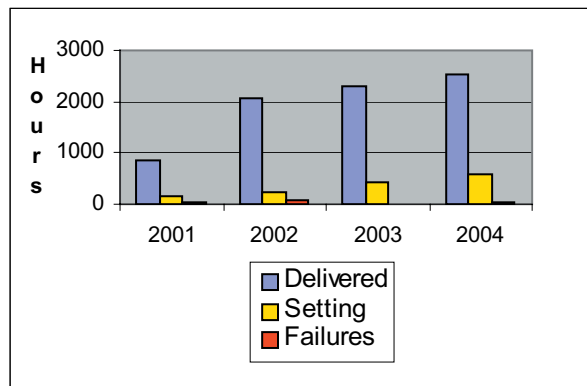


Figure 2: 2004 Tandem beam statistics scaled for 8 months

All over the year 2004, 5 experiments were performed with Chimera, for a total of 900 Cyclotron hours.

In 2004, 3 sessions of proton therapy of ocular tumors (Catana) were accomplished, using the 62 MeV proton beam from the Superconducting Cyclotron, for a total

consuming preparation before each experiment, especially when a difficult beam (for instance a metallic beam with good timing properties, i.e. FWHM less than 1 nsec and inter-burst separation more than 100 nsec) is requested.

2 SUPERCONDUCTING CYCLOTRON

In 2004 the Superconducting Cyclotron delivered beams in a quite reliable way. As usually, when requested bunch length was reduced down to 1 nsec by using the phase slits installed inside the dees. Time separation as high as 120-150 nsec was also obtained using the high energy chopper installed in the extraction beam line. Table 1 shows the Cyclotron beam types delivered in 2004.

Table1: Cyclotron beams delivered in 2004

Beam	Time
Protons 62 MeV	421 h
Deuterons 62 MeV	28 h
He-H 21 AMeV	44 h
¹² C 62 AMeV	108 h
¹² C 80 AMeV	40 h
²⁰ Ne 21 AMeV	88 h
²⁰ Ne 45 AMeV	160 h
⁵⁸ Ni 35 AMeV	96 h
⁵⁸ Ni 45 AMeV	96 h
¹¹² Sn 35 AMeV	224 h
¹¹² Sn 43.7 AMeV	68 h
¹²⁴ Sn 35 AMeV	60 h
¹⁹⁷ Au 21 AMeV	96 h
Total	1529 h

The operating diagram was extended towards high energies inside the allowed area: the maximum operating energy for fully stripped light ions was increased from 62 to 80 AMeV, and a ¹¹²Sn beam was accelerated to 43.7 AMeV, to be delivered to the experiment Cecil asking for good timing too. The 80 AMeV beam was made possible by applying a voltage as high as 64 KV and 61 KV in the electrostatic deflectors E1 and E2 respectively, on a gap of 6 mm. The 43.7 AMeV Sn beam was obtained by accelerating the charge state 31+ produced by the source Serse in a reliable way.

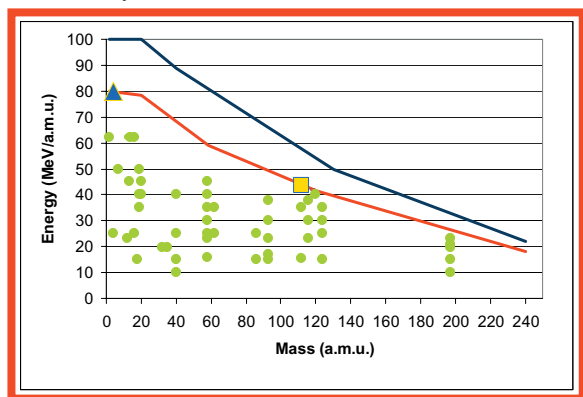


Figure 3: Operating diagram of the Cyclotron

In figure 3 the operating diagram of the Cyclotron is displayed. The light blue triangle is the 80 AMeV beam, the yellow square is the 43.7 AMeV ¹¹²Sn beam, green circles are used to display the beams developed up to now. Therefore the red line shows the best performance of the Cyclotron as really obtained, and is approaching the black line describing the nominal design values.

In figure 4 a plot of the experiments performed in 2004 with Cyclotron beams is presented, showing the beam time distribution among different experiments.

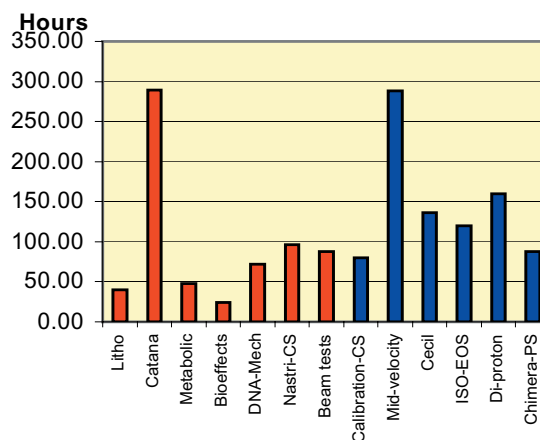


Figure 4: Cyclotron beam time distribution

EXPERIMENT	BEAM	RESEARCH
LITHO	¹² C, 62 MeV	LITHOGRAPHY
CATANA	p, 62	THERAPY
METABOLIC	p 62	BIOLOGY
BIOEFFECTS	p, 62	BIOLOGY
DNA-MECH	¹² C, 62	BIOLOGY
NASTRI-CS	¹⁹⁷ Au, 21	SUPERCOND. MATERIALS
BEAM TESTS	¹² C, 80, p, 62	ACCELERATOR
CALIBRATION	HeH, p,d, ²⁰ Ne, 21-62	CHIMERA
MID-VELOCITY	¹¹² Sn, 35 ⁵⁸ Ni, 35-45	CHIMERA
CECIL	¹¹² Sn, 35-43	CHIMERA
ISO-EOS	^{112,124} Sn, 35	CHIMERA
DI-PROTON	²⁰ Ne, 45-62	FRIBS
CHIMERA-PS	²⁰ Ne, 21	CHIMERA

In view of the completion of the EXCYT project, a high intensity test was accomplished to confirm the result obtained in 2003, when a 100 watt 13C, 45 AMeV beam was extracted from the Cyclotron. This beam will in fact be used as a primary beam to produce ^8Li fragments in a thick graphite target. The test was also intended to verify the possibility of extracting an intense beam for several hours, since in 2003 the 100 watt beam was measured for 10 minutes only, because it was necessary to shut down the machine.

The test was made using a small chopper (figure 5) installed in the injection beam line, allowing to decrease the beam current in the longitudinal way, i.e. suppressing several bursts. This guarantees that the beam characteristics in the transverse plane are maintained when increasing the intensity.

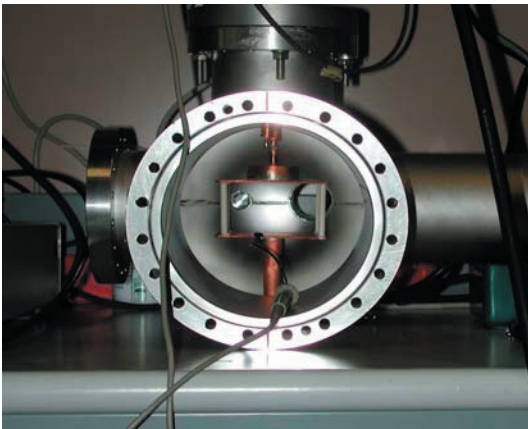


Figure 5: Chopper installed in the axial beam line

An internal current probe (figure 6) allowed to find the best conditions of minimum beam dissipation in the septum by comparing the amount of accelerated and extracted beam intensity. Phase slits were used to increase the extraction efficiency, which reached a maximum value of 60%.

In figure 7 the current plot vs. time is displayed. The beam was measured on a cooled Faraday cup for a time interval of 3 hours, at the end of which current instabilities were by far reduced, as a consequence of a conditioning process of the deflector, which was able to stand a beam power of almost 100 watt.



Figure 6: Cooled internal beam current probe

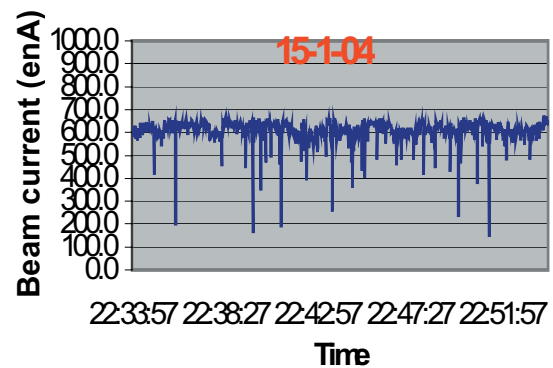


Figure 7: Extracted beam intensity vs time

At the end of the year, a new deflector, with an improved cooling circuit, was constructed (figure 8). As compared to the previous one, where only the rear part was cooled (see figure 9), the new type has the septum directly cooled, since the cooling circuit runs both in the front and in the rear part of the housing. The new prototype will be assembled in 2005, and beam tests will follow as soon as possible.



Figure 8: Front part of the new deflector with cooling



Figure 9: Rear part of the cooled deflector

3 TANDEM

Tandem beams have been delivered mainly to the 60° and 80° beam lines, the so-called by-pass area allowing the complete decoupling of the two accelerators, with two beams contemporarily sent to two different experimental areas.

In 2004 the following Tandem beam types were delivered.

Beam	Time
Protons 5-26 MeV	211 h
Deuter. 5-13 MeV	36 h
⁶ Li 20-50 MeV	185 h
⁹ Be 10-40 MeV	202 h
¹² C 60 MeV	333 h
¹⁴ N 60 MeV	58 h
¹⁶ O 80 MeV	140 h
⁵⁸ Ni 150 MeV	170 h
⁷⁹ Br 230 MeV	170 h
¹⁹⁷ Au 237 MeV	69 h
Total	1574 h

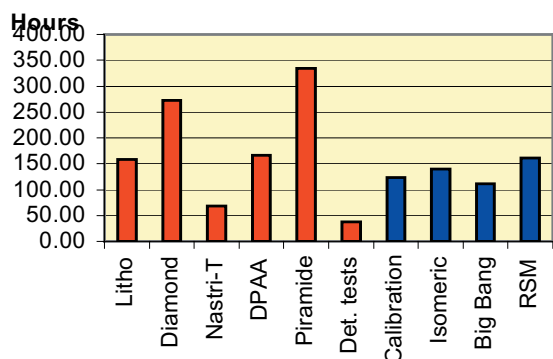


Figure 10: Tandem beam time distribution

LITHO	¹² C, 5 AMeV	LITHOGRAPHY
DIAMOND	⁶ Li, ¹² C, 7.5	DETECTORS
NASTRI-T	¹⁹⁷ Au, 1	SUPERCOND.
DPAA	p, 22	ARCHAEOLOGY
PIRAMIDE	⁵⁸ Ni, ⁷⁹ Br, 2.5	RAD. HARDNESS
DETEC. TESTS	¹⁴ N, 5	DETECTORS
CALIBRATION	p, 5-26, d 5-13	CHIMERA
ISOMERIC	¹⁸ O, 5	SPECTROSCOPY
BIG BANG	⁹ Be, 1	NUCL. ASTRO.
RSM	⁹ Be, ¹⁸ O, 4	CLUSTERING

In figure 10 a plot of the experiments performed in 2004 with Tandem beams is presented, showing the beam time distribution among different experiments.

4 CONCLUSION

In 2004, a reduced amount of beam time has been delivered to users as compared to the previous three years, in order to have time and resources for the Excyt project. However, thanks to the high reliability level achieved, all the experiments approved were accomplished.

Proton-therapy, which started in 2002, has successfully gone on with 3 sessions, during which 19 patients were treated. Throughout the year 2004, a lot of research activity has been performed in the field of nuclear physics, but also a significant amount of interdisciplinary applications have been carried out.

THE STATUS REPORT OF THE EXCYT FACILITY

G. Cuttone, R. Alba, L. Calabretta, L. Celona, F. Chines, G. Cosentino, P. Finocchiaro, D. Garufi, M. Menna, E. Messina, G. Raia, M. Re, D. Rifuggiato, A. Rovelli, G. Schillaci, A. Amato, R. Avolio, F. Caruso, S. Cavallaro, C. D'Amato, V. D'Amato, G. De Luca, B. Diana, E. Furia, G. Gallo, A. Grmek, P. Maniscalco, R. Marletta, S. Marletta, S. Passarello, M. Piscopo, S. Pulvirenti, P. Reina, S. Russo, S. Tringale, F. Tudisco, A. Varisano, V. Scuderi, E. Zappalà

INFN - Laboratori Nazionali del Sud, via S. Sofia 62, 95123 Catania, Italy

Abstract

The EXCYT facility (EXotics with CYclotron and Tandem) is based on a K-800 Superconducting Cyclotron injecting stable heavy-ion beams (up to 80 MeV/amu, 1 μ A) into a target-ion source assembly (TIS) to produce the required nuclear species, and on a 15 MV Tandem for post-accelerating the radioactive beams. Some key devices such as the TIS and the Charge Exchange Cell have been successfully tested, the former at Ganil on 2003 while the latter at Oak Ridge National Laboratory on August 2004. The data collected during these off-line experiments confirm the expected production yield to provide a radioactive ion beam suitable for the experiments with the users. The commissioning of the facility with stable beam is foreseen at the beginning of 2005 together with the start of nuclear experiments programme with ^8Li .

1 PROJECT STATUS

During the second half of 2004 the installation of the facility has been completed and the commissioning of the facility with stable beams is going to be started.

To achieve such important results the accelerators activity, hence the nuclear experiments at the LNS have been suspended to promote a higher accessibility to the HV platforms of the EXCYT project.

This was necessary to perform the final tests on any singular device of the facility in the real working conditions when all the equipments are linked together. Both the primary and the secondary beam lines have been tested in high vacuum together with the pumps, valves and sensors. All the EXCYT lines were uninterruptedly connected under vacuum before the end of 2004. Figure 1 shows the Target Ion Source assembly (TIS) positioned in the high activity platform A. The primary beam impinge to the TIS from the top through the vertical beam line. Figure 2 shows the first stage of the isobaric mass separator on the platform B, together with all the diagnostic devices. Figure 3 shows the remote handling system, dedicated to store the TIS in the shielded cabinet and to place it into the platform A.

Hereinafter the progress in the different activities involved are reported.

1 K-800 SUPERCONDUCTING CYCLOTRON

Following the upgrading process of the Superconducting Cyclotron (CS) accomplished in the last few years [1] we are able to steadily accelerate a ^{13}C beam up to a power of 100 W and an energy of 45 MeV/amu.

The expected ^8Li yield with such initial working parameters is in the order of 10^4 - 10^6 pps on Target.

Such starting point will permit to begin in the first months of 2005 the test of the whole facility (diagnostic, remote handling, computer control,...) with radioactive beams.

Since it is foreseen to improve the primary beam power up to 500W, a new water-cooled deflector was successfully tested off-line by applying a thermal load of 500 W and was installed inside the CS at the end of 2004. This new design [2] outcomes form an improvement of the previous deflector version already applied during the first 100W power test on 2003.



Figure 1: The high activity platform (A) and the pre-separator

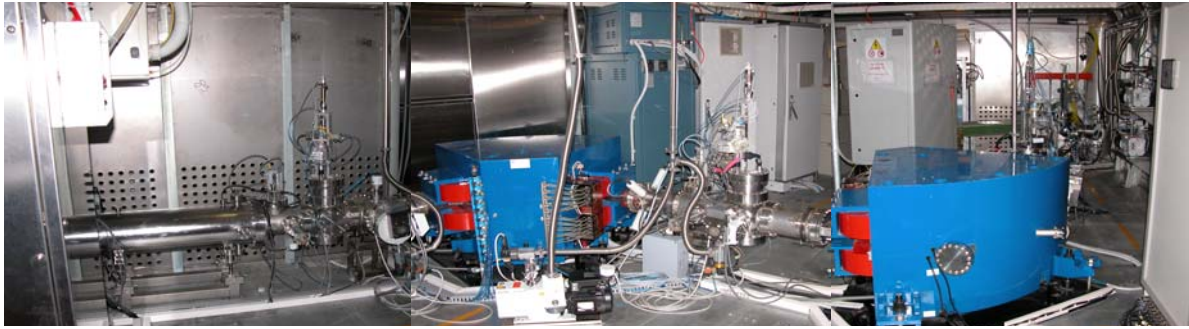


Figure 2: The first stage of isobaric mass separator



Figure 3 : remote handling system of the TIS.

2 EFFICIENCY TESTS FOR THE CHARGE EXCHANGE CELL

By its nature, the Tandem requires the injection of negative ions, usually obtained either by direct negative ionisation or by inserting a CEC on the extraction side of a positive ion source. Li^+ can be obtained with high ionisation efficiency ($> 70\%$) by means of a positive ion source with a W (Re-lined) ioniser [3]; therefore the most appealing scheme to get negative lithium ions is to couple a CEC to the aforementioned ion source.

In August 2004, at the HRIB Facility of the Oak Ridge National Laboratory, we carried out efficiency tests for the Charge Exchange Cell (CEC), helped and supervised by the local scientists D.W. Stracener and J.-C. Bilheux.

The CEC consists of a chamber containing Cs vapours at a variable temperature T , in which positive accelerated ions coming from an ion source are transformed into negative ones by collision with the Cs atoms. The efficiency of the charge exchange process is defined as the ratio of the negative ions extracted from

the CEC to the positive ions supplied by the ion source, taking into account that some of the latter are transformed only into neutral atoms.

We performed the tests according to the following programme:

- 1) CEC set-up and start-up with a $^7\text{Li}^+$ beam originating from a Li-containing specimen and a Hot Plasma Ion Source.
- 2) Efficiency measurements for $^7\text{Li}^+/^7\text{Li}^-$ at extraction energies of 55, 45, 35, 25 keV (measured parameters: charge exchange efficiency; transmission efficiency; positive, negative, neutral beam currents; CEC temperatures).
- 3) Efficiency measurements for $^7\text{Li}^+/^7\text{Li}^-$ and $^6\text{Li}^+/^6\text{Li}^-$ at extraction energies of 5, 10, 20, 30, 40, 50 keV (measured parameters as above); only $^7\text{Li}^+/^7\text{Li}^-$ exchange efficiency was measured at 5 keV due to the beam transmission difficulty at this very low energy.

The charge exchange efficiency (see figure 4) at the EXCYT's extraction energy of 20-25 keV is around 1%, as expected. Since all the available efficiency curves for the other elements show a maximum [4], by analogy the same behaviour is supposed for Li, but our data did not give indication of a maximum for beam energies up to 5 keV.

The efficiency was slightly better for low positive currents respectively around 50 nA (^7Li) and 3 nA (^6Li), the latter corresponding at the same specimen/source temperature settings. This can be attributed to the pollutants produced in the specimen/source assembly when increasing their temperatures to obtain larger beam currents of Li.

The new set of data for ^6Li clearly indicates an isotopic effect, never presented in literature. This in turn leads to the conclusion that efficiencies for $^8, ^9\text{Li}$ at EXCYT will be higher than the corresponding measured ones for $^6, ^7\text{Li}$.

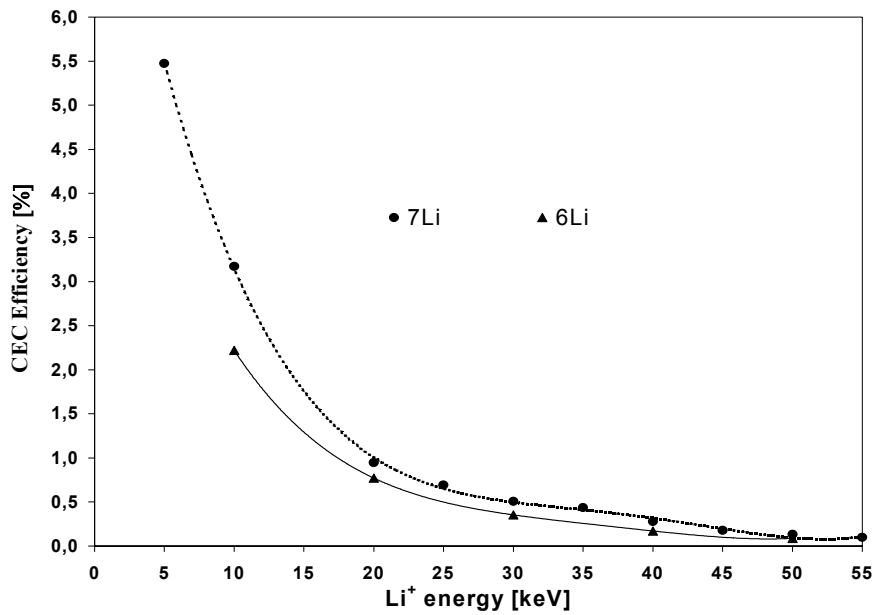


Figure 4: CEC efficiency. The dot and triangles refer respectively to ^7Li and ^6Li ions experimental data, while dotted (^7Li) and continuous (^6Li) lines are drawn as eye guide

3 CONCLUSIONS

By taking into account the availability of the MAGNEX detector [5] by the beginning of 2005, the requests from the “Big Bang” collaboration [6] and the RSM experiment [7], we decided to deliver ^8Li as the first EXCYT radioactive beam.

Off-line experiments concerning the TIS and the CEC confirm the expected production yield of the radioactive ion beam which is therefore suitable for the experiments requested by the users. Table 1 summarises the calculated values from the experimental measurements.

The commissioning of the facility with stable beam is foreseen at the beginning of 2005 together with the start of nuclear experiments programme with ^8Li .

Table 1 : radioactive Li ion beam yield as calculated from experimental data

Beam	Projectile	Energy (MeV/amu)	Target	Intensity		
				Pre-accelerated (pps/pμA)	Post-accelerated (pps/pμA)	Post-accelerated, 500W primary beam (pps)
^8Li	^{13}C	60	^{12}C	$1.4 \cdot 10^7$	$1.0 \cdot 10^5$	$6.6 \cdot 10^4$
^9Li	^{13}C	60	^{12}C	$3.2 \cdot 10^5$	$2.4 \cdot 10^3$	$1.5 \cdot 10^3$

4 REFERENCES

[1] D. Rifuggiato, “Tandem and Superconducting Cyclotron Activity” This LNS Report 2004

[2] S. Passarello et al. “Activity report of the device design group”. This LNS Report 2004

[3] M. Menna et al. LNS Report 2003, p. 161

[4] G.D. Alton NIM **B 73** (1993), 221

[5] A. Cunsolo et al. NIM **A484** (2002), 56

[6] S. Cherubini et al., Eur. Phys. Journ. **A20** (2004), 355

[7] A. Di Pietro et al., LNS Report 2003, 42

RESEARCH AND DEVELOPMENT OF ION SOURCES

S. Gammino^{a,*}, G. Ciavola^a, L. Torrisi^{a,b}, L. Celona^a, L. Andò^a, F. Consoli^a, S. Passarello^a, M. Presti^a, S. Manciangli^a, D. Margarone^{a,b}, F. Chines^a, S. Marletta^a, G. Manno^a, E. Zappalà^a, D. Mascali^a, A. Scuderi^a, A.M. Mezzasalma^b, C. Gentile^b, E. Amato^b, F. Neri^b, A. Picciotto^b, F. Caridi^b, J. Beltrano^b, A. Mangione^b, A. Galatà^c, M. Winkler^d, P. Spadtke^d, K. Tinschert^d, R. Gobin^e, S. Barbarino^f, G. Sorbello^f, L. Laska^g, J. Krasa^g, M. Pfeifer^g, K. Rohlena^g, J. Wolowski^h, P. Parys^h, L. Ryc^h, V. Nassisiⁱ, A. Lorussoⁱ, F. Belloniⁱ, D. Doriaⁱ, J. Sherman^j, XZh. Zhang^{a,k}

- a) INFN Laboratori Nazionali del Sud, Catania, Italy*
- b) University of Messina, Italy*
- c) INFN Laboratori Nazionali di Legnaro, Italy*
- d) GSI, Darmstadt, Germany*
- e) CEA, Saclay, France*
- f) University of Catania, Italy*
- g) Institute of Physics, Czech Academy of Sciences, Prague, Czech Republic*
- h) Institute for Plasma Physics and Laser Microfusion, Warsaw, Poland*
- i) University of Lecce and INFN, Lecce, Italy*
- j) Los Alamos National Laboratory, New Mexico, USA*
- k) Chinese Academy of Sciences, Lanzhou, China*
- * Corresponding author, e-mail: gammino@lns.infn.it*

Abstract

The activity of the Ion Source R&D Team at LNS was devoted in 2004 to the following themes:

1. the new layout of the GyroSERSE design that fits the needs of the Multipurpose Superconducting Electron Cyclotron Resonance Ion Source (MS-ECRIS) to be built by the ISIBHI collaboration;
2. the study of electron injection inside microwave generated plasmas and the completion of the EDIPO experiment;
3. the explanation of the ECRIS performances' improvements with TWT generators in place of klystron observed in the previous year;
4. the emittance, neutralization and proton fraction measurements for the beams produced by the TRIPS source;
5. the measurements of plasma parameters in Laser Ion Sources' plasmas;
6. the study and analysis of ion implantation from laser-generated ion streams.

A brief review of each of these issues follows.

1 MS-ECRIS: THE EUROPEAN ROADMAP TO 3RD GENERATION ECR ION SOURCES

The GyroSERSE design was completed in 2002 but its funding was not made available and in 2003 the same project was proposed for the Joint Research Project named ISIBHI within the 6th Framework Programme proposal named EURONS. The ISIBHI collaboration aims to build before 2008 a prototype able to fulfill the request of the accelerators of the involved laboratories (CERN, GANIL, GSI, HMI, JYFL, KVI, LNL, LNS, TSL), as e.g. 1 eμA of U⁶⁰⁺ and 5 pμA of light ions up to Ar¹⁶⁺ in cw mode, or 1 emA of Xe²⁰⁺, 0.3 emA of U³⁰⁺ (dc mode) and 6 emA of U²⁸⁺ (short pulse, 200 μs).

For injection into the accelerator, all these beams should have energy from 2.5 to 5.0 keV/nucleon, emittance lower than 200 π mm.mrad and high reliability, either in dc mode and in pulsed mode [1].

The approval of the proposal in 2004 for the period 2005-08 was affected by a substantial reduction of the resources that obliged the collaboration to set some limits to the GyroSERSE design in order to be able to

keep the cost as low as possible. The major renunciations were done in terms of maximum frequency for High B mode operations (which was decreased from 37 GHz to 28 GHz with a remarkable reduction of plasma density and finally of maximum expected beam current) and in terms of analysis beamline, by removing the focusing solenoid embedded in the cryostat [2, 3].

The source to build was named Multipurpose Superconducting Electron Cyclotron Resonance Ion Source (MS-ECRIS) as this prototype will permit to define the main design parameters for each facility. It is based on a plasma chamber of 180 mm, 50 mm larger than the one of SERSE, which may be advantageous provided that enough rf power is available. The use of high critical temperature superconducting currents leads and of cryocoolers will permit to operate the cryostat without external feed. The effect of X-ray produced by the ECRIS plasma in terms of heat load over the cryostat was analyzed, according to the X-ray spectra available from SERSE and from other sources; adequate lead shielding is included in the source design to

minimize the heat load. The injection of a maximum microwave power of 10 kW at 28 GHz and an extraction voltage of 50 kV are envisaged. The maximum axial field will be 4.5 T and the maximum radial field will be 2.7 T at the plasma chamber wall radius, but even a slightly lower axial field is acceptable for 28 GHz operation. A view of the magnets as calculated with the OPERA code is presented in fig. 1. A full description of the project through the years is available in references [1,2,3,4,5].

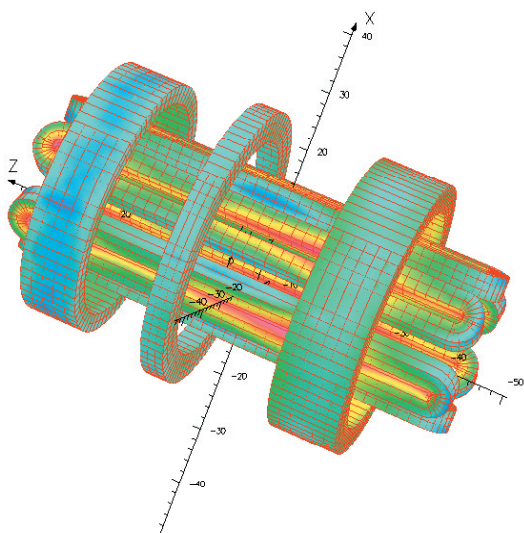


Fig. 1 – The magnets of MS-ECRIS source.

2 EDIPO EXPERIMENT : ELECTRON DONORS IN ECRIS AND MDIS

A series of measurements were carried out with the TRIPS proton source [6,7,8,9] to determine the effectiveness of different materials as electron donors.

It is well known that the use of boron nitride (BN) disks inside the plasma chamber increases the current extracted from a microwave discharge ion sources, generating additional electrons. In the past, we replaced one of the two disks with a coating over the extraction electrode. The coating of 40 μm of Al_2O_3 was effective and the current increased about 10%, but after less than 200 hours the coating was damaged so this procedure is not appealing for long-lasting operating. The tests here reported concerns three different options, with the use of three different electron donors:

- a 100 μm Al_2O_3 layer deposited over the extractor, with the same characteristics and technique of the previous 40 μm coating;
- a 1 mm thick aluminium foil over which an alumina layer is deposited;
- a 5 mm thick Al_2O_3 tube embedded in the TRIPS plasma chamber (the outer diameter of the tube being slightly smaller than the inner diameter of the chamber).

All these investigations were carried out with the same magnetic field topology and only rf power and gas input were variable. A special attention was paid to the proton fraction. In fact this parameter is strongly influenced by the presence of a higher number of electrons, as the number of ionizing interactions increase. More generally, a higher proton fraction can be considered as a signature of the higher availability of electrons in the plasma. The results of the experiments were rather unsatisfactory for the MD-liner which gave no better results than the BN disks and a modest reliability; a good increase of performances was obtained with the alumina coating of the extraction electrode inner face, but the lifetime was still not acceptable, being limited to a few hundred hours, while better performances along with the evidence of higher reliability were obtained with the thick alumina tube. Fig. 2 shows that a much higher current is obtained at the beam stop, either due to a higher extracted current and also to the higher proton fraction. A full report is given in [10]. Similar results may be exported to ECR sources operating at higher frequency as the principle has no limitation in terms of plasma density, so that we may expect significant improvements of the beam produced by SERSE or CAESAR through the insertion of a thick alumina tube. In the meantime, an aluminium chamber was designed and built for the SERSE source but its installation and tests were postponed to 2005. The mechanical design of such a chamber was quite difficult but a compromise between different constraint was found. More details are available in [11].

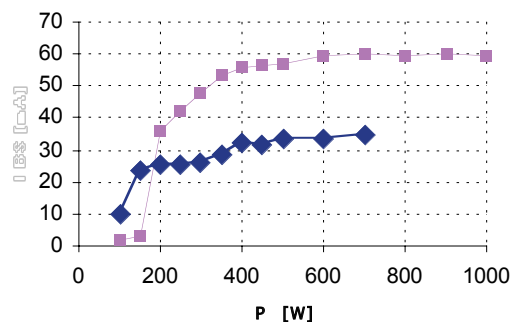


Fig. 2 – Proton beam current increase with Alumina tube (upper curve) and without (lower), measured by the beam stop at the end of the TRIPS beamline.

3 STUDY OF TWT AMPLIFIER FOR ECRIS INJECTION

Measurements have been carried out in order to analyze the enhancement of the SERSE source performances, previously observed, when microwaves are fed by means of a TWT instead of the Klystron generator, commonly used.

It is useful to focus on the highest charge states, i. e. O^{7+} and O^{8+} , as they need a higher electron energy and they are a clear evidence of the plasma energetic content. It

clearly came out [12] that the TWT generator permits to get at lower power the performance obtained with klystron at higher power levels. The gain in power, changing with the charge state and the working frequency, oscillates between 1,5 and more than 3 times (for O^{8+} at 18 GHz) and this result was experienced in various experiments and it was perfectly reproducible. A possible explanation is connected to the increase of electrons' temperature and density which is evident from the spectra analysis; this increase can be attributed to the larger electromagnetic wave bandwidth provided by the TWT.

In order to confirm such a hypothesis, preliminary investigation of the -3dB width of the output signal and the presence of harmonics or spurious with a spectrum analyser have been carried out. All the generators are driven by a pure source signal: the klystron-based generators show a very clean and narrow frequency spectrum without any spurious or harmonics, while the Travelling-Wave-Tube based generators show a broader frequency spectrum with some spurious about -40 and -50 dB under the carrier in a frequency span of 200 MHz. A complete report is presented in ref. [12,13] where it is shown that the potential well is deepened, leading to an enhanced confinement time τ_i for a given charge state z :

$$\tau_i \propto \exp\left(\frac{z|q_e|\Delta\varphi}{KT_i}\right).$$

An increase of the negative potential well produces a greater increase in τ_i as higher is the value of z . It was also qualitatively observed that the improvement obtained with a TWT is lost if the plasma become noisy, as the ion temperature increases and the potential well depth at the centre of the chamber decreases.

In any case the number of ionizing interactions is increased because we change the dimensions of the ECR layer, thus replacing a resonant ECR surface with a thick layer, as explained by the fig.3.

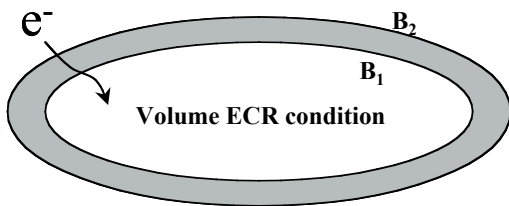


Fig. 3: The 'volume' plasma layer which is generated inside the plasma chamber.

4 TRIPS EMITTANCE AND RELIABILITY

The TRasco Intense Proton Source (TRIPS) was installed at INFN-LNS in 2000 and it has been operating for four years. The requested performance in terms of beam energy (80 keV) and extracted current (60 mA from 8 mm extraction aperture) was achieved

already in 2001. In 2004 the full characterization of the analyzed beam was obtained along with emittance, neutralization factor and proton fraction measurements, for an extraction hole of 6 mm, which is sufficient to obtain the required current (35 mA) [6,7]

The Emittance Measurement Unit (EMU) provided from CEA/Saclay was used to measure such quantities on both the 0° and 30° line, after an analysis dipole.

The emittance measurements have confirmed that the normalized emittance of TRIPS source is lower than the TRASCO project requirements (0.2π mm mrad); the same conclusions can be drawn by measuring this quantity on the 30° line, in vertical and horizontal position, after a magnetic dipole. The fact that the emittance did not increase significantly through the bending magnet encouraged to consider the use of two or more sources connected to the RFQ by means of a switching magnet.

We also carried out a set of tests on the proton fraction measurements of the beam by using the analysing dipole to separate the different ion species (H^+ , H_2^+). Values between 70 and 90% were obtained, in any case higher than the project request. Finally the evidence of an excellent beam neutralization was obtained by means of the Los Alamos Four Grid Analyzer [14], except for the case of excessive beam focusing, as described by fig. 4.

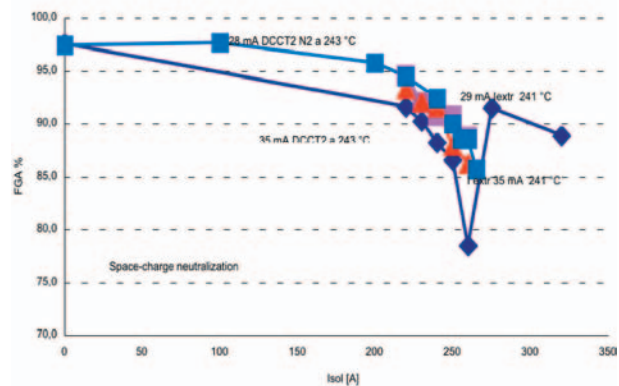


Fig. 4: Space charge compensation for different conditions of beam focalisation, either in the horizontal and vertical plane.

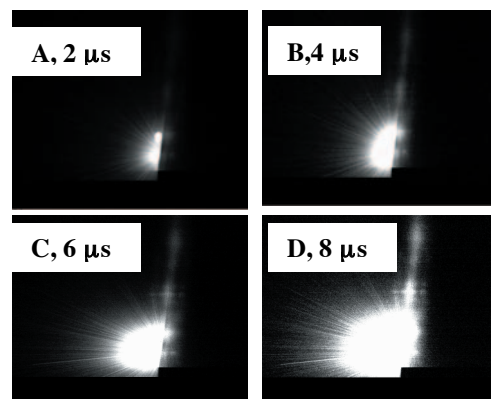


Fig. 5: Photos of expanding plasma produced in the LNS vacuum chamber during Ta ablation.

5 MEASUREMENTS OF LASER ION SOURCES' PLASMA PARAMETERS

In order to measure the plasma density different approach methods have been used. One of these concerns the measure of the plasma volume from the visible light detectable with a fast CCD camera triggered with the laser pulse. The photos of Fig. 5 show the plasma plume expansion in the vacuum chamber as a function of the exposition time. The photos give interesting information about the directivity, angular distribution, expansion velocity, plume geometry and plasma dimensions as a function of the time. Measurements of ablation yield in tantalum, Y, in terms of ablated atoms per pulse, can be given from the crater depth profile produced by a single shot or by a known amount of laser shots. The plasma dimension depends on the time from the laser shot because the plasma expands adiabatically with supersonic velocity in the vacuum chamber. Fig. 5 shows that at 2 μ s the plasma plume dimension is about 5 mm³, thus, because the ablation yield at LNS is about 1.5×10^{15} ats/pulse, the plasma density after 2 μ s is about 3×10^{17} /cm³. The plasma density decreases exponentially with the expansion time. Similar investigations at PALS indicate that the plasma density is more than two order magnitude higher.

Many other studies concerning ion production, plasma production and application of laser ion sources have been carried out at LNS and at PALS in Prague and the full report is given in ref. [15-22].

6 ION IMPLANTATION STUDIES

By using ns laser pulses with intensity of the order of 10^{15} W/cm² it is possible to produce ion emission with charge state up to about 50⁺ and kinetic energies up to about 10 MeV. In such conditions the ions have sufficient energy to be implanted deeper in different substrates. In the experiment carried out by the PLAIA collaboration at PALS multiple laser pulses were used, in order to implant high ion doses. The ion implantation induced by laser ion sources is characterized by multi-energetic ion beam, with Boltzmann distributions depending on the ion charge state. This property produces ion penetration at different depth in the substrate then modifying the chemical and physical properties of the surface layers of the implanted solids. This aspect is not an inconvenient of the implantation but, instead, it can be used as an advantage especially in the field of treatment of large depths of material surfaces in which is possible to modify the chemical and physical properties (wetting, hardness, chemical reactivity,...).

Ion implantation processes was investigated at INFN-LNS of Catania and PALS Laboratory of Prague by using different laser intensities, different ions and substrates, and measurements of ion depth profiles by

RBS, AES and other surface analysis as presented in more details in [23-26].

We acknowledge the support of the Fifth Committee of INFN (EDIPO and PLAIA experiments).

REFERENCES

- [1] S. Gammino et al., Czech Journ. of Phys. 54 (2004) 883
- [2] S. Gammino, G. Ciavola, L. Celona, L. Andò, P. Spadtke, M. Winkler, Superconducting ecr ion sources: high intensity beams extraction and transport Proc. Int. Conf. On Cyclotrons and Appl., Tokyo (2004) to be published
- [3] S. Gammino et al., Nucl. Instr. & Meth B205, (2003) 162
- [4] S. Gammino et al., Rev. Sci. Instr. 75 (5), (2004) 1637
- [5] S. Gammino, Nukleonika 48 (2003) 73
- [6] G. Ciavola et al., Rev. Sci. Instr. 75 (5), (2004) 1453
- [7] L. Celona et al., Rev. Sci. Instr. 75 (5), (2004) 1423
- [8] G. Ciavola et al., Improvement of reliability of the TRASCO intense proton source (TRIPS) at INFN-LNS, Proc. 4th Int workshop on Utilization and reliability of high power proton accelerators, Daejeon, Korea (2004) to be published
- [9] G. Ciavola, L. Celona, F. Consoli, A. Galatà, S. Gammino, M. Presti, High intensity monocharged beams of gaseous elemento from the TRIPS source, 16th Int. Vacuum Conf., Venezia, (2004) 900
- [10] S. Gammino et al., Enhancement of ion current from the TRIPS source by means of different electron donors, in preparation for the 11th Int. Conf. on Ion Sources, Caen
- [11] S. Passarello et al., this report
- [12] L. Celona, S. Gammino, G. Ciavola, F. Consoli, A. Galatà, Analysis of the SERSE Ion Output by Using Klystron-based or TWT-based Microwave generators, Proc. Workshop on ECR ion Sources, Berkeley (2004) to be published
- [13] L. Celona, Application of traveling wave tubes to ECRIS plasmas, in preparation for IEEE Trans. on Plasma Science
- [14] P.Y. Beauvais et al., Rev. Sci. Instr. 71 (3) (2000) 1413
- [15] L. Láska et al., Rev. Sci. Instr. 75 (5), (2004) 1588
- [16] L. Láska et al., Rev. Sci. Instr. 75 (5), (2004) 1546
- [17] S. Gammino et al., Journ. of Appl. Phys. 96 (5), (2004) 2961
- [18] L. Torrisi et al., Czech Journ. of Phys. 54 (2004) 421
- [19] L. Láska et al., Braz. Journ. of Phys. 34 (4B), (2004) 1615
- [20] L. Láska et al., Appl. Phys. Lett. 86 (2005) 081502
- [21] S. Gammino et al., Production of Highly Charged Heavy Ions by means of a Hybrid Source in Dc mode and in Afterglow Mode, accepted on Plasma Proc. and Polym.
- [22] L. Torrisi, E. Amato, S. Gammino, Study of the photon emission from plasma generated by fast pulsed laser, 2nd German-Polish Conf on Plasma Diagnostics, Krakow (2004) to be published
- [23] L. Torrisi et al., Ion implantation induced by Cu ablation at high laser fluence, submitted to Appl. Surf. Science
- [24] F. P. Boody et al., Flexible laser ion sources for ion implantation, Proc. of Int. Conference on High Power Laser ablation, Taos (2004) to be published
- [25] J. Wolowski et al., Laser-produced ion streams useful for technological applications, Proc. 27th Eur. Conf. on Laser Inter. with Matter, Frascati (2004) to be published
- [26] L. Torrisi et al. Appl. Surf. Science 227 (2004) 164

ION BEAM MONITORING DEVICES BASED ON THIN SCINTILLATING MATERIALS

M. Re^a, L. Cosentino^a, E. Costa^a, G. Cuttone^a, P. Finocchiaro^a, C. Marchetta^a,
 P. Vynck^b, B. Volckaerts^b, M. Vervaeke^b, J. Van Erps^b, A. Hermanne^b, H. Thienpont^b

a) INFN Laboratori Nazionali del Sud (LNS), Via S. Sofia, 44 95123 Catania, Italy

b) Department of Applied Physics and Photonics (TW-TONA), Vrije Universiteit Brussel (VUB), Pleinlaan 2, 1050 Brussels, Belgium

Abstract

In this work we present the development of two specific types of monitoring devices both consisting of an inorganic scintillation film deposited on Aluminum support layer. In a first prototype a thin Aluminum support layer of 10 μm allows the ion beams to pass easily through without significant energy loss and scattering effects. This becomes an attractive device to characterize beam shape and beam position without interfering with the rest of the irradiation process. A second device consists of an Aluminum support which is thick enough to completely stop the beam to allow the simultaneous monitoring of the beam profile and the beam intensity. In order to develop radiation hard beam monitors, we preferred to use inorganic scintillation materials like $\text{Al}_2\text{O}_3(\text{Cr})$, $\text{CsI}(\text{TI})$. In this contribution we discuss different deposition techniques and we present our first scintillation experimental results obtained in a joint irradiation program for Proton and Carbon ion beams from 8 to 45 MeV/u.

1 INTRODUCTION

The increasing demand for accurate beam diagnostics in a variety of application domains such as nuclear and particle physics [1], materials and life sciences and waste transmutation [2], is the driving force behind our research activities. We developed two specific types of monitoring devices both consisting of an inorganic scintillation film with thickness ranging between 1 μm and 10 μm deposited on aluminum supports. A CCD-camera measures the emitted light signals originating from the scintillation film under beam irradiation

In a first prototype a 1-10 μm thin scintillating material is deposited on a 10 μm thin aluminum foil. This device is thin enough to allow the ion beams to pass easily through it without significant energy loss or heat dissipation and scattering effects. ANSYS (Figure 1) and SRIM simulations confirm these assumptions: the beam thermal dissipation is about 0.6 % of the total beam power while the minimum detectable beam power is around 1W.

This is an attractive device to characterize beam shape and position without interfering with the rest of the irradiation process. It is foreseen to employ this monitoring device at the EXCYT facility in Catania designed to produce radioactive ion beams [3]: the scintillating device will be placed at a few centimeters above the Target Ion Source which operate at 2000 K in a high-radiation environment, and at a potential of 50 kV with respect to a platform biased at 250 kV with respect to ground. Studies and tests on prospective windows indicated that - as for thermal dissipation, irradiation heating and activation is concerned - Al has

better properties with respect to graphite, Ti, Cu, Ag and Au.

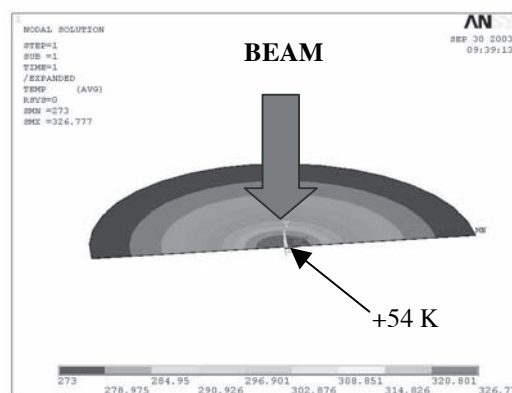


Figure 1 : results of an ANSYS thermal simulation of 10 μm Al_2O_3 on 10 μm Al substrate crossed by 100 W $\varnothing=5\text{mm}$ ^{13}C 45 MeV/u beam (Temperatures are in K).

A second device consists on a 1-10 μm thin scintillating material deposited on an aluminum support which is thick enough to completely stop the impinging ions allowing the simultaneous monitoring of the beam profile and the beam intensity. It is foreseen to employ several of these devices in the primary beam line at the VUB cyclotron laboratory in Brussels [4], and to install some new beam collimators such as the one showed in figure 2.

By means of this device it will be possible to align the beam with the collimating hole, to detect its shape and position, while its current is measured. In-situ diagnostics of the intensity, the spatial distribution and the pointing stability of high density light ion beams are appealing issues at the VUB: for the production of

short-lived radio-nuclides in biomedical applications, to fabricate micro-optical and micro-mechanical components using Deep Lithography with Protons [5], and investigate the nuclear activation cross sections of solid targets.

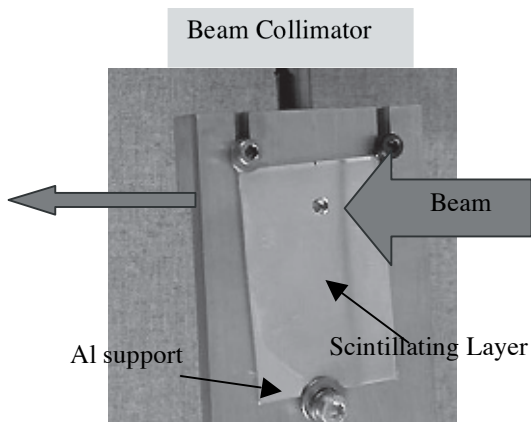


Figure 2 : prototype of a beam collimator: the beam is collimated through a 3 mm hole, while its position and current is measured respectively by a CCD camera and a charge integrator.

In order to develop radiation hard beam monitors, we preferred to use inorganic scintillation materials like $\text{Al}_2\text{O}_3(\text{Cr})$ or $\text{CsI}(\text{Tl})$ instead of organic materials. We discuss in this contribution different deposition techniques we investigated and we present our first experimental results obtained in a joint irradiation program for Proton and Carbon ion beams from 8 to 45 MeV/u.

2 DEPOSITION TECHNIQUES

$\text{Al}_2\text{O}_3(\text{Cr})$ scintillating material was evaporated by electron-gun bombardment and deposited on Al supports. The evaporating material is prepared from Al_2O_3 powder doped with Cr_2O_3 (10 % in weight). To set the evaporation rate of about $1 \text{ \AA/s}$ it was necessary to locally melt (a spot of $\varnothing 2\text{-}3 \text{ mm}$) the material at 2100°C .

$\text{CsI}(\text{Tl})$ scintillating material was evaporated by thermal evaporation by heating a CsI tablet doped with 0.1 % in weight of Tl I. Its melting temperature is about 620°C , but at 500°C the vapour tension (10^{-4} mbar) is enough to establish an evaporation rate of about $5 \text{ \AA/s}$.

For both scintillating materials, the Al supports were heated by a quartz lamp up to 300°C , while during the process the pressure in the deposition vessel was 10^{-6} mbar .

Alternative film deposition techniques, like Ion Beam Assisted Deposition (IBAD) and Plasma Spray (PS) are currently under study. The aim is to increase the crystalline quality of the grown scintillating layers and thus their scintillating efficiency. Since the supports are on Al it is not possible to increase their deposition temperature above 300°C . The IBAD technique uses a 3 keV Ar beam that impinges the support surface with an angle of 45° during the evaporation process. This enhances the surface atomic mobility even at low

substrate temperatures, and simultaneously reduces the crystalline defects by surface sputtering. The PS technique in “non-melting” mode is only suitable for layers thicker than $10 \mu\text{m}$. During the deposition the scintillating powder is heated up with Ar plasma but its crystalline grains are melted only on the surface. This should be able to preserve a good crystalline quality.

3 EXPERIMENTS AND RESULTS

3.1 Experimental set-up

The emitted light signals, originating from the scintillation film, are measured by means of a 0.5 lux sensitive CCD-camera from jAi (CV-M50-768x576 pixels). The sample was positioned, as described in figure 3, at 45° with respect to both the CCD view direction and the ion beam impinging direction. A 1 cm collimator was fixed in the beam line while a second 3 mm collimator, shown in figure 2, was removable. The operating pressure was in the range of 10^{-5} mbar .

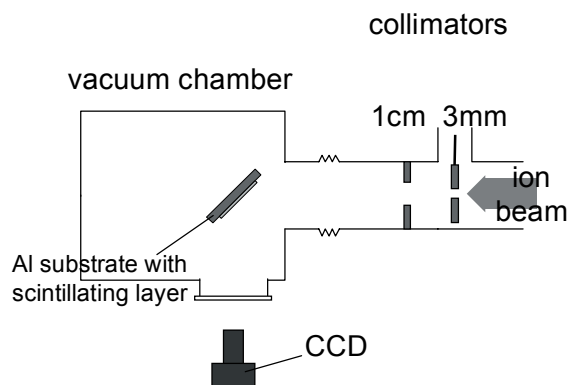


Figure 3 : experimental set-up set to measure the scintillating light emitted by the deposited layers during the beam irradiation.

3.2 Light emission from an Al_2O_3 layer

A $5.6 \mu\text{m}$ thick layer of $\text{Al}_2\text{O}_3(10\%\text{Cr})$ deposited on a thick Al support was irradiated by an 8.3 MeV beam of protons generated by the VUB cyclotron in Brussels. The 3 mm beam spots captured by the CCD are shown in figure 4. The background signal from the CCD is already subtracted. The minimum detectable light signal is related to a current of 10 nA i.e. a current density of $1.4 \cdot 10^{-9} \text{ A/mm}^2$ which corresponds to a power density released by the beam into the scintillating material of 23 mW/mm^3 . The released energy amounts to 95.2 keV per proton.

The total light emitted from the scintillating layer shows a good linear correlation with the beam current flux and does not exhibit saturation at the maximum testing current (see figure 5). Further investigations have to be done on $\text{Al}_2\text{O}_3(\text{Cr})$ layers exposed to higher beam intensities and produced at different growing conditions such as deposition rate, doping and substrate temperature.

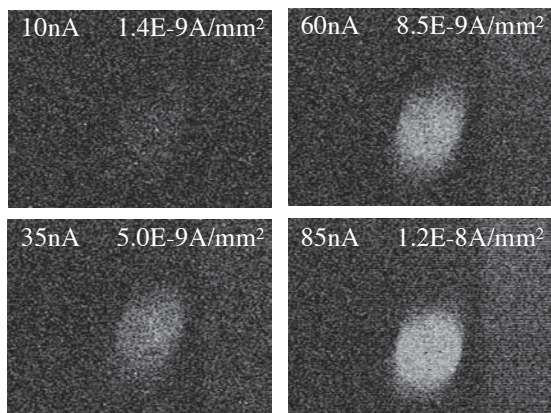


Figure 4 : 5.6 μm $\text{Al}_2\text{O}_3(\text{Cr})$ layer irradiated by 8.3 MeV protons. 3mm diameter beam spots at different beam intensities.

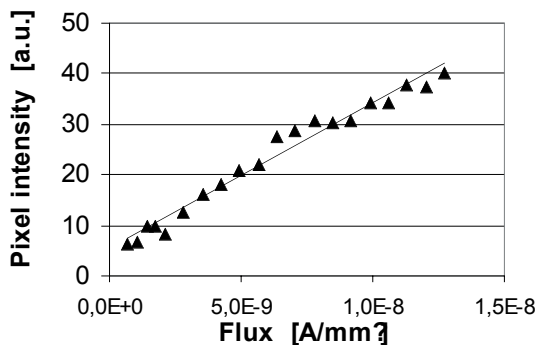


Figure 5 : Total light intensity (expressed as sum of the intensity values of each pixel) versus the beam current density. For a 5.6 μm $\text{Al}_2\text{O}_3(\text{Cr})$ layer irradiated by 8.3 MeV protons.

3.3 Light emission from CsI(Tl) layers.

CsI scintillating layers have been both irradiated with a 40 MeV $^{12}\text{C}^{5+}$ ion beam at LNS in Catania and 8.3 MeV proton beam at the VUB cyclotron in Brussels.

During a test at LNS we obtained our highest beam sensitivity. This was measured by a 0.3 lux sensitive CCD camera capturing the light emission from a 2 μm CsI(0.1%Tl) layer irradiated with a 45 MeV/u $^{13}\text{C}^{4+}$ beam. The scintillating layer was grown at room temperature. At the lowest detectable light signal, the power density of the beam released into the layer was 20 $\mu\text{W}/\text{mm}^2$. Such a high sensitivity suggests several applications of these devices to detect very low intensity beams and high energy beams which release low power densities while crossing the thin scintillating material.

3.3.1 $^{12}\text{C}^{5+}$ 40 MeV ion beam irradiation

Figure 6 reports the light emitted as a function of the beam current for a 2 μm thick CsI(0.1%Tl) layer deposited on a Al support irradiated by a $^{12}\text{C}^{5+}$ 40 MeV ion beam. The irradiated area was about 1.5x0.86 mm^2 (figure 7). The background signal from the CCD is already subtracted.

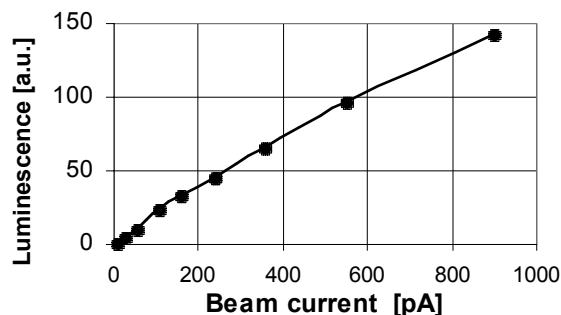


Figure 6 : Light emission from a CsI(0.1%Tl) layer irradiated by a $^{12}\text{C}^{5+}$ 40 MeV ion beam.

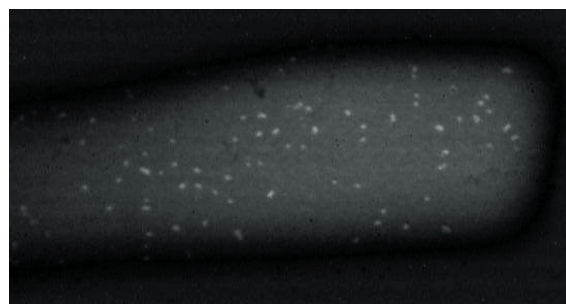


Figure 7 : Light emission from a CsI(0.1%Tl) layer: the area is irradiated by 900 nA of $^{12}\text{C}^{5+}$ 40 MeV and the spot size is about 1.5x0.86 mm^2

The minimum detectable beam current was 30 pA which corresponds to a current density of $2.3 \cdot 10^{-11}$ A/ mm^2 , related to a released beam power density of 12 mW/ mm^2 . The released beam energy is 1.35 MeV per particle. The total light emitted from the scintillating layer shows a good linear correlation with the beam current and does not exhibit saturation effects.

Figure 7 points out that the thin film deposition quality must be improved, since inhomogeneities in the light emission indicate an irregular surface morphology.

3.3.2 $^1\text{H}^+$ 8.3 MeV ion beam irradiation

Samples of CsI(0.1%Tl), 2 μm thick, deposited on Al support have been irradiated by an 8.3 MeV proton beam. Treatments with 350 nA of beam current for about 1 hour exhibit a good stability in terms of emission efficiency, though after 30 minutes a small decrease of the luminescence yield was detected.

Figure 8 shows an example of a 1 cm beam spot before and after 1 hour of $\varnothing$ 3 mm beam irradiation; it is evident in the right picture that the $\varnothing$ 3 mm long time irradiated area created a darker spot. It is still under investigation whether if this is due to the scintillating material degradation or to a thin carbon layer deposition caused by the residual gas contamination.

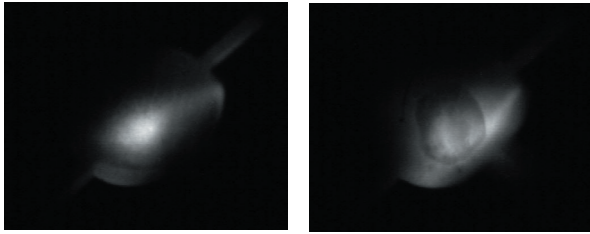


Figure 8 : a 2 μ m CsI(Tl) layer irradiated by a 28 nA proton beam spot, before (left) and after (right) 1h of 350 nA Ø3mm beam. In the right picture is visible a darker area.

The light emission yield for a 2 μ m CsI(0.1%Tl) film deposited on Al is reported in figures 9. To avoid the CCD saturation, optical diaphragms were interposed, the related attenuation factors are reported in the pictures of the figures 9.

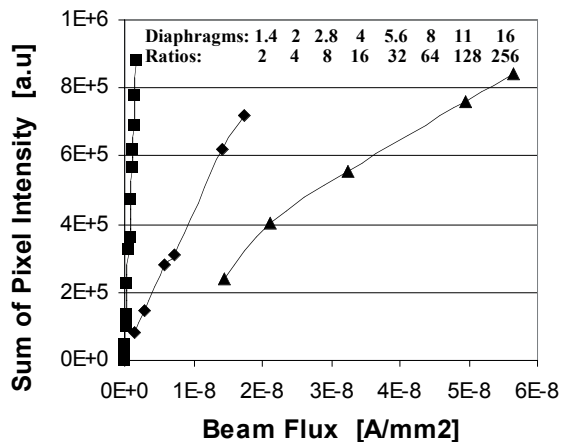


Figure 9 : Light emission versus beam flux for different optical diaphragm apertures: squares (2.8), diamonds (11) and triangles (16). Beam size Ø3mm.

The minimum detectable current was 1nA (beam size = Ø 3 mm), which corresponds to a beam flux of $1.4 \cdot 10^{-10}$ A/mm² related to a released beam power of 1.6 mW/mm³. As shown in the figures 9 the light emission is quite linear up to a beam flux of about $6 \cdot 10^{-8}$ A/mm². Figure 10 shows an example of the beam spots recorded by the CCD-camera.

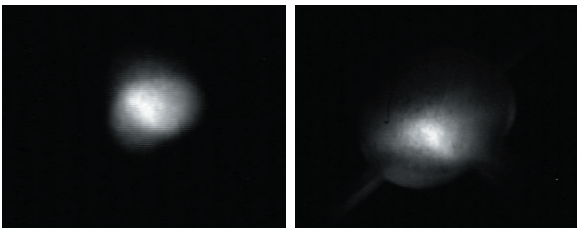


Figure 10 : 2 μ m CsI(Tl) proton beam spots. Ø 3mm 400 nA left and Ø1cm 1240 nA right. The picture are differently magnified.

4 OUTLOOKS

Further investigation has to be done to:

- Increase the film radiation hardness also selecting different materials than CsI and Al₂O₃.
- Reducing the film hygroscopicity by a thin protective coating.
- Enhance the film substrate adhesion (by a transition layer deposition) and thus its radiation hardness.
- Perform absolute luminescence calibration for quantum efficiency determination.
- Perform light emission angular and spectra distribution.
- Perform chemical and morphological characterisations.
- Improve film uniformity and image resolution.

5 ACKNOWLEDGMENTS

We fully acknowledge the accelerators staff of LNS, Eng. D. Garufi for the ANSYS simulation.

6 REFERENCES

- [1] G. Vernier et al. "The EURISOL report" Report to the European Commission. Ed. J. Cornell GANIL(Dec 2003)
http://www.ganil.fr/eurisol/Final_Report/EURISOL-REPORT.pdf
- [2] S. Tanaka et. al "High intensity proton accelerator project in Japan (J-PARC)" Proc. of 10th International Conference on Radiation Shielding. Submitted (2004).
- [3] G. Cuttone et al., "Status of the EXCYT facility at INFN-LNS", AIP Conf. Proc. February 27, 2004 -- Volume 701, Issue 1, pp. 354-360
- [4] P. Vynck et al., "Beam monitoring enhances Deep Proton Lithography: towards high-quality micro-optical components", proceedings of the IEEE/LEOS Benelux Chapter symposium, Amsterdam, The Netherlands, pp. 298-301, 2002.
- [5] B. Volckaerts et al., "Deep Lithography with Protons: a generic fabrication technology for refractive micro-optical components and modules", Asian Journal of Physics, vol. 10, no. 2, pp. 195-214, 2001.

DESIGN OF THE RF SYSTEM FOR A 250 A.MEV SUPERCONDUCTING CYCLOTRON*

M.Maggiore ^(a,c), L.Calabretta ^(a), M. Di Giacomo ^(b)

- (a) Laboratori Nazionali del Sud, INFN - 64, Via S.Sofia I-95123 Catania
 (b) Grand Accélérateur National d'Ions Lourds, Bvd. H. Becquerel F-14076 Caen
 (c) University of Catania, Dept. of Physics, Via S.Sofia I-95123 Catania

* presented at 17th ICCA, Tokyo, October 2004

Abstract

A superconducting cyclotron accelerating $q/A=0.5$ ions up to 250 A.MeV, for medical applications and radioisotopes production (SCENT project) is being studied at Laboratori Nazionali del Sud in Catania. The RF system, working in the fourth harmonic, is based on four cavities operating at 93 MHz, which are connected in the central region. The paper describes an unusual multi-stem RF design, performed with 3D electromagnetic codes. The aim is to obtain a cavity, completely housed in the valley, with a voltage distribution going from 65 kV in the injection region to a peak value of 120 kV in the extraction region, and a low power consumption.

INTRODUCTION

Superconducting cyclotron RF systems typically work in the range 10-50 MHz and need big apertures in the pole to house the vertical stems. The cavities are half-wave resonators, practically symmetric with respect to the median plane, characterised by strongly spiralled electrodes (dees). In the case of the SCENT machine, whose extraction diameter is 130 cm, the size of the dees is large and we searched for a solution which allows us to house the resonators inside the valleys. The available depth in the valley is of ± 45 cm respect to the median plane. For this reason and to maximize the energy gain it was decided to work in the 4th harmonic at 93 MHz.

To minimize the risk of discharges, voltages lower than 70 kV are required in the area of the central region, while voltages around 120 kV or higher are required at the outer radius to achieve an adequate turn separation of the beam extracted by the electrostatic deflectors. Due to the strong spiral angle, the electrode equivalent length is around 2.5 metres which results in a capacity of more than 200 pF. In order to control the radial voltage distribution and to obtain the required resonant frequency, a multi-stem configuration is then the only feasible solution [1,2].

THE MODELING METHOD

For simplicity's sake, we will consider the median symmetry plane and talk about quarter-wave resonators (QWR). A multi-stem QW resonator can in principle be modelled as several paralleled QWR, having all the same eigen-frequency and whose field distribution stays almost unchanged if they are coupled in such a way that they don't interact each other. This is feasible when the stems

are far enough apart, and each QWR is simulated with the proper boundary conditions, as we shall see later.

Each QWR consists of one stem, charged on one section of the electrode. Such a structure usually presents a voltage distribution having a minimum near to the stem base and increasing towards the dee extremities.

The combination of two or more structures like this, gives a voltage distribution where the adjacent maxima join in a plateau as no current has to flow in either direction.

By cutting the dee into sections of different length, it is possible to obtain several different profiles, where the lower voltage will correspond to the minimum of the section with higher capacity.

To simulate each section with the proper boundary conditions, we tested two different solutions, both giving comparable results.

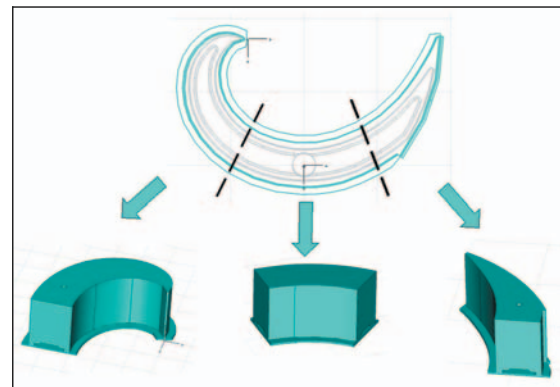


Figure 1: example of cavity subdivision. Normal magnetic boundaries are selected on the vertical surfaces.

In the first case, a magnetic symmetry condition is set among two adjacent stems as shown in figure 1. This method greatly reduces the number of mesh cells. In the second case, tested on a simplified structure, each stem with its section of dee, is simulated in the whole cavity volume.

In both cases the stem position and diameter are adjusted in order to obtain the required voltage distribution and frequency. For this last adjustment, we know that, lowering the cut frequency of each portion, arises the local voltage level. Then the whole structure is simulated using the geometry found in this way, and few local adjustments are done to compensate the effects of the method's approximations.

At least one simulation of the whole volume is required to check the position of other resonant modes that could be not too close. In the case of a 3-stem structure, for instance, the two nearest modes typically have voltages of opposite sign on the dee extremities, or lower voltages on the extremities than on the central part.

In order to optimize the shunt impedance, we have chosen to have higher electrode voltages on the inner and outer extremities and to keep a lower voltage in the most part of the dee. The obtained resonator is shown in fig 2.

The big central stem (low inductance) concentrates the currents coming from most of the electrode, while the two lateral ones (high inductance) resonate with the much smaller capacities of the dee extremities.

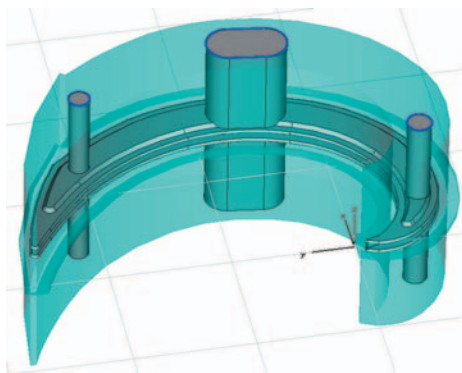


Figure 2: layout of the cavity

THE CAVITY GEOMETRY

The total height of the half-wave cavity is 80 cm, while a vertical aperture of 30 mm along the median plane is left for the beam.

In order to reduce the dee capacity and the electric field, the acceleration gap size ranges from 1.5 cm at inner radii to 6 cm at the outer end.

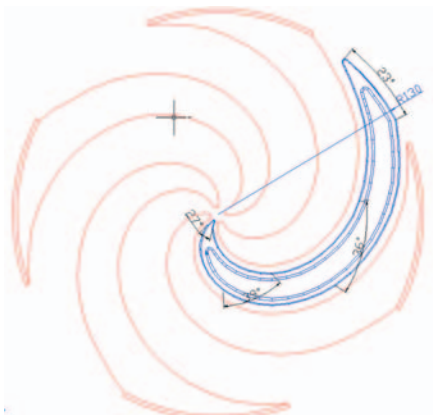


Figure 3: layout of a dee between the poles

The electrode's angular width gradually increases up to 39 degrees near to the first stem, then it is rather constant in the proximity of the main stem and decrease down to 23 degrees at full radius (see fig. 3).

The three stems are centred at radii 30, 90 and 120 cm. Their diameters are 8.6 cm for the external stem and 10 cm for the internal stem. The main stem extends 32 cm radially and up to 30 deg azimuthally.

RF SIMULATION RESULTS

The simulations have mainly been performed with the eigenmode module of Microwave Studio (MWS) [3] and table 1 reports the calculated parameters.

Table 1: RF cavity parameters

Parameters	value
Resonance frequency	~ 93 MHz
Voltage range	30-160 kV
Quality factor	~ 8500
Max power density	16 W/cm ²
RF Power	~ 45 KW
E Max	10 MV/m
Mode 2	98 MHz

The effective voltage distribution, going from 60 kV in the injection region to a peak value of 120 kV in the extraction region, is shown in figure 4. The values are obtained by integrating the electric field profiles across the gaps in the median plane of the cavity: it has to be noted that, due to the reduced width of the electrode in the injection region, the transit time factor is there very low.

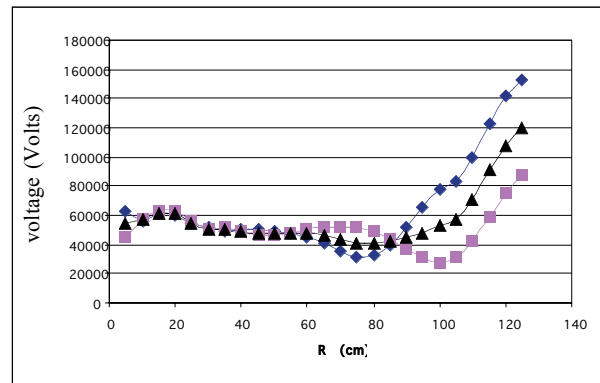


Figure 4: effective voltage vs radius: the internal gap distribution (squares), the external one (diamonds) and the average (triangles).

Loss calculations were also carried out with the SOPRANO code.

	SOPRANO [kW]	MWS [kW]
LINER	7.50	7.60
DEE	4.40	7.33 (dee + main stem)
INTERNAL STEM	2.14	1.87
EXTERNAL STEM	4.87	5.25
MAIN STEM	1.76	
TOT for 120 kV@130 cm	20.67	22.05
Total losses per cavity	41.34	44.10

Table 2: comparison between losses calculated with SOPRANO and MWS for different cavity elements

To take into account the surface roughness and the average working temperature, the copper conductivity has

been set as 5.0×10^7 S/m instead of 5.8×10^7 . Results are summarized in table 2. The current distribution on the dee surface is shown in figure 5, which shows very clearly how the different sections interact with the stems.

The maximum current density is about 69 amp/cm and is located on the edges of the two gaps near to the external stem. High currents are also visible at the base of the external stem, requiring special care for the connection to the electrode.

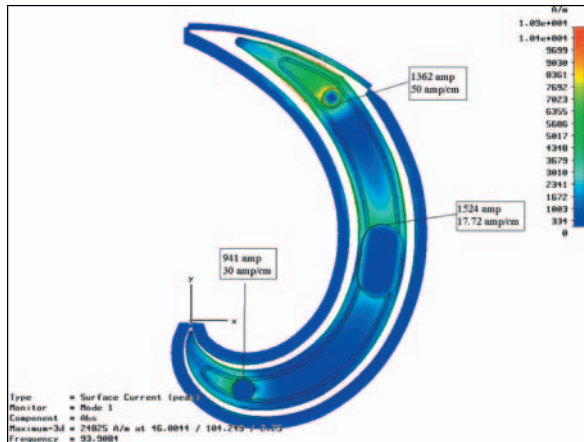


Figure 5: current distribution on the dee ; current values at the short-circuit plate are given in boxes

Figure 6 is a closer view of the critical areas of figure 5 and shows the corresponding loss values. The currents, coming from the large radii, gather along the gaps towards the stem and heat the electrode along the gap. The maximum power density is estimated at 16 watt/cm², for a peak voltage of 120 kV.

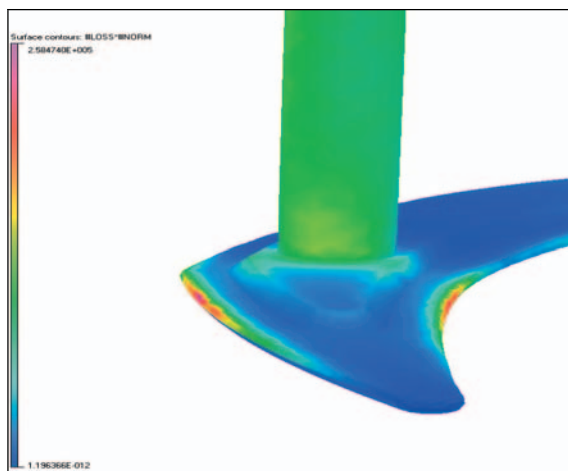


Figure 6: power density distribution (watt/m²) for 150 kV of peak voltage. The peak value is 25 watt/cm².

COUPLER DESIGN

The inductive coupling has been chosen to feed the RF power into the cavity. Simulations, performed with MWS, has shown that it is possible to get critical coupling with

reasonable loop dimensions near all the different stems: i.e., positioning the loop near to the main one, requires a loop surface around 20 cm².



Figure 7: inductive loop layout.

CONCLUSION

Multi-stem cavities are a good solution to the design of cyclotron resonators with challenging dee shapes and dimensions. Although the degrees of freedom of the structure grow with the number of stems, the RF design can be approached with some simple but realistic approximations that, with the help of modern 3D EM codes, lead to a quick definition of the stem diameters and positions. Then, multi-stem cavities can easily be designed to provide the voltage distribution needed to optimize the power consumption, to reach high resonant frequencies in spite of the dee dimensions, and to reduce the current densities and the total losses. Last but not least, using more stems will also help to increase the mechanical stability of the structure and allows us to provide an easier path for the dee cooling pipes.

ACKNOWLEDGEMENT

The authors want to thank Mr. D. Battaglia and Mr. L. Piazza of the Engineering Dept. of Catania's University for his contribute to the cavity and inductive coupler design and Mr. A. Caruso of the Laboratori Nazionali del Sud for his technical suggestions for cavity improvements.

REFERENCES

- [1] E.Acerbi et al., "Design of the RF cavity for a 200 MeV PSC", 14th ICCA 1995, Sout Africa.
- [2] C.Bieth et al., "A very compact protontherapy facility based on use of HTS", 15th ICCA 1998, Caen, June.
- [3] MWS by CST www.cst.de.
- [4] SOPRANO by Vector Fields www.vectorfields.com.

CYCLOTRON PROJECT FOR THERAPY AND RADIOISOTOPE PRODUCTION

L.Calabretta^a, G. Cuttone^a, M.Maggiore^{a,b}, M. Re^a, D. Rifuggiato^a

a) INFN Laboratori Nazionali del Sud, Catania, Italy

b) University of Catania

** Corresponding author, e-mail: calabretta@www.lns.infn.it*

Abstract

The design of a superconducting cyclotron able to delivering protons and light ions is in progress. The magnetic circuit, the isochronous field, the extraction trajectories and beam dynamic have been studied and are here presented.

1 CYCLOTRON MAIN PARAMETERS

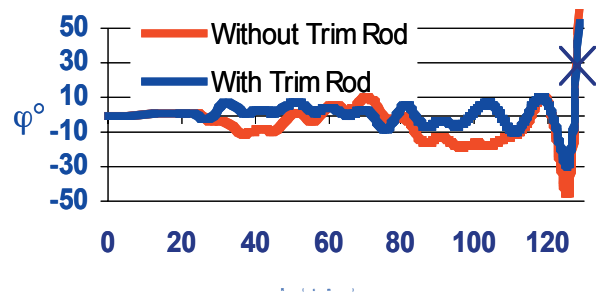
A cyclotron able to accelerate particles having a charge to mass ratio $Q/A=0.5$, up to 250 A·MeV has been studied [1,2]. H_2^+ molecules and light ions can be accelerated using the same frequency while the magnetic field need to be changed of $\approx 4 \cdot 10^{-3}$. The main characteristics of the cyclotron are show in Table 1. This cyclotron does not need any trim coils. The moderate value of the mean magnetic field, 3.8 T, together with the 50 mm hill gap produces a value of flutter quite high to achieve a focusing power $K_{FOC} > 500$ maintaining the maximum spiral of the sectors at a value of 140° , smaller than that of the MSU K1200 cyclotron. The cryostat design is not yet completed but enough room has been allocated to guarantee safe operation and minimum consumption of liquid helium, the evaluated thermal losses being below 8 W. This moderate value of refrigeration power could be delivered by 4 commercial re-liquefiers.

1.1 Isochronous Field

The magnetic field has been simulated by the 3D electromagnetic code OPERA. A parametric model of the cyclotron has been built, and an iterative process has been realised in order to optimise several parameters of the machine. The beam dynamics properties have been evaluated by the code GENSPE1, which calculates the equilibrium orbits using the

Table 1: Cyclotron parameters

Sectors n°	4	Hill width	$34^\circ \pm 44^\circ$
$K_{bending}$	1000	Cavities n°	4
$K_{focusing}$	500	Frequency	92.3 MHz
Pole radius	1320 mm	harmonic	4^{th}
Yoke diameter	4.9 m	Power max.	<45 kW
B at centre	3.1 T	Max. Field	4.1 T
Coil size: width height	150 x 210 mm ²	Current density	<41 A/mm ²
Total weight	<320 t	LHe Losses	<8 W



magnetic field maps produced by OPERA. The final setting of the magnetic field was achieved by adding the contribution of a set of Trim Rods (T.R.). Twelve trim rods per each hill, placed along the center of the hill were simulated to obtain the individual magnetic field maps. The curve “with T.R.” in Fig.1 shows the final phase vs. radius produced by GENSPE1 using the optimized final magnetic field map. The two curves were evaluated assuming an average acceleration voltage of 100 kV to take account of the angular width of the Dees. Fig. 2 shows the working path of the accelerated beam in the plane v_z vs. v_r . In figures 1 and 2 the selected orbit to be extracted are labelled by *. It is assumed to extract the beam before the last orbit and after the crossing of the $v_z=1$ resonance. Although the final result is satisfactory a residual oscillation with amplitude of 10° is present in the curve ϕ vs. R . A different solution at the Trim Rods will be investigated in future to achieve a better solution.

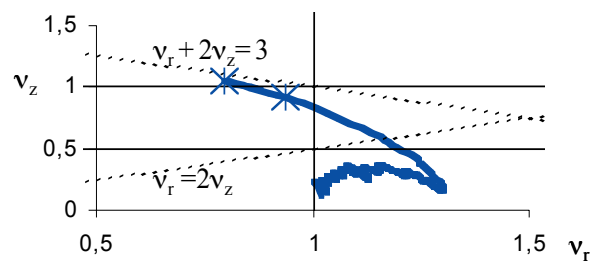


Figure 2: Working path in the (v_r, v_z) plane

2 LOSSES AND VACUUM REQUIREMENTS

Due to the high binding energy of the H_2^+ molecule, it is possible to use magnetic fields as high as 10 T even at energies as high as 1 A GeV without any beam losses due to electromagnetic dissociation. Beam losses, along H_2^+ ionized molecule with the residual gases, which produce stripping of the the acceleration path, are due to the interactions of the electron of H_2^+ . In general for a molecule this probability is higher than for a simple ion. The fraction of lost beam particles was evaluated according to the Betz-Bohr model [3], that takes into account the beam cross section for electron lost versus the beam energy, and it is summarized by the following formula:

$$Losses = 1 - N / N_0 = 1 - e^{-\frac{P}{KT} \int \sigma(E) dl} \quad (1)$$

where P is the pressure (Pa) , L is the path length (m), $\sigma(E)$ is the cross section of electron loss. We evaluate both the intensity and power losses, by integrating formula (1) turn by turn, the expected beam lost all along the machine should be of 2.7%, which means a power loss of 100 W for an accelerating beam of 10 kW. Our tests of extraction from the K800 superconducting cyclotron show that also with beam power higher than 100 W dissipated at the extraction radius, very close to the cryostat, there are no detectable effects on the cryogenic parameters of the cryostat.

3 EXTRACTION

The extraction of a fully stripped light ion like C^{6+} needs Electrostatic Deflectors (E.D.). According to our experience E.D. devices are reliable if electric field and voltage applied are lower than 120 kV/cm and 60 kV respectively. Our choice to operate the cyclotron with 4 RF cavities forced us to install 2 E.D. inside two hills. The housing of the 2 E.D. have been designed to stay inside the 50 mm gap of the hill. The ends of E.D.1 are at about 8 cm from the boundary of the iron hill. A gap of 5 mm between the electrode and the septum was selected. The simulation studies show that an electric field of 110 kV is enough to extract the beam. To increase the margin of reliability our simulation studies were accomplished not with the last orbit but with a 2 mm inner orbit. Following the second E.D., placed on the same hill and 4° long, the beam cross the first Magnetic Channel (M.C.), which increases the steering towards the outer radii. In Fig. 3 the extraction trajectories of the protons produced by stripping of H_2^+ on a carbon foil, and of C^{6+} ions, extracted by electrostatic deflectors, are shown. As it is quite evident the two trajectories can be delivered to the same direction. This result was achieved quite easily adjusting just the angular position of the stripper. The

dashed curve, in Fig. 3, is the trajectory without M.C.correction.

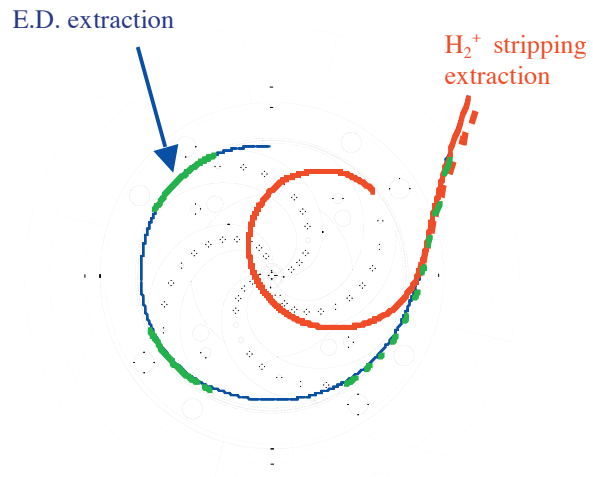


Figure 3: Layout of the cyclotron with overdrawn the extraction trajectories by E.D. and by stripper. The E.D. and the M.C. positions are also shown.

During July'04 a test for a “quasi extraction” by stripping was performed in our k800 cyclotron. A Ne^{9+} beam was accelerated up to 45 AMeV and stripped by a 0.1 mm (22 mg/cm²) carbon foil. After one turn inside the cyclotron the beam strike an alumina screen and a Faraday cup. The experimental results agree quite well with the simulation. Also the full current measured before and after the stripping scale according to the ratio of the charge states. No beam losses have been detected.

4 CONCLUSIONS AND PERSPECTIVES

The cyclotron here presented is bigger than the usual cyclotron used for proton therapy and of course also its cost will be higher. Anyway the cost of the accelerator is only a 15-20% of the total cost of a medium size radiotherapy facility. So the higher cost of the accelerator could be acceptable looking at the advantages and versatility of the new cyclotron.

The cyclotron here described has been proposed for the radiotherapy center for the hospital “A.O. Cannizzaro”. Although the proposal has been approved by the Sicilian regional government, we are again waiting for the final founding approval.

5 REFERENCES

- [1] L. Calabretta et Al., Nuclear Physics A734 (2004) pp. 378-381
- [2] L. Calabretta et Al., “LNS Catania project for therapy and radioisotope production”, XVIIth ICCA 2004, Tokyo
- [3] Betz, Rev. of Mod. Phys. Vol.44, N° 3(1972) 465

ACTIVITY REPORT OF DEVICES DESIGN GROUP

S. Passarello, F. Caruso, G. De Luca, G. Gallo, A. Grmek, G. Manno, F. Musarra, E. Zappalà .

INFN Laboratori Nazionali del Sud, Catania, Italy

Abstract

The devices design group's activity is presented; its aim is to design and develop sophisticated devices for accelerators, including ion sources, and experimental devices with servomechanism and remote handling system, able to operate in radioactive or high-risk contaminated areas.

1 NEW ELECTROSTATIC DEFLECTORS FOR HIGH POWER BEAMS FOR THE SUPERCONDUCTING CYCLOTRON.

The extraction of high intensity beams have required to completely redesign the electrostatic deflectors.

In 2003 a water cooled electrostatic deflector was realized and installed into the cyclotron.

In October 2003 the new deflectors were tested inside the cyclotron with fully operational conditions and a 100 W power beam was successfully extracted.

A new E1 deflector with an improved cooling circuit has been studied in order to increase the amount of power that can be safely managed.



Fig. 1- E1 deflector

Old deflector had only one cooled plates at the beam input, so that a small surface (few cm²) was available for thermal exchange.

We designed a new E1 deflector with a cooling circuit which follows the beam input plate, covering even the septum either on the upper part and on the lower part.

In such a way the surface is increased by a factor 100 and a much better thermal balance is reached. In addition, the cooling pipes were brazed in a high vacuum oven to ensure a perfect contact of the components . Finally a better thermal contact between the septum and the cooling pipe was obtained by connection the two part with a 18 screws link, that increased a lot the amount of dissipated power (see Fig. 2).



Fig. 2- E1 cooling system view

The new deflector was tested in a test bench under vacuum with a 1000 W power applied on the septum.

We calculated that more than half power was directly dissipated by the septum (the remaining part being irradiated).

The deflector didn't present any damage so that we decided to assembly it into the cyclotron.

Improvement for the deflector will be further obtained with the new septum realized in tungsten in order to have better thermal exchange.

This component is under construction.

2 NEW ALUMINUM SERSE CHAMBER.

In the case of an Electron Cyclotron Resonance ion source the high plasma temperature and the high thermal stresses makes unsuitable the wall coating with secondary electrons emitter (as it has been done for other kind of plasma sources) and quite complicate the use of thick alumina tubes (as the useful plasma confinement field decreases on the radial side). The degradation of the coating is already a problem for microwave discharge ion sources, but the wearing is absolutely not acceptable in the case of an ECRIS.



Fig.3- The new aluminum chamber of SERSE over the test bench

For this reason it was decided to use Aluminum chambers for two ECRIS at LNS. For the smaller source, CAESAR, the solution was quite simple in terms of mechanical design, but for the superconducting ECRIS, SERSE, the length and the mechanical interfaces make complicate the chamber design and the tolerances were quite hard to be reached for an Aluminum made chamber .

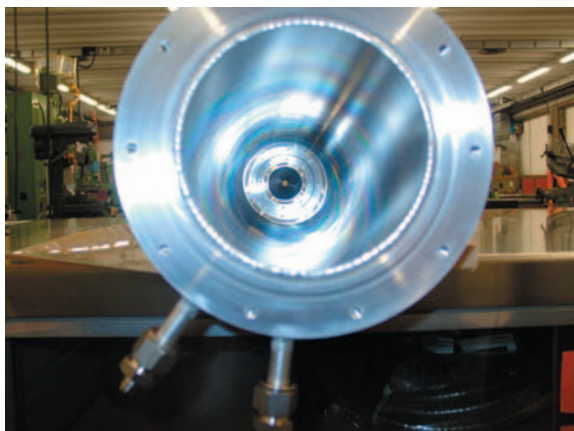


Fig. 4- Inner view of the Aluminum SERSE chamber

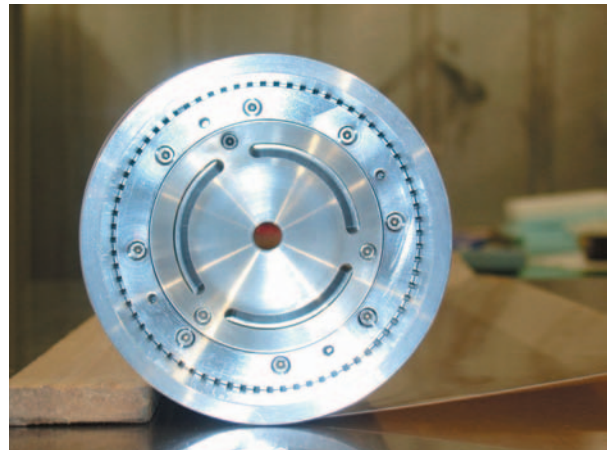


Fig.5-Aluminum SERSE chamber assembled with the plasma electrode

Finally the good solutions were found and the chamber was delivered in July 2004 (see figs. 3-4-5). The schedule of the accelerator has not permitted to install the chamber in 2004 but it will become a priority in 2005.

3 CHOPPER 500

The Chopper 500 is a RF device designed to reduce down to 500 psec the length of beam bunches (from 3-4 nsec) delivered by the Superconducting Cyclotron. It consist of two deflecting plates followed by a couple of slits.

Presently beams with bunch length of 1 nsec are delivered to experiments, but this goal is achieved by tuning the machine parameters and using phase slits, which are thin interceptors located inside the dees. This procedure results to be quite complicated, therefore we expect to simplify the beam operations by using the Chopper 500.

To select a beam bunch length of 500 psec, a high frequency voltage is applied in order to induce a fast variation of the electric field at a time interval of ± 0.25 nsec during the transit of the particles.



Fig. 6-Chopper 500 disassembled

In the chopper 500 the sliding contacts were substituted with others more performing and an alignment device. was realized. Then it was installed into its vacuum chamber and vacuum test was carried with positive result.



Fig. 7- Coupler for chopper 500

All the components were assembled and successful vacuum tests and mechanical tests was done.

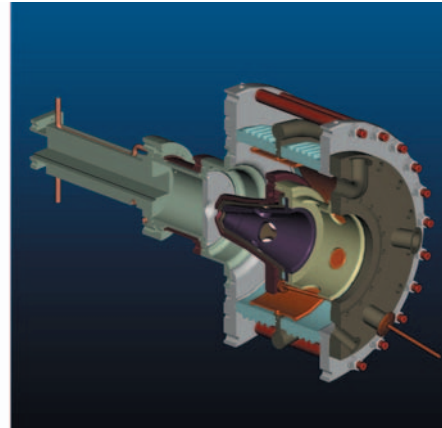


Fig. 8-3D view of PM-TRIPS source

4 NEW PERMANENT MAGNET ECR ION SOURCE FOR ADS PROJECT.

The ADS (Accelerator Driven System) project requires a high power proton beam (1 GeV-30 mA) with high stability and reliability. A new source has been designed on the basis of the experience gained with the 2.45 GHz TRIPS source [1], in order to increase the long-term reliability from 99.8% to 100%. The permanent magnet source PM-TRIPS [2] (see figs.8-9-10) was designed with a few important changes with respect to TRIPS:

- a new magnetic system with NeFeB of VACODYM 745HR type.
- Compact acceleration column.
- Four electrodes extraction system to simplify the mounting/dismounting and maintenance operations.
- Redesign of the high voltage platform (see fig.10), with compact high voltage shielding and source-beamline alignment systems, in order to have a simple and reliable setup.

In 2004 the major parts were realized:

- the extraction column complete of electrodes, alumina's insulator, flanges and PEEK's rods.
- the support system of extraction column which permit a easily dismounting.
- the support of source complete of HV platform.

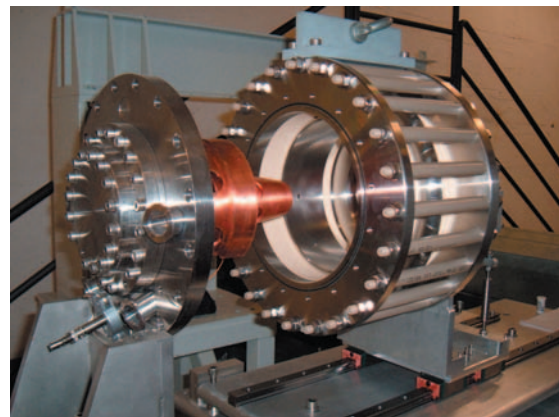


Fig. 9 – The PM-Trips extraction column

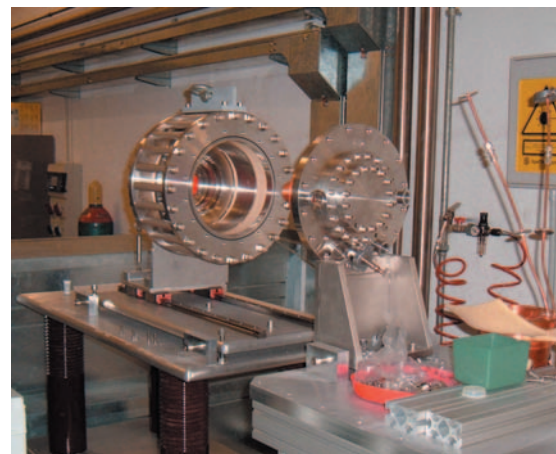


Fig.10- The PM-Trips on platform

Because of an excessive stray field outside the extractor, the assembly on the test bench was

postponed to the next year, in order to have the possibility to slightly modify the magnets' set-up.

5 ACTIVITY FOR EXCYT PROJECT.

The devices' design group has designed a lot of special systems for the EXCYT project in the previous years; in 2004 all systems were installed on the preseparator and in the 1st stage of the mass separator. The support of the group during the assembly was mandatory, as many of the devices require particular care in the positioning and alignment. All the mechanical tests in order to verify the diagnostic devices installed on the platforms were carried out. Many efforts were done in order to interface the electronic control to mechanical devices; in particular a lot of time was dedicated on movable extraction electrode of the source and on remote handling of the source's chamber by platform to temporary storage, using special robot.

This argument will become particularly relevant as soon as the facility will come in operation and activated parts' management will require a fully robotized handling [3].

REFERENCES

- [1] L. Celona et. al, Rev. Sci. Instrum. 75(5), 2004, 1423
- [2] G. Ciavola et. al, Rev. Sci. Instrum. 75(5), 2004, 1453
- [3] G. Cuttone et al., this report

RADIOFREQUENCY GROUP ACTIVITY REPORT 2004

A.Caruso^{a,*}, L.Calabretta^a, F.Consoli^a, A.Spartà^a, J.Sura^b

a) INFN Laboratori Nazionali del Sud, Catania, Italy

b) University of Warsaw, Heavy Ion Laboratory, Poland

** Corresponding author, email: Caruso@lns.infn.it*

Abstract

The activity report of the RF Group during 2004 can be divided in to three main parts. The first part is about the existing radio frequency systems. It includes the RF of the superconducting cyclotron and the related RF devices placed along the injection and extraction beam line, as buncher and choppers. The second part of this activity report shows the status of the most important new projects at the end of 2004. It includes the Chopper-500, the sinusoidal low energy chopper, the new idea for a complete RF control system, including amplitude and phase stabilization loop, based on the DDS technique. The third part is dedicated to a positive experience of the technical-scientific collaboration between Infn-Lns, CEA and Ganil for the full high power test on the first RFQ stage of the SPIRAL 2 project.

1 RF OF THE CYCLOTRON AND PULSING SYSTEMS

This first chapter is about the status of the main RF parts of the superconducting cyclotron and all the related pulsing systems. Particular care is given to the upgrades and innovations of the existing systems. The systems themselves have been completely described in the previous reports, articles and technical notes.

1.1 RF system of the K-800 superconducting cyclotron

The main goal of the system is to feed the RF signal into three $\lambda/2$ resonators in order to stabilize the right accelerating high voltage on the three electrodes, called dees. The main components to obtain this goal are:

- The cyclotron RF control system
- The RF power amplifiers
- The $\lambda/2$ resonators

The cyclotron RF control system is based on an analog wide band system, running from 15 to 50 MHz, where the most important innovation is the introduction of the “DDS-based multiple frequencies generator”. This generator allows the generation of two or more sinusoidal signals perfectly in phase. The system has been used since 2003. The good results of this DDS generator led us study a new complete control system based on the same DDS technique [1]. The results of this new DDS control system will be given in the specific part on innovations and improvements.

While the control system ensures amplitude and phase stability, the RF power amplifiers section takes the sinusoidal signals from few mW to several kW in order to reach the right accelerating voltage. The power amplifiers are based on three solid state amplifiers as drivers and three double tetrode stages as finals. This section has been involved in a massive upgrade campaign. The most important improvement was made in the power supply system of the final stage amplifiers. The final stages, three 90kW CW amplifiers, were supplied by the former Brown Boveri Company more

than 20 years ago. Several components, mainly in the electronic control parts, are obsolete. The risk for future maintenance, for example the lack of spare parts of the amplifiers, can be very high. A couple of years ago we decided to begin a specific maintenance and innovation plan in order to change the most critical obsolete parts of the amplifier. Together with Thales (former Brown Boveri) we began this upgrade of our power amplifiers in 2003. Two of the three power supply controls have been changed together with the relative high voltage transformer. At the moment we have 2 amplifiers with the new high voltage controllers and the third still has the old one.



Figure 1: the new high voltage transformer already installed.

The old controllers removed from the upgraded amplifiers can be used as spare parts for the BBC amplifier which still has the old power supply controller. We are confident we will carry out the same upgrade in the last amplifier in the near future, next budget permitting.

The $\lambda/2$ coaxial resonators of the superconducting cyclotron require an upgrade program too, because several accidental arrests in the movement of the sliding shorts stopped the accelerator activity for a few days, in

the last years. To avoid this kind of problem a new solution has already been presented in the LNS activity report 2003 [2]. In the meanwhile a regular annual maintenance plan is carried out, in order to reduce or avoid these accidents.

1.2 Radio frequency pulsing system

We include under the pulsing system, the buncher and chopper devices installed along the injection and extraction cyclotron beam line. At the moment we have installed along the beam line the following devices:

- The low energy chopper
- The axial buncher
- The high energy chopper

The low energy chopper is used as an attenuator of the injected cyclotron beam. We can easily set the transmission of the beam from 1% to 100% . During the high intensity test for the Excyt project, this chopper was used to decrease the beam current longitudinally. In the near future we would like to drive the deflecting plates of this chopper also with a sine wave. A description of this idea will be described in chapter two of this report.

The Axial Buncher consists of a drift tube, placed in the axial hole of the cyclotron yoke, at 0.5 metre before the inflector. The electrode is driven by an RF signal, in the range of 15÷50 MHz. We would like to upgrade the matching box, between the 50 Ω solid state amplifier and the drift tube, together with its controls in the near future. However the buncher still allows a gain on the extracted cyclotron beam of about a factor 4.

The high energy chopper allows the separation time between two consecutive accelerated beam bursts between 100 to 200 ns [3]. Placed along the extracted beam line, we have improved the cooling system through the installation of a certain number of fans around the inductive component of the equivalent L-C circuit. The discharges were reduced and the general stability of the peak voltage on the deflecting electrodes was improved.

2 NEW DEVICES, PROTOTYPES AND IDEAS

In this chapter we are going to present the status of the new projects. Some devices already mentioned in the first paragraph are linked to the second part of the paper: sometimes as a starting point, like in the DDS control system, sometimes as an evolution, like in the new chopper-500, sometimes as a transformation of the same device, like in the case of the sinusoidal low energy chopper.

2.1 DDS-based control loop system

The good results of the already mentioned DDS-based multiple frequencies generator make us feel confident in developing a complete DDS control system for the RF cyclotron and in general for all the various RF equipment [1]. The AD9852/54 a commercial DDS

microchip, is the core of this new control system. The component allows, through digital ports, the manipulation of the frequency, amplitude and phase of the developed RF-carrier without any interruption to the latter. In this way we would have a complete DDS control system capable of stabilizing amplitude, phase and tuning ensuring the present stability of the analog control loops. The remaining operations, such as turning on/off and protection of the system will be performed at the same time. A specific software and the use of high speed electronic components around the AD9854 architecture takes this system near the analog loops performance. At the moment the first prototype is ready. It is under continuous bench tests, in order to ensure the same performances of present analog control loops. The present system has become in some parts quite obsolete, consequently we sometimes experience difficulty to finding old components still in production, to repair the electronic boards. This is another reason for exploring the DDS alternative. The new system should be compact and easy to use. To give an idea of the difference in size between the present system, the black cabinets on the left and the new DDS one on the right, see figure 2.

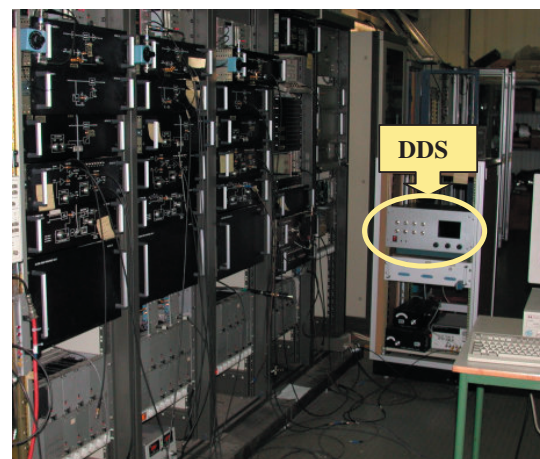


Figure 2: present and new dds control, comparison.

2.2 Chopper-500 status report

The production of consecutive accelerated bunches with a separation time of up to 200 ns and a width of 500 ps FWHM, is the goal of this new chopping beam system. The chopper 500 should cut the present length of the accelerated beam bunches, delivered from the superconducting cyclotron, from 1.5÷2 ns to 0.5 ns. Now all the components of the system are ready. The $\frac{1}{4} \lambda$ resonator, the coupling capacitor, the 3"1/8 coaxial line, the 50 kW final stage RF amplifier, the driver pre-amplifier, the DDS frequency synthesizer, are on site. All the elements of the system, except the resonator, have to be fully tested. At the moment the conditioning of the cavity, under vacuum, is going on. The first stage amplifier, a solid state of 1kW, with its protection system and a pulse generator is pulsing the cavity at a

frequency of about 80 MHz. Two different multipactoring levels has been found and we are confident to feed this first kW into the resonator soon. From this point we can better estimate the behaviour of the cavity for the final installation along the extraction cyclotron beam line. Table 1 summarized the parameters of the chopper 500 system.

Table 1: Main parameters and values

Parameters	Value and limits
Maximum Peak Voltage	200 kVolts
Frequency range	65÷110 MHz
Qo	6000÷9000
R shunt	450÷720 kΩ
Power dissipated	27÷45 kW
VSWR	< 1.1
Coupling	Capacitive
Input impedance	50Ω on 3"1/8

The measurement of the shunt resistor, using the perturbation method has been carried out at different frequencies along the bandwidth of the chopper. These results together with the available power from the RF amplifier allows 200kV on the electrodes along the entire frequency range. Fig 3 shows R_{shunt} , Q_o and RF power.

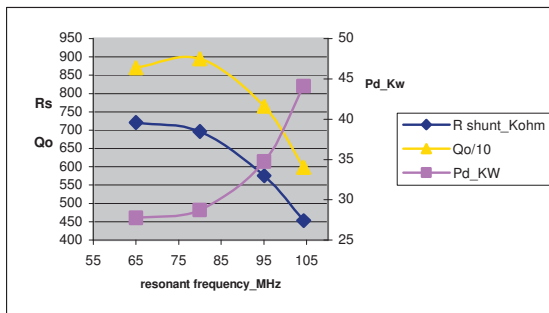


Figure 3: relation between R_{shunt} , Q_o and RF Power

2.3 Sinusoidal low energy chopper

The sinusoidal low energy chopper uses the same pair of deflecting electrodes of the low energy chopper.

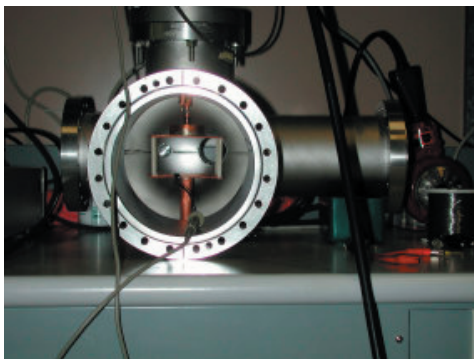


Figure 4: the deflecting plates of the low energy chopper

In figure 4 an internal view of the deflecting plates of the low energy chopper is given. At the moment we are using the low energy chopper as a beam attenuator. The deflecting plates are driven by a pulsed high voltage signal of about 800 Volts at the frequency pulses of 1 kHz, the duty cycle can be linear changed from 1 to 100%. This gives a perfect 1:1 ratio between the setting of the chopper parameters and the accelerated beam in the cyclotron. Now we are going to drive the same chopper with a sine wave. In this way we can use the chopper in two different modes: beam attenuator or proper RF chopper. For the latter, the applied sinusoidal signal will be a sub harmonic integer or non integer of the RF cyclotron. The sine mode version of the low energy chopper foresees the use of the Chopper-500, too. The use of the two choppers at the same time should give consistent assistance in terms of suppression of the accelerated beam bunches by the chopper-500. When the H.E.Chopper is removed, the Chopper 500 will take its position along the extraction beam line. In other papers there is a full description of the present status of the beam delivered to the users from the cyclotron, in terms of separation time and length [1]. The target of this new chopper system is two fold: the separation time of 100÷200ns between two consecutive accelerated beam bunches and the width of the single bunch equal to 500ps.

In graph figure 5 shows the relation between the blue RF cyclotron sinusoid and the black chopper-500 signal. In this case the sinusoid low energy chopper is turned off. The bold blue line focused our attention on the selected bunches, the red on the suppressed ones. As you can see the selected beam bunches cross the chopper sinusoid at 0 degree, while we have a beam bunch from the cyclotron at 90°. The relation chosen between the chopper-500 and cyclotron sinusoids is linked to this rate $1+(n-1)/n$. If we choose $n=3$, the rate will be 1,666. The first selected bunch crosses the chopper sine wave at 0°, the successive two bunches will be deflected at 60° and 120°, the next one will meet the RF chopper at 180° without any deflection. A suppression of 2/3 bunches has been done. According to the peak voltage value in table 1, the relative voltage at 60 and 120 degrees is enough to deflect the beam.

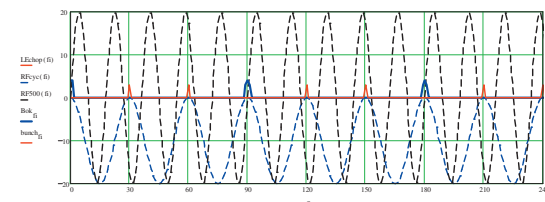


Figure 5: relation between chopper-500 and RF cyclotron

If we take to account $n=4$, the suppression should be $3/4$ and the interval between the bunches becomes 45°. In this case the bunches around the selected one can easily contains some "tails", due to the bunch length itself, around 30°÷40°. This unwanted tail will cross the

chopper sine wave at 10° before and after the selected bunch at 0° . This is a sort of “pollution” of the beam delivered to the users. The expected beam should be free of tails. If we exasperate the phenomenon and we chose $n=6$, the suppression between the bunches should be $5/6$ and the interval will be reduced again. The sinusoidal low energy chopper, together with the chopper-500 should be the solution to avoid the problem of spurious tails if the number of suppressed bunches becomes more than $2/3$. The graph in figure 6 shows at the same time the blue RF cyclotron, the black chopper-500 signal and the superimposed red sine wave of the low energy chopper.

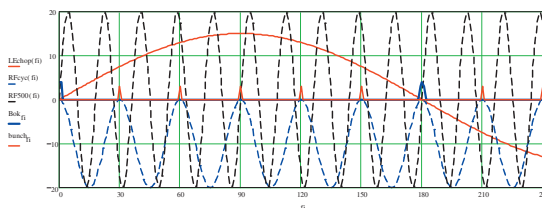


Figure 6: L.E.chopper switched on, in red. Blue sinusoid is the RF cyclotron, while, in black there is the chopper-500 signal.

The low energy chopper sine wave meets the beam along the axial injection line before the cyclotron. It will present the beam to the cyclotron completely deflected at 90° and 270° and, strongly attenuated around $\pm 45^\circ$ from the peak voltage values. This operation should reduce greatly the intensity of the nearest beam bunches tail around the surviving selected bunch from the chopper 500 deflecting plates. So, if the suppressed bunches are $5/6$, with the combination of the two choppers, low energy and 500, we are confident to obtain a good and clean selection of the beam bunch. The synthesis of the driving sinusoids, in phase with these odd relations, 1.666 or 1.8333, will be performed by the new DDS multiple frequencies generator.

The sinusoid version of the low energy chopper is ready and some preliminary test have been done.

The system consists of the same deflecting plates of the low energy chopper, a solid state power amplifier of 50 Watts maximum, a matching box and a semi rigid coaxial cable. The matching box allows the impedance matching between the 50Ω output stage of the RF amplifier and the capacitive impedance value of the deflecting electrode plates, around 43pF.

The technical characteristics of the sinusoidal L.E. Chopper, already tested are summarized below:

- Bandwidth I, $3 \div 5$ MHz
- Bandwidth II, $4.4 \div 8.6$ MHz
- Nominal peak to peak voltage, 2kV
- Maximum voltage, 3kVpp
- Maximum RF power, 25W
- Forced air cooled on the matching box
- 45 minutes to reach the warm up stability

We have introduced two different working bandwidths to increase the versatility of the low energy chopper,

which be used with the present High Energy Chopper and with the future Chopper 500, along the two bands, I and II. We plan to carry out tests on the beam, in order to see the first preliminary positive effects on the suppression of some accelerated beam bunches from the cyclotron. A mini control system is under study too.

3 INFN-LNS, CEA AND GANIL COLLABORATION

A collaboration agreement was reached between the LNS-Catania, the CEA-Saclay and Ganil-Caen Institute, in September 2004. The full power test of the RFQ prototype was done in our laboratory. The RFQ is the first part of the SPIRAL2 project [4]. For four weeks the RFQ cavity was been conditioned at 89 MHz from few watts to 50 kW.

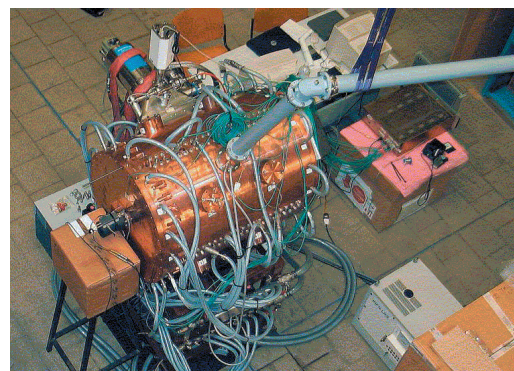


Figure 7: the RFQ installed at INFN-LNS

Technically our 50kW amplifier of the chopper 500 was joined to their RFQ. In figure 7 the RFQ is fully installed with all the connections ready to be tested at full RF power. In less than one month the full power test was done successfully. In our case we tested our amplifier on a real cavity for the first time, as for the CEA-Ganil team all the expected results were reached.

4 ACKNOWLEDGMENTS

The 2004 RF activity were done thanks to the support of many contributions: E. Zappalà and the Devices Design Group for the Chopper 500, Ferdinand Robin for RFQ power test, B. Trovato and his workshop for their availability in providing mechanical general support.

5 REFERENCES

- [1] A.Caruso, L.Calabretta et al., proc. of the 17th International Conference on Cyclotrons and their Applications, 18-22 October 2004, Tokyo.
- [2] S.Passarello, F.Caruso et al, INFN-LNS activity report 2003, p.219.
- [3] L.Calabretta, A.Caruso et al, 16th International Conference on Cyclotrons and their Applications, 13-17 May 2001, East Lansing, USA, p. 297.
- [4] R. Ferdinand et al, EPAC 2004, 5-9 July 2004, Lucerne, Switzerland.

THE CATANA PROTON THERAPY FACILITY: THREE YEARS OF CLINICAL AND DOSIMETRIC EXPERIENCE

G.A.P. Cirrone^{a*)}, G. Cuttone^{a)}, F. Di Rosa^{a)}, P.A. Lojacono^{b)}, E. Mongelli^{a)}, S. Lo Nigro^{c)}, J. Ott^{d)}, V.I. Patti^{a)}, G. Privitera^{b)}, L. Raffaele^{b)}, M.L. Rallo^{d)}, A. Reibaldi^{d)}, G. Russo^{a)}, V. Salamone^{b)}, M.G. Sabini^{a)}, C. Spatola^{b)},
L. Valastro^{a)}

a) INFN Laboratori Nazionali del Sud, Catania, Italy

b) Istituto di Radiologia, Azienda Policlinico, Catania, Italy

c) Dipartimento di Fisica ed Astronomia, Università di Catania, Catania, Italy

d) Istituto di Oftalmologia, Università di Catania, Catania, Italy

** Corresponding author, e-mail: cirrone@lns.infn.it*

Abstract

After three years of activity 78 patients have been treated inside the CATANA (Centro di AdroTerapia ed Applicazioni Nucleari Avanzate) facility. CATANA is the first and unique proton therapy facility in which the 62 MeV proton beams, accelerated by a Superconducting Cyclotron, are used for the radio-therapeutic treatments of choroidal and iris melanomas. Inside CATANA new absolute and relative dosimetric techniques have been developed in order to achieve the best results in terms of treatment precision and dose release accuracy. The follow-up results for 42 patients demonstrated the efficacy of high energy protons in the radio-therapeutic field and encouraged us in our activity in the battle against cancer.

1 INTRODUCTION

High energy protons represent a very promising alternative in the tumor irradiation, as respect the photon and electron beams. Proton beams, in fact, offer the advantage to improve tumor control, especially for the treatment of small tumors, where it is necessary to obtain a localized dose distribution while sparing the surrounding normal tissues [1], [2].

The hadrons allow conformation of the dose distribution better than photons or electrons, so the use of these charged particles has developed rapidly in the last decades. There are nearly 20 hadrontherapy facilities worldwide, among them about 10 in Europe. In Italy, the first and actually unique protontherapy facility, named CATANA (Centro di AdroTerapia e Applicazioni Nucleari Avanzate) was built in Catania, at the Istituto Nazionale di Fisica Nucleare-Laboratori Nazionali del Sud (INFN-LNS). Here a 62 MeV proton beam, produced by a Superconducting Cyclotron (SC), is used for the treatment of shallow tumors like those of the ocular region. The CATANA project was developed to treat ocular pathologies like uveal melanoma, which is the most frequent eye tumor in adults. Moreover, we treat other less frequent lesions like choroidal haemangioma, conjunctiva melanoma, eyelid tumors and embryonal sarcoma.

2 THE PROTON BEAM LINE

The CATANA proton beam line has been entirely built at INFN-LNS and its global view is shown in Figure

1. The proton beam exits in air through 50 μm Kapton window placed at about 3 meters from isocenter. Just before the exit window, under vacuum, is placed the first scattering foil made from 15 μm tantalum. The first element of the beam in air

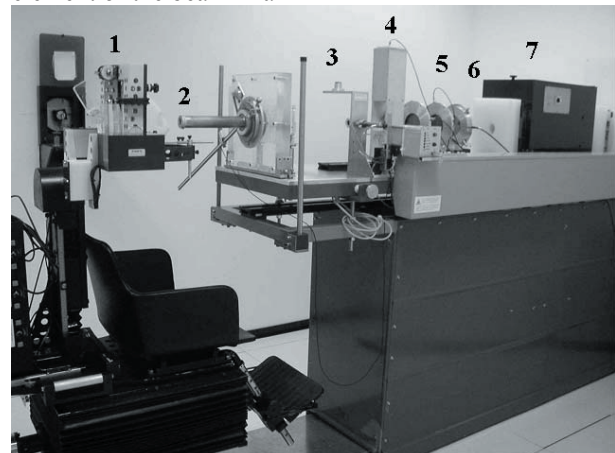


Figure 1: View of the CATANA beam line: 1. Treatment chair for patient immobilization; 2. Final collimator; 3. Positioning laser; 4. Light field simulator; 5. Monitor chambers; 6. Intermediate collimator; 7. Box for the location of modulator wheel and range shifter.

is a second tantalum foil 25 μm thick provided with a central brass stopper of 4 mm in diameter. The double foils scattering system is optimised to obtain a good homogeneity in terms of lateral off-axis dose distribution, minimizing the energy loss. Figure 2 shows the experimental lateral dose distribution for the 62 MeV proton beam measured with a final 25 mm diameter circular brass collimator (reference

collimator). Beam data are acquired with a silicon diode in a water phantom, at the treatment depth of 12 mm, corresponding to the middle of the Spread Out Bragg Peak (SOBP).

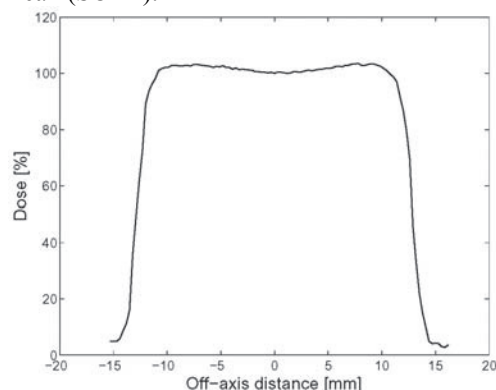


Figure 2: Lateral dose distribution for 62 MeV proton beam.

Range shifter and range modulator are placed inside a box, downstream of the scattering system. Two diode lasers, located orthogonally and coaxially to beam line, provide a system for the isocenter identification and for patient centering. The emission light of a third laser is spread out to obtain the simulation field. A key element of the treatment line is represented by two transmission monitor ionization chambers. The aim of the chambers is, respectively, to provide the on-line control of the dose delivered to the patient and of the beam symmetry. The last element before isocenter is the patient collimator located at 8.3 cm upstream of the isocenter. Finally, two Philips x-Ray tubes, with axes defined by crosshairs, are placed perpendicular and coaxial to beam line, to provide lateral and axial view of the tumor, during simulation of treatment [3].

3 ABSOLUTE AND RELATIVE DOSIMETRY

Inside the CATANA collaboration particular care is devoted to the development of dosimetric techniques and 2D and 3D dose distributions reconstruction.

For reference dosimetry a plane-parallel PTW Markus Ionization Chamber has been adopted. The Markus chamber has an electrode spacing of 1 mm, a sensitive air-volume of 0.02 cm³ and a collector electrode diameter of 5.4 mm. The dose measurements are performed in a water phantom, according to International Atomic Energy Agency Technical Report Series (IAEA TRS) 398 Code of practice [4].

The absorbed dose to water per monitor unit (cGy/M.U.) is measured at isocenter, for each combination of modulator and range shifter used for treatment; the measurement is carried out at the depth corresponding to the middle of SOBP, for the reference collimator [4]. The clinical proton beam calibration is performed just before each treatment fraction; the variation of dose/(monitor unit) on the four consecutive days of treatment results within 3%.

The proton beam calibration is strongly dependent on modulator and range shifter adopted in the clinical

practice; for the same modulator, the decrease in dose/(monitor unit), when the range shifter thickness increases from 6 to 12 mm, is about 35%.

To investigate whether small irregular fields used in the clinical practice will affect the radiation output, an *output factor* is determined, by using the Scanditronix Hi-p Si diode detector.

This diode has a 0.6 mm detector diameter and is designed for field measurements in small proton beams in water. The value of the *output factor* is determined [4] as the ratio of diode signals for the patient and reference collimators with the same M.U. setting.

Considering the experience so far gained, the dose/(monitor unit) decreases by less than 3% for areas between 490 mm² (reference collimator) and 100 mm². The latter represents the lower limit of collimator areas associated to the clinical practice. For relative dosimetry we use radiochromic films, radiographic films (Kodak X Verification (XV) and Kodak Extended Dose Range (EDR2)), ThermoLuminescent Detectors (TLD), natural and Chemical Vapour Deposition (CVD) diamond and silicon detectors.

Depth dose curves and transverse dose distributions, either for the full energy or the modulated proton beams, are acquired with a water-tank system provided with three fully computer-controlled stepping motors. A software, entirely developed at INFN-LNS, controls this system and provides the acquisition and dosimetric analysis data. Figure 3 shows the depth dose distribution obtained with the Markus chamber for the unmodulated full energy (62 MeV) beam. The maximum error on the relative dose is 0.5%.

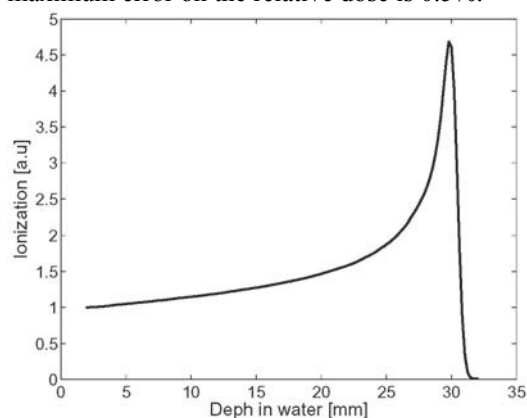


Figure 3: Bragg peak of 62 MeV proton beam acquired in a water-tank with the Markus ionization chamber at CATANA facility.

The Full Width at Half Maximum of the Bragg Peak is 2.76 mm. The 90-10 % and 80-20 % distal fall-offs are 0.8 mm and 0.6 mm respectively and the peak to entrance ratio is 4.72. The Bragg peak as shown in Figure 3, cannot be used in the clinical practice. It, in fact, must be “enlarged” in order to obtain an uniform dose distribution over the entire tumor mass. For this purpose we developed a set of modulators. A modulator is a plastic wheel made of steps of different thickness that permit the energy modulation of the pristine Bragg peak producing the so-called Spread Out Bragg Peak

(SOBP). Figure 4 shows the SOBP obtained with the first prototype of the modulator wheel. Actually a set of modulator wheels (10, 12, 15, 20, 25 mm SOBP) has been tested and currently used in clinical practice. Proton beam energies lower than 62 MeV are obtained inserting PolyMethylMethAcrylate (PMMA) range shifters of different thickness along the beam path. Experimental depth dose profiles reported in Fig.5 and Fig.6, have been compared with a Monte Carlo simulation application, using the Geant4 toolkit, developed by us. Results of this comparison are extensively reported in [5].

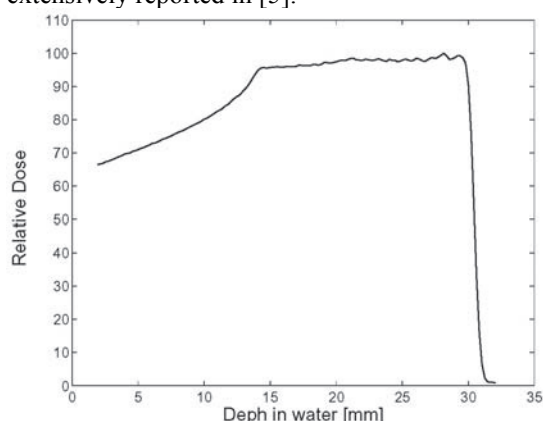


Figure 4: Spread Out Bragg Peak obtained with a modulator wheel.

4 THE TREATMENT PROCEDURE

As explained before, protons allow a high dose deposition in a small deep-seated space, with precise irradiation of the target. The radiotherapist therefore needs to know the exact position of the tumor. To do that, tantalum clips are placed around the lesion on the outer sclera by the ophthalmologist, generally very close to the tumor. The surgeon also defines the tumor position and measurements, as transverse and longitudinal base diameters, elevation or height, distance to the optic disk, to the macula, to the limbus. He also makes the radiotherapist know about the eye measurements (axial length, transverse diameter, thickness of the coats, distance between anterior cornea and posterior lens, limbus diameter) and clips measurements (distance between clips to limbus, clips to clips and clips to tumor). The final result is the drawing of a precise fundus view model with tumor and clips locations. The ophthalmologist makes use of A-mode and B-mode ultrasound scan, retinal fluorangiography, wide-angle fundus photographs and, especially, surgical measurements to define all those parameters. He also informs the radiotherapist about the visual acuity of the effected as well as the fellow eye, the presence of exudative retinal detachment, ocular pressure and all other information he considers to be significant. A total retinal detachment or the presence of a glaucoma are contraindications to a conservative approach. Together with the diagnosis, for all patients a systemic staging is provided through a total body spiral Computed Tomography (CT) scan to exclude metastatic

disease, which is, obviously, another contraindication. After this first phase, the patient arrives at the INFN-LNS, where the workup by the physicist and radiotherapist begins. First of all, a fixation device is made by means of a customized thermoplastic mask and bite block, with the patient in a seated position (Figure 5).

The patient is invited to gaze at a light point and two orthogonal X-ray pictures (axial and lateral) are taken. This step is repeated 3-6 times with the patient gazing at different points, depending on the tumor position in order to make the physician sure about the position of the clips. A measurement of the eyelid thickness and slope is also needed for the planning procedures. All the informations are then elaborated by means of three-dimensional therapy planning program EYEPLAN, developed at the Massachusetts General Hospital for eye tumor therapy using proton beams.

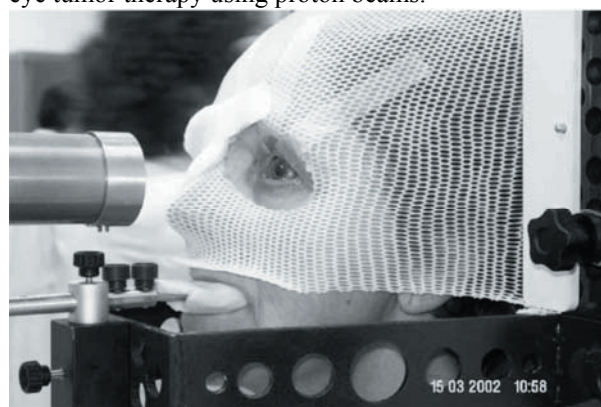


Figure 5: Thermoplastic mask and bite block.

Actually, the improved version of EYEPLAN, by M. Sheen [6], is used in our facility. This software schematically displays a model of the patient's eye, including the lens, optic nerve and fovea, where the tumor is finally drawn by means of the specified measurements and position reference.

A second simulation is performed on the first day of the treatment week, with the eye in the final position to verify and to accept the treatment. If the eyelids cannot be retracted completely outside of the irradiation field, they have to be calculated in the treatment plan. For uveal melanoma a total dose of 60 Gray Equivalent (GyE) is delivered in 4 fractions on 4 consecutive days, using a constant Relative Biological Effectiveness (RBE) of 1.1 over the modulated Bragg peak. Before each treatment fraction the eye position is verified and compared to the planned position. A video camera is directed to the eye to verify its position outside the treatment room during the irradiation. The treatment time is between 30 - 60 sec.

5 CLINICAL RESULTS

5.1 Patient data

Since March 2002, 78 patients with different ocular tumors have been treated at the CATANA facility. All patients had localized disease, with no systemic metastasis, and had specific indications for a conservative approach by means of proton beams, depending on their tumor size or location. Most of them suffered from uveal melanoma (92%), is the most common tumor of the ocular region in the adult. We have also treated other pathologies with proton beams, like conjunctival melanoma (2 patients), conjunctival rhabdomyosarcoma (1), eyelid carcinoma (1) and conjunctival Mucosa-Associated Lymphoid Tissue-Non Hodgkin Lymphoma (MALT-NHL) (1). Among the 78 patients, 51% were women and the 49% men. Patient age ranged from 14-81 years (mean 55.6).

5.2 Results

During the follow-up, the first data regarding local tumor control are available only after 6-8 months from the end of the treatment. Actually, we have the preliminary results of the follow-up for 52 patients at 6-8 months, and for 32 patients at 1 year. The local control is defined as a tumor shrinkage or cessation of growth at B-Mode ultrasonography, or as an increase of ultrasound reflectivity at A-Mode ultrasonography (a surrogate for tumor control). A size reduction, especially regarding the thickness of the tumor, was seen in 39 patients (75%), while 13 patients maintain a stable dimensional lesion (25%). An increased A-Mode ultrasound reflectivity was detected in almost all patients. These data clearly show a tumor control, particularly for those patients with 1 year follow-up. No major side effects requiring eye enucleation have been detected: an exsudative retinal detachment at the time of the diagnosis was seen in 40% of the patients and it remains stable in about half of them. In 25 patients a new cataract formation related to the treatment, generally at the periphery of the lens, was diagnosed. About 40% of the patients still maintain a useful visual acuity. This is obviously not always possible, especially when the tumor infiltrated directly or is located close to the optic disc or the macula.

6 FUTURE DEVELOPMENTS

During the second half of the year 2004 the treatment room was moved in its final position inside the new irradiation areas of the LNS. The movement and reconfiguration of the room is now ultimate. Actually the medical physicists are completing the acceptance tests in order to verify each element of the treatment procedure. The first patient, in the new room, will be treated in April 2005. and the treatment sessions will continue at the rate of 4/5 session per year.

8 FUTURE DEVELOPMENTS

The preliminary results show an high percentage of local tumor control, despite the limited follow-up period, with a limited acute and subacute toxicity and visual outcome according to the previsions. The results are in agreement with those reported in the literature, regarding the treatment of uveal melanoma by means of hadrons.

Even if CATANA should not be the clinical answer for all the Italian patients affected by this kind of disease, it represents the first successfully Italian example of the collaboration between Nuclear and Medical Physicists together with Medical Doctors in fighting tumors with hadrons. CATANA is the first milestone in Italy through the extensive use of hadrontherapy in cancer treatment.

7 REFERENCES

- [1] D.W Miller et al., Med. Phys., Vol. XXII, N.11, 1995, pp. 1943-1954.
- [2] M. Fuss, L.N. Loredi, et al., Int. J. Radiat. Oncol. Biol. Phys., N.49, 2001, pp. 1053-1059.
- [3] G. Cuttone, G.A.P. Cirrone, et al., Particle, Journal of the Proton Therapy Co-Operative Group, N.28, July 2002, pp. 8-10.
- [4] International Atomic Energy Agency (IAEA). Technical Report Series N.398, 2000, pp. 135-150.
- [5] G.A.P. Cirrone, G. Cuttone et al., Proceedings of the IEEE NSS MIC 2003, pp. 26.
- [6] M.A. Sheen. Abstracts of XX PTCOG meeting at Chester, UK, May 16-18, 1994

DELAYED LUMINESCENCE AS A TOOL TO DISCRIMINATE BETWEEN NORMAL AND CANCER SKIN CELLS

F.Musumeci^{a,b,*}, A.Scordino^{a,b}, S.Tudisco^{a,b}, S.Privitera^{a,b}

a) INFN Laboratori Nazionali del Sud, Catania, Italy

b) DMFCI - Università di Catania, Viale A. Doria 6, 95125 Catania, Italy

** Corresponding author, e-mail: fmusumec@dmfci.unict.it*

Abstract

Abstract: The time resolved emission spectrum of delayed luminescence from human fibroblast and melanoma cells was measured. Noticeable differences both in the emission spectra, and in the time trend of the spectral components were found.

1. INTRODUCTION

In recent years, several researches were carried out with the aim of developing new techniques able to recognize in early stage malignant changes in human tissues. In fact, the use of the traditional diagnostic techniques to identify such pathologies in early stages is complicate and very expensive. Some authors used objective morphologic parameters in order to characterize the changes in tissue. Nevertheless, new non-invasive techniques are required such as optical diagnostic tools based on potential new information achieved after cells was exposed to light irradiation. In order to discriminate between normal and altered tissues, the common techniques used are infrared spectrometry [1] and, in many application, the spontaneous fluorescence analysis [2-5], also in connection with the study of the time resolved spectral components [6]. Several investigations are based on imaging tools in order to get the diagnostic information [7-10]. These attempts however, although important and very promising, have been not able to replace the traditional biopsy technique from its leading role as diagnostic reference. It is therefore important to search for more sophisticated detection procedures. In this respect several papers have recently demonstrated that the ultraweak delayed luminescence (DL) is closely connected to the differentiation stage of the biological system [11-13]. This connection has been justified suggesting a model which connect DL emission to the formation of soliton states inside the quasi uni-dimensional polymeric chains that constitute the cytoskeleton [14]. Recent reports on the DL from some solid state systems [15] have confirmed this connection between DL and structure of the emitting systems. Recently, we build up a very sensitive tool to study DL from biological systems after ultraviolet-A laser irradiation [16]. We report now our results on the time resolved spectral analysis of DL of human fibroblast and melanoma cells.

2. MATERIAL AND METHODS

2.1. Cell strains and Cell Culturing

Well defined cultured cell strains were used. Normal skin fibroblasts, and human white melanoma were purchased from the American Type Culture Collection (Rockville, USA). Foreskin derived normal human fibroblasts were a gift from Dr. Robert Zimmerman (Boston, USA). Normal cells were plated 1:2 and melanoma cells 1:10. Cells were frozen gently in liquid nitrogen in DMEM with 10% DMSO by using the cryopreservation apparatus from Biotech Research Laboratories (Rockville, MD, USA). Then frozen samples were transferred to the liquid nitrogen transport storage system. Cells were counted in triplicates in a haemocytometer from Neubauer (Flow Laboratories, Baar, Switzerland). For DL measurements cell samples were transported in liquid nitrogen from Lausanne to Catania. Before measurement the cells were thawed and finally diluted in phosphate buffered saline (PBS) up to a density of 4 million cells/ml and 150 μ l of cell suspension was placed directly in the measurement chamber. Mean values of five independent experiments with standard deviation are given.

2.2. Ultraweak Delayed Luminescence Spectroscopy

In order to measure the DL of cell cultures an improved version of a previous set-up [16] was used. In short, this equipment is able to detect single photons and has a very low background signal; the optics of the system are constructed for samples of small dimensions and, in spite of that, to have signals well discriminated from the background and from the luminescence arising from other parts of the device itself. The samples, with a volume of about 150 μ l, confined by surface strength in a hemispherical shape, were placed on the upper side of a horizontal quartz window. The background signal, of the order of ten percent of the total one, originating

from the device as well as from the culture medium was measured apart and subtracted from the signal of the samples. An electric heater, allows to change the sample temperature from 10°C (heater off) to 35°C and maintains the temperature within 1°C. The temperature value was measured by a digital thermometer (NIMEX NI600). As a light source a nitrogen laser (Laser Photonics LN 230C), characterized by a wavelength of 337 nm, a 5 ns pulse width and an energy of $100 \pm 5 \mu\text{J/pulse}$, was chosen. The laser power was sometimes reduced to prevent the dimpling of photomultiplier. The spectral analysis has been performed by a set of five broad band (about 80 nm FWHM) interference filters (Lot-Oriel 57530 / 50 / 90 / 610 / 30) put, in a suitable wheel, between the sample and the photomultiplier. The wavelength λ_{emiss} corresponding to the maximum filter's transmittance was 460, 509, 567, 645, 686 nm, respectively. A multi-alkali photomultiplier tube (PMT) (Hamamatsu R-7602-1/Q), cooled down up to -30°C , selected for single photons counting, was chosen as a detector. The detector was placed as close as possible to the sample which resulted, from a geometrical point of view, in a total efficiency of nearly 8%, an order of magnitude higher than obtained with most of the previous systems. During the laser pulses, the photomultiplier has been protected by an electronic gate. The detected signals were acquired by a Multi-channel Scaler (MCS) (Ortec MCS PCI), able to collect analogical or logical signals as a function of time, with a minimum dwell time of 200 ns.

3 RESULTS AND DISCUSSIONS

It was shown, in the last few years, that light-induced ultraweak photon emission relaxation dynamics are closely connected to the functional state of the investigated biological system [17-18]. A recent paper illustrates a remarkable difference between the intensities of the DL from normal fibroblasts and tumor cells [19]. Nevertheless the intensity is an extrinsic parameter depending on various factors which can lead to remarkable differences in the determination of ultraweak photon yields. Therefore it is important to include in the analysis other parameters, as the time trend and the spectral distribution of DL, in order to get further information.

Based on this aim we have determined, in the present study, the time trend $I(t)$ of the spectral components of the DL emission spectrum, coming from human fibroblast and melanoma cells. These measurements have been repeated several times with distinct cell culture samples in order to increase the statistical significance. The intensity $I(t)$ of luminescence is related to the number of excited level $n(t)$ which decay, in a radiative way, at time t by the expression $I(t) = -dn(t)/dt$. Starting from the experimental values of the

intensities $I(t)$ at time t , we can determine the values of the dimensionless function

$$P(t) = \left(\frac{dn}{n} \right) / \left(\frac{dt}{t} \right) = \frac{I(t)t}{n(t)} \quad \text{where} \quad n(t) = \int_t^\infty I(t') dt'$$

The $P(t)$ function curves, calculated in such a way, depend on the emission wavelength and/or the nature of the biological system. It was found (data not shown) that, according to some previous results obtained in some vegetable systems, the $P(t)$ curves relative to the spectral components with emission wavelength $\lambda_{\text{emiss}} > 550 \text{ nm}$ are identical inside the experimental errors, so the $P(t)$ curves of such components will be reported by their average value.

The overall result of this analysis is depicted in Fig. 1a. It appears that, in the longer time region ($t > 100 \mu\text{s}$), the various $P(t)$ trends tend to have similar values (inside the experimental errors), both for normal and tumor cells, so one can hardly distinguish between them. In contrast, in the shorter time region ($t < 100 \mu\text{s}$), the curves relative to fibroblasts and melanoma cells are quite different and dependent on the emission wavelength λ_{emiss} .

Another intrinsic parameter that could be used to develop a strategy of diagnostic discrimination is based on the measurement of the emission spectra.

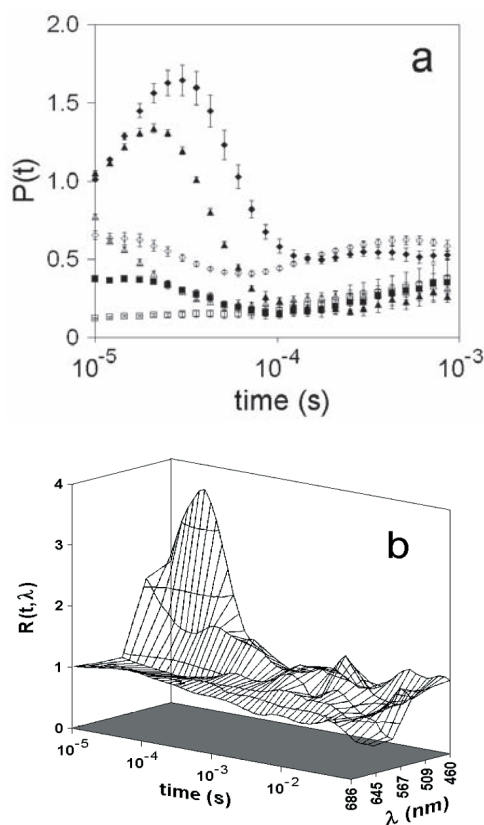


FIG. 1. a) Probability of decay of the spectral components of human fibroblasts (HF) and human melanoma (HM) cell cultures. ($\square$) HF, $\lambda_{\text{emiss}}=460$ nm, ($\blacksquare$) HM, $\lambda_{\text{emiss}}=460$ nm, ($\triangle$) HF, $\lambda_{\text{emiss}}=509$ nm, ($\blacktriangle$) HM, $\lambda_{\text{emiss}}=509$ nm, ($\diamond$) HF, $\lambda_{\text{emiss}}>550$ nm, ($\blacklozenge$) HM, $\lambda_{\text{emiss}}>550$ nm. b) Ratio between the emission spectral intensity of normal fibroblasts to melanoma cells.

Figure 1b shows the ratio $R(t, \lambda)$ between the emission spectral intensity $I(\lambda)$ of normal fibroblast to melanoma cells is reported as a function of the time and the emission wavelength. Accordingly to such data comparison between the emission spectra of fibroblast and melanoma cells depends strongly on the time window in which the measurement is performed, that is the time interval used to calculate the numerical integration of the $I(\lambda)$ function. By evaluating the emission spectra of fibroblast and melanoma cells, calculated on the average of the actual spectra in two different time intervals, 10-50 ns and 10-50 ms respectively it appears that the two spectra are quite different in the shorter time region while, on increasing the time range they converge to similar values. This difference between the relative intensities of the various spectral components could be used in order to distinguish the normal cells from the cancer cells [20].

4. CONCLUSIONS

In summary it has been also found that the differences between the DL from biological systems strongly depend on the time and the energy intervals in which measurements are performed. Our results shows that DL could be the basis for a new powerful non-invasive tool to determine biophysical changes within normal and tumor cells.

5 REFERENCES

- [1] Meurens M et al., "Breast cancer detection by Fourier transform infrared spectrometry," *Vibrational Spectroscopy* 10 (2), 341-346 (1996).
- [2] Wang CY et al., "Diagnosis of oral cancer by light-induced autofluorescence spectroscopy using double excitation wavelengths," *Oral Oncology* 35 (2), 144-150 (1999)
- [3] Panjehpour M et al., "Laser-induced fluorescence spectroscopy for in vivo diagnosis of non-melanoma skin cancers," *Laser Surg Med* 31 (5), 367-373 (2002)
- [4] Weingandt H et al., "Autofluorescence spectroscopy for the diagnosis of cervical intraepithelial neoplasia" *BJOG* 109, 947-951 (2002)
- [5] Mayinger B et al., "Endoscopic light-induced autofluorescence spectroscopy for the diagnosis of colorectal cancer and adenoma," *J Photoch Photob* B 70 (1), 13-20 (2003)
- [6] Pradhan A et al., "Steady state and time-resolved fluorescence properties of metastatic and non-metastatic malignant cells from different species," *J Photoch Photob* B 31 (3), 101-112 (1995)
- [7] Chwirot BW et al., "Ultraviolet laser-induced fluorescence of human stomach tissues: Detection of cancer tissues by imaging techniques," *Laser Surg Med* 21 (2), 149-158 (1997)
- [8] Frimberger D. et al., "Autofluorescence imaging to optimize 5-ala-induced fluorescence endoscopy of Bladder carcinoma," *Urology* 58, 372-375 (2001)
- [9] Kobayashi M et al., "Detection of early gastric cancer by a real-time autofluorescence imaging system," *Cancer Letters* 165 (2), 155-159 (2001)
- [10] Izuishi K et al., "Autofluorescence endoscopy images of pancreas cancer: Report of a case. *Hepato-Gastroenterology*," 50, 366-367 (2003)
- [11] Scordino A et al., "Influence of the presence of atrazine in water on the in-vivo delayed luminescence of *Acetabularia acetabulum*," *J Photoch Photob* B 32, 11-17 (1996)
- [12] Triglia A et al., "Delayed luminescence as an indicator of tomato fruit quality," *J Food Sci* 63, 512-515 (1998)
- [13] Niggli H.J et al., "Ultraweak photon emission in assessing growth factor efficiency using fibroblastic differentiation," *J Photoch Photob* B 64, 62-68 (2001)
- [14] Brizhik L et al., "Delayed luminescence of biological systems arising from correlated many-soliton states. *Phys Rev E* 64, 031902 (2001)
- [15] Wohlgenannt M et al., "Spin-dependent delayed luminescence from nongeminate pairs of polarons in pi-conjugated polymers," *Physical Review B* 66, 241201(2002)
- [16] Tudisco S et al., "Advanced research equipment for fast ultraweak luminescence analysis," *Rev Sci Inst* 74, 4485-4490 (2003)
- [17] Van Wijk R et al., "Light-induced photon emission by mammalian cells," *J Photoch Photob* 18 (3), 75-79 (1993)
- [18] Niggli H, "The cell nucleus of cultured melanoma cells as a source of ultraweak photon emission," *Naturwissenschaften* 83, 41-44 (1996)
- [19] Niggli HJ et al., "Laser-Ultraviolet-A induced ultraweak photon emission in mammalian cells", *Journal of Biomedical Optics* 10, 024006 (2005)
- [20] Musumeci F et al., "Discrimination between normal and cancer cells by using spectral analysis of delayed luminescence", *Applied Physics Letters* 86, 153902 (2005)

RADIATION EFFECTS IN CULTURED TUMOUR CELLS EXAMINED BY ^1H MAGNETIC RESONANCE SPECTROSCOPY

S. Grande^a, L. Guidoni^a, P.A. Lojacono^b, A.M. Luciani^a, A. Palma^a
V.I. Patti^b, L. Raffaele^b, A. Rosi^a, L.M. Valastro^b, V. Viti^{a,*}

a) *Dipartimento di Tecnologie e Salute and INFN Gruppo Collegato Sanita'*,
Istituto Superiore di Sanita', Roma, Italy.

b) *INFN Laboratori nazionali del Sud, Catania, Italy*

*Corresponding author, e-mail: viti@iss.it

Abstract

High Resolution Magnetic Resonance Spectroscopy (MRS) was applied to the study of the effects of proton irradiation on tumor MCF-7 cells. An increase in intensity of mobile lipid signals is observed in irradiated samples. The radiation quality affects noticeably the entity of the effects.

1 INTRODUCTION

Application of Magnetic Resonance Spectroscopy (MRS) in biomedicine has the advantage of being a non destructive technique that can be used also in vivo to gain information on cell and tissue metabolism.

This technique display many potentialities including its widespread use in medicine and the continuous technological advances to increase sensitivity.

MRS is then a good candidate to understand radiation induced alteration in cell metabolism, in particular after therapeutic radiation treatment.

Some signals, arising from selected metabolites have driven the attention of many groups aimed to exploit MRS potentialities in the field of cancer treatment [1-3]. Among these signals, those arising from the fatty acid chains of neutral lipids have been often studied in order to find a correlation among the spectral modification and the biological outcome after a therapeutic treatment [4-5].

Besides the effects on DNA and the related cell response, other radiation induced damages have driven the attention of radiobiologists.

In particular, the examination of the metabolic events following irradiation can be of great help in elucidating different mechanisms of tumor cell death after irradiation at therapeutic doses and their relative efficacy.

Aim of the present experiment (METABOLIC) is to exploit MR spectroscopy to study the effects of proton beams in cancer treatment, by means of identification of spectroscopic markers of radiation effects in tumor cells, possibly related to cell fate including death by apoptosis/necrosis or the onset of radio-resistance.

The experiments here described compare the effects of gamma and proton irradiation on cultured cells from breast human carcinoma.

2 EXPERIMENTAL

Tumor MCF-7 cells from breast human carcinoma were used. Cells were purchased from ATCC (Manassas, VA, USA) and kindly donated by Dr. Stefania Meschini, Istituto Superiore di Sanità, Roma (Italy). Cells were routinely grown in RPMI 1640 medium (Hyclone, Logan, Utah) supplemented with 10% fetal calf serum (Hyclone, Logan, Utah) and 50 $\mu\text{g/ml}$ gentamicyn. Cells were seeded in 175 cm^2 flasks, in 50 ml medium. Cells were kept in the culture flask until the MR measurement.

MRS experiments were performed on a packed sample of cells inserted in a coaxial tube system. ^1H MR spectra at high resolution were run at 400, 600 and 700 MHz on WB spectrometers (Bruker, Germany) to detect neutral lipid signals visible in cell suspensions (ML). 1D and 2D COSY spectra were acquired.

Cell systems were irradiated with the proton beam available at LNS at different depths along the 62 MeV proton beam, with single doses of 10 and 20 Gy.

The home built device to provide cell flask movements in the proper position in the plane perpendicular to the beam axis has been described elsewhere [6]. At present two flasks are required for a single MR sample. GafChromic films were applied on the surface of the flasks to control that all the cells growing adherent to the flask surface had been irradiated.

Gamma irradiation was performed with a ^{60}Co source, with single doses of 5, 10, 20, 40 Gy.

Cells were irradiated in the flasks at day 3 after seeding, and measured after different time intervals to detect metabolic mediated effects.

Cell survival, cell cycle analysis (FACS) and Annexin-V test for detection of apoptosis were performed in gamma irradiated cells.

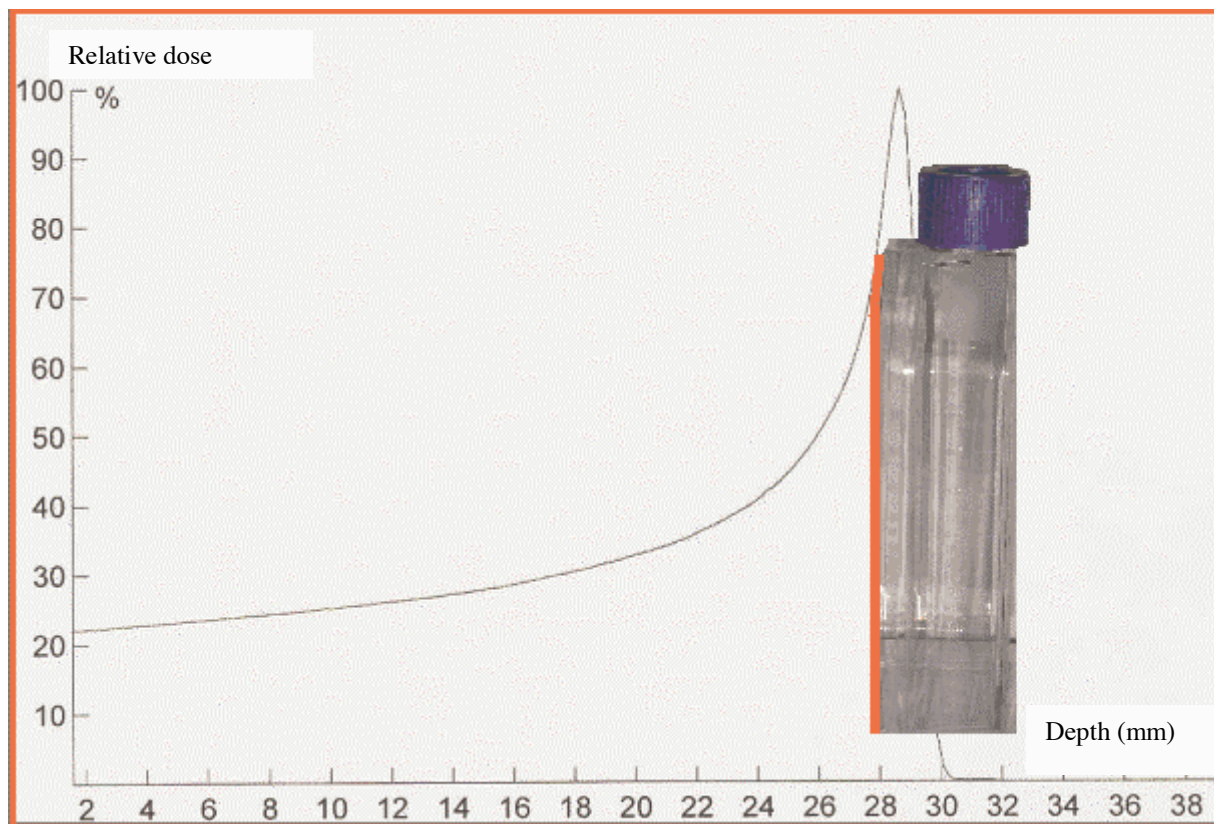


Figure 1 Idealized experimental set up for the proton beam irradiation, on Bragg peak, of MCF-7 tumor cells directly in the culture flask. Cells are grown on the flask surface marked by the red line

3 RESULTS AND DISCUSSION

Figure 1 shows an idealized experimental set up for cell irradiation at Bragg peak. Cells are irradiated

directly in the culture flask, where they grow as monolayers. This set up prevents undesired changes in lipid metabolism due to transfer of cell in other vials.

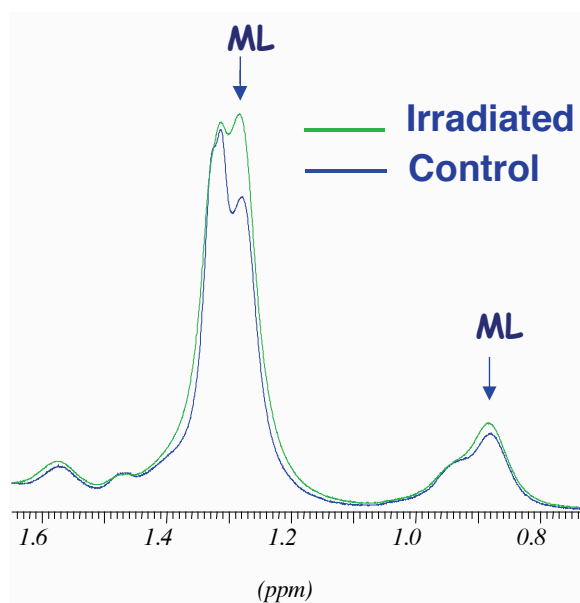


Figure 2 Mobile Lipids (ML) signal region of ^1H MR spectra of MCF-7 cell. Both irradiated (green line) and control (blue line) samples are shown. Spectra were acquired 44 hours after irradiation (10 Gy) with 62 MeV proton beam.

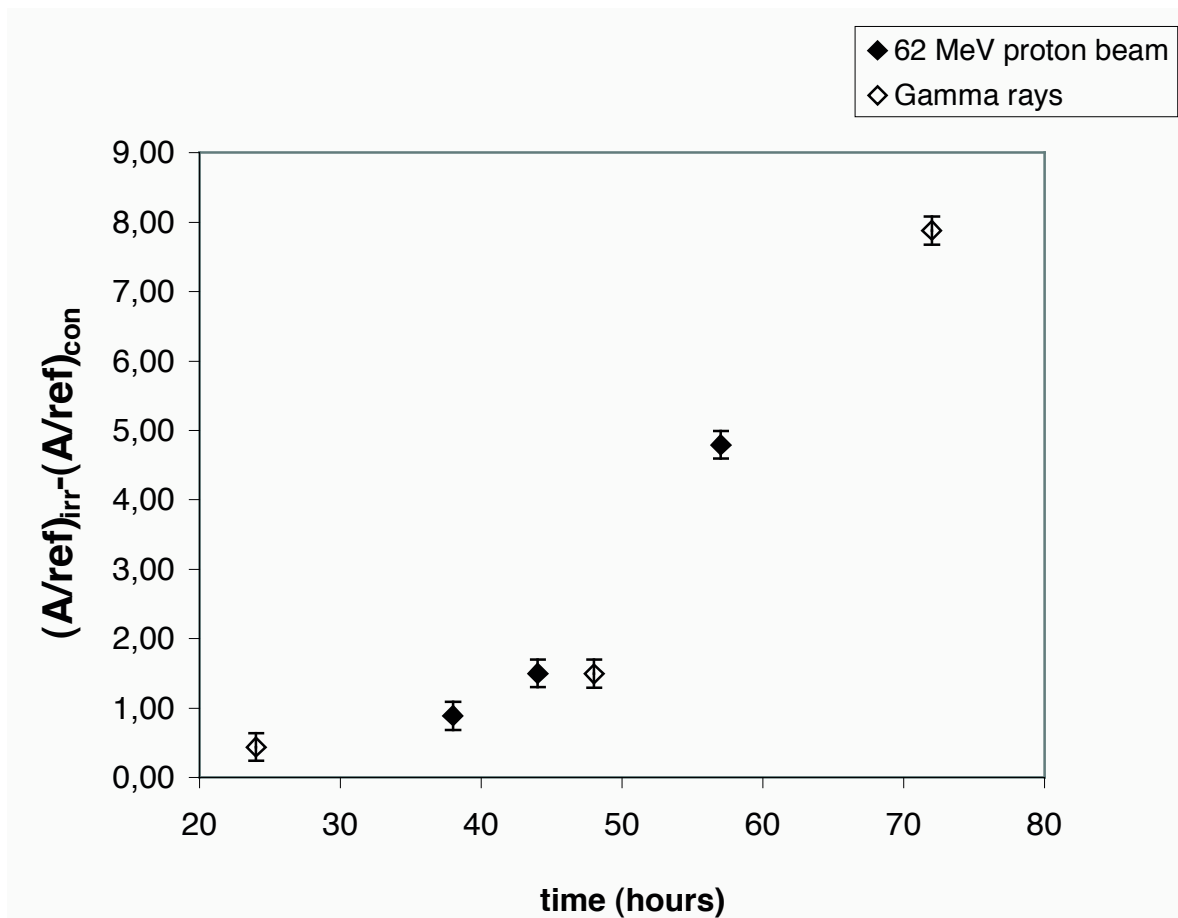


Figure 3. Difference between the mobile lipid signal (2D COSY experiments, peak A) measured in irradiated and control samples as a function of time after irradiation with either proton beams (10 Gy, $\blacklozenge$) or gamma rays (20 Gy, $\diamond$). Alanine plus Lysine cross peaks were taken as a reference for signal quantification (ref).

Range shifters are used for positioning the flask at different depths along the Bragg peak.

Signals from fatty acids of neutral lipids (mobile lipids, ML) visible in these tumor cells are affected by growth conditions, as their intensity changes when cells reach confluence slowing down cell proliferation.

All samples were then measured in similar proliferation conditions and the changes referred to corresponding control samples.

Figure 2 shows the variation in ML intensity of a cell sample 44 hours after irradiation at 10 Gy with proton beams at Bragg peak, with respect to the control one.

Intensities of ML signals were determined by integrating both bulk CH_2 peak at 1.28 ppm in 1D spectra (Figure 2) or the CH_3/CH_2 cross peak in the 2D COSY spectra (peak A) to provide independent measurements of the same molecular species. In both kind of experiments, an increase of ML signal after proton beam irradiation was observed.

Figure 3 shows two sets of measurements of ML intensities from 2D spectra (peak A) as a function of time after irradiation, in cells irradiated either with proton beams (10 Gy, $\blacklozenge$) at the Bragg peak, or with ^{60}Co (20 Gy, $\diamond$).

The change in ML intensity is related to the onset of metabolic changes in irradiated cells, becoming larger as time interval from the treatment increase.

The ML intensities increases observed in the region of low LET of the Bragg peak are very similar to those produced by gamma rays (not shown).

Though it is difficult to quantify the amount of the metabolic effect per cell, the difference in ML intensity reflects the neat increase in ML concentration. These results points to a LET dependence for the observed effects.

We have shown [7] that gamma irradiated cells undergo a cell cycle block in G2+M and G1, accompanied by a marked depletion of S phase.

Within this frame, increase in neutral lipids would be explained by decreased fatty acid consumption for phospholipid synthesis, due to the cell cycle arrest and S phase depletion.

Parallel measurements of the biological features following treatment with protons are in progress.

4 REFERENCES

- [1] C. Menard, I.C.P.Smith et al., *Int J Radiat Oncol Biol Phys* 50 (2001), 317.
- [2] A.A.Tzika et al., *Neuroradiology* 43 (2001), 169.
- [3] R.L. Somorjai et al., *J Med Biochem* 3 (1999) 24.
- [4] E.J. Delikatny et al., *Int J Cancer* 65 (1996) 238.
- [5] A. Rosi et al., *Magn Reson Med* 42 (1999) 248.
- [6] S. Grande et al. *LNS Activity Report* 2003, p 185
- [7] V.Viti et al., *Bollettino della SIRR "Radiazioni: ricerca e applicazioni"* Supplemento al Volume VII n.2, Agosto 2004, p. 94.

COMPARISON BETWEEN CARBON IONS AND γ -RAYS IN INDUCING MOLECULAR AND CELLULAR EFFECTS IN HUMAN FIBROBLASTS

F.Antonelli^a, M.Belli^{a,b,*}, G.Cuttone^c, V.Dini^{a,b}, G.Esposito^{a,b}, G.Simone^{a,b}, E. Sorrentino^{a,b}, M.A.Tabocchini^{a,b}

a) Istituto Superiore di Sanità, Roma, Italy

b) INFN, Sezione Roma1-Gruppo collegato Sanità, Roma, Italy

c) INFN Laboratori Nazionali del Sud, Catania, Italy

** Corresponding author, e-mail: m.belli@iss.it*

Abstract

Charged particles, such as carbon ions, are of interest in hadrontherapy and at the same time their use is an important tool for understanding the mechanisms of radiation action in mammalian cells. In this report we present preliminary results on the biological effects induced in AG1522 cells irradiated with 62 MeV/u carbon ions at the CS-LNS. The biological end points studied were cell inactivation and induction and repair of DNA double strand breaks (DSB), considered as the most relevant cell lesions.

1 INTRODUCTION

DNA double strand breaks (DSB) are considered the most important molecular lesions induced by radiation in mammalian cells. Failure to repair (or misrepair) radiation induced DSB is a potential cause of chromosome aberrations and cell death. The mechanisms that lead from initial DNA damage to cellular effects following irradiation remain an interesting area of investigation. Densely ionizing radiation gives more lethal events per unit dose than sparsely ionizing radiation does; this is thought to be related to differences in the spatial distribution of DNA damage that can affect its reparability [1]. Charged particles represent a useful tool to better understand the relation between radiation physical properties and their biological effectiveness.

In this study AG1522 human fibroblasts were irradiated with a carbon ion beam of 62 MeV/u at LNS (Catania). Beam dosimetry and irradiation conditions are reported together with the preliminary results relative to: a) the analysis of DNA fragmentation in the size range 5.7 – 0.023 Mbp in order to investigate on the DSB DNA induction and rejoining, b) the induction of cell inactivation and c) the enumeration of phosphorylated H2AX (γ -H2AX) histone foci at different post-irradiation times, in order to measure the induction and processing of DSB at low doses.

2 MATERIALS AND METHODS

2.1 Irradiation conditions

The fully stripped carbon ions from the Superconducting Cyclotron radiobiology facility of the LNS-INFN were used in the present work (62 MeV/u machine energy). Before impinging the sample, the beam passes through different types of materials. The energy distribution at the position of the cell monolayer

was simulated using the Monte Carlo simulation program TRIM [2]. Fluence uniformity in the sample position were measured by CR39 plastic track detectors. CR39 discs, 13 mm diameter and 1 mm thick, were placed at the sample position in the Petri dish, and were irradiated with a dose of 0.13 Gy in order to obtain a good count statistics with no or minimal pit overlapping. Eight independent irradiation were performed. After irradiation, each detector was etched in 6.25 N NaOH solution at 70°C for 4 h and the number of tracks included in several fields of 8.99×10^{-5} cm² area (at the center and at the edge of the Petri dish) were counted using an optical microscope equipped with a CCD camera. An ionisation chamber was used to monitor the dose received by biological samples.

Irradiation was performed in air with the biological sample (cells embedded in agarose plugs or cell monolayer) in vertical position attached on the 56 μ m thick mylar foil representing the bottom of the stainless steel Petri dish.

2.2 DNA fragment production (DSB measurements)

Confluent AG1522 human diploid fibroblasts embedded in agarose plugs were irradiated at 4°C to avoid DNA damage repair, with doses ranging from 40 to 200 Gy at a dose rate of about 10 Gy/min. After irradiation, plugs were lysed for 1 hour at 4°C followed by overnight incubation 50°C. Samples were stored in 0.5 M EDTA at 4°C.

For DNA DSB rejoining experiments, the cells were irradiated with 160 Gy and then incubated at 37°C for 30 or 120 minutes to allow repair of DNA damage. At the end of different repair times the cells were put on ice and processed as for DNA DSB induction. ⁶⁰Co γ -rays were used as reference radiation.

Calibrated Pulsed Field Gel Electrophoresis (PFGE) was used to analyze DNA fragments in the size range 5.7 – 0.023 Mbp. A Bio-Rad CHEF-DRIII system was

used, under two different conditions able to separate fragments in the size range 5.7 – 1.0 Mbp and 1.0 – 0.023 Mbp. The number of DNA DSB has been evaluated by the fragment number in many contiguous size interval as already reported [3, 4].

2.3 Cell inactivation

Log-phase AG1522 human diploid fibroblasts were irradiated as monolayer at room temperature. Doses up to 4 Gy were used, at a dose-rate of 1.0 Gy min⁻¹. After irradiation the cells were detached and plated at the appropriate density for survival determination. After about 12 days of growth at 37°C, samples were fixed, stained and scored for survivors (colonies with more than 50 cells). The dose-response curve for cell inactivation were obtained by fitting the experimental data with the linear model ($S = \exp(-\alpha D)$). ⁶⁰Co γ-rays were used as reference radiation.

2.4 H2AX foci formation

AG1522 human fibroblasts were irradiated in culture medium at 4°C, at a dose rate of about 1 Gy/min. After different times at 37 °C cells were fixed and permeabilized for immunofluorescence analysis, as described by Antonelli et al [5]. Briefly, cells were first incubated with anti-γ-H2AX antibody (Trevigen) for 2 h at 37°C in a humid chamber, then washed in PBS and incubated with Alexa Fluor 488-conjugated goat anti-rabbit secondary antibody (Molecular Probes) for 1 h at room temperature. After four washes in PBS Vectashield mounting medium (Vector Laboratories) was added. Fluorescence images were captured using a Leica Fluorescence Microscope System and γ-H2AX foci were counted by eye using a 100x immersion objective. For a single experiment, at least 400 foci were scored for each sample.

3 RESULTS AND DISCUSSION

3.1 Spectrometry and uniformity

The simulated average value of carbon ion energy at the cell entrance was 58.9 MeV/u and the energy resolution in terms of full width half maximum (FWHM) was less than 2.0 MeV/u. The corresponding average LET value in water was 39.6 keV/μm and the FWHM of the LET distribution was less than 1.0 keV/μm.

CR39 plastic discs have been used to measure the fluence of particles at the sample position as described in MATERIALS AND METHODS. In order to obtain particle fluence as a function of distance from the center of the circular irradiated area, several fields were counted at different positions along two perpendicular diameters and those at the same distance from the center were averaged. Fig. 1 shows two typical fields of the etched tracks. Uniformity was evaluated as the ratio of

the values measured at the edge and at the center of the CR39 disc. The value of this ratio was 0.99±0.04.

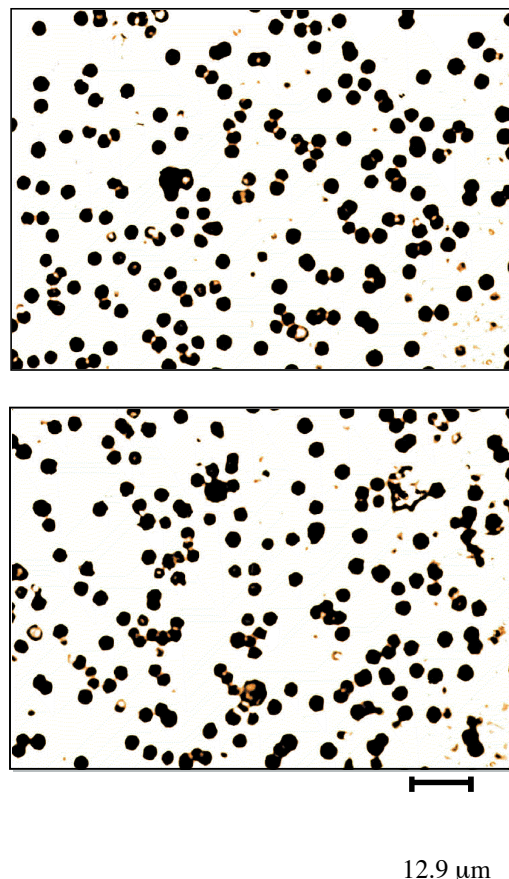
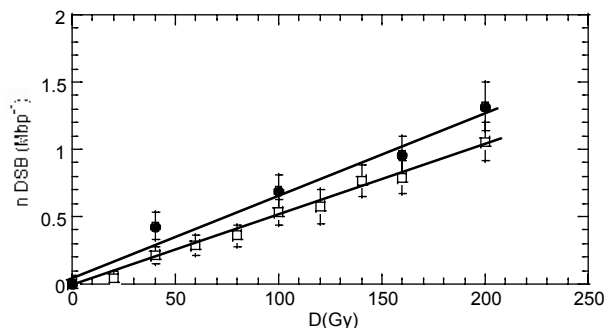


Figure 1: Photographs (magnification 100 ×) of the etched tracks in a CR39 disc irradiated with 0.13 Gy, showing a typical field at the center (top panel) and at the edge (bottom panel) of the Petri dish.

3.2 DNA DSB induction and rejoining

Fig. 2 shows the total number of DNA DSB, obtained by fragment counting in the size range 5.7 –



0.023 Mbp, plotted versus the radiation dose.

Figure 2: Dose-response curves for DSB induction. Each point is the mean and SE from two independent experiments. Carbon ions, solid circle; γ-rays open square

It can be seen that carbon ions are more effective than γ -rays. The DSB yields, together with the RBE value, calculated as the ratio y_c/y_γ , are reported in Table 1.

Table1: DNA DSB yields and RBE value.

	DSB YIELD ($10^{-9} \cdot \text{bp}^{-1} \cdot \text{Gy}^{-1}$)	RBE
γ -rays	5.27 ± 0.41	-
C-ions	6.46 ± 0.62	1.23 ± 0.15

Fig. 3 shows the preliminary results on the rejoining of DNA DSB induced by 160 Gy. It can be seen that DSB induced by carbon ions are rejoined more slowly than those induced by γ -rays. This is consistent with the presence of complex DSB more difficult to be rejoined. Further experiments are necessary to consolidate these data.

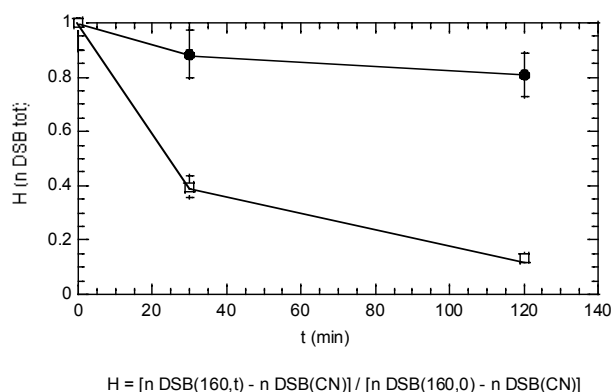


Figure 3: Rejoining time-course of DSB after a dose of 160 Gy. Carbon ions, solid circle; γ -rays open square

3.3 Survival curves

Fig. 4 shows the first result on cells inactivation.

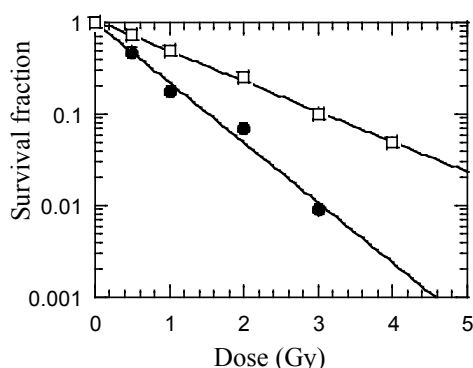


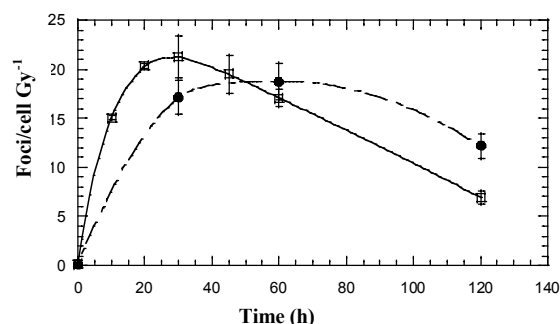
Figure 4: Dose-response curves for cell inactivation following irradiation with carbon ion beam (solid circle) and γ -rays (open square)

It can be seen that the surviving fraction after C-ions irradiation is less than that obtained after γ -rays irradiation. The RBE value, calculated as the ratio of the initial slopes (α_c/α_γ), is 2.2 ± 0.1 .

3.4 γ -H2AX foci formation

AG1522 cells irradiated with 1 Gy of carbon ions show γ -H2AX foci larger and more irregular in size compared to those observed after irradiation with γ -rays. Moreover the H2AX phosphorylation-dephosphorylation kinetics show several differences: the maximum number of foci counted is greater and is reached earlier after exposure to γ -rays than after carbon-ions irradiation; the number of carbon ion-induced foci at 2 h after irradiation is about two times higher than that induced by γ -rays (fig. 5). This finding could be a reflection of a more greatly clustered damage induced by carbon ions. Experiments are necessary to investigate on the γ -H2AX foci number at longer repair times (several hours), in order to evaluate the differences in the residual carbon ions-induced damage in comparison with that induced by γ -rays.

Figure 5: Comparison between H2AX phosphorylation-



dephosphorylation kinetics after irradiation with 1 Gy of γ rays (open square) or carbon ions (solid circle). Results were obtained by scoring the number of γ -H2AX foci

4 ACKNOWLEDGMENTS

The authors thank the staff at the LNS-INFN for their assistance during irradiation at the CS.

5 REFERENCES

- [1] M. Belli et al., Adv. Space Res. 18 (1996), 73-82.
- [2] JF Ziegler et al., New York: Pergamon Press; ISBN 0-08 021603-X; 1985.
- [3] M. Belli et al., LNL-INFN (REP) - 182/2002, 89
- [4] M. Belli et al., Int. J. Radiat. Biol. 78 (2002), 475-482
- [5] Antonelli et al., Radiat. Res., in press

THE FABRICATION OF A MINIATURIZED PRISM-BASED SPECTROGRAPH IN THE TANDEM BEAM LINE OF LNS

Bart Volckaerts, Jurgen Van Erps, Pedro Vynck, Michael Vervaeke, Luigi Cosentino[°],
Paolo Finocchiaro[°], Alex Hermanne, Hugo Thienpont

Vrije Universiteit Brussel, Dept. of Applied Physics and Photonics (TW-TONA),
[°] INFN Laboratori Nazionali del Sud, Catania, Italy

Abstract

The fabrication of high aspect ratio micro-structures is a challenge that pushes today's micro-machining technologies more and more to their physical limits. In the framework of the SINPHOS (SINgle PHOTon Sensing) project we fabricated dedicated passive micro-optical elements to detect photons coming from a weak source like Delayed Luminescence of biological systems.

INTRODUCTION: SITUATION OF OUR ACTIVITIES

During the last decades the use of photonics brought plenty of prospects for innovation in numerous research domains and opened up different unexplored market opportunities [1]. Recently, with the advancement of micro-photonics fabrication and hybrid integration technologies, we see that micro-optical components and micro-mechanical positioning structures are combined with opto-electronic emitter and receiver devices to play a key role in optical sensing, in high definition display and projection systems, in minimally invasive medical technologies, in bio-photonics, in optical interconnection technologies and many others. This vast domain of applications is the major driving force behind relentless efforts to push the limits of present-day micro-photonics integration and packaging technologies. At the same time it has caused a revival in the world of micro-optical fabrication technologies, because the successful implementation of micro-photonics modules also requires passive micro-optical and micro-opto-mechanical structures (MOMS) with extreme optical specifications, and for which no fabrication technologies are as yet available. In spite of all the efforts by various research teams, the number of mastering technologies for monolithic, robust and replicable optical modules is rather scarce. To our knowledge only Silicon micro-machining, Deep Lithography with X-rays and laser ablation have been engaged up-to-now to combine high-quality optical surfaces and micro-lenses with micro-mechanical alignment features. An alternative candidate technology dedicated to the fabrication of 3D micro-opto-mechanical systems is Deep Lithography with Ions (DLI).

The idea behind DLI originated in the Department of Physics at the Friedrich-Alexander-Universität in

Erlangen where the proof-of-principle for realizing basic plastic micro-optical components was demonstrated with collimated proton beams [2]. Since 1996 the TONA Department at the VUB has been upgrading this unique technology for the fabrication of micro-optical structures dedicated to free-space parallel optical data-links and fiber-based interconnects [3,4]. At present, we are continuously improving its performance and extending its range of practical applications. Recently, in collaboration with the Laboratori Nazionali del Sud (LNS) in Catania and with the Physik-Department E12 of the Technische Universität München (TUM), we started respectively to investigate the potentialities of heavy ion particles (as opposed to protons which we commonly use at the VUB) and of strongly-focused proton beams (as opposed to collimated micro-beams) to extend the functionality and to improve the surface quality and the aspect ratio of our present-day micro-structures [5-12].

In general the DLI process consists of the following basic procedures. First an ion beam is used to irradiate an optical grade PMMA-sample, changing the physical and chemical properties of the material in the irradiated zones. As a next step a selective solvent is applied to develop the irradiated regions allowing for the fabrication of 2D arrays of micro-holes, rows of smoothly curved cylindrical micro-lenses and optically flat micro-mirrors and micro-prisms. Also alignment features and mechanical support structures can be fabricated using this development procedure. On the other hand, an organic monomer vapor is used to expand the volume of the bombarded zones through a diffusion process. This process permits the fabrication of stable spherical micro-lenses with well-defined heights [13]. If needed, both processes can be applied to different regions on a same sample.

DESIGN AND FABRICATION OF THE PRISM-BASED SPECTROGRAPH

In the framework of the SINPHOS (SINgle PHOTon Sensing) project we used Deep Lithography with Ions (DLI) to fabricate a prism-based spectrograph for the simultaneous measurement of time distribution and spectrum of photons coming from a weak source like Delayed Luminescence of biological systems. We designed the spectrum analyzer by making use of optical ray-tracing algorithms, in a form suitable for the fabrication using DLI. In particular the component, optimized for operation around 600 nm, consists of three fiber alignment grooves (140 μm wide), aspherical lenses (300 μm wide) to compensate the divergence of the light beam originating from the input fiber in one direction and finally a prism. The irradiations of this first prototype are performed at the irradiation facility of LNS, Catania, using a 5MeV/n Carbon ion beam. The output facet of the prototype shows a RMS value of the roughness (R_q) of 62nm with a standard deviation of 12nm over an analyzed area of 50 μm by 50 μm .

In figure 1a we illustrate a 3D pictorial sketch of our system, and finally in figure 1b we show a real picture of the first iteration prototype produced by means of DLI. This prototype features three independent input channels, in order to verify the homogeneity of the fabrication process.

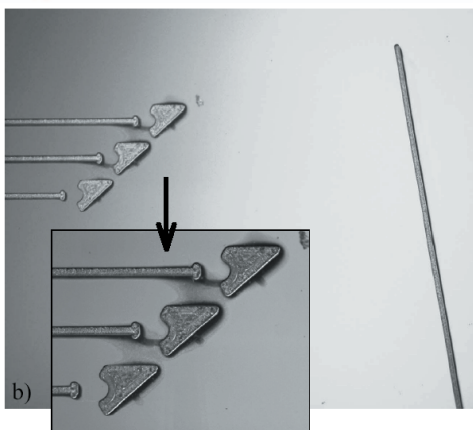
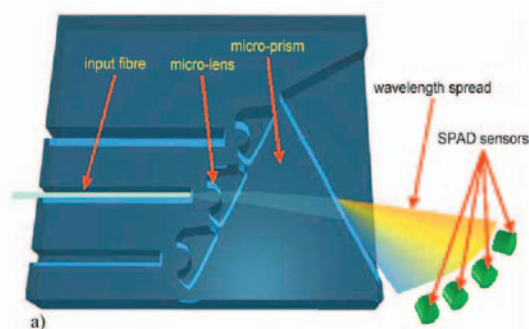


Figure 1a,b: The spectrographic components fabricated in the Tandem beamline of LNS

CHARACTERIZATION OF THE PRISM-BASED SPECTROGRAPH

In order to analyze the dispersion behavior of the prism, we decided to couple two light beams with different wavelengths into a single mode fiber (SMF) that is placed inside the alignment groove in front of the micro-lens. We used for these experiments a COHERENT argon laser with an output wavelength of 409 nm, and a LDS 635 diode laser with an output wavelength of 635nm. The mixture of the two wavelengths was obtained using an optical coupler FOCI C-NM-CQ-50-S-2250-85-FC/FC designed to combine the light coming from two fibers with a ratio 50/50. In order to detect the position of the two spectral spots after transfer through the prism, we placed a CCD camera behind the output facet of the spectrograph. After calibration we retrieved that the pixel size of our images corresponds to 4.39 μm . Due to the light diffusion at the optical interfaces of the component, it was not possible to separate two different peaks when both lasers were switched on. The distribution of light intensity, measured while switching only one laser on, smoothed and normalized to the same total intensity, is shown in figure 2 for the lower fiber alignment groove.

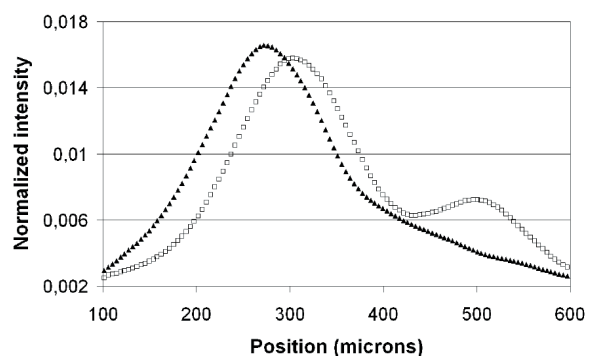


Figure 2: Distribution of light intensity of the two spectral components at the output facet of the prism for a light beam originating from an input fiber positioned in the lower alignment groove (Δ red light, $\circ$ blue light).

Similar graphs were obtained for the other grooves. Although the light diffusion on the surfaces produces broad distributions, it is remarkable that the spectral shift between the two distributions is clearly visible.

The distance between the two maxima for fibers positioned in the three grooves were 31 μm , 22 μm and 9 μm , respectively. In the future we plan to extend our

irradiation setup in the beam line of LNS to improve the surface quality of the inner walls and therefore to reduce the width of the output beams. This should allow us to clearly separate the spectral information from the input light beam that can be coupled into a linear array of Single Photon Avalanche Diodes (SPAT) detectors positioned at the output facet of the prism-based spectrograph.

OVERVIEW OF RELEVANT AND JOINT PUBLICATIONS

At the end of 2004 Pedro Vynck and Bart Volckaerts will finish their PhD at the TONA department of the VUB. Their work partially relates to the activities we performed during previous irradiation sessions at LNS concerning ion beam monitoring and Deep Lithography with heavy Ions. The outcome of their work will be subject of joint VUB-LNS publications in journal magazines.

P. Vynck, *Research and development of a beam line and irradiation set-up for Deep Lithography with Protons*, PhD dissertation, defense planned in November 2004.

B. Volckaerts, *Deep Lithography with Ions: A journey from ion interaction phenomena to high precision fiber connector components*, PhD dissertation, defended on October the 7th of 2004.

[1] S. Sinzinger and J. Jahns, *Microoptics*, Wiley-VCH, 1999.

[2] K.-H. Brenner, M. Frank, M. Kufner and S. Kufner, *H⁺-Lithography for 3-D integration of optical circuits*, Applied Optics, Vol.29, Nr.26, pp.3723-3724, 1990.

[3] H. Thienpont, C. Debaes, V. Baukens, H. Ottevaere, G. Verschaffelt, P. Tuteleers, P. Vynck, B. Volckaerts, M. Hanney, A. Hermanne, *Plastic Micro-Optical Interconnection Modules for Parallel Free-Space intra MCM Data Communication*, Proc. of the IEEE, Special Issue on "Short Distance Optical Interconnects for Digital Systems", Vol. 88, No. 6, pp. 769-779, 2000.

[4] B. Volckaerts, H. Ottevaere, P. Vynck, C. Debaes, P. Tuteleers, A. Hermanne, I. Veretennicoff and H. Thienpont, *Deep Lithography with Protons: a Generic Fabrication Technology for Refractive Micro-Optical Components and Modules*, Asian Journal of Physics, Vol. 10, No. 2, pp. 195-214, 2001.

[5] G. Dollinger, G. Datzmann, A. Hauptner, R. Hertenberger, H.-J. Körner, P. Reichart and B. Volckaerts, *The Munich ion microprobe: Characteristics and prospect*, NIMB, Vol.210, pp.6-13, 2003.

[6] L. Cosentino, P. Finocchiaro, A. Pappalardo, A. Hermanne, H. Thienpont, M. Vervaeke, B. Volckaerts, P. Vynck, *Ion Micro-Beam Diagnostics with Photodetectors*, Nuclear Instruments and Methods in Physics Research, Section B, Vol. 209, pp. 340-344, 2003.

[7] L. Cosentino, P. Finocchiaro, A. Pappalardo, A. Hermanne, H. Thienpont, M. Vervaeke, B. Volckaerts, P. Vynck, *Ion Micro-Beam Diagnostics with scintillators for Application of deep Lithography with Particles*, IEEE Transactions on Nuclear Science, Vol. 50, pp. 774-777, 2003.

[8] L. Cosentino, P. Finocchiaro, A. Pappalardo, A. Hermanne, H. Thienpont, M. Vervaeke, B. Volckaerts, P. Vynck, *Ion micro-beam diagnostics with photodetectors for Deep Lithography applications*, Proceedings of the 5th SHIM, Taormina, May 22-25, 2002.

[9] L. Cosentino, P. Finocchiaro, A. Pappalardo, A. Hermanne, H. Thienpont, M. Vervaeke, B. Volckaerts, P. Vynck, *Ion micro-beam diagnostics with photodetectors*, Proceedings of the 3th International Conference on New Developments on photodetection, Beaune, France, June 17-21, 2002.

[10] L. Cosentino, P. Finocchiaro, A. Pappalardo, A. Hermanne, H. Thienpont, M. Vervaeke, B. Volckaerts, P. Vynck, *Ion micro-beam diagnostics with photodetectors*, Proceedings of the IEEE Nuclear Science Symp. Norfolk, Virginia (USA), November 12-14, 2002.

[11] L. Cosentino, P. Finocchiaro, A. Pappalardo, A. Hermanne, H. Thienpont, M. Vervaeke, B. Volckaerts, P. Vynck, *Diagnostic Tools For Low Intensity Ion Micro-Beams*, 17th International Conference on the Application of Accelerators in Research and Industry CAARI 2002 November 12-16, 2002 University of North Texas Department of Physics Denton, Texas, USA.

[12] P. Vynck, B. Volckaerts, M. Vervaeke, H. Ottevaere, P. Tuteleers, L. Cosentino, P. Finocchiaro, A. Pappalardo, A. Hermanne, H. Thienpont, *Beam monitoring enhances Deep Proton Lithography: towards high-quality micro-optical components*, Proceedings of the Annual Symposium of the IEEE/LEOS Benelux Chapter. Amsterdam (N), November 2002.

[13] H. Ottevaere, B. Volckaerts, M. Vervaeke, P. Vynck, A. Hermanne, H. Thienpont, *Plastic Microlens Arrays by Deep Lithography with Protons: Fabrication and Characterization*, Jap. J. Appl. Phys., Special Issue on Micro-optics, 2004, accepted for publication.

NON-DESTRUCTIVE CHARACTERIZATION OF PICTORIAL LAYERS FROM ANCIENT ROMAN FRESCOES

*L. Pappalardo^{a,b)}, F. Amorini^{a)}, M. G. Branciforti^{d)}, F. P. Romano^{a,b)}, J. de Sanoit^{e)}, E. Scafiri^{c)},
A. Taormina^{d)}

- a) INFN, Laboratori Nazionali del Sud, LANDIS, Via S. Sofia, 44, 95123 Catania, Italy.
- b) CNR, Sezione di Catania dell'Istituto per i Beni Archeologici e Monumentali, Via A. di Sangiuliano 62, 95100, Catania, Italy
- c) Dipartimento di Fisica e Astronomia dell'Università di Catania, Via S. Sofia, 64, 95123, Catania, Italy
- d) Servizio Archeologico, Soprintendenza per i BBCCAA di Catania, Via L. Sturzo 62, 95100 Catania, Italy
- e) CEA LIST - Département des Technologies du Capteur et du Signal, CE-Saclay, 91193 Gif-sur-Yvette

* Corresponding author, e-mail: lighea@lns.infn.it

Abstract

In the present work the portable PIXE- α system realized within a collaboration between the INFN/LANDIS (Catania, Italy) and the CEA LIST (Saclay, France) has been used for the non destructive analysis of roman frescoes fragments belonging to different archaeological sites of Catania. Moreover, a portable XRD diffractometer has been used to individuate the mineralogical phases. It is shown that, by combining the two techniques, a fully quantitative analysis of the frescoes surface is possible. It is also shown that, comparing the XRF data to PIXE ones, information on stratigraphic sequence of layers components is possible.

1 INTRODUCTION

During the last decades an increasing interest has been devoted to the study of wall paintings (frescoes and “a secco”). In particular, the use of a given pigment has been the object of extensive investigation in order to determine the evolution of the technology and the aesthetic taste. Chemical and mineralogical analysis carried out on thin sections taken away from the artefacts have enabled to obtain a complete information on the various layers [1,2]. More recently, non-destructive methods applied with the use of portable instruments have been employed to characterize the surface of the paintings. Micro-Raman spectroscopy has shown to be one of the most appropriate methods to qualitatively identify the chemical compounds present as single microstructures in the surface [2,3]. Also, the PIXE method (Particle Induced X-ray Emission) has been successfully employed as a powerful tool for elemental analysis of pigments [4]. Recently portable PIXE systems have been developed [5]. They limit the analysis to elements of $Z \geq 11$. It must be noticed that PIXE enables quantitative analysis only if all the present elements are visible as X-ray peaks in the energy spectrum or, alternatively, if the stoichiometric

composition of the chemical compound related to the visible elements is exactly known. In these cases PIXE analysis, that in general involves several mm² surface area, can give the average composition in a quantitative way. This last property is useful when pigments are present as mixed elementary colours or when inorganic binders are presents (as CaCO₃). XRD (X-Ray Diffraction) portable systems have been used to determine “*in situ*” the mineralogical composition of the samples [4,6]. In the present work we will show how the complementary use of the PIXE and XRD portable non-destructive systems can give satisfactory information on the surface composition of wall paintings. In particular, we will apply the above techniques to the surface characterization of some fragments of roman frescoes. Finally, we will give an example that shows, in a simplified case, that the use of the PIXE and XRF (X-Ray Fluorescence) techniques can give information on the stratigraphic sequence of the painted layers.

2 THE SAMPLES

All the fragments belong to excavations of Soprintendenza ai Beni Culturali e Monumentali of

Catania (Italy). In particular they were found in the context of various Roman buildings dated back to the first and the second century A. D.

Affn2 (FIG.1a) is a fragment found in the 1982 excavations at the ex Benedictine Monastery where an important roman domus was discovered. Main dimension is 4.5 cm. The colour is red bright. A black zone is also visible.

Affn10 (FIG.1b) was found in the 2001 excavations of a roman criptoporticus in via Crociferi. The fragment main dimension is 5.2 cm. The colour is red but less brilliant than the Affn2 one. A grey zone is also visible

Affn12p (FIG.1c) was found in the 2001 excavations of a roman criptoporticus in via Crociferi but in a different stratigraphic context than the Affn 10. Main dimension is 4.5 cm. The colour is white.

Aff15 (FIG.1d) was found in the 2000 excavations of a roman criptoporticus in via Crociferi. Main dimension is 7.0 cm. The colour is brown.

Aff17 (FIG.1e) found in the 2000 excavations of a roman criptoporticus in via Crociferi in the same stratigraphic context than Affn10. The colour is bleu /green.

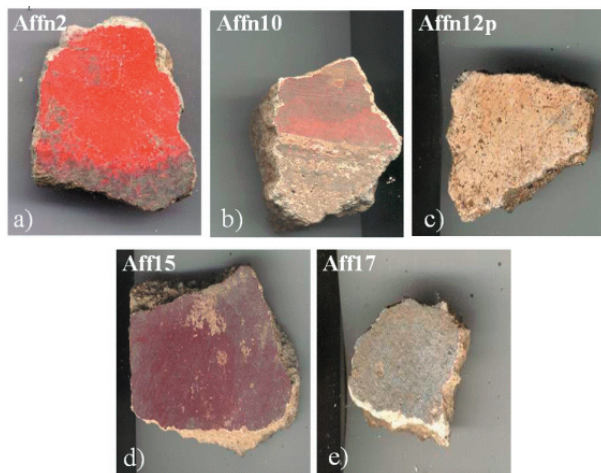


FIG.1 - Experimental set-up along LNS 80° beam line for the DPAA method. It is visible the collimator which defines the beam spot on the dummy coin

3 EXPERIMENTAL APPARATUS

The samples have been approached to the two portable systems: PIXE- α and the X-Ray Diffractometer (FIGs. 2, 3). The PIXE- α portable system has been described in various papers [5,6]. It is based on the use of a low intensity radioactive ^{210}Po alpha source, a high-resolution Si-drift detector and a portable electronic apparatus. The system has been realized in collaboration between the CEA LIST and the INFN/LNS. X-Ray spectra are acquired by means of an AMPTEK acquisition system. Qualitative and quantitative

analyses have been performed by means of the GUPIX [7,8] code in the “matrix calculation” option. Preliminary measurements on certified standards enabled to determine the geometrical factor “H”.

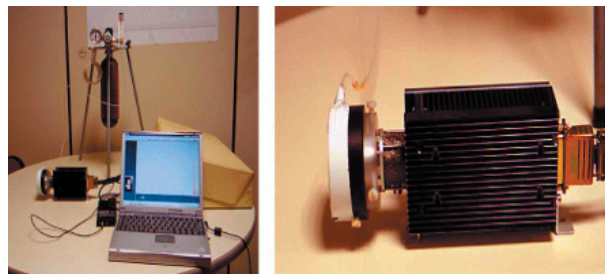


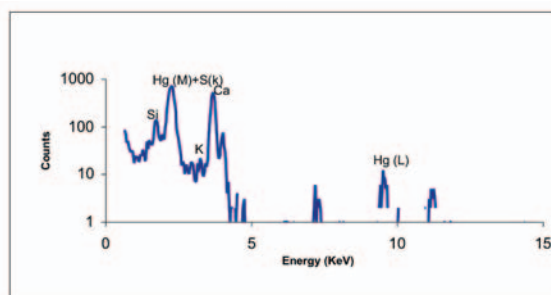
FIG.2 – The portable PIXE-alpha spectrometer.



FIG.3 – The portable XRD spectrometer.

In order to perform quantitative analysis, the GUPX software asks for the chemical stoichiometric composition related to the visible element lines on the spectra. The final results are presented in the compounds (oxides) form, normalized to 100 %. The Correction Factor (C.F.) gives the drift from 100 %. In our case, the overall relative uncertainty on the concentration value is less than 10 %. FIG. 4 shows an X-ray spectrum taken on the surface of the Affn2 fragment by using the PIXE- α system. The presence of a line corresponding to Hg (L) is evident at 9.98 keV; also the Hg (M) line is visible at 2.19 keV together with the S (k) line at 2.30 keV. Ca is also well represented.

FIG.4 – X-ray spectrum taken on the surface of the Affn2 fragment, by using the PIXE- α system.



The XRD portable apparatus is a commercial instrument (ASX-DUST supplied by ASSING). It is based on the motor controlled rotation of an X-Ray tube (30 kV and 0.2 μ A, iron anode) and a Si-Pin detector (AMPTEK). Windows limit the tube and the detector efficiency. The angle-resolution is about 0.3 degrees, which corresponds to a 1.6 % resolution on the reticular distance, at small angles. As can be seen, the resolution is rather poor and some ambiguity can be originated in the individuation of the mineralogical phases. However the qualitative analytical results of PIXE reduce strongly - by a factor of about ten - the above ambiguity. FIG. 5 shows the diffraction pattern of the Affn2 fragment; calcite and the cinnabar minerals are well visible.

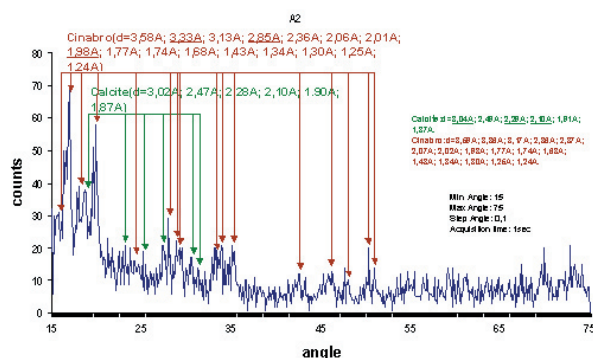


FIG.5 – Diffraction pattern of the Affn2 fragment.

Finally, in order to quantify the data, the results obtained by means of the mineralogical analysis are used to introduce in the GUPIX code the stoichiometric composition corresponding to the visible elements and, in turns, to compute absolute values of the chemical compounds concentrations.

The correctness of the procedure is checked by verifying that the total amount of chemical compound concentration is 100%.

Deviations are displayed by the correction factor (C. F.) value. In our case C. F. is very close to unity, ensuring that the totality of components present in the surface has been correctly quantified.

4 ANALYTICAL RESULTS

As previously described, the quantitative PIXE analysis was performed by using the GUPIX code. The invisible elements are introduced in the code ("matrix calculation" option) on the basis of the results of the XRD analysis. Table 1 summarizes the results.

5 STRATIGRAPHIC ANALYSIS OF AN OVERPAINTED FRESCO

In the present paragraph we will show, in a very simple case, that it is possible to obtain information on

the sequence of layers by combining two techniques involving different penetration depths. In the white-yellow surface of a roman fresco containing mainly Ca (fig. 6a), a layer of a modern pigment, Prussian blue ($\text{Fe}_4[\text{Fe}(\text{CN})_6]_3$), has been spread up. XRF data taken on this blue pigment by using a ^{109}Cd radioactive source (E_x 22.1 keV) show clearly the presence of Fe and Ca, (FIG. 6b). PIXE data, taken by using the PIXE- α portable system, show mainly the presence of Fe (FIG. 6 c). As expected, the results indicate that alpha particles are absorbed in the superficial Prussian blue layer and Fe X-Rays are detected. The 22.1 keV X-Rays reach the fresco surface inducing X-Ray emission in the elements present in it.

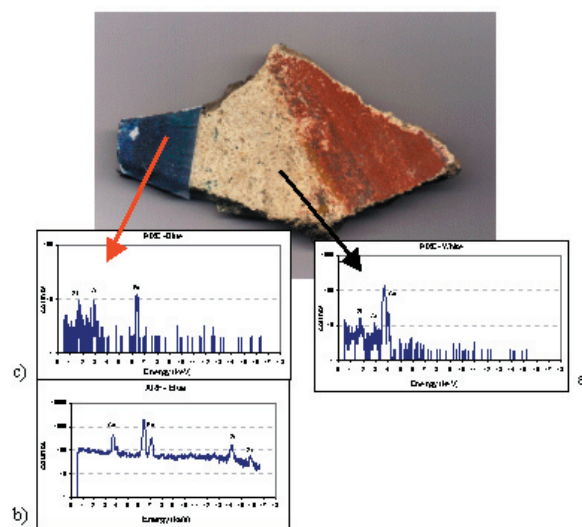


FIG.6 (a,b,c) - Roman frescoes fragment used for the determination test of Prussian blue; the PIXE-alpha spectrum related to the white pigment (a); the PIXE-alpha spectrum related to the blue pigment (c); the XRF spectrum related to the blue pigment (b).

5 CONCLUSIONS

The complementary use of the portable PIXE and the portable XRD systems has enabled to deduce the surface composition of some roman wall painting fragments found during the excavations of roman contexts in Catania (Italy). The pigments have been identified. In general, the obtained results are consistent with an "affresco" nature of the artefacts. This is mainly because the 100 % (within the uncertainties) of the chemical compounds are identified suggesting that only non-organic binders - in particular calcite - are present. In general earths, ochre or hematite have been used as pigments, however in a few cases, more rich pigments have been identified as the cinnabar of Aff15 and also the cinnabar mixed with a red heart of Affn10 and the Egyptian blue of Aff17. It is the first time that a quantitative indication of the mixing of pigment is possible in a non-destructive, "in situ" analysis. Finally an example has been given concerning the possibility of

distinguishing, in a simple case, the contribution of pigment over painted on a fresco surface.

the fit procedure and the comparison with the standard. Data are normalized to 100 %. The correction factor is given as C.F.

6 REFERENCES

- [1] H. Brecolaki, Electa, Elemond Editori Associati, L'esperienza del colore nella pittura funeraria dell'Italia preromana V-VII secolo a.C., Napoli, (2001).
- [2] D. Damiani et al., Archaeometry 48, 2 (2003) 341.
- [3] F. Delamare, in : F.Delamare, T. Hackens et B. Helly (eds.), Datation Caractérisation des peintures pariétales et murales, Ravello (1987) 333.
- [4] M. Uda et al., International Journal of PIXE 9, Nos. 3 &4 (1999) 441.
- [5] L. Pappalardo et al., Archaeometry 45, 2 (2003) 333.
- [6] L. Pappalardo et al., proc. of "Archaeometry 2004 Symposium", 3-4 May 2004, Zaragoza (Spain).
- [7] T.L. Hopman et al., Nucl. Instr. and Meth. B 189 (2002) 138.
- [8] J.A. Maxwell et al., Nucl. Instr. and Meth. B 95 (1995) 407.

Frescoes samples	Aff2	Aff10	Aff12	Aff15	Aff17
Colour	Red bright	Red	White	Brown	blue
CaCO ₃ (%)	60.2 ± 1.8	75.2 ± 1.8	90.4 ± 1.9	53.3 ± 1.6	56
Al ₂ O ₃ (%)	0.7 ± 0.2	3.5 ± 0.3	1.6 ± 0.2	3.5 ± 0.	6.8
SiO ₂	2.0 ± 0.3	10.9 ± 0.4	3.3 ± 0.2	11.7 ± 0.6	29
HgS	32.9 ± 3.3	2.8 ± 0.4	n.d.	n.d.	nd
Fe ₂ O ₃	nd	3.6 ± 0.8	n.d.	28.3 ± 1.0	1.6
CuO	n.d	n.d	n.d.	n.d.	2.6
Others	3.9	neglig.	4.3	4.2	4.0
C.F.	1.00	1.00	1.02	1.01	1.01
Pigments **	Cinnabar (32.9 %), Calcite	Red earth (ochre) mixed with Cinnabar (2.8 %); Calcite, Quartz.	Calcite.	Red ochre or Hematite, Calcite, Quartz	Egyptian blue (17 %), Calcite, Quartz

Table 1. Chemical and mineralogical determination on the analysed fragments by PIXE- α and XRD analysis.

*Others (Na, Mg, Al, P, S, Cl, K and O)

** Only the main components are reported. Calcite and quartz are to be considered as pigments and /or as plaster components.

Note: The average uncertainty in the absolute concentration determinations is less than 10 %. It is due to counting statistics,

SILVER CONTENT DETERMINATION IN THE CORE OF ANCIENT COINS THROUGH THE NON-DESTRUCTIVE METHOD DPAA (DEEP PROTON ACTIVATION ANALISYS)

*A.Esposito ^{a,b)}, G.A. Cirrone ^{a,b)}, S.Garaffo ^{c,d)}, G.Pappalardo ^{a,b)}, L.Pappalardo ^{b,d)}, F.Rizzo ^{a,b)},
F.P. Romano ^{b,d)}, S.Russo ^{b)}

a) Dipartimento di Fisica ed Astronomia Università di Catania, Catania, Italy

b) INFN Laboratori Nazionali del Sud, Catania, Italy

c) CNR, Istituto per le Tecnologie Applicate ai Beni Culturali, Montelibretti-Roma, Italy

d) CNR, Sez. di Catania dell'Istituto per i Beni Archeologici e Monumentali, Catania, Italy

** Corresponding author, e-mail: esposito@lns.infn.it*

Abstract

The new DPAA (Deep Proton Activation Analysis) method to perform non-destructive characterization of the ancient coin core will be illustrated. Quantitative experiments on the dummy coins and authentic Roman coins will be presented.

1 INTRODUCTION

Various studies [1,3] have evidenced the presence of effects that contribute to a meaningful variation of the alloy composition, especially in ancient coins. These effects seem to be related both to manufacturing techniques and to coin conservation environment during archaeological time. In particular, the coin surface composition can be not representative of the original alloy composition [4,5].

For example, in the case when the coins are copper-silver alloys, natural processes, such as corrosion and/or diffusion, can originate a compact enriched layer of silver on surface [3,5-6]. This mechanism can be responsible for the very beautiful aspect of numerous ancient coins. Generally, the thickness of the corroded surface layer may attain to 100 μm [2].

The different non-destructive methods usually used for this kind of analysis (X-Ray Fluorescence, Neutron Activation Analysis and Proton Activation Analysis) present some disadvantages because they are not able to distinguish between the surface and interior composition of the coins.

To solve this problem, the DPAA method has been developed which, by using energetic proton beam ($E_p=22.4$ MeV), allows to confine the analysis only in the interior of the coins without considering the surface contribution. The DPAA has been explained in ref. [4, 8].

2 EXPERIMENTS AND RESULTS

On the bases of the experimental results previously obtained [9], we are able to choose, for each element of

interest, the suitable radioisotopes whose production is all inside the sample.

In particular, in the present experiments we focused on the Ag content in the ancient coins.

Above all, quantitative experiments have been performed to demonstrate that we are able to overcome the surface contribution. So, four dummy coins were made up by alternating Cu and Ag foils of different thickness up to a total thickness $T=2000$ μm . The composition of the four dummy coins are summarized in Table 1.

Table 1: Compositions of the irradiated dummy coins.

Name	%Ag (IN)	%Ag (OUT)
DUMMY1	19%	0%
DUMMY2	19%	60%
DUMMY3	6%	0%
DUMMY4	6%	15%

In two dummy coins (DUMMY1 and DUMMY2) the Ag percentage was 19%, while in the remaining dummy coins it was 6% (indicated as %Ag (IN)). In order to simulate a surface enrichment, we placed in front of DUMMY2 and DUMMY4 a layer (about 50 μm thick), made up by alternating foils of Cu and Ag, whose silver content was about three times higher than the interior content (see %Ag (OUT)).

The samples were irradiated by proton beam having 40 nA of intensity during 120 minutes. The irradiation was performed on 80° beam line along which the beam emerged on air through an aluminium window

(thickness=75 μm). The samples were positioned at 950 mm far from Al-window (see FIG. 2).

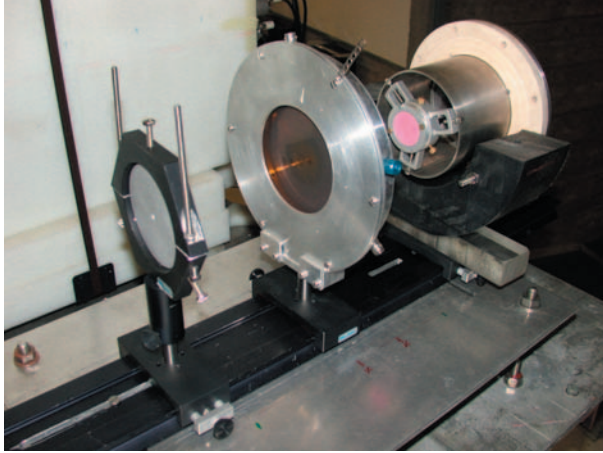


FIG.2 - Experimental set-up along LNS 80° beam line for the DPAA method. It is visible the collimator which defines the beam spot on the dummy coin.

The proton beam, accelerated at 22.4 MeV, was collimated by a collimator ($\varnothing=4\text{mm}$) and impinged on the samples with 19.2 MeV energy and 8 mm spot size.

After 2h waiting time, the gamma spectra for each one of the dummy coins were acquired, by means of a HPGe detector (diameter 52 mm, thickness 64.6 mm, FWHM=1.65 keV for the 1.33 MeV line of ^{60}Co source) during 2h counting time.

The activities, measured for each sample, were computed at “zero time”, i.e. at the end of the irradiation:

$$A^0 = A^w \cdot e^{\lambda t_w} \quad (1)$$

$$A^w = \frac{N_{\gamma}^{\text{det}} \lambda}{P_{\gamma} \eta (1 - e^{-\lambda t_c})} \quad (2)$$

where A^w is the activity at the beginning of the counting time, N_{γ}^{det} is the total number of γ -rays measured in the spectra, λ =decay constant, P_{γ} is the branching ratio, η is the detector efficiency, t_w the waiting time and t_c the counting time.

The DUMMY 1 was assumed as standard. Then, by comparing the activities A^0 , we obtained Ag percentage inside the other dummy coins, by using the following formula:

$$c_x = c_{st} \frac{\rho_{st}}{\rho_x} \frac{A_x^0}{A_{st}^0} \frac{Q_{st}}{Q_x} \quad (3)$$

where ρ_i and Q_i are the densities and the total proton number on standard and coin, respectively.

The results are summarised in Table 2. They compare satisfactorily with the nominal values of the Table 1, so that they confirm that the DPAA method limits the analysis only to the inner part of the sample.

Table 2: Measured Ag concentrations in the interior of the dummy coins.

Name	%Ag (IN)
DUMMY2	21.1 ± 0.6
DUMMY3	5.3 ± 0.3
DUMMY4	5.8 ± 0.4

Finally, we performed quantitative analyses on authentic silver coins. Five roman “folles” (see FIG.3), dated back ca 300 A.D., have been exposed to our proton beam.



FIG.3 – Roman coins “folles” measured through DPAA method.

The results on Ag content are summarized in Table 3. The XRF and PIXE values are reported in the same table (the XRF and PIXE errors are ca. 10% and 16%, respectively).

Table 3: comparison between DPAA, PIXE and XRF experimental data on ancient Roman coins.

	DPAA	PIXE	XRF
coin	%Ag	%Ag	%Ag
L1	1.01 ± 0.32	3.5	1.4
L2	1.03 ± 0.30	2.7	1.2
L7	1.83 ± 0.35	5.5	1.8
L9	1.48 ± 0.18	8.3	3.7
L12	1.75 ± 0.26	8.0	2.4

It is evident that the XRF and PIXE estimates of the Ag percentage are systematically larger than the ones obtained by means of DPAA method. The results

confirm the presence of the silver enriched layer on the surface of these ancient coins.

Then, our experiments show that the DPAA method is able to determine the true nature of the constituent metals of the coins, because it allows to estimate only the element content of the inner region of the ancient coins, overcoming the surface layers.

In the next future, the method will be systematically applied for the determination of Ag content in Roman silvered bronze coins.

3 REFERENCES

- [1] L. Beck et al., NIM B226, 1 – 2, (2004) 153.
- [2] F. Beauchesne et al., Archaeometry 30, 2 (1988) 187.
- [3] J. Condamin et al., Archaeometry 7 (1964) 98.
- [4] G. Pappalardo et al., proc. of the 3rd Congresso Nazionale AIAR, 12-13 February 2004, Bressanone, (Italy), to be published.
- [5] R. Klockenkamper et al., Archaeometry 41 (1999) 311.
- [6] L.H. Cope, in: E.T. Hall, D.M. Metcalf (Eds.), Methods of Chemical and Metallurgical Investigations of Ancient Coinage, RNS Special Publication No. 8, 1972, p. 261.
- [7] P.J. Daly et al., Nucl. Phys. 56 (1964) 322
- [8] A. Esposito et al., submitted to Nucl. Instr. and Meth. B.
- [9] F. Rizzo et al., LNS Activity Report 2003, pag.233.

AN IRRADIATION APPARATUS FOR DEEP PATTERNING OF BEAM SENSITIVE TARGETS BY MEANS OF HIGH-ENERGY ION BEAM

E. Mezzetti^{a,*}, D. Botta^a, A. Chiodoni^a, R. Gerbaldo^a, G. Ghigo^a,
 L. Gozzelino^a, F. Laviano^a, B. Minetti^a, A. Rovelli^b, A. Amato^b

a) INFN Sez. Torino and Dept. of Physics, Politecnico di Torino, Torino, Italy

b) INFN Laboratori Nazionali del Sud, Catania, Italy

** Corresponding author, e-mail: enrica.mezzetti@polito.it*

Abstract

The paper reports on a high precision equipment designed to modify over 3-dimensions (3D) by means of high-energy heavy ions the local properties of thin and thick films. A target-moving system aimed at creating patterns across the volume is driven by an x-y writing protocol that allows one to modify beam sensitive samples over micrometer-size regions of whatever shape. The issue of the local fluence measurement has been particularly addressed. The setup has been checked by means of different geometries patterned on beam sensitive sheets as well as on superconducting materials. In the last case the 3D modification consists of amorphous nanostructures. The nanostructures create zones with different dissipative properties with respect to the virgin regions. The main analysis method consists of magneto-optical imaging that provides local information on the electrodynamics of the modified zones. Features typical of non-linear current flow hint at which pattern geometry is more functional to applications in the framework of nanostructures across superconducting films.

1 INTRODUCTION

High-energy ions modify the 3D structural properties of a large class of thin and thick film systems [1, 2]. The confinement of the ion-affected region at micrometric scale allows one to address different issues: for example to simulate local damage on materials, to modify magnetic material properties and finally, in superconductors, to confine external excitations (for instance field-, particle- or photon- induced) [3]. In particular, in superconductor films, the 3D modification consists of a distribution of amorphous nanostructures [4]. These nanostructures set up zones with different dissipative properties with respect to the virgin regions: different field penetration and Meissner current distribution are created. In such a way an external perturbation will be localized through the change of a dissipative signal across the modified zone. Looking at these applications, we developed an apparatus to confine the high-energy heavy-ion beam into a micrometric size spot (down to 30 μm up to now) and to control with nanometric resolution the two-dimensional movement of the target with respect to the collimated heavy-ion beam. The apparatus was built at INFN-LNS.

2 THE EXPERIMENTAL SET-UP.

2.1 Main components.

A dedicated in-vacuum irradiation apparatus for high-

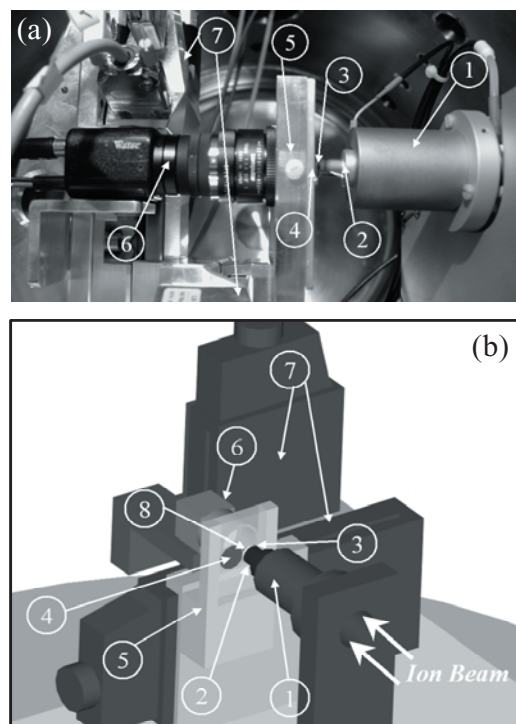


Figure 1 – (a) Image and (b) corresponding schematic drawing of the experimental arrangement of the irradiation set up for high-energy heavy-ion patterning: (1) Faraday Cup #1 – (2) Collimator – (3) Stainless steel disk with micrometric pinhole aperture – (4) Scintillating screen – (5) Lead-glass sample holder – (6) CCD camera – (7) Linear stages – (8) Sample.

energy heavy-ion patterning has been designed to be connected to the downstream part of the accelerator user lines. Figure 1 shows an image and the corresponding schematic drawing of the experimental set-up of this apparatus. Basic components are two cross-mounted MICOS Linear Stages LS-110 controlling the bi-directional movement of the target in a plane perpendicular to the ion beam direction. Each stage has an optical encoder that, once connected to the motor controller electronics Micos SMC Taurus, enables the target to move with a resolution of 15 nm over a total length of 28 mm. The target and a scintillating screen (Al_2O_3 , Morgan Matroc Chromox-6, 0.7 mm thick) are positioned on a 9 mm thick lead-glass sample holder fixed to the moving system. A control CCD camera (B/W CCD camera WAT-902H CCIR equipped with a lens of 16 mm and an extension tube of 20 mm exhibiting a viewing area of $6.5 \times 4 \text{ mm}^2$) is positioned close to the backside of the sample holder and is centered with respect to the ion beam direction. This CCD camera can visualize the ion beam spot through the scintillating screen. It is connected with a frame grabber NI-PCI 1411 installed into the control PC. Two Faraday Cups allow one to monitor and measure the irradiation fluences.

2.2 The fluence measurement system.

The irradiation-fluence measurement system consists of a suitably assembled Faraday Cup (Faraday Cup #1) and the related read-out electronics. A standard Faraday Cup (Faraday Cup #2) positioned upstream the apparatus is used for shutting down the beam during the irradiation as well as for providing reference beam current evaluation. The Faraday Cup #1 has been designed accordingly to the irradiation protocol requirements: it consists of a Faraday Cup with a threaded hole ($\varnothing$ 15 mm) in the bottom where a beam collimator with

changeable stainless steel disks with pinhole aperture can be screwed. The pinhole diameter, setting the beam spot size, is chosen on the basis of the irradiated pattern requirements. This Faraday Cup is positioned in front of the sample holder and is aligned with respect the beam direction (Fig. 1). During the beam characterization, before the sample irradiation, the beam passes through the threaded hole towards a scintillating screen fixed on the sample holder. When the stainless steel disk with the pinhole is fixed, a beam spot of known shape and size will be set for drawing the irradiation pattern.

Both the Faraday Cups are connected to an electronic board designed for this application (Fig. 2). It is equipped with two input channels: the first one is a current/voltage converter (gain factor = 1 nA/ 1 V) used for reading the reference Faraday Cup #2, the second one is a charge/pulse converter (1 pC/pulse) used for integrating the beam current during the irradiation. The typical beam current for the irradiation is lower than 1 nA. The charge/pulse converter has been checked for current values ranging from 1 pA to 10 nA. The linearity error is 0.002 % FSR. The electronic board is connected with a NI-PCI 6024E DAQ board installed into the local PC that also drives the motor controllers. This DAQ board is equipped with two 20 MHz 24-bit up/down counter/timers used for reading the integrated charge; it also has one 12-bit ADC and three 8-bit digital I/O ports employed in reading the ion beam current signal coming from the reference Faraday Cup #2 and in controlling the beam shutter, respectively.

3 THE IRRADIATION PROTOCOL.

3.1 Beam calibration and fluence evaluation.

The first step of the beam calibration is the beam tuning aimed at achieving a suitable homogeneity.

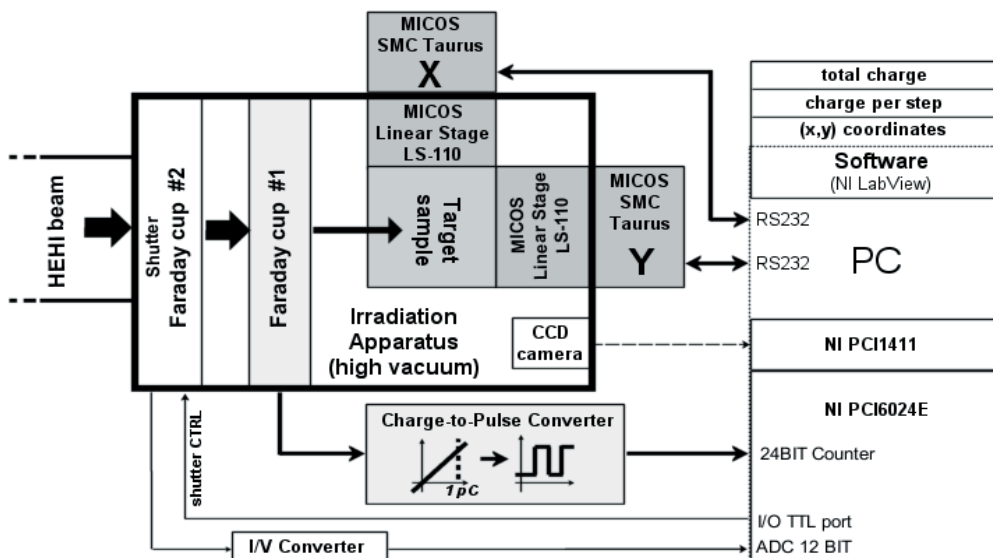


Figure 2 – Block diagram of the main components of the irradiation apparatus.

During this operation the ion beam, passing through the Faraday Cup #1 and the threaded hole in the bottom side, hits the scintillating screen positioned onto the lead-glass sample holder. The CCD camera visualizes the transmitted light. The output signal of the CCD camera is analyzed on the control PC and is used for a preliminary setting of the beam conditioning process. Then the beam shape and the ion fluence distribution are evaluated by irradiating an ion-beam sensitive polyester sheet (Fig. 3). For 4.2 GeV Au ions in the investigated range of fluence, for each (x,y) position the darkening level $d_l(x,y)$ is proportional to the local irradiation fluence. Once optimal beam conditions are steadily obtained, the stainless steel disk with the pinhole is screwed on the bottom side of the Faraday Cup #1. In this configuration the very small part of the beam passing through the pinhole aperture hits the scintillating screen and is visualized by the CCD camera. The user, by means of a digital zoom, can verify whether this micrometric beam spot is centered with respect to the previously measured millimetric beam spot. The (x,y) coordinates and the shape of the beam spot are then stored for the on-line cross check.

The irradiation fluence, ϕ , on the target is proportional to the charge, q_{hole} , released onto it:

$$\phi = q_{\text{hole}} / (n \cdot e \cdot A) \quad (1) \text{ where } n \text{ is the ion charge, } e \text{ is the elementary charge and}$$

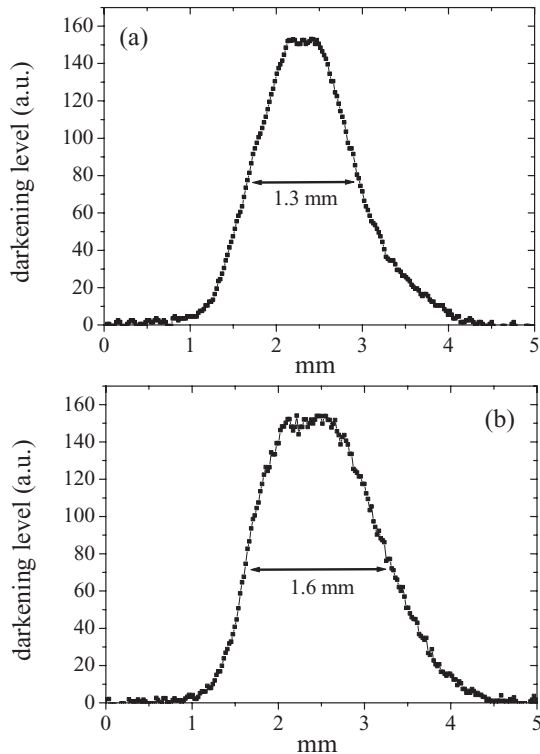


Figure 3 – Beam spot profiles evaluated from the darkening level of an ion-beam sensitive polyester sheet (see text) along the (a) horizontal and (b) vertical directions of movement.

A is the pinhole aperture area. From the two-dimensional darkening level $d_l(x,y)$ of the irradiated ion-beam sensitive polyester sheet we calculate the two dimensional charge probability density function $f(x, y)$:

$$f(x, y) = \frac{d_l(x, y)}{\sum_{i,j} d_l(x_i, y_j)} \quad (2)$$

Thus the relation between q_{hole} and the total released charge q_{tot} is:

$$\frac{q_{\text{hole}}}{q_{\text{tot}}} = \int \int_{\text{hole}} f(x, y) dx dy \quad (3)$$

The apparatus allows one to measure the ion current inside the Faraday Cup #1 and, by integration, the charge, q_{FC1} , released onto it. Therefore $q_{\text{tot}} = q_{\text{FC1}} + q_{\text{hole}}$, and the relation between q_{FC1} and q_{hole} results to be:

$$q_{\text{hole}} = q_{\text{FC1}} \left(\frac{\int \int_{\text{hole}} f(x, y) dx dy}{1 - \int \int_{\text{hole}} f(x, y) dx dy} \right) \quad (4)$$

It turns out that q_{hole} is about 0.2 % of q_{FC1} for a 70 μm pinhole aperture and becomes about 0.04 % for a 30 μm pinhole aperture.

After the beam calibration it is possible to start the irradiation procedure, consisting into combining the fluence evaluation with the x-y writing mode. The irradiation patterns are obtained by a sequence of linear steps: each x-y step is a fraction of the pinhole aperture diameter. This fraction is suitably chosen to draw patterns as smooth as possible. Two kinds of irradiations are possible: irradiation at constant dose and irradiation with a given dose profile. In the first case the charge per single step is constant, while in the second case the charge per single step follows a tailored law [5].

The velocity of the patterning process depends on the chosen ion beam current as well as on the irradiation fluence. The time of a single step movement is indeed negligible (typically 10^3 - 10^4 $\mu\text{m/s}$). Typical values of current and fluence are 650 pA and 10^{11} ions/ cm^2 , respectively. With these values, when the beam is collimated through a circular 30 μm wide pinhole, the patterning-process velocity is 1 $\mu\text{m/s}$.

3.2 Read-out and feedback controls

The movement of the two linear MICOS stages is controlled in feedback with the read-out signal of the Faraday Cup #1, by means of a NI Labview-based control software. This home-made software requires, as input parameters, the value of the total charge, a matrix containing the x-y coordinates of each step and the charge per step. As above mentioned the ion beam current output signal of the Faraday Cup #1 is converted into a frequency signal and then in TTL pulses. When the number of generated TTL pulses (i.e. pC of charge) reaches the charge per step previously set

by the user, the software gives the feedback signal (through two RS-232 ports) to move the linear stages on the next set of (x,y) coordinates. A new value of the charge per step can be set, if needed, until the total charge is reached.

4 EXPERIMENTAL RESULTS AND DISCUSSION

The x-y writing equipment has been tested by means of 4.2 GeV Au-ions at the Superconducting Cyclotron (CS) facility of INFN-LNS. In the first place the targets were the already mentioned polyester sheets. We patterned several x-y shapes with different geometries. The irradiation of these sheets is routinely performed before any change of pattern geometry.

0.3 μm thick $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ (YBCO) superconducting films were grown by means of pulsed laser deposition technique on yttria stabilized zirconia (YSZ) substrate, with a 10 nm thick CeO_2 buffer layer. The critical current density is about $3 \cdot 10^{11} \text{ A/m}^2$ at $T = 5 \text{ K}$. The YBCO films were irradiated with 4.2 GeV Au-ions. The beam was always directed perpendicular to the film surface. 4.2 GeV Au-ions cross the YBCO film and the CeO_2 buffer layer and implant in the YSZ substrate at a depth of 117 μm , corresponding to about 23% of the substrate thickness. The energy, E_p , released by the ions is almost constant along the whole YBCO film thickness and is high enough - $E_p \sim 35 \text{ MeV}/(\text{ion } \mu\text{m})$ - to induce columnar tracks. These extrinsic defects are insulating columns with a diameter of a few nanometers. In order to visualize into superconducting films the patterned regions whose signature is the induced modulation of the magnetic field, magneto-optical (MO) analysis was performed on the irradiated samples. The magneto-optical signal is obtained by coupling the superconductor with a ferromagnetic film whose domain orientation is decorated by the superconducting electro-dynamical signal. The change of the domain orientation is read as a rotation of a monochromatic light polarization plane [6]. In Fig. 4 MO images of different pattern geometries ("infinity", rings, spiral, triangles), observed by MO analysis, are reported. The resolution of the MO imaging with the used optical configuration is 1 μm .

Within this resolution we did not find any misplace of the irradiation patterns due to the automatic patterning set up, so we speculate that the accuracy of our writing system is either equal or even better than our MO resolution, it means at least 1 μm . Inside the superconducting condensate, the mentioned patterns behave as macroscopic defects. Many features typical of a non linear current flow (very similar to the charge flow in confined plasma) can be observed by MO technique, which indeed reveals long range disturbances of the normal component of $B(x,y)$. Typically with respect to the considered shape, characteristics magnetic flux jets are observed as flame-like patterns. These effects must be suitably controlled by changing the geometrical constraints.

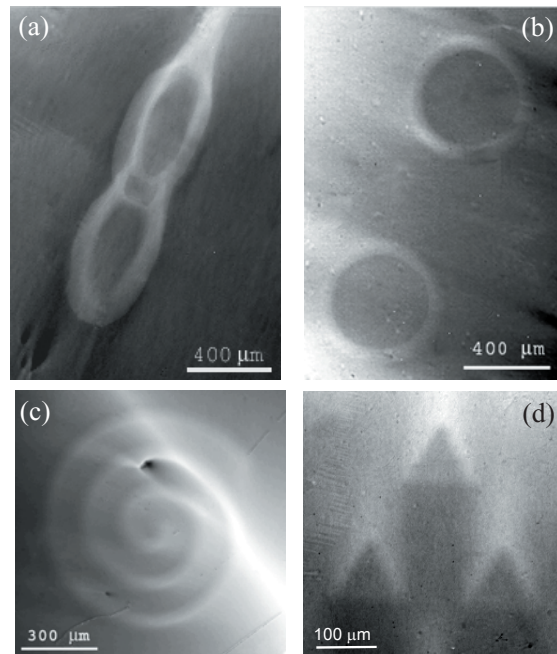


Figure 4 - Magneto-optical images of YBCO films after ion patterning with different geometries. These patterns were obtained by means of 4.2 GeV Au-ions ($\phi = 1.0 \cdot 10^{11} \text{ ion/cm}^2$) by collimating the ion beam through a circular 70 μm large pinhole (Figs. (a), (b), (c)) and through a circular 30 μm large pinhole (Fig. (d)). The images were taken at $T = 50 \text{ K}$ in remnant state after a field cooling in a magnetic field of 80 mT. Brighter grey levels: higher magnetic flux density regions (higher remnant magnetic field), darker grey levels: lower magnetic flux density regions.

5 ACKNOWLEDGEMENTS

We acknowledge the contribution of the I.N.F.N. under Na.St.R.I. (Nanostructure Radiation Induced) project. The support of the I.N.F.N.-L.N.S. staff during the irradiation runs is gratefully acknowledged

6 REFERENCES

- [1] E. Mezzetti et al., Phys. Rev. B 60 (1999) 7623.
- [2] F. Laviano et al, Phys. Rev. B 68, (2003) 014507.
- [3] E. Mezzetti et al., in "Magneto-optical Imaging" ed. by T.H. Johansen and D.V. Shantsev, NATO Science Series, Kluwer Academic Publishers, The Netherlands, (2004), p.197.
- [4] Y.Yan and M.A. Kirk, Phys. Rev. B 57 (1998) 6152.
- [5] G. Ghigo et al., Supercond. Sci. Technol. 17 (2004) 977.
- [6] F. Laviano et al., Supercond. Sci. Technol. 16 (2003) 71 and references therein.

EXPERIMENTAL AND 3D SIMULATION STUDY ON THE ROLE OF THE PARASITIC BJT ACTIVATION IN SEB/SEGR OF POWER MOSFET

G. Busatto^a, F. Iannuzzo^a, A. Porzio^{a,*}, A. Sanseverino^a, F. Velardi^a, A. Cascio^b, G. Currò^b, F. Frisina^b.

a) D.A.E.I.M.I., Università degli Studi di Cassino, Via G. Di Biasio 43, Cassino (FR), Italy

b) ST-Microelectronics – Stradale Primosole 50, 95100 Catania, Italy

** Corresponding author, e-mail: a.porzio@unicas.it*

Abstract

We present an experimental and 3-D simulation study which clarifies the role played by the parasitic BJT activation on the interaction between generated charge and electric field during ion impact in SEB/SEGR of power MOSFET. This activation is caused by the movement of the holes deposited during the ion impact and gives rise to a huge amount of charge that is sustained by avalanche multiplication. During SEGR phenomena this generated charge interact with the high electric field that is formed underneath the gate oxide thus causing damages to it. Whereas during SEB phenomena the generated charge causes a double injection phenomenon to take place that induces an electrical instability and, then, the MOSFET destruction.

1 INTRODUCTION

SEB/SEGR phenomena have been previously studied [1-9] indicating that SEB is related to the parasitic BJT activation and SEGR is more related to the amount of charge deposition during the heavy ion impact.

In this frame we present an experimental study, supported by 3-D simulation, which clarify the role played by the simultaneous presence of a high electric field and a large amount of charge in the gate and drain structure damage of a typical commercial MOSFET device. In order to gain useful insights we performed a behaviour comparison between a 200V commercial power MOSFET and its corresponding diode structure.

This structure was obtained by using exactly the same technological processes used to fabricate the MOSFET with the only difference that the process for implantation of source was not performed. In such a way we were able to obtain a structure practically equal to the corresponding MOSFET where the parasitic bipolar transistor is not present anymore. This structure obviously behaves like a power diode that can be easily biased by the external circuit.

2 THE EXPERIMENTAL PROCEDURE

The devices were irradiated at the Laboratori Nazionali di Legnaro (Padova) and at the Laboratori Nazionali del Sud (Catania) with ⁷⁹Br ions accelerated at energies varying between 223 MeV and 250 MeV.

This choice allowed us to achieve the Linear Energy Transfer in the epitaxial region high enough to generate a significant amount of charge within the device. Moreover, the longitudinal range was sufficient to ensure penetration into and through the active layers of the device. The schematic of the experimental circuit is reported in Fig.1. During the experiments the device was kept in the off state and a positive V_{ds} voltage was

applied so as to reverse biasing the N/epi-P+/body junction. In order to detect failure events the drain leakage current and the gate leakage current of the DUTs were continuously monitored. The current waveforms related to each ion impact are acquired and the related charges are numerically computed and processed by a statistical analysis. In particular we determine the gamma-like probability density functions (Γ pdf's) that best describe the correlated charge distributions. In this way we can perform a detailed study of the relationship between the generated charge, the ion energy and species, and the bias voltages. A complete description of the experimental procedure and the statistical analysis is reported in [11-12].

3 THE EXPERIMENTAL BEHAVIOUR WITH RESPECT TO SEB/SEGR

By employing the experimental setup of Fig.1 and varying the applied voltage V_{ds} we have detected the parameters of the Γ pdf that best describes the drain charge distribution. The relationship between the first moment of the charge distribution (average charge) of the drain pulses and the applied voltage V_{ds} is shown in Fig.2. In this figure the average charge is compared also with that one generated by the diode structure corresponding to the tested power MOSFETs.

The figure shows that the generated charge for the power MOSFET is much larger than the corresponding charge generated by the diode thus indicating that the parasitic bipolar transistor plays a major role in the charge generation mechanism. Regarding the Single Event Effect it is worth to outline that the diode structure exhibits no damage up to the maximum applicable voltage. On the other side the power MOSFET shows no damage for V_{ds} < 60V whereas for 65V < V_{ds} < 95V some damages are observed on the gate structure. An electrical failure analysis showed that

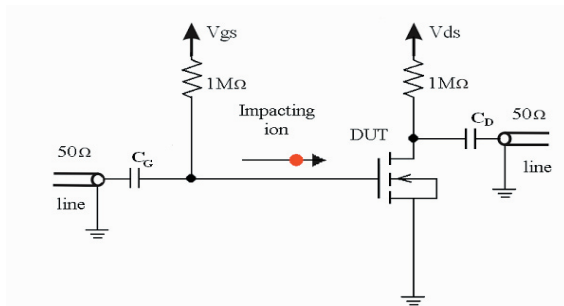


Fig.1: The schematic of the experimental test circuit.

the gate damage, present in all irradiated MOSFETs, decreases with time, i.e. a recombination-driven Room-Temperature annealing of gate charge is active. At $V_{DS}=95V$ the device was subject to a real Single Event Burn-Out after which it was severely and irreparably damaged.

4 THE RESULTS OF SEB SIMULATION

The above experimental results have been analyzed by means of 3-D finite element ATLAS simulations in order to get insights into the physics of SEB/SEGR in power MOSFETs.

The model used in the simulation have been chosen in order to include Shockley-Read-Hall and Auger recombination as well as the electric field mobility model accounting for doping, parallel and transverse electric field mobility dependencies. Moreover, the Selberrherr Model was used for the impact ionization for which the used parameters have been experimentally verified. Particular care has been dedicated to the model that describes the charge deposition on the device structure during the impact with the energetic particle. A Gaussian time evolution of the charge deposition and an exponential decay along the radius of the ion track have been assumed [13]. The time where the Gaussian has its maximum is $t_0=4ps$ whereas its standard deviation is $t_c=2ps$. The maximum concentration of the deposited charge is $10^{19}cm^{-3}$ and the decay constant for the exponential is $0.124\mu m$. The simulated circuit is reported in Fig.3.

The effects of the external circuit are accurately described by the lumped elements used for the boundaries at the external contacts. It is worth to outline that the MOSFET of Fig.3 corresponds to the portion of the elementary cell to be simulated where the impact is considered to takes place. Instead, the capacitor $C_D=20pF$ takes into account the capacitance of the body-drain junction that is placed in parallel to the single MOSFET elementary cell. L_d and R_d account for stray inductance of the external circuit and oscilloscope input resistance respectively. Due to its large value the coupling capacitance C_D of Fig.1 has been described by the V_d generator. The simulated waveforms of drain, source and gate current generated when the MOSFET is biased at 60V are reported in Fig.4. The drain current

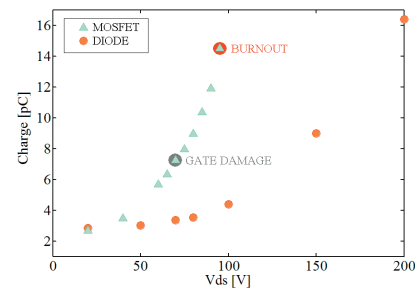


Fig.2: Mean charge vs V_{DS} biasing voltage for $V_{GS}=0V$ during the irradiation of 200V power MOSFET with ^{79}Br (250Mev).

(solid curve) exhibits two peaks. The current that causes the first rapid peak flows through the gate terminal (see dotted curve of Fig.4) and can be attributed to a displacement current due to the strong voltage variation that accompany the charge deposition. The second much slower current peak is originated by a current flowing through the source terminal (see dash-dotted curve of Fig.4). It starts after 18ps and has a duration of more than 3ns, not totally reported in Fig.4. For the sake of comparison the current obtained by the simulation of the diode corresponding to the MOSFET structure is also reported in Fig.4 (dashed curve).

Even if the test conditions are the ones used for the MOSFET simulation the amount of generated charge is much smaller for the diode. For the time being we can say that as a consequence of the charge deposition a large amount of holes are generated into the structure. The presence of a strong electric field within the JFET region causes these holes to be accelerated toward the gate oxide where they are diffused horizontally toward the body-drain junction. This charge flow causes the formation of a strong electric field that concentrate at the gate oxide in the JFET region. Due to the fact that the holes move at the saturated velocity the holes concentration at the body drain junction is initially very low and become significant after a ten of ps. After 18ps the hole current significantly increases into the channel region and causes the electric field to become very high into the gate oxide over the channel region. Moreover, a significant hole current is injected into the source N+ diffusion thus causing the activation of the parasitic bipolar transistor and, consequently, the drain current starts to increase and reaches its maximum after about 100 ps. After this point the current flow is sustained by the avalanche ionization that takes place due to the very high electric field across the body-drain junction in proximity of the MOSFET channel that keep the parasitic bipolar transistor in conduction. The importance of the impact ionization is outlined by the solid curve with circles of Fig.4 that refers to the simulated drain current waveform when the impact ionization model was not activated during the simulation. In this latter case the drain current rise is slower and its fall is much faster than the case when impact model is active thus indicating that impact

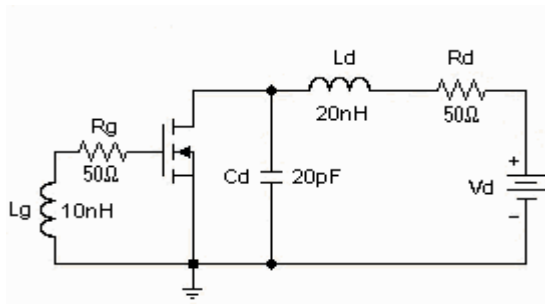


Fig.3: The schematic of the simulated circuit

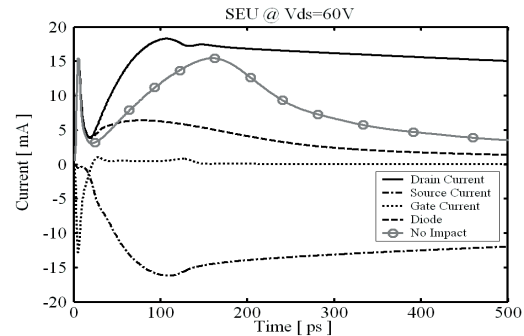


Fig.4: Simulated current waveforms for 200V standard MOSFET and corresponding diode at $V_{ds}=60V$ and $V_{gs}=0V$.

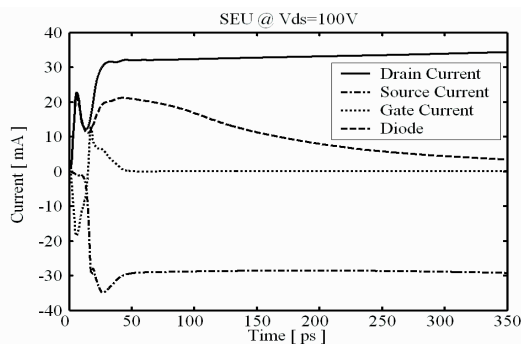


Fig.5: Simulated current waveforms for 200V standard MOSFET and corresponding diode at $V_{ds}=100V$ and $V_{gs}=0V$.

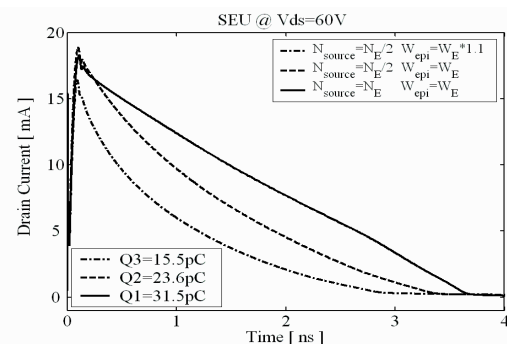


Fig.6: Simulated drain current waveforms for three type MOSFETs at $V_{ds}=60V$ and $V_{gs}=0V$.

ionization enhance the effects of the BJT activation. After the maximum current is reached the BJT starts to slowly turn-off due to internal recombination because it operates like an open base commutating BJT.

The simulation results indicate that a large electric field is present at the MOSFET channel together with a huge amount of holes that are forced to impact on the gate oxide. In this phenomenon the bipolar transistor activation helps in supplying more holes due to the impact ionization. On the other side the simulation results predict an even larger electric field in the corresponding diode structure whereas no gate damage is experimentally detected on those structures. Moreover, the simulation results indicate that the amount of generated charge and the phenomenon duration are much smaller for the diodes than the those observed for the MOSFET. This suggest us that a relevant amount of holes is required together with an intense electric field across the gate in order to cause a significant gate damage. As a first conclusion we can say that the simulation results are consistent with the experimental data for $65V < V_{ds} < 90V$ when gate damage are detected. As a matter of fact they prove that the generated charge is largely enhanced both by the parasitic BJT activation and by its operation in multiplication mode. Moreover, the contemporaneous presence of a large charge amount and a large electric field is required to produce a SEGR event.

The 3D simulation has been also used to study the burnout that was experimentally observed for

$V_{ds}=100V$. A resistance of $1M\Omega$ was placed in series to the output power supply in order to avoid convergence problems resulting from the tendency to the instability of the device in these conditions. The drain, source and gate currents are reported in Fig.5. The simulation indicates that the first part of the phenomenon is very similar to the one described in the previous section. The basic difference is observed after the second peak is reached. In fact in this case the drain current (solid curve) diverges instead of decreasing as it happened in the diode simulation in the same test conditions (dashed curve), or as it happened in the in the previous case (see solid curve in Fig.4).

The reason of this divergence can be explained by considering the simulation results for the electric field distribution not reported here for brevity. As a matter of fact they indicate that after 35ps conditions a double injection phenomenon takes place. It is related to the simultaneous presence into the epitaxial layer of a large current density and a large applied voltage that causes the formation a current induced space charge. This space charge causes the electric field to assume a large value at the interface between the epitaxial layer and the substrate thus causing impact ionization at this side. As a consequence the generated holes are accelerated toward the surface and originate a negative resistance condition that bring to the electrical instability. The above conclusion is consistent with the experimental observations that report the MOSFET SEB at these test conditions.

The simulation results also indicate that if the emitter efficiency of the parasitic BJT drops the collected charge to the drain drops too. In Fig.6 we compare the simulated drain current waveform of the 200V standard MOSFET with the same waveform of the MOSFET obtain from it halving the source doping; for this device the generated charge is $Q_2=23.6\text{pC}$ while the generated charge of the standard MOSFET is $Q_1=31.5\text{pC}$. For improving our analysis we have modified the further device increasing its epitaxial layer thickness. In Fig.6 is also reported the simulated drain current for this device; we note that the generated charge in the third device is $Q_3=15.5\text{pC}$, therefore reducing the emitter efficiency and increasing the epitaxial layer thickness the generated charge is reduced quite a lot. This simulated results are consistent with the experimental data that have showed how devices with shorter epitaxial layer thickness presented a larger quantity of generated charge. In Fig.7 we compare the generated charge for the 200V standard MOSFET (A type) with the generated charge for the 200V MOSFET with a longer epitaxial layer thickness (B type). The reduction of generated charge is showed with a lower sensitivity to the gate structure damage for the B-type MOSFET as showing in Tab.1 in which are reported the drain voltages corresponding to the gate damage experimentally observed.

5 CONCLUSIONS

On the basis of experimental data and simulation results, we demonstrated that the SEB is related to an electrical instability that takes place during parasitic BJT operation due to a double injection phenomenon correlated to the contemporaneous presence of a local large current density and an intense electric field. During irradiation at $V_{GS}=0\text{V}$, we observed also a gate damage that can be considered to be very similar to a SEGR event. For this phenomenon we founded-out that the gate damage can be attributed to the coexistence of a large amount of generated charge and an intense electric field that forms across the gate oxide due to the movement of generated holes underneath the oxide itself.

6 ACKNOWLEDGMENTS

The authors wish to acknowledge Prof. Migneco, Prof. Lattuada, Dr. Rifuggiato, and the management and the technicians of the INFN – Laboratori Nazionali del Sud for having permitted the experiment at the facility and for the precious assistance.

7 REFERENCES

[1] T. F. Wrobel, "On Heavy-Ion Induced ...," IEEE

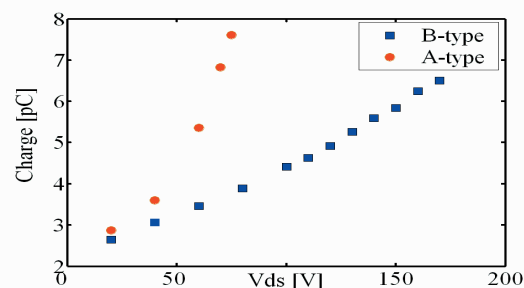


Fig.7: Charge vs voltage bias, A-type and B-type MOSFET

MOSFET TYPE	EPI-LAYER THICKNESS	V_{DS}^* DAMAGE VOLTAGE
A	HIGH	75-80V
B	LOW	180-185V

Tab.1: The damage voltage

- Trans. Nucl. Sci., NS-34, No. 6, pp. 1262-1268,1987.
- [2] J.H. Hohl, et al. "Features of ..." IEEE Trans. Nuc. Sci., Vol.36, No.6, pp.2260-2266 Dec., 1989.
- [3] E.G. Stassinopoulos, et al. "Charge Generation ..." IEEE Trans. Nuc. Sci., Vol.36, No.6, pp.1704-1711, 1992.
- [4] C.F. Wheatley, et al. "Single-Event Gate Rupture in ...," IEEE Trans. Nucl. Sci., NS-41, No. 6, pp. 2152-2159, 1994.
- [5] J.L. Titus, et al. "Experimental Studies ..." IEEE Trans. Nuc. Sci., Vol.46, No.2, pp.533-545, 1996.
- [6] Mouret, et al. "Measurement of ..." IEEE Trans. Nuc. Sci., Vol.17, No.4, pp.163-165, 1996.
- [7] M. Allenspach, et al. "SEGR and SEB ...," IEEE Trans. Nuc. Sci., Vol.43, No.6, pp.2927-2931, 1996.
- [8] L. E. Selva, et al. "On The Role of Energy Deposition in ...," IEEE Trans, Nucl, Sci., NS-46, No. 6, 1999.
- [9] J.L. Titus, et al. "A Study od Ion Energy ..." IEEE Trans. Nuc. Sci., Vol.48, No.6, pp.1879-1884, 2001.
- [10] S.K. Ghandi, "Semiconductor Power Devices", Wiley,1977.
- [11] F. Velardi, et al. "The Reliability ..." Microelectronics Reliability, Vol. 42, pp.1629-1634, 2002.
- [12] F. Velardi, et al. "Experimental Study..." Microelectronics Reliability, Vol. 43/4, pp.549-555, 2003.
- [13] J.L. Titus, et al. "A Conceptual Model..." IEEE Trans. Nucl. Sci., NS-40, No. 6, 1993.

List of Publications

Psalabura et al,

Studying in medium hadron properties with HADES

Acta Phys Polonica, vol 35, nr3, 1119

A.Kugler et al,

Charged hadrons and leptons identification at HADES

Acta Physica Slovaca, vol 54, nr 4, 1-10

L.Torrise, S.Gammino, A.M.Mezzasalma, A.M.Visco, J.Badziak, P.Parys, J.Wolowski, E.Woryna, J.Krása, L.Láska, M.Pfeifer, K.Rohlena, F.P.Boody

Laser ablation of UHMWPE-polyethylene by 438 nm high energy pulsed laser

Applied Surface Science 227, 164-174

P.M.Milazzo, G.V.Margagliotti, R.Rui, M.Sisto, G.Vannini, M.Bruno, M.D'Agostino, C.Agodi, R.Alba, R.Coniglione, A.Del Zoppo, P.Finocchiaro, C.Maiolino, E.Migneco, P.Piattelli, D.Santonocito, P.Sapienza, N.Colonna, F.Gramegna, P.F.Mastinu, I.Iori, A.Moroni

The reaction entrance channel and isotopic composition of fragment in a dynamical and statistical multifragmentation regime

Brazilian Journal of Physics, 34, 929

L.Láska, J.Badziak, F.P.Boody, S.Gammino, K.Jungwirth, J.Krása, M.Pfeifer, K.Rohlena, J.Ullschmied, J.Wolowski, E.Woryna

Laser production of highly charged ions

Brazilian Journal of Phys 34 (4B), 1615-1620

L.Torrise, L.Andò, S.Gammino, A.Picciotto, D.Margarone, L.Laska, M.Pfeifer, K.Krasa
Pulsed laser ablation of gold at 1064 nm and 532 nm

Czech Journ of Phys 54, 421-430

S.Gammino, G.Ciavola, L.Celona, L.Torrise, L.Andò, M.Presti

Innovative ion sources for accelerators: the benefit of the plasma technology

Czech Journ of Phys 54, 883-888

J.Wolowski, J.Badziak, P.Parys, M.Rosiski, L.Ryc, K.Jungwirth, J.Krasa, L.Laska, M.Pfeifer, K.Rohlena, A.Mezzasalma, L.Torrise, S.Gammino, J.Ullschmied, H.Hora, F.P.Boody
The influence of pre-pulse plasma on ion and x-ray emission from ta plasma produced by a high energy laser pulse

Czech Journ of Phys 54, 385-390

L.Laska, K.Jungwirth, J.Krasa, M.Pfeifer, K.Rohlena, J.Ullschmied, J.Badziak, P.Parys, J.Wolowski, F.P.Boody, S.Gammino, L.Torrise
Generation of extreme high laser intensities in plasma

Czech Journ of Phys 54, 370-377

O.Sorlin, Z.Sdombradi, D.Sohler, F.Azaiez, J.Timar, Yu-E.Penionzhkevich, F.Amorini, D.Baiborodin, A.Bauchet, F.Becker, M.Belleguic, C.Borcea, C.Bourgeois, Z.Dlouhy, C.Donzaud, J.Duprat, L.Gaudefroy, D.Guillemaud-Mueller, F.Ibrahim, M.J.Lopez, R.Lucas, S.M.Lukyanov, V.Maslov, J.M.Razek, C.Moore, F.Nowacki, F.Pougheon, M.G.Saint-Laurent, F.Sarazin, J.A.Scarpaci, G.S.Letten, M.Stanoi, C.Stodel, M.Taylor, C.H.Theisen
Structure of the neutron-rich 37 , ^{39}P and 43 , ^{45}Cl nuclei

European Physic Journal A 22

E.De Filippo, G.Lanzano, H.Rothard, C.Volant, S.Aiello, A.Anzalone, N.Arena, M.Geraci, F.Giustolisi, A.Pagano

Fast-electron ejection from C, Ni, Ag and Au foils by $^{36}\text{Ar}^{18+}$ (95 MeV/U): measurements of absolute cross-sections

European Physical Journal A 21 (1): 169-174

K.Turzo, G.Auger, M.L.Begemann-Blaich, N.Bellaize, R.Bittiger, F.Bocage, B.Borderie, R.Bougault, B.Bouriquet, J.L.Charvet, A.Chbihi, R.Dayras, D.Durand, J.D.Frankland, E.Galichet, D.Gourio, D.Guinet, S.Hudan, G.Imme, P.Lautesse, F.Lavaud, A.Le Fevre, R.Legrain, O.Lopez, J.Lukasik, U.Lynen, W.F.J.Muller, L.Nalpas, H.Orth, E.Plagnol,

G.Raciti, E.Rosato, A.Saija, C.Schwarz, W.Seidel, C.Sfienti, B.Tamain, W.Trautmann, A.Trzcinski, E.Vient, M.Vigilante, C.Volant, B.Zwieglinski, A.S.Botvina INDRA ALADIN Collaborations

Multiplicity correlations of intermediate-mass fragments with pions and fast protons in $^{12}\text{C}+^{197}\text{Au}$

European Physical Journal A 21 (2): 293-301

S.Cherubini, P.Figuera, A.Musumarra, C.Agodi, R.Alba, L.Calabretta, L.Cosentino, A.Del Zoppo, A.Di Pietro, M.La Cognata, L.Lamia, L.Pappalardo, M.G.Pellegriti, R.G.Pizzone, A.Rinollo, C.Rolfs, S.Romano, C.Spitaleri, F.Strieder, S.Tudisco, A.Tumino

Cross-section of $^8\text{Li}(\alpha, n)^{11}\text{B}$: inhomogeneous big bang nucleosynthesis

European Physical Journal A 20 (2): 355-358

F.Cappuzzello, S.E.A.Orrigo, A.Cunsolo, H.Lenske, M.C.Allia, D.Beaumel, S.Fortier, A.Foti, A.Lazzaro, C.Nociforo, J.S.Winfield

Excited states of ^{15}C

Europhys Lett 65 (2004) 766-772

N.Soic, S.Blagus, M.Bogovac, W.Catford, S.Cherubini, N.Clark, E.Costanzo, L.Donadilla, S.Fazinic, M.Freer, B.Fulton, B.Greenhalgh, K.Jones, M.Lattuada, P.Leask, D.Mahboub, M.Milin, D.Miljanić, D.Rendic, S.Romano, C.Spitaleri, T.Tadic, D.Watson, D.Weisser, M.Zadro

Experimental evidence for molecular structures in light nuclei

Fizika B 13, 433

W.Zuo, U.Lombardo, C.W.Shen, J.Y.Liu, J.Q.Li

Equation of state of spin-polarized nuclear matter

High Energy Physics And Nuclear Physics-Chinese Edition 28 (3): 284-289

G.A.P.Cirrone, S.Donadio, S.Guatelli, A.Mantero, B.Mascialino, S.Parlati, M.G.Pia, A.Pfeiffer, A.Ribon, P.Viarengo

A goodness-of-fit statistical toolkit

Ieee Transactions On Nuclear Science 51 (5): 2056-2063 Part 1

G.A.P.Cirrone, S.Coco, G.Cuttone, C.De Martinis, D.Giove, P.A.Lojacono, M.Mauri, R.Messina

A fast monitoring system for radiotherapeutic

proton beams based on scintillating screens and a CCD Camera

Ieee Transactions On Nuclear Science 51 (4): 1402-1406 Part 1

G.A.P.Cirrone, G.Cuttone, P.A.Lojacono, S.Lo Nigro, V.Mongelli, I.V.Patti, G.Privitera, L.Raffaele, D.Rifuggiato, M.GSabini, V.Salamone, C.Spatola, L.M.Valastro

A 62 MeV proton beam for the treatment of ocular melanoma at Laboratori Nazionali del Sud-INFN

Ieee Transactions On Nuclear Science 51 (3): 860-865 Part 3

M.Alderighi, A.Anzalone, R.Bassini, C.Boiano, G.Cardella, S., E.De Filippo, E.Geraci, F.Giustolisi, P.Guazzoni, E.Laguidara, G.Lanzano, G.Lanzalone, A.Pagano, M.Papa, S.Pirrone, G.Politi, R.Porto, S.Russo, M.Sassi, G.R.Sechi, L.Zetta

CHIMERA data acquisition via digital sampling technique

Ieee Transactions On Nuclear Science 51 (4): 1475-1481 Part 1

M.Lattuada, D.Vinciguerra

I Laboratori Nazionali del Sud

Il Nuovo Saggiatore 20, pag. 34

S.Gammino, L.Torrise, G.Ciavola, L.Andò, L.Celona, S.Manciagli, J.Krás, L.Láska, A.M.Mezzasalma, C.Gentile, A.Picciotto, J.Wolowski, E.Woryna, G.D.Shirkov, D.Hitz

The ECLISSE experiment: production of high intensity ion beams by means of a hybrid ion source

Journal Of Appl Phys 96 (5), 2961-2968

G.Pappalardo, E.Costa, C.Marchetta, L.Pappalardo, F.P.Romano, A.Zucchiatti, P.Prati, P.A.Mandò, A.Migliori, L.Palombo, M.G.Vaccari

Non-destructive characterization of Della Robbia sculptures at the Bargello museum in Florence by the combined use of PIXE and XRF portable systems

Journal Of Cultural Heritage, vol 5, issue 2

D.Doria, A.Lorusso, F.Belloni, V.Nassisi, L.Torrise, S.Gammino

A study of the parameters of particles ejected from a laser plasma

Laser And Particle Beams 22(4) 461-467

R.Raabe, J.L.Sida, J.L.Charvet, N.Alamanos, C.Angulo, J.M.Casandjian, S.Courtin, A.Drouart, D.J.C.Durand, P.Figuera, A.Gillibert, S.Heinrich, C.Jouanne, V.Lapoux, A.Lepine-Szily, A.Musumarra, L.Nalpas, D.Pieroutsakou, M.Romoli, K.Rusek, M.Trotta
No enhancement of fusion probability by the neutron halo of ^6He

Nature 431, pag. 823

R.Ghetti, N.Colonna, J.Helgesson, V.Avdeichikov, P.Golubev, B.Jakobsson, G.Tagliente, S.Brandenburg, V.L.Kravchuk, H.W.Wilschut, S.Kopecky, E.W.Anderson, P.Nadel-Turonski, L.Westerberg, V.Bellini, M.L.Sperduto, C.Sutera

Calibration of a neutron time-of-flight multidetector system for an intensity interferometry experiment

Nucl. Instrum. Meth. A 516 (2-3): 492-501

S.Tudisco, A.Scordino, G.Privitera, I.Baran, F.Musumeci

ARETUSA advanced research equipment for fast ultraweak luminescence analysis: new developments

Nucl. Instrum. Meth. A 518, 1-2, 463-464

G.Riccobene, L.Cosentino, M.Musumeci, G.Pavan, F.Speziale for the NEMO collaboration

Acoustic detection of UHE neutrinos: a station for measurement of the deep sea acoustic noise

Nucl. Instrum. Meth. A 518, 220-222

M.Bassan, S.Bouchigny, C.Commeaux, J.P.Didelez, G.Rouille, C.Schaerf, V.Bellini, J.P.Bocquet, M.Castoldi, A.D'Angelo, R.Di Salvo, A.Fantini, F.Ghio, B.Girolami, M.Guidal, E.Hourany, R.Kunne, P.L.Sandri, A.Lleres, Moricciani D, Rebreyend D

Static and dynamic polarization of HD

Nucl. Instrum. Meth. A 526 (1-2), 163-167

M.Anghinolfi For The ANTARES Collaboration
Status of ANTARES, an undersea neutrino telescope

Nucl. Instrum. Meth. A 535, 1-2, 126-128

Colonna M, Fabbri G, M: Di Toro, et al.
Fragmentation path of excited nuclear systems

Nuclear Physics A 742 (3-4): 337-347

M.Milin, S.Cherubini, T.Davinson, A.Di Pietro, P.Figuera, D.Miljanic, A.Musumarra, A.Ninane, A.N.Ostrowski, M.G.Pellegriti, A.C.Shotter, N.Soic, C.Spitaleri, M.Zadro

The ^6He scattering and reactions on ^{12}C and cluster states of ^{14}C

Nuclear Physics A 730, 285

Colonna M, Ayik S, Baran V, et al.

Dynamics of cluster formation in liquid-gas phase transitions

Nuclear Physics A 738: 108-114

U.Lombardo, P.Schuck, C.W.Shen

Screening effects on ^{15}O pairing in nuclear matter

Nuclear Physics A 731: 392-400

F.Cappuzzello, H.Lenske, A.Cunsolo, D.Beaumel, S.Fortier, A.Foti, A.Lazzaro, C.Nociforo, S.E.A.Orrigo, J.S.Winfield

Analysis of the $^{11}\text{B} (^7\text{Li}, ^7\text{Be}) ^{11}\text{Be}$ reaction at 57 MeV in a microscopic approach

Nuclear Physics A 739, 30-56

C.Sfienti, V.Baran, M.De Napoli, G.Imme, G.Raciti, E.Rapisarda, S.Rascuna, L.Spezzi

Temperature and density in heavy ion reactions at intermediate energies

Nuclear Physics A 734: 528-531

M.Milin, S.Cherubini, T.Davinson, A.Di Pietro, P.Figuera, D.Miljanic, A.Musumarra, A.Ninane, A.N.Ostrowski, M.G.Pellegriti, A.C.Shotter, N.Soic, C.Spitaleri, M.Zadro

Reactions induced by 18 MeV ^6He beam on ^6Li , ^7Li , and ^{12}C

Nuclear Physics A 746, 183c

A.Tumino, C.Spitaleri, L.Pappalardo, S.Cherubini, A.Del Zoppo, M.La Cognata, A.Musumarra, M.G.Pellegriti, R.G.Pizzone, A.Rinollo, S.Romano, S.Typel

The Trojan-Horse Method applied to the $^6\text{Li} (p, \alpha) ^3\text{He}$ reaction down to astrophysical energies

Nuclear Physics A 734, 639-642

C.Volant, K.Turzo, W.Trautmann, G.Auger, A.L.Begemann-Blaich, R.Bittiger, B.Borderie, A.S.Botvina, R.Bougault, B.Bouriquet, J.L.Charvet, A.Chbihi, R.Dayras, D.Dore, D.Durand, J.D.Frankland, E.Galichet,

D.Gourio, D.Guinet, S.Hudan, G.Imme, P.Lautesse, F.Lavaud, A.Le Fevre, O.Lopez, J.Lukasik, U.Lynen, W.F.J.Muller, L.Nalpas, H.Orth, E.Plagnol, G.Raciti, E.Rosato, A.Saija, C.Schwarz, W.Seidel, C.Sfienti, J.C.Steckmeyer, B.Tamain, A.Trzcinski, E.Vient, M.Vigilante, B.Zwieglinski

Intranuclear cascade plus percolation plus evaporation model applied to the $^{12}\text{C}+^{197}\text{Au}$ system at 1 GeV/nucleon

Nuclear Physics A 734, 545-548

W.Zuo, ZH.Li, A.Li, U.Lombardo

Effect of three-body interaction on phase transition of hot asymmetric nuclear matter

Nuclear Physics A 745 (1-2): 34-46

L.Calabretta, M.Maggiore, M.Re, D.Rifuggiato, S.Farinon, P.Fabbricatore, R.Musenich

A superconducting cyclotron as driver for radioactive beam facilities

Nuclear Physics A 734, 378-381

P.Sapienza, R.Coniglione, M.Colonna, C.Agodi, R.Alba, G.Bellia, A.Del Zoppo, P.Finocchiario, V.Greco, K.Loukachine, C.Maiolino, E.Migneco, P.Piattelli, D.Santonocito, N.Colonna, M.Bruno, M.D'Agostino, M.L.Fiandri, G.Tannini, F.Gramegna, P.F.Mastinu, L.Fabbietti, I.Iori, G.V.Margagliotti, P.M.Milazzo, A.Moroni, R.Rui, Y.Blumenfeld, J.A.Scarpaci

Energetic particle emission and nuclear dynamics around the Fermi energy

Nuclear Physics A 734, 601

M.Alderighi, A.Anzalone, L.Auditore, N.Arena, R.Bassini, J.Blicharska, C.Boiano, V.Campagna, G.Cardella, S.Cavallaro, M.D'Andrea, A.Di Stefano, F.Fichera, E.De Filippo, E.Geraci, N.Giudice, F.Giustolisi, Grzeszczuk, A. N.Guardone, P.Guazzoni, A.Grimaldi, E.Laguidara, G.Lanzano, G.Lanzalone, A.Limone, D.Nicotra, T.Paduszynski, A.Pagano, M.Papa, S.Pirrone, G.Politi, F.Porto, C.Rapicavoli, G.Rizza, E.Rosato, S.Russo, P.Russotto, S.Salomone, M.Sassi, G.Sacca, G.Sechi, M.L.Sperduto, A.Trifiro, M.Trimarchi, S.Urso, M.Vigilante, L.Zetta, V.Zipper,

Pulse shape method applied to silicon detectors of CHIMERA array

Nuclear Physics A 734, suppl.5, pp E88-E91,

E.Geraci, M.Bruno, M.D'Agostino, E.De Filippo, A.Pagano, G.Vannini, M.Alderighi, A.Anzalone, L.Auditore, V.Baran, R.Barnà, M.Bartolucci, I.Berceanu, J.Blicharska, A.Bonasera, B.Borderie, R.Bougault, J.Brzychczyk, G.Cardella, S.Cavallaro, A.Chbihi, J.Cibor, M.Colonna, D.De Pasquale, M.Di Toro, F.Giustolisi, A.Grzeszczuk, P.Guazzoni, D.Guinet, M.Iacono-Manno, A.Italiano, S.Kowalski, E.La Guidara, G.Lanzalone, G.Lanzanó, N.Le Neindre, S.Li, S.Lo Nigro, C.Maiolino, Z.Majka, G.Manfredi, T.Paduszynski, M.Papa, M.Petrovici, E.Piasecki, S.Pirrone, G.Politi, A.Pop, F.Porto, M.F.Rivet, E.Rosato, S.Russo, P.Russotto, G.Sechi, V.Simion, M.L.Sperduto, J.C.Steckmeyer, A.Trifirò, M.Trimarchi, M.Vigilante, J.P.Wieleczko, J.Wilczynski, H.Wu, Z.Xiao, L.Zetta, W.Zipper,

Isoscaling in central $^{124}\text{Sn}+^{64}\text{Ni}$, $^{112}\text{Sn}+^{58}\text{Ni}$ collisions at 35 AMeV

Nuclear Physics A 732, 173-201

Baran V, Colonna M, Di Toro M.

Neck fragmentation reaction mechanism

Nuclear Physics A 730 (3-4): 329-354

E.Geraci, M.Alderighi, A.Anzalone, L.Auditore, V.Baran, M.Bartolucci, I.Berceanu, J.Blicharska, A.Bonasera, B.Borderie, R.Bougault, M.Bruno, J.Brzychczyk, G.Cardella, S.Cavallaro, A.Chbihi, J.Cibor, M.Colonna, M.D'Agostino, E.De Filippo, M.Di Toro, F.Giustolisi, A.Grzeszczuk, P.Guazzoni, D.Guinet, M.Iacono-Manno, S.Kowalski, E.La Guidara, G.Lanzalone, G.Lanzanó, N.Le Neindre, S.Li, S.Lo Nigro, C.Maiolino, Z.Majka, G.Manfredi, T.Paduszynski, A.Pagano, M.Papa, M.Petrovici, E.Piasecki, S.Pirrone, G.Politi, A.Pop, F.Porto, M.F.Rivet, E.Rosato, S.Russo, P.Russotto, G.Sechi, V.Simion, M.L.Sperduto, J.C.Steckmeyer, A.Trifirò, M.Trimarchi, G.Vannini, M.Vigilante, J.P.Wieleczko, J.Wilczynski, H.Wu, Z.Xiao, L.Zetta, W.Zipper,

Isotope correlations as a probe for freeze-out characterization: central $^{124}\text{Sn}+^{64}\text{Ni}$, $^{112}\text{Sn}+^{58}\text{Ni}$ collisions

Nuclear Physics A 734, 524-527

A.Pagano, M.Alderighi, F.Amorini, A.Anzalone, L.Arena, L.Auditore, V.Baran, M.Bartolucci, I.Berceanu, J.Blicharska, J.Brzychczyk, A.Bonasera, B.Borderie, R.Bougault, M.Bruno,

G.Cardella, S.Cavallaro, M.B.Chatterjee, A.Chbihi, J.Cibor, M.Colonna, M.D'Agostino, R.Dayras, E.De Filippo, M.Di Toro, W.Gawlikowicz, E.Geraci, F.Giustolisi, A.Grzeszczuk, P.Guazzoni, D.Guinet, M.Iacono-Manno, S.Kowalski, E.La Guidara, G.Lanzano, G.Lanzalone, Le N.Neindre, S.Li, Lo Nigro, C.Maiolino, Z.Majka, G.Manfredi, T.Paduszynski, M.Papa, M.Petrovici, E.Piasecki, S.Pirrone, R.Planeta, G.Politi, A.Pop, F.Porto, M.F.Rivet, E.Rosato, F.Rizzo, S.Russo, P.Russotto, M.Sassi, G.Sechi, V.Simion, K.Siwiek-Wilczynska, I.Skwira, M.L.Sperduto, J.C.Steckmeyer, L.Swidorski, A.Trifirò, M.Trimarchi, G.Vannini, M.Vigilante, J.P.Wieleczko, J.Wilczynski, H.Wu, Z.Xiao, L.Zetta, W.Zipper

Fragmentation studies with the CHIMERA detector at LNS in Catania: recent progress
Nuclear Physics A 734, 504-511

Rizzo J, Colonna M, Di Toro M., et al.
Transport properties of isospin effective mass splitting
Nuclear Physics A 732: 202-217

S.Romano, C.Spitaleri, L.Lamia, A.Tumino, R.G.Pizzone, S.Cherubini, A.Del Zoppo, P.Figuera, M.Gulino, M.La Cognata, A.Musumarra, M.G.Pellegriti, A.Rinollo, S.Tudisco
The astrophysical factor for the $^{11}\text{B} (p, \alpha_0) ^8\text{Be}$ reaction extracted via the Trojan Horse Method
Nuclear Physics A 738, 406-410

A.Kugler et al,
Particle identification at HADES
Nuclear Physics A 734, 78

E.Korolkova for the ANTARES collaboration
The status of the ANTARES experiment
Nuclear Physics B 136, 69

E.Migneco, S.Aiello, E.Amato, M.Ambriola, F.Ameli, G.Andronico, M.Anghinolfi, M.Battaglieri, R.Bellotti, A.Bersani, A.Boldrin, M.Bonori, F.Cafagna, A.Capone, L.Caponnetto, T.Chiarusi, M.Circella, R.Cocimano, R.Coniglione, M.Cordelli, M.Costa, S.Cuneo, A.D'Amico, V.D'Amico, C.De Marzo, R.De Vita, C.Distefano, A.Gabrielli, E.Gandolfi, A.Grimaldi, R.Habel,

A.Italiano, M.Leonardi, L.Lo Nigro, D.Lo Presti, A.Margiotta, A.Martini, M.Masetti, R.Masullo, T.Montaruli, R.Mosetti, M.Musumeci, C.A.Nicolau, R.Occhipinti, R.Papaleo, C.Petta, P.Piattelli, G.Raia, N.Randazzo, S.Reito, G.Ricco, G.Riccobene, M.Ripani, M.Romita, A.Rovelli, M.Ruppi, G.V.Russo, M.Russo, P.Sapienza, J.P.Schuller, M.Sedita, I.Sokalski, M.Spurio, M.Taiuti, L.Trasatti, L.Ursella, V.Valente, P.Vicini, G.Zanarini

NEMO: status of the project
Nuclear Physics B 136, 61

G.X.Peng, M.Loewe, U.Lombardo, X.J.Wen
A new treatment of the in-medium chiral condensates
Nuclear Physics B-Proceedings Supplements 133: 259-264 (2004)

P.Finocchiaro, P.Salabura
Dielectron spectrometry with HADES
Nuclear Physics News, vol 14, no 3, 27

N.I.Ashwood, M.Freer, S.Ahmed, J.C.Angelique, V.Bouchat, W.N.Catford, N.M.Clarke, N.Curtis, O.Dorvaux, B.R.Fulton X, F.Hanappe, Y.Kerckx, M.Labiche, J.L.Lecouey, R.C.Lemmon, F.M.Marques, T.Materna, A.Ninane, G.Normand, N.A.Orr, S.Pain, N.Soic, L.Stuttge, C.Timis, A.Unshakova, J.S.Winfield, V.A.Ziman
Helium clustering in neutron-rich Be isotopes
Physics Letters B 580 (3-4), 129-136

Liu TX, van Goethem MJ, Liu XD, et al.
Isotope yields from central ^{112}Sn , $^{124}\text{Sn}+^{112}\text{Sn}$, ^{124}Sn collisions: Dynamical emission?
Phys. Rev. C 69 (1)

A. Di Pietro, P.Figuera, F.Amorini, C.Angulo, G.Cardella, S.Cherubini, T.Davinson, D.Lanza, J.Lu, H.Mahmud, M.Milin, A.Musumarra, A.Ninane, M.Papa, M.G.Pellegriti, R.Raabe, F.Rizzo, C.Ruiz, A.C.Shotter, N.Soic, S.Tudisco, L.Weissman
Reactions induced by the halo nucleus ^6He at energies around the Coulomb barrier
Phys Rev C 69, 044613

R.Ghetti, V.Avdeichikov, B.Jakobsson, P.Golubev, J.Helgesson, N.Colonna,

G.Tagliente, H.W.Wilschut, S.Kopecky,
V.L.Kravchuk, E.W.Anderson, P.Nadel-
Turonski, L.Westerberg, V.Bellini,
M.L.Sperduto, C.Sutera

*Isospin effects on two-particle correlation
functions in $E/A=61$ MeV $^{36}\text{Ar}+^{112}\text{Sn}$, ^{124}Sn
reactions*

Physical Review C 69 (3)

F.Amorini, G.Cardella, A.Di Pietro, P.Figuera,
G.Lanzalone, L.Jun, A.Musumarra, M.Papa,
S.Pirrone, F.Rizzo, W.Tian, S.Tudisco

*Statistical and pre-equilibrium γ -ray emission
in heavy ion reactions at 25 MeV/nucleon*

Phys Rev C 69, 014608

M.Milin, D.Miljanic, M.Aliotta, S.Cherubini,
T.Davinson, A.Di Pietro, P.Figuera,
A.Musumarra, A.Ninane, A.N.Ostrowski,
M.G.Pellegriti, A.C.Shotter, N.Soic,
C.Spitaleri, M.Zadro

*Two proton pickup reaction (^6He , ^8Be) on ^{12}C ,
 ^{16}O , and ^{19}F*

Phys Rev C70, 044603

V.Z.Goldberg, G.Rogachev, W.H.Trzazka,
J.J.Kolata, A.Andrejev, C.Angulo,
M.J.G.Borge, S.Cherubini, G.Chubarian,
G.Crowley, P.Van Duppen, M.Gorska,
M.Gulino, M.Huyse, P.Jesinger, K-M.Kallman,
M.Lattuada, T.Lönnroth, M.Mutterer, R.Raabe,
S.Romano, M.V.Rozhkov, B.B.Skorodumov,
C.Spitaleri, O.Tengblad, A.Tumino

*Investigation of the α -cluster structure of
 ^{22}Ne and ^{22}Mg*

Phys Rev C 69, 024602

A.Shrivastava, Y.Blumenfeld, N.Keeley,
T.Zerguerras, T.Aumann, D.Bazin, A.Chromik,
G.M.Crawley, T.Glasmacher, K.W.Kemper,
F.Marechal, D.J.Morrissey, T.Nakamura,
A.Navin, E.C.Pollacco, D.Santonocito,
B.M.Sherrill, T.Suomijarvi, M.Thoennessen,
E.Tryggstad, R.L.Varner

*^{11}Be continuum studied through proton
scattering*

Physics Letters B 596 (1-2), 54-60

M.Baldo, U.Lombardo, E.E.Saperstein,
M.V.Zverev

On the surface nature of the nuclear pairing

**Physics Reports-Review Section Of Physics
Letters 391 (3-6): 261-310**

X.R.Zhou, G.F.Burgio, U.Lombardo,
H.J.Schulze, W.Zuo

Three-body forces and neutron star structure
Physical Review C 69 (1)

H.R.Hora, C.Yu, X.T.He, Z.Jie, F.Osman,
J.Badziak, F.P.Boody, S.Gammino, R.Hopfl,
K.Jungwirth, B.Kralikova, J.Krasa, L.Laska,
L.Hong, G.H.Miley, P.Parys, P.Hansheng,
M.Pfeifer, K.Rohlena, J.Skala,
Z.Skladanowski, L.Torrise, J.Ullschmied,
J.Wolowski, W.Y.Zhang,

*Generation of nonlinear force driven blocks
from skin layer interaction of petawatt-
picosecond laser pulses for ICF*

Plasma Sci & Tech 6 (1), 2172-2178

W.Zuo, Z.H.Li, G.C.Lu, J.Q.Li, W.Scheid,
U.Lombardo, H.Schulze, C.W.Shen

*^{15}O proton and neutron superfluidity in
beta-stable neutron star matter*

Physics Letters B 595, 44-49

Gaitanos T, Colonna M, M. Di Toro, et al.

*Stopping and isospin equilibration in heavy
ion collisions*

Physics LettersB 595: 209-215

S.Terranova, A.Bonasera

*Constrained molecular dynamics simulation
of the quark-gluon plasma*

Phys Rev C70, 024906

C.Spitaleri, L.Lamia, A.Tumino, R.G.Pizzone,
S.Cherubini, A.Del Zoppo, P.Figuera, M.La
Cognata, A.Musumarra, M.G.Pellegriti,
A.Rinollo, C.Rolfs, S.Romano, S.Tudisco

*The ^{11}B (p, α_0) ^8Be reaction at sub-Coulomb
energies via the Trojan Horse method*

Phys Rev C 69 (5)

A.Valenza, A.M.Visco, L.Torrise, N.Campo
*Characterization of ultra-high-molecular
weight polyethylene (UHMWPE) modified by
ion implantation*

Polymer J 45, 1707-1715

M. Di Toro M., V. Baran, M. Colonna, et al.

*Isospin effects on reaction dynamics from low
to relativistic energies*

**Progress In Particle And Nuclear Physics 53
(1): 81-92**

P.Salabura et al,
Study of e^+e^- production in elementary and nuclear collisions near production threshold with HADES

Progress In Particle And Nuclear Physics, vol 53, 49

L.Torrise

Ion charge state distributions in plasma produced by pulsed laser irradiations

Rad Eff & Def In Solids 159, 249-258

L.Torrise, A.M.Visco, R.Barnà, D.De Pasquale, N.Campo, G.Di Marco, M.Trimarchi, A.Trifirò

Radiation effects induced by MeV electron beams irradiating dense polyethylene (UHMWPE)

Rad Eff & Def In Solids 159(4), 259-271

L.Torrise, N.Campo, L.Auditore, R.Barnà, D.De Pasquale, A.Italiano, A.Trifirò, M.Trimarchi, G.Di Marco

Mechanical modifications in dense polyethylene induced by energetic electron beams

Rad Eff And Def In Solids 159 (11-12), 597-606

G.Ciavola, L.Celona, S.Gammino, L.Andò, M.Presti, S.Passarello, C.Percolla, V.Calzona, X.Guo, X.Zhang

A new version of the TRIPS source optimized for ADS purposes

Rev Sci Instr 75 (5), 1453-1456

L.Celona, G.Ciavola, S.Gammino, L.Andò, M.Presti, X.Guo, R.Gobin, R.Ferdinand

Status of the TRIPS source and emittance measurements

Rev Sci Instr 75 (5), 1423-1426

S.Gammino, G.Ciavola, L.Celona, L.Andò, S.Passarello, Xzh.Zhang, P.Spädtke, M.Winkler

High intensity beams from electron cyclotron resonance ion sources: a study of efficient extraction and transport system

Rev Sci Instr 75 (5), 1637-1642

L.Láska, J.Krásá, M.Pfeifer, K.Rohlena, S.Gammino, L.Torrise, G.Ciavola, L.Andò

Generation of intense beams of metallic ions with charge state up to 10^+ in a laser ion source

Rev Sci Instr 75 (5), 1575-1578

L.Láska, K.Jungwirth, B.Králiková, J.Krásá, M.Pfeifer, K.Rohlena, J.Skála, J.Ullschmied, J.Badziak, P.Parys, J.Wolowski, E.Woryna, L.Torrise, S.Gammino, F.P.Boody

Charge-energy distribution of Ta ions from plasmas produced by 1ω and 3ω frequencies of the high-power iodine laser

Rev Sci Instr 75 (5), 1588-1591

L.Láska, K.Jungwirth, B.Králiková, J.Krásá, E.Krousk, K.Malek, M.Pfeifer, K.Rohlena, J.Skála, J.Ullschmied, J.Badziak, P.Parys, L.Ryc, A.Szydlowski, J.Wolowski, E.Woryna, G.Ciavola, S.Gammino, L.Torrise, F.P.Boody

Review of LIS developments in Prague and production of Q over 50^+ ions at PALS

Rev Sci Instr 75 (5), 1546-1550

I.Baran, C.Lopresti, F.Musumeci, G.Privitera, S.Privitera, A.Scordino, S.Tudisco, V.Baran, G.A.P.Cirrone, L.Raffaele, L.Valastro

Radiation effects on cell proliferation

Roumanian Biotechnological Letters 9 (5), 1853-1870

Communications to Conferences and Workshops

A km³ detector in the Mediterranean: status of the NEMO Project

P.Sapienza

Neutrino Oscillation Workshop 2004, Conca Specchiulla september 2004

Analysis of ion currents emitted by laser-produced plasmas

A.Picciotto, J.Kráska, L.Láska, K.Rohlena, A.Szydlowski, L.Torrise, S.Gammino, L.Andò, A.M.Mezzasalma

Proc.4th Int workshop on "Towards Fusion Energy - Plasma Physics, Diagnostics, Applications", (2004) Kudowa Zdroj, Poland

Analysis of the SERSE Ion Output by Using Klystron-based or TWT-based Microwave generators

L.Celona, S.Gammino, G.Ciavola, F.Consoli, A.Galatà

Proc.16th Workshop on ECR ion Sources, Berkeley (2004)

Dilepton Analysis in the HADES Spectrometer for C+C at 2AGeV

J.Otwinowski et al.

Proceedings of the 42th International Winter Meeting on Nuclear Physics, Bormio 2004

Disappearance of collective motion in hot nuclei

D.Santonocito, P.Piattelli, C.Agodi, R.Alba, G.Bellia, R.Coniglione, A.Del Zoppo, P.Finocchiaro, F.Hongmei, C.Maiolino, E.Migneco, P.Sapienza, Y.Blumenfeld, F.Delaunay, N.Frascaria, V.Lima, J.A.Scarpaci

5° Italy-Japan Symposium Recent achievements and perspectives in Nuclear Physics, Naples 3-7

Dynamical emission of fragments in the 35 AMeV ¹²⁴Sn+⁶⁴Ni and ¹¹²Sn+⁵⁸Ni reactions

E.De Filippo for the Isospin collaboration

Gordon Conference (Nuclear Chemistry), Colby Sawyer College, New London (NH, USA) 13-18 June 2004

Energy distribution of Cu ions generated by excimer laser ablation

Doria D., Lorusso A., Belloni F., Nassisi V., Torrisi L., Gammino S.

16th Int.Vacuum Conf., Venezia, (2004) 668

Evolution of the prompt dipole γ -ray emission with incident energy in fusion reactions

D.Pierroutsakou, B.Martin, G.Inglia, A.Boiano, A.De Francesco, A.De Rosa, M.Di Pietro, M.LaCommara, R.Mordente, M.Romoli, M.Sandoli, M.Trotta, E.Vardaci, T.Glodariu, M.Mazzocco, C.Signorini, L.Stroe, C.Agodi, R.Alba, M.Colonna, R.Coniglione, A.DelZoppo, M.DiToro, C.Maiolino, N.Pellegriti, P.Piattelli,

D.Santonocito, P.Sapienza, G.Cardella, E.DeFilippo, A.Pagano, S.Pirrone, V.Baran

5° Italy-Japan Symposium Recent achievements and perspectives in Nuclear Physics, Naples 3-7, 2004

Flexible lalon

F.P.Boody, P.Bickel, J.I.Kempf, G.Monkman, R.Hopfl, H.Hora, L.Láska, J.Kráska, M.Pfeifer, K.Rohlena, J.Wolowski, J.Badziak, P.Parys, L.Ryc, E.Woryna, A.Szydlowski, L.Torrise, S.Gammino, A.M.Mezzasalma

Proc.of Int.Conference on High Power Laser ablation, Taos (2004)

Hard gamma: a clock for multifragmentation

C.Agodi

XC SIF Brescia 20-9-2004

Hadron production in C+C at 2 A GeV measured by the HADES spectrometer

P.Tlusty et al.,

Proceedings of the 42th International Winter Meeting on Nuclear Physics, Bormio 2004

High intensity monocharged beams of gaseous elemento from the TRIPS source

G.Ciavola, L.Celona, F.Consoli, A.Galatà, S.Gammino, M.Presti,

16th Int.Vacuum Conf., Venezia, (2004) 900

Improvement of reliability of the TRASCO intense proton source (TRIPS) at INFN-LNS

G.Ciavola, L.Celona, S.Gammino, L.Andò, M.Presti, A.Galatà, F.Chines, S.Passarello, XZh.Zhang, M.Winkler, R.Gobin, R.Ferdinand, J.Sherman,

Proc.4th Int workshop on Utilization and reliability of high power proton accelerators, Daejeon, Korea (2004)

Ion Emission from Plasmas Produced by a 438-nm Laser Radiation Focused on Targets of Different Z-numbers

J.Wolowski, J.Badziak, F.P.Boody, S.Gammino, H.Hora, J.Krásá, L.Láska, A.Mezzasalma, P.Parys, M.Pfeifer, K.Rohlén, L.Torrise, J.Ullschmied, E.Woryna

Proc.EPS London (2004) ECA vol.28G, P4.034

Ions, electrons and X-rays produced by pulsed Nd:Yag laser irradiating metals

L.Torrise, S.Gammino, E.Amato, A.Mezzasalma, A.Picciotto, J.Krasa, L.Laska

Proc.28th Eur.Conf.on Laser Inter.With Matter, Frascati (2004)

Laser production of ions at different pre-pulse plasma conditions

L.Láska, J.Badziak, F.P.Boody, S.Gammino, K.Jungwirth, J.Krásá, P.Parys, M.Pfeifer, K.Rohlén, L.Torrise, J.Ullschmied, J.Wolowski

Proc.EPS London (2004) ECA vol.28G, P4.027

Laser-produced ion streams useful for technological applications

J.Wolowski, J.Badziak, F.P.Boody, S.Gammino, K.Jungwirth, J.Krasa, L.Laska, A.Mezzasalma, P.Parys, M.Pfeifer, M.Rosiski, K.Rohlén, L.Torrise, J.Ullschmied, E.Woryna,

Proc.28th Eur.Conf.on Laser Inter.With Matter, Frascati (2004)

Lns Catania Project for Therapy and Radioisotope Production

L.Calabretta

17th International Conference on Cyclotrons and their Applications

Measurement of angle between nuclear reaction products and depth profiling

Đ.Miljanić, M.Majer, S.Blagus, M.Bogovac, M.Lattuada, M.Milin, S.Romano, N.Soić, M.Zadro

9th Int.Conf.Nuclear Microprobe Technology and Applications, September 2004, Dubrovnik

NEMO: status of the project

E.Migneco

Cosmic Ray International Seminar, Catania, 31 may-4 june 2004

New Lines of Research With the Magnex Large-Acceptance Spectrometer

F.Cappuzzello, A.Cunsolo, A.Foti, A.Lazzaro, S.E.A.Orrigo, J.S.Winfield, C.Nociforo, H.Lenske

Proceeding of the "International Symposium on Exotic Nuclei "EXON2004" Peterhof, 5 - 12 July 2004

New Lines of Research With the Magnex Large-Acceptance Spectrometer

A.Cunsolo, F.Cappuzzello, A.Foti, A.Lazzaro, S.E.A.Orrigo, J.S.Winfield, C.Nociforo, H.Lenske

Proceeding of the "5th Italy-Japan Symposium: Recent Achievements and Perspectives in Nuclear Physics Napoli, 3 -7 Novembre 2004

Non destructive measurements on roman pottery

L.Pappalardo

International Workshop Old Pottery in a New Century: Innovating Perspectives on Roman Pottery Studies Catania 22-24 Aprile 2004.

Non-destructive and "in-situ" characterization of gemstones on museum jewels.The complementary use of PIXE-alpha and XRF portable systems

L.Pappalardo

Conferenza Internazionale "Archaeometry with IBA and related methods", Ljubljana (Slovenia) 8-10 June 2004

Non Destructive Measurements on Roman Frescoes Pigments

L. Pappalardo

International Conference "Archéométrie 2005", 18-21/04/2005, Saclay (Francia)

Non equilibrium plasmas produced by fast pulsed lasers

L. Torrisi, S. Gammino

16th Int. Vacuum Conf., Venezia, (2004) 343

NuPECC Long Range Plan 2004: Perspectives for Nuclear Physics Research in Europe in the Coming Decade and Beyond (2004)

P. Corvisiero, D. Frekers, S. Goriely, P. Haensel, W. Hillebrandt, J. Kiener, K. Langanke, M. Lattuada, O. Sorlin

Performances and perspectives of silicon detector telescopes

F. Amorini, G. Bottiglieri, L. Caponetto, G. Cardella, A. Di Pietro, G. Fallica, P. Figuera, E. Leonora, D. Lo Presti, A. Morea, M. Papa, G. Pappalardo, C. Petta, N. Randazzo, S. Reito, F. Rizzo, G. V. Russo, V. Sipala, G. Valvo.

9th Topical Seminar on Innovative Particle and Radiation Detectors, Siena, 23-26 May 2004

Performances and perspectives of silicon detector telescopes

F. Amorini, G. Bottiglieri, L. Caponetto, G. Cardella, A. Di Pietro, G. Fallica, P. Figuera, E. Leonora, D. Lo Presti, A. Morea, M. Papa, G. Pappalardo, C. Petta, N. Randazzo, S. Reito, F. Rizzo, G. V. Russo, V. Sipala, G. Valvo.

9th Topical Seminar on Innovative Particle and Radiation Detectors, Siena, Italy, 23 - 26 May 2004.

Position Monolithic Silicon Detector Telescope: Simulation Results

G. Bottiglieri, F. Amorini, G. Cardella, A. Di Pietro, P. Fallica, P. Figuera, S. F. Liotta, A. Morea, A. Musumarra, M. Papa, F. Rizzo, S. Tudisco, G. Valvo

IMTC 2004-Instrumentation and Measurement Technology Conference, Como, Italy, 18-20 May 2004.

Position Monolithic Silicon Detector Telescope: Simulation Results

G. Bottiglieri, F. Amorini, G. Cardella,

A. DiPietro, G. Fallica, P. Figuera, S. F. Liotta, A. Morea, A. Musumarra, M. Papa, F. Rizzo, S. Tudisco, G. Valvo.

IMTC 2004-Instrumentation and Measurement Technology Conference, Como, Italy, 18-20 May 2004.

Production of Highly Charged Heavy Ions by means of a Hybrid Source in Dc mode and in Afterglow Mode

S. Gammino, G. Ciavola, L. Torrisi, L. Andò, L. Celona, M. Presti, S. Manciangli, A. Picciotto, A. M. Mezzasalma, J. Krása, L. Láská, M. Pfeifer, J. Wolowski, E. Woryna, P. Parys, G. D. Shirkov, D. Hitz,

Proc. 16th Workshop on ECR ion Sources, Berkeley (2004) Proceedings of the 42th International Winter Meeting on Nuclear Physics, Bormio (2004) Dynamical fission in $^{124}\text{Sn} + ^{64}\text{Ni}$ collision at 35 AMeV

Paolo Russotto for Isospin collaboration

XIV Colloque Ganil Giens (Francia) 4-10 giugno 2004

Quantitative non destructive determination of trace elements in archaeological pottery by using the portable BSC-XRF (Beam Stability Controlled XRF) spectrometer of the LNS/INFN Laboratory

L. Pappalardo

EXRS2004 European Conference on X-ray Spectrometry, Alghero, 6-11 Giugno 2004

Recent improvements and applications of the LNS portable PIXE system

L. Pappalardo

10 International Conference on Particle Induced X-ray Emission and its Analytical Applications, 4-8 June 2004, Portoroze (Slovenia)

Relative velocity correlations for fragments emitted in the reactions $^{124}\text{Sn} + ^{64}\text{Ni}$ and $^{112}\text{Sn} + ^{58}\text{Ni}$ at 35 AMeV

G. Lanzalone for Isospin collaboration

Poster presentation at International Nuclear Physic Conference 2004, June 27 - July 2 2004, Goteborg (Sweden)

Studio comparativo mediante spettroscopia di Risonanza Magnetica Nucleare degli

effetti dell'irraggiamento con fasci di protoni e di fotoni in cellule tumorali

V.Viti, S.Grande, C.Giovannini, L.Guidoni, P.A.Lojacono, A.M.Luciani, A.Palma, V.I.Patti, L.Raffaele, A.Rosi, O.Sapora, L.M.Valastro

XII Convegno Nazionale della Società Italiana per le Ricerche sulle Radiazioni (SIRR), Genova, 9-12 nov-2004

Studio comparativo degli effetti dell'irraggiamento con fasci di protoni e di fotoni in cellule tumorali mediante ^1H NMR

S.Grande, A.Rosi, L.Guidoni, A.M.Luciani, P.A.Lojacono, V.I.Patti, L.M.Valastro, R.Cherubini, S.Gerardi, V.Viti

Acta Biophysica Romana 2004, Università degli Studi di Roma, "La Sapienza", 17-18/6/2004

Strip Monolithic Telescopes

F.Amorini, G.Cardella, A.Di Pietro, P.Fallica, P.Figuera, A.Morea, A.Musumarra, M.Papa, G.Pappalardo, A.Pinto, F.Rizzo, W.Tian, S.Tudisco, G.Valvo

IMTC 2004-Instrumentation and Measurement Technology Conference

Surface effects evidence in the non-destructive XRF analysis and the new Deep Proton Activation Analysis (DPAA) method

L.Pappalardo

Study of the photon emission from plasma generated by fast pulsed laser

L.Torresi, E.Amato, S.Gammino

2nd German-Polish Conf on Plasma Diagnostics, Krakow (2004)

Study of the quasi-projectile in $^{124}\text{Sn}+^{64}\text{Ni}$ and $^{112}\text{Sn}+^{58}\text{Ni}$ reactions with the CHIMERA detector

Emmanuel Galichet for Isospin collaboration
Colloquies des Ganil june 2004

Studi del quasi proiettile nelle reazioni $^{124}\text{Sn}+^{64}\text{Ni}$ e $^{112}\text{Sn}+^{58}\text{Ni}$ mediante il rivelatore CHIMERA

Emmanuel Galichet for Isospin collaboration
XC SIF Brescia 20-9-2004

Surface effects evidence in the non-destructive XRF analysis and the new Deep Proton Activation Analysis (DPAA) method.

G.Pappalardo, F.Rizzo, A.Esposito, L.Pappalardo, P.F.Romano, G.A.Cirrone, G.Cuttone, S.Garraffo, S.Russo.

III Congresso Nazionale AIAR, "L'Archeometria in Italia: La scienza per i Beni Culturali", Bressanone, 11/12 Febbraio, 2004.

Superconducting ecr ion sources: high intensity beams extraction and transport

S.Gammino, G.Ciavola, L.Celona, L.Andò, P.Spadtke, M.Winkler,

Proc. 17th Int. Conf. On Cyclotrons and Appl., Tokyo, 2004

Test of scintillator readout with single photon avalanche photodiodes

P.Finocchiaro et al.,

Proceedings of the IEEE Nuclear Science Symposium 2004, Rome, Italy, October 16-22, 2004

The Neutrino Mediterranean Observatory project

P.Piattelli

XXI International Conference on neutrino physics and astrophysics, Paris, 13-19 june 2004

The Physics Program of the HADES Experiment at GSI

R.Holzmann et al.,

Proceedings of the 42th International Winter Meeting on Nuclear Physics, Bormio (2004)

3° Congresso Nazionale - L'Archeometria in Italia: La Scienza per i Beni Culturali" Bressanone, 11-12 Febbraio 2004
No effect of modelled gravity on the chromosome aberration dose response curve following low LET irradiation

L.Manti, G.A.P.Cirrone, M.Durante, G.Gialanella, G.Grossi, M.Lattuada, P.Scampoli, M.Pugliese, M.G.Sabini, L.Valastro

33rd Annual Meeting of the European Society for Radiation Biology, August 2004, Budapest

Seminars at LNS

- March 15 **Alexey Korshennikov, RIKEN**
Recent experimental studies of exotic nuclei
- March 16 **Y.Blumenfeld, Institut de Physique Nucleaire d'Orsay**
Reactions at the neutron drip-line
- March 18 **J.A.Scarpaci, Institut de Physique Nucleaire d'Orsay**
Exclusive measurement of the ^{48}Ti (^{11}Be , $^{10}\text{Be} + n + \gamma$) reaction at 41 MeV/A
- April 5 **F. Hanappe, ULP Brussels**
Dynamics of capture reactions in super heavy element region
- April 20 **Kamran Akhtar, Wisconsin University**
Elicon Plasma Sources
- April 21 **Kamran Akhtar, Wisconsin University**
Millimeter wave interferometry for highly collisional plasma
- May 31 **T. Motobayashi, RIKEN**
Coulomb dissociation
- May 30 **T. Motobayashi, RIKEN**
Application of intermediate-energy Coulomb excitation to astrophysical reactions at RIKEN (1st part)
- June 1 **T. Motobayashi, RIKEN**
Application of intermediate-energy Coulomb excitation to astrophysical reactions at RIKEN (2nd part)
- June 3 **Akram Mukhamedzhanov, TEXAS A&M University**
Insight the Trojan Horse (part one)
- June 4 **Akram Mukhamedzhanov, TEXAS A&M University**
Insight the Trojan Horse (part two)
- June 7 **Akram Mukhamedzhanov, TEXAS A&M University**
p+d as a way to Trojan Horse Method
- June 25 **Alison M. Laird**
Exploding stars in the lab: nuclear astrophysics at TRIUMF
- June 30 **Armando Bazzani, Università di Bologna**
Applicazioni delle Forme Normali di Birkhoff alla Fisica degli acceleratori
- July 6 **Jacques de Sanoit, Saclay**
Electrodeposition of ^{244}Cm from DMF electrolyte
- July 7 **Jacques de Sanoit, Saclay**
Realisation of a ^{244}Cm source
- July 8 **Hui Hua, Peking University**
Experiments with the A1900 fragment separator at Michigan State University
- September 13 **Jirota Kasagi, Laboratory for Nuclear Science - Tohoku University, Sendai (Japan)**
Medium effects; hadrons in nuclear matter and nuclei in condensed matter
- November 9 **Alain Coc, CSNSM, Orsay**
Updated BIG BANG nucleosynthesis compared to WMAP and the abundance of light nuclei

November 15 **Francois De Oliveira Santos, GANIL**
The first SPIRAL experiment

December 7 **Thereza Borello-Lewin, Instituto de Física da Universidade de São Paulo, Brazil**
Isospin character of the first quadrupole transition in the region $A \sim 100$

EXPERIMENTS PERFORMED AT THE LNS ACCELERATORS

Superconducting Cyclotron				
Proposal	Spokesperson Affiliation	Title	Beam, Energy (AMeV)	Hours
LITHO	B.Volckaerts (Vrije Univ. Brussel)	The Fabrication of Micro Opto-Mechanical Components with High Energetic Heavy Ion Beams	^{12}C , 62 MeV	40
CATANA	G.Cuttone (INFN-LNS)	CATANA	p, 62	289
METABOLIC	V.Viti (ISS-INFN- Roma)	Metabolic effects induced by proton irradiation of human tumor cells as evidenced by Magnetic Resonance Spectroscopy	p 62	48
BIOEFFECTS	M. Purrello (Univ. Catania)	Analysis of proton beams biological effects and their therapeutic applications	p, 62	24
DNA-MECH	M. Belli Istituto Superiore di Sanità and INFN	Mechanisms of dna damage induction and repair by charged particles in cultured human cells	^{12}C , 62	72
NASTRI-CS	E. Mezzetti (I.N.F.N.-Sez. Torino and Politecnico di Torino)	NAno STructures Radiation Induced	^{197}Au , 21	96,
BEAM TESTS			^{12}C , 80, p, 62	88
CALIBRATION	A. Pagano (INFN-Sez. Catania)	Calibration of CHIMERA II campaign with CS beam	HeH, p,d, ^{20}Ne , 21-62	80
MID-VELOCITY	G. Poggi (INFN-Univ. Firenze)	Mid-Velocity LCP and IMF emission	^{112}Sn , 35 ^{58}Ni , 35-45	288
CECIL	W.U. Schröder University of Rochester	Cluster Emission with CHIMERA at LNS: Study of a new type of phase transition	^{112}Sn , 35-43	136
ISO-EOS	W.L. Lynch (MSU – USA)	Isospin dynamics and the isospin dependent EOS	$^{112,124}\text{Sn}$, 35	120
DI-PROTON	G. Cardella – G. Raciti (INFN-Univ. Catania)	Search for di-proton decay of ^{18}Ne	^{20}Ne , 45-62	160
CHIMERAPS	A.Pagano-G.Politi (INFN-Sez. Catania)	Pulse shape with the CHIMERA Detector	^{20}Ne , 21	88p
				1529

Tandem				
Proposal	Spokesperson Affiliation	Title	Beam, Energy (AMeV)	Hours
LITHO	B.Volckaerts (Vrije Univ. Brussel)	The fabrication of micro opto-mechanical components with highly energetic heavy ion beams	^{12}C , 5 AMeV	158
DIAMOND	R.Potenza, C.Tuvé (Univ. Catania)	Quality standardization of diamond detectors	^6Li , ^{12}C , 7.5	272
NASTRI-T	E. Mezzetti (I.N.F.N.- Sez. Torino and Politecnico di Torino)	NAno STructures Radiation Induced	^{197}Au , 1	69
DPAA	F. Rizzo (INFN-Univ. Catania)	Deep Proton Activation Analysis	p, 22	166
PIRAMIDE	G.Busatto (Univ. Cassino)	Particle IRadiation tests for Aerspase Missions of power DEvices	^{58}Ni , ^{79}Br , 2.5	334
DETEC.TESTS	R. Bonetti (Univ. Milano)		^{14}N , 5	38
CALIBRATION	A.Pagano (INFN-Sez.Catania)	Calibration of CHIMERA II campaign with Tandem beam	p, 5-26,d 5-13	124
ISOMERIC	G. Lo Bianco (Univ. Camerino-INFN Perugia)	A search for isomeric states in ^{139}Nd	^{18}O , 5	140
BIG BANG	C.Rolfs (Ruhr-Univ. Bochum)	Astrophysical S(E) factor of $^8\text{Li}(\alpha,n)^{11}\text{B}$: Big Bang nucleosynthesis	^9Be , 1	112
RSM	A. Di Pietro (INFN-LNS)	Study of ^9Li - α cluster states in ^{13}B using the Resonance Scattering Method	^9Be , ^{18}O , 4	161
				1574

INFN Fellows

- | | |
|-----------------------------|------------------------------|
| 1. CAO Ligang | 12. GALATA' Alessio |
| 2. CAPPUZZELLO Francesco | 13. KHOUAJA Abdenbi |
| 3. CIRRONE Giuseppe | 14. KIMURA Sakie |
| 4. COCIMANO Rosanna | 15. MUSUMECI Mario Salvatore |
| 5. CONSOLI Fabrizio | 16. NOCIFORO Chiara |
| 6. COSENTINO Luigi | 17. OCCHIPINTI AMATO Rosario |
| 7. COSTA Michele | 18. PELLEGRITI Nicola |
| 8. D'AMICO Antonio | 19. PIZZONE Rosario |
| 9. DISTEFANO Carla | 20. PRESTI Mario |
| 10. DIANA Benedetto Filippo | 21. SCUDERI Dario |
| 11. GAITANOS Theodoros | 22. TUDISCO Daniele |

INFN/CIAE Fellows

- | | |
|-----------------|------------------|
| 1. FAN Hongshen | |
| 2. LI Xia | 4. ZHANG Xuezhen |
| 3. MA JunYing | 5. ZHONG Junqing |

Other fellows

- | | |
|-------------------------|-----------------------------|
| 1. AMORINI Francesca | 13. MONGELLI Vincenza |
| 2. BONANNO Antonino | 14. PATTI Iolanda Valeria |
| 3. CABIBBO Maurizio | 15. PEDALINO Alberto |
| 4. CHERUBINI Silvio | 16. PELLEGRITI Maria Grazia |
| 5. DI ROSA Francesco | 17. SFIENTI Concettina |
| 6. GULINO Marisa | 18. SIRAGUSA Carmelo |
| 7. KUZNETSOV Viacheslav | 19. TUDISCO Salvatore |
| 8. LANZALONE Gaetano | 20. TUMINO Aurora |
| 9. LAZZARO Alberto | 21. VALASTRO Lucia Maria |
| 10. LOJACONO Pietro | |
| 11. MAMMOLITI Francesco | |
| 12. MIDILI Francesca | |

PHD Students

- | | |
|----------------------------------|----------------------------|
| 1. BONOMO Carmen | 14. PAVAN Giovanni |
| 2. CRUCILLA' Vincenzo | 15. PRIVITERA Giuseppe |
| 3. DE NAPOLI Marzio | 16. PRIVITERA Simona |
| 4. FERINI Graziella | 17. RAPISARDA Elisa |
| 5. GIUSA Antonio | 18. RINOLLO Angelo |
| 6. GUARINO Pietro | 19. RIZZO Joseph |
| 7. IACONO MANNO Carmelo Marcello | 20. RUSSO Giorgio |
| 8. LA COGNATA Marco | 21. RUSSOTTO Paolo |
| 9. LA GUIDARA Elena | 22. SABINI Maria Gabriella |
| 10. LAMIA Livio | 23. SALAMONE Vincenzo |
| 11. MAGGIORE Mario | 24. SPATARO Stefano |
| 12. MANCIAGLI Sebastiano | 25. SPEZZI Loredana |
| 13. ORRIGO Sonja | 26. TERRANOVA Salvatrice |

Under Graduated

- | | |
|---------------------------|--------------------------|
| 1. AMORE Isabella | 12. MARGARONE Daniele |
| 2. BATTAGLIA Daniele | 13. MASSIMINO Angela |
| 3. BONANNO Luca Salvatore | 14. MORABITO Vittoria |
| 4. BUFALINO Stefania | 15. MUDO' Francesca |
| 5. CALANNA Ausilia | 16. PANSINI Floriana |
| 6. CARACE Fausto | 17. PIAZZA Leandro |
| 7. CAVALLARO Manuela | 18. PITTERA Salvatore |
| 8. LIONTI Riccardo | 19. PUGLISI Donatella |
| 9. LO PRESTI Carmelo | 20. RAPISARDA Giuseppe |
| 10. LONGO Giovanni | 21. SANTINI Elvira |
| 11. MANZITTO Patrizia | 22. SCUDERI Valentina |
| | 23. SERGI Maria Letizia |
| | 24. STRAZZERI Elisabetta |

Scientific Guest

Events

January 19-24	Dynamics and Thermodynamics with Nucleonic Degrees of Freedom
February	Olimpiadi della Fisica
March 1-6	XIV Settimana della Cultura Scientifica eTecnologica
May 21	Premiazione vincitori Selezione Olimpiadi della Fisica
June 3	Innovazione e Industria... una necessità nazionale: le opportunità per Catania
July 19-22	Corso MATHLAB
Oct 3-9	GEANT 4 workshop
Oct 11-15	La risonanza magnetica nucleare nelle applicazioni mediche: qualità e sicurezza
Dec 1-2	LNS Scientific Committee
Dec 2-3	I rivelatori di radiazione in radioterapia
Dec 3	LNS Users' Committee

The NEMO Collaboration

S. Aiello ^a, M. Ambriola ^b, F. Ameli ^c, G. Andronico ^a, M. Anghinolfi ^d, M. Battaglieri ^d, R. Bellotti ^a, A. Bersani ^d, A. Boldrin ^e, M. Bonori ^c, F. Cafagna ^b, A. Capone ^c, L. Caponnetto ^a, E. Castorina ^f, V. Cavasinni ^f, T. Chiarusi ^c, M. Circella ^b, R. Cocimano ^g, R. Coniglione ^g, M. Cordelli ^h, M. Costa ^g, S. Cuneo ^d, A. D'Amico ^g, C. De Marzo ^b, R. De Vita ^d, C. Distefano ^g, E. Falchini ^f, V. Flaminio ^f, A. Gabrielli ⁱ, S. Galeotti ^f, E. Gandolfi ⁱ, A. Grimaldi ^a, R. Habel ^j, L. Lo Nigro ^a, D. Lo Presti ^a, A. Margiotto ⁱ, A. Martini ^h, M. Masetti ⁱ, R. Masullo ^c, E. Migneco ^g, T. Montaruli ^b, M. Morganti ^f, R. Mosetti ^k, M. Musumeci ^a, C.A. Nicolau ^c, R. Papaleo ^g, C. Petta ^a, P. Piattelli ^g, F. Raffaelli ^f, G. Raia ^g, N. Randazzo ^a, S. Reito ^a, G. Ricco ^d, G. Riccobene ^g, M. Ripani ^d, M. Romita ^b, A. Rovelli ^g, M. Ruppi ^b, G.V. Russo ^a, M. Russo ^a, P. Sapienza ^g, J.P. Schuller ^c, M. Sedita ^g, I. Sokalski ^b, M. Spurio ⁱ, M. Taiuti ^d, G. Terreni ^f, L. Trasatti ^h, L. Ursella ^k, V. Valente ^h, P. Vicini ^c, G. Zanarini ^c

(The NEMO Collaboration)

- a) INFN, Sezione di Catania & Dipartimento di Fisica dell'Università di Catania, Catania (Italy)*
- b) INFN, Sezione di Bari & Dipartimento di Fisica dell'Università di Bari, Bari (Italy)*
- c) INFN, Sezione di Roma 1 & Dipartimento di Fisica dell'Università di Roma "La Sapienza", Roma, (Italy)*
- d) INFN, Sezione di Genova & Dipartimento di Fisica dell'Università di Genova, Genova (Italy)*
- e) ISMAR-CNR, Venezia (Italy)*
- f) INFN, Sezione di Pisa & Dipartimento di Fisica dell'Università di Pisa, Pisa (Italy)*
- g) INFN, Laboratori Nazionali del Sud, Catania (Italy)*
- h) INFN, Laboratori Nazionali di Frascati, Frascati (Italy)*
- i) INFN, Sezione di Bologna & Dipartimento di Fisica dell'Università di Bologna, Bologna, (Italy)*
- j) INFN, Sezione di Cagliari & Dipartimento di Fisica dell'Università di Cagliari, Cagliari (Italy)*
- k) Istituto Nazionale di Oceanografia e Geofisica Sperimentale, Sgonico (TS), (Italy)*