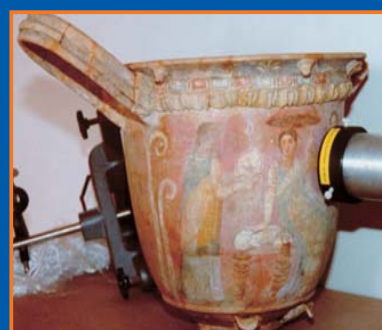


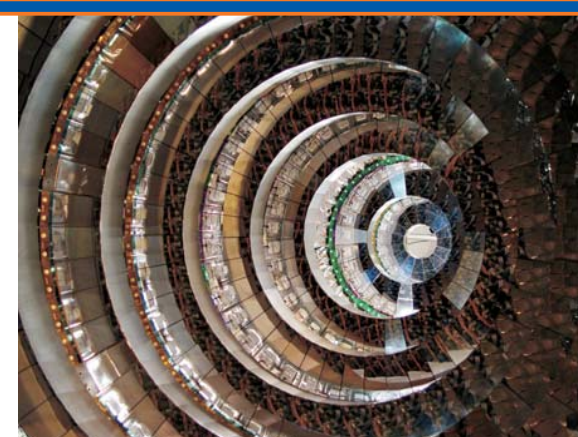
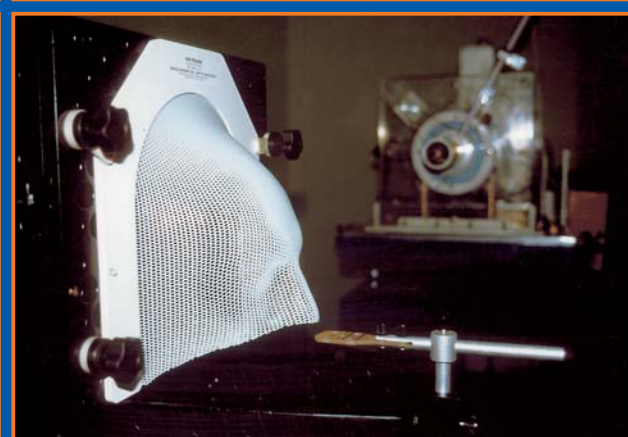
ACTIVITY REPORT 2006



INFN - LNS

ISTITUTO NAZIONALE DI FISICA NUCLEARE
LABORATORI NAZIONALI DEL SUD

Via S. Sofia, 62 - 95123 CATANIA
Phone ++39 095 542111 • Fax ++39 095 7141815
E-mail • direzione@lns.infn.it
<http://www.lns.infn.it/>



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LNS Activity Report 2006

**Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Sud**

LNS Activity Report 2006

Foreword

Catania, June 2007

In 2006 LNS celebrated its 30 years of life. It was founded in 1976, indeed, thanks to the agreement signed by INFN, the University of Catania and the Regional Government of Sicily that decided to join their efforts to create in Catania a nuclear research laboratory. Few years later it became the third National Laboratory of INFN, after the ones in Frascati and Legnaro and a fervent experimental activity started at the beginning of 80's with the ion beams produced by the first LNS accelerator, a SMP 13 MV Tandem, later upgraded to 15 MV.

The next important steps in the history of LNS were the installation of the Superconducting Cyclotron (SC) as post-accelerator of the Tandem in 1990 and the beginning of the experimental campaigns with intermediate energy beams in 1995. In 2000 the two accelerators were decoupled thanks to the axial injection of the SC by means of ECR sources developed at LNS. Since that time the two accelerators can run contemporarily, sending their respective beams to different experimental locations. From the point of view of the ion beam production, the last development is EXCYT, a radioactive beam ISOL-type facility using the SC as primary accelerator and the Tandem as post-accelerator, whose completion has been accomplished just in these last years.

During all this time, sophisticated detection systems have been developed, from the MEDEA-SOLE-MACISTE facility to TRASMA, from CHIMERA to MAGNEX, just to mention some of them, attracting users from everywhere in the world, as further acknowledgement of the high level of the LNS research infrastructures.

Research on nuclear structure and reaction mechanisms, from both the experimental and theoretical point of view, was of course the first activity of LNS and is still largely pursued, but during these years a number of new initiatives arose, mainly devoted to the application of nuclear techniques and the use of ion beams for interdisciplinary purposes, in the field of biology, medicine, solid state physics and cultural heritage. The most relevant example of these activities is represented, with no doubts, by the realization of CATANA, a facility allowing the treatment of ocular pathologies by means of the proton beam produced by the SC.

In the last years a new enterprise was undertaken in the field of astroparticle physics, with the final goal of realizing a submarine observatory for high energy cosmic neutrinos (NEMO), consisting in a cubic kilometer array of Cherenkov detectors to be deployed in the Mediterranean sea at a depth of 3000-4000 m. An intense R&D activity is performed at LNS in this field to test and validate the underwater technologies to be adopted for the construction of the observatory. Moreover a hard work of computer simulation is currently done, with the aim of designing the most efficient geometry of the array.

In the following the reader can find reports of the activities performed at LNS during 2006, that range from nuclear physics to astroparticle physics, from interdisciplinary researches to technological developments of accelerators and ion sources. All of them are the result of the synergic growth of LNS people and LNS facilities in these last 30 years.

Prof. Marcello Lattuada
LNS Director

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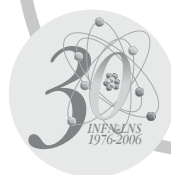
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Experimental Nuclear Physics

A



DYNAMICAL ASPECTS OF FRAGMENT PRODUCTIONS IN THE REACTION $^{124}\text{Sn}+^{27}\text{Al}$ AT 35 A.MEV, STUDIED WITH THE CHIMERA DETECTOR AT INFN-LNS

E. La Guidara^a, S.Pirrone^a, F.Amorini^b, A.Anzalone^b, L.Auditore^c, V.Baran^d, I.Berceanu^d, J.Blicharska^e, B.Borderie^f, R.Bougault^g, M.Bruno^h, J.Brzychczykⁱ, G.Cardella^a, S.Cavallaro^b, M.B.Chatterjee^j, A.Chbihi^k, M.Colonna^b, M.D'Agostino^h, R.Dayras^l, E.De Filippo^a, M.Di Toro^b, U.Emanuele^c, J.Frankland^k, E.Galichet^f, W.Gawlikowiczⁱ, E.Geraci^h, F.Giustolisi^b, A.Grzeszczuk^e, P.Guazzoni^m, S.Kowalski^{fe}, G.Lanzanò^a, G.Lanzalone^b, N.Le Neindre^f, C.Maiolino^b, Z.Majkaⁱ, A.Pagano^a, M.Papa^a, M.Petrovici^d, E.Piaseckiⁿ, R.Planetaⁱ, G.Politi^a, A.Pop^d, F.Porto^b, M.F.Rivet^f, E.Rosato^o, F.Rizzo^b, S.Russo^m, P.Russotto^b, K.Schmidt^e, K.Siwiek-Wilczynskaⁿ, I.Skwiraⁿ, L.Swidorskiⁿ, A.Trifirò^c, M.Trimarchi^c, G.Vannini^h, M.Vigilante^o, J.P.Wieleczko^k, J.Wilczynski^p, L.Zetta^m and W. Zipper^e

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

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

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

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

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

f) Institut de Physique Nucléaire, IN2P3-CNRS, Orsay, France

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

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

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

j) Saha Institute of Nuclear Physics, Kolkata, India

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

l) DAPNIA/SPH, CEA-Saclay, France

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

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

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

p) A. Soltan Institute for Nuclear Studies, Swierk/Warsaw, Poland

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

Abstract

Some properties of the intermediate mass fragments (IMF) with atomic number $3 \leq Z < 12$, emitted in the $^{124}\text{Sn}+^{27}\text{Al}$ reaction at 35 A.MeV were studied by using the forward part of the Charge Heavy Ion Mass and Energy Resolving Array (CHIMERA) and the method already applied by our group for the system $^{124}\text{Sn}+^{64}\text{Ni}$ at 35 A.MeV. We studied the fragment production in semi-peripheral collisions, in order to disentangle fragments produced in the initial dynamical stage of the collision from the ones coming from the sequential decay. The applied procedure, allows us to get information on the time scale and time sequence of the neck fragmentation processes. New results on $^{124}\text{Sn}+^{27}\text{Al}$ at 35 A.MeV will be presented.

1 INTRODUCTION

In this contribution we present results concerning the origin of the fragments produced in nuclear collision at intermediate energies. In particular we concentrate our attention on the study of the intermediate mass fragment production with special regard to the mid-rapidity source formed in semi-peripheral reactions, by investigating the system $^{124}\text{Sn}+^{27}\text{Al}$ at 35 A.MeV with the experimental method already applied in ref.[1]. A comparison with the system $^{124}\text{Sn}+^{64}\text{Ni}$ at 35 A.MeV is made.

2 EXPERIMENTAL SETUP

The experiment was performed by using beams delivered by the Super Conducting Cyclotron of the LNS in Catania. Charged particles were detected with the

CHIMERA apparatus, that is a 4π detector for charged particles with high granularity and large covering of the total solid angle (94%). The apparatus is formed by 1192 Si-CsI(Tl) telescopes, covering the angular range between 1° to 176° , arranged in 35 rings in a cylindrical geometry having 2π azimuthal symmetry along the beam axis. The data discussed were collected in the REVERSE campaign realized with the forward part of the CHIMERA detector, which consists of 688 modules arranged in 9 rings covering the polar angles between 1° and 30° . In order to identify the reaction products, three identification methods have been used: TOF, ΔE -E and PSD [2-5].

3 DATA ANALYSIS AND RESULTS

Experimental data on $^{124}\text{Sn}+^{27}\text{Al}$ collisions at 35 A.MeV have been collected with the beam intensity of about 5×10^7 pps, sufficiently low to minimize pile up at the most forward angles. In total, 3×10^7 events triggered by the condition of a detected particle multiplicity $M \geq 3$ were recorded.

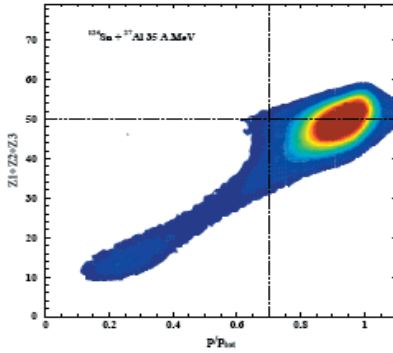


Fig.1 Sum of the charges of the three heaviest fragments, as a function of their linear parallel momentum, p , normalized to the beam particle momentum, p_{tot} .

In the following, we analyze almost completely reconstructed "nearly ternary" reactions, in which, in addition to the remnants of the projectile and target nuclei, PLF and TLF, respectively, also a third fragment, an IMF of $Z \geq 3$ was detected. So, in order to select this class of events, we have plotted in Fig. 1 the sum of the charge of the three heaviest fragments, $Z_1+Z_2+Z_3$, versus the sum of their linear parallel momenta (i.e. the projection of the linear momentum vector along the beam axis), normalized to the beam particle momentum, p_{tot} . The "nearly ternary" events are localized in the upper right-hand-side end of this plot, in which, possible charge and momentum missing can be attributed to pre-equilibrium emission and/or evaporation of light particles of $Z \leq 2$ at various stages of the reaction. Consequently, "good events" have been selected by requiring that the sum of the charge of the three heaviest fragments was $Z_1+Z_2+Z_3 > 50$. With such a condition the three fragments jointly carry a parallel linear momentum equal to at least 70% of the projectile momentum. For these classes of

events, we have plotted the charge of an individual fragment as a function of its parallel velocity, v_{par} , Fig. 2 (Left), for the system $^{124}\text{Sn}+^{27}\text{Al}$.

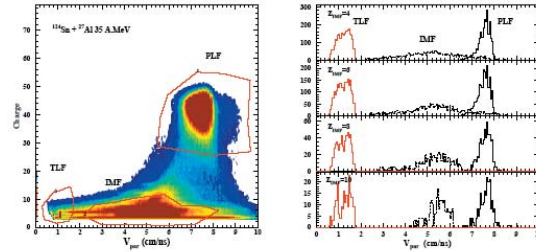


Fig.2 Left: Charge of the emitted fragment as a function of its parallel velocity v_{par} for $^{124}\text{Sn}+^{27}\text{Al}$ at 35 A.MeV. Right: Parallel velocity distributions of PLFs, TLFs, and IMFs for selected IMF with charge $Z_{IMF} = 4, 6, 8, 10$.

We can see that three distinctive groups of fragments can be separated and recognized as PLFs (fragments having the beam velocity), TLFs (slowing moving fragments) and IMFs (fragments with small charge and having intermediate velocity between the projectile-like one and the target-like one).

The analysis has been restricted to a selection of data, performed by considering the event space in which PLF, TLF, and IMF were classified by applying contour gates in Z vs. v_{par} distribution. In order to illustrate the basic properties of the selected events, in Fig. 2 (Right) the parallel velocity distribution for IMF with $Z_{IMF} = 4, 6, 8, 10$ respectively, is plotted in coincidence with PLF and TLF fragments for the same event. For this reaction $v_{beam} = 8$ cm/ns, $v_{NN} = 4$ cm/ns (nucleon-nucleon mid-velocity source) and $v_{cm} = 6.6$ cm/ns (centre of mass velocity source). We observe that the cross section for the IMF production decreases as the IMF charge increases and that increasing the charge of the IMF, the velocity distribution moves to larger values close to the PLF velocity component.

Important information on the time scale of the IMF emission for the selected class of events, can be obtained by inspecting the behavior of the relative velocities between the two sub systems PLF-IMF and TLF-IMF of the same ternary event. In our analysis by using the method already described in [1], we evaluated, event by event, the relative velocities of IMFs with respect to the PLFs and TLFs ones, i.e., $v_{rel}(\text{IMF-PLF})$ and $v_{rel}(\text{IMF-TLF})$, respectively. Each of these two quantities, was normalized to the respective Viola velocity, v_{Viola} , evaluated by assuming a value of the relative kinetic energy as given by the Viola systematic [7].

The values $v_{rel}/v_{Viola}(\text{IMF-PLF}) = 1$ and $v_{rel}/v_{Viola}(\text{IMF-TLF}) = 1$ indicate a sequential splitting of the sub systems, essentially determined by a Coulomb repulsion.

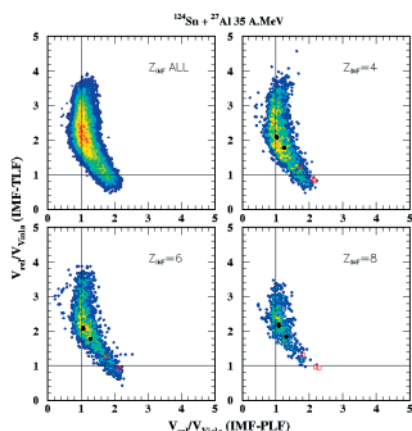


Fig.3 Relative velocity correlations for different IMF of $Z = 4, 6, 8$. The point in the figure represent the estimated time emission by Coulomb trajectory calculations for ternary events [6].

The correlation of these velocities is shown in Fig. 3 for the $^{124}\text{Sn} + ^{27}\text{Al}$ at 35 A.MeV. Beside the sequential decay of PLF's or TLF's, our analysis indicates a strong deviation of Viola systematic, for events located close to the diagonal of each plot of Fig.3. In agreement with ref.[1], these events are interpreted as prompt emission of IMF's from the transient overlap region between PLF and TLF, the so-called "neck region". We notice that fragments originating from the sequential target emission (events located nearly the horizontal line $v_{\text{rel}}/v_{\text{Viola}}(\text{IMF-TLF})=1$) are strongly suppressed to respect to the fragments originate from the sequential projectile emission (events located nearly the vertical line $v_{\text{rel}}/v_{\text{Viola}}(\text{IMF-PLF})=1$). A comparison with Sn induced reaction on Ni-target [1], indicates that this effect was already noticed. However for this lighter target ^{27}Al it is more pronounced (for a given IMF charge), indicating a sizeable influence of the mass asymmetry of the colliding systems on the neck fragmentation process. However, before to get more definitive conclusion about the detected phenomenon, we need to run simulations in order to better evaluate the effect of the mass asymmetry on the TLF detection efficiency. Further studies and simulations are in progress. An other effect, already observed in ref.[1], concerns the competition between dynamical component and sequential component of IMF production. Dynamical component is dominant for the lightest fragments and it is progressively replaced by the sequential emission when the mass of IMF increases. Evaluation of the time splitting needed to produce the observed deviation of the Viola systematic in the final stage of the reaction, indicates that the majority of IMF are emitted in almost a prompt or "fast-two-step" processes, within times of about 40-80 fm/c. Similar observations and time scale evaluations have been reported in ref.[8], for different system. On the contrary, the emission of heavy IMF's takes place at least 100-150 fm/c after the colliding system starts to re-separate. In this sense light IMF's are produced earlier than heavy fragments.

4 CONCLUSIONS

Ternary events for the $^{124}\text{Sn} + ^{27}\text{Al}$ at 35 A.MeV reaction have been analyzed by using a methods based on relative velocity correlation; a strong dynamical emission of IMF centred at mid rapidity has been evidenced and interpreted as fast neck emission produced during the collapse time between the interacting projectile and target, in agreement with ref.[1]. Simple estimations confirm a time scale for the process ranging between 40 and 120 fm/c. The data show a clear coexistence of a prompt and sequential component of IMF decay. Sequential component becomes the dominant component with increasing the charge of the IMF fragments.

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DYNAMICAL EMISSION OF HEAVY FRAGMENTS IN $^{124}\text{Sn}+^{64}\text{Ni}$ AND $^{112}\text{Sn}+^{58}\text{Ni}$ AT 35 A.MeV AS SEEN WITH CHIMERA

P.Russotto^{a*}, E.Piasecki^b, F.Amorini^a, A.Anzalone^a, L.Auditore^c, V.Baran^d, I.Berceanu^d, J.Blicharska^e, B.Borderie^f, R.Bougault^g, M.Bruno^h, J.Brzychczykⁱ, G.Cardella^j, S.Cavallaro^a, M.B.Chatterjee^k, A.Chbihi^l, M.Colonna^a, M.D'Agostino^h, R.Dayras^m, E.De Filippo^j, M.Di Toro^a, U.Emanuele^c, J.Frankland^l, E.Galichet^f, W.Gawlikowicz^l, E.Geraci^h, F.Giustolisi^a, A.Grzeszczuk^e, P.Guazzoniⁿ, S.Kowalski^e, E. La Guidara^j, G.Lanzanò^j, G.Lanzalone^a, N.Le Neindre^f, C.Maiolino^a, Z.Majkaⁱ, A.Pagano^j, M.Papa^j, M.Petrovici^d, S.Pirrone^j, R.Planetaⁱ, G.Politi^j, A.Pop^d, F.Porto^a, M.F.Rivet^f, E.Rosato^o, F.Rizzo^a, K.Schmidt^e, K.Siwiek-Wilczynska^p, I.Skwira^p, L. Swiderski^p, A.Trifirò^e, M.Trimarchi^c, G.Vannini^h, M.Vigilante^o, J.P.Wieleczko^l, J.Wilczynski^q, L.Zettaⁿ and W. Zipper^e.

- a) INFN, Sez. di Catania and Dipartimento di Fisica e Astronomia, Università di Catania, Italy
 b) Heavy Ion Laboratory, Univ. of Warsaw and Institute for Nuclear Studies, Swierk, Poland
 c) INFN, Gruppo Collegato di Messina and Dipartimento di Fisica, Università di Messina, Italy
 d) Institute for Physics and Nuclear Engineering, Bucharest, Romania
 e) Institute of Physics, University of Silesia, Katowice, Poland
 f) Institut de Physique Nucléaire, IN2P3-CNRS, Orsay, France
 g) LPC, ENSI Caen and Université de Caen, France
 h) INFN, Sezione di Bologna and Dipartimento di Fisica, Università di Bologna, Italy
 i) M. Smoluchowski Institute of Physics, Jagellonian University, Cracow, Poland
 j) INFN, Lab. Nazionali del Sud and Dip. di Fisica e Astronomia, Università di Catania, Italy
 k) Saha Institute of Nuclear Physics, Kolkata, India
 l) GANIL, CEA, IN2P3-CNRS, Caen, France
 m) DAPNIA/SPH, CEA-Saclay, France
 n) INFN, Sezione di Milano and Dipartimento di Fisica, Università di Milano, Italy
 o) INFN, Sezione Napoli and Dipartimento di Fisica, Università di Napoli, Italy
 p) Institute of Experimental Physics, Warsaw University, Warsaw, Poland
 q) A. Soltan Institute for Nuclear Studies, Swierk/Warsaw, Poland
 *Corresponding author e-mail: russotto@lns.infn.it

Abstract

A quantitative comparison regarding absolute weight of Statistical and Dynamical Fission in the systems $^{124}\text{Sn}+^{64}\text{Ni}$ and $^{112}\text{Sn}+^{58}\text{Ni}$ experimentally investigated at 35 A.MeV beam energy is presented. It results that Dynamical Fission process is about two times more probable in the neutron rich $^{124}\text{Sn}+^{64}\text{Ni}$ system than in the $^{112}\text{Sn}+^{58}\text{Ni}$ neutron poor one. This difference suggests an influence of entrance channel Isopin (N/Z) content on reaction mechanism [1].

1 INTRODUCTION

The phenomenon of fast, non-equilibrium splitting of projectile (Dynamical Fission) has been clearly seen, in $^{124}\text{Sn}+^{64}\text{Ni}$ and $^{112}\text{Sn}+^{58}\text{Ni}$ reaction at 35 A.MeV, in those cases where two strongly correlated (both in charge and in velocity space) heavy fragments coming from Projectile-Like Fragment (PLF) decay are observed [2,3,4]. The main signature of non equilibrium fission is that the heavier of the two PLF fission fragments is usually the faster one (i.e., it is forward directed in the

PLF reference system), while the lighter fragment is situated preferentially between its heavier partner and the target-like nucleus (TLF). At variance, in the case of the equilibrium PLF fission, the angular distribution of fission-like fragments is expected to be forward/backward symmetric in the PLF reference system.

In this work we have applied this useful framework of competition between statistical and dynamical fission to evaluate weight of Dynamical/Statistical effects in PLF decay in the experimental data obtained for $^{124}\text{Sn}+^{64}\text{Ni}$ (neutron rich) and $^{112}\text{Sn}+^{58}\text{Ni}$ (neutron poor) systems investigated at a laboratory energy of 35 A.MeV using the forward part ($1^\circ < \theta_{\text{lab}} < 30^\circ$) of the 4π CHIMERA multi-detector [5].

2 RESULTS

Since we are interested in the decay of PLF, we select for both systems peripheral collisions by requiring a low multiplicity of charged particles ($2 \leq M_{\text{tot}} \leq 7$), and concentrate our attention on events with two fragments

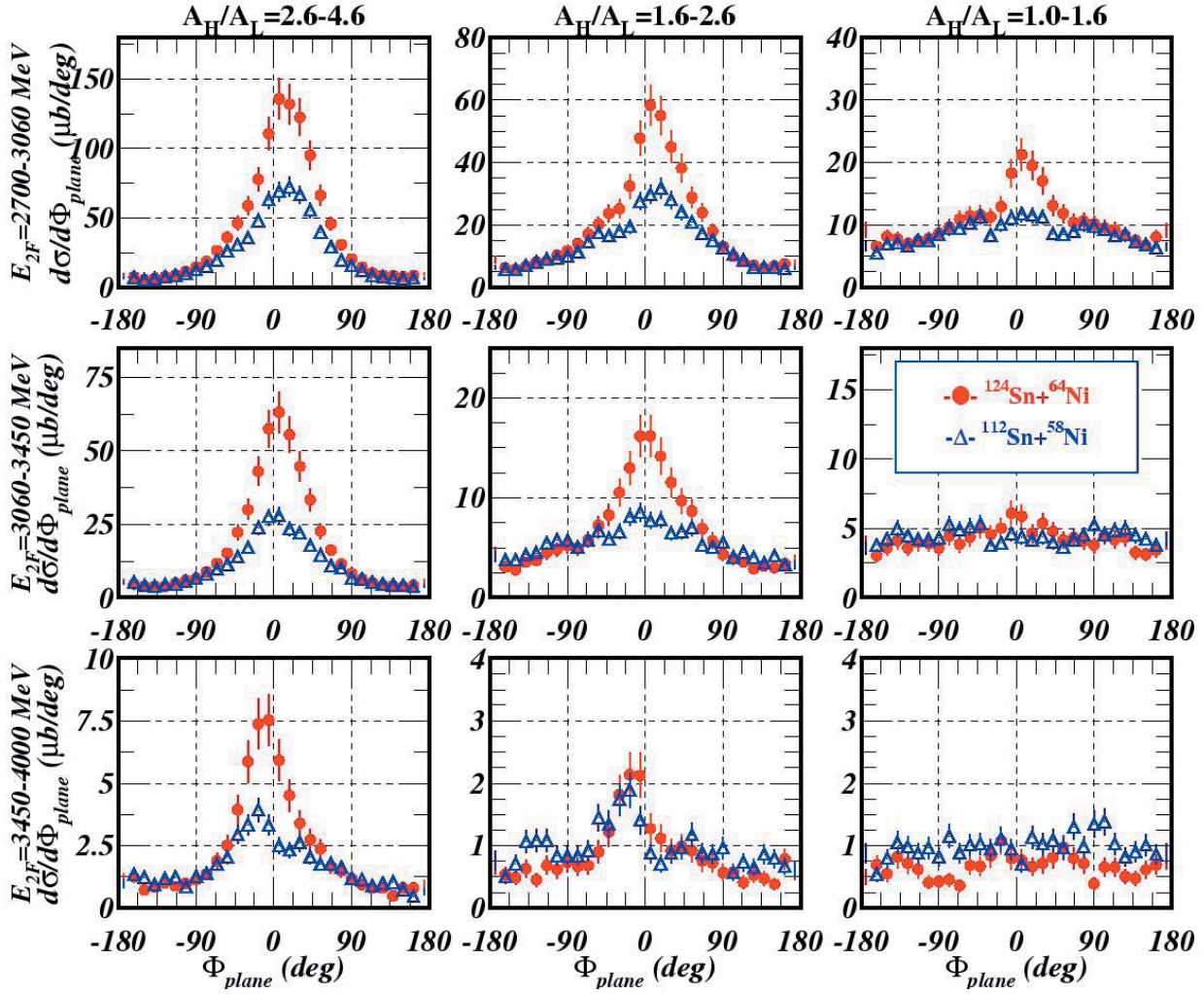


Fig. 1: PLF fission-like fragments "in-plane" angular cross sections for the $^{124}\text{Sn}+^{64}\text{Ni}$ (circles) and $^{112}\text{Sn}+^{58}\text{Ni}$ (triangles) systems at 35 A.MeV. Zero degrees indicates that heavier of the two fragments is forward emitted in the PLF reference system, strictly along PLF flight direction in the laboratory system.

forward emitted in CM reference system. Then we require the sum of the charges of these two fragments $37 \leq Z_{2F} \leq 57$, to be close to the charge of the PLF ($Z_{\text{proj}}=50$), and a Heavy/Light fragments mass ratios $A_H/A_L \leq 4.6$; in the systems investigated here this corresponds to $Z_L > \sim 9$ for the light fission fragments; a detailed description of this selection method is given in [2,3].

2.1 In-plane differential angular cross section

Once selected couple of PLF fission-like fragments, a detailed analysis of fission-like angular distribution has been performed. In Fig. 1 the obtained differential "in-plane" angular cross sections for the two Sn+Ni systems, in $\mu\text{barn/degree}$, are presented for three ranges of the mass asymmetry A_H/A_L (columns) and for three ranges of the total kinetic energy of the two selected fragments $E_{2F}=E_H+E_L$ (rows). The E_{2F} is a simple indicator of the collision violence: large values of E_{2F} are associated with most gentle (peripheral) collisions; more violent collisions lead to smaller E_{2F} values. The Φ_{plane} is the

fission angle in the reaction plane (see fig. 4 of [2] for definition). The value of $\Phi_{\text{plane}}=0^\circ$ corresponds to the heaviest fragment moving forward, strictly along the PLF flight direction. Equilibrated fission of PLF should result in a flat Φ_{plane} distribution, due to the loss of memory of the entrance channel. In both investigated systems, nearly symmetric splitting after peripheral collisions presents flat distribution characteristic of statistical fission. Instead, with the increasing mass asymmetry and collision inelasticity, we observe an increase of a forward peaked angular component with maxima located close to 0° , superimposed on a flat "statistical" distribution. This implies that the lighter fission-like partner is preferentially backward emitted in the PLF reference system, i.e. toward the TLF nucleus, resulting in an aligned three body configuration. This is the main signature of the persistency of dynamical emission also for heavy IMFs ($Z > \sim 10$) originating from the projectile-like decay, dynamical signals that were clearly observed in the case of light IMFs emission ($Z < \sim 10$) and there were well understood in the neck fragmentation scenario

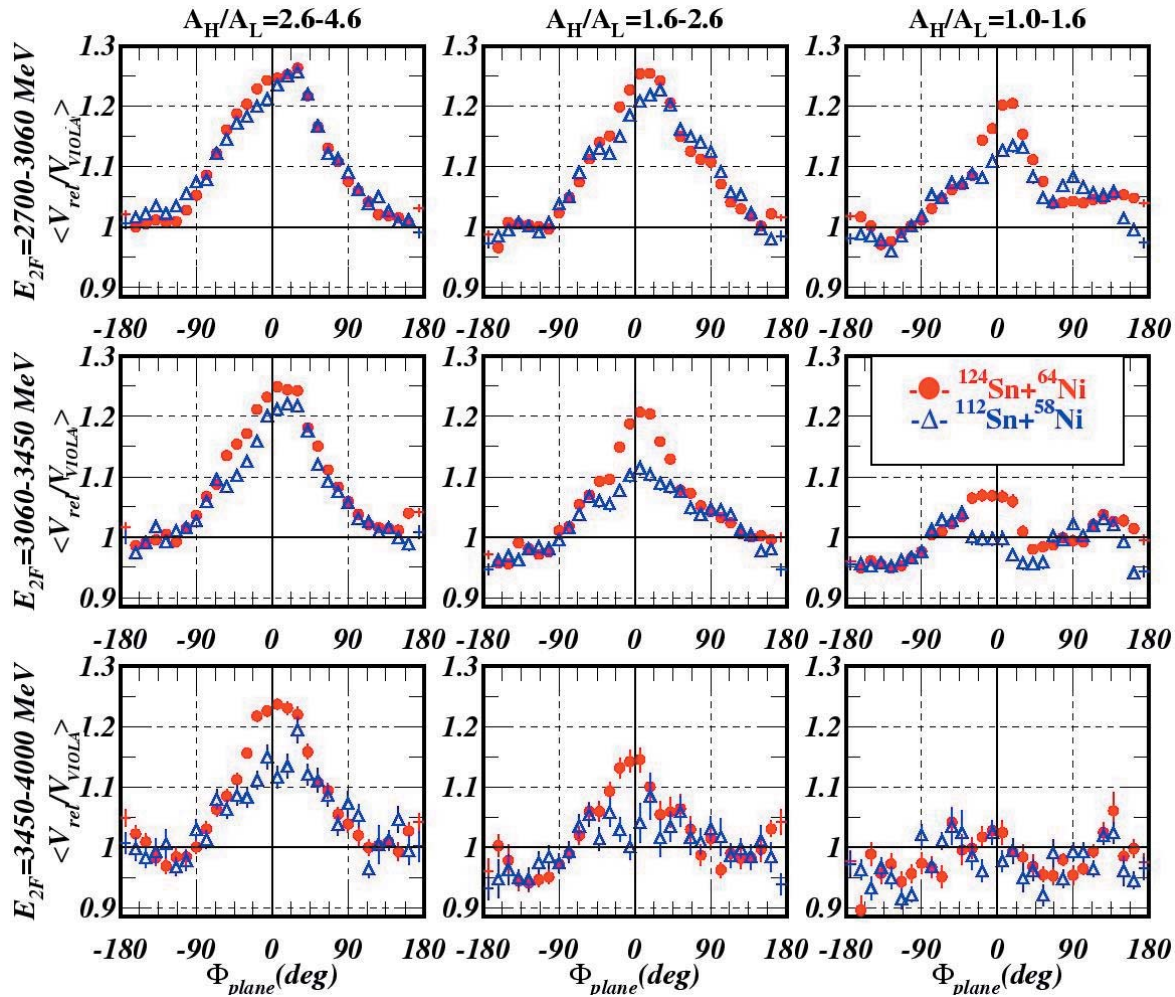


Fig. 2: Mean values of the fission-like fragments relative velocity (V_{rel}) normalized by Viola systematics (V_{Viola}), as a function of the in-plane angle for different violence of collision and asymmetries, for neutron rich (circles) and neutron poor (triangles) Sn+Ni systems at 35A.MeV.

[6,7]. Moreover, Dynamical Fission is a candidate to represent a step in a possible continuous transition of the time scale having prompt neck rupture as beginning, and statistical (equilibrated) fission as ending [4]. Integrating the angular distributions using the method reported in sect. III.c.1 of [1], we have estimated, for each selection the dynamical (non-isotropic) and equilibrated (flat) contributions to the cross section. It results that in all selected cases the statistical contribution to cross section is approximately the same for the two systems; instead the dynamical contribution is greater in the neutron rich system by a factor ~ 2 , with respect to the neutron poor system. For both systems we can observe that the strength of dynamical contribution increases with mass asymmetry and the violence of the collision, in agreement with the observation of [8]. On the other hand, statistical fission probability appears to be almost independent of the splitting mass asymmetry, what probably results from the fact that we are close to the Businaro-Gallone point.

Our evaluation suggests that, while statistical fission presents approximately the same probability in both systems, the dynamical fission process is about 2 times

more probable in the neutron rich system than in the neutron poor one. The origin of this enhancement, clearly related to the entrance channel Isospin (N/Z) difference between the two systems, is still an open question.

2.2 Fragment-fragment relative velocities

Other valuable information on the properties of the Dynamical Fission phenomenon is obtained from analysis of relative velocities of the two selected PLF fission-like fragments.

In Fig. 2 we present, for the two Sn+Ni investigated systems, the Φ_{plane} angular distributions of mean value of the fragment-fragment relative velocity, normalized to the velocity resulting from Coulomb repulsion, taken event by event according to the Viola systematics [9].

An “equilibrated” PLF fission should results in a V_{rel}/V_{Viola} distribution around $V_{rel}/V_{Viola} = 1$, since in sequential (and isolated) emission of PLF fission fragments, total kinetic energy release will be mainly governed by Coulomb repulsion. Looking at the plots of Fig. 2, we observe that, in the leftmost and central columns (more asymmetric splitting) the predictions

based on the systematics, established for equilibrium fission, agree with our data only for fragments emitted at large angles ($|\Phi_{\text{plane}}| > 90^\circ$), while for the “dynamical” events ($\Phi_{\text{plane}} \sim 0^\circ$) the most probable relative velocity is higher up to some 25 % than predicted by the Viola systematics. A similar trend is observed for almost symmetric splitting after more violent collisions. Instead, for almost symmetric splitting after less violent collisions, the predictions based on Viola systematics agree with our data, confirming substantially angular distribution observations, that is the statistical fission scenario.

The observation of this deviation from equilibrium fission systematic is compatible with a dynamical neck instability influencing the PLF decay, in a similar way as it was observed for the light IMFs neck-like decay mechanism [6,7].

What is, however, a new observation concerns comparison between the two Sn+Ni systems, namely that for the neutron rich system the deviation from Viola systematic is clearly higher. This tendency is more evident in the classes of selection presenting higher dynamical component weight (e.g $E_{2F}=3060-3450$ MeV, $A_H/A_L=1.6-2.6$ and $1.0-1.6$, and $E_{2F}=3450-4000$ MeV, $A_H/A_L=2.6-4.6$ and $1.6-2.6$).

3 CONCLUSIONS

This is the first time that dynamical fission contribution has been quantitatively compared between a neutron rich and neutron poor systems [1]; in literature, few works state that dynamical fission contribution in peripheral heavy-ion reactions increases with target size, asymmetry of PLF splitting and energy dissipation, but, practically no data exist on isospin dependence. The results are very interesting, since, if confirmed in further analysis and by extension to other systems and energies (e.g. systems investigated in 2003 ISOSPIN campaign) it would indicate a sensitivity of heavy Intermediate Mass Fragments dynamical production to the entrance isospin of the colliding system.

At this point of our analysis we are studying how to explain the observed relation between the strength of the dynamical fission component and the isospin of the systems. Recent reaction simulations, apparently reproducing such dynamical fission process [10], are thus highly interesting; further efforts are strongly required to look for correlation (if any) between the observed results and the symmetry term of nuclear equation of state (EOS).

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ISOSPIN DEPENDENCE OF HEAVY RESIDUE PRODUCTION IN THE REACTIONS $^{40}\text{Ca} + ^{40,48}\text{Ca}, ^{46}\text{Ti}$

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

a) INFN Laboratori Nazionali del Sud, Catania, Italy

b) INFN, Sezione di Catania

c) Dipartimento di Fisica e Astronomia Università di Catania

d) Saha Institute of Nuclear Physics, Kolkata, India

e) Dipartimento di Fisica 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

Abstract

The analysis of the mass of the heaviest fragment produced in the $^{40}\text{Ca} + ^{40,48}\text{Ca}, ^{46}\text{Ti}$ reactions at 25 MeV/A shown a suppression of binary respect to fusion reactions in the $^{40}\text{Ca} + ^{48}\text{Ca}$ reaction more asymmetric in the isospin of the reaction partners.

1 INTRODUCTION

The aim of the Limiting experiment, performed with the CHIMERA detector in its full configuration, is the investigation of an isospin dependence of the limiting temperature of excited nuclear systems. Indications of an isospin dependence of such temperature were observed in a previous experiment performed with the TRASMA apparatus[1], studying the GDR decay in nuclei at high excitation energies. The persistence of the GDR up to a higher excitation energy was in fact observed in the $^{40}\text{Ca} + ^{48}\text{Ca}$ reaction respect to what observed in the case of the $^{40}\text{Ca} + ^{46}\text{Ti}$ reaction. With the use of CHIMERA in its full configuration we were able to perform a more complete detection of nearly all particles emitted in the reactions and to verify the presence of the heavy residue remnant of quasi-fusion reactions.

2 EXPERIMENTAL SET-UP AND DATA ANALYSIS

This experiment was one of the experiments performed during the first CHIMERA campaign performed with the detector in its full configuration. $^{40,48}\text{Ca}, ^{46}\text{Ti}$ targets respectively 2, 3 and 2 mg/cm² thick were used. Details on the detector can be found in[2]. Being interested to quasi fusion reactions the main trigger of the experiment was the detection of at least 3 charged particles over the threshold of our silicon constant fraction discriminator. The analysis has been performed selecting as much as possible complete events. This selection allows also to

clean the data from reactions on oxygen targets contaminant mainly present in the calcium targets. We selected in fact events with at a total event detected charge of at least 30 (oxygen contamination can produce fragments with no more than 28 charge units in total). An upper total charge threshold was also set in order to exclude pile up.

3 OBSERVED MASS DISTRIBUTION

In fig.1 we plot the mass versus speed of the three biggest detected fragments for well reconstructed events in the $^{40}\text{Ca} + ^{46}\text{Ti}$ reaction. Mass has been evaluated with time of flight (TOF) for particles stopped in the silicon detector or from the charge measured using $\Delta E-E$

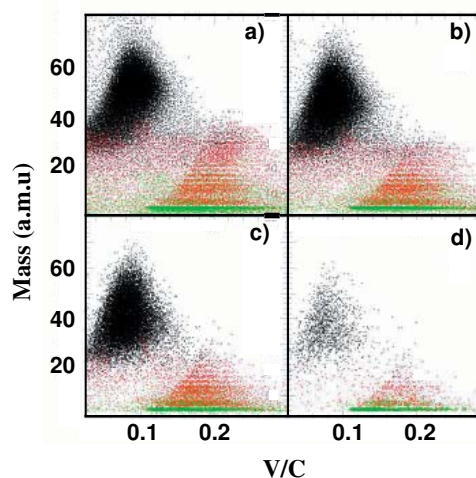


Fig.1 Mass versus speed distribution of the three largest detected fragments (in order of size black, red and green) for all data and charged particle multiplicity 5, 7, 9.

Information. At the present status of the analysis we are still verifying the time calibration for detectors of the sphere, therefore we are probably missing slow quasi target particles of binary reactions. The biggest fragment detected (black) has an average mass of 50 units peaked around $V/C=0.1$ i.e. near the Center of Mass (CM) velocity ($V_{CM}/C=0.107$). The second fragment in size (red) shows a larger range of speeds from the projectile ($V_{beam}/C=0.22$) to almost zero. The third fragment (green) detected has a small mass and is most frequently identified as an α -particle).

A Dalitz plot of the 3 fragments is shown in fig.2. We observe that there are very few fragments emitted with similar size and that in most of the events a big fragment is emitted with two other small fragments. Notwithstanding the above reported missing events with a quasi target detected on the sphere, often two fragments of similar size are emitted as demonstrated by the large amount of events far from the vertex of the Dalitz triangle.

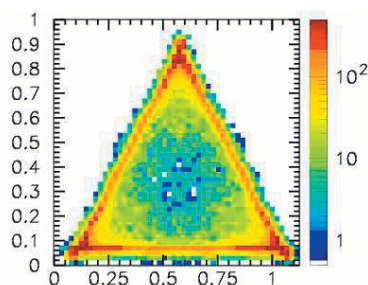


Fig.2 Dalitz plot of the 3 biggest fragments for the reaction $^{40}\text{Ca}+^{46}\text{Ti}$

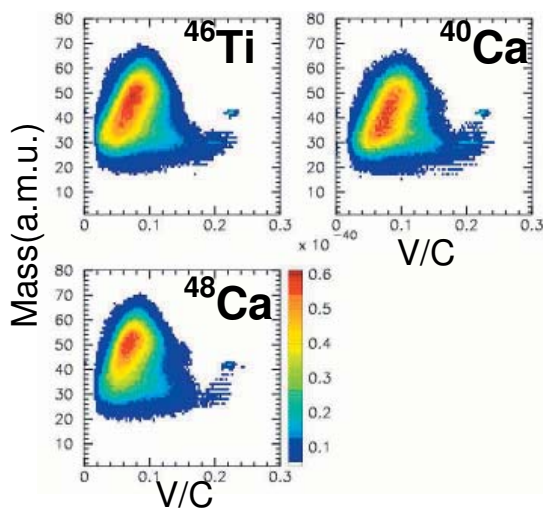


Fig.3 Mass versus speed (V/C) for the biggest fragment produced with the different targets

It is very interesting to compare the fragment production in the three reactions investigated. In fig.3 the plots of mass versus velocity for the biggest are shown respectively for ^{46}Ti , ^{40}Ca and ^{48}Ca targets. The larger mass are produced with a speed slightly lower than CM speed ($V_{CM}/C=0.107$) indicating an incomplete fusion

reaction mechanism. Moreover there are marked differences between the three reactions in the relative amount of particles with mass $A\approx 50$ having an average $V_{CM}/C\approx 0.09$ and those with mass $A\approx 30$ and $V_{CM}/C\approx 0.06$. These last particles are predominant with ^{40}Ca target while higher mass are more important in the ^{48}Ca case. ^{46}Ti shows an intermediate behavior. Further analysis including the data from backward detection are needed to support this scenario. However, if confirmed one could infer that incomplete fusion reactions are more probable in the more asymmetric N/Z reaction. This is even more clear looking at the distributions of the fragment with largest mass shown in fig.4

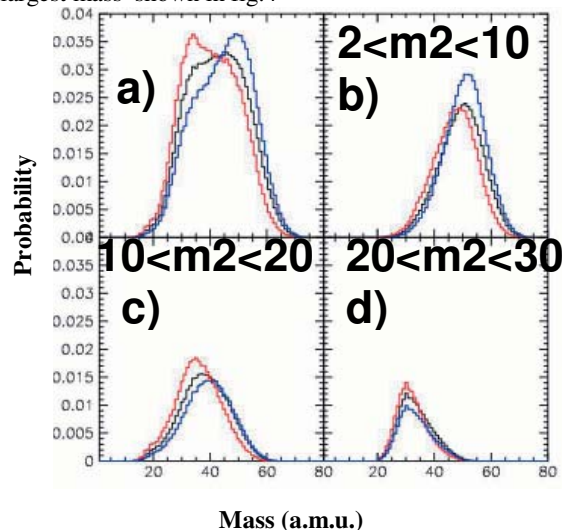


Fig.4 Biggest mass probability spectra for the three targets ^{46}Ti black, ^{40}Ca red, ^{48}Ca blue. a) Inclusive and coincidence spectra with the second biggest fragment in selected mass ranges b)-d).

Such probability spectra clearly shows large differences in the behavior of the three targets that can be correlated to their isospin difference, even if, in the case of ^{40}Ca , a not negligible mass difference also exists. The shape of the mass spectra obtained in coincidence with different windows of a second fragment in size are very similar as shown in b)-d), small differences being concentrated in the higher mass region where the mass difference of the entrance channel could play a major role. However there are important differences on the yield. With ^{40}Ca (red lines) the contribution of binary reactions is similar than ^{46}Ti (black lines) and larger than for ^{48}Ca (blue lines). This last target is instead more effective in the production of a heavier residue. The analysis of such spectra it seems to indicate that the quasi fusion channel is more favored by the isospin asymmetry in the entrance channel. This observation is in agreement with the results of the GDR experiment [1] where the dipole oscillation was observed to survive at higher excitation energies using the ^{48}Ca target [1].

4 LIGHT PARTICLE DECAY

In order to better characterize the hot system produced an analysis of the light charged particle spectra was undertaken. A preliminary analysis on charge $Z=1$ particles is presented below.

The largest contribution to charge 1 is given by protons. However, the production of different N/Z particles strongly depends from the target isospin. In fact a larger triton emission was observed using the ^{48}Ca target compared to the ^{40}Ca one as shown in fig.5.

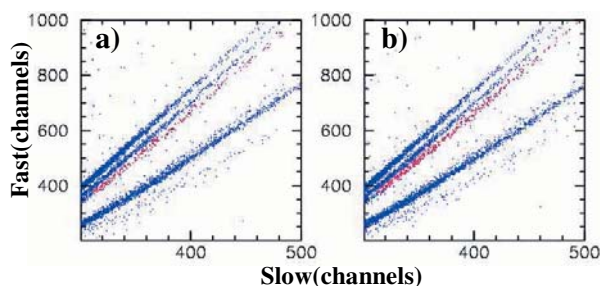


Fig.5 Zoom of Fast slow identification plot of a CsI(Tl) detector of ring 11 built using the same number of events (2×10^6) for ^{40}Ca a) and ^{48}Ca b) targets events. Well identified tritons are plotted in red.

In fig.6 proton energy spectra measured in the forward direction in the reaction $^{40}\text{Ca}+^{46}\text{Ti}$ are shown. Due to preequilibrium emission high energy protons with energy above 100 MeV can be detected also at relatively large angles.

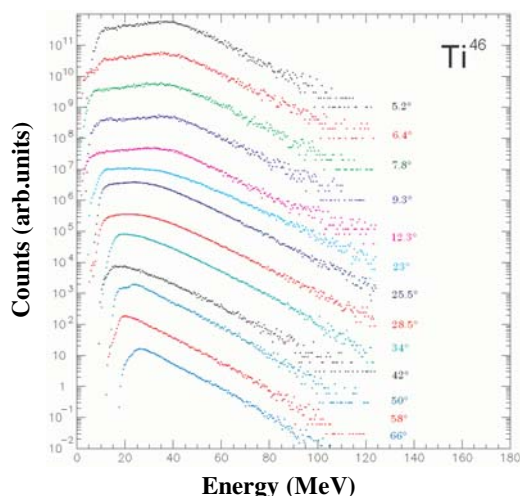


Fig.6 Proton energy spectra measured at various angles for the $^{40}\text{Ca}+^{46}\text{Ti}$ reaction.

These spectra can be reproduced at least at forward angles as shown in fig.7 with CoMD2 calculations[3].

Fig.8 shows the multiplicity distribution of $Z=1$ particles for the three reactions investigated.. A larger probability to detect higher multiplicity of $Z=1$ particles

with the ^{40}Ca target (red line) was measured. Such High $Z=1$ multiplicity events are correlated to heavier residues. This is shown in fig.9 where we plot, on panel a), a preliminary probability distribution of the mass of the biggest fragment without any condition for the three reactions investigated. Panel b) shows, as a comparison, the same quantities gated with the condition that at least five $Z=1$ particles have been identified in each event. As in fig.4 the shape of the spectra collected in the various reactions become rather similar, and higher masses show an enhanced probability.

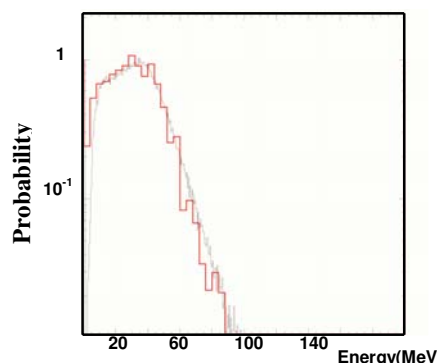


Fig.7 Black proton energy spectrum in the $^{40}\text{Ca}+^{46}\text{Ti}$ reaction, red CoMD2[3] calculations.

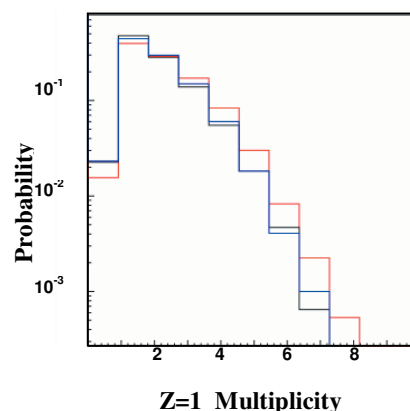


Fig.8 Preliminary multiplicity distribution for $Z=1$ particles emitted for the reactions on ^{40}Ca (red), ^{46}Ti (black) ^{48}Ca (blue).

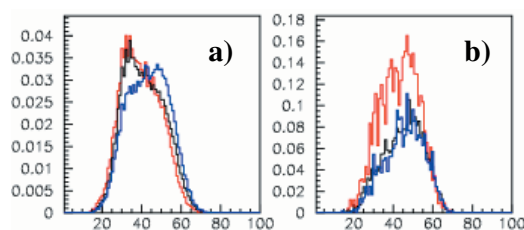


Fig.9 Preliminary mass distribution of the biggest fragment in events with $Z=1$ particles. b) the same spectrum but with $Z=1$ multiplicity >4 .

5 CONCLUSIONS AND OUTLOOKS

Preliminary results of the analysis of the limiting experiment has confirmed that a quasi-fused system is formed leading to a heavy residue. The large isospin asymmetry in the entrance channel seems to play a role as suggested by the enhancement of the production of a heavy quasi-compound system in the $^{40}\text{Ca}+^{48}\text{Ca}$ reaction. This could be due to the fact that the asymmetric entrance channel ($^{40}\text{Ca}+^{48}\text{Ca}$) produces a quasi-compound system more near to the stability valley than the ones formed with $^{40}\text{Ca}+^{40}\text{Ca}$, ^{46}Ti reactions. The large dynamical dipole[4] generated at the beginning of the reaction in the $^{40}\text{Ca}+^{48}\text{Ca}$ system and its γ -decay has been proposed as a cooling method[5] able to enhance the fusion reaction probability. However the γ -decay probability of such mode is generally too low (10^{-3+4}) [4] to get the large measured effect. Further investigations are going also with the help of CoMD2 calculations[3] in order to better understand the overall behavior.

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ISOSPIN EFFECTS ON REACTION DYNAMICS

E. De Filippo^{a*}, F. Amorini^b, A. Anzalone^b, L. Auditore^c, V. Baran^d, I. Berceanu^d, J. Blicharska^e, B. Borderie^f, R. Bougault^g, M. Bruno^h, J. Brzychczykⁱ, G. Cardella^a, S. Cavallaro^b, M.B. Chatterjee^j, A. Chbihi^k, M. Colonna^b, M. D'Agostino^h, R. Dayras^l, M. Di Toro^b, U. Emanuele^c, J. Frankland^k, E. Galichet^{b,f}, W. Gawlikowiczⁱ, E. Geraci^h, F. Giustolisi^b, A. Grzeszczuk^e, P. Guazzoni^m, D. Guinetⁿ, S. Kowalski^e, E. La Guidara^a, G. Lanzalone^b, G. Lanza^o, N. Le Neindre^f, C. Maiolino^b, Z. Majkaⁱ, A. Pagano^a, M. Papa^a, M. Petrovici^d, E. Piasecki^o, S. Pirrone^a, R. Płanetaⁱ, G. Politi^a, A. Pop^d, F. Porto^a, M.F. Rivet^f, E. Rosato^p, F. Rizzo^b, P. Russotto^b, K. Schmidt^e, A. Sochockaⁱ, K. Siwek-Wilczyńska^o, I. Skwira^o, L. Swiderski^o, A. Trifiro^c, M. Trimarchi^c, G. Vannini^h, M. Vigilante^p, J.P. Wieleczko^k, J. Wilczyński^q, L. Zetta^m and W. Zipper^e

- a) INFN Sezione di Catania and Dipartimento di Fisica, Università di Catania, Italy*
- b) INFN LNS and Dipartimento di Fisica, Università di Catania, Italy*
- c) INFN, gruppo coll. Messina and Dip. di Fisica, Università di Messina, Italy*
- d) Institute for Physics and Nuclear Engineering, Bucharest, Romania*
- e) Institute of Physics, University of Silesia, Katowice, Poland*
- f) Institut de Physique Nucléaire, IN2P3-CNRS, Orsay, France*
- g) LPC, ENSI Caen and Université de Caen, France*
- h) INFN Sezione di Bologna and Dipartimento di Fisica, Università di Bologna, Italy*
- i) M. Smoluchowski Institute of Physics, Jagellonian University, Krakow, Poland*
- j) Saha Institute of Nuclear Physics, Kolkata, India*
- k) GANIL, CEA, IN2P3-CNRS, Caen, France*
- l) DAPNIA/SPhN, CEA Saclay, France*
- m) INFN Sezione di Milano and Dipartimento di Fisica, Università di Milano, Italy*
- n) IPN, IN2P3-CNRS and Université Claude Bernard, Lyon, France*
- o) Institute for Experimental Physics, Warsaw University, Warsaw, Poland*
- p) INFN Sezione di Napoli and Dipartimento di Fisica, Università di Napoli, Italy*
- q) A. Soltan Institute for Nuclear Studies, Swierk/Warsaw, Poland*

* Corresponding author; e-mail: defilippo@ct.infn.it

Abstract

Intermediate mass fragments produced in the reactions $^{124}\text{Sn}+^{64}\text{Ni}$ and $^{112}\text{Sn}+^{58}\text{Ni}$ have been studied with the CHIMERA 4π multidetector. For prompt and sequential IMFs emission the correlations between IMFs angular alignment and their isotopic content will be shown and compared with preliminary results of stochastic BNV code simulations in order to extract information on the symmetry term of nuclear equation of state.

1 INTRODUCTION

The study of isospin degree of freedom in nuclear reactions induced by stable or radioactive beams is suited to probe the nuclear equation of state (EOS). In particular, recent investigations on both dynamical and thermodynamic features of heavy ion reactions at Fermi energies (allowing to access densities below the saturation point) have shown the influence of the density dependent symmetry energy of EOS on the isotopic contents of the emit-

ted fragments [1]. Theoretical predictions show different forms of the symmetry energy as a function of density going from a linear dependence ("stiff") to a saturation around normal density followed by a decreasing at higher densities ("soft"). The main idea is that experimental observables based upon the N/Z composition of the particles emitted in the reaction are sensitive to the stiffness of the symmetry energy potential; this is the case, for example, of recent symmetry energy coefficient determination based on "isoscaling" analysis [2-5].

In particular, the isotopic content of IMF's produced in the overlapping region between projectile-like (PLF) and target-like (TLF) nuclei at mid-rapidity (neck region) plays an important role: the transient neck structure is formed in a dilute region in proximity of the overlapping surfaces of the interacting projectile and target. A migration of neutrons against protons from region at saturation density to the lower density of the neck is expected [6]. In this report we show new results relative to the correla-

tions between isotopic content of IMF fragments emitted in a short time scale and the degree of alignment of IMFs with respect to the separation axis between PLF and TLF. This analysis is a valid constraint for dynamical models such as stochastic BNV (Boltzmann-Nordheim-Vlasov) simulations of the reaction dynamics in order to study the role of symmetry energy in determining fragment properties in fragmentation process.

2 DATA SELECTION AND RESULTS

The experiment has been performed at the LNS in Catania using the Superconducting Cyclotron and the forward part (688 telescopes, covering the angular range between 1° and 30°) of the 4π CHIMERA detector (see ref. [6] for details). Data for two reactions $35 \text{ A.MeV } ^{124}\text{Sn} + ^{64}\text{Ni}$ and $^{112}\text{Sn} + ^{58}\text{Ni}$ were collected.

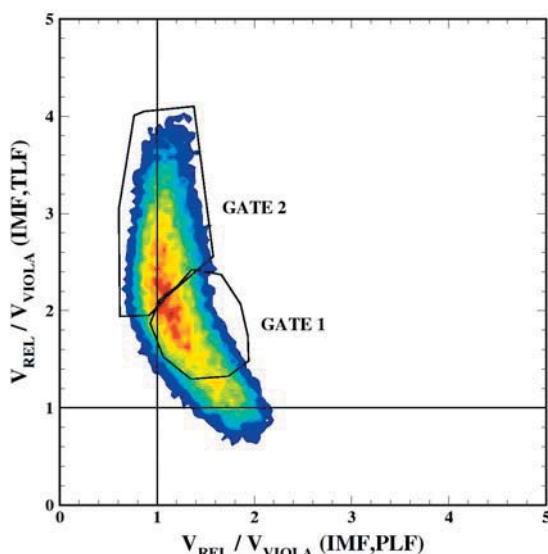


Fig. 1: Correlation between relative velocities $V_{\text{rel}}/V_{\text{Viola}}$ (IMF-PLF) vs. $V_{\text{rel}}/V_{\text{Viola}}$ (IMF-TLF) for fragments of charge $3 \leq Z \leq 6$ in the $35 \text{ A.MeV } ^{124}\text{Sn} + ^{64}\text{Ni}$ reaction. A sketch of the gates used for data selection is also indicated.

Recently [8] we have analyzed the $^{124}\text{Sn} + ^{64}\text{Ni}$ reaction selecting a class of ternary events in which along with PLF and TLF a third fragment “IMF” with a velocity distribution centered at the mid-velocity (between PLF and TLF velocity) is produced; these IMFs mostly originate from the neck region after the separation of the colliding system.

In order to estimate the time scale for fragment formations we have used a method based on relative velocity correlations in the subsystems (IMF-PLF) and (IMF-TLF), respectively. In fig. 1 we report for IMFs with charge Z between 3 and 6 the $r_1 = V_{\text{rel}}/V_{\text{Viola}}$ (IMF-PLF) versus $r_2 = V_{\text{rel}}/V_{\text{Viola}}$ (IMF-TLF) correlation, where V_{Viola} is the velocity corresponding to the Coulomb repulsion energy. Light IMFs produced at mid-velocity in a short time scale (less than 100 fm/c) correspond to loci in Fig. 1 where both r_1 and r_2 are larger than 1 in contrast to sequential emission from PLF ($r_1 \sim 1$) or TLF ($r_2 \sim 1$). Results

about emission time are consistent with theoretical predictions on IMF emission in neck fragmentation based upon stochastic BNV transport model simulations [9] and molecular dynamic calculations [10]. In the following we will use two different gates as shown in Fig. 1 to characterise the average isotopic ratio of the fragments as a function of their emission time.

A meaningful physical observable in the study of the neck emission properties, is the degree of alignment between the PLF-TLF and IMF-PLF relative velocity directions. This is measured by means of the ϕ -plane angle defined as the angle between the PLF-TLF separation axis and the projection of the IMF-PLF relative velocity axis onto the reaction plane (for a detailed description see for example [11] and references therein). A ϕ -plane ≈ 0 corresponds to the maximum degree of alignment (and shorter time scale) while sequential emission from PLF should result in a flatter ϕ -plane distribution.

In order to study the isospin dependence in neck dynamics, we have correlated the information on alignment with the isospin content of IMF fragments by selecting different emission times. This kind of correlations, as recently stated [12], can contribute to disentangle between effects due to isospin dynamics and symmetry term of EOS from effects that can be merely linked to the phase space accessible to the reaction.

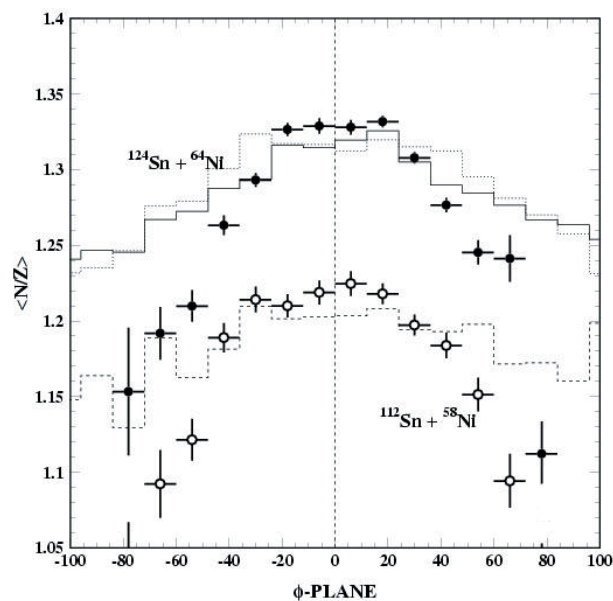


Fig. 2: Experimental $\langle N/Z \rangle$ as a function of the ϕ -plane for IMFs of charge $3 \leq Z \leq 9$ in the $35 \text{ A.MeV } ^{124}\text{Sn} + ^{64}\text{Ni}$ reaction: filled points: prompt emitted IMFs selected with gate 1; solid histogram: all IMFs (no selection); dotted histogram: sequential emitted IMFs selected with gate and $^{112}\text{Sn} + ^{58}\text{Ni}$: empty points: prompt emitted IMF selected with gate 1; dashed histogram: all IMFs (no selection).

In Fig. 2 we show the $\langle N/Z \rangle$ as a function of the ϕ -plane for IMFs with charge $3 \leq Z \leq 9$ for the two reactions $^{124}\text{Sn} + ^{64}\text{Ni}$ (neutron rich) and $^{112}\text{Sn} + ^{58}\text{Ni}$ (neutron poor) for different selection gates as sketched in Fig. 1. When gate 2 is selected (sequentially emitted fragments

from PLF), a relatively wide distribution (dotted histogram) is obtained. A similar result is obtained with no selection corresponding to solid histogram. When gate 1 is selected (prompt emitted IMFs) the distribution has the tendency to be much narrower and with the maximum of $\langle N/Z \rangle$ centered around ϕ -plane ≈ 0 . Note that the same effect, but with a lower N/Z average value, is also present for the neutron poor system.

As the evaluation of the average N/Z value depends on the charge range chosen for IMFs, thus we have verified that light IMFs ($Z \leq 5$) have N/Z vs. ϕ -plane behavior similar to the one shown in Fig 1a) for gate 1, while for heavier fragments ($Z > 6$) a flatter distribution with lower average N/Z is obtained. The neutron enrichment of the neck region has been experimentally observed in different reactions (for a review see [13]); transport simulation codes [9] attribute this effect to a neutron migration towards low density neck region particularly favored if a more repulsive density dependence of the symmetry term of EOS (asy-stiff) is assumed in the calculation.

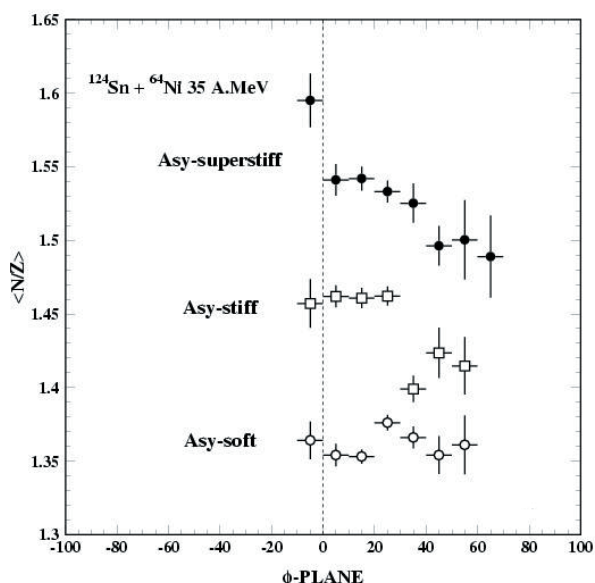


Fig. 3: BNV calculations showing $\langle N/Z \rangle$ as a function of the ϕ -plane for primary IMF fragments (charge $3 \leq Z \leq 12$) for three different potential symmetry term of the EOS. Calculations are done at impact parameters from 5 to 8 fm.

Fig. 3 shows results of preliminary simulations for $^{124}\text{Sn} + ^{64}\text{Ni}$ reaction at 35 A.MeV using the stochastic transport equation (BNV) of ref. [9]. In the figure we show $\langle N/Z \rangle$ as a function of ϕ -plane for “primary” neck emitted IMF fragments with charge $3 \leq Z \leq 12$ and for three different choices of the symmetry energy term in the range of impact parameters from 5 to 8 fm. Note that $\langle N/Z \rangle$ as a function of ϕ -plane decreases for the asy-stiff case while a flat distribution is obtained for the asy-soft case of EOS symmetry term, thus, showing that the alignment vs. IMFs isotopic contents is an observable sensitive to symmetry energy term of EOS. Qualitative

comparison with experimental data of fig. 2 shows a better agreement with the “stiff” behaviour.

However a detailed study of the influence of sequential decay for primary fragments is essential for a proper quantitative comparison with experimental data.

Our approach shows the link between the isospin dynamics with the time-chronology in the fragment emission process. This method is appropriate in order to follow intermediate mass fragment formation in a broad range of time scale covering different reaction mechanisms (neck emitted fragment, dynamical fission, sequential emission).

It will be crucial for future experiments to improve the fragment identification capabilities in both isotopic identification and angular coverage. This goal can be achieved by the recent CHIMERA pulse-shape upgrade for silicon detectors [14]. This will substantially reduce the energy threshold for light IMFs charge and mass identification from about 10 A.MeV to about 4 A.MeV, allowing for a more complete study of fragments isotopic properties.

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TRANSPORT OF INTERMEDIATE ENERGY RADIOACTIVE BEAMS TO THE NEW CHIMERA SCATTERING CHAMBER

F.Amorini^{a,c}, G.Cardella^b, L.Calabretta^a, E.De Filippo^b, E.La Guidara^{b,c}, P.Figuera^a, C.Maiolino^a, M.De Napoli^{b,c}, A.Pagano^b, I. Pawelczak^d, S.Pirrone^b, M. Quinlan^d, G.Raciti^{b,c}, E.Rapisarda^{b,c}, F.Rizzo^{a,c}, D.Santonocito^a, W. U. Schröder^d, J. Töke^d

a) INFN Laboratori Nazionali del Sud, Catania, Italy

b) INFN, Sezione di Catania

c) Dipartimento di fisica e astronomia Università di Catania

d) Departments of Chemistry and Physics, University of Rochester, USA

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

Abstract

¹⁸Ne secondary beam produced by ²⁰Ne primary beam fragmentation has been transported to the new CHIMERA scattering chamber at LNS. Different tests have been performed in order to obtain the best configuration, which allows the maximum transmission along the beam line. First of all, the last four dipoles placed in the final part of the beam line before the entrance of the CHIMERA scattering chamber were used as a new Fragment Separator. In the second test, the transmission of secondary beams produced by the standard FRIBS set-up was measured. Moreover, using the standard FRIBS configuration for the RIBs production, the action of the two spectrometers optically set as a unique double spectrometer was tested in order to check a better efficiency in contaminants suppression.

1 INTRODUCTION

Secondary (“radioactive”) particle beams have opened a new frontier for nuclear physics research. At LNS we have developed exotic beams at Fermi energy by projectile fragmentation using the FRIBs layout [1] which could be used to complement the low energy beams of the EXCYT facility. The fragment separator used to select the beam is realized using the extraction line of the Superconducting Cyclotron (SC). The setup is capable of servicing all beam lines and experimental stations of the laboratory with fragmentation beams, albeit with different transport efficiency and selectivity. For example, in previous tests [2] transmission through the CICLOPE beam line has turned out to be quite low. However, since the new beam line to the CHIMERA scattering chamber has been designed more generously for better acceptance, much higher secondary beam transport efficiencies are expected for service to this latter chamber. Moreover, elements of the final section of this beam line can be combined to function as a second fragment separator in line. The present tests demonstrate that both transmission to the new CHIMERA scattering chamber and beam selectivity are good. These results provide additional scientific motivations to move the CHIMERA detector in the new

scattering chamber in order to benefit of the higher transport efficiency for new experiments with RIBs.

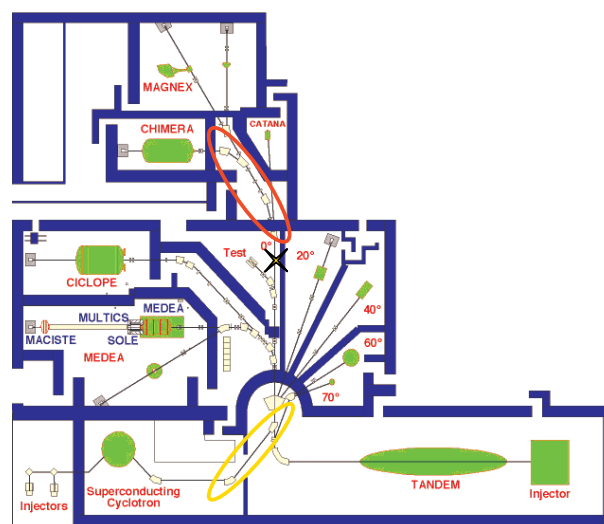


Fig.1 Layout of the beam lines at LNS. Red and yellow circles indicate the new and standard fragment separators, respectively.

2 THE NEW FRAGMENT SEPARATOR

Fig.1 depicts the layout of the LNS beam transport lines. The standard FRIBs fragment separator corresponds to the extraction line of the SC (yellow circle). The second fragment separator has been obtained using an opportune setting of the last four magnets in the beam line to the CHIMERA scattering chamber (Fig.1, red circle). With the conventional location of the ⁹Be, 500 μm thick, production target marked in Fig. 1 by a star. Primary ²⁰Ne beam is transported up to the new target location where

undergoes fragmentation. Of advantage is the higher selectivity afforded by a larger number of tunable beam transport elements, which also provides for more opportunities to place slits or wedges to provide better selectivity of the line to fragmentation beam species. A standard CHIMERA telescope of the sphere, shown in Fig.2, was mounted at the entrance of the new CHIMERA scattering chamber to monitor the products of the ^{20}Ne fragmentation. The ΔE -E scatter plot shown in Fig.3 is a typical example of data obtained with this setup. The produced fragments occupy specific regions (spots) depending on their mass and charge. A rather large momentum acceptance of this fragment separator is indicated by the continuity of the distributions for different isotopes. However, from the picture one can also see that the suppression of the primary ^{20}Ne beam obtained in the configuration was not high. As a consequence, the intensity of the selected ^{18}Ne fragmentation beam amounted to only 4% of the total.



Fig.2: View of the ΔE -E telescope used to identify the fragmentation products.

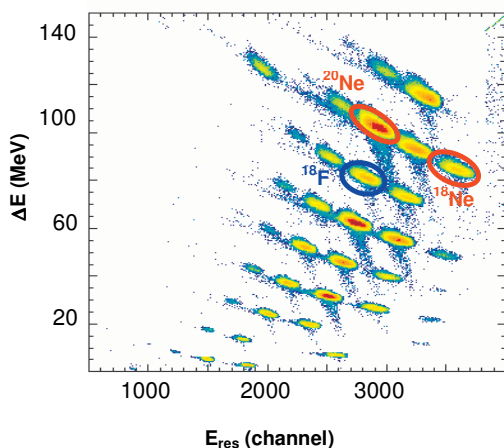


Fig.3 ΔE -E plot for the isotopes produced and selected in the new fragment separator.

3 TRANSPORT EFFICIENCY FROM THE FRIBS FRAGMENT SEPARATOR

Another test was performed to explore the transport efficiency of the CHIMERA beam line, for a ^{18}Ne beam produced with the FRIBS fragment separator (yellow line of fig.1) and the standard location of the production target, again a 500- μm ^9Be foil. The transport beam line was tuned using a pilot ^{20}Ne beam, degraded in energy to simulate the ^{18}Ne fragmentation beam in magnetic rigidity. The optimized transport achieved for the “pilot” beam is, in principle, valid for the secondary beam as well.

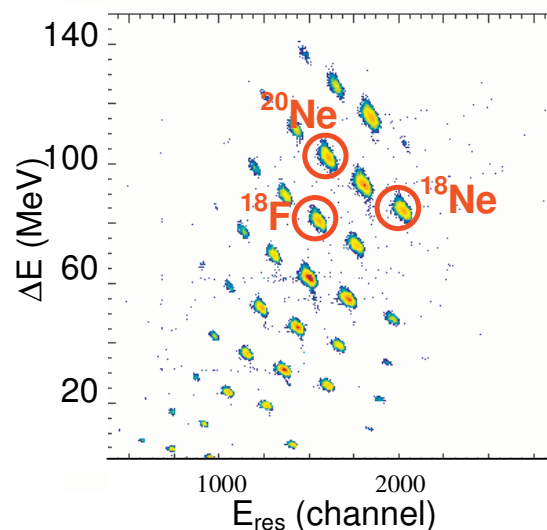


Fig.4 ΔE -E plot for the isotopes produced with the standard FRIBS layout and transported along the new beam line.

We measured a transmission in the order of 50% which is lower than the one obtained along the 20° beam line (>90%), where all the experiments with RIBs produced by FRIBs have been performed up to now, but rather better than the value measured along the CICLOPE beam line (20%) [2].

In Fig.4 a typical ΔE -E scatter plot is shown as obtained behind the CHIMERA chamber for fragmentation beams and the above setup. Comparing the scatter plots of Figs. 3 and 4, one notes a much larger momentum selectivity of the FRIBS fragment separator combined with the CHIMERA beam line magnets (Fig. 4). The bumps of the isotopes are much more separated than in the setup with the target at the entrance to the new fragment separator. Indeed, the momentum acceptance of the fragment separator coupled with the beam line acceptance is in the order of 1%. This induces a larger suppression of the ^{20}Ne primary beam and leads to a relative amount of ^{18}Ne of about 7% of the total mixture of secondary beams. From a study of the profile of the transported beam it is known that the main losses occurring in the beam line is due to

the small vertical aperture of dipole magnets in the 0° beam line upstream of the new fragment separator. The vacuum chambers of such dipoles have a vertical gap of 5 cm. We plan to install new vacuum chambers during the CS maintenance of 2007. The new chambers will certainly improve the transmission efficiency greatly.

4 USE OF THE DOUBLE FRAGMENT SEPARATOR

Tests were also conducted, in which both fragment separators, the regular FRIBS separator and the new separator, were configured in series, in the hope for a better selectivity for fragmentation beam particles and more efficient suppression of the primary beam. This configuration is normally used in other Fragment Separator present in various laboratories like the FRS at GSI and the A1900 spectrometer at MSU. Tuned in a proper way, the two fragment separators could act as a double filter. For this purpose, we inserted a $300\mu\text{m}$ Al degrader between the two spectrometers, and at optimum tuning, the relative intensity of ^{18}Ne particles was found increased to 14% of the total secondary beam intensity. Figure 5 illustrates the selectivity obtained with this setup. In such configuration, one was able to reject all particles heavier than ^{19}Ne . Unfortunately the higher selectivity comes at the cost of a loss in absolute intensity.

the beam line increasing the vertical gap of the vacuum chambers of some beam line magnets. It is worth noting that the good results obtained for the transport of the fragmentation beams to the CHIMERA chamber apply also to the Magnex beam line, benefitting secondary-beam experiments using this new spectrometer.

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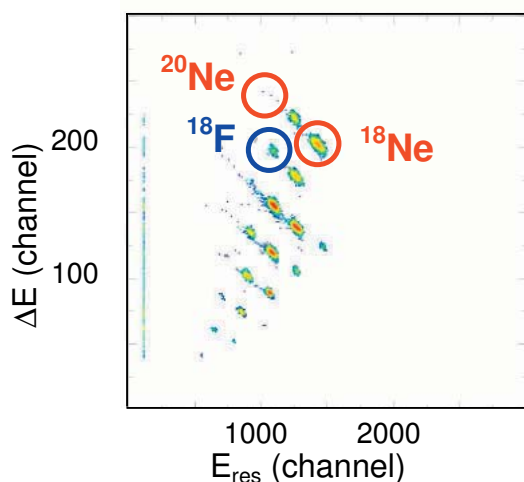


Fig.5 ΔE -E plot for the isotopes produced and selected using the double fragment separator.

More tests are needed in order to improve the performances of the coupling of the two spectrometers.

5 CONCLUSIONS

High transport efficiency to the CHIMERA scattering chamber was obtained for secondary ^{18}Ne beam produced with the LNS FRIBS fragment separator. This large transport efficiency provided for a good scientific motivation to move the CHIMERA detector from the CICLOPE scattering chamber to the new position. We are also working to further increase the transport efficiency of

PULSE SHAPE DISCRIMINATION IN SILICON DETECTOR FOR CHIMERA DETECTOR UPGRADING

F.Amorini^a, A.Anzalone^a, N. Arena^b, L.Auditore^c, R.Bassini^d, C.Boiano^d, G.Cardella^b,
 S.Cavallaro^a, M.B.Chatterjee^b, M.D'Andrea^b, E.DeFilippo^b, U.Emanuele^c, F.Fichera^b, E.Geraci^f,
 F.Giustolisi^a, N.Guardone^a, A.Grimaldi^b, P.Guazzoni^b, E.La Guidara^a, G.Lanzalone^a,
 G.Lanzanò^d, C.Maiolino^b, D.Nicotra^d, A.Pagano^a, M.Papa^a, S.Pirrone^{b*}, G.Politi^a, F.Porto^g,
 A.Pullia^d, F.Rizzo^b, S.Russo^d, P. Russotto^a, D.Santonocito^a, G.Saccà^d, W.U.Schröder^g, J.Töke^g,
 A.Trifirò^c, M.Trimarchi^c, S.Urso^b and L. Zetta^d.

a) Dipartimento di Fisica dell'Università and Istituto Nazionale di Fisica Nucleare - LNS Catania, Italy

b) Dipartimento di Fisica dell'Università and Istituto Nazionale di Fisica Nucleare - Sezione di Catania, Italy

c) Dipartimento di Fisica dell'Università and Istituto Nazionale di Fisica Nucleare - Gruppo collegato di Messina, Italy

d) Dipartimento di Fisica dell'Università and Istituto Nazionale di Fisica Nucleare - Sezione di Milano, Italy

e) NAP Division, Saha Institute of Nuclear Physics, 1/AF Bidhannagar, Kolkata 700 064, India

f) Dipartimento di Fisica dell'Università and Istituto Nazionale di Fisica Nucleare - Sezione di Bologna, Italy

g) Departments of Chemistry and Physics, University of Rochester, Rochester, NY 14627, USA

** Corresponding author, e-mail: sara.pirrone@ct.infn.it*

Abstract

The 4π multidetector CHIMERA operates at the Laboratori Nazionali del Sud (LNS) in its complete configuration since 2003. In these years, essentially different physics experiments were realized to study heavy-ion reactions at Fermi energies. At the same time an intense R&D activity was carried out, to improve the charge identification capability of the device by applying a pulse shape discrimination technique to the silicon detector. A new module for the CHIMERA electronic chain has been thus developed and tested with low and high energy beams.

1 INTRODUCTION

The 4π multidetector CHIMERA has been successfully operating at the LNS since 2000 with the forward part and since 2003 in its full configuration [1].

The data collected in the different campaigns shown very good performances of the device in the field of detection and identification of the reaction products. The different identification techniques used, ΔE -E, TOF, PSD on CsI, allowed velocity measurement and provided good particle identification with different thresholds [2-4]. Nevertheless in this configuration no direct information about the charge of particles stopped in the first stage of

telescope (silicon) is achievable (the low energy component of the charge spectrum). For these ions only average mass number (A) is available by the time of flight (TOF), the mass by mass identification being limited in the range $A \leq 30$ at the most forward angles. In order to increase the identification capability for particle stopped in the silicon detector an upgrading of the device was proposed [4,5], based on a Pulse Shape Discrimination technique (PSD) performed on silicon detector signal [7]. The method is possible because energy, charge and mass of the detected particle, together with the entrance side operation, can strongly affect the pulse shape of the signal. The resulting relationship between these parameters and the rise time of the current or charge signal can be used to identify the particles.

This PSD method, usually applied for small area detector (some cm^2) operating in reverse injection [8], has been successfully used in CHIMERA for large detectors (about 20 cm^2 , 1000 pF) and operating in direct injection [5,6], in order to avoid a deterioration of the timing information, a key issue in TOF technique used in this device. Our hardware technique allows to measure the rise time of the charge signal as generated by a charge preamplifier of good timing performances and processed by a fast timing amplifier. The timing signal is sent to two Constant Fraction Discriminators (CFD) with different constants (30% and 80%) so that the time difference between the two logic outputs provides a measurement of

the rise time. Fast amplifier, CFD's and an energy channel amplifier are included in a new module realised in a standard NIM, shown in figure 1, developed for CHIMERA and tested with Tandem and Cyclotron beams.



Figure 1: 16 channel NIM module including Fast amplifier, CFD's and Energy amplifier.

2 TEST RESULTS

Beam tests at low energy were performed with ^{19}F beams of 105 MeV, delivered by the Tandem accelerator of LNS at Catania, bombarding a ^{12}C thin target; the reaction products were detected with a standard CHIMERA silicon detector placed at a distance of 70 cm from the target and at $\theta_{\text{lab}}=8^\circ$, operated in front injection configurations. Two BaF_2 scintillators were used to give a gamma prompt signal to be used as time reference for TOF measurement.

A first example of in beam particle discrimination is shown in figure 2, where energy versus rise time is presented for particles produced by $^{19}\text{F}+^{12}\text{C}$ at 105 MeV impinging on front side detector.

Isotope identification is achieved up to $Z=4$ while the different nuclear species can be identified in charge up to Fluorine, with a measured minimum energy ranging of about 3.75 MeV/A. The timing and energy resolutions were tested by looking at the Energy vs TOF plot and were found comparable to the standard CHIMERA electronic chain.

Beam tests at higher energy were performed with Ca beam at 45 MeV/A on Sn targets. The pulse shape analysis allowed a charge discrimination up to the highest atomic number produced in the reaction, $Z = 18$. Even in these energy range timing and energy resolution obtained with the new NIM module were comparable to the standard CHIMERA electronic chain.

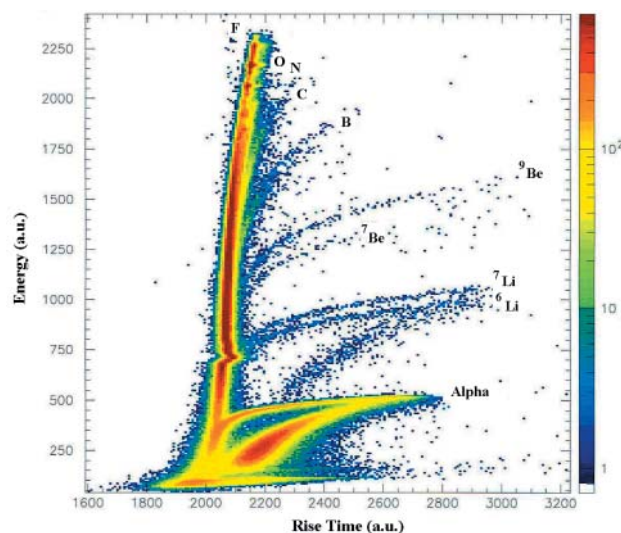


Figure 2: Energy (a.u.) versus Rise Time (a.u.) for front side injection.

3 CONCLUSIONS

A new method of pulse shape discrimination was developed in order to obtain charge identification of particles stopped in silicon detectors. The technique was based on a simple hardware processing of the charge timing signal by two different CFD, included in a new NIM module realised for CHIMERA electronic chain. A first 16 channels prototype of the module was tested, showing good results in charge discrimination with the large area silicon detector of CHIMERA, operated in "front side injection" to achieve good timing performance, a basic requirement in CHIMERA; very good results in both energy and timing resolution were found as well.

A large part of the CHIMERA will be equipped with these modules on 2007 allowing for new experiments in direct kinematics. The device will thus be able to identify in charge and mass low energy particles stopped in the silicon, thus opening new possibilities in the field of heavy ions reactions at low and intermediate energies for both stable and exotic beams. New applications in the field of reaction studies with low energy stable beams and nuclear astrophysics have been envisaged [9]

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BEHAVIOUR OF INSULATING FOILS IRRADIATED WITH 23 A.MEV $^{129}\text{Xe}^{26+}$ IONS

E. De Filippo^a, G. Lanzano^{a,*}, S. Hagmann^b, H. Rothard^c

a) INFN Sez. di Catania, Via S. Sofia 64, I-95123 Catania, Italy

b) IKF, University of Frankfurt and GSI, Darmstadt, Germany

c) CIMAP-CIRIL-Ganil, CEA/CNRS/Université de Caen/ENSICAEN, F-14070 Caen Cedex 05, France.

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

Abstract

A deuterated polypropylene foil has been bombarded by 23 A.Mev $^{129}\text{Xe}^{26+}$ beam at the Catania CS. The evolution with the elapsed time of binary encounter (BE) electrons and X-ray time-of-flight spectra has been studied. It is shown that the polypropylene target charges-up positively and subsequently breaks down under ion bombardment incessantly in the run. Furthermore the yield of BE electrons in the forward direction is strongly decreasing as the insulating target charges-up. On the contrary it is observed for the first time a clear positive correlation between the charging up of the target and the emission of X-rays.

1 INTRODUCTION

Fast electrons produced by bombarding thin solid, conducting foils with very energetic heavy ion beams ($20 \text{ A.MeV} < E < 100 \text{ A.MeV}$) have recently been the object of accurate studies [1]. In the forward direction the velocity spectra present two main components. Convoy electrons stem in the present case mainly from projectile electron loss. Electron capture to the continuum or a two-step process (capture to a bound state and subsequent loss) may also contribute. BE electrons are produced in close collisions between the incoming projectile and the target electron (inverse kinematics), and travel with a velocity almost twice the beam velocity. A component of Auger electrons emitted in flight from the excited projectile has also been observed [1,2]. These electrons travel with velocity between v_{beam} and $2v_{\text{beam}}$.

Experiments involving energetic beams impinging on solid insulating targets are very rare. Recent results from the reaction $64 \text{ A.MeV } ^{78}\text{Kr}^{32+} + \text{Mylar}$ and some general properties observed in such collisions are reported in [3]. In particular, the “position” of the above components are affected by the charging-up of the insulator surface. In fact both convoy and BE electrons emerging from the target are slowed down. The velocity difference is related to (and allows a quantitative determination of) the charging-up induced positive target potential. This positive potential can be as high as 9 kV, as observed in the case of $64 \text{ A.MeV } ^{78}\text{Kr}^{32+} + \text{Mylar}$ reaction [3].

In the following we present the results obtained at the Catania CS for the reaction $23 \text{ A.Mev } ^{129}\text{Xe}^{26+} + \text{deuter-}$

ated polypropylene, during a short run aimed to test some detectors.

2 EXPERIMENTAL METHOD

The experiment was performed with the superconducting cyclotron at LNS, Catania. A $23 \text{ A.MeV } ^{129}\text{Xe}^{26+}$ beam was impinging on a deuterated polypropylene target $\sim 100 \mu\text{g}/\text{cm}^2$ thick. Two carbon targets, ~ 50 and $\sim 100 \mu\text{g}/\text{cm}^2$ thick respectively, were also used for the purpose of comparison. Ten hexagonal phoswich-detectors from the ARGOS multidetector were modified and tested in this experiment. Each one of the new cylindrical shaped detectors consisted of a 3-5 mm thick BC400 fast scintillator 2” disc optically coupled to a 2” fast photomultiplier. The detectors were positioned in the forward direction ($2^\circ - 6^\circ$) at a distance of $\sim 183 \text{ cm}$ from the target inside the “neutron vacuum chamber array” at LNS [4]. This array is constituted by a small scattering chamber coupled by means of a flange ($\Phi = 20 \text{ cm}$) to a cylindrical, 167.5 cm long extension, having a maximum circular width of 70 cm.

Concerning the treatment of the fast output signal from the photomultiplier, we refer the reader to ref. [1]. The electron velocity was measured by time-of-flight techniques, where the pulsed beam radiofrequency was used as a start and the photomultiplier signal as a stop. Time-of-flight resolutions of $\sim 1 \text{ ns}$ were achieved, mainly due to the beam burst width. Finally, electronic thresholds set a limit to the detection of low-energy electrons ($v_{\text{thr}} \sim 7 \text{ cm/ns}$, corresponding to almost 20 keV).

For $23 \text{ A.MeV } ^{129}\text{Xe}^{26+}$ beam we expect convoy electrons of velocity $v \sim 6.5 \text{ cm/ns}$ (corresponding to almost 12.5 keV). Probably due to threshold effects (see above), we do not observe this component of the velocity spectrum. On the contrary, BE electrons ($v_{\text{BE}} \sim 12.5 \text{ cm/ns}$ at 0° , corresponding to $\sim 51 \text{ keV}$) are clearly observed, as shown in Fig. 1a), where the electron or/and X-ray yield is reported as a function of their time-of-flight, at the end of the run. The target is a deuterated polypropylene foil $\approx 96 \mu\text{g}/\text{cm}^2$ thick and the detector is placed at $\sim 6^\circ$. Besides prompt X-ray and BE electron peaks, other secondary peaks are observed, attributable to the radiation coming out from the Faraday cup, distant about 845 cm from the target.

3 RESULTS

As in the previous experiment reported in [3], we observe a clear displacement of the BE peak as a function of the elapsed time in the run. Note that the BE peak of Fig. 1a) is reported at the end of the run, so that possible fluctuations of the peak position during the elapsed time in the run cannot be observed. As said above, we do not observe any hint for a significant structure attributable to convoy electrons. This fact is quite intriguing, as our detection threshold is not so sharp and the same for all the tested detectors. At the moment we cannot say how much this experimental fact can be imputed to experimental threshold effects or to an intrinsic physics process affecting in particular the convoy component, or to both of them. On the other side we observe, for the first time and for most of the detectors, a “forked” BE peak, when using carbon conducting targets, see Fig. 1b). We do not know at the moment, if this experimental fact has a physical origin (inelastic BE collision, for instance?) or it is simply due to an experimental artefact.

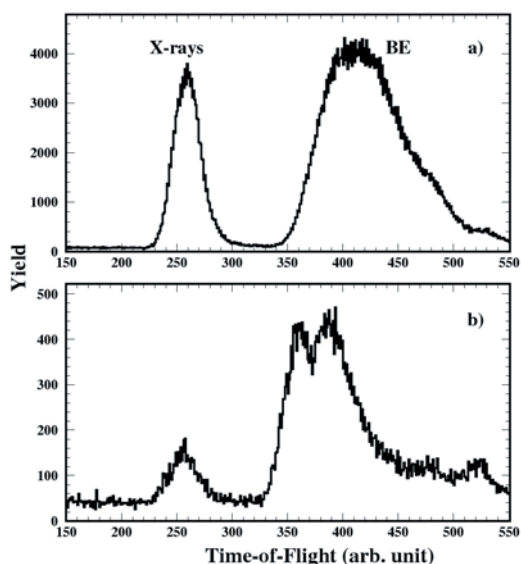


Fig. 1: Time-of-flight spectra for fast electrons and X-rays issued at $\theta_{lab}=6^\circ$ from the reaction induced by 23 A.Mev $^{129}\text{Xe}^{26+}$ ions on a solid, $96 \mu\text{g}/\text{cm}^2$ thick deuterated polypropylene foil, a), and on a $47 \mu\text{g}/\text{cm}^2$ thick carbon target, b). The BE electron peak and the prompt X-ray peak are indicated.

Due to the lack of the Convoy electron component in the present data, in the following we present a statistical analysis based on the BE electron and X-ray peaks as a function of the elapsed time in the run. With respect to the results shown in [3], we want to stress the following points: i.) The absolute physical variable “elapsed time” was read from a scale and stored at every 400th master-trigger event. ii) The run was allowed to last much longer time than in [3], $\sim$ some hours. iii) The target and the beams are different. In particular the incident energy of the beam is much less.

The same statistical method as in [3] was applied to the BE or X-ray data. Shortly, i) BE electrons or X-rays were separated from the background in an Energy – time-of-flight bidimensional plot, including all the events from the beginning up to the end of the run. Only for BE electrons the detected energy corresponds to the total electron kinetic energy. ii) We divided then the whole elapsed time in the run in elementary intervals Δt (in the example shown in Fig. 2, $\Delta t=20$ sec). iii) In each elementary interval Δt we calculate the mean time-of-flight t , the standard deviation s , and the total number of events n . iv) These statistical quantities are then reported as a function of the elapsed time, in bins of Δt .

Fig. 2 resumes the results in the restricted range of time 2400 – 2600 sec. in the run, for a forward detector at 6° . The results are similar in the whole run.

First, consider part a) of Fig. 2, where the time-of-flight average value for the BE electron peak is reported as a function of the elapsed time. This average value oscillates between channel ≈ 400 and channel ≈ 430 , corresponding to larger and slighter electron velocity (or energy) respectively. After a proper normalization of relative time-of-flight in absolute velocity units based on the X-ray peak position (see Fig. 1), the following scenario can be argued from Fig. 2a). Under Xe ion bombardment electrons are emitted from an insulating surface that then charges positively with a characteristic time-constant up to a maximum electric potential V_0 . A charge-breakdown follows, in correspondence of the “jumps” in Fig. 2a), and the target reaches the normal ground potential of the target holder. This process of positive charge-up and subsequent breakdown of the target is taking place incessantly during the whole run. To have a hint of the maximum potential V_0 , consider that the average BE electron time-of-flight has been lengthened by almost 30 channels ($\approx 3\text{ns}$) in a flight path of ≈ 183 cm. By a simple calculation we find $V_0 \approx 12$ kV. Note that this value is similar to the value found for a Mylar target bombarded by 64 A.MeV Kr beam [3] ($V_0 \approx 9$ kV).

Fig. 2b) shows the BE electron yield as a function of the elapsed time in the run. A strong anticorrelation between the BE electrons average time-of-flight and their yield is observed, as a function of the elapsed time. In other words, as the target charges-up the BE electron yield significantly decreases, by a maximum of almost a factor 2. The physical mechanism/s leading to this *puzzling* behaviour of BE electron yield is not clear at the moment. Some mechanisms that could explain in part this behaviour are reported in [3].

Much more puzzling is the behaviour of energetic X-ray yield as a function of the elapsed time, for the first time observed in this experiment. Let us first clarify what “X-ray” means in the context of our apparatus. The fast plastic scintillator in front of the photomultiplier is sensitive, with a given efficiency, also to X-rays. Because of detection-threshold effects, the detection of a X-ray implies that the energy released by the X-ray in the scintillator must be not less than some keV. X-ray from excited carbon or oxygen atoms of the insulating target are in the range of some hundred of eV. X-rays from excited Xe

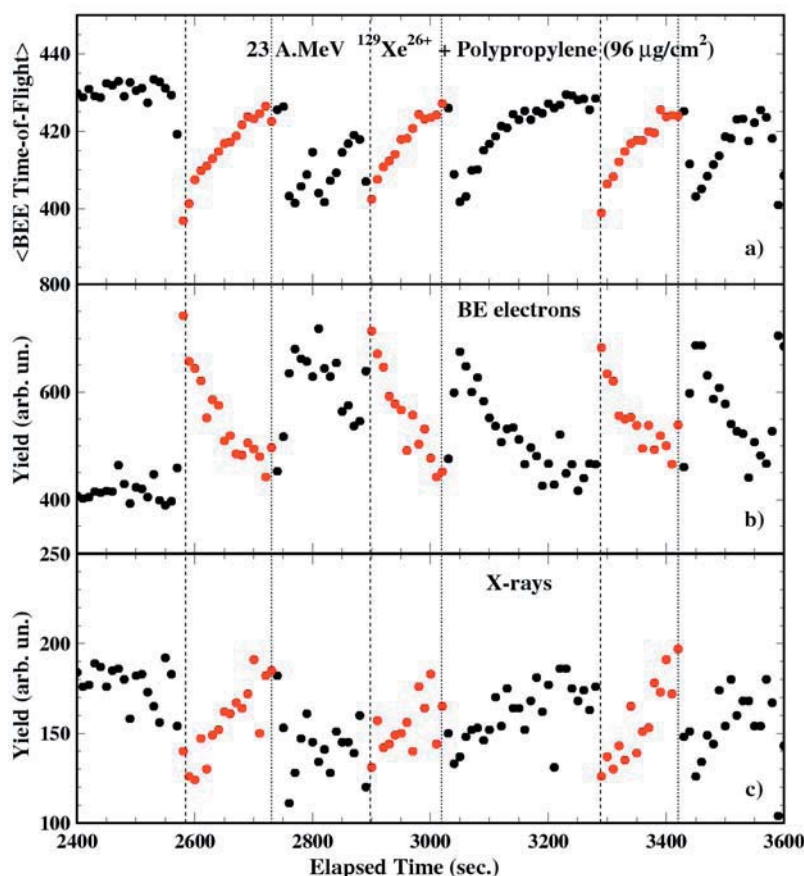


Fig. 2: The average BE electron time-of-flight, a), the average BE electron yield, b), and the average X-ray yield, c), are reported as a function of the elapsed time in the run (from 2400 up to 3600 sec.) in bins of Δt . In this case the averaging bin is $\Delta t = 20$ sec. The reaction is 23 A.MeV $^{129}\text{Xe}^{26+}$ + polypropylene and the observation angle $\theta_{\text{lab}} = 6^\circ$. For clarity, some loci of the figure are delimited by vertical, dotted and dashed, lines and the enclosed points in red.

ions are of the order of 30 keV and less. Therefore, although our experimental technique is much more appropriated for the detection of fast electrons, a fraction of X-rays can be unambiguously identified by time-of-flight measurements, and a lower limit to their energy can be roughly assigned. As a consequence of the above reasoning, the origin of the observed X-rays must be related to the excited Xe ion. A closer look to Fig. 2c) shows that on the average the X-ray yield increases each time as the target charges-up, and up to a maximum of a factor almost 2. We have no explication for this correlation at the moment.

4 CONCLUSIONS

In order to study the behaviour of insulating targets under irradiation of highly energetic, highly charged heavy ions, an insulating polypropylene target has been bombarded by 23 A.MeV $^{129}\text{Xe}^{26+}$. Fast BE electrons produced in the interaction beam-target have been studied to deduce the properties of the insulating target under bombardment. Following a simple statistical analysis of the results, it is shown that the insulating target charges-up and breaks down incessantly from the beginning up to the

end of the run. Positive potentials of the target surface as high as ≈ 12 kV have been observed. A puzzling result concerns the behaviour of BE electrons and X-ray yields as a function of the elapsed time in the run. It is shown, for the first time, that the forward BE electron yield decreases as the target surface charges-up, and that the contrary happens for the X-ray yield, so that BE electron and X-ray yields are anti-correlated each time the target surface charges-up. There is no clear explanation for these phenomena at the moment.

More resolute experiments at different incident energies and/or with different beams are planned in the next future to confirm these results.

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TARGET LIKE MULTI-BREAKUP IN THE $^{124}\text{Sn}+^{64}\text{Ni}$ SYSTEM AT 35 MEV/NUCLEON

M.Papa^j, F.Amorini^a, A.Anzalone^a, L.Auditore^c, V.Baran^d, I.Berceanu^d, J.Blicharska^e,
 B.Borderie^f, A.Bonasera^a, R.Bougault^g, J.Brzychczykⁱ, G.Cardella^j, S.Cavallaro^a,
 M.B.Chatterjee^k, A.Chbihi^l, M.Colonna^a, R.Dayras^m, E.De Filippo^j, M.Di Toro^a, J.Frankland^l,
 E.Galichet^f, W.Gawlikowiczⁱ, E.Geraci^h, G.Giuliani^j, F.Giustolisi^a, A.Grzeszczuk^e, P.Guazzoniⁿ,
 S.Kowalski^e, E. La Guidara^j, G.Lanzano^j, G.Lanzalone^a, N.Le Neindre^f, C.Maiolino^a, Z.Majka^l,
 A.Pagano^j, M.Petrovici^d, E.Piasecki^b, S.Pirrone^j, R.Planetaⁱ, G.Politi^j, A.Pop^d, F.Porto^a,
 E.Rosato^o, F.Rizzo^a, P.Russotto, K.Schmidt^e, K.Siwiek-Wilczynska^p, I.Skwira^p, L. Swiderski^p,
 A.Trifirò^c, M.Trimarchi^c, G.Vannini^h, G.Verde^j, M.Vigilante^o, J.P.Wieleczko^l, J.Wilczynski^q,
 L.Zettaⁿ and W. Zipper^e.

- a) INFN, Lab. Nazionali del Sud and Dip. di Fisica e Astronomia, Università di Catania, Italy
- b) Heavy Ion Laboratory, Univ. of Warsaw and Institute for Nuclear Studies, Swierk, Poland
- c) INFN, Gruppo Collegato di Messina and Dipartimento di Fisica, Università di Messina, Italy
- d) Institute for Physics and Nuclear Engineering, Bucharest, Romania
- e) Institute of Physics, University of Silesia, Katowice, Poland
- f) Institut de Physique Nucléaire, IN2P3-CNRS, Orsay, France
- g) LPC, ENSI Caen and Université de Caen, France
- h) INFN, Sezione di Bologna and Dipartimento di Fisica, Università di Bologna, Italy
- i) M. Smoluchowski Institute of Physics, Jagellonian University, Cracow, Poland
- j) INFN, Sez. di Catania and Dipartimento di Fisica e Astronomia, Università di Catania, Italy
- k) Saha Institute of Nuclear Physics, Kolkata, India
- l) GANIL, CEA, IN2P3-CNRS, Caen, France
- m) DAPNIA/SPH, CEA-Saclay, France
- n) INFN, Sezione di Milano and Dipartimento di Fisica, Università di Milano, Italy
- o) INFN, Sezione Napoli and Dipartimento di Fisica, Università di Napoli, Italy
- p) Institute of Experimental Physics, Warsaw University, Warsaw, Poland
- q) A. Soltan Institute for Nuclear Studies, Swierk/Warsaw, Poland

*Corresponding author e-mail: papa@ct.infn.it

Abstract

According to CoMD-II predictions an analysis of the experimental data collected for the $^{124}\text{Sn}+^{64}\text{Ni}$ collisions at 35 MeV/A highlights a class of events in which the target like fragments break in at least three intermediate mass fragments and light particles. The calculation suggests that this processes can be described as a target like–multi breakup generated by the projectile mean-field.

1 INTRODUCTION

One of the most challenging subjects in studying nuclear reactions at the Fermi energies is the understanding of the basic mechanisms leading to fragments formation. In particular, the multi-breakup process (or multi-fragmentation) is the result of a fast time evolution of the initial nuclear ground state structure, which undergoes a deep modification of the local densities. Therefore, by studying fragment

production, corresponding to different characteristics times, from prompt emission to more delayed and sequential emission, we explore different stages of the dynamical evolution which is sensitive to the different kinds of effective interactions modeled by the local densities.

Another aspect involves the nature itself of the process. It is well known that a wide class of experimental evidences about multi-fragmentation processes can be reasonably well described by statistical models in which the time variable disappears (at least as an independent variable of the problem) whereas others variables, more familiar to the macroscopic world, like temperature and volume, play the main role. These cases are normally understood as examples of complicated processes, probably long enough, to reach partial equilibrium of the hot sources at least with respect to the degrees of freedom related to the investigated observable. In this multi-faceted context, the experimental identification of

complex processes with clear dynamical features acquires noticeable relevance.

The system $^{124}\text{Sn}+^{64}\text{Ni}$ at 35 MeV/nucleon was investigated by means of the forward part ($1^\circ < \theta_{\text{lab}} < 30^\circ$) of the Charge Heavy Ion Mass and Energy Resolving Array (CHIMERA) in the REVERSE configuration.

Clear dynamical effects have been evidenced in ref.[1], for almost complete ternary events generated in mid-peripheral collisions.

The aim of this report is to illustrate the results of an analysis devoted to highlight complex multiple breakup contributions [2] occurring in the same time scale in which the overwhelming ternary (including “neck” emission and PLF fission) processes develop.

The analysis and dynamical nature of all the above-mentioned breakup processes will be discussed in the framework of the Constrained Molecular Dynamical-II (CoMD-II) [3]. This self-consistent N-body approach overcomes the main typical problems related to the semi-classical many-body dynamics by solving the equations of motion using constraining procedures to fulfill the Pauli principle and to satisfy the conservation of the total angular momentum. This last feature plays a crucial role to produce dynamical processes with different characteristic times and it has been applied also to describe fragments- GDR- γ -rays coincidence measurements [3].

2 MAIN SELECTION CRITERIA

We studied the system $^{124}\text{Sn}+^{64}\text{Ni}$ at 35 MeV/nucleon with the forward part of the CHIMERA detector and we discuss the experimental results obtained by selecting events with at least three fragments with charge $Z \geq 3$ and satisfying the following conditions: $P_{\text{tot}}^d \geq 0.65 P_{\text{tot}}$ and $Z_{\text{tot}}^d \geq 55$. P_{tot} is the linear momentum of the total system while Z_{tot}^d and P_{tot}^d represent the total charge and the total linear momentum of the detected fragments, respectively. For these events in Fig. 1a) we show the correlation between the charges of the three biggest fragments and their velocities along the beam direction V_{par} . From the figure it is seen that the aforementioned conditions mainly select events which include the PLF the TLF and one IMF with a parallel velocity in the mid-rapidity region. These conditions give a first level of selection that is also applied to the analysis discussed in the next sections. Details on the CHIMERA detector and on its capability to measure the charge, mass and velocity of particles according to their sizes, energies and directions are reported in [4].

3 COMPLEX TLF BREAKUP PROCESSES

In this section, we show results of an analysis devoted to reveal a class of events that can be interpreted as corresponding to a light partner multi-breakup.

To this aim, we have divided the fragment velocity space into two regions: the so-called TLF-side, corresponding

to fragments having negative values of the center of mass (c.m.) parallel velocity, and the complementary region corresponding to the PLF-side.

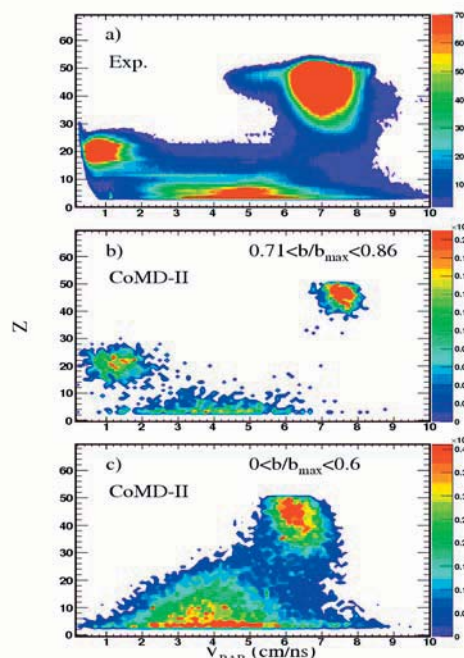


FIG.1- Upper panel: experimental charge Z versus parallel velocity V_{par} plot for the three biggest fragments with $Z \geq 3$. Central and bottom panels represent the analogous plots evaluated with CoMD-II model for different impact parameter b windows.

Among the “well reconstructed” experimental events, according to the criteria exposed in the previous section, we have selected those fulfilling the following conditions. We have considered all the events having a multiplicity of charged fragments, detected on the TLF-side, greater than three. The total charge Z_{ntg} of the detected particles on the TLF-side changes within the interval $20 < Z_{\text{ntg}} < 34$. Moreover we have applied further restrictions concerning the size of the three biggest fragments with charges, Z_{d1} , Z_{d2} , Z_{d3} (produced on the TLF-side). Their total charge Z_d is less than $0.8 Z_{\text{ntg}}$ and the distance D_d of the related Dalitz variables $C_1 = Z_{d1}/Z_d$, $C_2 = (Z_{d1} + 2Z_{d2}) / (3^{1/2} Z_d)$ from the center of the characteristic triangle ($C_1^0 = 1/3$, $C_2^0 = 1/3^{1/2}$) is less than 0.26. These restrictive conditions aim to select complex processes in which the TLF breaks in light particles and at least three IMFs with a limited mass asymmetry. This process therefore is difficult to be interpreted as due to a sequential statistical TLF decay. For these events in Fig. 2 we show, as a function of time, the average mass A_1 of the biggest fragment (PLF fragment) and the average masses of 3 biggest fragments, A_{d1} , A_{d2} , A_{d3} , produced on the TLF-side. From the figure, we note that the multi-breakup process is simultaneous and evolves almost in the same time scale of ternary events.

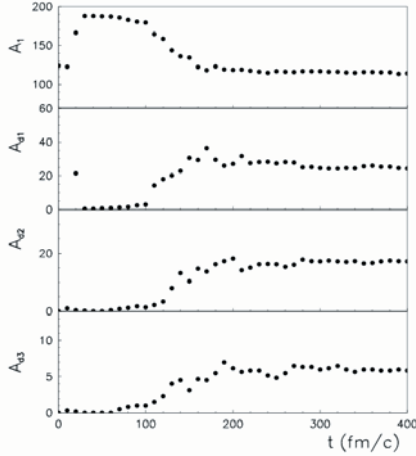


Fig.2- We show the time evolution for the average masses of the 4 biggest fragments produced in more complex multi-breakup processes as evaluated through CoMD-II calculations.

For the same events, in Fig. 3 we show a comparison between the model calculations and the experimental data concerning the Dalitz and the Z - V_{par} plots for particles with $Z \geq 3$.

The comparison, involving the correlations in charge, velocity and size of at least four fragments is globally satisfactory. Most relevant differences concern the charge of the PLF. In about 75% of cases, the charge of the biggest fragment detected on the PLF-side, is less than 30 units. The calculations produce, instead, an average higher value. The coupling of CoMD-II calculations with a statistical model describing the secondary stage of cooling of the biggest fragments, can improve the agreement.

In the following part of this section, we will perform a comparison concerning the degree of centrality and the energy balance between the described complex multi-breakup processes and the so-called "ternary" events producing at least one IMF (1-IMF process) and a PLF with a parallel velocity greater than 6.5 cm/ns. In particular, in Fig. 4a) we show with dashed and continuous lines the impact parameter distributions for 1-IMF and 3-IMF multi-breakup processes respectively. They have been obtained from CoMD-II calculations.

The dotted line represents the impact parameter distribution used in the simulations (it is linear in b).

From the figure we can see that 3-IMF processes are a small fraction (about 10%) of the more frequent 1-IMF events and that the corresponding b-window is shifted to smaller impact parameters. To compare the related degree of energy dissipation, as obtained from CoMD-II calculations, we have reduced the configuration of the final system into a binary one.

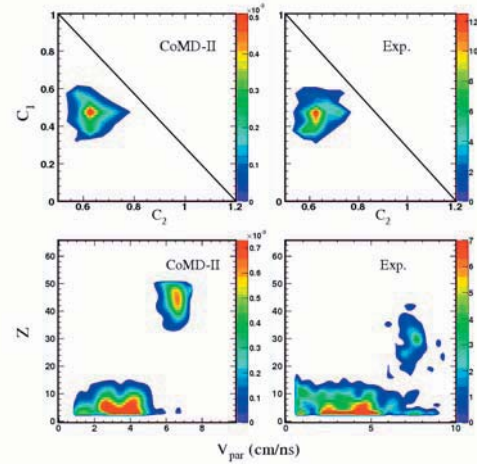


FIG.3- In the upper part calculated and experimental Dalitz plots are shown for the 3 biggest fragments of the so called TLF-multi-break-up. In the bottom part the related Z - V_{par} correlation plots are also shown

The charges, masses, excitation energies, binding energies and relative kinetic energies of all fragments and particles produced on the TLF-side have been composed to define a virtual source (not really observed) with a proper center of mass velocity. It has been labeled with 2 in Fig. 4c). The same procedure has been applied to fragments and particles produced on PLF-side giving rise to a virtual source which we label with 1 in the same figure. From the reconstructed c.m. velocities, in Fig. 4b) we show the corresponding total kinetic energy loss T_{kel} spectrum for 3-IMFs events (continuous line) and for 1-IMF ones (dashed line). From the figure it is evident that the 3-IMFs event give rise to more dissipative processes (with an average T_{kel} value of about 750 MeV) with respect to the 1-IMF events (average T_{kel} value of about 536 MeV). In TLF-multi-breakup processes, the average experimental value of the T_{kel} deduced from the two virtual sources can be roughly estimated by considering, on average, 20% of undetected mass. It results about 785 MeV in satisfactory agreement with the calculations. The different degree of dissipation affects also the excitation energies of the two virtual sources E^*_1 and E^*_2 as shown in Fig. 4c). In particular, E^*_2 for the 3-IMFs process is on average equal to 6.5 MeV/nucleon, about 1.5 MeV/nucleon higher than the one related to the ternary events. Finally, we observe that the reconstruction of these two primary sources allows to show that the two involved mechanisms produce a relevant unbalance between the excitation energy per nucleon absorbed on the TLF and PLF-sides. This further confirms the high non-equilibrium character of the investigated processes.

4 MICROSCOPIC DESCRIPTION

We now briefly describe the mechanism of the TLF-multi-breakup at

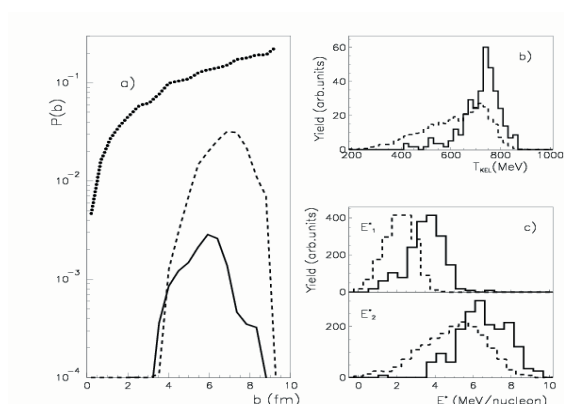


FIG.4- a) Impact parameter distributions from CoMD-II calculation. The points represent the distribution

used in the simulations. The dashed line is the distribution obtained for the selected ternary events (1 IMF processes), the continuous line is related to events with at least 3 IMFs produced in the target side (see text); b) calculated T_{KEL} spectra related to ternary events (dashed lines) and TLFs multi-breakup events (continuous lines); c) Evaluated intrinsic excitation energies E^*_1 , E^*_2 related to the two virtual sources reconstructed from CoMD-II calculations in the PLF and TLF-sides respectively. The dashed line is referred to ternary events whereas the continuous one is related to TLFs multi-breakup events.

a microscopic level. The left part of Fig. 5 refers to projectile nucleons, and shows the average density evaluated at different times on the entrance reaction plane. On the right panels of Fig.5 similar plots are shown for target nucleons. The reference system corresponds to the c.m. reference frame. From the figure it results that a substantial fraction of the target mass is transferred into the region where most of nucleons form the projectile nucleus (half-space with $z > 0$). Within the same time scale, other nucleons are transferred from the projectile to the target side (half-space with $z < 0$). The net transfer of mass is small and the remnant nucleons of the target form a region of low density in which the nucleons coming from the projectile, are involved in the cluster formation. On the contrary, the nucleons of the target migrating into the projectile side are on average bounded by the stronger projectile mean-field. In fact we can see in Fig. 5 that, for $z > 0$, the target nucleons form an almost compact region in density distribution, embedded in the corresponding more dense and extended region of projectile nucleons, to form the PLF nucleus. As result, the TLF undergoes the multi-breakup process. Therefore, the process seems to be triggered by the fast stripping of a non-negligible fraction of the target mass in the projectile mean-field. This stripping generates the instability of the lighter partner, which now includes a similar fraction of projectile nucleons.

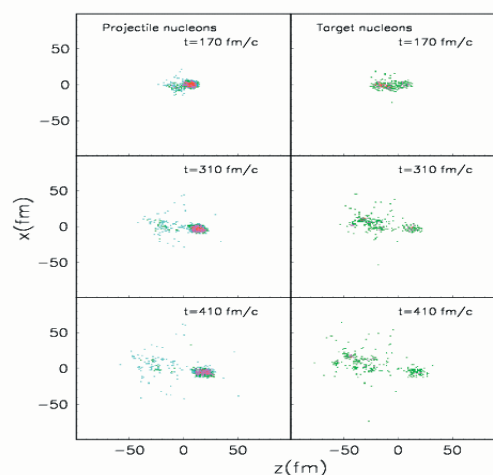


FIG.5- Average density plots on the entrance reaction plane, evaluated at different times, related to projectile (left column) and target nucleons (right column) for TLF multi-breakup processes. In particular, due to the kinematics of process the PLF and TLF regions are located in the $z > 0$ and $z < 0$ half-spaces respectively.

5 CONCLUDING REMARKS

In this work we have discussed the results of an analysis performed on experimental results obtained for the $^{124}\text{Sn} + ^{64}\text{Ni}$ system at 35 MeV/nucleon investigated with the forward part of the CHIMERA detector.

The analysis is devoted to highlights the existence of event in which the hot sources break in at least three IMFs and light particles. The comparison with CoMD-II calculations suggests that this kind of events can in large part associate to the TLF multi-breakup processes.

The calculations indicate that this mechanism is characterized by prominent non-equilibrium effects in the excitation energy sharing between two virtual sources built by considering the fragments emitted on the PLF and TLF-sides. Moreover, the calculations suggest that, at a microscopic level, this TLF multi-breakup process is triggered by the transfer of nucleons between PLF and TLF leading to low density instability of the quasi-target. This process can be considered as a "prototype" of a fully dynamical induced multi-fragmentation mechanism of nuclei in which the heavy partner mean-field plays a dominant role. Deeper investigations on this subject need to be performed in the next future. In particular a more detailed investigation of these processes can be obtained through the already planned experiment at LNS in which the same system will be studied in direct kinematical condition.

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FISSION AND ROTATIONAL DYNAMICS IN THE COLLISION $^{124}\text{Sn} + ^{64}\text{Ni}$ AT 35 MEV/NUCLEON

M.Papa^j, F.Amorini^a, A.Anzalone^a, L.Auditore^c, V.Baran^d, I.Berceanu^d, J.Blicharska^e,
 B.Borderie^f, A.Bonasera^a, R.Bougault^g, J.Brzychczykⁱ, G.Cardella^j, S.Cavallaro^a,
 M.B.Chatterjee^k, A.Chbihi^l, M.Colonna^a, R.Dayras^m, E.De Filippo^j, M.Di Toro^a, J.Frankland^l,
 E.Galichet^f, W.Gawlikowiczⁱ, E.Geraci^h, G.Giuliani^j, F.Giustolisi^a, A.Grzeszczuk^e, P.Guazzoniⁿ,
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- a) INFN, Lab. Nazionali del Sud and Dip. di Fisica e Astronomia, Università di Catania, Italy
- b) Heavy Ion Laboratory, Univ. of Warsaw and Institute for Nuclear Studies, Swierk, Poland
- c) INFN, Gruppo Collegato di Messina and Dipartimento di Fisica, Università di Messina, Italy
- d) Institute for Physics and Nuclear Engineering, Bucharest, Romania
- e) Institute of Physics, University of Silesia, Katowice, Poland
- f) Institut de Physique Nucléaire, IN2P3-CNRS, Orsay, France
- g) LPC, ENSI Caen and Université de Caen, France
- h) INFN, Sezione di Bologna and Dipartimento di Fisica, Università di Bologna, Italy
- i) M. Smoluchowski Institute of Physics, Jagellonian University, Cracow, Poland
- j) INFN, Sez. di Catania and Dipartimento di Fisica e Astronomia, Università di Catania, 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) INFN, Sezione Napoli and Dipartimento di Fisica, Università di Napoli, Italy
- p) Institute of Experimental Physics, Warsaw University, Warsaw, Poland
- q) A. Soltan Institute for Nuclear Studies, Swierk/Warsaw, Poland

*Corresponding author e-mail: papa@ct.infn.it

Abstract

Multi-breakup processes for the $^{124}\text{Sn} + ^{64}\text{Ni}$ system at 35 MeV/nucleon have been studied with the forward part of the CHIMERA detector. A comparison between experimental data corresponding to almost complete ternary events and Constrained Molecular Dynamics (CoMD-II) calculations suggests different characteristic times in the selected processes. A dedicated study of the rotational dynamics leading to slower dynamical fission processes is presented.

1 INTRODUCTION

One of the most challenging subjects in studying nuclear reactions at the Fermi energies is the understanding of the basic mechanisms leading to fragments formation. In particular, the multi-breakup process (or multi-fragmentation) is the result of a fast time evolution of the initial nuclear ground state structure, which undergoes a deep modification of the

local densities. Therefore, by studying fragment production, corresponding to different characteristics times, from prompt emission to more delayed and sequential emission, we explore different stages of the dynamical evolution which is sensitive to the different kinds of effective interactions modeled by the local densities.

Another aspect involves the nature itself of the process. It is well known that a wide class of experimental evidences about multi-fragmentation processes can be reasonably well described by statistical models in which the time variable disappears (at least as an independent variable of the problem) whereas others variables, more familiar to the macroscopic world, like temperature and volume, play the main role. These cases are normally understood as examples of complicated processes, probably long enough, to reach partial equilibrium of the hot sources at least with respect to the degrees of freedom related to the investigated observable. In this multi-faceted context, the experimental identification of

complex processes with clear dynamical features acquires noticeable relevance.

The system $^{124}\text{Sn}+^{64}\text{Ni}$ at 35 MeV/nucleon was investigated by means of the forward part ($1^\circ < \theta_{\text{lab}} < 30^\circ$) of the Charge Heavy Ion Mass and Energy Resolving Array (CHIMERA) in the REVERSE configuration.

Clear dynamical effects have been evidenced in ref.[1], for almost complete ternary events generated in mid-peripheral collisions.

The aim of this report is to illustrate an analysis devoted to describe dynamical fission events observed in ref.[1] including its time scale and the related rotational dynamics of the pre-fission PLFs [2].

The analysis and dynamical nature of all the above-mentioned breakup processes will be discussed in the framework of the Constrained Molecular Dynamical-II (CoMD-II) [3]. This self-consistent N-body approach overcomes the main typical problems related to the semi-classical many-body dynamics by solving the equations of motion using constraining procedures to fulfill the Pauli principle and to satisfy the conservation of the total angular momentum. This last feature plays a crucial role to produce dynamical processes with different characteristic times and it has been applied also to describe fragments- GDR- γ -rays coincidence measurements [3].

2 MAIN SELECTION CRITERIA

We studied the system $^{124}\text{Sn}+^{64}\text{Ni}$ at 35 MeV/nucleon with the forward part of the CHIMERA detector and we discuss the experimental results obtained by selecting events with at least three fragments with charge $Z \geq 3$ and satisfying the following conditions: $P_{\text{tot}}^d \geq 0.65 P_{\text{tot}}$ and $Z_{\text{tot}}^d \geq 55$. P_{tot} is the linear momentum of the total system while Z_{tot}^d and P_{tot}^d represent the total charge and the total linear momentum of the detected fragments, respectively. For these events in Fig. 1a) we show the correlation between the charges of the three biggest fragments and their velocities along the beam direction V_{par} . From the figure it is seen that the aforementioned conditions mainly select events which include the PLF the TLF and one IMF with a parallel velocity in the mid-rapidity region. These conditions give a first level of selection that is also applied to the analysis discussed in the next sections. Details on the CHIMERA detector and on its capability to measure the charge, mass and velocity of particles according to their sizes, energies and directions are reported in [4].

3 DYNAMICAL FISSION AND TIME SCALES

Interesting velocity correlations reported in ref.[1] are closely related to the time scale of these processes. In Fig. 2a) we show the plot of the experimental reduced relative velocity of the IMF (third biggest fragment) with respect to the TLF fragment $V_{\text{red}}^{\text{IT}}$, as function of its reduced velocity with respect to the PLF $V_{\text{red}}^{\text{IP}}$. As usual, the quantities $V_{\text{red}}^{\text{IT}}$ and $V_{\text{red}}^{\text{IP}}$ represent the relative velocities

of the IMF divided by the corresponding value obtained from the Viola systematics.

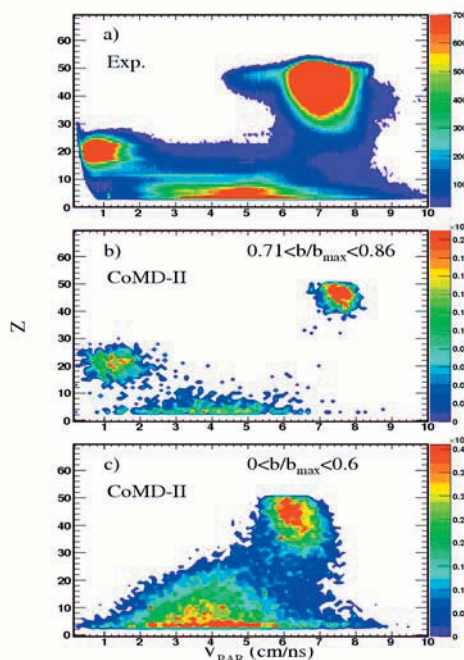


FIG.1- Upper panel: experimental charge Z versus parallel velocity V_{par} plot for the three biggest fragments with $Z \geq 3$. Central and bottom panels represent the analogous plots evaluated with CoMD-II model for different impact parameter b windows.

In ref. [1] the average correlation shown in the figure, was calibrated in time by using a basic three-body kinematics model. This includes the mutual Coulomb interactions between fragments and the use of simple assumptions about their relative distances and velocities. In particular, it was shown that processes with the shortest emission time, corresponding to IMF velocities around the mid-rapidity region, fill, on average, the central region of the $V_{\text{red}}^{\text{IT}}-V_{\text{red}}^{\text{IP}}$ plot along characteristic lines which depend on the model parameters. This is seen more clearly by comparing Fig. 2a) with Fig. 2b), which represents the experimental results obtained for IMF velocities ranging between 2.5 and 5 cm/ns. More delayed sequential processes [2] should fill the region along the axes. These last cases correspond to prompt binary processes followed by a delayed PLF or TLF fission. The study performed in ref.[1], allowed us to evaluate a separation time for mid-rapidity IMFs ranging between 40 and 120 fm/c. The corresponding plots obtained from CoMD-II calculations are shown in Fig. 2c) and Fig. 2d) respectively. From Fig. 2d) we can see that the experimental correlations close to the mid-rapidity IMF velocities are well reproduced. However, the greater

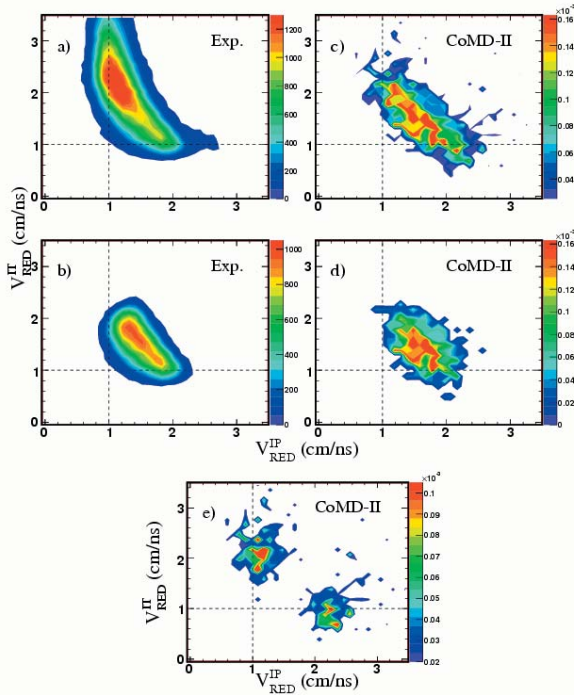


FIG.2- In panels a) and b) we show the experimental $V_{red}^{IT}-V_{red}^{IP}$ plots for ternary events. In panel b) only IMFs having a velocity range 2.5-5 cm/ns have been considered. The panels c) and d) show the analogous plots obtained from CoMD-II calculations. The panel e) show the calculation results obtained for IMFs velocities outside the range 2.5-5 cm/ns

yield seen in Fig. 2a) along the $V_{red}^{IP}=1$ axis, corresponding to a longer time scale towards the PLF fission, is not reproduced in Fig. 2c). This could be connected to the finite time of the calculations.

Nevertheless, in Fig. 2c), the region along the $V_{red}^{IP}=1$ axis is not empty. This is clearly seen in Fig. 2e) where we show the calculated $V_{red}^{IT}-V_{red}^{IP}$ plot for IMF velocities outside of the range 2.5-5 cm/ns. The simulated events that fill the region along the $V_{red}^{IP}=1$ axis include the PLF fission evolving with an average decay time of about 300 fm/c and producing an IMF with an average mass of about 35 units. This is clearly seen in Fig. 3 where the open circles show the time evolution of the average masses calculated for the three biggest fragments A_1 , A_2 , A_3 for the process selected. We see that this evolution is characterized by a "time delay" of about 130 fm/c. The TLF (A_2) is formed after about 50 fm/c and the PLF (A_1) undergoes a binary splitting in the subsequent time interval of about 300 fm/c. In the same part of the figure, the full dots refer to the same quantities related to ternary events corresponding to the selected events of Fig. 2d). In this case, for the three fragments, we obtain a time delay and a formation time of about 70 fm/c, therefore the character of the breakup process can be described through a faster simultaneous mechanism. This last prompt mechanism was also reproduced in the framework of stochastic BNV (Boltzman Nordheim Vlasov) calculations. Finally, in Fig. 4 we show

configuration maps calculated at different times representing a typical event evolving with the longer time scale and leading to a PLF fission event.

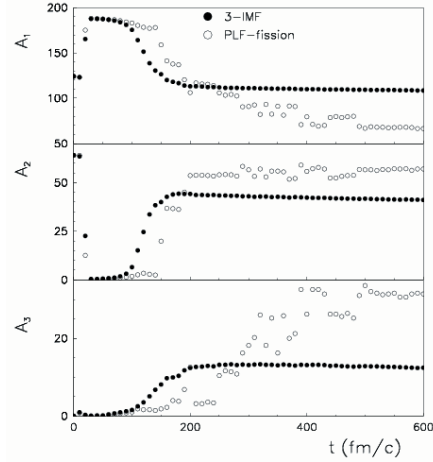


FIG.3- Time evolution of the average mass numbers of the three biggest fragments according to the CoMD-II model for ternary (full dots) and dynamical fission events (open circles).

We conclude this section by observing that to reproduce these different characteristic times with the CoMD-II approach, it has been necessary to constrain the equations of motion to fulfill the total angular momentum conservation law. This conservation principle is violated in all the microscopic

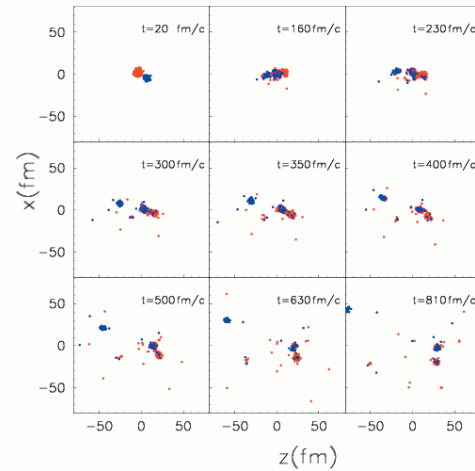


FIG.4- Configuration map, at different time steps, of one event related to the $^{124}\text{Sn}+^{64}\text{Ni}$ at 35 MeV/nucleon leading to the fission of the heavy partner.

approaches which use random impulsive forces (as for example the ones necessary to simulate the nucleon-

nucleon hard-core interaction) without including dedicated algorithms to overcome the problem [3].

4 ROTATIONAL DYNAMICS

According to the results obtained in ref.[1] and to the study performed in Sec. III (see Fig. 3 and Fig. 4) [2], in ternary events a large contribution from a sequential breaking of the hot compound is visible for moderate asymmetry between the masses of the PLF and the IMF produced at mid-rapidity. These events also show a Φ_{plane} distribution strongly peaked at forward angles. Φ_{plane} is defined as the oriented angle between the projection of the fission axis and of the separation axis on the reaction plane.

The average value of Φ_{plane} is an observable having an important meaning. In fact it contains implicitly the information related to the characteristic time of the process. To extract this information however one needs to know both the rotational and fission dynamics.

In particular, for the system under study, these problems were raised in ref.[1] to understand the relatively small value of the observed average Φ_{plane} .

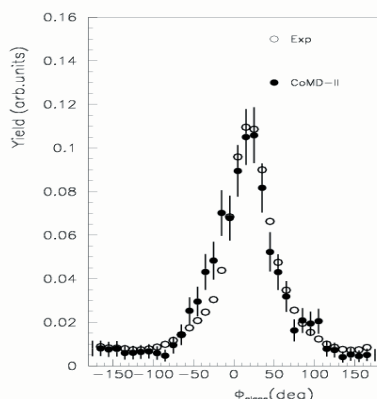


FIG.5- Experimental and calculated Φ_{plane} distribution for ternary events with $A_{\text{HL}} < 5$ and $V_{\text{thr}} = 3$ cm/ns. The bars indicate the errors related to the statistics of simulations. For the experimental data the errors are smaller than the size of the symbol.

Fig.5 shows a comparison between the experimental Φ_{plane} distribution and the calculations obtained from an analysis of ternary events. In particular, the open circles indicate the experimental results obtained by selecting IMFs emitted with a velocity greater than $V_{\text{thr}} = 3$ cm/ns and with a ratio between the masses of the PLFs and IMFs A_{HL} less than five. In the same figure, CoMD-II results are plotted with full dots. They have been obtained for the same values of V_{thr} and A_{HL} .

Model calculations reproduce the experimental distribution well, including the value of the average Φ_{plane} (about 10 degree), and the background associated to the primary PLF splitting processes with longer emission times. In particular a detailed study has been performed starting from the microscopic description of the processes to clearly establish a link between the observed average

Φ_{plane} distribution the fission process and the rotational dynamics, the main results are the following:

- 1)-the most important non-collective rotational effects, for the whole system, are not related to the biggest fragment or PLF, but are associated to the development of TLFs and the main IMFs relative motion with respect to the remaining system. This concerns a restricted time interval of about 120 fm/c during which these fragments arise from the hot intermediate system;
- 2)-at the involved energy, the characteristic time intervals of the processes leading to dissipation, transfer of angular momentum and the formation and splitting of the hot fragments are partially overlapped;
- 3)-a non-negligible fraction of the total angular momentum is absorbed by the relative motion of the developing binary system formed by the PLF and the mid-rapidity fragment 3. The maximum relative angular momentum J^r is about 120h at 200 fm/c inertia parameter governing the relative motion between fragment 1 and 3 is about 3500 fm² at 180 fm/c. This high value, which determines the low value of the maximum angular velocity, is due to expansion and hyper-deformation effects experienced at this stage by the fragments involved.

5 CONCLUDING REMARKS

In this work we have illustrated a dedicated study of the results of an analysis performed on the $^{124}\text{Sn} + ^{64}\text{Ni}$ collision at 35 MeV/nucleon concerning dynamical fission process.

The rotational dynamics of processes leading to dynamical fission of the heavy partner has been described in the framework of the CoMD-II model. The calculation shows that the average alignment observed, can still be understood in terms of the relative rotation between the forming PLF and IMF and therefore through an essential collective rotational dynamics. However, the results also show that the overlap in time of processes related to the transfer of angular to the splitting nucleus and to the dynamical fission itself has to be properly taken into account. Therefore in this case, simple models based on a rigid body rotation, the transfer of spin and the subsequent fission could be inadequate. Finally, we would like to note that the possibility of describing both the existence of dynamical processes, evolving with different characteristic times, and the rotational dynamics leading to PLF fission are results largely due to the novel constraint introduced in the CoMD-II approach concerning the conservation rule of the total angular momentum.

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PHASER 8 – A PHASE-LOCKED RF PRESCALER FOR CHIMERA EXPERIMENTS

J. Töke^{a)}, I. Pawełczak^{a)}, M. J. Quinlan^{a)}, W. U. Schröder^{a)}, G. Cardella^{b)},
 E. De Filippo^{b)}, A. Pagano^{b)}, and S. Pirrone^{b)}

a) Departments of Chemistry and Physics, University of Rochester, Rochester, NY, USA

b) INFN Sezione di Catania

Abstract

An electronic module has been designed and built that automates the synchronization of prescaled RF timing signal to the beam monitor signals. The module, named *Phaser 8*, can be operated as an autonomous phase-locked prescaler or as a phase controller for an external prescaler. Its mode of operation and the desired RF phase with respect to the beam bursts is programmable via jumpers and two front-panel rotary switches. The logic of *Phaser 8* is implemented in an XC95144XL CPLD (Complex Programmable Logic Device) by Xilinx and can thus be readily updated by an (in-system) reprogramming of the CPLD.

In experiments at cyclotron facilities with well defined beam microstructure, the RF signal is often used in data acquisition as a timing reference signal. When the facility is set up to generate a beam burst at the target site not at every RF cycle, but at a definite “sub-harmonic” of the RF frequency, need arises to extract a subset of RF signals that have a fixed timing with respect to the beam bursts. A simple way of generating such a subset is to use a prescaler operating at the same prescaling factor as is established between the RF pulses and the actual beam bursts. Unfortunately, because of the operating instabilities of the cyclotron, the timing relationship or the phase between the RF prescaler pulses and the beam bursts will occasionally change causing inconvenience in the subsequent interpretation of the data acquisition timing information. To minimize such an inconvenience, it is desirable to constantly monitor the relative phase between the (timing) prescaled RF signal and the beam bursts and to take appropriate corrective measures whenever this relative phase changes.

To automate and facilitate the control of the phase of the prescaled RF signal, a versatile NIM module, named *Phaser 8*, was designed that synchronizes the 1-of- n ($n=2-8$) prescaler output signal to a dominant component in the time spectrum of a reference signal. In its main design function, *Phaser 8*, called from here on simply *Phaser*, generates a prescaled cyclotron RF signal with a phase locked to a quasi-periodic and noisy reference signal – the dominantly elastic scattering events contaminated by some inelastic events. Thus, in this main

mode of operation, it serves as a phase-locked RF prescaler, with the output signal useful as a time reference (stop signal) for TOF measurements. All that is in this case required from the reference signal is that a dominant component be present in its time spectrum that is at least $17/3$ or $17/7$ (jumper-selected) times more intense than the second strongest component – a condition that is easily fulfilled by the timing signal from almost any detector responding to beam-produced radiation.

Apart from the above phase-locked prescaler (Presc) mode, the *Phaser* can be used as an external prescaler phase controller (Ext) for an independent RF prescaler, such that it will generate RF *Veto* signals of a duration needed to shift the phase of the prescaler output to a desired value with respect to the reference signal.

In the absence of a suitable reference signal, *Phaser* can be also operated in an interactive-only phase-control mode, both, in Presc and the Ext settings. In this interactive mode, the phase of the prescaler output shifts in response to an external trigger (when in Presc mode) or a single-period RF *Veto* signal is generated in response to such a trigger (when in Ext mode).

A photograph of the completed *Phaser* is shown in Fig. 1, featuring prominently eight diagnostic LEDs and a number of LEMO jacks and control switches.

In spite of its many capabilities and an apparently complex look of the front panel, the actual use of *Phaser* is quite simple and may entail only one-time hardware setup consisting of

- 1) Setting the prescale factor consistent with the beam microstructure (front-panel rotary selector).
- 2) Supplying cyclotron RF and beam monitor timing pulses (NIM) to dedicated NIM inputs.
- 3) Selecting the desired phase of the prescaler output relative to the elastic scattering signal (rotary selector).
- 4) Selecting automatic operation (three-position switch).
- 5) Routing the RF/ n phase-locked signal from the dedicated NIM output to the data acquisition setup.

Phaser is in fact an enhancement to the existing setup of the phase control of the cyclotron RF prescaler at the Chimera location, which makes its setup even more obvious to those familiar with the existing setup.



Fig.1. Photograph of the front panel of *Phaser 8*.

The operation of the *Phaser* can be understood from the timing diagram of the relevant signals shown in Fig. 2. In this diagram, it is assumed that the beam bursts arrive at the target every 4-th RF cycle and, for the sake of simplicity, any delays between the various waveforms are neglected. Accordingly, elastic scattering signals arrive sparsely simultaneously with beam bursts and,

occasionally, inelastic events occur at “random” times. The presence of the RF signal is essential for the functioning of *Phaser*. An RF failure is indicated by the red LED labeled as “RF Fail”. The latter comes on whenever the duration of the RF pulse is shorter than approximately 1/8 of the RF period.

Phaser sorts monitor events into $n=n_{\text{presc}}$ (prescale factor) time bins of width equal to the RF period, representing different phases of the monitor signals with respect to the prescaler output. Then, it identifies the dominant component in the monitor signal (elastic events) as the one that has an intensity of at least 17/3 (optionally, 17/7) of the next strongest component. When such a component exists and the module is set to operate in automatic phase-locking mode, *Phaser* compares the phase (bin number) of this component to the desired phase selected on the rotary selector. When these phases do not match, *Phaser* generates an RF veto signal of duration T_{Veto} equal to

$$T_{\text{Veto}} = T_{\text{RF}} * \Delta\text{Phase},$$

where T_{RF} is the RF period and ΔPhase is the difference between the measured and preset phases. This veto applied to the RF prescaler input causes the phase of the prescaler output to shift so as to match the dominant phase of the monitor signal relative to prescaler output to the desired preset value. The attainment of the latter match is indicated by the green *Lock* LED lighting up, and the measured phase displayed in binary fashion on four yellow LEDs marked *Phase*. The generation of the *Veto* signal is indicated by blinking of the red *Veto* LED.

When operated in phase-locked prescaler mode (*Presc*), *Phaser* applies the above veto signal to its internal prescaler input resulting in the *RF/n* (NIM) signal that is phase-locked to the dominant component in the monitor signal timing spectrum. Whenever a dephasing occurs (see the bottom two traces in Fig. 2, *Phaser* establishes the new phase of the dominant monitor signal and generates again a suitable veto signal. Note that because of how the algorithm defines the dominant phase, it takes 17 dominant events to determine a new phase and to initiate the corrective action.

When operated in external phase-controller mode, *Phaser* routes the veto signal to the *Veto* I/O port for use in conjunction with an external prescaler.

A completed *Phaser* underwent successful tests both, on bench and in experiments.

This work was supported by the U.S. Department of Energy grant No.DE-FG02-88ER40414.

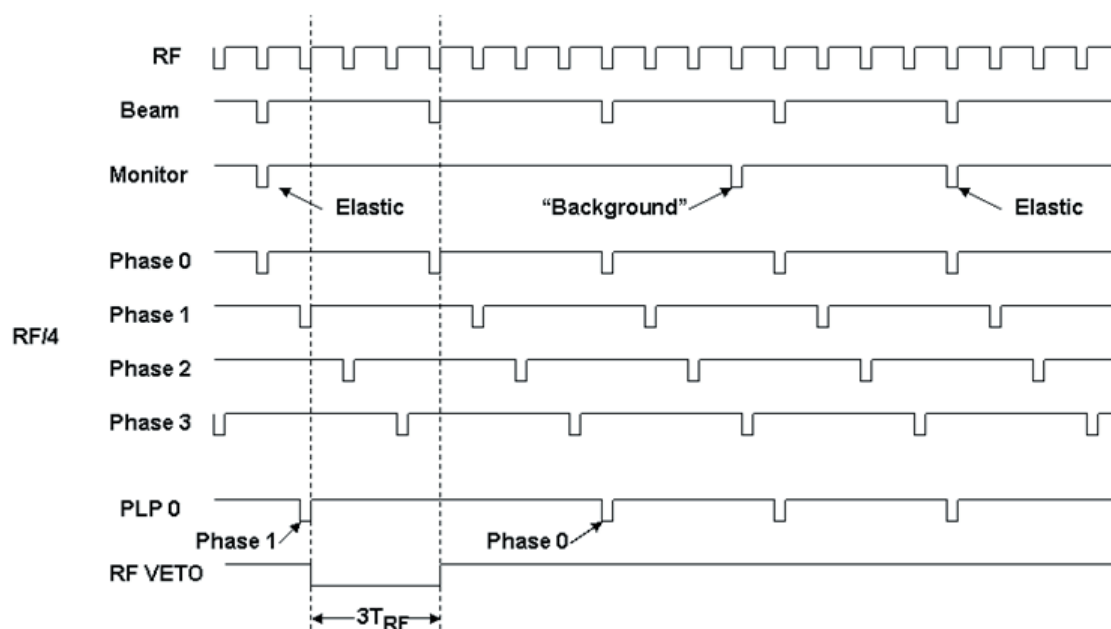


Fig. 2. Timing diagram of *Phaser*. Traces illustrate (from top to bottom) the cyclotron raw RF, the beam microstructure obtained by suppressing 3 out of 4 original beam bursts, a sample (exaggerated) monitor signal, the four possible phases of an RF/4 prescaler, the output of a phase-locked 1/4 prescaler locked to phase 0, and the RF veto generated by *Phaser* to restore phase 0 (after a "nuisance" dephasing to phase 1). Note that in a Presc operation, the RF Veto is generated only internally, while in Ext mode it is available at the Veto I/O port for the use in conjunction with an independent prescaler.

^{12}C FRAGMENTATION MEASUREMENTS AT 62 MEV/A

C.Agodi^a, L.Calabretta^a, G.Cardella^d, G.A.P.Cirrone^a, G.Cuttone^a, F.Fiorini^{e,f}, P.Lojacono^a,
M.C.Morone^{b,e}, M.De Napoli^c, G.Raciti^{c,d},
E.Rapisarda^c

a) INFN Laboratori Nazionali del Sud, Catania, Italy

*b) Dipartimento di Biopatologia e Diagnostica per Immagini,
Sezione di Fisica Medica, Università di Roma Tor Vergata*

c) Dipartimento di Fisica Università degli Studi di Catania

d) INFN Sezione di Catania

e) INFN Sezione di Roma Tor Vergata

f) Dipartimento di Fisica Università di Roma Tor Vergata

Abstract

In the framework of the MOBIDIC experiment we have started the systematic measurement of light ions fragmentation cross sections at intermediate energies.

We measured, as a first step, the fragmentation of the ^{12}C beam accelerated by the Superconducting Cyclotron (SC) at 62 AMeV on ^{197}Au and ^{12}C targets. Motivation and preliminary results are reported.

1 INTRODUCTION

The study of the nuclear fragmentation process involves many fields of interest, such as the hadrontherapy and the spatial vehicles shielding. Indeed, the measure of the fragmentation cross sections [1] is an important information to estimate how this process modifies dose distributions and biological effectiveness [2].

At present, simulations with analytical codes are used to deal with these problems. Such approach presents considerable uncertainty, especially because of a reduced number of experimental data, both on the fragmentation cross sections and on the different quality of radiations biological effectiveness.

All these reasons claimed more fragmentation cross section data, in a wide energy range and with different ions and materials.

In the last year, the INFN supported a study on a new Superconducting Cyclotron (SC) for applications in hadrontherapy [3]. To modulate the fixed energy of the ions accelerated by the new SC, an external passive system will be used. Therefore, the study of a modulator system started into a new experimental proposal, named MOBIDIC (Modulator for Beams Ions Delivered by INFN Cyclotron).

It is necessary to consider that a passive system, along the transport beam line, induces the projectile fragmentation that could contaminate the primary beam and contribute to an additional dose for the patient, that it is necessary to estimate.

In order to perform a systematic study of projectile fragmentation cross sections at intermediate energies, we measured the ^{12}C fragmentation cross section on Au and C target at 62 AMeV.

2 THE EXPERIMENT

A schematic view of the experimental set-up inside the TRASMA scattering chamber is shown in Fig. 1. The detection system [4] consisted of two Si-CsI hodoscopes with different granularity, called Hodo-small and Hodo-big. The Hodo-small, set up at a distance of 80 cm from the target consisted of 81 two-fold telescopes: 300 μm Silicon detectors 1x1 cm² of active area followed by a 1x1 cm² and 10 cm long CsI(Tl). The Hodo-small covered the angular range $\theta_{lab} = \pm 4.5^\circ$. The Hodo-big, set up at a distance of 0.6 m from the target, consisted of 89 three-fold telescopes 50 μm + 300 μm Silicon detectors both having 3x3 cm² surface followed by a 6 cm long CsI(Tl) of the same surface. It covered the angular range θ_{lab} between $\pm 4.5^\circ$ and $\pm 16.5^\circ$. Both hodoscopes were used to measure the energy of the isotopically resolved fragments.

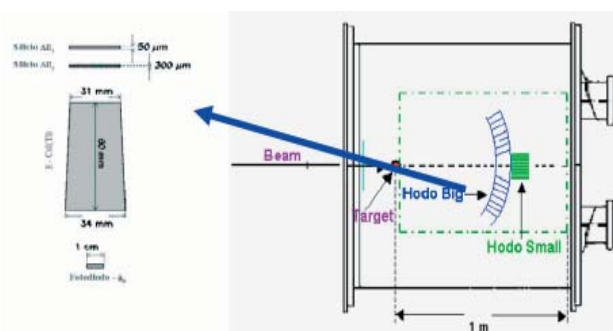


Fig.1 Schematic view of an Hodo-Big telescope (left) and of the experimental setup (right).

2.1 Preliminary results

Figure 2 shows a typical inclusive ΔE -E scatter plot of a Hodo-Big telescope. It is possible to distinguish the Carbon elastic scattering and the well resolved reaction products.

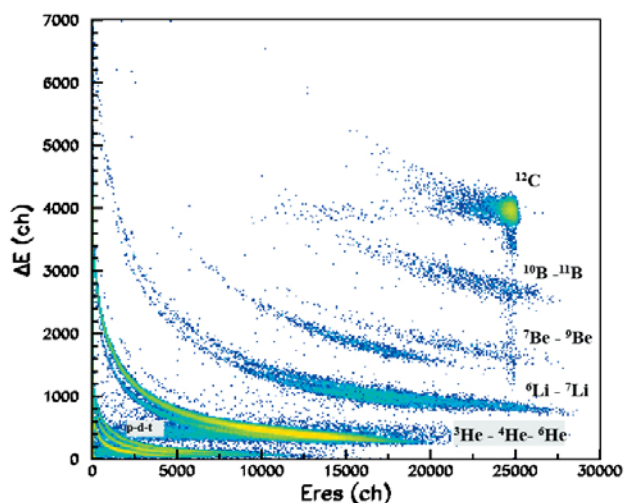


Fig. 2. ΔE -E scatter plot for one Hodo-Big telescope.

From a preliminary analysis we obtained the rough estimate of the relative angular distribution of the reaction products for $^{12}\text{C} + ^{197}\text{Au}$ at 62 AMeV shown in Fig. 3.

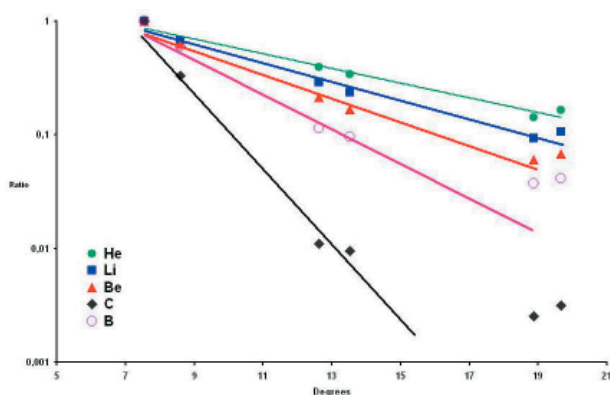


Fig.3 Reaction products angular distribution for the $^{12}\text{C} + ^{197}\text{Au}$ at 62 AMeV. The lines refer to exponential fits.

For both reactions, $^{12}\text{C} + ^{197}\text{Au}$ and $^{12}\text{C} + ^{12}\text{C}$, the analysis is still in progress.

In the next future, a similar experiment, on different targets and at several incident energies will be performed at the Laboratori Nazionali del Sud.

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TOTAL REACTION CROSS SECTION MEASUREMENTS OF ${}^7,8\text{Li}+{}^{28}\text{Si}$ AROUND THE COULOMB BARRIER: PRELIMINARY RESULTS

A.Musumarra^{a,b,*}, F.De Luca^{a,c}, A.Di Pietro^a, P.Figuera^a, P. Finocchiaro^a, M.Fisichella^{a,c}, M.Lattuada^{a,c}, T.J.Mertzimekis^d, A.Pakou^d, G.Randisi^{a,c}, G.Scalia^{a,c}, C. Scirè^a, S. Scirè^a, V.Scuderi^{a,c}

a) INFN Laboratori Nazionali del Sud, Catania, Italy

b) DMFCI dell'Università di Catania, Italy

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

d) Department of Physics, The University of Ioannina, Greece

• Corresponding author, e-mail: musumarra@lns.infn.it

Abstract

Total reaction cross section measurements for the ${}^7\text{Li}+{}^{28}\text{Si}$ system have been performed at energies $E_{\text{lab}}=12,13,14.56,15,16$ MeV by using a new experimental technique. The deduced $\sigma_R(E)$ excitation function agrees with the data obtained via optical model analysis of elastic scattering measured in a previous experiment. The same technique has been used in order to determine the total reaction cross section for the ${}^8\text{Li}+{}^{28}\text{Si}$ system at $E_{\text{lab}}=14.56$ MeV. This experiment was performed with the first ${}^8\text{Li}$ radioactive beam produced and accelerated by the new EXCYT facility at LNS.

1 INTRODUCTION

Total reaction cross sections are of fundamental interest in nuclear physics. Their measurement leads, for example, to the determination of nuclear size, thus directly revealing unusual spatial extension of the nucleus (halos, skin).

Furthermore, they are a direct measurement of absorption probability, which affects the elastic scattering by removing flux. Consequently they are useful in order to provide constraints on the imaginary part of the optical potential, included in the theoretical analysis of elastic scattering. In this context, investigation of reaction cross sections has been undertaken at Demokritos National Research Center in Athens and INFN-LNS Catania in order to deduce the total reaction cross section for the ${}^{6,7,8,9}\text{Li}+{}^{28}\text{Si}$ systems at energies around the Coulomb barrier (i.e. $E_{\text{lab}}=7-15$ MeV). In this energy range we can investigate on the peculiar behavior of the optical potential referred as "Threshold Anomaly" [1], where we expect fluctuations for both the real and imaginary part of the potential according to the well-known dispersion relation. With this study we aim finally to get information on reaction dynamics of a given system by using a comprehensive set of data from different measurements (elastic, break-up, transfer, fusion and reaction cross section). The new experimental technique, used in the present experiment, allows the discrimination of reaction

events by using TOF. It can be, in some cases, implemented for other systems, representing an evolution of the direct method used by Warner and collaborators [2,3].

2 EXPERIMENTAL METHOD

The basics of the method were originally established by Warner et al. [2,3] and were successfully used for determining reaction cross sections of many stable light to medium systems at energies ranging from few MeV up to intermediate energies. Nevertheless, the experimental set-up proposed by Warner for stable beams [3] cannot be properly exploited at low energies in case of radioactive beams due to the very low intensity available (10^3-10^7 pps). In order to overcome this problem we developed a new coincidence technique inserting a Micro Channel Plate (MCP) upstream with a Si(Li) detector, acting as active target.

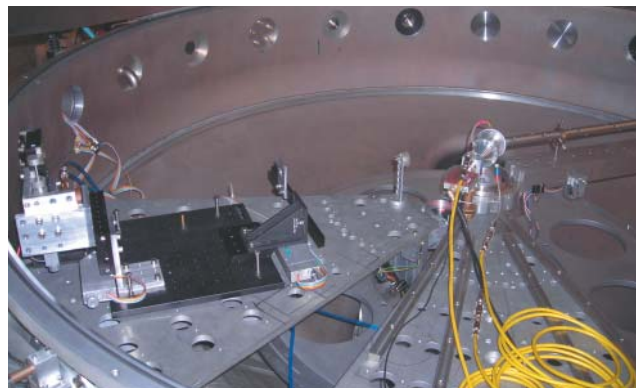


Fig.1: Experimental set-up mounted inside the CT2000 scattering chamber. The MCP detector (right) is placed in front of the last beam collimator, the Si(Li) active target is mounted on the X-Y stage (left).

In the experiment, performed in the "CT2000" scattering chamber of Laboratori Nazionali del Sud (INFN-Catania), a silicon detector, Lithium compensated Si(Li), 3000 μm

thick, has been used both as target and as detector. The detector has been cooled down to 0° Celsius in order to decrease the leakage current and it has been operating with strong over depletion voltage to reduce charge collection time, consequently improving time resolution. Detector thickness was selected in order to stop all the forward emitted particles produced in reaction events. We measured Time of Flight (TOF) of the impinging beam particles by recording coincidences between a Micro Channel Plate (MCP) detector and the Si(Li), both placed in front of the last beam collimator. Fig. 1 shows the experimental set-up mounted inside the large scattering chamber. This coincidence technique is crucial in order to reject two classes of spurious events:

- 1) frame scattered particles produced in MCP grid and beam collimators,
- 2) single decay events occurring when radioactive species are implanted in the Si(Li) detector (alpha's coming from ^8Li decay in our case).

The collimation system was carefully designed in order to prevent frame scattering on the Si(Li) collimator to be recorded as reaction events. In addition, the detector was placed on a X-Y remote controlled stage, allowing precise in-beam alignment. The ^7Li beam intensity on target was downscaled to 200-800 pps, defocusing beam at the TANDEM source.

Standard electronics and data acquisition were used during the experiment. We correct leading edge effect by using Constant Fraction Discriminators obtaining, after Si(Li) bias optimization, a time resolution of 900 ps FWHM at $E_{\text{lab}}(^7\text{Li})=15$ MeV. The time resolution was limited mainly by the Si(Li) timing spread contribution. The measured energy resolution was rather good, 50 keV FWHM at 15 MeV.

Since we were expecting reaction events with positive Q-value, pile-up rejection was carefully set-up by recording the veto signal provided by the Pile-Up Rejection (PUR) output of a 672 ORTEC spectroscopy amplifier.

3 EXPERIMENTAL RESULTS

Since our first aim was to test the technique, we started measuring the excitation function $\sigma_R(E)$ of the $^7\text{Li}+^{28}\text{Si}$ stable system in the energy range $12 < E_{\text{lab}} < 16$ MeV. The ^7Li beam was provided by the SMP TANDEM accelerator of INFN-LNS at $E_{\text{lab}}=12, 13, 14.56, 15$ and 16 MeV. The Si(Li) detector was in-beam aligned after each energy change by moving the X-Y stage. We used two different collimation set-up's in order to exclude the presence of contamination coming from frame scattering. The effect of the collimation geometry on the reaction probability was found negligible within the experimental errors.

In fig.2 we present a typical Energy-TOF spectrum recorded at $E_{\text{lab}}=16$ MeV; superimposed the calculated E-TOF function related to the frame scattering coming from the beam collimator and MCP wires. $^7\text{Li}-^7\text{Li}$ pile-up

events were rejected up to an energy of 27 MeV. Reaction events appear at both sides of the main peak, which contains contribution from non-interacting beam particles. The ratio of reaction events to the total events is the reaction probability η :

$$\eta = \frac{N_r}{N_{\text{tot}}}$$

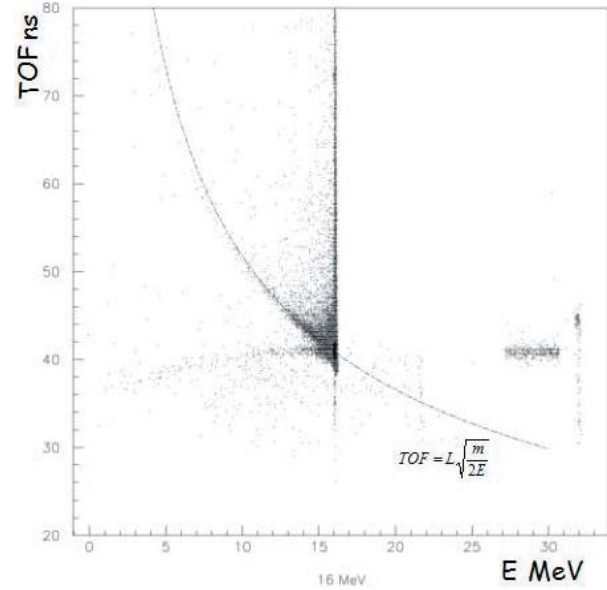


Fig.2: E-TOF matrix showing separation between frame scattering and reaction events.

The total number of reaction events was corrected for backscattering contamination. Missing reaction events, lying under the main peak placed at E_{lab} , were estimated and considered for the final data. The resulting reaction probability excitation function is shown in fig. 3.

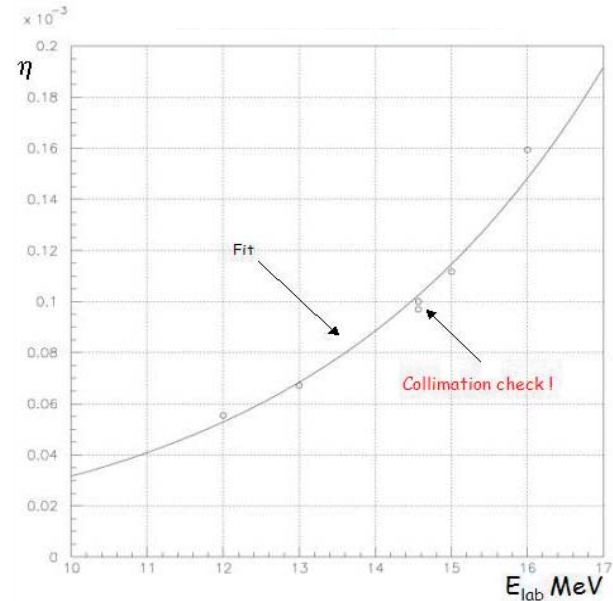


Fig.3: Interaction probability excitation function. The continuous line is an exponential fit to the data. The two points at $E_{\text{lab}}=14.56$ MeV were obtained by using different collimation set-up.

4 $^7\text{Li}+^{28}\text{Si}$ REACTION CROSS SECTION

The reaction cross section was unfolded via the interaction probability. The following formula was used:

$$\sigma_R(E_n) = \frac{dA}{dE} \cdot \frac{dE}{dx}$$

Where:

$$A(E) = - \frac{m \cdot \ln(1 - \eta(E))}{\rho \cdot N_A}$$

m is the Si mol-weight, ρ the target density and N_A the Avogadro number. After fitting the stopping powers dE/dx and reaction probability $\eta(E)$, we extracted the final reaction cross section excitation function as reported in fig 4.

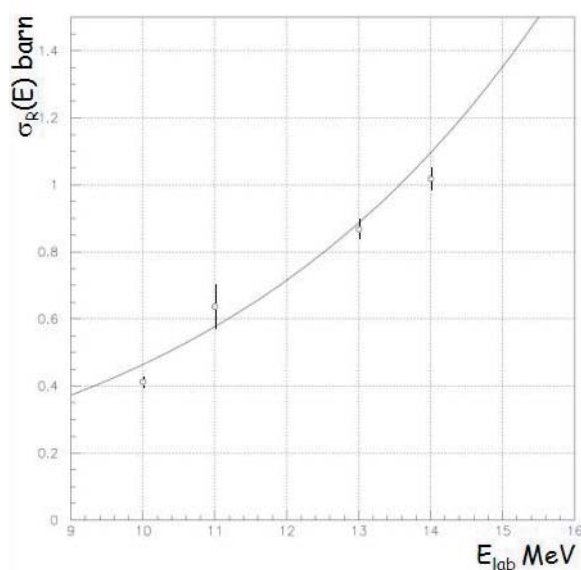


Fig.4: $^7\text{Li}+^{28}\text{Si}$ reaction cross-section excitation function (line). Also shown the experimental points deduced by optical model analysis of elastic scattering.

The trend of $\sigma_R(E)$ was compared with the data deduced by optical model analysis of elastic scattering measured in a previous experiment [4]. The good agreement between the two independent set of data can be inferred by fig. 4 and it makes us confident on the reliability of the present experimental technique.

5 PRELIMINARY TEST FOR THE $^8\text{Li}+^{28}\text{Si}$ SYSTEM

The same experimental method was applied to the $^8\text{Li}+^{28}\text{Si}$ system at $E_{\text{lab}}=14.56$ MeV. During a short test, the ^8Li radioactive beam was produced and accelerated by the new LNS-EXCYT facility. The non-interacting ^8Li , implanted in the Si(Li) active target, decays with half-life $\tau=838$ ms, the β^- decay populates the 3 MeV first excited state of ^8Be leading to two alpha particles in the final channel. Unfortunately, in this short run it was not possible to reject part of the ^8Li -alpha pile-up events and consequently the E -TOF spectrum exhibits a pile-up contribution contaminating the reaction events at $Q_{\text{value}} > 0$. (see fig. 5)

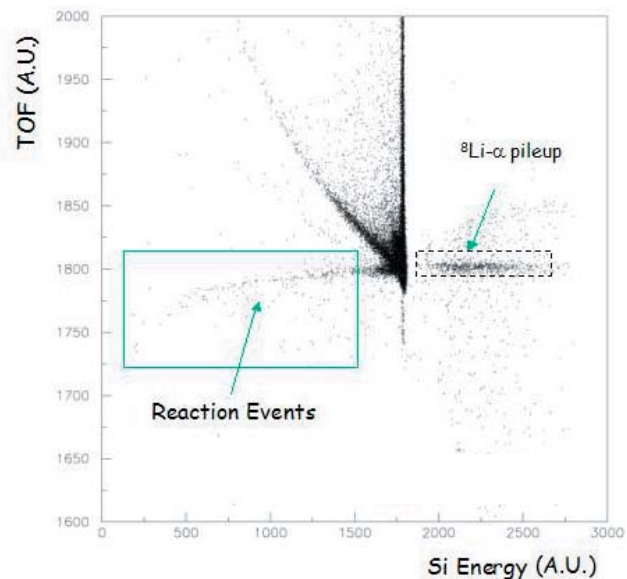


Fig.5 E -TOF matrix for the $^8\text{Li}+^{28}\text{Si}$ system at $E_{\text{lab}}=14.56$ MeV.

A slightly different set-up will be used in the final run in order to overcome this contamination problem. Nevertheless, the reaction probability for events with negative Q -values was extracted and it was found similar to the measured reaction probability for the $^7\text{Li}+^{28}\text{Si}$ system in the same Q -value range.

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CLUSTER STATES IN ^{10}Be STUDIED VIA THE $^9\text{Be}+^9\text{Be}$ COLLISION

A.Di Pietro^a, P.Figuera^{a*}, M.Fischella^{a,c}, O.Goryunov^b, M.Lattuada^{a,c}, A.Maggio^a,
 V.Ostashko^b, F.Pansini^{a,d}, M.Papa^a, V.Scuderi^{a,c}, M.Zadro^e.

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

b) Institute for Nuclear Research, Kiev, Ukraine

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

d) Centro Siciliano Fisica Nucleare e Struttura della Materia, Catania, Italy

e) Rudjer Boskovic Institute, Zagreb Croatia.

** Corresponding author*

Abstract

The $^9\text{Be}+^9\text{Be} \rightarrow ^8\text{Be}+^{10}\text{Be}$ transfer reaction has been studied at the LNS Tandem in order to obtain information on cluster structures of ^{10}Be states. New decay modes of different ^{10}Be states have been observed.

1 INTRODUCTION

It is well known that clustering is a peculiar aspect of the structure of light and medium-light nuclear systems. Due to its unique compactness, the alpha particle can be considered as the cluster par excellence and for this reason cluster structures with different degree of deformation have been observed in ground and excited states of even-even $N=Z$ nuclei. The extension of the experimental studies to systems far from the stability valley lead to the opinion that approaching the neutron dripline clustering plays also an important role. In nuclei with neutron excess new forms of clustering have been predicted and observed. In some, states of neutron rich nuclei are described as alpha particles and additional neutrons, leading to a description in terms of nuclear molecules where the neutrons play the role of valence particles. For other unstable systems the idea of exotic clustering has been introduced where the role of cluster may be played by substructures which are weakly bound themselves, thus overcoming the usual concept of cluster as strongly bound particle. We will present here some results concerning the study of the reaction $^9\text{Be}+^9\text{Be} \rightarrow ^8\text{Be}+^{10}\text{Be}$, performed at the LNS Tandem in order to obtain information on cluster structures of ^{10}Be states.

2 EXPERIMENTAL SETUP

A ^9Be beam at 50 MeV has been sent onto a $100 \mu\text{g}/\text{cm}^2$ ^9Be target placed in the CT2000 scattering chamber of LNS. Outgoing particles have been detected by four detector arrays. Each array consists of 12 position sensitive silicon detectors of $5 \times 0.8 \text{ cm}^2$ and 500 μm thick. Two of such detector arrays have been placed on one side of the beam and used to reconstruct energy and momentum of the ^8Be nuclei detecting the 2 alpha

particles coming from the ^8Be decay. Two ΔE Silicon detectors, 60 μm thick, have been placed in front of the other two arrays on the other side of the beam. These two telescopes have been used to detect and identify ^4He , ^6He and ^9Be nuclei coming from the decay of ^{10}Be and emitted in coincidence with the ^8Be nuclei.

3 RESULTS AND DISCUSSION

As already mentioned ^8Be nuclei have been detected in singles and in coincidence with ^4He , ^6He and ^9Be nuclei coming from the decay of ^{10}Be .

Since ^8Be immediately decays into 2 alpha particles, its energy and momentum have been reconstructed by measuring these 2 alpha particles in coincidence. As an example, in figure 1 we show the ^8Be excitation energy spectrum obtained from the relative energy of the two alpha particles. A clear peak corresponding to the ^8Be ground state is present and has been selected for all the subsequent data analysis. The bump at 0.5 MeV, often called "ghost peak" in the literature [e.g. 1], does not

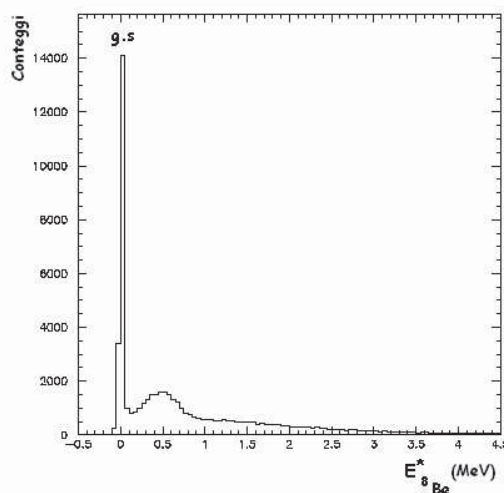


Figure1: ^8Be excitation energy spectrum.

correspond to a ^8Be state but is mainly due to the decay of the 2.43 MeV state in ^9Be via the low energy tail of the 3 MeV state in ^8Be .

Different reaction channels have been analyzed.

As first step, by looking at the single ^8Be events the excitation energy spectrum of ^{10}Be was reconstructed by using the relation :

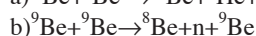
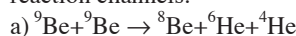
$$E^*(^{10}\text{Be}) = Q_g - Q$$

Here $Q_g = 5.14\text{MeV}$ and Q is the experimental Q value:

$$Q = E(^{10}\text{Be}) + E(^8\text{Be}) - E(^9\text{Be}).$$

In this way several known ^{10}Be states in the excitation energy range 0-12 MeV have been observed but no new information has been obtained.

In order to look for new information on the decay modes of different ^{10}Be states we then looked at the following reaction channels:



The kinematics of the two reaction channels has been completely reconstructed by detecting in coincidence two of the three particles in the final channel and using the energy and momentum conservation laws.

3.1 The $^9\text{Be} + ^9\text{Be} \rightarrow ^8\text{Be} + ^6\text{He} + ^4\text{He}$ reaction channel

This reaction channel has first been studied by looking at ^8Be - ^6He coincidences. In figure 2 we show the Q value spectrum reconstructed as:

$$Q = (E(^8\text{Be}) + E(^4\text{He}) + E(^6\text{He})) - E(^9\text{Be}).$$

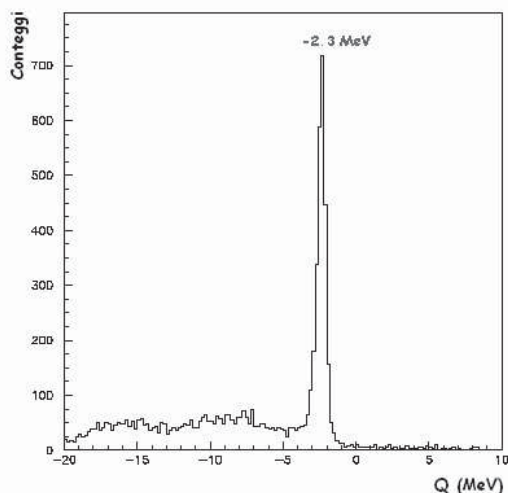


Figure 2: experimental Q value spectrum for the reaction channel $^9\text{Be} + ^9\text{Be} \rightarrow ^8\text{Be} + ^6\text{He} + ^4\text{He}$ extracted from ^8Be - ^6He coincidences.

A sharp peak corresponding to the Q_g of the considered reaction channel $Q_g = -2.3\text{MeV}$ is clearly visible and has been selected for the subsequent analysis. Once selected the desired reaction channel by placing a gate on its corresponding peak in Q value, the excitation energy of

the ^{10}Be states decaying into $^6\text{He} + ^4\text{He}$ has been reconstructed as:

$$E^*(^{10}\text{Be}) = E_{\text{rel}}(^6\text{He}-^4\text{He}) + E^*(^6\text{He}) + Q_{\text{breakup}}$$

Here $E_{\text{rel}}(^6\text{He}-^4\text{He})$ is the relative energy between ^6He and ^4He , $E^*(^6\text{He})$ is the excitation energy of ^6He equal to zero in the present case and Q_{breakup} is the Q value for the breakup of ^{10}Be into $^6\text{He} + ^4\text{He}$. However, before extracting information on possible ^{10}Be states from the relative energy between ^6He and ^4He , one has to consider that the selected three nuclei in the final channel (^6He , ^4He and ^8Be) can be produced not only through the formation of ^{10}Be and its subsequent decay into $^4\text{He} + ^6\text{He}$ but also by the decay of ^{12}C and ^{14}C states which could also be populated in the $^9\text{Be} + ^9\text{Be}$ collision. In order to investigate on the possible presence of such background contributions, we constructed event by event the ^{12}C and ^{14}C excitation energy by looking at ^8Be - ^4He and ^8Be - ^6He relative energies respectively. In figure 3 and 4 we show the $E^*(^{10}\text{Be})$ versus $E^*(^{12}\text{C})$ and $E^*(^{10}\text{Be})$ versus $E^*(^{14}\text{C})$ spectra reconstructed event by event.

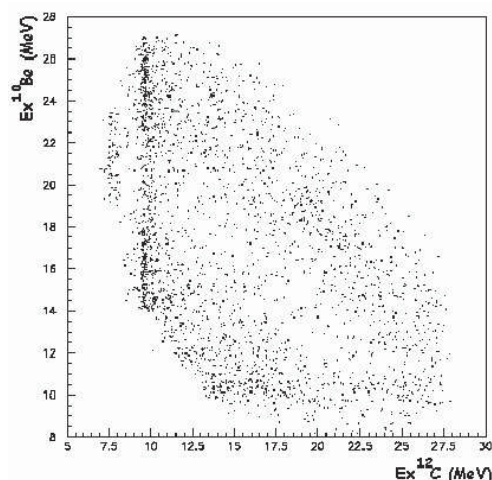


Figure 3 see text for details.

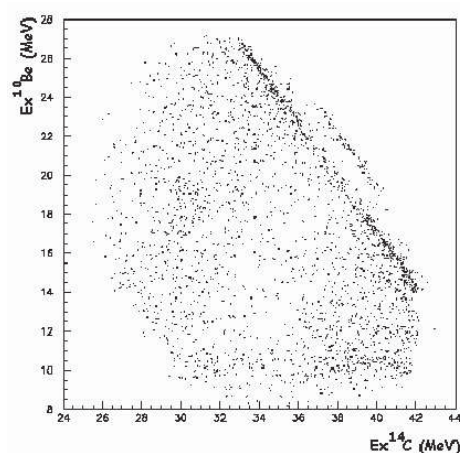


Figure 4 see text for details.

As one can see figure 3 shows a clear population of the 7.6 and 9.6 MeV states in ^{12}C . On the other hand, from figure 4, there is no evident population of ^{14}C states. We notice that the two ^{12}C states identified in figure 3 are also evident in figure 4 as angled lines. In order to reduce the background from the sequential decay of ^{12}C , in the subsequent analysis we selected only the events at $E^*(^{12}\text{C}) > 11$ MeV in figure 3.

The obtained ^{10}Be excitation energy spectrum is shown in figure 5.

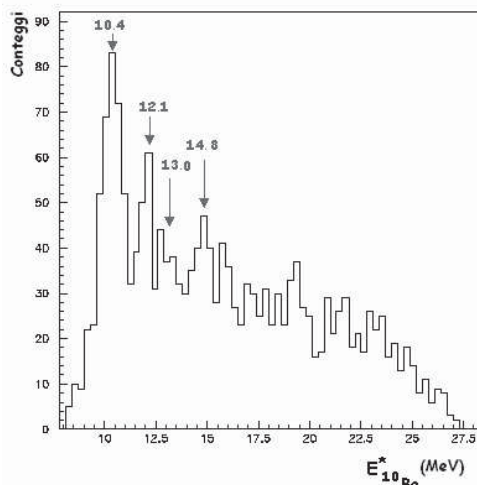


Figure 5: ^{10}Be excitation energy spectrum.

Some structures present in the spectrum and marked by arrows can be clearly associated to known ^{10}Be states. Of particular interest is the structure at 12.1 MeV since it confirms the existence of a state around 12 MeV which was suggested in [2] but not observed in other experiments.

The study of the reaction channel $^9\text{Be}+^9\text{Be} \rightarrow ^8\text{Be}+^6\text{He}+^4\text{He}$ detecting $^8\text{Be}-^4\text{He}$ coincidences allowed to

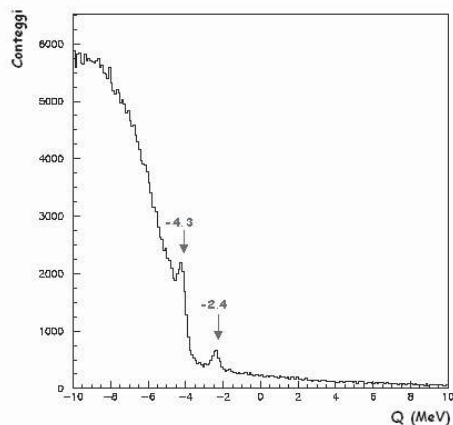


Figure 6: Experimental Q value spectrum for the reaction channel $^9\text{Be}+^9\text{Be} \rightarrow ^8\text{Be}+^6\text{He}+^4\text{He}$ extracted from $^8\text{Be}-^4\text{He}$ coincidences.

observe ^{10}Be states decaying into $^6\text{He}+^4\text{He}$. A Q value spectrum reconstructed from the $^8\text{Be}-^4\text{He}$ coincidences is shown in figure 6. In this figure, together with a peak corresponding to the Q_g value of -2.3 MeV, we observe a second peak at $Q = -4.3$ which corresponds to the emission of an ^6He in its first excited state at 1.8 MeV. By selecting this peak, we obtained the ^{10}Be excitation energy spectrum shown in figure 7. This spectrum not only

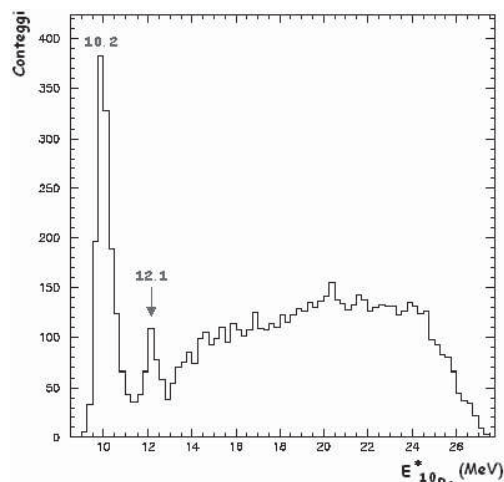


Figure 7: ^{10}Be excitation energy spectrum extracted from $^8\text{Be}-^4\text{He}$ coincidences.

confirms the presence of a state around 12 MeV, but it also shows, for the first time, that this state can also decay into $^6\text{He}+^4\text{He}$. The peak at 10.2 MeV confirms that the 10.15 MeV state in ^{10}Be can decay not only into $^6\text{He}+^4\text{He}$ but also into $^6\text{He}^*+^4\text{He}$ as suggested in [3].

3.2 The $^9\text{Be}+^9\text{Be} \rightarrow ^8\text{Be}+n+^9\text{Be}$ reaction channel

This reaction channel has been studied by looking at $^8\text{Be}-^9\text{Be}$ coincidences. Following a procedure equal to the one used in the study of the reaction channel $^9\text{Be}+^9\text{Be} \rightarrow ^8\text{Be}+^6\text{He}+^4\text{He}$, we obtained the ^{10}Be excitation energy spectrum shown in figure 8. Some of the structures observed in this spectrum, marked by arrows, correspond to known ^{10}Be states. What is interesting in this figure is that the states at an excitation energy larger than 11 MeV were only observed to decay into $^6\text{He}+^4\text{He}$. Therefore this is the first experimental result showing that they can also decay into $^9\text{Be}+n$ suggesting a possible configuration mixing for these states.

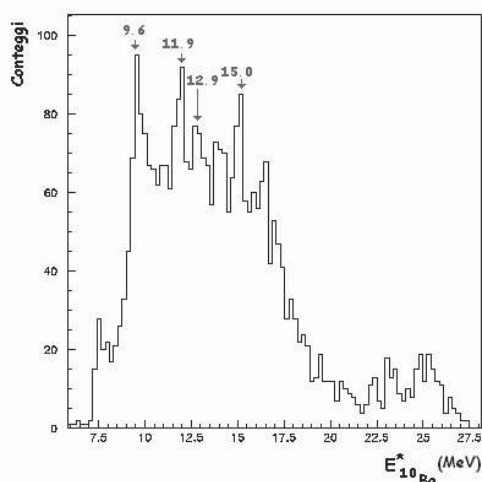


Figure 8: ^{10}Be excitation energy spectrum extracted from ^8Be - ^9Be coincidences.

4 SUMMARY AND CONCLUSIONS

Different ^{10}Be states in the excitation energy range 0-15 MeV have been observed in the study of the transfer reaction $^9\text{Be}+^9\text{Be}\rightarrow^8\text{Be}+^{10}\text{Be}$.

From the study of the reaction channel $^9\text{Be}+^9\text{Be}\rightarrow^8\text{Be}+^6\text{He}+^4\text{He}$ the following results have been obtained.

a) The existence of a state around 12 MeV excitation energy previously suggested in [2] has been confirmed. In addition, for the first time, data clearly show that this state can decay not only into $^6\text{He}_{gs}+^4\text{He}$ but also into $^6\text{He}^*+^4\text{He}$ suggesting that it could be associated to a mixing of configurations.

b) The decay into $^6\text{He}^*+^4\text{He}$ has also been observed for the state at 10.15 MeV confirming what suggested in a previous experiment [3].

The study of the reaction channel $^9\text{Be}+^9\text{Be}\rightarrow^8\text{Be}+n+^9\text{Be}$ has shown for the first time that some known states in the excitation energy range 10-15 MeV can decay not only $^6\text{He}+^4\text{He}$ but also $^9\text{Be}+n$ again suggesting a configuration mixing for these states.

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ASTROPHYSICAL S(E)-FACTOR OF THE $^{15}\text{N}(\text{p},\alpha)^{12}\text{C}$ REACTION AT SUB-COULOMB ENERGIES VIA THE TROJAN-HORSE METHOD

M. La Cognata^{a,b}, S. Romano^{a,b}, C. Spitaleri^{a,b*}, S. Cherubini^{a,b}, V. Crucillà^{a,b}, M. Gulino^{a,b}, L. Lamia^{a,b}, R.G. Pizzone^{a,b}, S.M.R. Puglia^{a,b}, G.G. Rapisarda^{a,b}, M.L. Sergi^{a,b}, A. Tumino^{a,b}, S. Tudisco^{a,b}, R. Tribble^c, Changbo Fu^c, V. Goldberg^c, A. Mukhamedzhanov^c, D. Schmidt^c, G. Tabacaru^c, L. Trache^c, S. Typel^d, B.F. Irgaziev^e

a) INFN Laboratori Nazionali del Sud, Catania, Italy

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

c) Cyclotron Institute, Texas A&M University, College Station, TX 77843, USA

d) Ganil, Caen, France

e) IGIK Institute of Engineering Sciences and Technology, Topi, District Swabi, N.W.F.P., Pakistan

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

Abstract

The low-energy bare-nucleus cross section for $^{15}\text{N}(\text{p},\alpha)^{12}\text{C}$ is extracted by means of the Trojan Horse Method applied to the $^2\text{H}(^{15}\text{N},\alpha)^{12}\text{C}$ reaction at $E_{\text{beam}}=60$ MeV. For the first time, Coulomb $^{15}\text{N}-\text{d}$ scattering in the initial channel and off-shell effects in the reaction have been taken into account. The results extracted via the Trojan Horse method (THM) are compared to direct data in the same energy region and show very good agreement in the energy interval 70-312 keV. These results confirm the extrapolations of the S-factor reported in literature.

1 INTRODUCTION

An open question in nuclear astrophysics is the ^{19}F abundance in the Milky Way [1]. Even its production sites are still a largely debated topic: it has been shown that this isotope is synthesized in type II supernovae explosions as well as in Wolf-Rayet stars and during the AGB phase of stellar evolution [1].

The understanding of ^{19}F nucleosynthesis is of great importance in astrophysics since the fluorine abundances observed in giants can constrain AGB star models [2]. In particular it has been shown that a key isotope for F production in AGB stars is ^{15}N and a crucial role is played by the $^{15}\text{N}(\text{p},\alpha)^{12}\text{C}$ reaction, removing both proton and ^{15}N nuclei from ^{19}F production chain in the AGB intershell environment.

The present work reports on a new recent investigation of the $^{15}\text{N}(\text{p},\alpha)^{12}\text{C}$ reaction by means of the THM applied to the $^2\text{H}(^{15}\text{N},\alpha)^{12}\text{C}$ three-body process. Here we estimate the impact of the Coulomb $^{15}\text{N}-\text{d}$ scattering in the entry channel of the TH reaction $^2\text{H}(^{15}\text{N},\alpha)^{12}\text{C}$ and we take into account the off-shell character of the transferred proton.

2 THE EXPERIMENT

The experiment was performed with a 60 MeV ^{15}N beam, with a spot size on target of 1 mm diameter and intensities up to 5 nA, which was provided by the K500 superconducting cyclotron at Texas A&M University. The relative beam energy spread was about 10^{-3} . Self supported deuterated polyethylene targets (CD_2) of about $150 \mu\text{g}/\text{cm}^2$ thickness were placed at 90° with respect to the beam direction. The detection setup consisted of a telescope (A) made up of an ionization chamber and a silicon position sensitive detector (PSD A) to discriminate carbon nuclei, and of two silicon PSD's (B, C) placed on the opposite side with respect to the beam direction. A more detailed discussion about the experimental setup is reported in [3].

After detection calibration, the first step of the analysis is the selection of the $^2\text{H}(^{15}\text{N},\alpha)^{12}\text{C}$ reaction channel, the only relevant for astrophysical application [4]. To this purpose the reaction kinematics is studied and the experimental spectra and compared to the simulated ones. In particular, only the events corresponding to the high energy peak in the Q-value spectrum (fig. 1) are taken into account in the following analysis. Anyway, the same reaction can proceed through several mechanism, thus a thoroughly analysis of the reaction dynamics is also crucial. Indeed the simple factorization of the three body cross section [5]

$$\frac{d^3\sigma}{dE_C d\Omega_C d\Omega_c} \propto \text{KF} |\phi(-\vec{p}_b)|^2 \cdot \left(\frac{d\sigma}{d\Omega_{c.m.}} \right)^{\text{off}}$$

is valid only if the QF mechanism is dominant in the investigated phase space region, thus allowing to extract the cross section of the binary subreaction.

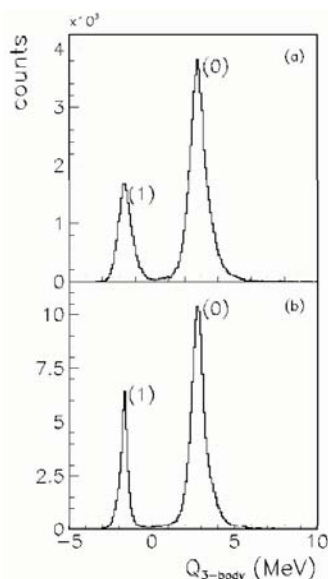


Fig. 1: Q-value spectra for the A-B (upper panel) and the A-C (lower panel) coincidence events. Two dominant peaks corresponding to the ${}^2\text{H}({}^{15}\text{N}, \alpha_0 {}^{12}\text{C})\text{n}$ ($Q = 2,74$ MeV) and ${}^2\text{H}({}^{15}\text{N}, \alpha_1 {}^{12}\text{C})\text{n}$ ($Q = -1,7$ MeV) reactions are evident.

A quantity which turns out to be very sensitive on the reaction mechanism is the shape of the experimental momentum distribution of the undetected neutrons. In order to reconstruct the experimental distribution, the energy sharing method is applied. A narrow $E_{15\text{N-p}}$ relative energy window, $\Delta E = 80$ keV for the A-C coincidence and $\Delta E = 200$ keV for the A-B coincidence (because of the lower statistics), is selected in a region where the two-body cross section is almost constant. Dividing the resulting quasi-free coincidence yield by the kinematical factor, a quantity which is proportional to the product of the p_s momentum distribution and the differential ${}^{15}\text{N} - \text{p}$ binary cross section is deduced [3], that is the momentum distribution in arbitrary units. The result is shown in fig. 2, where the momentum distributions deduced from the two data sets are averaged out (full dots). The full line is the theoretical momentum distribution given in term of the square of the Hulthen function in momentum space. This curve contain a single fitting parameter, the normalization constant, while the a and b factors which characterize the distribution, determining its width, are fixed to their theoretical values. This is in agreement with the fact that the momentum transfer is very high (about 350 MeV/c), thus the momentum distribution assumes its saturation value [6].

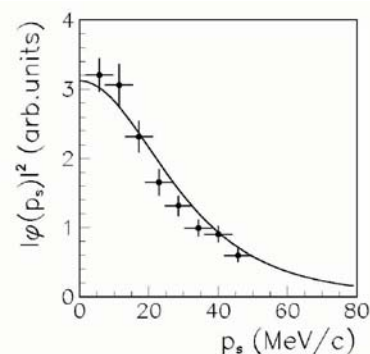


Fig. 2: FIG. 10: Average experimental momentum distribution (full dots) obtained from the A-B and A-C ones compared with the theoretical distribution (full line), normalized to the experimental data.

At this point in the data analysis we conclude that the QF mechanism gives the main contribution to the ${}^{15}\text{N} + \text{d}$ reaction at an energy of 60 MeV in the selected kinematical experimental regions; the QF mechanism can be selected without significant contribution from contaminant SD processes; the analysis in PWIA is sufficient to describe the process.

Therefore the astrophysical $S(E)$ -factor is deduced from both A-B and A-C coincidence yields and the results are averaged out according to the procedure extensively discussed in [3]. The result is shown in fig. 3 (red dots) where, for comparison, direct data from [7,8,9] (black symbols) and the Breit-Wigner parameterization from [7] (black line) are also displayed. A simple polynomial plus Breit-Wigner fit (red line) has been adopted in the present work to obtain the $S(E)$ -factor at zero energy, $S(0) = 62 \pm 10$ MeVb, in good agreement with previous estimates [7,8]. Thus no relevant changes are expected as regards ${}^{15}\text{N}$ proton-induced destruction in AGB stars.

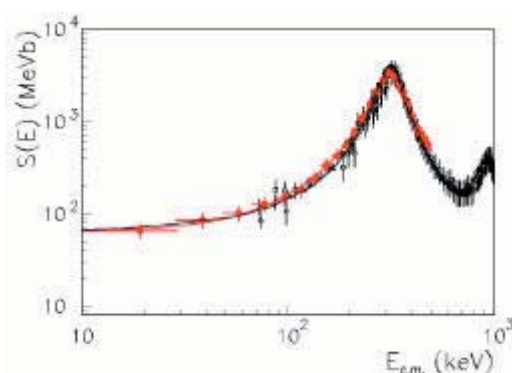


Fig. 3: Indirect astrophysical $S(E)$ -factor (full red dots): the data are obtained averaging the two data set from AB and AC coincidences. Direct data from [7, 8, 9] are also reported as open symbols (circles, squares and triangles respectively). The red line represents a fit to the THM data to extract $S(0)$. For comparison, the Breit-Wigner parameterization from [7] is also displayed as a black line.

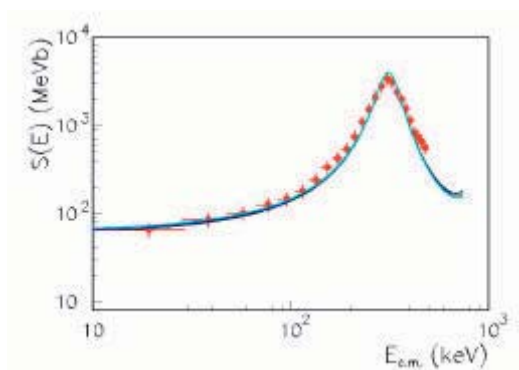


Fig. 4: Comparison of the modified R-matrix calculations (full lines) with THM data (red dots), for a number of interaction radii, 5.0 fm (black), 5.5 fm (blue) 6.0 fm (light blue).

3 MODIFIED R-MATRIX

Here, for the first time, we estimate the impact of the Coulomb $^{15}\text{N} + d$ scattering in the entry channel of the TH reaction $^2\text{H}(^{15}\text{N}, \alpha^{12}\text{C})n$ and we take into account the off-shell character of the transferred proton by applying a half-off-energy-shell R-matrix analysis. Indeed, since the transferred particle in the entry channel is off-the-energy-shell, we cannot apply standard R-matrix theory. In the modified approach the resonance width in the entry channel which appears in standard R-matrix is replaced by the form factor. In addition interference effects have to be taken into account due to the presence of the two 1^- levels at 312 keV and 962 keV. A complete discussion is reported in [3]. In fig. 4 the result of the modified R-matrix approach is shown as a full line. The calculation has been repeated for a number of interaction radii to check for the dependence on this parameter. As the picture clearly displays a good agreement is found in the whole energy region, thus showing that Coulomb distortion or off-energy shell effects are negligible, that is their contribution to the overall error budget is much smaller than the statistical one.

4 FINAL REMARKS

In the present paper we report on the complete analysis of the $^2\text{H}(^{15}\text{N}, \alpha^{12}\text{C})n$ reaction at $E_{\text{beam}}=60$ MeV. Owing to a larger data sample (two couples of coincidence detectors) and an accurate investigation of all the sources of systematic uncertainties (including normalization to direct data and adopted theoretical framework in the S-factor extraction), both statistical and systematic errors are reduced with respect to the previous analysis [10]. On the other hand the present knowledge of the $^{15}\text{N}(p, \alpha)^{12}\text{C}$ S(E)-factor has been extended down to 20 keV (to be compared to 73 keV in direct measurements), thus covering for the first time the whole Gamow window (94

± 66 keV for a temperature of 10^8 K). Moreover the S(E)-factor obtained via the THM is free of electron screening, thus this systematic uncertainty is not introduced in further astrophysical considerations. The present measurement confirms previous low-energy extrapolations used to calculate the reaction rate.

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SUPPRESSION OF THE COULOMB INTERACTION IN THE OFF-ENERGY-SHELL $P - P$ SCATTERING FROM THE $P + D \rightarrow P + P + N$ REACTION

A. Tumino^{a,b,*}, C. Spitaleri^{a,b}, A. Mukhamedzhanov^c, G.G. Rapisarda^{a,b}, S. Cherubini^{a,b},
V. Crucillà^{a,b}, Z. Elekes^d, Z. Fülöp^d, M. Gulino^{a,b}, G. Gyürky^d, G. Kiss^d, M. La Cognata^{a,b},
L. Lamia^{a,b}, F. Mudó^{a,b}, R.G. Pizzone^{a,b}, S. Romano^{a,b}, M.L. Sergi^{a,b}, E. Somorjai^d

^aDipartimento di Metodologie Fisiche e Chimiche per l'Ingegneria - Università di Catania, Catania, Italy

^bLaboratori Nazionali del Sud - INFN, Catania, Italy

^cCyclotron Institute, Texas A&M University,

College Station, Texas, USA

^dATOMKI - Debrecen, Hungary

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

Abstract Off-energy-shell effects in the $p - p$ scattering have been investigated applying the Trojan Horse Method (THM) to the $p + d \rightarrow p + p + n$ reaction. The three-body experiment was performed at 5 MeV corresponding to a $p - p$ relative energy ranging from 80 to 600 keV. The on-energy-shell $p + p$ cross section exhibits a deep minimum within this relative energy region, due to the Coulomb plus nuclear destructive interference. No minimum at all has been found in the extracted THM $p - p$ cross section, due to the drastic suppression of the Coulomb amplitude as predicted by the half-off-energy shell calculations. This hypothesis is strengthened by the agreement between the THM $p - p$ data and the calculated on-energy-shell $n + n$, $n + p$ and nuclear $p + p$ cross sections.

The proton-proton scattering has been extensively investigated in the past in order to gather more information on the nuclear force [1, 2]. Despite the simplicity of the $p-p$ system, the analysis of such interaction is complicated by the presence of the Coulomb scattering that has to be considered in addition to the nuclear effects. The Coulomb scattering is coherent with the nuclear one, so that interference terms between the two effects are expected to contribute to the cross section. In particular, there is a region at low $p-p$ relative energy (E_{pp}) in which the nuclear scattering amplitude in the 1S -state and the even part of the Coulomb scattering amplitude give destructive interference [2], leading to the deep minimum in the $p-p$ cross section (about 1 mbarn/sr) which occurs at $E_{pp}=191.2$ keV and $\theta_{c.m.} = 90^\circ$ [3]. Such a strong signature has recently triggered the idea that an indirect study of the $p - p$ scattering at low energy can provide another important test for the Trojan Horse Method (THM). Indeed the interference pattern should be missing if there is no sizeable Coulomb amplitude, and this is what the THM is for.

The THM is an indirect tool for studying charged particle two-body reactions at sub-Coulomb energies [4–9]. When dealing with direct measurements, Coulomb

barrier plus electron screening effects prevent one to reach the ultra-low energies without extrapolating the behaviour of higher energy data. The extrapolation is done by means of the definition of the astrophysical $S(E)$ -factor which represents essentially the cross section free of Coulomb suppression caused by the Coulomb barrier factor (Gamow factor). The THM offers a novel approach to avoid the extrapolation providing the only existing way to measure the bare nucleus astrophysical $S(E)$ -factor down to sub-Coulomb energies. In the conventional THM the energy dependence of the cross section for the binary $A + x \rightarrow C + c$ reaction is determined by measuring the triple differential cross section for the Trojan Horse (TH) $A + a(x \oplus s) \rightarrow C + c + s$ process in the quasi-free (QF) kinematics regime off particle s in a .

The $A + a$ interaction occurs at a c.m. energy E_{Aa} above the Coulomb barrier. However, thanks to the key role of the $a=x \oplus s$ binding energy (B_{xs}) in compensating for the beam energy, the $A + x$ process can take place even at very low sub-Coulomb energy (quasi-free two-body energy), given by:

$$E_{qf} = E_{Ax} - B_{xs} \quad (1)$$

where E_{Ax} represents the beam energy in the center-of-mass of the $A - x$ two-body system. A cutoff in the momentum distribution, due to the $x - s$ Fermi motion inside a , fixes the accessible energy region around the "quasi-free two-body energy". Due to the virtual character of fragment x (initially it is in the bound state of a) the Gamow factor does not appear in the initial $A + x$ state of the binary subprocess making it possible to extract its cross-section down to the relevant energies without experiencing the Coulomb suppression. The absolute magnitude of the THM cross-section is then derived from a scaling to the direct data available at higher energies. The THM was successfully applied to a number of nuclear rearrangement reactions of astrophysical interest (see [8, 10–15] and references therein). In the present work we extend the application of the THM to scattering processes. In particular, we address the study of the $p + p$

elastic scattering through the ${}^2\text{H}(p, pp)n$ reaction. The aim of the experiment is to investigate the suppression of the Coulomb amplitude also for scattering. This will be done by checking whether there is still evidence of the nuclear plus Coulomb interference pattern in the half-off-energy-shell (HOES) $p+p$ cross-section extracted via the THM. This experimental cross-section will be compared with the calculated HOES one and with the on-energy-shell (OES) counterpart in the energy region where the Coulomb-nuclear interference occurs.

We note that in the case of elastic scattering, the suppression mechanism of the Coulomb interaction due to the off-shell effects is quite different from that of rearrangement reactions mentioned before. In particular, in the case of elastic scattering the total amplitude is given by the sum of Coulomb and Coulomb-modified nuclear parts. As we will show, the off-shell effects make the Coulomb amplitude suppressed compared to the nuclear part.

The low energy ${}^2\text{H}(p, pp)n$ reaction in the QF kinematics was measured several times before (see [16] and references therein), but not in the region where the $p-p$ Coulomb-nuclear interference takes place. The first measurements of this reaction at 6 MeV of beam energy in the interference area have been reported in [17, 18]. Even though it was not possible from those experiments to cover all the relative energy region within the interference minimum, experimental data seem to exclude its presence. In order to substantiate this result and reach lower $p-p$ relative energies, the ${}^2\text{H}(p, pp)n$ experiment was performed at the Institute of Nuclear Research of the Hungarian Academy of Sciences in Debrecen (Hungary). A 5 MeV proton beam was delivered onto a deuterated polyethylene target, $200 \mu\text{g}/\text{cm}^2$ thick. Proton-proton coincidences were measured by Position Sensitive Detectors (PSD), two of them placed almost symmetrically with respect to the beam direction and covering angles 5° to 19° and 9° to 19° . On the same side of the less forward detector, other two PSD's were centered at 29° and 59° , covering also 10° . This set-up allowed us to populate a E_{pp} range from 600 keV down to 80 keV, right within the characteristic interference minimum in the direct $p-p$ differential cross section, and a $p-p$ center-of-mass angle $\theta_{c.m.}$ ranging from 30° to 150° . Moreover, the angular ranges were chosen in order to cover momentum values p_s of the undetected neutron up to 60 MeV/c. This assures that the bulk of the QF contributions for the break-up process of interest falls inside the investigated regions. The trigger for the event acquisition was given by the coincidences between the most forward PSD, placed alone on one side of the scattering chamber, and any one of the three PSD's placed on the other side with respect to the beam direction. Energy and position signals for the detected particles were processed by standard electronics together with the coincidence relative times. The energy and position calibration of the PSD's was performed using data ac-

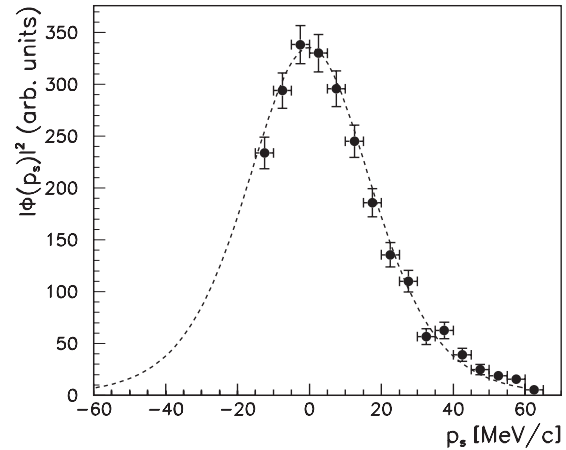


FIG. 1: Experimental neutron momentum distribution. The dashed line represents the shape given by the square of the $n-p$ Hulthén bound state wave function in momentum space.

quired in preliminary runs of the $p+{}^{12}\text{C}$, $p+d$ and $p+p$ elastic scatterings. Energy and angular resolutions of the PSD's were found to be better than 2%. The kinematics were reconstructed under the assumption of a neutron as third particle leading to a Q-value of -2.22 MeV, which refers to the $p+p+n$ channel of interest. A first selection of events was performed on the $p-p$ kinematic locus, then in order to investigate the reaction mechanism involved, a calculation of the Final State Interaction (FSI) [16] between the neutron and any one of the two protons was performed in the investigated E_{pp} region. In the present case, the $n-p$ FSI is expected to slightly contribute to the total cross-section, due to the low relative energy of the two protons. The calculated $n-p$ FSI yield experiences a quite flat energy dependence giving indeed a contribution of less than 10% to the three-body coincidence yield. This contribution was subtracted from the total events and a shape analysis of the experimental momentum distribution for the neutron was carried out with the remaining data. This is an observable which turns out to be very sensitive to the reaction mechanism. The experimental distribution is presented in Fig. 1 as full dots. The experimental width (FWHM) of about 40 MeV/c, is lower than the theoretical asymptotic width for the $p-n$ system in the deuteron (58 MeV/c), but in agreement with the expected value for the $p+d$ interaction at this beam energy. The narrowing of the momentum distribution was investigated in the past as a function of the transferred momentum [19, 20], resulting in a close connection between the two variables. In particular the lower the transferred momentum with decreasing beam energy, the narrower the FWHM.

The dashed line superimposed onto the data in Fig. 1

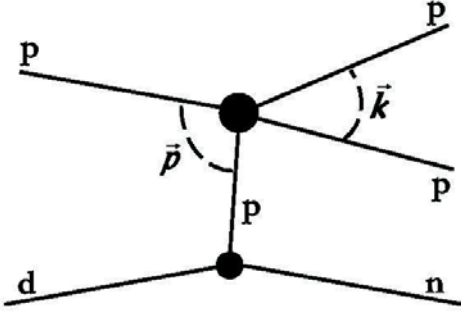


FIG. 2: Pole diagram describing the PWIA mechanism.

gives the shape of the squared Fourier transform of the s -wave radial Hulthén function associated to the deuteron bound state. The theoretical curve is normalized to the experimental maximum. A quite good agreement shows up, making us confident that in the experimentally selected kinematical region the QF mechanism gives the main contribution. For the further data analysis, only events with p_s values lower than 20 MeV/c were considered, since they give contribution in the $\theta_{c.m.}$ region close to 90° ($80^\circ \leq \theta_{c.m.} \leq 100^\circ$).

We note that a rigorous analysis of the experimental data requires the full three-body Faddeev calculations with the Coulomb $p-p$ interaction (see ref. [21] for details). However, it is impossible to extract the HOES $p-p$ scattering amplitude from such calculations. In order to derive this quantity we employ a simple Plane Wave Impulse Approximation (PWIA) described by the pole diagram shown in Fig. 2. The amplitude of this diagram is proportional to the HOES $p-p$ scattering amplitude, where one of the incoming protons is HOES while both exiting protons are OES. The PWIA has been successfully applied to determine the energy dependence of the triple differential cross section at E_{pp} higher than the Coulomb-nuclear interference minimum [16]. In this work we extend the PWIA to the lower energies within the interference region. We underscore that such a procedure, if working, would allow us to determine only the energy dependence of the HOES $p-p$ cross section but not its absolute value. In order to check the applicability of the PWIA, the extracted energy dependence of the $p+p$ cross section will be compared with the calculations. The PWIA factorizes the three-body cross section given by

$$\frac{d^3\sigma}{dE_1 d\Omega_1 d\Omega_2} \propto KF |\Phi(p_s)|^2 \left(\frac{d\sigma}{d\Omega_{cm}} \right)^{off}. \quad (2)$$

Here, $\Phi(p_s)$ is the Hulthén bound state wave function shown in Fig.1. The HOES differential cross section for the p - p scattering is given by:

$$\frac{d\sigma^{off}}{d\Omega_{cm}} = \frac{1}{4} [2\mu_{pp}(Ze)^2 e^{-\pi\eta} \Gamma(1+i\eta) \left(\frac{(p^2 - k^2)^{i\eta}}{(\vec{p} - \vec{k})^{2(1+i\eta)}} \right.$$

$$\left. + \frac{(p^2 - k^2)^{i\eta}}{(\vec{p} + \vec{k})^{2(1+i\eta)}} \right) - T_{CN}(k, p)|^2] + \frac{3}{4} [2\mu_{pp}(Ze)^2 e^{-\pi\eta} \Gamma(1+i\eta) \left(\frac{(p^2 - k^2)^{i\eta}}{(\vec{p} - \vec{k})^{2(1+i\eta)}} \right.$$

$$\left. - \frac{(p^2 - k^2)^{i\eta}}{(\vec{p} + \vec{k})^{2(1+i\eta)}} \right)|^2] \quad (3)$$

with T_{CN} representing the Coulomb-modified nuclear elastic scattering T-matrix. The remaining part is the HOES Coulomb amplitude, with $\vec{p}$ and $\vec{k}$ entrance (off-shell channel) and exit (on-shell-channel) $p-p$ relative momenta, correspondingly, η is the $p-p$ Coulomb parameter in the exit channel, μ_{pp} is the reduced mass of two protons, Ze is the proton charge. The cross section in the first brackets corresponds to a total spin of the two protons $S=0$ and even partial waves; at low energies $T_{CN}(k, p)$ contributes only to the s partial wave. $T_{CN}(k, p)$ is calculated by adopting a simple separable s -wave Yamaguchi potential of the first rank whose parameters are chosen to reproduce the $p-p$ s -wave phase shift [22]. The cross section in the second brackets corresponds to a total spin $S=1$ and contains only odd partial waves. KF is a kinematical factor containing the final state phase-space factor and it is a function of energies E_1 and E_2 and angles θ_1 and θ_2 of the outgoing protons.

Following the PWIA approach (Eq. (2)), it is possible to derive the THM differential two-body cross section from the selected three-body coincidence yield divided by the $|\Phi(p_s)|^2 KF$ factor. The geometrical efficiency of the experimental setup as well as the detection thresholds were accounted for in the procedure. An error calculation for E_{pp} was also performed giving a value ranging from 15 to 20 keV, the minimum estimate corresponding to the phase space region where the magnifying glass effect is more efficient [23].

The extracted $p-p$ HOES cross section is presented in Fig. 3 as a function of E_{pp} (red full dots) and compared to the free p - p cross section (solid line) where the $l=0$ phase shift is calculated by using the formalisms reported in [2] with effective length $a_p = -7.806$ fm and scattering radius $r_0 = 2.794$ fm. The dashed-dotted line represents the calculated HOES $p-p$ cross section (Eq. (3)). Both calculated curves are integrated over ($80^\circ \leq \theta_{c.m.} \leq 100^\circ$) and averaged out at an energy bin of 20 keV. Experimental and calculated HOES cross-sections are normalized to the calculated OES one at E_{pp} close to the Coulomb barrier (500 keV). Vertical error bars in the figure include statistical and normalization errors as well as the error coming from the subtraction of the FSI contribution. Points from previous $p+d \rightarrow p+p+n$ experiments [17, 18] (black and blue full dots) are also shown. We observe a striking disagreement between the THM (HOES) and free $p-p$ (OES) cross sections throughout the region of

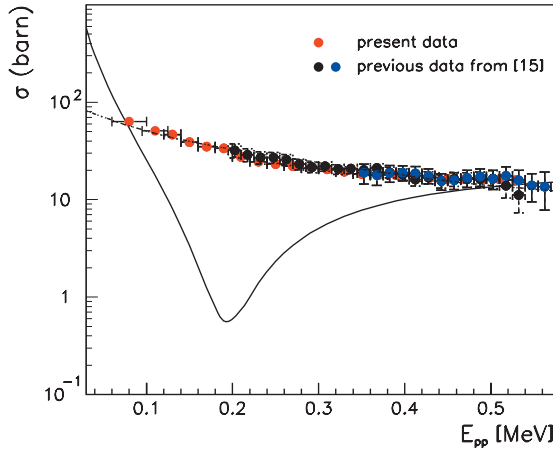


FIG. 3: (Color online) THM two-body cross section (red full dots from present experimental work, black and blue ones from previous work [17, 18]) vs. E_{pp} . Solid line represents the theoretical OES $p-p$ cross section calculated as explained in the text. The dashed-dotted line is the HOES cross section calculated using Eq. (3).

the interference minimum, which is missing in the THM data. Instead, the calculated HOES $p-p$, Eq. (3), nicely fits the THM data. First of all it proves that the PWIA in the QF kinematics can be used to obtain the energy dependence of the $p-p$ cross section also in the region where strong Coulomb-nuclear interference takes place for the OES $p-p$ scattering. The reason for such a big difference in energy dependence between low-energy OES and HOES cross sections can be easily explained using Eq. (3). When dealing with a HOES scattering, the initial p and final k momenta are different by definition. In particular, for the $p+d \rightarrow p+p+n$ reaction in the QF kinematics ($p_s = 0$) $p^2 = k^2 + 2\mu B_d$, where B_d is the deuteron binding energy. Thus p is always larger than k . Hence the transfer momentum $|\vec{p} - \vec{k}|$ at angles near 90° becomes large enough, compared to the OES case, to suppress the Coulomb HOES amplitude. The resulting HOES cross section at low energy is dominated by T_{CN} .

In order to strengthen these considerations, the THM $p-p$ cross section was compared with the on-shell $n-n$, $p-n$ and pure nuclear $p-p$ ones [2]. The expression of the nuclear two-body cross section at low energy was considered for different values of the a and r_0 parameters: $a=-18.5$ fm, $r_0=2.75$ fm for the $n-n$, $a=23.748$ fm, $r_0=2.75$ fm for the $n-p$, $a=-17.3$ fm, $r_0=2.85$ fm for the nuclear $p-p$ scattering [24]. Results are reported in Fig. 4 (solid line for the $n-n$, dashed line for the $p-n$ and dotted line for the pure nuclear $p-p$ cross section). The calculated HOES cross section is

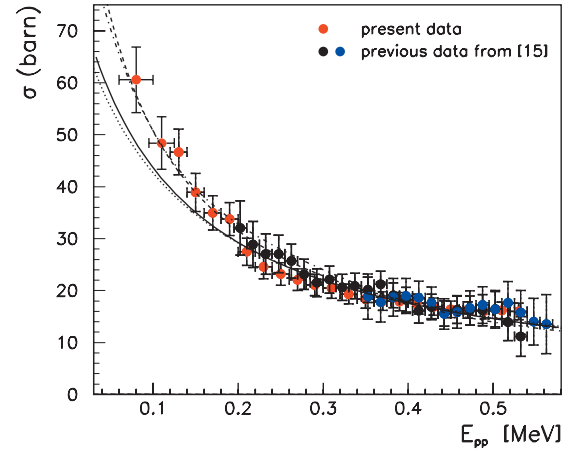


FIG. 4: (Color online) THM two-body cross section (red full dots from present experimental work, black and blue ones from previous work [18]) vs. $p-p$ relative energy E , compared with the on-shell $n-n$ (solid line), $p-n$ (dashed line) and pure nuclear $p-p$ (dotted line) ones. The HOES calculated cross section is also reported as dashed-dotted line.

again shown for completeness (dashed-dotted line). It is clearly seen a nice agreement of the OES nucleon-nucleon nuclear cross sections with THM data. This agreement represents a compelling evidence of the validity of the THM method for the elastic scattering: the HOES $p+p$ scattering cross section has the same energy dependence as pure nuclear OES nucleon-nucleon cross sections. In conclusion, the present results show that the low-energy $p-p$ scattering cross section extracted via the THM using the $p+d \rightarrow p+p+n$ reaction does not exhibit the interference minimum due to the off-shell effects. The energy dependence of its cross section is very well reproduced by the HOES $p-p$ cross section, very much similar to the OES $n-n$, $n-p$ and nuclear $p-p$ cross sections which in turn formally fit the THM data. Thus, it appears that the energy dependence of the HOES $p-p$ cross section is completely dominated by the nuclear field, behaviour which is typical of the higher energy $p-p$ cross section, far from the interference region. Through a mechanism different from that of nuclear rearrangement reactions, the present results strongly confirm the THM hypothesis, i.e. the suppression of Coulomb effects in the two-body cross section at sub-Coulomb energies. This is the hypothesis which makes the THM so powerful in the framework of nuclear astrophysics as well as in all physics contests where it can be important to investigate nuclear effects at low energies.

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INDIRECT MEASUREMENT OF THE $^{18}\text{O}(\text{p},\alpha)^{15}\text{N}$ REACTION RATE THROUGH THE THM

M. La Cognata^{a,b}, C. Spitaleri^{a,b*}, R. Tribble^c, T. Al-Abdullah^c, A. Banu^c, S. Cherubini^{a,b}, V. Crucillà^{a,b}, C. Fu^c, V. Goldberg^c, M. Gulino^{a,b}, L. Lamia^{a,b}, A. Mukhamedzhanov^c, R.G. Pizzone^{a,b}, S.M.R. Puglia^{a,b}, G.G. Rapisarda^{a,b}, S. Romano^{a,b}, M.L. Sergi^{a,b}, G. Tabacaru^c, L. Trache^c, S. Tudisco^{a,b}, A. Tumino^{a,b}, S. Typel^d

a) INFN Laboratori Nazionali del Sud, Catania, Italy

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

c) Cyclotron Institute, Texas A&M University, College Station, TX 77843, USA

d) Ganil, Caen, France

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

Abstract

A preliminary indirect investigation of the $^{18}\text{O}(\text{p},\alpha)^{15}\text{N}$ reaction via the THM is discussed, focusing on the extraction of the resonance parameters of the 656 keV peak. Even though a non negligible discrepancy is found, regarding both the strength and the energy of the resonance, no change in the reaction rate takes place in the astrophysically relevant temperature range.

1 INTRODUCTION

^{19}F is one of the few naturally occurring isotopes whose nucleosynthesis is still uncertain. SNe, AGB and WR stars are its most likely sources [1]. In particular fluorine abundances observed in giants can constrain AGB star models since they are sensitive to the environmental conditions in the intershell region and to the dynamics of the mixing phenomena taking place in such stars [2]. The $^{18}\text{O}(\text{p},\alpha)^{15}\text{N}$ reaction can affect fluorine yield from AGB stars since it produces ^{15}N nuclei later burnt to ^{19}F during a thermal pulse [3]. Anyway, large uncertainties characterize ^{19}F nucleosynthesis since experimental ^{19}F abundances are not reproduced by current AGB models [2]. Besides fluorine observations, the study of meteorite grains can also provide useful clues to understand the processes taking place inside AGB stars as they allow to investigate isotopic ratios of a number of key elements (C, N, O, Al), which are also strongly affected by the internal structure of AGB stars [4].

In this paper the THM is applied to the $^2\text{H}(^{18}\text{O},\alpha^{15}\text{N})\text{n}$ three-body process to deduce the sub-Coulomb astrophysical $\text{S}(\text{E})$ -factor for the $^{18}\text{O}(\text{p},\alpha)^{15}\text{N}$ reaction. Indeed, this reaction has been extensively studied both using direct [7] and indirect [8] approaches. Nevertheless, the reaction parameters of some important resonances are not well established yet. In particular, the width and the strength of the 676 keV resonance are poorly known, though this resonance provides a non negligible contribution to the reaction rate both at high and low temperatures, showing a width of about 300 keV wide [9]. In the present work, our preliminary analysis focuses on

the extraction of the resonance parameters of the 656 keV peak and on the evaluation of the maximum contribution of the 7.9 MeV ^{19}F subthreshold state.

2 THE EXPERIMENT

The experiment was performed at Texas A&M Cyclotron Institute, with a 54 MeV, 5 enA ^{18}O beam impinging on a 100 $\mu\text{g}/\text{cm}^2$ thick CD_2 target. The experimental setup was very simple: a single silicon position sensitive detector (PSD A) detected ^{15}N nuclei at small angles and two telescopes (B,C) made up of a PSD and a silicon, large-area ΔE detector (450 mm^2 wide) were used to discriminate α particles, on opposite sides with respect to the beam direction. Standard electronics was used to filter and shape the signals. Two types of events were recorded: coincidences between A and B and between A and C. ^{15}N is identified from three-body reaction kinematics, thus no ΔE detector was needed in front of PSD A.

After detector calibration, the first step in the analysis is the selection of the $^2\text{H}(^{18}\text{O},\alpha^{15}\text{N})\text{n}$ channel. To this purpose the three-body kinematics is studied in order to disentangle the contribution of the channel of interest from others. First the kinematical locus in compared to the theoretical one and then the Q-value spectrum is deduced (fig. 1). A single peak in the spectrum shows up, demonstrating that only the $^2\text{H}(^{18}\text{O},\alpha^{15}\text{N})\text{n}$ channel only contributes to the three-body coincidence yield. In addition, this test represents a cross check making us confident about the quality of the performed calibrations since a good agreement is apparent between the theoretical Q-value and the experimental one.

The following step is the selection of the QF mechanism. The QF contribution to the three-body cross section can be disentangled by studying the reaction dynamics, since the QF contribution has to satisfy a number of necessary conditions. For instance, the shape of the experimental momentum distribution has to agree with the theoretical one if deuteron breakup originates from a direct mechanism. In addition, the coincidence yield has

to be maximum for small p_s if phase space effects are divided out (see, for instance, the angular correlation test [5,6]).

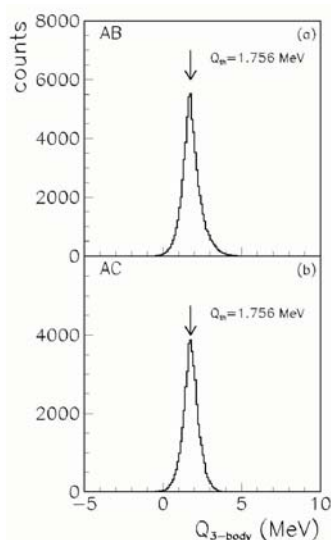


Figure 1. Q-value spectra for the A-B (upper panel) and the A-C (lower panel) coincidence events. A single peak shows up, marked by an arrow in each picture, corresponding to the ${}^2\text{H}({}^{18}\text{O}, \alpha {}^{15}\text{N})\text{n}$ three-body reaction ($Q = 1.756$ MeV).

The momentum distribution for the p-n system is shown in fig. 2. In Plane Wave Impulse Approximation (PWIA) the experimental distribution is deduced by imposing $d\sigma/d\Omega = \text{const.}$ in the equation [5]:

$$|\Phi(p_s)|^2 \propto \frac{d^3\sigma}{d\Omega_\alpha d\Omega_{15\text{N}} dE_{c.m.}} \times \left[\text{KF} \frac{d\sigma}{d\Omega} \right]^{-1}$$

that is by fixing the ${}^{18}\text{O}$ - p relative energy and dividing the coincidence yield by the KF factor. In the THM approach no absolute values can be deduced, thus in order to compare the theoretical distribution to the experimental one a normalization parameter has to be introduced. In fig. 2 the theoretical distribution, given by the square of the Hulthen wave function in momentum space, is superposed to the experimental one. The good agreement demonstrates that the QF mechanism is present and dominant in the $p_s < 40$ MeV/c momentum range. Thus in the further analysis the S(E)-factor is deduced from the events inside this region, where the simple PWIA factorization of the cross section is valid.

The astrophysical S(E)-factor is extracted according to the prescription discussed in [6] (and references therein). Because of the approximations involved, no absolute values are available, but normalization can be retrieved from the comparison with direct where available. The S(E)-factor for the ${}^2\text{H}({}^{18}\text{O}, \alpha {}^{15}\text{N})\text{n}$ reaction is shown in fig. 3. The resonance parameters were deduced in this preliminary analysis by fitting the THM S(E)-factor (in arbitrary units) with the sum of two Breit-Wigner functions, taking into account the 656 keV and 799 keV

resonances, plus an interference term, since the two resonances are both $J^\pi = 1^-$.

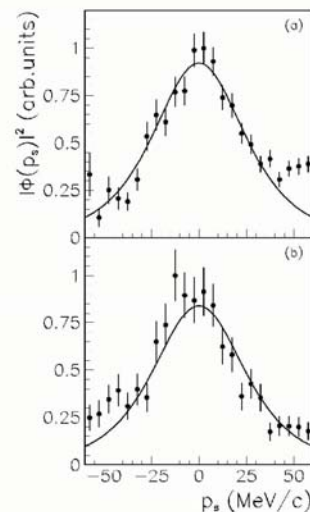


Figure 2. Experimental momentum distributions (full dots) from both A-B and A-C coincidences (panel a and b respectively). For comparison, the theoretical momentum distribution given in terms of the Hulthen function in momentum space is reported as a full line. The characteristic parameters of the distribution, a and b, are fixed to their theoretical values [6] in both cases, while the normalization constant was deduced by fitting the theoretical curve to the experimental data.

The fitting procedure provide a resonance energy of 590 ± 20 keV (slightly smaller than the value reported in literature) and a FWHM of 208 ± 26 keV. The strength is obtained from the ratio of the strengths of the 656 keV level to the one of the 799 keV resonance, which is instead well established. It is found $(\omega\gamma)_1 / (\omega\gamma)_2 = 14.8 \pm 2.5$ (where the cited error is only statistical), to be compared with about 0.5 [9], 3 [7] and 0.4 [10]. A more accurate R-matrix analysis of the experimental data is in progress.

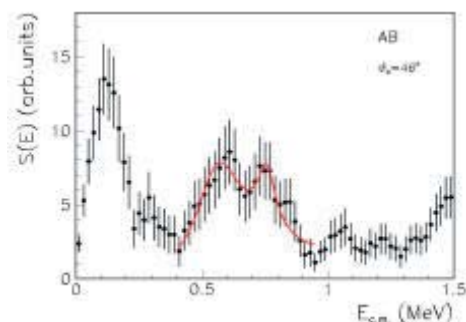


Figure 3. Indirect astrophysical S-factor at $\theta_{c.m.} = 46^\circ$, extracted from A-B coincidences (black dots). Experimental data has been averaged out to reduce statistical fluctuations. The red line represents a fit of the

two levels at 656 keV and 799 keV including interference effects

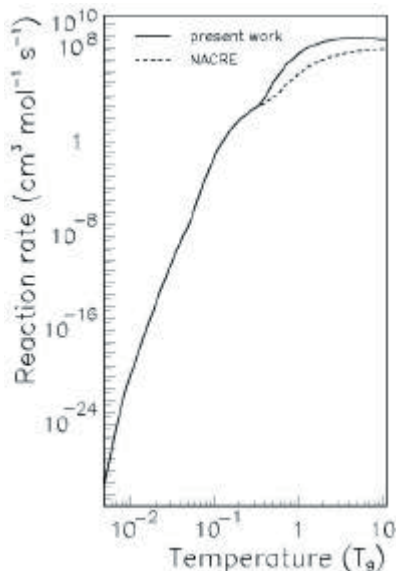


Figure 4. $^{18}\text{O}(p,\alpha)^{15}\text{N}$ reaction rate as a function of temperature ($T_9 = T/10^9$ K). The rate from [9] is reported as a dashed line, while the revised rate based on the present preliminary estimates is shown as a full line.

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3 ASTROPHYSICAL IMPLICATIONS

In order to evaluate the astrophysical implications of the present result, the reaction rate was extracted by introducing the new resonance parameters of the cited state instead of the ones in literature. As a first approximation the contribution of the 656 keV peak was evaluated by assuming the narrow resonance limit [9]. The obtained rate is given in fig. 4 together with the one from [9]. The plot clearly shows that the THM rate is about 50 times larger than the NACRE one at about 1 GK, while a good agreement it is found in the temperature region of interest for ^{19}F nucleosynthesis in AGB stars. Therefore no change is expected in ^{19}F calculated yields, while interesting consequences can be predicted in the case of different environments, such as novae, where much higher temperatures are expected. Anyway this is a preliminary result providing only an estimate of the expected correction. An improved analysis will be given in forthcoming papers.

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THE $^{19}\text{F}(\alpha, p)^{22}\text{Ne}$ REACTION AND THE NUCLEOSYNTHESIS OF FLUORINE

M. La Cognata^{a,b}, C. Spitaleri^{a,b*}, S. Cherubini^{a,b}, V. Crucillà^{a,b}, M. Gulino^{a,b}, L. Lamia^{a,b}, R.G. Pizzone^{a,b}, S.M.R. Puglia^{a,b}, G.G. Rapisarda^{a,b}, S. Romano^{a,b}, M.L. Sergi^{a,b}, A. Tumino^{a,b}, S. Tudisco^{a,b}, B.W. Green^c, G.V. Rogachev^c, E. Johnson^c, A.M. Crisp^c, K.W. Kemper^c, V.Z. Goldberg^d, A. Mukhamedzhanov^d

a) INFN Laboratori Nazionali del Sud, Catania, Italy

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

c) Dept. of Physics, Florida State University, Tallahassee, USA

d) Cyclotron Institute, Texas A&M University, College Station, Texas, USA

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

Abstract

The $^{19}\text{F}(\alpha, p)^{22}\text{Ne}$ reaction is considered to be the main source of fluorine depletion during the Asymptotic Giant Branch and Wolf-Rayet phases in stars. The reaction rate still retains large uncertainties due to the lack of experimental studies available in the astrophysically relevant energy region. To this purpose the cross section has been studied through the Trojan Horse method by extracting the QF contribution from the $^6\text{Li}(^{19}\text{F}, p^{22}\text{Ne})^2\text{H}$ three-body process.

1 INTRODUCTION

Despite the fact that ^{19}F is by far the least abundant of stable nuclides in the 12-32 atomic-mass range, its contribution is extremely important in the computation of the chemical evolution of AGB stars. Available data from observations provide strong evidence that fluorine is deeply produced within the interiors of these stars during helium flashes and its abundance, enhanced by large factors with respect to the solar one, cannot be matched by the models [1]. Primary sources of uncertainty in predicting fluorine abundances in AGB stars are both the adopted reaction rates and the treatment of nucleosynthesis during the thermal pulses and the interpulse periods [1].

In this context the $^{19}\text{F}(\alpha, p)^{22}\text{Ne}$ reaction plays a very important role since this process constitutes the main fluorine destruction channel in AGB and WR stars. In contrast there is very little experimental data available for the $^{19}\text{F}(\alpha, p)^{22}\text{Ne}$ reaction cross section at low energies. Experiments were limited to the higher energy range. For instance, the most recent measurement of its cross section span the 990-1570 keV c.m. energy range [2], well above the Gamow window, about $300 < E_{\text{c.m.}} < 900$ keV. Only model cross sections are available below the experimentally investigated energy range, based on either the Hauser-Feshbach approximation or the single resonance approach. However in the excitation energy region of the ^{23}Na compound nucleus, the level density

and the resonance widths have such intermediate values which do not fulfill the requirements for any of the two approaches. The result is that the estimated uncertainties of the reaction rate which is used as input parameter for the AGB star nucleosynthesis models are of fourteen orders of magnitudes at the temperatures of the He intershell region. Indeed, the $^{19}\text{F}(\alpha, p)^{22}\text{Ne}$ reaction rate represents the largest source of uncertainty on the calculated fluorine abundance for the most massive AGB stars (above about 5 $M_{\odot}$) and for the WR stars [1].

Therefore a measurement of the low-energy bare-nucleus S(E)-factor of the $^{19}\text{F}(\alpha, p)^{22}\text{Ne}$ reaction is extremely important. In the following we report on the status of the indirect study of the $^{19}\text{F}(\alpha, p)^{22}\text{Ne}$ through the $^6\text{Li}(^{19}\text{F}, p^{22}\text{Ne})^2\text{H}$ three-body process by applying the Trojan Horse Method (THM).

2 THE EXPERIMENT

The experiment was performed at Department of Physics, Florida State University, with a 14 MeV, 3 nA ^{19}F beam impinging on a 100 $\mu\text{g}/\text{cm}^2$ thick ^6Li self-supported target. The experimental setup is very simple: a single silicon position sensitive detector (PSD A) to detect ^{22}Ne nuclei at small angles (7.5°) and two telescopes (B,C) made up of a PSD and a silicon, large-area ΔE detector (450 mm^2 wide) to discriminate protons at larger angles ($\theta_B=30^\circ$, $\theta_C=75^\circ$) on the opposite side with respect to the beam direction. Standard electronics is used to filter and shape the signals. Two events are recorded: coincidences between A and B and A and C. ^{22}Ne is identified from three-body reaction kinematics, thus no ΔE detector is needed in front of PSD A. This allows for a better energy and angular resolution. A sketch of the experimental setup and a picture are given in fig. 1 (upper and lower panel respectively).

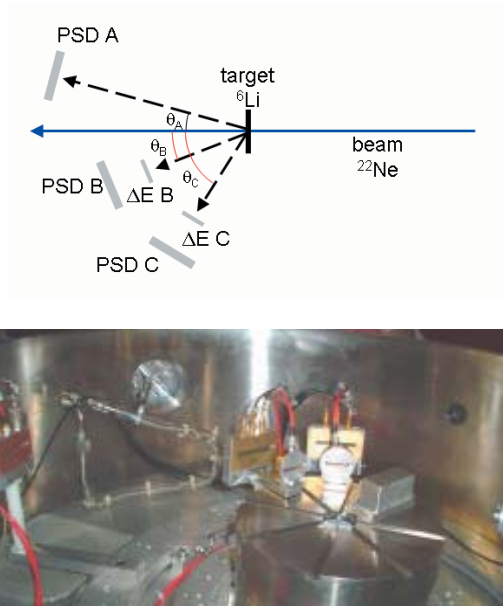


Fig. 1: Upper panel: drawing of the experimental setup for the indirect study of the $^{19}\text{F}(\alpha, p)^{22}\text{Ne}$ reaction via the $^6\text{Li}(^{19}\text{F}, \alpha^{22}\text{Ne})^2\text{H}$. Lower panel: picture of the experimental setup. At the center the two telescopes B, C are clearly visible. Beam is coming from the right (where the beam collimator is apparent) while on the left PSD A shows up.

Figure 1 shows a typical ΔE -E 2D spectrum. Though a pure ^6Li is used, some water is present as impurity (since lithium is highly hygroscopic) thus in the ΔE spectrum a huge peak is apparent due to protons scattered out from the target. In the analysis the scattering peak, corresponding to low energy protons is left apart. In fig. 1 an additional locus is apparent, corresponding to α particles from ^6Li breakup. Similar results are obtained for telescope C.

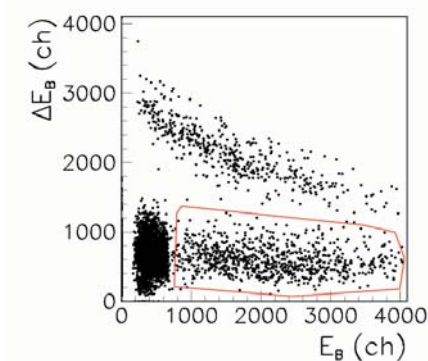


Fig. 2: Typical ΔE -E 2D spectrum from PSD B. The red line marks the proton locus, which is selected for the further analysis.

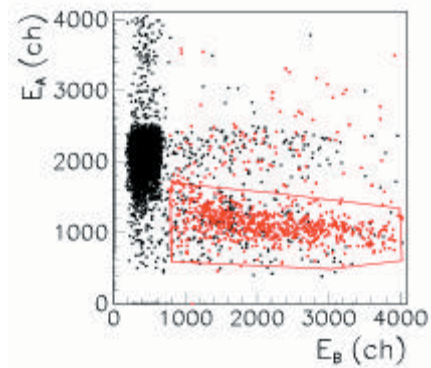


Fig. 3: Kinematical locus for the A-B coincidences. Black dots are chosen to show the behavior of the full coincidence yield. Proton events are marked by red dots. Finally the kinematical locus for the $^6\text{Li}(^{19}\text{F}, p^{22}\text{Ne})^2\text{H}$ three-body process is enclosed by a red line.

The experimental kinematical locus is shown in fig. 3. In order to show the effect of the selection of proton events (from reaction, red line in fig. 2), these are displayed together with the events from the full coincidence yield (red and black dots respectively). The experimental kinematical locus is compared to the simulated ones and an additional graphical cut is introduced to single out coincidence ^{22}Ne nuclei.

Data analysis is in progress.

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DIRECT AND INDIRECT MEASUREMENT

OF THE $^{18}\text{F}(\text{p}, \alpha)^{15}\text{O}$ REACTION IN NOVAE

S. Cherubini^{*a,b}, C. Spitaleri^{a,b}, V. Crucillà^{a,b}, M. Gulino^{a,b}, M. La Cognata^{a,b}, L. Lamia^{a,b},
R.G. Pizzone^{a,b}, SMR Puglia^a, G. Rapisarda^{a,b}, S. Romano^{a,b}, M.L. Sergi^{a,b}, S. Tudisco^{a,b}, A.
Tumino^{a,b}

S. Kubono^c, H. Yamaguchi^c, Y. Wakabayashi^c, G. Amadio^c, S. Hayakawa^c
N. Iwasa^d, S. Kato^e, S. Nishimura^f, T. Teranishi^g

a) INFN Laboratori Nazionali del Sud, Catania, Italy

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

c) Center for Nuclear Science, University of Tokyo, Wako Branch at RIKEN, Wako, Japan

d) Department of Physics, Tohoku University, Sendai, Japan

e) Department of Physics, Yamagata University, Yamagata, Japan

f) Institute of Physical and Chemical Research (RIKEN), Wako, Japan

g) Department of Physics, Kyushu University, Fukuoka, Japan

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

Abstract

We plan to measure the cross section of the $^{18}\text{F}(\text{p}, \alpha)^{15}\text{O}$ reaction in the energy range of interest for the study of the Nova phenomena.

We report here on the ^{18}F beam production test that was performed using the CRIB set-up of the Center for Nuclear Studies (CNS) of the University of Tokyo, based at the RIKEN campus in Wako.

1 INTRODUCTION

Astronomical observations suggest that nova explosions and x-ray bursts occur in close binaries in which the hydrogen-rich material from the outer layers of an extended star is filling its Roche lobe and accreting onto the surface of its companion, a white dwarf or a neutron star, respectively. In such explosive events, the temperatures and densities involved are sufficiently high so that proton and alpha-particle induced nuclear reactions can be fast enough to by-pass beta-decay processes. These nuclear reactions involving radioactive nuclei can greatly increase both the rate of energy generation and the total amount of energy produced and can have a dramatic impact on both the isotopic and elemental abundances produced. It has been shown in [1] that classical novae emit γ -ray at and below 511 keV soon after the explosion. The positrons which give rise to this electron-positron annihilation γ -ray emission in the expanding envelope mainly come from ^{18}F β -decay, because its life-time ($\tau=158$ min) is such that positrons are emitted when the nova-envelope begins to be transparent to gamma radiation.

Thus, the radiation intensity strongly depends on the ^{18}F abundance; for this reason it is necessary to study processes that produce and destroy this isotope in novae. Among these, the $^{18}\text{F}(\text{p}, \alpha)^{15}\text{O}$ reaction stands as one of

the main ^{18}F destruction channels. Consequently, its study in the relevant energy regions is strongly required.

From these observations it follows that the reaction $^{18}\text{F}(\text{p}, \alpha)^{15}\text{O}$ has to be studied in the energy range 100-500 keV (center of mass) roughly. In particular, the contribution to the cross section of the resonance at 330 keV has to be investigated together with the interferences between several other levels occurring in the region of interest. In spite of several attempts to measure this cross section (see e.g. [2-15]) the situation is still not satisfactory. For this reasons we proposed a new measurement of the $^{18}\text{F}(\text{p}, \alpha)^{15}\text{O}$ reaction.

2 EXPERIMENTAL APPROACH

We plan to study the $^{18}\text{F}(\text{p}, \alpha)^{15}\text{O}$ reaction using a ^{18}F beam produced at the CRIB set-up of the Center for Nuclear Studies (CNS) of the University of Tokyo, based at the RIKEN campus in Wako. We intend to study the excitation function on the full range of astrophysical interest. To this end, we will implement two different experimental approaches. We will make a direct measurement for the higher (i.e. > roughly 400 keV) energy region. Owing to the expected extremely small values of the cross section of the reaction in the low energy region (200 keV - 400 keV roughly), we will use the Trojan Horse (TH) method [16,17,18] in order to explore this part of the excitation function. This will be the first application of the TH method in a reaction where a radioactive ion beam is used.

3 BEAM PRODUCTION TEST

In 2006 we performed a preliminary test of the ^{18}F beam production. The CRIB set-up is shown in figure 1 and

described in ref.[19]. The beam is produced in-flight by the $^{18}\text{O}(p,n)^{18}\text{F}$ reaction. A 72 MeV ^{18}O beam of intensity as high as 1 μA was used to bombard a primary target consisting of a 8 cm long gas cell containing H_2 at a pressure of roughly 600 torr. The products coming from the cell were separated from the primary beam by the CRIB set-up. After the doubly acromatic separator a Wien filter was also used to further purify the ^{18}F beam.

As a result, the beam test showed that it is possible to obtain a practically pure beam of ^{18}F (purity > 99%) and with a good intensity (order of 10^6).

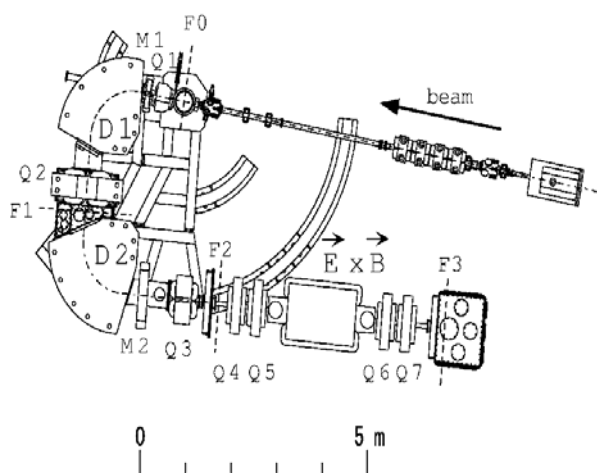


Figure 1. Top view of the CRIB setup

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THE LOW-ENERGY PROTON-NEUTRON ELASTIC SCATTERING STUDIED VIA THE $^2\text{H}(p,pn)p$ QUASI-FREE THREE-BODY REACTION

G.G. Rapisarda^{a,b*}, A. Tumino^{a,b}, C. Spitaleri^{a,b}, A. Brondi^c, L. Campajola^c, S. Cherubini^{a,b}, V. Crucillà^{a,b}, L. Gialanella^c, M. Gulino^{a,b}, G. Kiss^d, M. La Cognata^{a,b}, L. Lamia^{a,b}, A. Ordine^c, R.G. Pizzone^{a,b}, S.M.R. Puglia^{a,b}, M. Romano^c, S. Romano^{a,b}, M.L. Sergi^{a,b}, S. Tudisco^{a,b}

a) INFN Laboratori Nazionali del Sud, Catania, Italy

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

c) Dipartimento di Scienze Fisiche, Università Federico II and INFN, Napoli, Italy

d) ATOMKI – Debrecen, Hungary

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

Abstract

The Trojan Horse Method was applied to the three-body reaction $^2\text{H}(p,pn)p$ in order to study the low-energy $p+n$ elastic scattering. This measurement allows to check how relevant half-off-shell effects are in a reaction where the Coulomb barrier is absent. The experiment was performed at the Dipartimento di Scienze Fisiche of Univerità Federico II Napoli using a proton beam of 4.7 MeV.

1 INTRODUCTION

One of the main problems rising in the study of charged particle induced reactions at sub-Coulomb energies is the strong suppression of the cross section with decreasing energy, due to the Coulomb barrier. This makes cross section measurement difficult, particularly at very low energies, so in many cases the only possibility to extract it at those energies is extrapolation. The Trojan Horse Method (THM) [1-4] is a powerful indirect technique which allows to extract a two-body $t(p,a)b$ cross section at very low energies by selecting the quasi-free breakup channel of an suitable three-body reaction $A(p,ab)s$, A having a large amplitude for a $t \oplus s$ cluster configuration. In a quasi-free interaction the target A breaks-up in t and s . In the hypothesis of an Impulse Approximation [5-6], then it is assumed that s behaves like a spectator while t interacts with the projectile p to give in the final state particles a and b . The two-body reaction is half-off-energy-shell (HOES) because nucleus t is not free being bounded inside the nucleus A . This produces the suppression of the Coulomb amplitude in the two-body channel.

The formalism of the Plane Wave Impulse Approximation (PWIA) [5-6] gives us the equation for the three-body cross section (eq.1)

$$\frac{d^3\sigma}{dE_a d\Omega_a d\Omega_b} \propto KF |\phi(p_s)|^2 \left(\frac{d\sigma}{d\Omega} \right)_{ab}^{HOES} \quad (1)$$

This equation shows that the three-body cross section is factorized in three parts: KF is a kinematical factor,

$\phi(p_s)$ is the Fourier transform of the radial wave function for the p - n intercluster motion inside deuteron, described in terms of a Hulthén function [3], the last term is the HOES cross section for the two-body reaction $t(p,a)b$. Following the PWIA, one can extract a quantity proportional to the two-body cross section, by dividing the three-body coincidence yield by the factor $KF |\phi(p_s)|^2$.

The three-body reaction takes places at energies well above the Coulomb barrier but the high energy of the projectile is compensated for by the bounding energy of the target nucleus A . In this way the two-body reaction can take place at very low energy. The THM was successfully applied to several nuclear reactions of astrophysical interest [1-4].

In this paper we report on the application of THM to study the *proton-neutron* quasi-free elastic scattering by means of the $p+d \rightarrow p+n+p$ (one of the two protons behaves as spectator). The same three-body reaction was already used to study the proton-proton quasi-free elastic scattering at very low energies (in this case the neutron is the spectator) [7-9]. That measure confirms the suppression of the Coulomb interaction. Indeed the proton-proton excitation function at very low energies (around $E_{lab}=382$ keV, $\vartheta_{cm} = 90^\circ$), does not show the characteristic deep minimum caused by the interference between nuclear and Coulomb scattering amplitudes [10-12]. The proton-neutron scattering is a good test to study the half-off-shell effects in a case where there is no presence of the Coulomb interaction. In fact if the only half-off-shell effects consist in the suppression of the Coulomb interaction then the proton-neutron elastic cross section, extracted via THM, will look like the direct one.

2 EXPERIMENTAL SETUP

The experiment was performed at the Dipartimento di Scienze Fisiche of Univerità Federico II Napoli, using a Tandem accelerator. A protons beam of 4.7 MeV was delivered onto a deuterated polyethylene target, 200

$\mu\text{g}/\text{cm}^2$ thick. The energy and the position of the outgoing particles were detected using three position sensitive silicon detectors (PSD). The experimental apparatus was set-up in order to investigate the two body process $p+n$ and $p+p$. Figure 1 shows a scheme of the experimental setup. In particular the two PSD, named PSD1 and PSD2 in fig.1 are used for the study of the $p+n$ channel, while the coincidences PSD3-PSD1 and PSD3-PSD2 are used to study the $p+p$ scattering. PSD1 and PSD2 were placed at same sides with respect to the beam direction covering the angular ranges $7^\circ < \vartheta_1 < 27^\circ$ (PSD1) and $34.3^\circ < \vartheta_2 < 51.7^\circ$ (PSD2). The coincidence between these two detectors allows to extract the $p-n$ excitation function between 150 keV and 650 keV. Moreover in the selected kinematical conditions the quasi-free breakup should be separated from other possible reaction mechanisms. PSD3 was placed on the opposite side with respect to the other two detectors. It covered the $7.7^\circ < \vartheta_3 < 28.3^\circ$ angular range. In this case the trigger for the data acquisition was given by the coincidences PSD3-PSD1 and PSD3-PSD2. It allows to extract the $p-p$ excitation function between 50 keV and 900 keV.

The detector calibration and the data analysis is currently in progress.

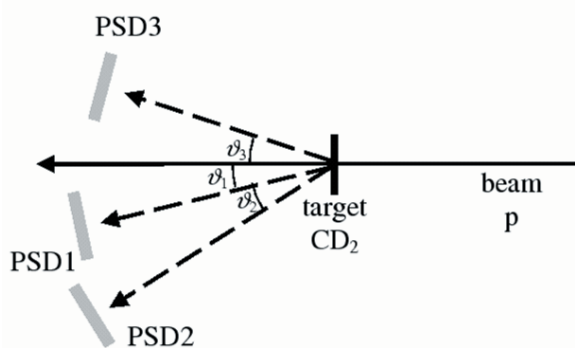


Fig. 1.

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USE OF DEUTERON AS A VIRTUAL SOURCE OF NEUTRONS: THE ${}^6\text{Li}(n,\alpha){}^3\text{H}$ REACTION STUDIED VIA THE ${}^2\text{H}$ BREAK-UP

M. Gulino^{a,b,*}, S. Cherubini^{a,b}, V. Crucillà^{a,b}, M. La Cognata^{a,c}, L. Lamia^{a,b}, R.G. Pizzone^a,
SMR Puglia, S. Romano^{a,b}, M.L. Sergi^{a,c}, C. Spitaleri^{a,b}, S. Tudisco^a, A. Tumino^a, Z. Elekes^d,
E. Somorjai^d, V. Burjan^e, V.Kroha^e

a) INFN Laboratori Nazionali del Sud, Catania, Italy

b) DMFCI, Università degli Studi di Catania, Catania, Italy

c) Dipartimento di Fisica ed Astronomia, Università degli Studi di Catania, Catania, Italy

d) ATOMKI Institute of Nuclear Research, Debrecen, Hungary

e) Nuclear Physics Institute, Academy of Sciences of the Czech Republic, Rez, Czech Republic

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

Abstract

The quasi-free break-up of deuteron was used to study the neutron induced ${}^6\text{Li}+n$ reaction, via the ${}^6\text{Li}(d,\alpha){}^3\text{H}$ reaction. The aim of the experiment is to reproduce the resonance in the cross section of the two body ${}^6\text{Li}(n,\alpha){}^3\text{H}$ reaction corresponding to the excited level at 7.454 MeV of ${}^7\text{Li}$, with the same resolution of the direct measurement. Two experimental runs were performed at Laboratori Nazionali del Sud (LNS) in Catania. In both experiments, the energy and the position of the outgoing α and ${}^3\text{H}$ particles were measured and the kinematics were reconstructed assuming a proton as third particle. The quasi-free events were then selected in order to reconstruct the ${}^6\text{Li}(n,\alpha){}^3\text{H}$ cross section in the center of mass energy. The obtained cross section is compared with the direct measured one and the two show a very good agreement.

1 INTRODUCTION

The study of neutron induced reactions is important not only to get information about fundamental nuclear physics, but also in applied nuclear physics and in nuclear astrophysics. Indeed, neutrons are ideal to probe the mere nuclear interaction without the interference of electromagnetic forces. Neutron cross-sections are relevant for the development of nuclear technologies to be used for energy production and nuclear waste transmutation. Moreover, neutron cross-section at low energies are of interest in nuclear astrophysics. For example all elements heavier than iron were made in environments where neutrons play an important role and the abundance of several light nuclides is modified by (n,γ) , (n,p) and (n,α) reactions during the s-processes or during explosive nucleosynthesis [1-2].

Despite to this big interest, the experiments involving neutrons present many problems. Indeed, it is difficult to produce a monochromatic neutron beam whose energy can be changed in small steps and also the detection of neutrons presents problems of efficiency and poor resolution. The experiments studying neutron induced reactions rely on different methods of producing the

neutrons in the appropriate energy range, either the use of thermal neutrons produced at reactors, which can be utilized to measure the s-wave component of the cross section, or the use of low energy neutron beams for the measurement of possible p-wave or higher energy resonant contributions.

Two complementary methods are presently used to provide neutrons beams. The first method is based on time of flight techniques (TOF) at modern accelerators in connection with neutron sources producing a wide neutron energy range from nearly thermal energies up to energies in the MeV range. The second method is based on neutron energy spectra which simulate a stellar ($kT \approx 25$ keV) Maxwell-Boltzmann distribution, typically produced by ${}^7\text{Li}(p,n){}^7\text{Be}$ or similar light-particle-induced reactions at low energy, high intensity Van de Graaff accelerators. The on-line detection of the reaction products is often limited by high neutron fluxes. Therefore, the activation technique is used frequently, measuring the characteristic decay of the reaction product, in case it is radioactive [3]. Otherwise new on-line detection techniques have to be used for capture γ -radiation at high neutron fluxes (arrays of BaF2 detectors less sensitive to neutron radiation or heavily shielded NaI detectors).

For all these reasons, taking advantage from the big experience in the study of Quasi-free (QF) reactions achieved by the Catania nuclear astrophysics group [4-6], the possibility to use the ${}^2\text{H}$ break-up as source of virtual neutrons was investigated.

The selection of QF events in a three body reaction, $A+a \rightarrow B+b+s$, where a have a strong x - s cluster structure and s acts as spectator, allows to get information about the two body reaction of interest $A+x \rightarrow B+b$. Many theoretical approaches, based on the Impulse Approximation [7-8], describe this kind of processes using a pseudo-Feynman diagram (see fig.1). The upper pole of the diagram represents the break-up of the nucleus a in x and s , while the lower one describes the virtual two body reaction $A+x \rightarrow B+b$. In Plane Wave Impulse Approximation (PWIA) the three body cross section is then factorized in

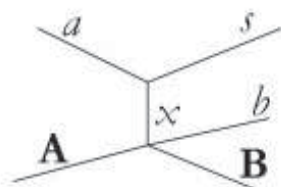


Figure. 1 Feynman diagram of the three body reaction

two terms representing the two poles of the Feynman diagram:

$$\frac{d^3\sigma}{dE_b d\Omega_b d\Omega_B} = KF \left(\frac{d\sigma}{d\Omega} \right) \cdot |\Phi(p_s)|^2 \quad (1)$$

where $(d\sigma/d\Omega)$ is the off-energy shell differential cross section for the two body reaction, KF is a kinematical factor depending on masses, energy and angles of the outgoing particles and $|\Phi(p_s)|^2$ is the Fourier transform of the radial wave function for the p-n inter-cluster motion inside the deuteron [9-11].

In this work the QF reaction mechanism was applied to study the ${}^6\text{Li}(n,\alpha){}^3\text{H}$ neutron induced reaction via the 3 body ${}^6\text{Li}(d,\alpha){}^3\text{H}p$. This reaction represents a good benchmark to verify this new application of the QF reaction mechanism. Indeed, the directly measured data show a resonance in the cross section at about $E({}^6\text{Li}-n) = 210$ keV with 100 keV FWHM corresponding to the excited level at 7.454 MeV of ${}^7\text{Li}$.

2 THE EXPERIMENT

Two measurements of the ${}^6\text{Li}+d$ reaction were performed at Laboratori Nazionali del Sud in Catania. The first experiment, described in [12], has shown the possibility of selecting the events that leave a proton as spectator. However, this first run was optimized for the indirect study of the two body ${}^6\text{Li}+p$ reaction, so the poor resolution of the indirect data acquired for the ${}^6\text{Li}+n$ channel did not allow to reproduce the width of the resonance at $E({}^6\text{Li}-n) = 210$ keV shown by the directly measured data.

A new experiment was then devoted to the measurement of this resonance. The aim was to reproduce the resonance width with a resolution comparable with the directly measured one. For this reason, the beam energy and the experimental set-up were chosen such that the “magnifying glass” effect [13] can be exploited to obtain a good resolution.

In a three body reaction, if the angles of two outgoing particles are fixed in a “in plane” geometry, the events related to the reaction of interest describe a well defined curve in the correlation spectra of the detected energies. The allowed energy combinations map the variation of any two of the three particles relative energy and of the momentum of the spectator. Under proper kinematical conditions, it is possible to translate a slow variation in the relative energy into a large variation in the energy of the two outgoing particles, obtaining the so called “magnifying glass” effect.

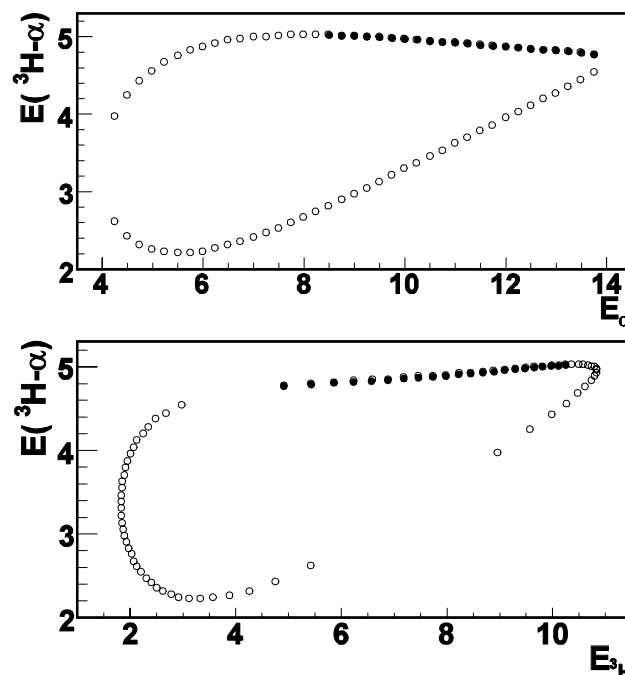


Figure 2. ${}^3\text{H}-\alpha$ relative energy as a function of ${}^3\text{H}$ energy (lower plot) and α energy (upper plot) from kinematical simulation. The full dots indicate the region where the proton momentum ranges from -40 MeV/c up to 40 MeV/c.

This effect enables detailed studies of the variation of the cross section with the relative energy. Detailed kinematical calculations have then been performed in order to define the experimental set-up useful to exploit the “magnifying glass” effect. The best kinematical conditions were found using a beam energy of 17 MeV and selecting α and ${}^3\text{H}$ particles falling respectively in the angular ranges $22^\circ - 26^\circ$ and $36^\circ - 40^\circ$. Indeed, under these conditions, the calculated kinematical loci present a region where the ${}^3\text{H}-\alpha$ relative energy is almost constant while the energy of the two outgoing particles have a range of 4-5 MeV. As an example, in fig.2 it is reported the correlation between the relative energy $E({}^3\text{H}-\alpha)$ and the energy of ${}^3\text{H}$ and α , calculated using a beam energy of 17 MeV, $\theta({}^3\text{H})=36^\circ$ and $\theta(\alpha)=25^\circ$. The full dots in fig. 2 indicate the region where the momentum of the undetected proton ranges from about - 40 MeV/c up to 40 MeV/c, thus assuring that the phase region where a QF contribution to the break-up process of interest is favored falls inside the investigated region.

Following these calculations, the second experiment was performed using a ${}^6\text{Li}$ beam delivered by the SMP Tandem Van de Graaf with an energy of 17 MeV and focused on the target, using a system of collimator and anti-scattering, with a spot of 1 mm diameter. The ${}^6\text{Li}$ beam was sent in the scattering chamber named 2000 and bombarded a CD_2 target of about $100 \mu\text{g}/\text{cm}^2$.

The experimental set-up consists of two 1000 μm Silicon Position Sensitive Detector (PSD) detecting the position and the energy of the two outgoing particles,

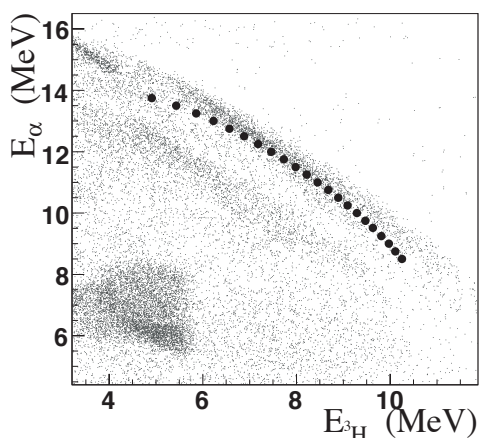


Figure 3. Correlation spectra of the energies detected by the two PSD detectors. A kinematical calculation of the reaction of interest is superimposed on the data (full dots).

α and ^3H . The two PSDs were placed on opposite side with respect to the beam line, covering the laboratory angular range 36° to 40° for ^3H particles (PSD1) and 22° to 25° for the α particles (PSD2). The trigger for the data acquisition was given by the coincidence between the two PSD.

The chosen value of beam energy and angular ranges allows to cover the ^6Li -n relative energy range from 400 keV down to zero.

Thanks to the diameter of the scattering chamber (2000 mm), the detectors were fixed very far from the target (at a distance of 780 mm) in order to obtain an angular resolution of the outgoing particles of about 0.1° , taking into account the angular and energy spread of the beam on the target and of the detected particles on the target and on the dead layer of the detector. Moreover, as it is possible to discriminate the ^3H and α particles by kinematics, no DE detectors were used in order to avoid the angular and energy straggling of the detected particles and consequently to improve the energy resolution.

Using this experimental set-up and taking advantage from the magnifying glass effect it was possible to have a resolution of about 30 keV in the ^6Li -n relative energy.

3 DATA ANALYSIS AND EXPERIMENTAL RESULTS

The PSDs used in the experiment were calibrated in position and energy using the elastic scattering peaks measured at different beam energies for the reactions $^6\text{Li}+^{197}\text{Au}$ and $^6\text{Li}+^{12}\text{C}$ and the two body reaction $^6\text{Li}+^{12}\text{C}\rightarrow^{14}\text{N}^*+\alpha$. All the kinematical quantities were reconstructed under the hypothesis of a proton as third particle. The beam spot and the beam energy spread on the target, the detected particle energy loss on the target and on the dead layer of the detectors were also taken into account.

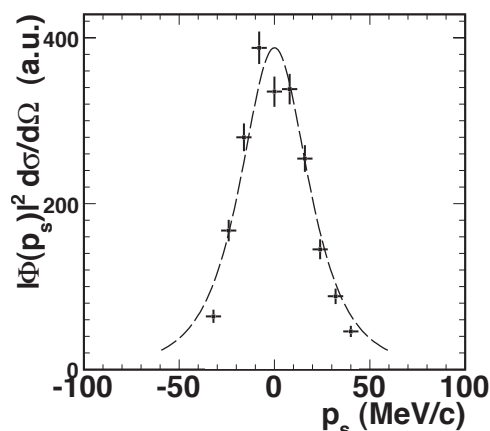


Figure 4. Reconstructed momentum distribution of the undetected proton inside the cluster nucleus, deuteron. The dashed line represents the theoretical Hulthén function.

The identification of the $\alpha+^3\text{H}+p$ channel of interest was done by selecting the correspondent kinematical locus on the correlation spectra of the energies measured by the two PSDs. In fig. 3 the correlation between the measured energies is reported. A kinematical calculation (full dots) has been superimposed on the experimental data in order to select the three body channel of interest, $^6\text{Li}+d\rightarrow\alpha+^3\text{H}+p$.

For the events falling in the region of interest the q -value is reconstructed and it is centered at 2.58 ± 0.05 MeV to be compared with the theoretical value of 2.56 MeV.

Sequential processes through the ground state of ^5Li or excited states of ^4He or ^7Li can also in principle feed this channel. The two dimensional plots reporting the correlation between the relative energy of two out of three outgoing particles calculated in post collision prescription do not show such contributions.

A possible way to investigate the mechanisms involved in the reaction and to identify the QF coincidence events is examining the shape of the experimental momentum distribution of the proton inside the deuteron. This distribution is described by the Hulthén function. If we select a region where the two body cross section can be approximate as a constant and we calculate the term KF via a Monte Carlo simulation, then it is possible to reconstruct the experimental momentum distribution for the spectator p using the equation (1).

In fig. 4 the experimental momentum distribution of the proton (p_s) is shown. A fit performed using the Hulthén function and leaving the width of the distribution as a free parameter is also shown in the figure as a solid line. A good agreement is evident and gives confidence that the QF mechanism is predominant in the chosen kinematical region. The experimental momentum distribution has width of 44 ± 6 MeV.

The two body cross section is extracted by dividing the three body coincidence yield with $|p_s| < 40$ MeV/c by the term $\text{KF} |\Phi(p_s)|^2$ (see Eq.1) calculated using a Monte

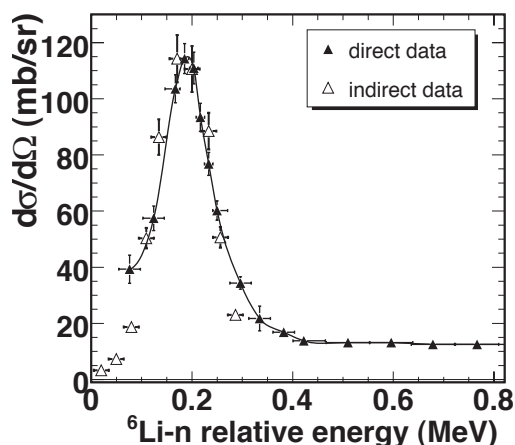


Figure 5. Two body cross section (open triangles) obtained in this work compared with the directly measured one (full triangles) integrated over the center of mass angular region $\theta_{cm} = 60^\circ$ - 90° . The line just guides the eye.

Carlo simulation. In fig. 5, the extracted two body cross section is compared with the experimental direct data integrated over the same center of mass angular region, $\theta_{cm} = 60^\circ$ - 90° [14]. The indirect data are normalized at the top of the resonance, around $E(^6\text{Li-n}) = 200$ keV. The two sets of data show a good agreement not only in the energy value but also in the width of the resonance peak. Moreover the comparison to the direct data was performed without the need to smear them out at a larger energy bin.

To compare the resolution achieved in the two different indirect measurements, previous data are reported together with the present ones in fig. 6, both integrated over the same center of mass angular region, $\theta_{cm} = 60^\circ$ - 70° . The strong improvement achieved using the magnifying glass effect is evident.

4. CONCLUSIONS

A new application of the QF reaction mechanism to study neutron induced reaction is showed in this work. In particular the $^6\text{Li}+d$ reaction was studied at LNS to get information about the $^6\text{Li}+n$ processes by using the break-up of ^2H . The experiment was optimized in order to reproduce the central value and the width of the resonance at 7.454 MeV of ^7Li that was already measured in direct experiments. To achieve a resolution in the $^6\text{Li-n}$ relative energy comparable with that of the direct measurements, it is necessary to have a very good angular and energy resolution in the outgoing particles detection. For this reason the detectors were placed very far from the target and no DE detector for particle identification was used to avoid angular and energy straggling. Moreover the “magnifying glass” effect was used in order to increase the energy resolution.

A careful analysis was performed taking into account the beam spot and the beam energy spread on the target,

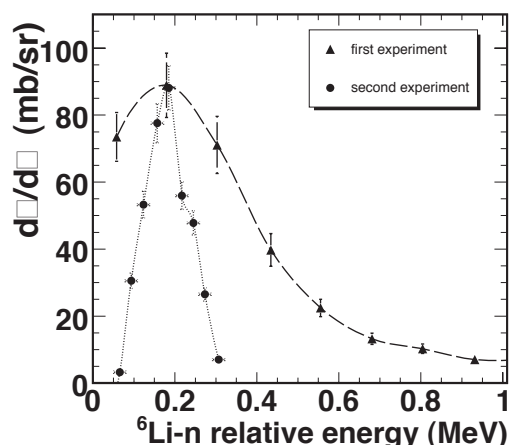


Figure 6. Indirect two body cross section measured in the two experimental runs integrated in the same center of mass angular region $\theta_{cm} = 60^\circ$ - 70° . The line just guides the eye.

the energy loss of the detected particle in the target and in the dead layers of the detectors.

The comparison of the $^6\text{Li}(n,\alpha)^3\text{H}$ cross section obtained in this work and the direct measured data in the same two-body center of mass angular region shows a very good agreement and demonstrates that it is possible to reach a good resolution in the measure of neutron induced two body cross section by using an indirect method. This result represents an important test in view of further applications to measure key neutron induced reactions using deuterons as source of virtual neutrons.

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INDIRECT STUDY OF BORON BURNING REACTIONS IN ASTROPHYSICAL ENVIRONMENTS

L. Lamia^{*,a,b}, C. Spitaleri^{a,b}, S. Romano^{a,b}, S. Cherubini^{a,b}, V. Crucillà^{a,b}, M. Gulino^{a,b}, M. La Cognata^{a,b}, R.G. Pizzone^{a,b}, S. Puglia^{a,b}, M.L. Sergi^{a,b}, S. Tudisco^{a,b}, A. Tumino^{a,b}, S. Typel^c, N. Carlin^c, M.G. Munhoz^c, M.G. Del Santo^c, R. Liguori Neto^c, M.M. De Moura^c, F.A. Souza^c, A.A.P. Suaide^c, E.M. Szanto^c, A. Szanto de Toledo^c

a) INFN Laboratori Nazionali del Sud, Catania, Italy

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

c) GANIL, Bd. H. Becquerel, BP 55027, F-14076 Caen Cedex 05, France

d) Departamento de Física Nuclear, Universidade de São Paulo, São Paulo, Brasil

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

**Present address: CSNSM, CNRS/IN2P3/UPS, Bâtiment 104, 91405 Orsay Campus, France*

Abstract

Due to the role played by the light elements lithium, beryllium and boron as “probe” of stellar mixing phenomena, the (p,α) channel for the boron destruction at astrophysically relevant energies was investigated. The reactions $^{11}\text{B}(p,\alpha)^8\text{Be}$ and $^{10}\text{B}(p,\alpha)^7\text{Be}$ are the main channels for its burning in stellar interior at about $T=10^6$ Kelvin. By means of the indirect Trojan Horse Method the astrophysical $S(E)$ -factor was then extracted for both reactions.

With the future aim to evaluate the impact of the still present nuclear uncertainties on the depleting rate for such light elements, the study of $^{10}\text{B}(p,\alpha)^7\text{Be}$ and $^{11}\text{B}(p,\alpha)^8\text{Be}$ was performed by means of the Trojan Horse Method (THM). After the selection of the quasi-free (QF) contribution on a suitable three-body reaction, this approach allows to extract the two-body “bare”-astrophysical $S(E)$ -factor [5]

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

1 INTRODUCTION

Besides the role of such light elements LiBeB in different astrophysical topics, in the last 30 years big efforts were made about the possibility to use these elements as probes of internal stellar structure and as messengers of mixing processes acting in the stellar interior. Different authors [1] suggest that the study of LiBeB abundances in young F and G stars can give useful informations about different mixing processes presently not well known. In particular for such stars, standard stellar model does not take into account the possibility of “communication” between the convective zone and the nuclear destruction zone where the burning of such elements occurs mainly via (p,α) reactions induced at temperatures of some $\sim 10^6$ Kelvin. This means that the residual LiBeB abundances in such stars would have to reflect the abundances of the original interstellar gas [2]. The observational evidence suggests, in spite of the standard stellar models, that for F main sequence young stars there is a depletion of lithium and beryllium as the observations on Hyades, Praesepe (~ 600 My) and on other young clusters reveal, while there is not evidence of this depletion in F pre-main sequence stars as the observations on Pleiades cluster (~ 70 My) reveal [3]. The evidence of a Li-dip connected with a less pronounced Be-dip and the constancy of boron abundance as the stellar temperature varies together with the Li-Be and Be-B correlation are interpreted as a signature of non-standard mixing mechanisms acting inside these stars: in particular, mixing mechanisms induced by stellar rotation well describe the current observational status [4].

down to energetic region of interest for astrophysics, overcoming the usual problems of Coulomb barrier penetration and electron screening effects connected with direct measurements of two-body reactions relevant for astrophysics. Further, by using this indirect approach, the behavior of the bare astrophysical S -factor in the region around ultra-low energy values can be reached without extrapolations [6], usually made on the direct measurements. However, a normalization procedure of the TH data to the direct ones is needed, making the TH a complementary tool for the experimental nuclear astrophysics.

2 STUDY OF THE $^{10}\text{B}(p,\alpha)^7\text{Be}$ REACTION

Aim of the experiment was to extract the astrophysical $S(E)$ -factor for the $^{10}\text{B}(p,\alpha)^7\text{Be}$ reaction through the THM applied to the $^2\text{H}(^{10}\text{B},\alpha)^7\text{Be}n$ reaction.

“Hot-spot” for the study of this reaction is the presence of the $E_x=8.701$ MeV ^{11}C resonant level ($J=5/2^+$) at about $E_{\text{cm}(^{10}\text{B-p})}=10$ keV. Because the Coulomb barrier penetration and electron screening effects, only an extrapolation on the bare S -factor is present on the available direct data [7]. The application of the TH was then needed in order to get more information about the behavior of the excitation function in the energetic region around the resonant peak.

The experiment was performed at the Pelletron-Linac laboratory (Departamento de Física Nuclear (DFN)) in São Paulo (Brazil). The Tandem Van de Graaf accelerator

provided a 27 MeV ^{10}B beam impinging on a deuterate polyethylene target (CD_2) of about $192 \mu\text{g}/\text{cm}^2$ with a spot size on target of about 2 mm and intensities up 1 nA. Using the experimental setup described in [8,9], the presence of the QF-contribution on the three-body reaction $^2\text{H}(^{10}\text{B},\alpha^7\text{Be})\text{n}$ reaction was investigated by studying the experimental neutron momentum distribution and behavior of the coincidences yield as a function of neutron momentum “ p_n ” values. These studies confirmed that the neutron acted as “spectator” to the two-body reaction of interest. The data within $|p_n| < 30 \text{ MeV}/c$ were further selected in order to get the bulk of the quasi-free contribution for the extraction of the bare-astrophysical $S(E)$ -factor.

Figure 1 shows the final result of this experiment. The indirect data are showed with red points while the direct data of [7] are reported in form of histogram. In particular below $\sim 20 \text{ keV}$ only an extrapolation on the available direct data is present.

A clear increase of the $S(E)$ -factor down to 300 keV shows up, due to the contribution of the 8.701 MeV level of ^{11}C . The FWHM obtained in the present experiment for the resonance is about 110 keV, while independent measurements of such level report a value of about 16 keV. Due to the poor resolution, it was not possible to extract any information about the value of the astrophysical $S(0)$ -factor or about the electron screening potential. However, this first approach to the study of the present reaction confirmed the power of the THM to reach the ultra-low energy values since its application allowed to study the resonant contribution even in the energy region reached through the extrapolations.

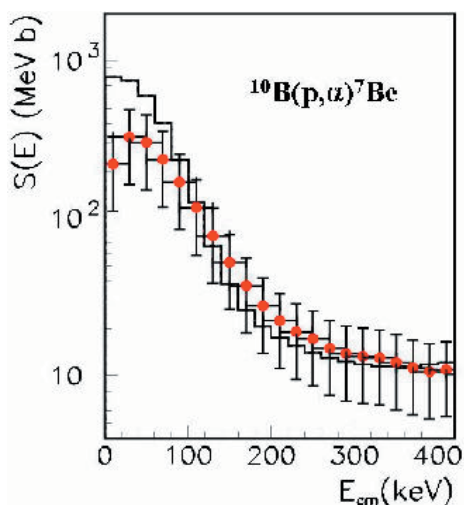


Figure 1: $S(E)$ -factor for the $^{10}\text{B}(p,\alpha)^7\text{Be}$ reaction. The indirect TH data are reported as red points while the direct data [7] are in form of histogram. Below $\sim 20 \text{ keV}$ only an extrapolation is present on the direct data.

Because the importance of such resonant level for astrophysics and with the encouragement of the international scientific community, a new experiment, aimed to improve both angular and energy resolution, was

proposed and it will be performed in our laboratory in the next May 2007.

3 STUDY OF THE $^{11}\text{B}(p,\alpha)^8\text{Be}$ REACTION

Aim of the experiment was to extract the astrophysical $S(E)$ -factor for the $^{11}\text{B}(p,\alpha)^8\text{Be}$ reaction through the THM applied to the $^2\text{H}(^{11}\text{B},\alpha^8\text{Be})\text{n}$ three-body reaction. “Hot-spot” for the study of this reaction is the presence of the $E_x = 16.106 \text{ MeV}$ ^{12}C resonant level ($J=2^+$) at about $E_{\text{cm}}(^{11}\text{B}-p) = 150 \text{ keV}$.

The experiment was performed at the LNS of Catania. The SMP Tandem Van de Graaf accelerator provided a 27 MeV ^{11}B beam impinging on a deuterated polyethylene target (CD_2) of about $170 \mu\text{g}/\text{cm}^2$ with spot size on target of about 2 mm and intensities of about 2 nA. Due to its instability against alpha-decay, the detection of ^8Be 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° (PSD1), 37° (PSD2) and 57° (PSD3) on opposite side with respect to the beam. The trigger for the acquisition was made by selecting the coincidences between the DPSD and one of the three PSD’s. Further details about experimental setup and selection of the data are deeply discussed in [10].

Recently the data were further analyzed in order to evaluate the different energy resolution on the three different angular pairs of detectors. In particular an estimation of the energy resolution leads at about 50 keV for DPSD-PSD1 pair, at about 40 keV for DPSD-PSD2 pair and finally at about 80 keV for DPSD-PSD3.

In order to extract the behavior of the astrophysical $S(E)$ -factor, we have recently re-studied only the DPSD-PSD2 pair, having the lowest energy resolution estimated at about 40 keV in E_{cm} . However, due to the present resolution on the variable E_{cm} of our interest, the FWHM of the mentioned resonant contribution is quite larger ($\Gamma^{\text{exp}} \sim 120 \text{ keV}$) if compared to that of about $\Gamma^{\text{the}} \sim 5 \text{ keV}$ reported by the direct measurements [11].

Moreover, the presence of sequential mechanisms on the selected data was further checked. In more details, the selected particles in the exit channel of interest for the TH investigation could come from formation and subsequent decay of an intermediate compound nucleus. Obviously these processes are quite different from the quasi-free ones and a detailed investigation on their contribution in the selected data is needed. In particular, as deeply discussed in more articles, these kind of mechanisms represent an “expected”-background to subtract on our data. As sketched in figure 2, the particles ^8Be and the neutron “n” could come from the formation and subsequent decay of the intermediate ^9Be compound nucleus from its excited states. Reconstructing then the relative ^8Be -n energies it was possible to study the populations of three different states of the ^9Be .

The contribution of these three levels of ^9Be on the E_{cm} spectrum was then established and the situation is reported in figure 3. The upper part of the figure shows how the selected background affects the selected data in

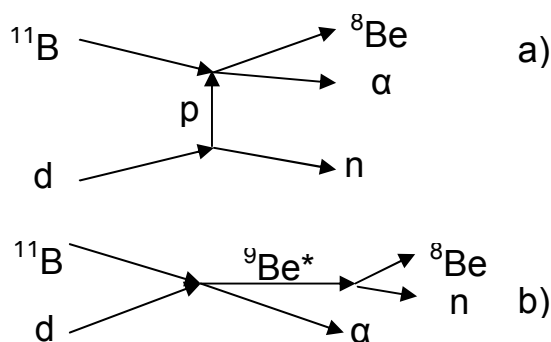


Figure 2: a) Diagram representing the quasi-free reaction $^2\text{H}(^{11}\text{B},\alpha^8\text{Be})\text{n}$. b) Typical diagram showing a sequential decay from an intermediate compound nucleus.

the momentum region of $|p_n| < 40 \text{ MeV/c}$. The black points represent the coincidence yield within $|p_n| < 40 \text{ MeV/c}$, while the red ones represent the contribution of the selected levels of the intermediate ^9Be compound nucleus. In the lower part, the three-body coincidence yield is reported (red points) after the correction for the selected background.

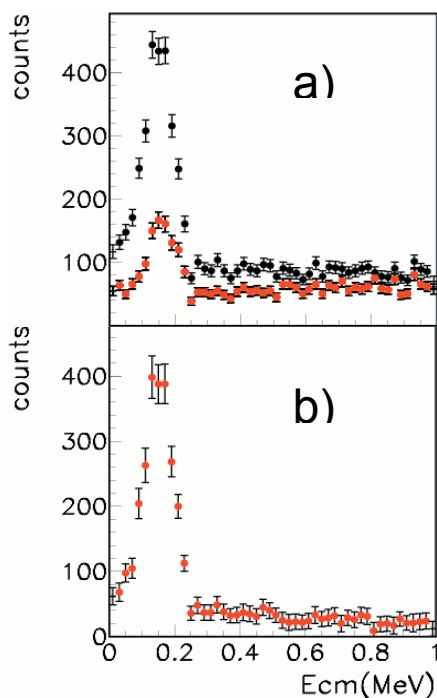


Figure 2: Panel a) Comparison between 3-body coincidence yield (black points) and the selected background (red points). Panel b) Three-body coincidence yield after background subtraction.

Following the usual description of the method, the MPWIA was then applied in order to extract the astrophysical $S(E)$ -factor [12].

The experimental three-body coincidence yield was fitted with a second order polynomial plus a Breit-Wigner function. Knowing the contribution coming from both resonant ($l=1$) and non-resonant ($l=0$), it was possible to calculate the astrophysical $S(E)$ -factor. Moreover, because the energy resolution of about 40 keV on the present TH data, a folding of these fits was then needed in order to make the normalization and then the comparison with the direct ones. Because the presence of two different contributions in excitation function, two constants of normalization were needed in order to compare the TH data with the direct ones.

The preliminary results of this very recent analysis is reported in figure 3 and now under analysis. The full black line represents the behavior of the $S(E)$ -factor as extracted by means of THM while the full red line represents the fit on the direct data as reported in [11]. The two set of data are however in agreement within the experimental error and more details about the analysis are at moment under study.

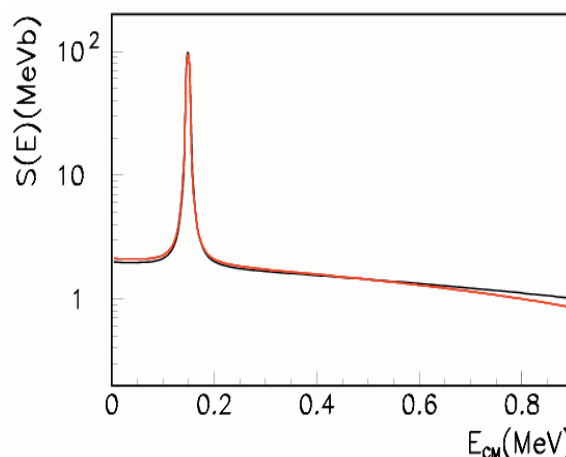


Figure 3: Comparison between the fit on the TH $S(E)$ -factor (black line) and direct $S(E)$ -factor (red line) as reported in [11]. The TH-data are here reported after a correction for the experimental energy resolution of about 40 keV and then compared to the direct ones.

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THE ROLE OF OXYGEN IN ASTROPHYSICAL DOMAINS: STUDY OF $^{17}\text{O}(\text{p},\alpha)^{14}\text{N}$ REACTION VIA THE TROJAN HORSE METHOD

M.L. Sergi^{*,a,b}, C. Spitaleri^{a,b}, M. Gulino^{a,b}, V. Burian^c, A. Coc^d, S. Cherubini^{a,b}, V. Crucillà^{a,b},
V.Z. Hons^c, F. Hammache^c, G. Kiss^f, V. Kroha^c, M. La Cognata^{a,b}, L. Lamia^{a,b}, R.G. Pizzone^{a,b},
S.M.R. Puglia^{a,b}, G.G. Rapisarda^{a,b}, S. Romano^{a,b}, N. de Sereville^d, E. Somorjai^f, S. Tudisco^{a,b},
A. Tumino^{a,b}

a) INFN Laboratori Nazionali del Sud, Catania, Italy

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

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

d) CSNSM, CNRS/IN2P3/UPS, Bâtiment 104, 91405 Orsay Campus, France

e) IPN, IN2P3-CNRS et Université de Paris-Sud, 91406 Orsay Cedex, France

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

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

Abstract

The role of oxygen in astrophysics is related to different problems as novae nucleosynthesis and gamma-ray astronomy. In particular, owing to the still present uncertainties on its rate, the $^{17}\text{O}(\text{p},\alpha)^{14}\text{N}$ is one of the most important reaction to be studied in order to get more information about the fate of oxygen in different astrophysical scenarios. The preliminary study of the three-body reaction $^2\text{H}(^{17}\text{O},\alpha)^{14}\text{N}$ is presented here as a first stage of the indirect study of the astrophysically relevant $^{17}\text{O}(\text{p},\alpha)^{14}\text{N}$ reaction through the Trojan Horse Method (THM).

1 INTRODUCTION

The role of oxygen, in particular of the isotope ^{17}O , is related to various open questions in astrophysics. First of all, it is one of the very few isotopes whose nucleosynthetic origin can be attributed to novae.

In novae, ^{17}O is presented in one of the two paths leading to ^{18}F production of special interest for gamma ray astronomy [1,2]. Secondly, the relative abundances of the oxygen isotopes have been observed at the surface of some Red Giant stars [3]. Thirdly, hundreds of presolar grains found in meteorites are composed of oxides with laboratory measured isotopic compositions [4].

Hence it is important to evaluate the nuclear path involving ^{17}O . While the nuclear reaction rate $^{16}\text{O}(\text{p},\gamma)^{17}\text{F}(\beta^+)^{17}\text{O}$ governing the production of ^{17}O is rather well known (NACRE), the experimental status for its destruction by proton capture is much less satisfactory. The $^{17}\text{O}(\text{p},\gamma)^{18}\text{F}$ reaction is important for ^{18}F production in novae while $^{17}\text{O}(\text{p},\alpha)^{14}\text{N}$ represent the dominant channel for oxygen destruction [5].

At nova temperatures ($\sim 10^8$ K) several measurements [2,5] of the $E_{\text{r}}^{\text{cm}} = 183$ keV resonance ($E_{\text{x}} = 5.790$ MeV) both in

the (p,γ) and (p,α) have drastically reduced the uncertainties on these rates in the context of explosive H-burning. At lower temperatures relevant for hydrostatic H-burning in AGB and RG stars ($2-8 \times 10^7$ K), the only direct measurement [6] concerns the $E_{\text{r}}^{\text{cm}} = 65$ keV (p,α) resonance ($E_{\text{x}} = 5.672$ MeV) but different uncertainties are still present on the available direct data mainly due to the presence of different resonant levels. In addition some sub-threshold levels could contribute to the total reaction rate and then a further study of this reaction appears necessary.

The energies of the nuclear reactions interesting for astrophysics are the Gamow energies, that are of the order of few keV. These energies are than low if compared with the Coulomb barrier, usually of the order of MeV's, thus implying that 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). Owing 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

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

For non resonant reactions, this factor varies smoothly with energies. Nevertheless this extrapolation procedure can introduce some uncertainties due to the presence of unexpected subthreshold resonances or electron-screening effects [7].

However, in recent years many indirect methods have been developed in order to extract the $S(E)$ -factor without extrapolations. In particular the THM [8-11] 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 and electron screening effects.

The present study of the $^{17}\text{O}+p \rightarrow ^{14}\text{N}+\alpha$ reaction in the energy window relevant for astrophysics was performed after selecting the QF-contribution of the $^2\text{H}(^{17}\text{O}, \alpha)^{14}\text{N}$ three body reaction. The deuteron was used like “trojan horse nucleus” because of its strong $p+n$ cluster structure, and the proton is brought in the nuclear field of ^{17}O while the neutron acts like a spectator to the reaction [12].

2 EXPERIMENTAL SETUP

The experiment was performed at LNS in Catania. The Tandem accelerator provided a 41 MeV ^{17}O beam of intensities up to 8 nAe. By using a collimator-antiscattering system, the beam spot diameter on target was of about 1.5 mm. A deuterated polyethylene target (CD_2) of about $160 \mu\text{g}/\text{cm}^2$ was placed at 90° with respect to the beam axis direction. The detection setup (Fig. 1) was symmetric with respect to the beam line and it consisted of four $500 \mu\text{m}$ Position Sensitive Detectors (PSD2, PSD3, PSD5 and PSD6) and two telescopes made up of an ionization chamber and a $500 \mu\text{m}$ PSD detector (PSD1 and PSD4).

The telescope systems were placed at a distance $d_{1,4}=470$ mm from the target, covering the angular range 5.0° - 11.0° . The PSD2 and PSD5 were placed at a distance $d_{2,5}=372$ mm from the target, covering the angular ranges 13.8° - 21.0° and PSD3 and PSD6 were placed at $d_{3,6}=392$ mm from the target covering the angular range 24.4° - 31.1° .

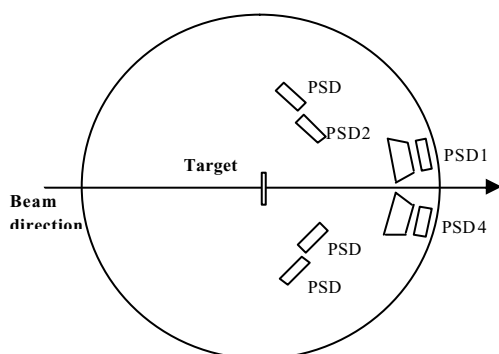


Figure 1: Schematic representing of experimental setup.

The ionization chamber was filled with 60 mbar isobutane gas and two foils of $1.5 \mu\text{m}$ Mylar were used as windows. The pressure of the gas inside the ionization chamber was monitored during the whole experiment through a standard pressure sensor.

The setup was chosen in order to cover the whole QF-angular range, known “a priori” from a Monte Carlo simulation. In particular we aspect ^{14}N in the angular range 5° - 11° and α particles in the angular range 5° - 32° . The use of a telescope at lower angles is necessary to discriminate the ^{14}N reaction product from the ^{14}C coming from the $^{17}\text{O}(n,\alpha)$ reaction. The others detectors were devoted only

to a detection that are identified by kinematic. The trigger signal was given by the logic “OR” of the three different coincidences: PSD1-PSD4 coincidence, PSD1 in coincidence with “OR” of PSD5 and PSD6 signals, and the coincidence between PSD4 and “OR” of PSD2 and PSD3 signals.

Energy and position signals of the detected particles were processed by standard electronics, together with the coincidence relative time, and sent to the acquisition system.

3 DATA ANALYSIS: THREE-BODY REACTION IDENTIFICATION

The data analysis is still in progress. The energy and position calibration of the PSD detectors was performed using elastic scattering data acquired in preliminary runs using the $^6\text{Li} + ^{197}\text{Au}$, $^6\text{Li} + ^{12}\text{C}$ reactions at beam energy of 14.8 MeV. Moreover, a standard three peaks α source was used for the calibration of the low-energy region. The ionization chambers were calibrated using the same reactions measured without and with gas inside the detectors.

In order to identify the channel of interest and to choose the kinematical conditions where the quasi-free process is dominant, ^{14}N particles were selected in the ΔE -E two-dimensional plots as is shown in Fig. 2. The energy correlation between ^{14}N and α and only for the coincidence PSD1-PSD5 is shown in Fig. 3.

Moreover the experimental Q-value spectrum (Fig. 4) for the three-body reaction is centered at about $Q_{\text{expe}} = -1.046$ MeV, according to the expected theoretical value ($Q_{\text{theor}} = -1.033$ MeV). Events below this peak were showed in function of $E_{\text{c.m.}}$ in Fig. 5. From this picture the presence of several resonance levels clearly appears. In particular is evident the presence of $E_{\text{R}}^{\text{cm}} = 183$ keV and $E_{\text{R}}^{\text{cm}} = 65$ keV (p,α) resonances. In addition, subthreshold levels are present so an accurate study of interference effects could be necessary.

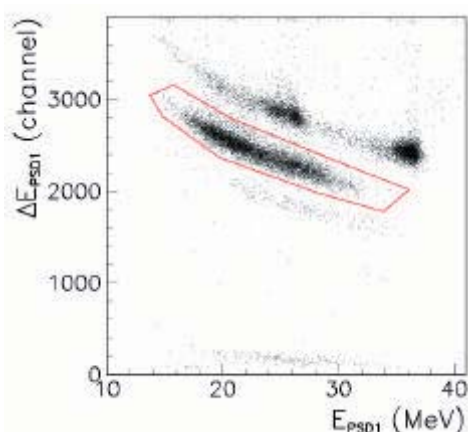


Figure 2: DeltaE-E matrix for ^{14}N identification in the PSD1 telescope.

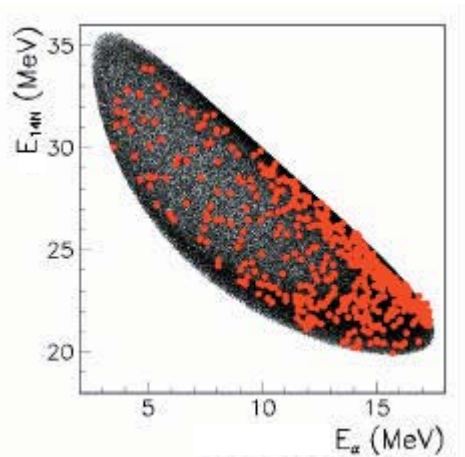


Figure 3: Comparison between the experimental (red points) and simulated (black points) kinematical locus for the three-body reaction ${}^2\text{H}({}^{17}\text{O}, {}^{14}\text{N})\text{n}$. The agreement make us confident about the selection of the channel.

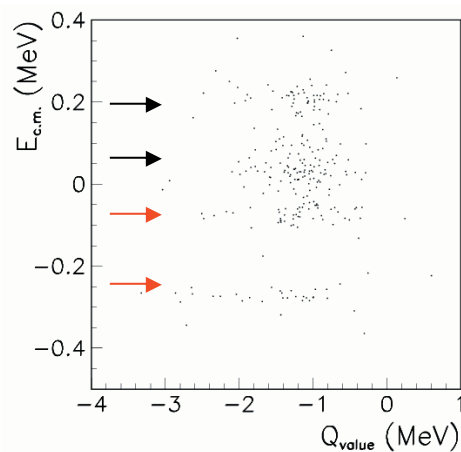


Figure 5: $E_{\text{c.m.}}$ vs. Q_{value} . The two black arrows correspond to $E_{\text{R}}^{\text{cm}}=65$ keV and $E_{\text{R}}^{\text{cm}}=183$ keV resonance levels while the two red arrows correspond to subthreshold resonance levels.

In conclusion, even if only the coincidence PSD1-PSD5 was analyzed, the preliminary results show that it was possible the selection of our reaction channel (Fig 3, Fig 4). Moreover, the presence of resonance levels in the energetic region of interest (Fig 5) make us confident that the experimental setup was well optimized during the preparation of the experiment.

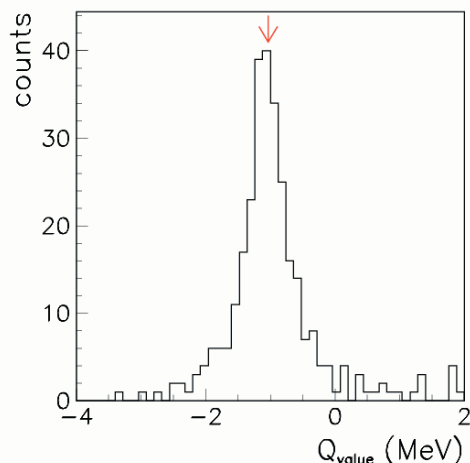


Figure 4: Q_{value} experimental spectrum for the three-body reaction ${}^2\text{H}({}^{17}\text{O}, {}^{14}\text{N})\text{n}$. The red arrow corresponds to expected theoretical Q_{value} ($Q_{\text{theor}} = -1.033$ MeV).

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η MESON RECONSTRUCTION IN PP REACTIONS AT 2.2 GEV WITH HADES

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

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

b) II. Physikalisches Institut, Justus Liebig Universität Giessen, 35392 Giessen, Germany

** Corresponding author, e-mail: stefano.spataro@exp2.physik.uni-giessen.de*

Abstract

The HADES spectrometer installed at GSI Darmstadt is devoted to study the production of di-electron pairs from proton, pion and nucleus induced reactions at 1-2 AGeV. In pp collisions at 2.2 GeV we have focused mainly on exclusive reconstruction of the η meson decays in the hadronic ($\eta \rightarrow \pi^+\pi^-\pi^0$) and the electromagnetic channels ($\eta \rightarrow e^+e^-\gamma$). We present analysis techniques and discuss first results on η production, with the main focus on comparisons of reconstructed distributions to results obtained by other experiments and theoretical predictions.

1 THE EXPERIMENT

The HADES spectrometer, which is described in more details in the contribution of [1], is a highly selective tool specially suited for the study of the high energy dielectron decay channels in nucleus-nucleus collisions around 1-2 AGeV, as well as in proton and pion induced reactions. In order to provide absolute measurements of invariant mass distributions a good knowledge of the dielectron reconstruction efficiency is mandatory, which can be achieved by means of well known calibration reactions, as the $pp \rightarrow pp\eta$ channel.

A proton-proton run was done on January 2004 at 2.2GeV, to measure the $pp \rightarrow pp\eta$ reaction through an exclusive reconstruction of 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 a calibration reaction for the dielectron identification, in order to normalize the dielectron yields in the heavy ions experiments.

The study of the η meson is of particular interest for several reasons. In the vicinity of the threshold the production of the η meson was studied extensively and the inclusive cross sections are well known [2], while at higher energies the uncertainties are larger. Moreover the observed electron pair invariant mass distribution for the η Dalitz decay branch can be used to check contributions from other sources (such as π^0 Dalitz, combinatorial background, etc.) as well as the lepton trigger efficiency. In addition, if both protons and both leptons are detected, the reconstruction of this decay mode is kinematically complete without requiring an additional photon detector, and a missing mass technique can be applied. This would allow to separate the η Dalitz from all other sources and to map the effective acceptance of the spectrometer.

2 TIME-OF-FLIGHT MEASUREMENTS

In HADES, however, the main algorithm for particle identification requires a combination of momentum and time-of-flight measurements. In the pp experiment it was not possible to use a START detector as a time reference, because of the high number of secondaries produced. This means that there is no 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 time-of-flight wall. In this case we measure the difference in time with respect to the fastest particle, instead of the real time-of-flight. Thus it was necessary to develop an algorithm to reconstruct the start time of the reaction, and make particle identification possible.

The used algorithm relies on identifying one particle in the event and calculating its theoretical time-of-flight: from the assumed mass and the measured momentum we calculate the time-of-flight of the particle, thus the offset to the real start time of the reaction. The first kind of identification comes from the Cherenkov detector, which is hadron blind and can select electron/positron tracks. If a lepton candidate is not found, a negative charged track in the same event is assumed as a negative pion. Finally, we recalculate the time-of-flight of the other particles inside the same event using the extrapolated reaction time. Figure 1 shows the momentum times polarity versus reconstructed velocity distributions after the time reconstruction, separately for events with an identified lepton (left) and with an identified negative pion (right).

In this way we obtained an average time resolution of 340 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 [3].

After the start time reconstruction it is possible to use the recalculated time-of-flight in order to identify particles, for exclusive analysis of η decay channels. In figure 1 it is possible to see that different particles cover well separated regions in the plot, so particle identification can be performed.

3 EXCLUSIVE η RECONSTRUCTION

The main goal of the p+p experiment was to verify the dielectron reconstruction efficiency needed for a correct interpretation of the HI data, by means of the well known η meson decays into hadronic [4] and electromagnetic channels [5].

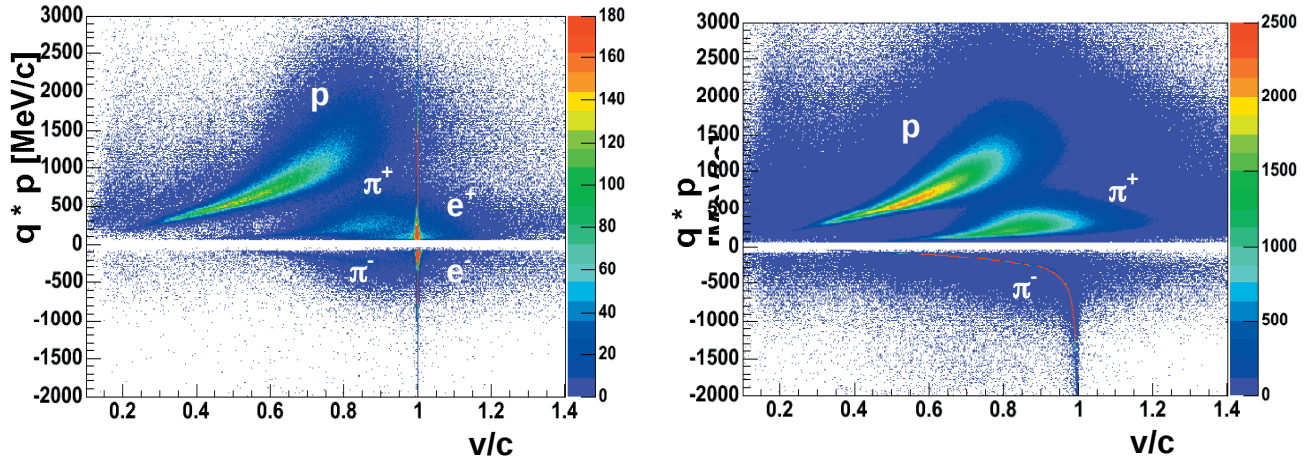


Figure 1. Plots of momentum times polarity versus reconstructed velocity, for events with an identified e^+e^- (left), and with an identified π^- (right).

In the simulation we assumed resonant production of the meson via $pp \rightarrow pN(1535) \rightarrow pp\eta$, with the Dalitz matrix element taken from [4]. For the eta hadronic decay the matrix element from [6] has been implemented, and for the η Dalitz decay the vector dominance model (VDM) was assumed. In addition a full cocktail of reaction channels based on measured proton-proton cross sections [7] was generated. Simulated events were processed through the HADES GEANT code and reconstructed with the same analysis program used for the experimental data.

Reconstruction of the $pp \rightarrow pp\eta \rightarrow pp\pi^+\pi^-\pi^0$ reaction started with charged particle identification (PID) based on momentum and reconstructed time of flight. After PID a kinematical condition was used on events with two protons and two charged pions: by imposing a cut of 3σ around the π^0 region in the four-particle missing mass we selected the $\eta \rightarrow \pi^+\pi^-\pi^0$ reaction, σ being determined from a fit to the missing π^0 peak. The missing-mass resolution was further improved with a kinematical refit of the full event [8]. Finally, the η mesons were identified in the two-proton missing-mass distribution shown in the left plot of figure 2. A prominent η peak, centred at the expected position, is clearly visible on top of a non-resonant three-pion background.

By fitting the distribution by means of a gaussian plus a background function, we obtain the value of the η mass with a resolution of 2.5%, and evaluate the hadronic production yield.

Moreover, by fitting the pp missing mass peak in various $\cos\theta_{\eta}^{cm}$ slices [9], the angular distribution on the η meson emission has been evaluated and compared to simulation, by using the anisotropic angular model verified by the DISTO collaboration [4] (right plot of figure 2). The two distributions are in agreement within error bars, showing that the hadron efficiency is understood in the covered phase space region.

The reconstruction of the $pp \rightarrow pp\eta \rightarrow ppe^+e^-$ decay was done in a similar way. As a first step, events with two proton and two electron tracks were selected, thus the ppe^+e^- reaction channel was identified by imposing a 3σ selection on the four-particle missing mass around the

missing photon peak. The left side of figure 3 shows the proton-proton missing mass distribution, obtained after a kinematical refit was applied to the ppe^+e^- events with a constraint on a missing photon. The prominent peaks centered at 140 and 546 MeV/c^2 correspond to the π^0 and η mesons respectively.

The distribution is dominated by events $\eta \rightarrow \gamma\gamma$ (branching ratio $\sim 40\%$) where one of the decay photons produces a conversion pair. However, as the simulation also shows, it can be completely removed by conditions on the quality of the track reconstruction and the pair opening angle. The right plot of figure 3 shows the invariant mass distribution of dielectron pairs coming from the η decay after the conversion rejection [10], in comparison with simulation by using QED (point-like interaction) and VDM (η form factor) theoretical models. The agreement demonstrates our good understanding of the dielectron invariant mass spectrum, and that the form factor measurement is feasible with the HADES spectrometer.

Finally we compare the ratio R of the η yieldsⁱ reconstructed in the hadronic and electromagnetic decays (including conversion contribution) to the predictions of the simulation with the following results: $R_{\text{exp}} = 15.3 \pm 1.8$ (stat) and $R_{\text{sim}} = 15.6 \pm 0.9$ (stat). The agreement in between the two values shows how the simulation well reproduces the experimental yields, and it confirms the global good understanding of the response of the HADES spectrometer.

4 ACKNOWLEDGEMENTS

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ⁱ Yields before the kinematic refit procedure were considered, to avoid systematic effects.

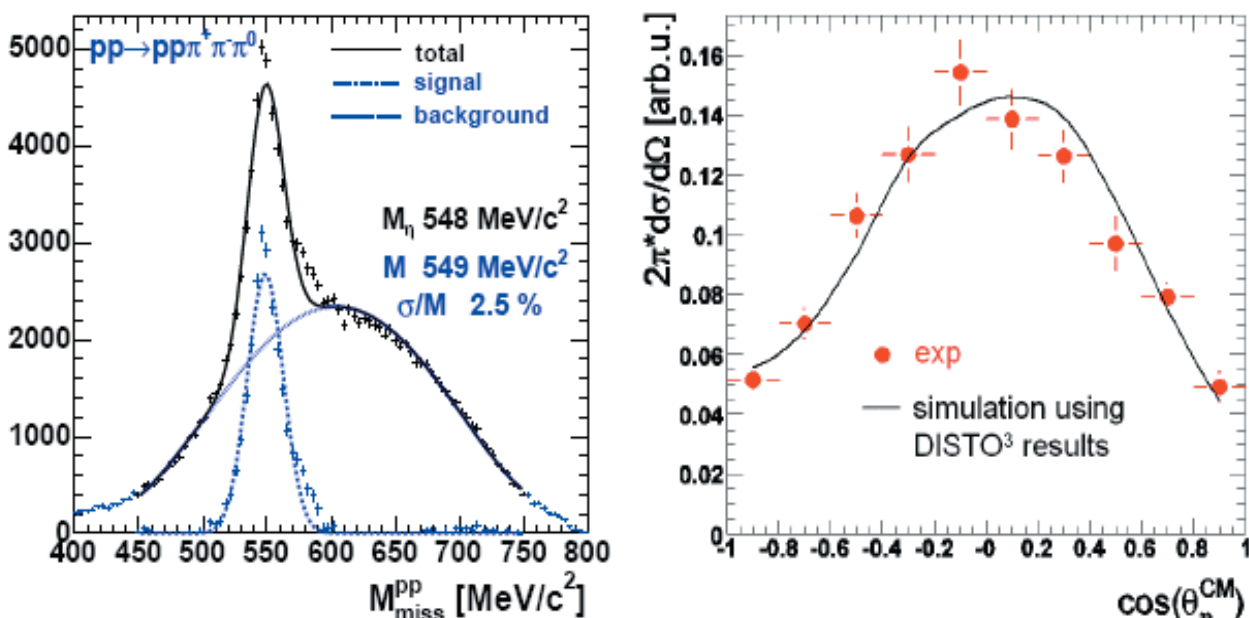


Figure 2. *Left*: Proton-proton missing mass plot for the hadronic decay channel, after a kinematic refit procedure. *Right*: Distribution for the η center-of-mass polar angle for $\eta \rightarrow \pi^+ \pi^- \pi^0$ events, without correction for acceptance and efficiency.

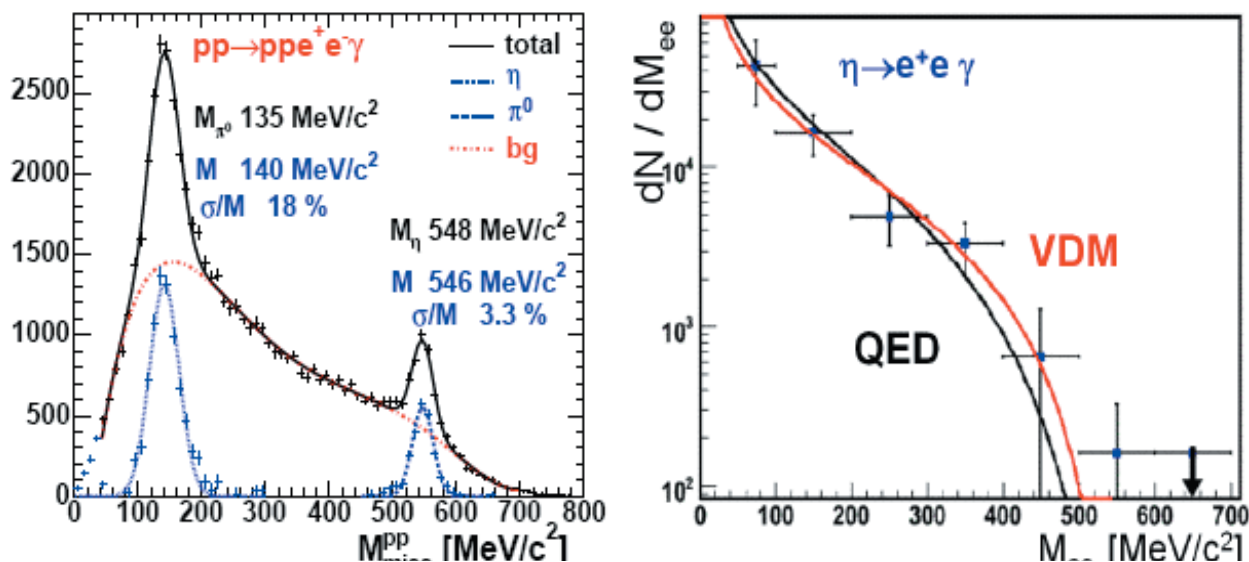


Figure 3. *Left*: Proton-proton missing mass plot for electromagnetic η meson decay, after a kinematic refit procedure. *Right*: Invariant mass distribution of dielectron pairs coming from η decay, after the conversion rejection, in comparison with simulation by using QED or VDM η form factor.

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MEASURING THE ASTROPHYSICAL S-FACTOR IN PLASMAS: A PRELIMINARY TEST

A. Bonasera^{a,c)}, A. Anzalone^{a)}, S. Kimura^{a)}, D. Leanza^{a,c)},

a) INFN Laboratori Nazionali del Sud, Catania, Italy.

C. Strangio^{b)}, M. Aglione^{b)}, P.L. Andreoli^{b)}, G. Cristofari^{b)}, G. Di Giorgio^{b)}

b) ICF-ENEA, Frascati, Roma, Italy.

A. Caruso^{c)}

c) Libera Università Kore, Enna, Italy.

G. Immè^{d)}, D. Morelli^{d)}

d) Dip. Fisica, Catania and INFN sez. Catania, Italy.

J. Sura^{e)}

e) Physics dept., Warsaw, Poland.

Abstract

We discuss a method for a direct measurement of the astrophysical S-factor for neutron-less nuclear reactions induced in laser plasmas. A very preliminary experiment to test the concepts supporting our theoretical predictions was performed at the ENEA ABC-facility. The target material, shoot during a facility tuning up activity*, was provided by LNS**. The preliminary results are reviewed as well as some theoretical predictions.

1 INTRODUCTION

A precise measurement of the low-energy fusion cross section is a very 'hot' topic nowadays. These measurements are needed both for astrophysical studies and also in view of possible energy production applications [1]. In this context it is of particular interest to know the fusion cross-section at very low energies where unfortunately, due to the low statistics or because the electrons screening becomes important, it is difficult to make reliable measurements. Usually, the fusion cross section is factorized in terms of a Gamow factor representing the probability of tunneling through the Coulomb barrier and an S factor hopefully featured by a smooth dependence on energy. Based on this scheme the cross section at zero energies is sometimes extrapolated. Due to the influence of the electron screening, the difficulty arises for the determination of the S-factor at low energies [2]. Being able to derive a bare cross-

section in the zero-energy limit, we could calculate the reaction rate for instance in a plasma at given density and temperature T.

In our proposed experiment we plan to do exactly the opposite, i.e. to measure the reaction rate in plasmas where the electronic screening is negligible and at the same time to measure the ionic distribution function of the plasma. From the knowledge of those two ingredients we can derive the fusion cross section (and the S-factor) which is now a function of temperature T. In order to test

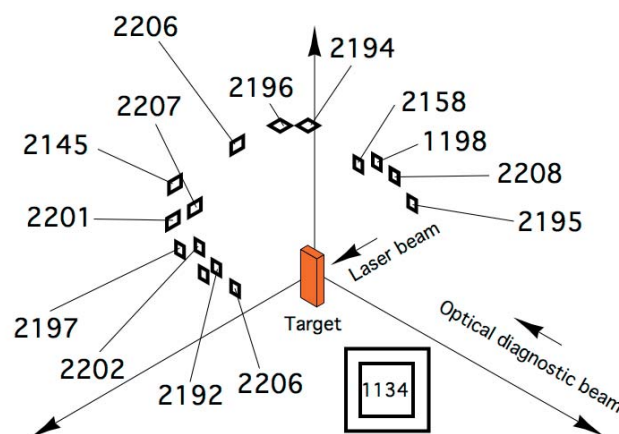
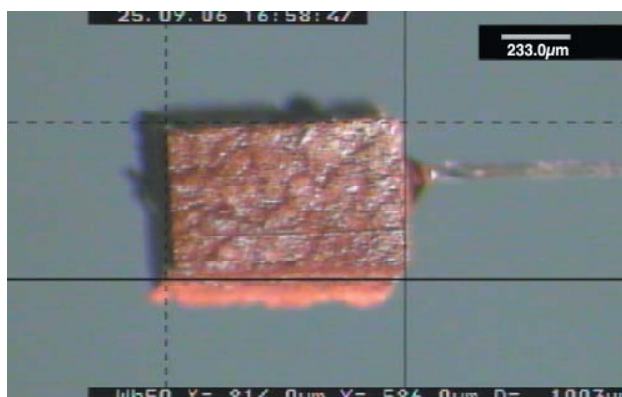


Fig. 2 General Layout of the experiment showing the positions of the CR39 detectors. Numbers are CR39 plates identifiers



the some concept relevant for the experiment feasibility we used the ABC facility of ENEA in Frascati, where power densities up to $\approx 3 \times 10^{15}$ W/cm² can be delivered on the target for times of the order of 2÷3 ns [3]. For this aspheric F/0.8 large aperture optics is used.

Theoretical Nuclear Physics

B



APPLICATION OF THE X-RAY LASER TO MUON-CATALYZED D-T FUSION

Sachie Kimura^{a,*}, Aldo Bonasera^{a,b}

a) INFN Laboratori Nazionali del Sud, Catania, Italy

b) Libera Università Kore, Enna, Italy

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

Abstract

We discuss the alpha-muon sticking coefficient in the muon-catalysed d-t fusion in the framework of the Constrained Molecular Dynamics model. Especially the influence of muonic chaotic dynamics on the sticking coefficient is brought into focus. The chaotic motion of the muon affects not only the fusion cross section but also the μ - α sticking coefficient. Chaotic systems lead to larger enhancements with respect to regular systems because of the reduction of the tunneling region. Moreover they give smaller sticking probabilities than those of regular events. By utilizing a characteristic of the chaotic dynamics one can avoid losing the muon in the μ CF cycle. We propose that the application of the so-called “microwave ionization of a Rydberg atom” to the present case could lead to the enhancement of the reactivation process by using X-rays.

1 INTRODUCTION

The muon catalyzed fusion (μ CF) of hydrogen isotopes, especially *d-t* fusion, has been studied as a realizable candidate of an energy source at thermal energies. In the liquid D_2 and T_2 mixture, the muon assists the fusion through the formation of a muonic molecule, since the size of the muonic molecule is much smaller than that of the ordinary molecules and the fusing nuclei tend to stay closer. After the fusion process the muon is released normally and again it is utilized for a subsequent fusion until the muon decays. The efficiency of the μ CF is governed by not only the life time of muons but also the muon-sticking on the α particle which is produced in the fusion[1,2]. The muon is lost from the μ CF cycle by the initial sticking(w_0), unless it is not released through the interaction with the medium. The rate of the stripping of the stuck muon from the α particle is known as the reactivation coefficient R and thus the effective sticking probability(w_0^{eff}) is determined by $w_s^{eff} = w_0(1 - R)$. In this paper we do not take into account the medium effects which are supposed to be important to determine the precise value of R in the actual experimental setup. We rather aim to propose a method to enhance the reactivation process, by making use of the stochastic instability of the stuck muon in an oscillating field. For this purpose we are mainly interested in investigating the impact of the regular and chaotic dynamics [3]. At thermal energies, where the μ CF takes

place, fluctuations are anticipated to play a substantial role. We investigate the influence of the fluctuations by using a semi-classical method, the constrained molecular dynamics (CoMD) approach. In the CoMD, the constraints restrict the phase space configuration of the muon to fulfill the Heisenberg uncertainty principle. The results are given as an average and a variance over ensembles of the quantity of interest which is determined in the simulation. Especially we determine the enhancement factor of the reaction cross section by the muon as a function of the incident energy. The enhancement factor of each event indicates the regularity of the system. Subsequently we determine the initial muon sticking probability, using the phase space distribution of the muon at the internal classical turning point. The muon does not stick necessarily to the ground state of the alpha particle and this fact plays an important role when we proceed to the stripping of the bound muon in the oscillating field. The chaotic dynamics could prevent the muon from being lost in the μ CF cycle due to the sticking. It is achieved by utilizing the characteristic as a nonlinear oscillator of the trapped muon on the alpha particle. We draw an analogy between the muonic He ion in the present case and microwave-ionization of Rydberg atoms [4,5], where the driven electron in the highly excited hydrogen atom in a strong microwave electric field exhibits the chaotic dynamics and is ionized. We carry out a numerical simulation by enforcing an oscillating field(linearly polarized, oscillatory electric field) on the system. This can be, experimentally, achieved by X-ray lasers. The oscillating force causes the resonance between the force itself and the oscillating motion of the muon around the alpha, especially when the driving frequency coincides with integer multiples of the eigen frequency of the muonic helium.

2 FRAMEWORK

The detail of the framework of the CoMD is discussed in the references[6,7]. In the following we apply the CoMD to the simulation of the fusion and the subsequent muon sticking processes.

3 ENHANCEMENT OF THE CROSS SECTION BY THE MUONIC SCREENING EFFECT

We introduce the enhancement factor of the cross section by the bound muon f_μ

$$f_\mu = \sigma(E)/\sigma_0(E), \quad (1)$$

where $\sigma(E)$ and $\sigma_0(E)$ are the real cross section and the cross section in the absence of the muon, respectively. In the following discussion, the enhancement factor is referred as an indicator of the regularity of the muonic motion. It plays a role of a sort of order parameter and is determined through the obtained values in the numerical simulation.

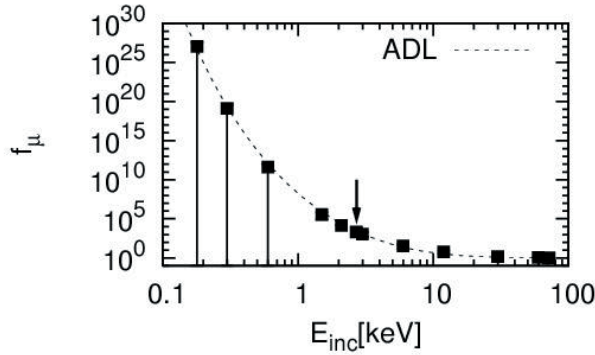


FIG. 1: Enhancement factor by the bound muon as a function of the incident center-of-mass energy. The arrow in the figure indicates the point where the total energy is zero.

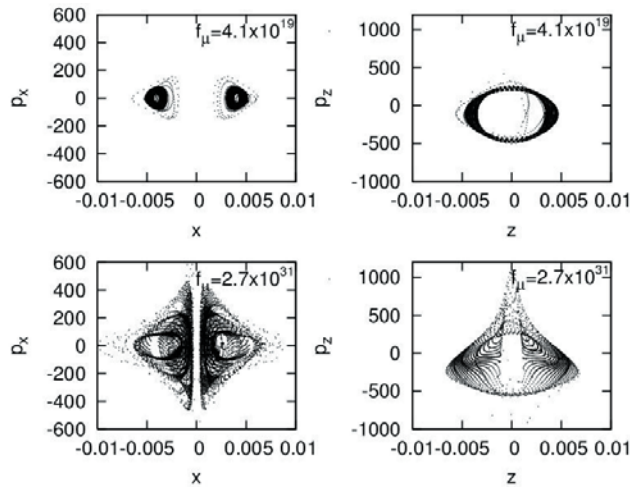


FIG. 2: Surface of section for 2 events, one has a small enhancement factor (top panels) and the other has a large enhancement factor (bottom panels), on the $x - p_x$ (left panels) and the $z - p_z$ (right panels) planes at the incident c.o.m energy 0.18 keV, in the atomic unit.

In Fig. 1 we plot f_μ as a function of the incident center-of-mass energy between the triton and the deuteron. From our simulation of the collisions using an ensemble of events, we determine the average enhancement factor $\bar{f}_\mu$ and its variance: Δf_μ . These are shown by squares and error-bars, respectively. Both the average enhancement factor and its variance increase exponentially as the

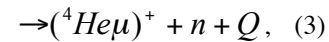
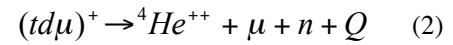
incident energy decreases. The dashed line in the figure corresponds to the enhancement factor in the adiabatic limit. The obtained average enhancement factor is in agreement with the adiabatic limit. The arrows in the figure denotes the ionization energy of the muonic tritium. At this energy the total energy of the system is zero. At the incident energies higher than this point, the total system is unbound, while the 3-body system is bound at lower energies. In the low energy limit the variance, which is shown by error-bars, becomes large. It implies that the system exhibits a sensitive dependence of the dynamics on initial conditions, i.e., occurrence of chaos.

We indeed verify the manifestation of chaos by plotting the Poincare surface of section with respect to the enhancement factor for two events in Fig. 2. In the figure we show the surface of section for two selected events at the incident energy 0.18 keV on the $x - p_x$ plane (FIG.

2 left panels) and on the $z - p_z$ plane (FIG. 2 right panels), respectively. We choose the beam axis to coincide with the z -axis. At the incident energy 0.18 keV the average enhancement factor, $\bar{f}_\mu = 2.9 \times 10^{29}$ as one can see in Fig. 1. In the top panels, with $f_\mu = 4.1 \times 10^{19} (< \bar{f}_\mu)$ and the ratio of the external classical turning point in the presence of the muon to the one in the absence of the muon: $ctp_\mu / ctp_0 = 0.15$, the points show a map of a typical regular event. By contrast in the bottom panels, with $f_\mu = 2.7 \times 10^{31} (> \bar{f}_\mu)$ and $ctp_\mu / ctp_0 = 0.06$, the points show the map of an irregular event; the points cover a large section of the map. The irregular muonic motion leads to smaller external classical turning point. As a consequence it gives larger enhancements factors.

4. MUON STICKING PROBABILITY

We estimate the sticking probability of muons on the alpha particle in the exit channel;



where $Q = 17.59$ MeV is the decay Q-value of this reaction. The muon remains bound (3), if the binding energy of the muon on an alpha particle is negative, in the center-of-mass system of the muon and the alpha particle. From this condition we deduce the following equation for the angle b between the velocities of the muon and the alpha particle: v_μ and v_a .

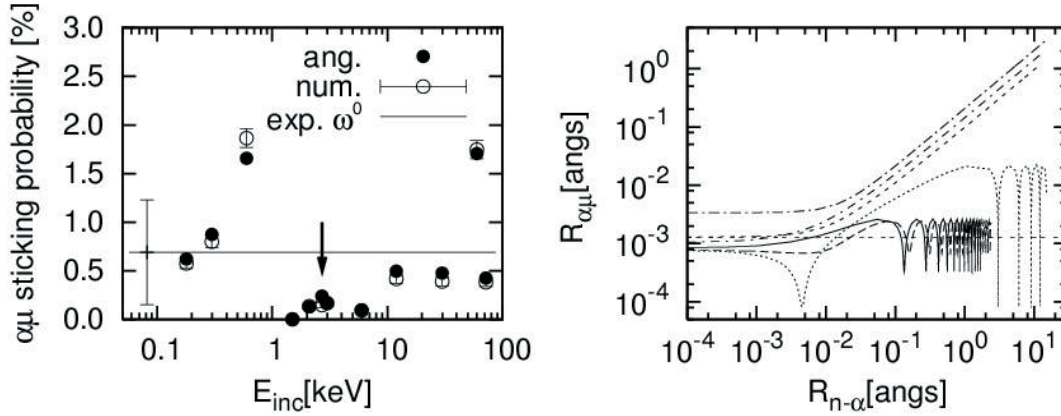


FIG. 3: Incident energy dependence of the sticking probability of the muon on the alpha particle. The statistical error is shown by error-bars, otherwise it is within the size of the points in the figure. (Left panel) Distance between the muon and the alpha particle as a function of the inter-nuclear separation. (Right panel)

$$\cos b \geq \frac{\frac{M_{a\mu}}{2}(|v_\mu|^2 + |v_a|^2) - \frac{2e^2}{|r_{a\mu}|}}{M_{a\mu}|v_\mu||v_a|} \equiv g, \quad (4)$$

$M_{a\mu}$ denotes the reduced mass of the muon and the alpha particle. The condition Eq. (4) is fulfilled when the r.h.s of the equation g is equals to 1 or less and for the solid angle $\Omega = 2\pi(1 - g)$ [steradian] in the 3-dimensional space. We can therefore estimate the sticking probability by $\Omega/4\pi$, if $g \leq 1$. By inspecting each event, one could find out some events which satisfy the condition $g < 1$. Indeed one of the two events shown in the top panels in Fig. 2, which is regular, has $g = 0.93 (< 1.0)$ therefore the sticking probability of this event itself is not zero (3.8 %), while the other in the bottom panels has $g = 1.9 (> 1.0)$ and its sticking probability is zero. In the same way we calculated g for all the events which are created in our simulation. The obtained sticking probability is shown in the left panel in Fig. 3 as a function of the incident energy with filled circles. At the same time, we carry out the simulation of the exit channel by creating 20000 events (randomly chosen directions of outgoing particles). We distinguish the muon sticking event (3) from the release event (2) by monitoring the binding energy of the muon on alpha particles and the radius of the muonic ion. We count the events where the binding energy of the muon on the alpha particle and the distance between the muon and the alpha particle maintain to be negative and small respectively, up to the point where the alpha is distant enough from the neutron. In the right panel in Fig. 3 typical trajectories of the distance between the muon and the alpha particle are shown as a function of the inter-nuclear separation. Among the 6 curves shown in the right panel in the figure, 3 curves, which show oscillational

behaviors, are corresponding to the sticking events. While 3 other curves increase monotonically after $R_{n\alpha}$ exceeds 0.01 Å. The horizontal straight line in the figure indicates the size of the radius of the ground state muonic He atom. The obtained sticking probability is shown with open circles with error-bars in the left panel in Fig. 3. First, as one can see clearly, the result of numerical simulation agrees with the sticking probability which is calculated considering the solid angle. In the figure the solid line with an error bar denotes the sticking coefficient obtained from the direct measurement of the initial sticking probability[2]. The resulting sticking probability ranges nearby the experimental value as a function of the incident energy except for several points, which have zero and relatively large sticking probability. We mention specially that the incident energies at which the sticking probability becomes zero is slightly below than the ionization energy of the muonic tritium.

5. MUON STRIPPING

The stuck muon is possibly stripped from the alpha particle, by enforcing a linearly polarized oscillatory field on the system. The periodic motion of the stuck muon can be expressed in terms of nonlinear oscillations. For a nonlinear oscillator the oscillating driving force, i.e., oscillating field causes the resonance between the force itself and the oscillating motion of the muon at driving frequencies which are integer multiples of the fundamental frequencies of the muon. In our present case the muonic He is not stuck necessarily in its ground state. So that the muon can be ionized directly from one of such an excited state by the radiation of an electrostatic wave, otherwise the muon is, at first, prompted to an excited state and then ionized. In either cases it will be achieved using X-ray lasers, since the fundamental frequencies for the ground and the first excited state of the muonic He ion corresponds to 0.11nm and 0.44nm, respectively, in terms of the wave length. In our numerical simulation, instead of the discontinuous frequencies, we get the proper frequency of the stuck muon for each event. We perform the simulation of stripping with above external force.

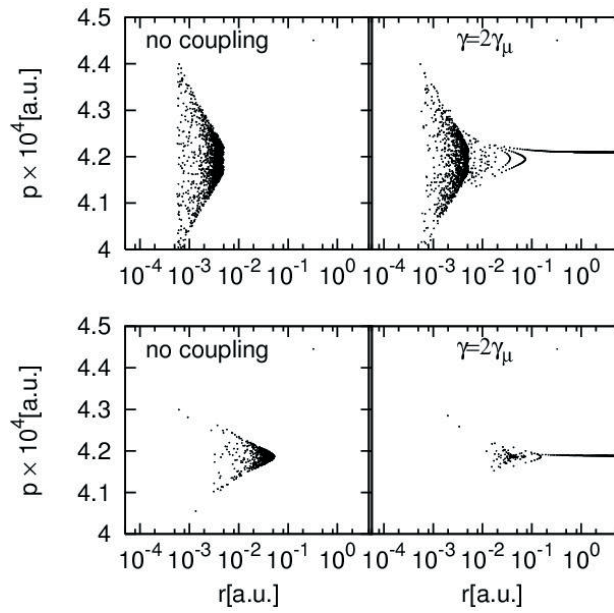


FIG. 4: Time T map of a stuck muon on the r - p plane (left panels). One with the external oscillating force (right panels) with frequency $2\gamma_\mu$, both in the atomic unit.

In Fig. 4 we show the time T map of the oscillational motion of the muon on the r - p plane, where r is relative distance between the muon and the alpha and p is its conjugate momentum. We follow 1000 cycles of the driven oscillation in our simulation. We choose two sticking event which are shown in the bottom panel in the figure 3 and the one has a smaller amplitude, a tightly bound state (top panels), and the other has a larger amplitude, a loosely bound state (bottom panels). The left panels show the map of the stuck muon without external force, with peak amplitude $F = 0$ of the applied field. The map remains in a limited manifold around $r = 0$. The right panels show the case with an external force with driven frequency $2\gamma_\mu$, where γ_μ is the angular frequency of the muon in the muonic helium ion. In the case of the tightly bound muon, the muonic atom is excited in a loosely bound state and then ionized, while the tightly bound muon is ionized in one step. The muonic atom in the external oscillating field is captured into the resonance and ionized due to its stochastic instability. One can see clearly that the muon is expelled from the Helium with the external oscillational force with the corresponding frequency of the unperturbed system. We point out that the muonic molecule is not destroyed by the external force with same frequency which we used in the above discussion.

6. CONCLUSIONS

We discussed the alpha-muon sticking coefficient in muon-catalyzed d-t fusion. We performed numerical

simulation by the Constrained Molecular Dynamics model. Especially the influence of muonic chaotic dynamics on the sticking coefficient is brought into focus. The chaotic motion of the muon affects not only the fusion cross section but also the sticking coefficient. The irregular (chaotic) dynamics of the bound muon lead to larger enhancements with respect to regular systems because of the reduction of the tunneling region. Moreover they give smaller sticking probabilities than those of regular events. We proposed a method to strip the stuck muon from the alpha particle by exposing the system in the X-ray radiation field. Its numerical experiment has been performed under an oscillating external force with the driving frequency twice as high as the angular frequency of the stuck muon and the muon has been released successfully with the selected frequency. By utilizing the chaotic dynamics one can prevent the muon from losing in the μ CF cycle by the sticking.

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BOUND ELECTRON SCREENING CORRECTIONS TO REACTIONS IN HYDROGEN BURNING PROCESSES

Sachie Kimura^{a,*}, Aldo Bonasera^{a,b}

a) INFN Laboratori Nazionali del Sud, Catania, Italy

b) Libera Università Kore, Enna, Italy

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

Abstract

We estimate the bare astrophysical S-factor($S_b(E)$) of reactions in PP-chains, through a polynomial expression with the adiabatic enhancement factor due to the electron screening. The obtained $S_b(E)$ is significantly different from the simple extrapolation from high energy data, however $S_b(E)$ at zero incident energy is in agreement with the results of a recent R-matrix analysis.

1 INTRODUCTION

The series of reactions which convert hydrogen into helium on stellar site is known as the proton-proton chains. It is a key to understand the evolution of the stars. These reactions are measured at laboratory energies and are then extrapolated to thermal energies [1], because of their small cross sections at such low energies. This extrapolation is done by introducing the astrophysical S-factor. Since one has factored out the strong energy dependence of the cross section due to the barrier penetrability, the S-factor could be approximated by a polynomial expression in the absence of low-energy resonance. In laboratory experiments, the targets are usually in gas or solid state. There, in the low energy region, the S-factors obtained from experiments show large enhancement to the extrapolation from high energy data for various reactions [2]. This enhancement is, usually, attributed to the screening by the bound electrons around the target. In contrast, in the stellar nucleosynthesis, nuclei are almost fully ionized and are surrounded by the plasma electrons. The nuclear reactions in such a circumstance are affected by a different mechanism of the plasma electron screening. Hence the screening effect of the bound electrons should be removed from the S-factor data, in order to assess the reaction rate in the stellar site correctly.

The enhancement by the bound electrons is discussed in terms of a constant potential shift (screening potential U_e). However, a puzzle had been that the experimentally observed enhancements are systematically and significantly larger than the adiabatic limit.

On this issue, the dynamical effect to this problem has been studied by Caltech group [3]. They followed the time evolution of the atomic wave function in the classical allowed region by solving the time dependent Hartree-Fock equation and evaluated the screening potential. Their results suggest that the screening potential approaches the adiabatic limit as the incident energy becomes lower. The influence of the tunneling

phenomenon to this problem has been studied as well [4]. And, there, the screening potential could go over the *conventional* adiabatic limit, only in the case there is an excited state component at the classical turning point. The modification to the adiabatic limit is, nevertheless, too small to explain the large discrepancies of all the reactions.

We have examined the problem using molecular dynamics approach with constraints [5, 6], to see the effect of the fluctuations in our previous studies [7, 8]. The obtained average enhancement factors, again, do not exceed the adiabatic limit, there are events which give larger enhancement factors than that in the adiabatic limit. There are other attempts [2, 9, 10] to explain the mechanism to get such a large enhancement, over the adiabatic limit, however none of them is affirmative to the screening potential which goes over the adiabatic limit.

In this connection, we mention that the difficulty lies in the determination of the bare S-factor. Recall that the bare S-factor is usually determined by extrapolations from high energy data and then the screening potential is determined by taking the ratio of the data and extrapolated S-factor. Instead, Barker [11] performed the fit including the whole data using either a polynomial (quadratic or cubic) or R-matrix determining the parameters simultaneously and he obtained more consistent values of screening potentials to the adiabatic limit for some reactions. Experimentally, a group at this laboratory has tried to extract the bare cross section using the Trojan Horse method (THM) [12, 13, 14].

In this paper, we determine the bare S-factors ($S_b(E)$) of the reactions, especially in hydrogen burning process, through the polynomial expression with the screening enhancement in the adiabatic limit. The results are compared with the extrapolated $S_b(E)$ by polynomial expressions from high energy data. The obtained bare S-factors at the zero incident energy are compared with the results of the R-matrix analyses [15].

This paper is organized as follows, In Sec. 2 we describe the enhancement factor by the bound electrons within the adiabatic limit briefly. We list up the reactions in PP-chains in Sec. 3 and explain how we incorporate the adiabatic limit into the fitting procedure. Sec. 4 is devoted to the analyses of some reactions. We summarize the paper in Sec. 5.

2 ENHANCEMENT FACTOR IN THE ADIABATIC LIMIT

In order to discuss the enhancement quantitatively, we determine the enhancement factor as a ratio of the real cross section to the bare cross section. If one assumes that the effect of the electron screening can be represented by the constant shift U_e (screening potential) of the potential barrier, the enhancement factor is approximated by,

$$U_e = \frac{E}{\pi\eta(E)} \log f_e \quad (1)$$

The screening potential can be estimated easily in two limiting cases. One is the case where the inter-nuclear velocity is much higher than that of electrons velocity, i.e. at the sudden limit. Within this limit the electron wave function is frozen during the reaction. In the opposite case where the inter-nuclear motion is much slower than electrons motion, the bound electrons follow the motion of the nuclei adiabatically. Within this adiabatic limit the screening potential is expressed by the difference of the binding energies between the initial target atom and the united atom which is formed during the reaction. The screening potential within this limit gives the upper limit.

3 BARE S-FACTORS OF PP-CHAIN REACTIONS

Table 1 Reactions in PP-chains, their minimum incident energy in the center-of-mass system measured so far and the enhancement factor within the adiabatic limit at the minimum energy.

Reactions	$E_{\min}$ [keV]	$f_e^{(AD)}(E_{\min})$
$D(p, \gamma) {}^3\text{He}$	2.52	1.07
${}^3\text{He}({}^3\text{He}, 2p) {}^4\text{He}$	20.76	1.22
${}^3\text{He}(\alpha, \gamma) {}^7\text{Be}$	107.2, 127.	1.02
${}^7\text{Li}(p, \alpha) {}^4\text{He}$	12.7, 10.	1.18
${}^7\text{Be}(p, \gamma) {}^8\text{B}$	115.6	1.01

A list of charge induced reactions in PP-chains is shown in Table 1. We, therefore, concentrate on the other 5 reactions. In the table the minimum incident energies, measured so far, for each reaction are also shown. For three reactions $D(p, \gamma) {}^3\text{He}$, ${}^3\text{He}({}^3\text{He}, 2p) {}^4\text{He}$ and ${}^7\text{Li}(p, \alpha) {}^4\text{He}$ cross sections have been measured already including the low energy region. The other two reactions are radiative capture reactions which have even smaller cross sections. The S-factor of the reaction ${}^3\text{He}(\alpha, \gamma) {}^7\text{Be}$ has been re-determined with high precision recently by detecting gamma-ray from ${}^7\text{Be}$ [17]. Its S-factor in the low energy region is extrapolated from high energy data by R-matrix fitting. The reaction ${}^7\text{Be}(p, \gamma) {}^8\text{B}$ involves unstable nuclei. The S-factor of

this reaction has been determined by means of the direct capture reaction [16, 17] and the Coulomb dissociation method [18] and it is one of questions under discussion that there is a discrepancy between the results by two methods [17, 19].

The previous studies of the electron screening effect suggest that the enhancement factor cannot be over the adiabatic limit. We, therefore, adopt the enhancement factor within the adiabatic limit:

$$f_e^{(AD)} = e^{\pi\eta(E) \frac{U_e^{(AD)}}{E}}, \quad (2)$$

and determine the bare S-factor by fitting the experimental data of the reactions. The fit of the experimental data is performed by assuming a polynomial expression for bare S-factor:

$$S(E) = S_b(E) \cdot f_e^{(AD)}; \\ S_b(E) = S_b(0) + S_1 E + S_2 E^2 + S_3 E^3, \quad (3)$$

using an implementation of the nonlinear least-squares Marquardt-Levenberg algorithm.

4. PARTICULAR REACTIONS

In this paper, we present the fitting results on the reaction ${}^7\text{Li}(p, \alpha) {}^4\text{He}$ only. The other reactions are discussed in [20].

4.1 ${}^7\text{Li}(p, \alpha) {}^4\text{He}$

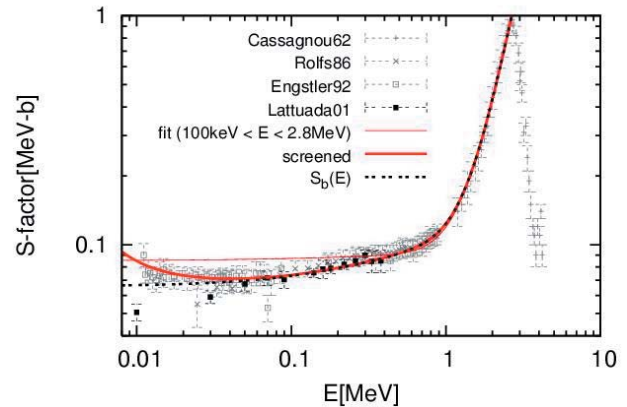


Figure 1 S-factor for the reaction ${}^7\text{Li}(p, \alpha) {}^4\text{He}$ as a function of the incident center-of-mass energy. The experimental points are from [21](Cassagnou62), from [22](Rolfs86), from [23, 24](Engstler92) and from [13](Lattuada01).

In Fig. 1 the S-factor of the reaction ${}^7\text{Li}(p, \alpha) {}^4\text{He}$ from several direct measurements are shown with error bars. Extracted S-factor data by THM are especially shown with the closed squares [13]. We performed fitting of the data by direct measurements in the incident energy region higher than 100keV using a cubic polynomial. In this energy region the screening enhancement is estimated to be 1% at utmost. The corresponding S-factor is shown with the thin solid curve in the figure 1. The curve

supposed to give an extrapolation of low energy data, however it strays away from the trend of experimental data in the lower energy region. Instead of fitting higher-energy data, if we fit the whole data by the direct measurements in the form of Eq.(3) and $U_e^{(AD)} = 175\text{eV}$ [8], we obtain the fitting parameters in the second row of the table 2. The corresponding S-factor is shown with thick dashed curve in Fig. 1. Note that there is a big difference between these two curves. The extrapolation of the S-factor to the lower energy region should be done, therefore, with caution.

In Ref. [15] R-matrix fitting for higher energy region ($E > 40\text{keV}$) has been used to determine the S-factor. They obtained the zero-energy S-factor $0.06 \pm 0.004[\text{MeVb}]$ and the screening potential $U_e = 100 \pm 25\text{eV}$, which is less than that within the adiabatic limit. The S-factor at zero-energy from our result $S_b(0) = 0.066 \pm 0.002[\text{MeVb}]$ is in agreement with this result from R-matrix fitting but higher than $S_b(0) = 0.055 \pm 0.003[\text{MeVb}]$ by THM [13].

5. CONCLUSIONS

We discussed the bound electron screening corrections to the S-factors of the reactions in PP-chains. We have assumed the screening enhancement within the adiabatic limit and have determined the bare S-factors for the reactions through the polynomial fitting of the experimental data. The obtained bare S-factors are significantly different from the simple extrapolation from high energy region, but the bare S-factor at the zero incident energy is in agreement with the results from R-matrix fitting in Ref. [15].

We conclude that the polynomial expression of the bare S-factor for reactions without resonant component in the low energy region is valid, only if the experimental S-factor data in this region are available and one considers the screening effect properly.

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STRUCTURE OF HYBRID STARS AND SUPERFLUIDITY

U. Lombardo^a

a) INFN Laboratori Nazionali del Sud, Catania, Italy

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

Abstract

The problem of structure of neutron stars and the possible onset of superfluid states is studied within the microscopic theory of nuclear matter.

1 STRUCTURE OF HYBRID STARS

The models of the neutron stars are reviewed on the basis of the present microscopic theories of nuclear matter and quark matter.

In the hadron sector the EoS of nuclear matter is derived from realistic two body force (2BF) and three body force (3BF) based on meson-exchange models (Nijmegen potential).

The 3BF, which includes virtual processes such as NN, $\Delta(1232)$, $N^*(1440)$, provides a satisfactory description of dense matter, while keeping nice agreement with the empirical properties of nuclear matter. In the quark sector the quark matter EoS is derived from the DDM phenomenological model, where the confinement is achieved by means of a density dependence of the quark mass.

The possible transition from hadron matter to quark matter through a mixed phase is studied combining the two equations of state (see fig. 1).

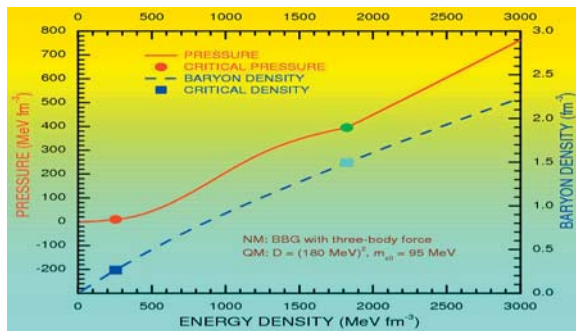


fig. 1

In order to understand the role the confinement mechanism a comparison is made with MIT bag model and Nambu-Jona Lasinio model.

Finally the Tolman-Oppenheimer-Volkov is solved with the resulting EoS for such a hybrid matter to study the structure of neutron stars. The effects of the possible onset of kaon condensation are also investigated.

2 PAIRING IN NUCLEAR MATTER

The screening of pairing in homogeneous nuclear matter leads to the remarkable result that the surrounding

medium favours the pairing formation if it is made of nuclear matter, i.e. neutron and proton mixture (see fig. 2 and 3)

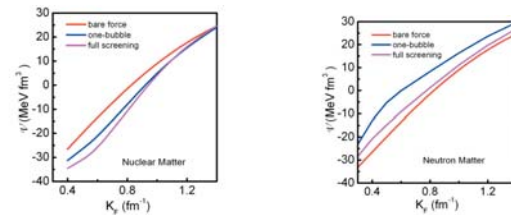


fig. 2 -3

This property give a chance to two-nucleon configurations, for which the nuclear interaction is repulsive, to form Cooper pairs.

Therefore new pairing states are expected to occur in the neutron stars, that have not been predicted earlier.

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Heavy Ion Collisions at Relativistic Energies: Probing a Nuclear Matter at High Baryon and Isospin Densities

M.Colonna¹, V.Baran^{1,2}, M.Di Toro¹, G.Ferini¹, T.Gaitanos³,
V.Greco¹, Liu Bo⁴, F.Matera⁵, V.Prassa⁶, J.Rizzo¹ and H.H.Wolter⁷

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 *Institut für Theoretische Physik, Universität Giessen, D-35392 Giessen, Germany*

⁴ *IHEP, Beijing, China*

⁵ *Istituto Nazionale di Fisica Nucleare, Sezione di Firenze,
Via G. Sansone 1, I-50019, Sesto F.no (Firenze), Italy*

⁶ *Dept. of Theoretical Physics, Aristotle University, Thessaloniki Gr-54124, Greece and*

⁷ *Dept. für Physik, Universität München, D-85748 Garching, Germany*

We show that the phenomenology of isospin effects on heavy ion reactions at intermediate energies (few AGeV range) is extremely rich and can allow a “direct” study of the covariant structure of the isovector interaction in a high density hadron medium. We work within a relativistic transport frame, beyond a cascade picture, consistently derived from effective Lagrangians, where isospin effects are accounted for in the mean field and collision terms. Rather sensitive observables are proposed from collective flows (“differential” flows) and from pion/kaon production (π^-/π^+ , K^0/K^+ yields). For the latter point relevant non-equilibrium effects are stressed. The possibility of the transition to a mixed hadron-quark phase, at high baryon and isospin density, is finally suggested. Some signatures could come from an expected “neutron trapping” effect.

I. INTRODUCTION

Recently the development of new heavy ion facilities (radioactive beams) has driven the interest on the dynamical behaviour of asymmetric matter, see the recent reviews [1, 2]. Here we focus our attention on relativistic heavy ion collisions, that provide a unique terrestrial opportunity to probe the in-medium nuclear interaction in high density and high momentum regions. An effective Lagrangian approach to the hadron interacting system is extended to the isospin degree of freedom: within the same frame equilibrium properties (*EoS*, [3]) and transport dynamics can be consistently derived.

Within a covariant picture of the nuclear mean field, for the description of the symmetry energy at saturation (a_4 parameter of the Weizsäcker mass formula) (a) only the Lorentz vector ρ mesonic field, and (b) both, the vector ρ (repulsive) and scalar δ (attractive) effective fields [4, 5] can be included. In the latter case the competition between scalar and vector fields leads to a stiffer symmetry term at high density [2, 4]. We present here observable effects in the dynamics of heavy ion collisions. We focus our attention on collective isospin flows, in particular the elliptic ones, and on the isospin content of particle production, in particular kaons. We finally show that in the compression stage of isospin asymmetric collisions we can enter a mixed deconfined phase, if the *EoS* conditions for the existence of quark stars are met.

II. RELATIVISTIC TRANSPORT

The starting point is a simple phenomenological version of the Non-Linear (with respect to the iso-scalar, Lorentz scalar σ field) effective nucleon-boson field theory, the Quantum-Hydro-Dynamics [3]. According to this picture the presence of the hadronic medium leads to effective masses and momenta $M^* = M + \Sigma_s$, $k^{*\mu} = k^\mu - \Sigma^\mu$, with Σ_s , Σ^μ scalar and vector self-energies. For asymmetric matter the self-energies are different for protons and neutrons, depending on the isovector meson contributions. We will call the corresponding models as *NLρ* and *NLρδ*, respectively, and just *NL* the case without isovector interactions. For the more general *NLρδ* case the self-energies of protons and neutrons read:

$$\begin{aligned}\Sigma_s(p, n) &= -f_\sigma \sigma(\rho_s) \pm f_\delta \rho_{s3}, \\ \Sigma^\mu(p, n) &= f_\omega j^\mu \mp f_\rho j_3^\mu,\end{aligned}\quad (1)$$

(upper signs for neutrons), where $\rho_s = \rho_{sp} + \rho_{sn}$, $j^\alpha = j_p^\alpha + j_n^\alpha$, $\rho_{s3} = \rho_{sp} - \rho_{sn}$, $j_3^\alpha = j_p^\alpha - j_n^\alpha$ are the total and isospin scalar densities and currents and $f_{\sigma, \omega, \rho, \delta}$ are the coupling constants of the various mesonic fields. $\sigma(\rho_s)$ is the solution of the non linear equation for the σ field [2, 4].

For the description of heavy ion collisions we solve the covariant transport equation of the Boltzmann type within the Relativistic Landau Vlasov (*RLV*) method, using phase-space Gaussian test particles [6], and applying a Monte-Carlo procedure for the hard hadron collisions. The collision term includes elastic and inelastic processes involving the production/absorption of the

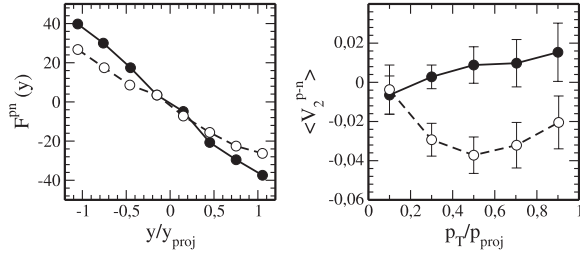


FIG. 1: Differential neutron-proton flows for the $^{132}\text{Sn} + ^{124}\text{Sn}$ reaction at 1.5 AGeV ($b = 6\text{fm}$) from the two different models for the isovector mean fields. Left: Transverse Flows. Right: Elliptic Flows. Full circles and solid line: $NL\rho\delta$. Open circles and dashed line: $NL\rho$.

$\Delta(1232\text{MeV})$ and $N^*(1440\text{MeV})$ resonances as well as their decays into pion channels, [7].

III. COLLECTIVE FLOWS

The flow observables can be seen respectively as the first and second coefficients of a Fourier expansion of the azimuthal distribution: $\frac{dN}{d\phi}(y, p_t) \approx 1 + 2V_1\cos(\phi) + 2V_2\cos(2\phi)$ where $p_t = \sqrt{p_x^2 + p_y^2}$ is the transverse momentum and y the rapidity along beam direction. The transverse flow can be expressed as: $V_1(y, p_t) = \langle \frac{p_x}{p_t} \rangle$. The sideward (transverse) flow is a deflection of forwards and backwards moving particles, within the reaction plane. The second coefficient of the expansion defines the elliptic flow given by $V_2(y, p_t) = \langle \frac{p_x^2 - p_y^2}{p_t^2} \rangle$. It measures the competition between in-plane and out-of-plane emissions. The sign of V_2 indicates the azimuthal anisotropy of emission: particles can be preferentially emitted either in the reaction plane ($V_2 > 0$) or out-of-plane (*squeeze-out*, $V_2 < 0$) [8]. For the isospin effects the neutron-proton flow differences $V_{1,2}^{(n-p)}(y, p_t) \equiv V_{1,2}^n(y, p_t) - V_{1,2}^p(y, p_t)$ have been suggested as very useful probes of the isovector part of the EoS since they appear rather insensitive to the isoscalar potential and to the in medium nuclear cross sections, [9]. In heavy-ion collisions around 1 AGeV with radioactive beams, differential flows will directly exploit the Lorentz nature of a scalar and a vector field. In Fig.1 transverse and elliptic differential flows are shown for the $^{132}\text{Sn} + ^{124}\text{Sn}$ reaction at 1.5 AGeV ($b = 6\text{fm}$), [9]. The effect of the different structure of the isovector channel is clear. Particularly evident is the splitting in the high p_t region of the elliptic flow. 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

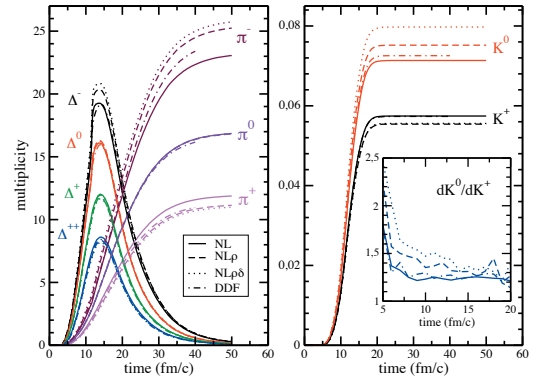


FIG. 2: Time evolution of the $\Delta^{\pm,0,++}$ resonances and pions $\pi^{\pm,0}$ (left), and kaons ($K^{+,0}$) (right) for a central ($b = 0$ fm impact parameter) Au+Au collision at 1 AGeV incident energy. Transport calculation using the NL , $NL\rho$, $NL\rho\delta$ and DDF models for the iso-vector part of the nuclear EoS are shown. The inset contains the differential K^0/K^+ ratio as a function of the kaon emission time.

to the larger ρ -field in the compression stage. We expect similar effects, even enhanced, from the measurements of differential flows for light isobars, like ^3H vs. ^3He .

IV. ISOSPIN EFFECTS ON SUB-THRESHOLD KAON PRODUCTION AT INTERMEDIATE ENERGIES

Kaon production has been proven to be a reliable observable for the high density EoS in the isoscalar sector [10, 11]. Here we show that the $K^{0,+}$ production (in particular the K^0/K^+ yield ratio) can be also used to probe the isovector part of the EoS , [12, 13].

Using our RMF transport approach we analyze pion and kaon production in central $^{197}\text{Au} + ^{197}\text{Au}$ collisions in the 0.8 – 1.8 AGeV beam energy range, comparing models giving the same “soft” EoS for symmetric matter and with different effective field choices for E_{sym} . We will use three Lagrangians with constant nucleon-meson couplings ($NL...$ type, see before) and one with density dependent couplings (DDF , see [5]), recently suggested for better nucleonic properties of neutron stars [14, 15].

Fig. 2 reports the temporal evolution of $\Delta^{\pm,0,++}$ resonances, pions ($\pi^{\pm,0}$) and kaons ($K^{+,0}$) for central Au+Au collisions at 1 AGeV. It is clear that, while the pion yield freezes out at times of the order of 50 fm/c, i.e. at the final stage of the reaction (and at low densities), kaon production occur within the very early (compression) stage, and the yield saturates at around 20 fm/c. From Fig. 2 we see that the pion results are weakly dependent on the isospin part of the nuclear mean field. However, a slight increase (decrease) in the π^- (π^+) multiplicity is observed when going from the NL (or DDF) to the $NL\rho$ and then to the $NL\rho\delta$ model, i.e. increasing the vector contribution f_ρ in the isovector channel. This trend is more pronounced for kaons, see the right panel, due to

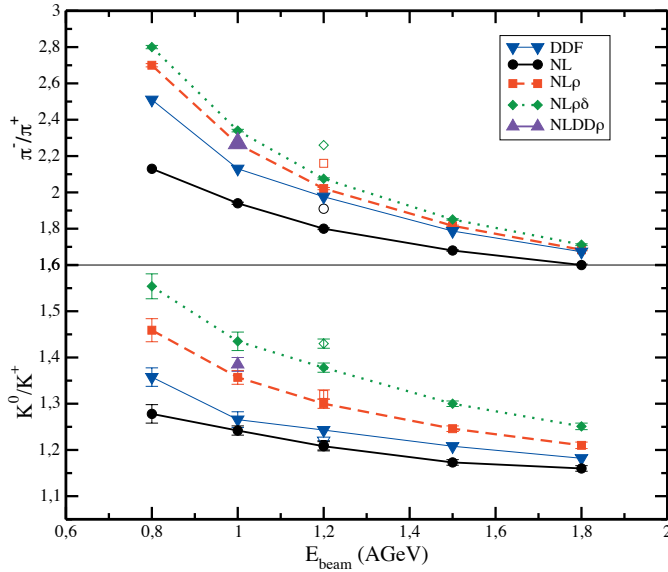


FIG. 3: π^-/π^+ (upper) and K^0/K^+ (lower) ratios as a function of the incident energy for the same reaction and models as in Fig. 2. In addition we present, for $E_{beam} = 1$ AGeV, $NL\rho$ results with a density dependent ρ -coupling (triangles). The open symbols at 1.2 AGeV show the corresponding results for a $^{132}\text{Sn} + ^{124}\text{Sn}$ collision, more neutron rich. Note the different scale for the π^-/π^+ ratios.

the high density selection of the source and the proximity to the production threshold. Consistently, as shown in the insert, larger effects are expected for early emitted kaons, reflecting the early N/Z of the system.

When isovector fields are included the symmetry potential energy in neutron-rich matter is repulsive for neutrons and attractive for protons. In a *HIC* this leads to a fast, pre-equilibrium, emission of neutrons. Such a *mean field* mechanism, often referred to as isospin fractionation [1, 2], is responsible for a reduction of the neutron to proton ratio during the high density phase, with direct consequences on particle production in inelastic NN collisions.

Threshold effects represent a more subtle point. The energy conservation in a hadron collision in general has to be formulated in terms of the canonical momenta, i.e. for a reaction $1 + 2 \rightarrow 3 + 4$ as $s_{in} = (k_1^\mu + k_2^\mu)^2 = (k_3^\mu + k_4^\mu)^2 = s_{out}$. Since hadrons are propagating with effective (kinetic) momenta and masses, an equivalent relation should be formulated starting from the effective in-medium quantities $k^{*\mu} = k^\mu - \Sigma^\mu$ and $m^* = m + \Sigma_s$, where Σ_s and Σ^μ are the scalar and vector self-energies, Eqs.(1). The self-energy contributions will influence the particle production at the level of thresholds as well as of the phase space available in the final channel. Finally the beam energy dependence of the π^-/π^+ (left) and K^0/K^+ (right) ratios is shown in Fig. 3. At each energy we see an increase of the yield ratios with the models $NL \rightarrow DDF \rightarrow NL\rho \rightarrow NL\rho\delta$. The effect is larger for the K^0/K^+ compared to the π^-/π^+ ratio. This is

due to the subthreshold production and to the fact that the isospin effect enters twice in the two-step production of kaons, see [12]. Between the two extreme DDF and $NL\rho\delta$ isovector interaction models, the variations in the ratios are of the order of 14 – 16% for kaons, while they reduce to about 8 – 10% for pions. Interestingly the *Iso- EoS* effect for pions is increasing at lower energies, when approaching the production threshold.

We have to note that in a previous study of kaon production in excited nuclear matter the dependence of the K^0/K^+ yield ratio on the effective isovector interaction appears much larger (see Fig.8 of ref.[7]). The point is that in the non-equilibrium case of a heavy ion collision the asymmetry of the source where kaons are produced is in fact reduced by the $n \rightarrow p$ “transformation”, due to the favored $nn \rightarrow p\Delta^-$ processes. This effect is almost absent at equilibrium due to the inverse transitions, see Fig.3 of ref.[7]. Moreover in infinite nuclear matter even the fast neutron emission is not present. This result clearly shows that chemical equilibrium models can lead to uncorrect results when used for transient states of an *open* system.

V. TESTING DECONFINEMENT AT HIGH ISOSPIN DENSITY

The hadronic matter is expected to undergo a phase transition into a deconfined phase of quarks and gluons at large densities and/or high temperatures. On very general grounds, the transition’s critical densities are expected to depend on the isospin of the system, but no experimental tests of this dependence have been performed so far. Moreover, up to now, data on the phase transition have been extracted from ultrarelativistic collisions, when large temperatures but low baryon densities are reached.

Here we study the isospin dependence of the transition densities. Concerning the hadronic phase, we use the relativistic non-linear model of Glendenning-Moszkowski (in particular the “soft” *GM3* choice) [16], where the isovector part is treated just with ρ meson coupling, and the iso-stiffer $NL\rho\delta$ interaction [17]. For the quark phase we consider the *MIT* bag model with various bag pressure constants. In particular we are interested in those parameter sets which would allow the existence of quark stars [18], i.e. parameters sets for which the so-called Witten-Bodmer hypothesis is satisfied [19, 20]. One of the aim of our work it to show that if quark stars are indeed possible, it is then very likely to find signals of the formation of a mixed quark-hadron phase in intermediate-energy heavy-ion experiments [17].

The structure of the mixed phase is obtained by imposing the Gibbs conditions [21, 22] for chemical potentials and pressure and by requiring the conservation of the total baryon and isospin densities

$$\mu_B^{(H)} = \mu_B^{(Q)}, \quad \mu_3^{(H)} = \mu_3^{(Q)},$$

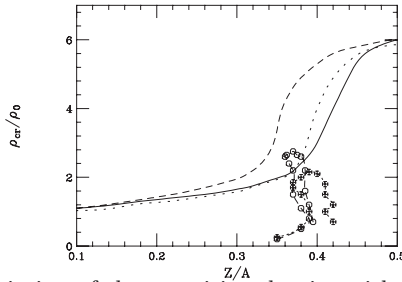


FIG. 4: Variation of the transition density with proton fraction for various hadronic *EoS* parameterizations. Dotted line: *GM3* parametrization; dashed line: *NLρ* parametrization; solid line: *NLρδ* parametrization. For the quark *EoS*, the *MIT* bag model with $B^{1/4}=150$ MeV. The points represent the path followed in the interaction zone during a semi-central $^{132}\text{Sn}+^{132}\text{Sn}$ collision at 1 AGeV (circles) and at 300 AGeV (crosses).

$$\begin{aligned}
 P^{(H)}(T, \mu_{B,3}^{(H)}) &= P^{(Q)}(T, \mu_{B,3}^{(Q)}), \\
 \rho_B &= (1 - \chi)\rho_B^H + \chi\rho_B^Q, \\
 \rho_3 &= (1 - \chi)\rho_3^H + \chi\rho_3^Q,
 \end{aligned} \quad (2)$$

where χ is the fraction of quark matter in the mixed phase. In this way we get the *binodal* surface which gives the phase coexistence region in the (T, ρ_B, ρ_3) space. For a fixed value of the conserved charge ρ_3 we will study the boundaries of the mixed phase region in the (T, ρ_B) plane. In the hadronic phase the charge chemical potential is given by $\mu_3 = 2E_{sym}(\rho_B) \frac{\rho_3}{\rho_B}$. Thus, we expect critical densities rather sensitive to the isovector channel in the hadronic *EoS*.

In Fig. 4 we show the crossing density ρ_{cr} separating nuclear matter from the quark-nucleon mixed phase, as a function of the proton fraction Z/A . We can see the effect of the δ -coupling towards an *earlier* crossing due to the larger symmetry repulsion at high baryon densities. In the same figure we report the paths in the $(\rho, Z/A)$

plane followed in the c.m. region during the collision of the n-rich $^{132}\text{Sn}+^{132}\text{Sn}$ system, at different energies. At 300 AGeV we are just reaching the border of the mixed phase, and we are well inside it at 1 AGeV. Statistical We expect a *neutron trapping* effect, supported by statistical fluctuations as well as by a symmetry energy difference in the two phases. In fact while in the hadron phase we have a large neutron potential repulsion (in particular in the *NLρδ* case), in the quark phase we only have the much smaller kinetic contribution. Observables related to such neutron “trapping” could be an inversion in the trend of the formation of neutron rich fragments and/or of the π^-/π^+ , K^0/K^+ yield ratios for reaction products coming from high density regions, i.e. with large transverse momenta. In general we would expect a modification of the rapidity distribution of the emitted “isospin”, with an enhancement at mid-rapidity joint to large event by event fluctuations..

VI. PERSPECTIVES

We have shown that collisions of n-rich heavy ions at intermediate energies can bring new information on the isovector part of the in-medium interaction at high baryon densities, qualitatively different from equilibrium *EoS* properties. We have presented quantitative results for differential collective flows and yields of charged pion and kaon ratios. Important non-equilibrium effects for particle production are stressed. Finally our study supports the possibility of observing precursor signals of the phase transition to a mixed hadron-quark matter at high baryon density in the collision, central or semi-central, of neutron-rich heavy ions in the energy range of a few GeV per nucleon.

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Instrumentation and related techniques



THE POSITION START DETECTOR FOR THE MAGNEX SPECTROMETER

S.E.A.Orrigo^{a,*}, F.Cappuzzello^{a,b}, A.Cunsolo^{a,b}, M.Cavallaro^{a,b}, A.Foti^{b,c}, M.R.D.Rodrigues^a, C.Cali^a, P.Litrico^a, S.Marino^a, G.Passaro^a, E.Costa^a, C.Marchetta^a, B.Trovato^a, H.Petrascu^d

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: orrigo@lns.infn.it

Abstract

A new Position Start Detector (PSD) for the MAGNEX spectrometer was designed and constructed, on the basis of the results and conclusions following the “ β -version” of the PSD, which was developed and tested under several aspects. In the new PSD both the magnetic and electric field homogeneities were improved. The size of the detector was reduced, making it more compact.

A big effort was devoted to the development of the PSD anode, in which the read-out of the position signals from the 192 pads makes use of the Gassiplex technology.

Various windows were tested in order to study the electron back emission and to choose the most suitable to the working conditions of both the Gassiplex chips and microchannels for the timing signal.

1 INTRODUCTION

The PSD β -version [1] of the MAGNEX spectrometer [2-5] has the shape of a parallelepiped having a total volume of $24.6 \times 12.8 \times 8.7 \text{ cm}^3$ and it is based on the electron detection. A scheme that shows the concept of a such detector is represented in fig. 1.

The heavy ions 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. These electrons are accelerated by the applied electric field and their trajectories are bend, out of the main beam, by a magnetic field perpendicular to the electric one. The electric field E has a value of 1560 V/cm and the magnetic field B is $\sim 85 \text{ Gauss}$ in the center of the detector. The maximum height of the electron's path, from simulations using the 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 fall on two microchannel plates in chevron configuration, arriving at the first microchannel surface with a residual energy $\sim 620 \text{ eV}$, enough to excite the chevron. This value depends directly on the level difference between the chevron and the aluminized mylar window, which is 4 mm . The timing signal is extracted directly from the lower surface of the chevron using a special fast transimpedance preamplifier [6]. The electron bursts emerging from chevron are

accelerated by a 70 V electric field to the XY matrix. The electric charge released here by the electrons is transferred by capacitive effect to the Gassiplex preamplifiers [7] and, after coding, further to the data acquisition system.

In fig. 2 one can see an image of the PSD β -version. The detector view is from emerging beam side. Below the connector support there is the position sensitive anode, mounted behind the chevron. It has two main parts: the XY matrix, composed by 192 rectangles (pads), and the Gassiplex motherboard, containing three boards, each one with four Gassiplex chips. Each chip is composed of 16 analogue multiplexed channels, allowing the independent read-out of all the 192 channels.

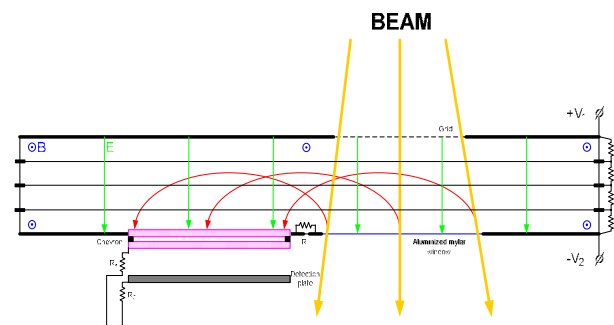


Fig. 1: Scheme of the PSD of the MAGNEX spectrometer.

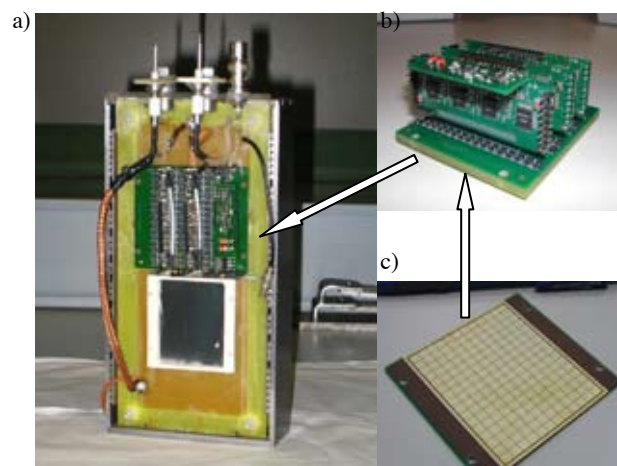


Fig. 2: a) The PSD β -version. b) The anode with the Gassiplex motherboard (192 channels). c) The XY matrix with 192 pads.

2 RESULTS FROM THE PSD β -VERSION

The PSD β -version was tested mainly using one α source and a Si detector for measurements in coincidence. During the MAGNEX initial commissioning the timing signal was observed under beam also [8], showing a rise time of ~ 2 ns and an efficiency $\sim 89\%$ with respect to the Silicon detectors of the spectrometers.

2.1 The anode

The first measurements were done by using a Cu plate [1] placed after the chevron and before the XY matrix to collect the electrons, which induced signals on the pads. Then we decided to remove the copper plate because it behaves like an absorber for such high-frequency signals, stopping them. Thus now the electrons arrive directly to the matrix of the pads. This created different problems, mainly due to the fact that the Gassiplex chips were optimized and used only with induced signals, and for the first time we had to use them with direct electrons signals.

This gave us the need to connect each pad to a common ground through an individual resistance, i.e., to mount 192 resistors on the matrix. In order to make sure that there is not cross-talk between the different pads, the signals of all the 192 pads were tested one by one with a fast pulser. The mapping of the Gassiplex channels, as they appear at the oscilloscope, on the XY matrix was a delicate procedure due to the special construction of the printed circuits inside the matrix, where the two central chips of each of the three boards have a channel inversion.

SMD resistors are used for the pad-ground connections. Four different values ($R = 1, 10, 100, 1000$ k Ω) were tested in the same time in order to look for the optimal working conditions. Two aspects have to be tacking into account concerning the Gassiplex pedestals [7]: the fluctuation around the mean value, always present since they are constantly in a live state, and the long term drift. By looking at the single-pad spectra we measured the fluctuation and drift of each pedestal during 5 days, starting from the turning on of the Gassiplex. The results are reported in table 1 for the different resistances, where the values in channel are the mean on the pads with same R .

Table 1: Pedestals fluctuation and drift for the different R .

$R[k\Omega]$	$\sigma_i[ch]$	$(\sigma_i - \sigma_f) [ch]$		$(p_i - p_f) [ch]$		
		1 st 24h	4days	1 st 24h	4days	1h
1	41.8	6.2	0.7	255.8	85.6	4.5
10	17.5	2.4	-0.1	270.2	98.4	2.7
100	6.1	0.4	-0.03	288.8	115.3	4.5
1000	3.9	1	0.03	238.0	86.2	2.8

The fluctuation, taken as the standard deviation σ_i around the mean value, decreases with increasing R , becoming quite small for $R = 1$ M Ω . The values of the fluctuation are stable, indeed their variation with the time ($\sigma_i - \sigma_f$), calculated for each pad and then mediated for

the same R pads, is only few channels. On the contrary, the drift is a much more relevant phenomenon, however it is stabilizing with time. The variation of the pedestal central values ($p_i - p_f$) is very strong in the first 24 hours from the turning on (~ 250 -300 channels), then it tends to stabilize: in the next 4 days the total variation is ~ 100 ch. only, after this it is few channels in 1 hour. It's clear from table 1 that the most stable pedestal condition with respect to both fluctuation and drift is achieved for $R = 1$ M Ω .

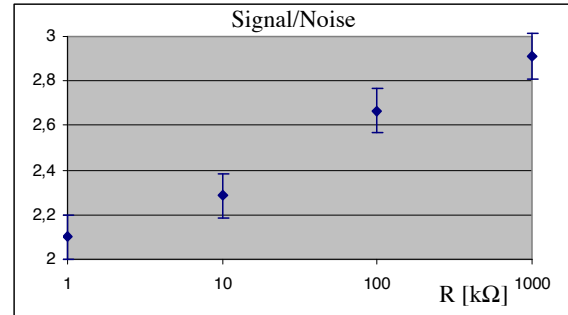


Fig. 3: Signal to noise ratio as a function of the R value.

After the stabilization, we measured the signal to noise ratio (noise is the fluctuation). As shown in fig. 3, such ratio is increasing with R , confirming the best case to be $R = 1$ M Ω . A few-channels pedestal drift in the opposite direction was also observed during a measurement run of 1 hour, like a “heating” of the Gassiplex, minimum for $R = 1$ M Ω . In conclusion we chose $R = 1$ M Ω as final value.

Then different voltages ($-6, -12, -24$ V) were applied to a group of pads of the matrix, in comparison with the no voltage case and in combination with the different R also. The signal is slightly enhanced with the voltage, but also the fluctuation increases, making the signal to noise ratio almost the same, not justifying the high mechanical effort to mount 192 voltage connections on the matrix.

The connection on a motherboard of N Gassiplex chips (“daisy chain”) allows the analogue multiplexed outputs of the $N \times 16$ channels (for PSD $N=12$) to be sent on a single line to a VME read-out module, such as C-RAMS, performing the digitization and zero suppression of that analogue signal sequence [7]. Another problem arising from the use of direct signals is that the sign of the signal is opposite with respect to the pedestal one, not allowing the pedestal subtraction and zero suppression directly at the C-RAMS level. Thus we implemented a procedure in the program to perform first the pedestal subtraction and then the zero suppression by accepting only the signals under the threshold, fixed as 3σ under the pedestal central value. A new method concerning the digital signal processing is under development [9].

A specific calibrator, shown in fig. 4, was constructed to calibrate the different sensitive to signals of the Gassiplex chips. In it a fast pulse can be sent independently to each channel through 192 springs. The anode was calibrated by using five pulses, obtained tuning the fast pulser by a potentiometer. The signals of four Gassiplex chips (i.e., one board) as response to the pulser, without and with calibration, are shown in fig. 5 (a) and (b), respectively.

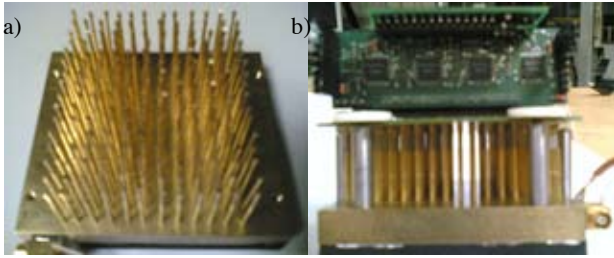


Fig. 4: a) The calibrator with 192 springs. b) The calibrator connected to the XY matrix and the Gassiplex.

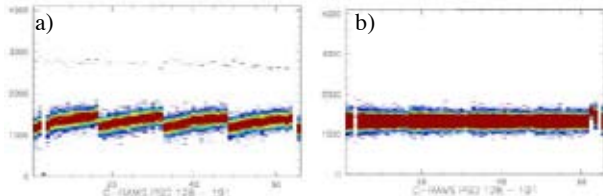


Fig. 5: Gassiplex signals from a fast pulser, without (a) and with (b) calibration.

An example of signals from one α source, measured by PSD in coincidence with a Si detector, is shown in fig. 6: in (a) and (b) the signals are shown long rows (Y) and columns (X), respectively, while in (e) the row-column matrix is shown. The spot of the α signal is compatible with the size of the diaphragm ($\phi = 12$ mm) at the PSD entrance. The expected correlation between the vertical position of the peak and the applied voltage was seen. Different algorithms for the centroid calculation are under study; in (c), (d), (f) there is an example of centroid calculation for Y, X and the centroid matrix, respectively. The not-perfectly circular shape of the α spot is an indication of some not-homogeneity in the detector optics.

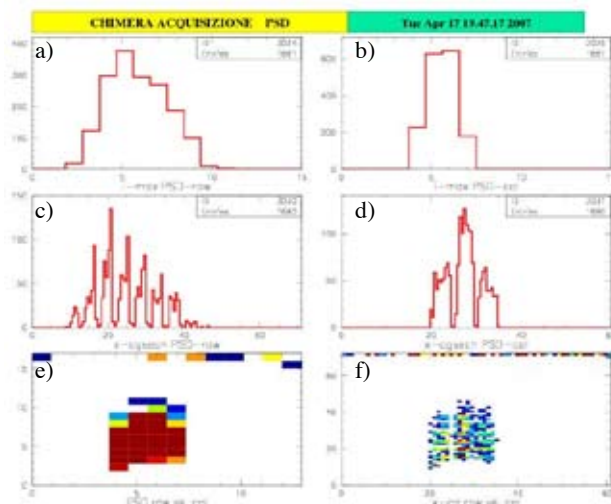


Fig. 6: Position signals from one α source.

2.2 The optics

In the PSD β -version we checked the device optics, i.e., the homogeneity of the electric and magnetic fields, in order to improve both these aspects in the new PSD.

The detector's electric cavity has 3 equipotential wires made by Cu-Be with $\phi = 100$ μm . The upper and lower electrodes are realized using 1.6 mm printed circuit foils. The Cu layer is covered by 0.2 μm of gold. The uniformity of the $\mathbf{E}$ field was increased by modifying mechanically the contact with the microchannel holder, as suggested by SuperFish Poisson simulations.

The magnetic circuit is realized using 320 small but powerful permanent magnets, each one $12 \times 4 \times 2$ mm³. In this way the magnetic field can be tuned very precisely to the requested value (85 Gauss). The $\mathbf{B}$ field was measured by an Hall probe inside the detector, finding differences between the border and central regions. SuperFish Poisson simulations show that improvements are obtained if the pole gap is reduced.

2.3 The window

The PSD detector is based on the phenomenon of the back emission of electrons due to the interaction of the heavy ions with a window. Thus, a particular care has to be taken in order to choose the window with better efficiency for the electron emission and, at the same time, well suitable to the working conditions of both Gassiplex chips and microchannels. Indeed, on one side to increase the voltage applied to the microchannels may enhance the efficiency, but on the other side, since the dynamic range accepted by the Gassiplex chips is limited, the too high signals will saturate the chips, being cut.

Thus various windows were tested with an α source, starting from the simple aluminized mylar window to other three windows, where different materials were evaporated on aluminized mylar (3.5 μm): C "nanotubes" (40 $\mu\text{g}/\text{cm}^2$), B₆La (200 $\text{\AA}$) and ⁷LiF (15 $\mu\text{g}/\text{cm}^2$). The tests were made with $V_2 = -3300$ V and $V_1 = +1100$ V (see fig. 1), values for which the α spot is centered on the XY matrix, as in fig. 6. In fig. 7 there is an example of the microchannel signal, in purple, corresponding to the ⁷LiF window. The microchannel signal appears in coincidence with the signal of the Silicon detector, in green, which is used as a trigger. The yellow histogram gives the distribution of the microchannel signals. The quantization in the number of the emitted electrons is visible.

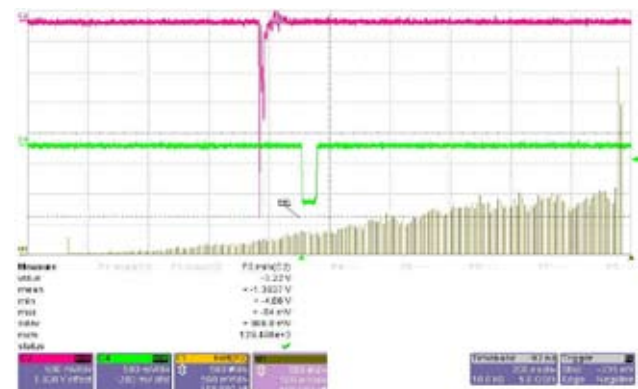


Fig. 7: Microchannel (purple) and Silicon (green) signals in coincidence during the test of the ⁷LiF window with α source. The histogram of the microchannel signals is shown in yellow.

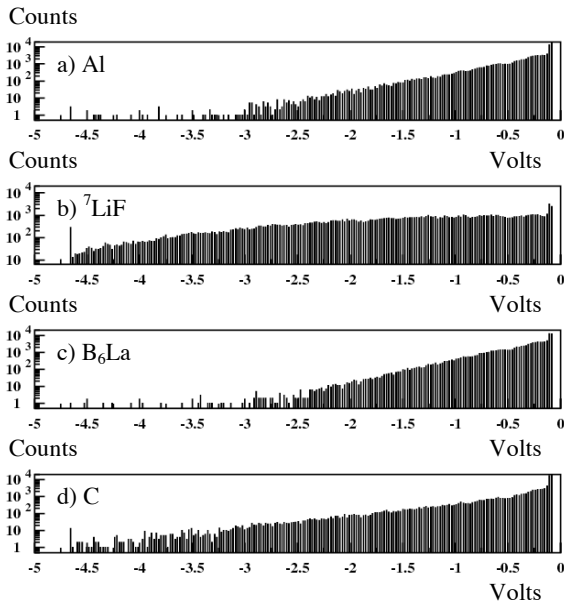


Fig. 8: Distribution of the microchannel signals obtained in the tests with α source of the four windows: a) Al, b) ${}^7\text{LiF}$, c) B_6La , d) C.

The distributions obtained for the four windows are shown in fig. 8. The efficiency, i.e., the signal to noise ratio, is 59% for Al, 94% for ${}^7\text{LiF}$, 74% for B_6La , and 54% for C. Even if ${}^7\text{LiF}$ has the highest efficiency, the distribution of the signals is too broad for the dynamic range of the Gassiplex. Concerning the other three windows, the B_6La one has higher efficiency than the Al and C ones and a sharper shape, which makes it the more suitable for the Gassiplex operative conditions.

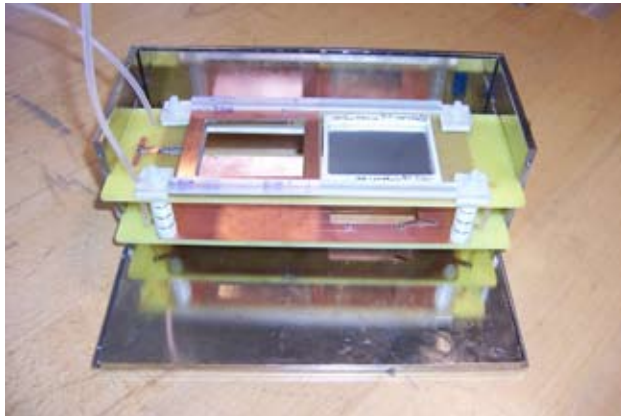


Fig. 9: The final PSD detector.

3 THE PSD FINAL VERSION

The new PSD detector is shown in fig. 9. It was designed taking into account all the results from the β -version and improving different aspects. Now the detector is more compact, being the total volume $24.6 \times 10.1 \times 8.7 \text{ cm}^3$. A copper screen connected to the common ground is added in order to screen the Gassiplex chips from the border effects, observed in the previous version and solved in this way. Both the magnetic and electric field

homogeneities are improved. In order to have $\mathbf{B} = 85$ Gauss the final number of permanent magnets is 266 pieces. The distance between the magnetic poles is reduced from 11.3 to 8.4 cm. The measurement of $\mathbf{B}$ inside the new PSD detector confirms that the field homogeneity is improved within $\sim 15\%$.

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IMAGING MONOLITHIC SILICON DETECTOR TELESCOPE

F.Amorini^{a,c}, T.Basso^f, C.Boiano^f, G.Cardella^b, L.Cosentino^a, A.Di Pietro^a, G.Fallica^d, P.Figuera^a, P.Finocchiaro^a, A.Pappalardo^a, F.Rizzo^{a,c}, N.Randazzo^b, V.Russo^{b,c}, S.Scirè^a, C.Scirè^a, V.Sipala^{b,c}, A.Trifirò^e, M.Trimarchi^e, G.Valvo^d

a) INFN Laboratori Nazionali del Sud, Catania, Italy

b) INFN, Sezione di Catania

c) Dipartimento di fisica e astronomia Università di Catania

d) ST Microelectronics stradale Primosele CT

e) INFN gruppo coll. Messina and Dip. Fisica Università di Messina

f) INFN Sez. Milano and Dip. Fisica Università di Milano

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

Abstract

We have performed the first tests on a new monolithic silicon detector telescope designed to produce also x-y position information of the detected particles. Position sensitivity up to 3 μ m in both dimension was achieved.

1 INTRODUCTION

Monolithic silicon detector telescopes have been developed in strict collaboration between INFN and ST Microelectronics since many years[1]. The characteristic of such detectors is the rather low threshold for charge identification. They have been used in many experiments with beams from low energy up to 10 MeV/A and also with radioactive beams[2]. We have now developed a new version of such telescope able to produce also X-Y position information. The first detector prototype, shown in fig.1 is 10*10 mm² and is characterized by the presence of 16 ΔE strips 500 μ m width, built over a single E stage.

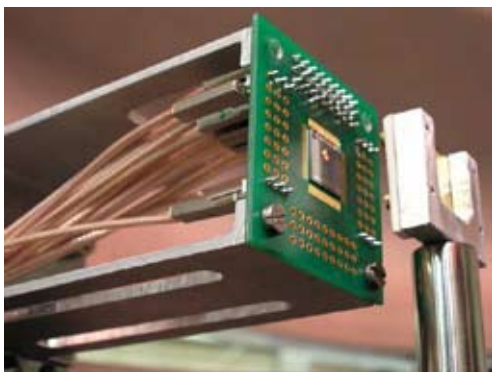


Fig.1 The monolithic strip detector used during the laser alignment phase.

2 IRRADIATION TESTS

To verify the position sensitivity of the new device we have irradiated it by using the micro-beam system of the LNS[3]. This facility consists of an optical table equipped with under vacuum high precision motors allowing up to 3 different independent computer controlled translations with micrometric precision and reproducibility. Using a set of 4 collimators we realized a micro-beam with a spot size of about 50*100 μ m².

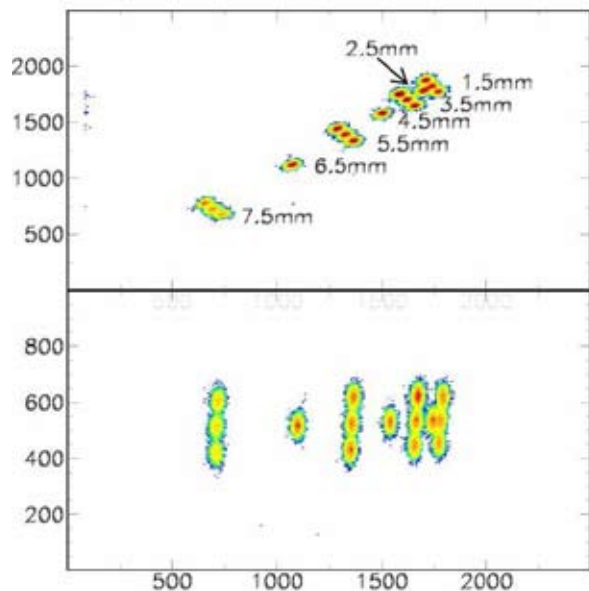


Fig.2 The image of the irradiation points realized by a combination of the induction signals taken from the different strips.

The detector was mounted on the remotely controlled arm. We have irradiated some of the 16 strips of the detectors in 8 different points with a step along the vertical position of 1 mm. Moreover we have also irradiated some points at $\pm 130 \mu\text{m}$ from the centre of the strip. The position information has been obtained looking to the signal induced on various strips by the charge collected in the E stage. An opportune combination of these signals is reported in fig.2 for all irradiation points. The obtained resolution is quite good and surely better than the beam spot size at least in the coordinate along the width of the strip. In the coordinate along the length of the strip a sort of saturation is present in the position answer.

3 REACTION MEASUREMENTS

The detector has been also tested under real reaction conditions using a ^{14}N beam of 54 MeV on a LiF target. The obtained charge identification was quite good as shown in fig 3a,b,c, where the ΔE -E scatter plot obtained in 3 of the 16 detector strips are reported. In fig.4d we also plot ΔE -E scatter plot obtained in the same experimental conditions irradiating the detector with an alpha source. In this picture we can see the light particle identification that can be obtained when there is no the induction generated by the detection of heavy fragments.

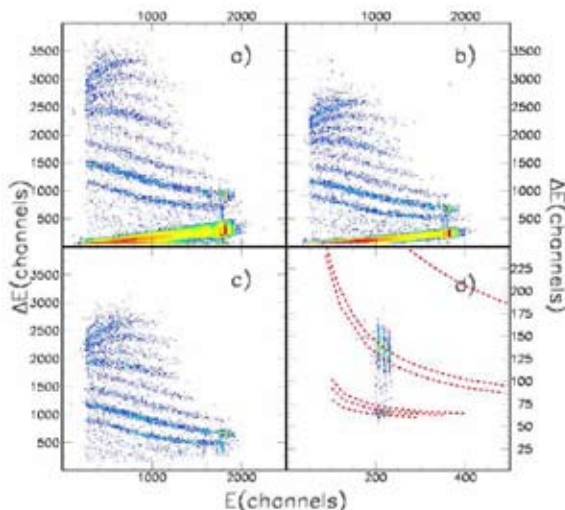


Fig.3 a,b,c ΔE -E scatter plot obtained in 3 of the 16 detector strips with the reaction $^{14}\text{N}+\text{LiF}$ target. d) ΔE -E scatter plot obtained with alpha source. The lines are predictions for $Z=1,2$ and 3 isotopes.

4 UNDER BEAM IMAGING

To verify the position measurement under real beam conditions we covered the detector with a plastic strip 2 mm width and with a fishing wire 200 μm diameter.

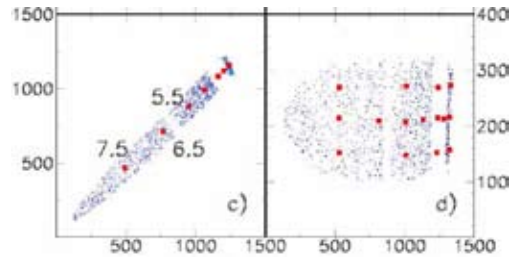


Fig.4 Position of elastically scattered ^{14}N particles detected in a strip. The shadow of a plastic strip and of a fishing wire can be seen.

In fig. 4 we show the position of elastically scattered particles hitting one strip of the detector. In the same picture we have reported the calibration points obtained with the micro-beam. With such calibration points we can verify that we correctly measure the shadow of the plastic strip (2mm) and the diameter of the fishing wire (200 μm). It is also evident the non linear position resolution obtained along the length of the strip in such first prototype. Simulations are going to improve the linearity of the position response function of the detector.

5 CONCLUSIONS AND OUTLOOK

A prototype of a new strip monolithic silicon detector telescope has been tested to verify its ability to produce position information. A position sensitivity up to 3 μm was obtained along the vertical coordinate and of about 2 mm along the width of the strips. The strip length coordinate is however affected by non linearity in the position response. Simulations are going to improve the linearity of the position response function of the detector. A patent in collaboration INFN-ST Microelectronics is pending.

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ON-BEAM DIGITAL PULSE SHAPE ACQUISITION FROM NE102A-BaF₂ PHOSWICH DETECTOR

F.Amorini^a, E.De Filippo^b, P.Guazzoni^{c,*}, E.La Guidara^a, G.Lanzanò^b, A.Pagano^b, S.Pirrone^b,
S.Russo^c, P. Russotto^a, L.Zetta^c

a) INFN Laboratori Nazionali del Sud, Catania, Italy

b) INFN – Sezione di Catania, Catania, Italy

c) Dipartimento di Fisica dell'Università and INFN – Sezione di Milano, Milano, Italy

** Corresponding author, e-mail: paolo.guazzoni@mi.infn.it*

Abstract

We have applied digital signal processing to the signals on-beam collected with NE102A-BaF₂ phoswich. In this contribution we present the results obtained for the heavy ion charge identification (up to Z=50) and light particle mass identification using digital pulse shape acquisition and a 12-bit, 2GSample/s sampling analog to digital converter.

1 INTRODUCTION

In order to improve the charge identification of the reaction products and the isotopic identification of light charged particles (LCP), we have carried out some tests using a 12-bit, 2GSample/s Sampling Analog-to-Digital Converter (SADC) to perform a real-time digital pulse-shape analysis of the signals coming from a standard detection cell of the Argos multidetector, i.e. a NE102A-BaF₂ phoswich. In a contribution of 2005 LNS Activity Report [1] we have presented the preliminary results obtained for the natural background of BaF₂. In this contribution we present the results concerning the response of the BaF₂-plastic phoswich to the reaction products issued at forward angles in the collision of a 35.1 MeV/u ¹²⁴Sn beam on ⁶⁴Ni target obtained at the LNS Superconducting Cyclotron.

2 EXPERIMENTAL SET-UP AND RESULTS

2.1 Experimental Set-Up

Normally the acquisition of fast and slow components of the BaF₂ signals in order to obtain particle discrimination, needs of two different electronic chains (the one for the Fast and the other for the Slow components of the signal) and logical signals of different widths as gates. In order to simplify the electronic chain, we decided to apply the Digital Pulse Shape Acquisition (DPSA) to collect signals from the BaF₂ and BaF₂-plastic phoswich. In fact using DPSA it is sufficient to use an only electronic chain to collect the whole signal pulse shape and no logical gates are necessary. The collected pulse shapes are digitally processed in order to obtain the 2-D matrices giving the physical observables.

For this experiment we have used a CAEN-V1729 Sampling Analog to Digital Converter (SADC) [2], a

SIS1100/3100 PCI-to-VME Bridge [3], and a host PC, used for data handling and displaying.

The board performs the coding of 4 analog channels of bandwidth up to 300MHz, with a 12-bit resolution at a sampling frequency reaching up to 2GHz with a 1V dynamical range. Waveforms of 2560 consecutive samples are collected at 500 ps time intervals and stored in the SADC buffer in wrap-around mode. For each event a post-trigger is used to stop the sample collection. The pulse-form is reconstructed and stored. The use of post-trigger allows accurate baseline restoring of each pulse, before the computation.

For in-beam measurements we used BaF₂-plastic (NE102A 300 μ m) phoswich. The BaF₂ crystal used is shaped as a right hexagonal prism (5 cm x 5 cm x 10 cm). It is optically coupled to an EMI 9954 photomultiplier (PM). The anode of PM is connected to a Lecroy 612A amplifier (A). The amplifier output is digitized using the CAEN-V1729, as previously said (Fig. 1).

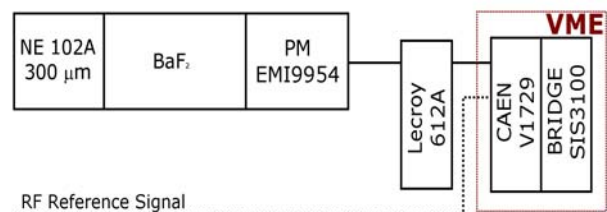


Fig. 1. Electronic chain used for digital pulse shape acquisition.

All the measurements quoted in this work have been made at room temperature.

In order to perform particle identification, the integration of the total, fast and slow components of the collected pulse shapes are computed using proper algorithms that will be described in the following and represent a proper modification of the charge comparison method.

Several algorithms are computed during digital signal processing. Initially the pulse form is digitally filtered by means of a FIR filter, using a symmetric triangle kernel with a time baseline of 7 samples (3.5 ns). Then a simple baseline restorer algorithm is applied. The baseline value is calculated as mean value of the first 500 samples, and subtracted from the collected pulse form. Then start-time, maximum value, and the sample corresponding the

maximum value (maximum-time) are calculated on each collected pulse shape.

Finally, Fast, Slow and Total components are computed, using proper gates. Each gate time-position is related to the maximum-time and has an own fixed width. They are: 40 ns $\{(-15 \div 25)$ ns with respect to the maximum-time $\}$ for Fast, 50 ns $\{(25 \div 75)$ ns with respect to the maximum-time $\}$ for Slow and 90 ns $\{(-15 \div 75)$ ns with respect to the maximum-time $\}$ for Total. Consequently the time position of each gate depends on the pulse shape. Each component is computed as numerical integration with different integration times in order to match different decay times. Each component is normalized to its own gate width.

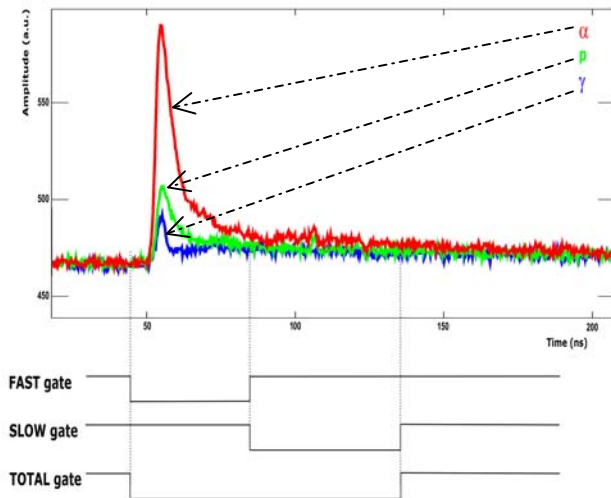


Fig. 2. Typical pulses from BaF_2 phoswich obtained in beam. The gate of Fast, Slow and Total components used are also indicated.

2.2 Results: In-Beam Measurements

The discrimination of charged particles and heavy ions is achieved by using the BaF_2 -phoswich and the electronic chain previously described (Fig.1).

The in-beam measurements have been done at LNS Superconducting Cyclotron, by using a ^{124}Sn beam on a ^{64}Ni target at 35.1 MeV/u incident energy. To be identified a reaction product must punch through the plastic film and deposit a sufficient amount of energy in the BaF_2 crystal. This introduces an energy threshold directly related to the thickness of the plastic film.

Fig. 3 shows the bidimensional (Fast,Slow) matrix obtained for a photomultiplier bias-voltage of 800 V. Energetic particles that stop in the BaF_2 crystal are resolved according to their atomic number from $Z=2$ up to $Z=50$. The line on the left of the figure corresponds to particles that stop in the plastic scintillator.

Fig. 4 shows the zoomed area of a bidimensional (Fast,Slow) matrix obtained for a photomultiplier bias-voltage of 1000V. It is possible to see that now the identification is improved: charge identification from $Z=1$ is achieved.

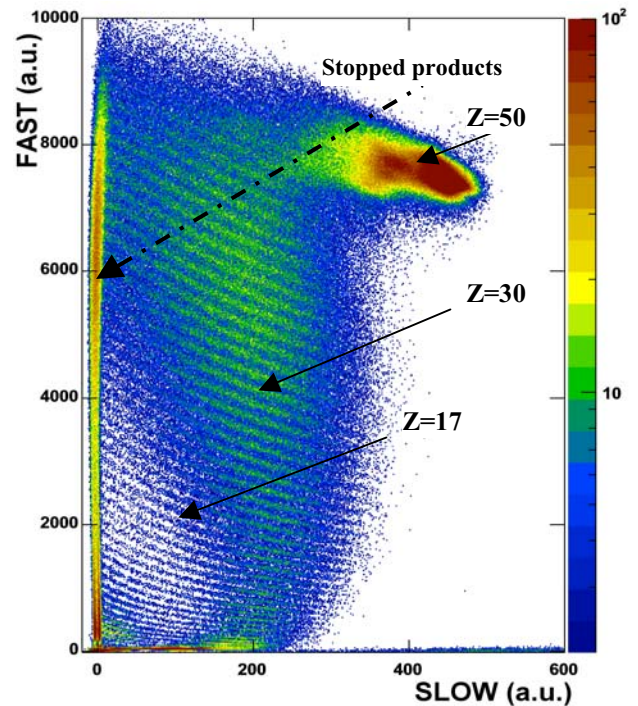


Fig. 3. (Fast,Slow) scatter plot for BaF_2 -plastic phoswich. A charge identification up to $Z=50$ is obtained at forward angles for the reaction $^{124}\text{Sn} + ^{64}\text{Ni}$ at 35 MeV/u. Particles stopping in NE102A are indicated. The used photomultiplier bias-voltage is 800V.

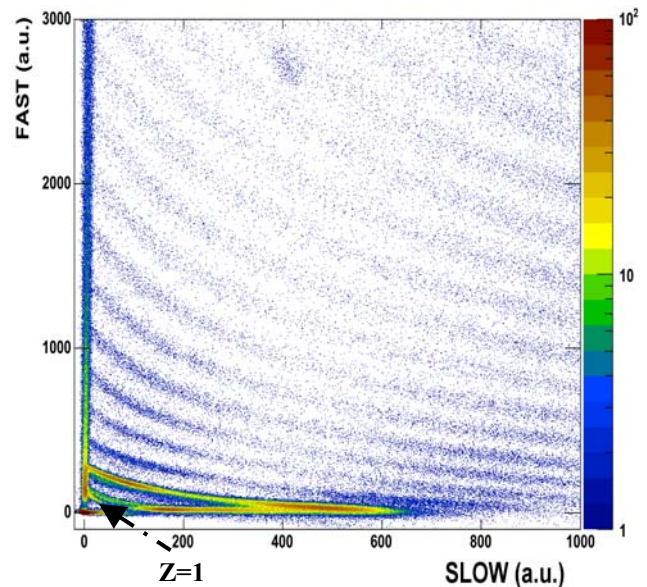


Fig. 4. Zoomed area of a bidimensional (Fast,Slow) matrix obtained for a photomultiplier bias-voltage of 1000V. The $Z=1$ line is indicated.

The fast response of both phoswich components allows exploiting Time of Flight (ToF) techniques, in addition.

By using the higher bias value for the PM and of ToF technique a better identification of light charged particles is achieved. ToF is computed as time difference between

a proper reference signal from Superconducting Cyclotron and the starting point of the phoswich signal. (ToF, Total) scatter plot obtained at forward angles for the reaction $^{124}\text{Sn} + ^{64}\text{Ni}$ at 35 MeV/u is shown in Fig. 5. A good mass identification up to $A=4$ is obtained.

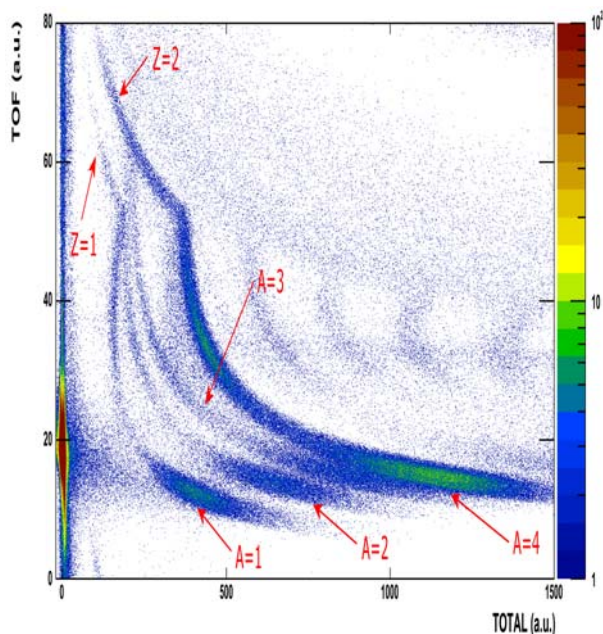


Fig. 5. (ToF, Total) scatter plot for BaF₂-plastic phoswich at forward angles for the reaction $^{124}\text{Sn} + ^{64}\text{Ni}$ at 35 MeV/u.

4 SUMMARY

The BaF₂-phoswich signals have been digitized for software processing using the CAEN-V1729 (4-channel, 12-bit, 2GSample/s sampling analog to digital converter). Each collected pulse shape consists of 2560 consecutive samples. In-beam measurement, done at LNS, by using a ^{124}Sn beam on a ^{64}Ni target at 35.1 MeV/u incident energy and a BaF₂-phoswich, allowed the charge identification from $Z=1$ up to $Z=50$, and light particle identification up to $A=4$, $Z=2$ by means of ToF measurements, in addition.

In our knowledge, it is the first time that high-resolution (12-bit) and high sampling frequency (2 GHz) digital signal processing has been carried out on BaF₂ and BaF₂-phoswich. In fact previous attempts of digitization, done for the DANCE detector, use sampling analog to digital converters with lower resolution (8-bit) and lower sampling frequency (500MHz) [4]. Our results confirm the goodness of the DPSA approach allowing more flexibility in the signal integration and making simpler the electronic chain.

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MASS IDENTIFICATION VIA ToF MEASUREMENT AND DPSA

F. Amorini^a, A. Anzalone^a, R. Bassini^b, C. Boiano^b, G. Cardella^c, S. Cavallaro^a, E. De Filippo^c, P. Guazzoni^{b,*}, E. La Guidara^a, G. Lanza^c, A. Pagano^c, M. Papa^c, S. Pirrone^c, G. Politi^c, F. Porto^a, F. Riccio^b, F. Rizzo^a, S. Russo^b, P. Russotto^c, and L. Zetta^b.

a) INFN Laboratori Nazionali del Sud, Catania, Italy

b) Dipartimento di Fisica dell'Università and INFN – Sezione di Milano, Milano, Italy

c) INFN – Sezione di Catania, Catania, Italy

** Corresponding author, e-mail: paolo.guazzoni@mi.infn.it*

Abstract

In order to improve the resolution in mass identification, we have applied digital signal processing to time of flight measurements directly acquiring silicon detector and RF pulse form. In the present contribution, we report the results obtained at different sampling frequencies (mass identification up to $A=33$ for the reaction products produced by a 20.5 MeV/u ^{20}Ne beam on ^{27}Al target).

1 INTRODUCTION

In order to improve the resolution and the upper limit of mass identification, we have applied Digital Pulse Shape Acquisition (DPSA) and digital signal processing to the Time of Flight (ToF) measurement. Sampling analog to digital converters (SADC) with different sampling frequencies and CHIMERA large area planar silicon detectors ($5\times 5\text{cm}^2$, 1nF) in standard experimental conditions, i.e. no cooling and no collimation, have been used to this purpose. In a contribution of 2005 LNS Activity Report [1] we have presented the preliminary results obtained, i.e. a good mass identification in the range $4\leq A\leq 20$. In the present contribution we report the methodology that allows to obtain a mass identification up to $A=33$ for the $^{20}\text{Ne} + ^{27}\text{Al}$ reaction at 20.5 MeV/u incident energy, by using a 14 bit, 100 MS/s SADC.

2 EXPERIMENTAL SETUP

In order to produce a good mass identification via DPSA we employed SADCs with different characteristics. The one, SIS3301 [2], is an 8 channels digitizer/transient VME recorder, with a sampling rate up to 105 MHz for the individual channel, 14-bit resolution, 80 MHz of analog bandwidth, and 5 V of dynamics. The other, V1729 [3], is a VME module suited for sampling acquisition of fast analog signals. It is based on a circular buffer, the MATAcq chip [4]. The board performs the coding of 4 analog channels of bandwidth up to 300 MHz over 12-bits at a sampling frequency up to 2 GHz, with 1 V of dynamics.

To date, the two employed SADCs well represent top possibilities in digital pulse shape acquisition with commercial modules: for the resolution (14-bit for SIS3301, at 100 MHz) the one, for the maximum

sampling frequency (2GHz for V1729 with 12-bit resolution) the other.

In this way, on one side we can inspect the relative importance of resolution versus sampling rate. On the other side, the feasibility of flight time measurement through digital acquisition can be tested in a more general way, being not strictly related to the characteristics of the chosen SADC.

3 ALGORITHMS AND DATA ANALYSIS

The algorithms used in the present tests in order to fully reconstruct the pulse shapes and to obtain event parameters from each stream of samples have been already described in ref. [5]. They are: zero-pulse suppression; baseline restorer; mean-square noise; finite impulse response (FIR) filtering; pileup inspector; pulse height and rise time calculation. In the following we will only describe the simple and improved algorithms used for the time of flight computation.

To compute flight time it is necessary to collect Start and Stop signals. For both, a precise timing evaluation of one point of the collected waveform is needed. To this purpose, we use a Threshold Crossing-Time (TCT) algorithm, able to compute the time at which the pulse form crosses a chosen threshold level, i.e. a previously stated fraction of the pulse height. The algorithm is based on a polynomial fitting. Its working mode was described in ref. [1].

In order to improve the flight time measurement using SIS3301, a better estimate of the start and stopping times is needed. First of all, the sampling rate satisfying the Nyquist theorem is well below 100MS/s for the Silicon signal, so the sampling frequency of SIS3301 is able to reconstruct accurately this signal. From this point of view, we can explain the better results obtained with a 2GS/s sampling rate –as will be shown in the next section– with the fact that the cubic fit used does not provide an enough accurate reconstruction when a 100MS/s rate is used, so limiting the accuracy of the TCT algorithm. In order to obtain with the 100MS/s SADC results comparable to those of V1729 [1], we have to use a better interpolation function $f(t)$. The problem with this approach is that we have to solve the equation $f(t) = S$ for the time t , where S is the threshold, in order to obtain the threshold crossing-

time t_s . This is a computationally intensive task, if f is not a simple function of t . So we use another approach, as illustrated in Fig. 1.

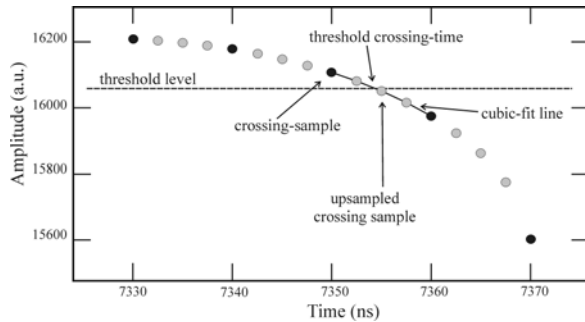


Fig. 1. Zoomed area of a Silicon pulse collected with SIS3301, where the upsampling is shown. The black dots indicate the collected samples. The gray dots indicate the interpolated samples. The solid line indicates a cubic fit. The origin of the time scale is the acquisition start time. For sake of visibility, only one upsampled sample every four is represented.

The collected samples are upsampled by a factor of 16, by using an appropriate interpolation filter [6]. In this way, a virtual increasing of the sampling frequency up to 1.6GS/s is obtained. In order to improve efficiency, the upsampling is computed only on a small interval starting from the crossing-sample (Fig. 1). A new crossing-sample (*upsampled crossing-sample*) is chosen between the interpolated samples, and the TCT algorithm with the usual cubic fit is applied.

On the other hand, the RF signal is a periodic signal with a well-known frequency f_{RF} . Thus, by applying the Fourier Transform, $P(k)$, to the product of the RF signal, $s(t)$, times a proper window function, $w(t)$, we have:

$$P(k) = \sum_{n=0}^{N_s-1} e^{-2\pi i k n T_s} w(n T_s) s(n T_s),$$

where N_s ($= 2048$ in our case) is the number of samples collected per waveform and T_s ($= 10$ ns in our case) is the sampling period. The resulting spectrum is a sequence of peaks.

Each peak has the shape of the Fourier Transform $\tilde{w}(k)$ of $w(t)$ and is centered on the frequencies corresponding to f_{RF} and its harmonics, eventually aliased in the 0-50MHz range [6]. At the fundamental frequency f_{RF} , is $P(f_{RF}) \approx a \tilde{w}(0)$, where a is the complex amplitude of the fundamental component of the RF signal.

How good is the approximation depends on the shape of the RF signal, i.e. on the magnitude of its harmonics, and on the choice of $w(t)$. The approximation is as better as much the side lobes of the window function are attenuated. Good results are obtained with a Kaiser-Bessel window [6]. The phase φ of the fundamental component of the signal is related to the stopping time T_{STOP} through the formula $T_{STOP} + T_0 = 2\pi f_{RF} / \varphi$, where T_0 is an appropriate constant.

Being $w(t)$ real, $\tilde{w}(0)$ is a real constant and $P(f_{RF})$ has the same phase as a , so it is enough to compute $\varphi = \arg[P(f_{RF})]$ and apply the above formula to obtain T_{STOP} . The computation of $P(f_{RF})$ is also very fast, since it requires the evaluation of only a single value of the Fourier Transform of $s(t) * w(t)$.

4 EXPERIMENTAL RESULTS

The on beam tests have been done at the LNS Superconducting Cyclotron in Catania, with a 20.5 MeV/u ^{20}Ne beam bombarding a ^{27}Al target. A Silicon detector at $\theta_{lab} = 9^\circ$ (5th wheel) was employed.

We have acquired the RF waveform together with those from Silicon, by using both SIS3301 and V1729. In this case the flight time τ is calculated as the difference between the threshold crossing-time of the rising edge of the Silicon (Start) and that of one bump of RF (Stop). Using SIS3301 and V1729 with the simple algorithm of ref. [1], a mass identification fully comparable with the standard CHIMERA mass identification has been reached, being, obviously, the results of V1729 a little bit better.

Thus we decided to combine the results of SIS3301 and V1729, in order to construct a scatter plot with a resolution of 14-bit (energy measured from SIS3301) and a frequency of 2 GS/s (ToF measurement from V1729).

The obtained results are shown in Fig. 2, where the scatter plot ($E\Delta t^2, \Delta t$) is shown. The use of the ($E\Delta t^2, \Delta t$) representation allows a quite good linearization of the mass curves. Moreover the constant t_0 we have to subtract from the measured flight time τ to obtain the true flight time Δt is independent from the reaction product mass.

This important simplification of the data analysis is due to the choice of the starting point of the Silicon pulse shape (10% of the maximum). In this way our calculation is not influenced by the dependence of the signal rise time from the reaction product charge [7, and references therein quoted].

As is possible to see in Fig. 2, the resolution is clearly improved by using the combination of the results from the two SADCs, allowing mass identification up to $A=30$, at least, proving the importance of a 14-bit resolution in measuring the energy.

On the basis of the results shown in Fig.2, we decided to devote our attention to improve the analysis algorithms for time of flight calculation, as previously described. Applying the improved algorithms to the signals sampled at 100MS/s with the SIS3301, we have computed the ($E_{Si}\Delta t^2, \Delta t$) scatter plot for the same reaction, obtaining a full mass identification up to $A=30$, at least. Heavier products have not been identified due to the low statistic. We have also obtained for the elastic scattering peak a time resolution of 800 ps, identical to the value obtained with the V1729.

As expected, we obtained no advantage by applying the improved algorithms to the data collected with V1729. Thus no further enhancement of mass identification can be obtained for the combined data by applying the improved algorithms.

To compare the improvement reached with the new algorithms, we have compared the mass identification spectra obtained by projecting on the $E_{Si}\Delta t^2$ axis the portion of the $(E_{Si}\Delta t^2, \Delta t)$ scatter plot, corresponding to the Δt interval indicated in Fig.2, for both algorithms.

The obtained results are shown in Figs. 3 (SIS3301 data and improved algorithms) and 4 (SIS3301 data and simple algorithm). For this portion of data mass identification up to $A = 33$ is obtained with the improved algorithms, while only up to $A = 25$ with the simple algorithm.

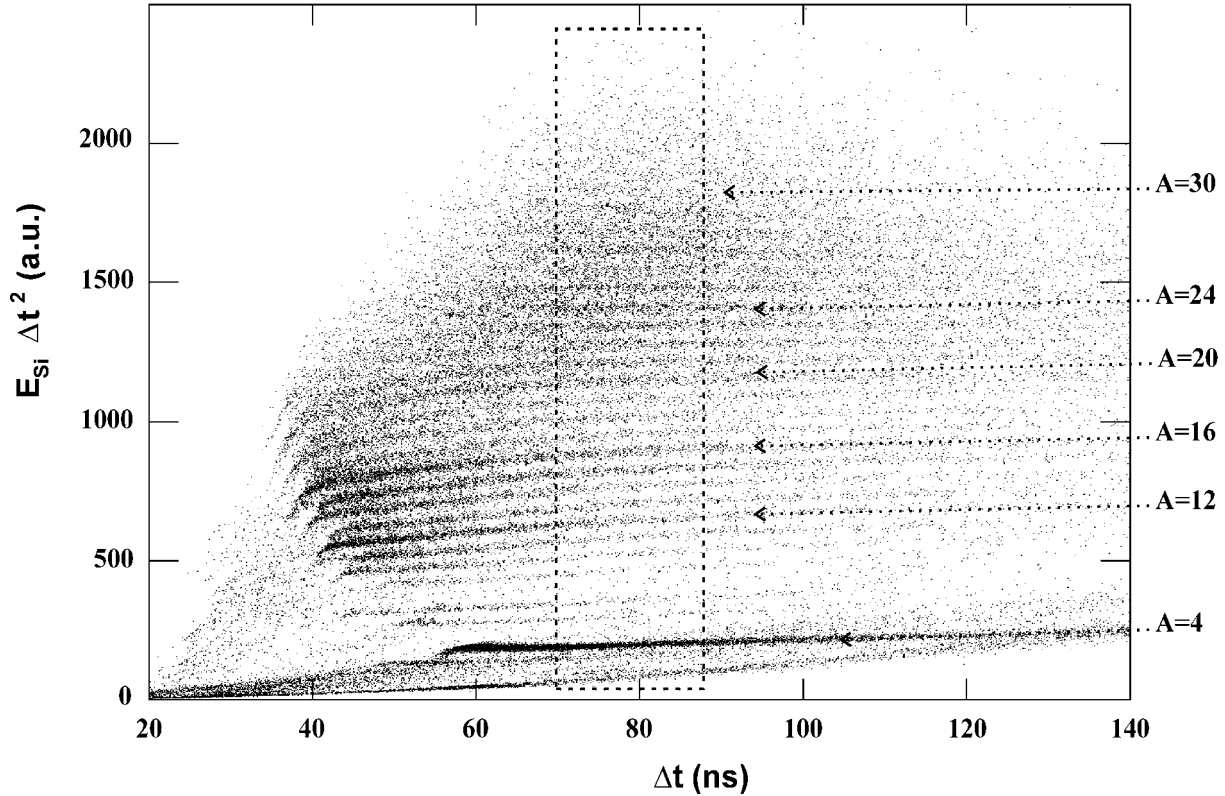


Fig. 2. $(E_{Si}\Delta t^2, \Delta t)$ scatter plot for the $^{20}\text{Ne} + ^{27}\text{Al}$ reaction at 20.5 MeV/u incident energy. The scatter plot is obtained combining the results obtained with V1729 and SIS3310, i.e. 14-bit and 2 GS/s. The dotted box indicates the Δt interval used to construct the mass identification spectra shown in Figs. 3 and 4.

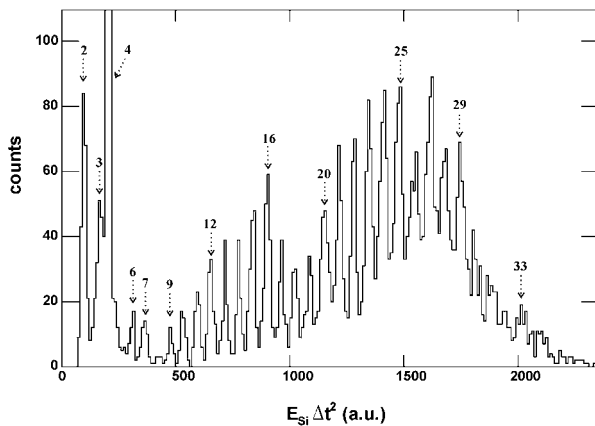


Fig. 3. SIS3301 data and improved algorithms: mass identification spectrum for the $^{20}\text{Ne} + ^{27}\text{Al}$ reaction at 20.5 MeV/u incident energy. It is obtained by projecting on the $E_{Si}\Delta t^2$ axis the portion of the $(E_{Si}\Delta t^2, \Delta t)$ scatter plot corresponding to the Δt interval indicated by the dashed box in Fig.2.

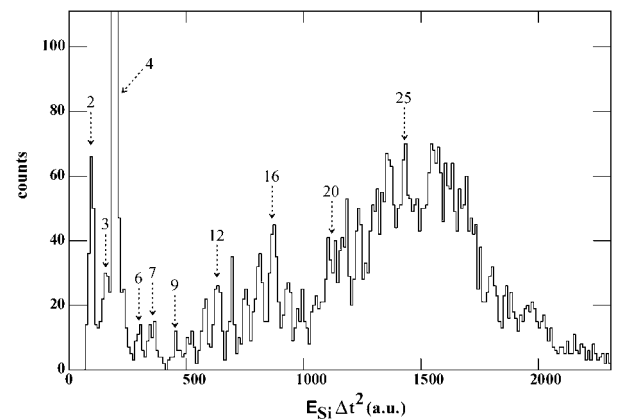


Fig. 4. SIS3301 data and simple algorithm: mass identification spectrum for the $^{20}\text{Ne} + ^{27}\text{Al}$ reaction at 20.5 MeV/u incident energy. It is obtained by projecting on the $E_{Si}\Delta t^2$ axis the portion of the $(E_{Si}\Delta t^2, \Delta t)$ scatter plot corresponding to the Δt interval indicated by the dashed box in Fig.2.

Some important conclusions.

By upsampling the collected data and using Fast Fourier Transform for flight time computation, a mass identification up to $A=33$, for the $^{20}\text{Ne} + ^{27}\text{Al}$ reaction at 20.5 MeV/u incident energy, has been obtained by using the 100 MS/s SADC. This result is considerably better than that normally obtained using the VRF solution and the traditional acquisition.

We have established the importance of using SADCs with a 14-bit resolution. Moreover it can be stated that by using more sophisticated algorithms, a 100 MHz SADC may allow a very high-resolution mass identification with a very high upper limit (Fig. 3).

Finally, the possibility to use only one type of SADCs for both Silicon and CsI(Tl) allows an easy integration of the digital pulse shape acquisition technique in the standard acquisition systems, by means of the on-board digital signal processing [8].

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SINGLE PHOTONS AVALANCHE DIODES ARRAYS: A NEW DETECTOR FOR ULTRA WEAK LIGHT SOURCES

A.Campisi^{a*}, L.Cosentino^a, P.Finocchiaro^a, A.Pappalardo^a, F.Musumeci^{a,b}, S.Privitera^{a,b},
A.Scordino^{a,b}, S.Tudisco^{a,b}, G.Fallica^c, D.Sanfilippo^c, M.Mazzillo^c, G.Condorelli^c, A.Piazza^c,
G.Valvo^c, S.Lombardo^d, E.Sciacca^d, G.Bonanno^e, M.Belluso^e

a) INFN-LNS, Via Santa Sofia 62, 95125 Catania, Italy

b) DMFCI-Università di Catania, Viale A. Doria 6, 95125 Catania, Italy

c) STMicroelectronics, MPA R&D, Statale Primosole 50, 95121 Catania, Italy

d) CNR-IMM, Statale Primosole 50, 95121 Catania, Italy

e) INAF-Astrophysics Observatory of Catania, Via Santa Sofia 78, 95123 Catania, Italy

Abstract

Arrays of Single Photon Avalanche Detectors (SPAD) are considered today as a possible alternative to PMT's and other semiconductor devices in several applications, like physics research, bioluminescence, PET systems, etc. We have developed and characterized a first prototype array produced by STMicroelectronics in silicon planar technology and working at low voltage (30-40V) in Geiger mode operation. The single cell structure (size down to 20 μ m) and the geometrical arrangement give rise to appealing intrinsic characteristics of the device, such as photon detection efficiency, dark count map, cross talk effects, timing and energy resolution. New prototypes are under construction with a higher number of pixels that have a common output signal to obtain a so called SiPM (Silicon PhotoMultiplier) configuration.

1 INTRODUCTION

Photon handling is nowadays considered an emerging issue, with so many applications covering a full branch of science and technology dedicated to it, namely photonics. High resolution small size photon detectors are fundamental to develop photonic systems with high performances in terms of sensitivity, precision, large scale integration, etc. Examples of such applications are high density charged particle trackers with position and timing capabilities, gamma-ray detectors suitable for a high resolution Positron Emission Tomography (PET), servo control systems in adaptative optics, 3-D imaging cameras, cameras for very weak light intensity, biophysical spectrometry. In this paper we propose bidimensional arrays of Single Photon Avalanche Detectors (SPAD's) fabricated via a standard planar silicon production processing. We developed prototype arrays of 5*5 elements operating at low voltage (30-40V) with active diameter of the single cell of 20 and 40 μ m. We are going to illustrate our characterization of such arrays, in terms of bias voltage, operating temperature,

dark-counting rates, photon detection efficiency, cross-talk. We also describe tests we made in common output mode, thus achieving a photon-resolving operational mode called Silicon PhotoMultiplier (SiPM [2,3,4]) which has shown to resolve very efficiently the peaks of few-photon spectra produced by an ultra weak light source.

2 SENSOR DESCRIPTION

The arrays of Geiger mode avalanche photodiodes we describe in this section are constituted of single pixels fabricated in silicon planar technology [5]. These pixels can detect very weak light fluxes, down to the single photon regime, thanks to the working principle described in the following. The single pixel is a circular highly doped n-p silicon junction biased above the breakdown voltage (the exceeding voltage is called overvoltage OV) and with a uniform high electric field over the depletion layer. The junction is quiescent until an electron-hole pair is photogenerated, and so that an avalanche is triggered by an impact ionization mechanism. The current rises up to a macroscopic level (mA range) in few tens of picoseconds and the rise-up time of the avalanche marks the arrival time of the photon [6]. Because of the multiplication process above breakdown the avalanche presents a self sustaining mechanism, and an external quenching circuit has to be used in order to reset the pixel and make it ready to detect another photon [7]. Microscopic views of our array are illustrated in Figure 1. We have characterized two 5x5 sensors with five independent rows, and the diameter of the active area of the single cell 20 and 40 μ m respectively. The pitch, the distance between two adjacent pixel centers, is 200 μ m for both sensors. The anode contacts are in common for each row and the single pixel cathode is separately available by means of external pads. Breakdown voltage distribution over an array has a mean value of 28 V with a standard deviation of 0.08 V.

* Corresponding author. Tel.: +39-095542305; fax: +39-095542252; e-mail: campisi@lns.infn.it.

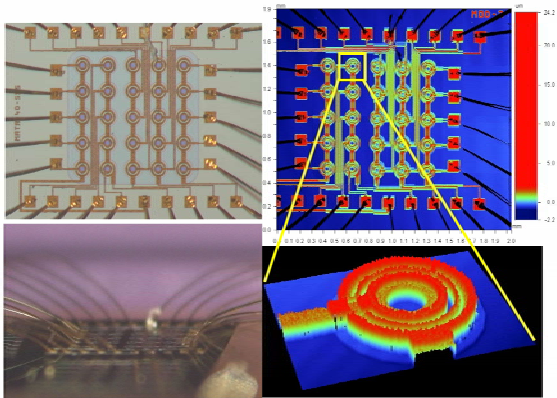


Figure 1: Two micro-photographs of the tested 5x5 SPAD array (left side); corresponding image reconstructed by means of a non-contact profilometer (upper right); 3D profile of a cell, with exaggerated z-axis, as reconstructed using the mentioned profilometer.

The quenching circuit we have chosen to employ is passive and makes use of a ballast resistor higher than 100K Ω in series with the cathode contact, whereas the anode is connected to 50 Ω load resistor (typically a coaxial cable or an oscilloscope input). Such a kind of circuit allows us to keep the overall circuitry very simple. The intrinsic noise of a SPAD is due to charges thermally generated with a poissonian statistical distribution and it is called dark counting rate (s^{-1}). When a charge has a sufficiently thermal energy to reach the conduction band, an avalanche is generated and the output signal has exactly the same shape as the photo generated e-h pair. An array of SPADs, where each pixel is separately accessible, finds application in fields where the sensor is read in parallel or in imaging-like mode. In the latter the dark counting rate uniformity over many pixels is important to avoid strong off line corrections. We have measured dark counting rates for many arrays, discovering that our fabrication process gives a very narrow statistical distribution, as reported in Figure 2 for a 20 μm diameter array with a mean value of about 400 s^{-1} .

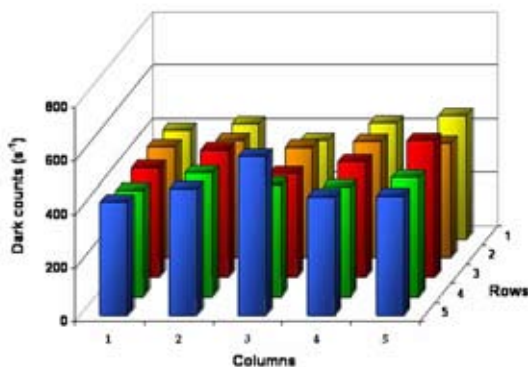


Figure 2 Dark counting map of a 5*5 array with 20 μm active diameter of single cell with 20% applied OV.

For the single pixel the timing jitter introduced in the Time Correlated Single Photon Counting (TCSPC), the technique to measure the time correlation degree between the light source and the detector [12,13], is down to 70ps for the 40 μm diameter. For each pixel we define the Photon Detection Efficiency (PDE) as the ratio between the number of photoelectrons that can trigger an avalanche and the total number of photons arrived on the active area. The results show remarkable PDE above 60% in the visible range and still above 20% at 800 nm. PDE depends on the silicon absorption coefficient and the electric field that accelerates photoelectrons to trigger avalanches, therefore it increases with the OV applied on the junction. In the Table 1 we report the mean value and standard deviation of the PDE for the 5x5 40 μm array for different wavelengths and overvoltages.

Wavelength (nm)	PDE _{OV} 10% (%)	σ PDE OV10% (%)	PDE _{OV} 15% (%)	σ PDE OV15% (%)	PDE _{OV} 20% (%)	σ PDE OV20% (%)
400	9.59	0.70	12.98	0.86	14.85	1.09
450	19.27	0.90	25.33	1.11	29.19	1.54
500	35.01	1.91	----	----	48.00	2.91
550	42.04	1.42	50.97	1.76	56.42	1.92
600	43.43	1.57	51.89	1.89	57.61	2.23
650	39.25	2.33	45.68	2.72	50.47	4.05
750	21.35	0.93	25.40	1.09	27.46	1.21
800	16.13	0.69	19.03	0.83	20.54	0.87
850	11.49	0.48	13.89	0.62	14.74	0.65
900	6.12	0.25	7.18	0.30	7.66	0.32
950	3.91	0.24	4.60	0.28	5.01	0.31

Table 1: PDE for a pixel of the with 40 μm diameter at various overvoltages and wavelength.

The table shows how the technological process permits to obtain a very good uniformity of this parameter.

When the array operates in SiPM mode, we have to consider also the fill factor due to the ratio between the total active area and the entire area of the device. Therefore the PDE of the SiPM detector considered as a whole decreases to very low values because of the poor geometrical efficiency.

When the distance between pixels is of the order of tens of microns, important coupling effects between adjacent pixels, called cross talk, can be present. An avalanche produces about 100 photons because of e-h pair recombination and Bremsstrahlung effects [8], that can reach adjacent pixels and hence triggering spurious avalanches. Other electrical effects can generate cross talk that strongly depends on the internal structure of the array. In order to measure the cross talk, we have exploited the intrinsic noise itself, to study the correlation between counts from a reference pixel and its neighbours. For a 40 μm device at room temperature and with an applied overvoltage of about 20%, we observed a cross talk probability to the order of 10^{-4} , while we did not observe any indication of a dependence on the distance

between the pixels. We also tested another sensor where each pixel was optically insulated from the neighbours by means of an optical trench suitably built around it. No difference was observed with respect to the standard sensor, and this excludes the presence of the optical cross-talk. This was somehow expected because the photon attenuation length in silicon is about $50\mu\text{m}$ [3,9] and the minimum distance between two pixels is $200\mu\text{m}$ [10].

2 TEST IN PHOTON RESOLVING MODE: SIPM CONFIGURATION

In Figure 3 we report the total avalanche charge as a function of the supply voltage for the central cell of our array; the corresponding gain, that is the average number of electrons in the avalanche, is reported on the righthand axis. A single pixel SPAD is not capable of resolving the number of detected photons, as it operates in Geiger mode thus providing always the same signal. The slope of the mentioned straight line can be ascribed to the effective capacitance of the pixel junction (plus a stray capacitance): during the avalanche the only available charge is the one stored in the junction, since the external quenching circuit prevents the introduction of any additional charge.

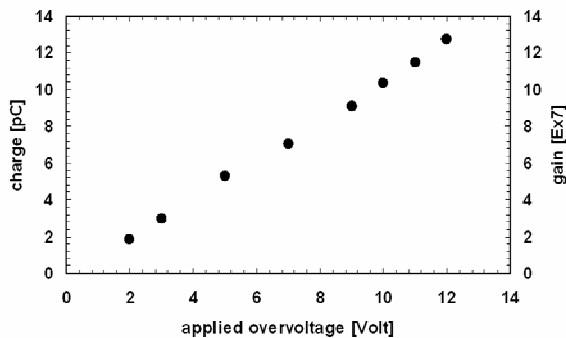


Figure 3: The SPAD signal charge ($40\mu\text{m}$ device) as a function of the supply voltage; on the righthand axis the corresponding gain is reported.

Therefore the ratio between the stored charge and the corresponding voltage is the total capacitance, that in our case is of the order of 1-2 pF. When the pixels of the array operate simultaneously in a common readout anode, more photons are detected at the same time and the array operates like a photon resolved sensor called Silicon PhotoMultiplier (SiPM). The following step in our testing was to show whether our array sensor could be suitable for the detection of few photons and for this purpose we connected the 25 output electrodes to the same 50Ω load, so that the final output charge collected is the analog sum of the avalanches produced over the 25 pixels. What one expects is to have an output signal that is the analog sum of the 25 on/off (Geiger mode) signals from the pixels. In order to produce a light signal in the range of few photons we made use of a pulsed blue diode laser ($\lambda=420\text{nm}$) with a low-tune light transmission. The

output signal of the 5×5 array is sent to a charge-to-digital converter. In Figure 4 we report the charge spectrum for the $20\mu\text{m}$ device obtained at an overvoltage of 4% and a ballast resistor of $100\text{K}\Omega$.

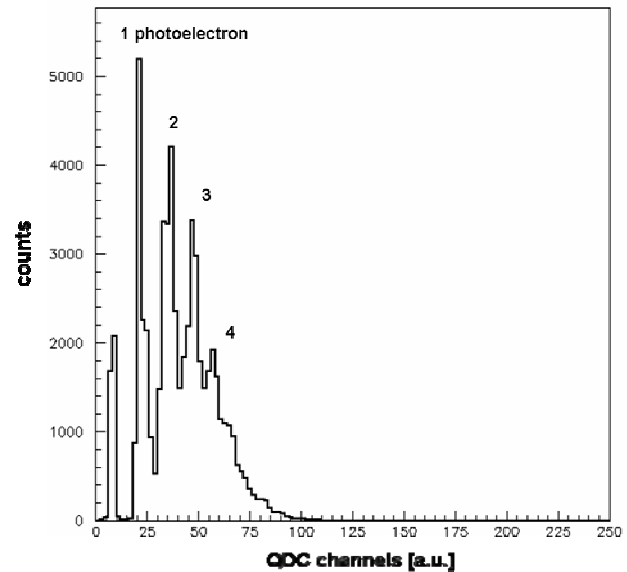


Figure 4: Charge spectrum of the 25-pixel array ($20\mu\text{m}$ device) in photon resolving mode, when illuminated by a pulse diode laser with a low light intensity and with 4% applied OV; good photoelectron resolution is shown for the various peaks (therefore the peak on the left side is the pedestal of the converter).

Pixel-to-pixel non-uniformity is introduced by the external passive quenching circuits and their stray capacities, so that the single photoelectron resolution is reduced because of this effect. We measured a Full Width at Half Maximum (FWHM) of the first photoelectron peak of about $\text{FWHM}_{\text{charge}} \approx 0.12\text{pC}$. Increasing the applied overvoltage on the pixel, the Photon Detection Efficiency also increases but the latching current effect reduces the single photoelectron resolution; such an effect depends on the ballast resistor value and on the voltage applied over the junction [7]. In order to show it, in Figure 5 we report a charge spectrum with an overvoltage of 20% and at the same light intensity: it is evident that the number of detected photons is increased but the single photoelectron resolution is reduced ($\text{FWHM}_{\text{charge}} \approx 0.6\text{pC}$). To keep a good photoelectron resolution, the value of the ballast resistor has to take into account the overvoltage and it is typically chosen as $50\text{K}\Omega \cdot \text{overvoltage (Volt)}$ [7].

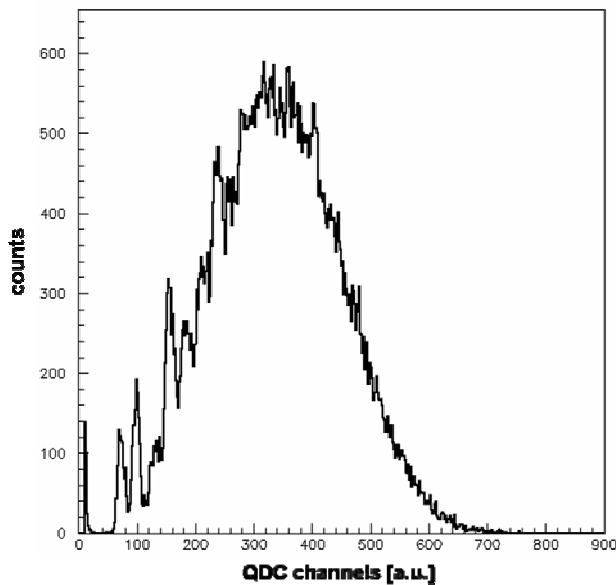


Figure 5: Charge spectrum of the 25-pixel array (20 μ m device) in photon resolving mode with 20% applied OV; the resolution is somewhat poor with respect to figure 4, for additional details and the explanation see the text.

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4 CONCLUSIONS AND OUTLOOKS

We tested our cheap-technology 5x5 SPAD arrays coupled to a laser, characterizing them with respect to the dark count, PDE, amplitude and cross-talk. We also tested it in SiPM photon-resolving mode, showing that the device is quite a promising micro-photosensor with relevant timing performance. New versions of the chip are currently being fabricated, in order to produce two kinds of improved arrays, working in individual-pixel mode and in SiPM mode respectively. For the former a large number of independent pixels will be used to achieve high position resolution, for the latter an array with a number of 5000 pixels is going to be employed, with integrated passive quenching circuit to reduce the stray capacitance effects. In the longer term we would like to fabricate micro-optical fiber coupler arrays with the technology briefly described in [10] and references therein, in order to achieve the goal of high-sensitivity high-resolution solid state photon counters with micro-optical coupling systems. We believe that the subject of our research contains the embryo of a forthcoming whole bunch of innovative devices and techniques.

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SINGLE PHOTON AVALANCHE DIODES: NEW DEVELOPMENTS

S.Privitera^{a,b,*}, S.Tudisco^a, F.Musumeci^{a,b}, L.Lanzanò^{a,b}, A.Scordino^{a,b},
A.Campisi^a, L.Cosentino^a, P.Finocchiaro^a,
S.Lombardo^c, M.Mazzillo^c, E.Sciacca^c

a) INFN Laboratori Nazionali del Sud, Catania, Italy

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

c) ST-Microelectronics & IMM-CNR Stradale Primosole 50, 95100 Catania, Italy

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

Abstract

Design and the complete characterization of a new generation of single photon avalanche diodes (SPAD) and their 1-D and 2-D array, manufactured by ST-Microelectronics in Catania, Italy, are presented as continuous of the previous work [9]. Device performances, which had been tested, are suitable in many applications. Dark counting rate at room temperature is down to 10 s^{-1} for devices with an active area of $10 \text{ }\mu\text{m}$ in diameter, and 10^3 s^{-1} for those of $50 \text{ }\mu\text{m}$. SPAD quantum efficiency, measured in the range 350-1050 nm, can be comparable to that of a typical silicon based detector and reaches the values of about 50% at 550 nm for bigger samples. The low production costs and the possibility of integrating are among the favorable features in sight of the integration of high density of detectors in 1-D or 2-D arrays, whose first prototypes had been characterized in terms of uniformity on both the dark counting rate and breakdown voltage, the induced noise (Cross-Talk) on adjacent elements, and synthetically here presented.

1 INTRODUCTION

Single photon counting method and time correlated photon counting technique are employed in the field of the medical applications, for the detection of single molecules by means of lifetime measurement and its correlation spectroscopy or, in general, to measure luminescence from several biological systems¹, for high resolution Positron Emission Tomography (PET), for particles tracking [2], optical fiber testing [3], in laser ranging [4] etc..

Actually, both photomultiplier tubes and silicon avalanche photodiodes are commercially available detectors acting for those purposes. Unfortunately, their dimension, high bias voltages, frailty, the high costs and, in some cases, their limited timing resolution prevent their co-integration in form of arrays and in many cases represent a serious limitation. Moreover, planar technology for the fabrication of SPAD devices is cheaper than others and compatible with the standard process of the microelectronic industry, as the CMOS process.

Tests on SPAD-ST-Microelectronics of several dimension, both actively and passively quenched, and in different illuminating conditions, have been completely performed, demonstrating their very high quality, in terms of low noise, high photon detection efficiency, fast timing response with high resolution [9]. The results obtained with the passive quenching circuitry was very promising especially in direction of the monolithic integration of the mono and bi-dimensional arrays of elements together with their associated quenching circuits. In sight of which, the passive quenching circuitry suggests the simple management of a very large number of detectors. The characterization of the single SPAD-ST-M device had been posed the basis for the characterization of a prototypal array of identical 5x5 elements, which was completed and here summarized.

So, if each SPAD device works as a trigger circuit, whose response is independent on the number of the impinging photons; by means of the parallel lecture of all the devices on a common substrate the so-called Silicon-PhotoMultiplier (SiPM) is realized.

Finally, the well performing 2D miniaturized detection system will be based on thin SPAD devices and take advantage of the micro-optical coupling between sources for the increasing of the photon collection efficiency.

2 SPAD-STM PERFORMANCES

A complete characterization of single elements SPAD-STM was performed. Noise, quantum detection efficiency and timing resolution of both passively and actively quenched detectors of different active areas were evaluated.

In order to minimize the number of impurities and defects, that contribute to dark counts, and to avoid the possible non uniformity of the junction breakdown, the use of high quality material and a proper device fabrication technique are requested. Our characterization work of the STM-devices (see reference [5]) had demonstrated that are affected from a very low noise. Dark counting rate, measured at room temperature, is less than few tens of cps for samples with an active diameter of $10 \text{ }\mu\text{m}$ and than 1K

cps for those of 50 μm . Gain of the order of 10^7 determines an amplitude signal of about 50 mV on a 50 Ω load. Generally, in a SPAD detector, noise is due to both the contribution from carriers thermally generated, whose statistical fluctuations are the basic internal noise source, and to the occurrence of the delayed pulses, caused to the carriers trapping and their after releasing by the deep trap levels inside the junction. The released carriers have a certain probability to trigger other avalanches, because the high electric field inside the junction, and so affect the photon counting. The effect of such delayed pulses is commonly called afterpulsing.

The afterpulsing effect on SPAD-STM junctions was quoted for passively quenched devices with an active area of 20 μm on diameter [7]. In order to detect all the pulses succeeding a start (dark) signal, the detector signal was duplicated and the two parts sent on a Time Digital Converter (TDC Multi-Hit): one represents the trigger input and the other the stop (delayed) pulses. The collection time is 50 μs for each measurement and the bin is 100 ps per channel. Measurements were repeated at different temperatures ranging from 15°C to 25°C.

In particular, figure 1 reports the resulting after-pulses distribution for the three values of the excess voltage, at room temperature; counts were normalized to the total number of starts. From data it was also extrapolated the expected super-linear increasing of the afterpulsing with the supply voltage [6] and its increasing with the temperature. Finally, SPAD-STM device shows a very low afterpulsing probability also at room temperature, in the order of 10^{-5} to 10^{-4} , varying with the excess bias voltage and extending up to less than about 2 μs . The experimental cut-off on data around the zero of figure 1 is connected to both the recovery time of the device and the threshold of the discriminator. The uncorrelated background of figure 1 represents the dark noise of the detector.

In order to investigate the nature of the afterpulsing phenomenon, a dedicated analysis was done. The existence of many (independent) excited trap levels supports the idea that a distribution of relaxation kinetics exists, each decay process being characterized by a lifetime t . In such a way, by denoting $P(t)$ the (density) function which represents the probability of an exponential decay characterized by a lifetime t , the emitted intensity $I(t)$ is the Laplace transform of the function $P(t)$. Analytical expression of the $P(t)$ function can be determined if experimental data $I(t)$ can be fitted to a curve that can be Laplace inverted.

In our case data relative to the SPAD-STM junction of 20 μm , reversely biased at several excess supply voltage and temperatures (in dark condition) have been considered, after having subtracted the dark counts background. More precisely the time trend of the experimental points at time $t > t_{\text{max}}$ (being t_{max} the time at which it reaches its maximum value), appeared to well accord a power-law

trend, whose parameters can be obtained by using a non-linear least-square procedure. Starting from such parameters the corresponding decay times distribution function $P(t)$ has been evaluated. Figure 3 represents the $P(t)$ distribution of the involved deep levels inside the junction, biased at a voltage value of 9,67 % over its breakdown and in different thermal conditions. It appears that the process extends up to few tens of μs [7], while the cut-off at small values of the decay constants is due to the quenching and subsequent recharging processes, as above discussed.

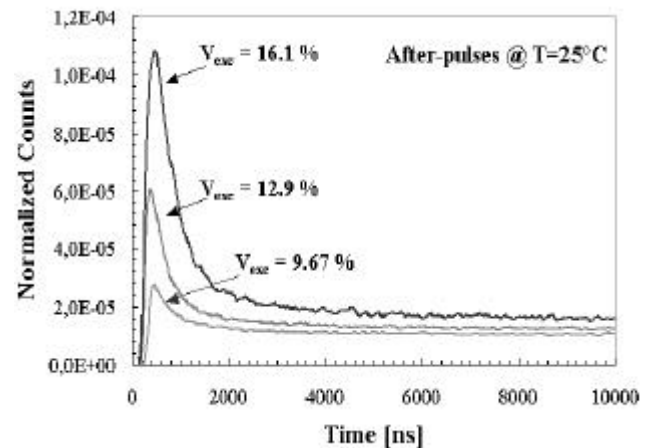


Figure 1: Afterpulsing probability for a passively quenched SPAD-STM device with an active diameter of 20 μm , at the temperature of 25°C, for three values of the bias voltage exceeding the breakdown.

Experimental tests on the quantum detection efficiency and linearity measurements were done on actively quenched samples of different active areas, biased at several voltage values above the breakdown, and reported in reference [5]. Experimental data have been demonstrated, for all the devices, a maximum of the performance in the range of the near infrared, with values greater than about 50% for samples with an active diameter of 50 μm , while about 10% at 850 nm and 3% at 1000 nm, and a very good linearity on the response.

Finally, several tests on SPAD-STM devices with an active diameter of 50 μm , passively quenched by a series resistor of 100 k Ω , have been demonstrated a very good timing performance, even at room temperature. For the experimental set-up and the analysis procedure see reference [8]. Devices dead-time is of the order of 200 ns. Actually timing performance offers an intrinsic resolution, depurated from the laser and electronic contributions, of about 60ps when in many photons regime and about 100ps in single photon condition. The real single photon operating condition was experimentally reached by the use of a particular set-up, and guaranteed by the off-line coincidence selection between the two detectors.

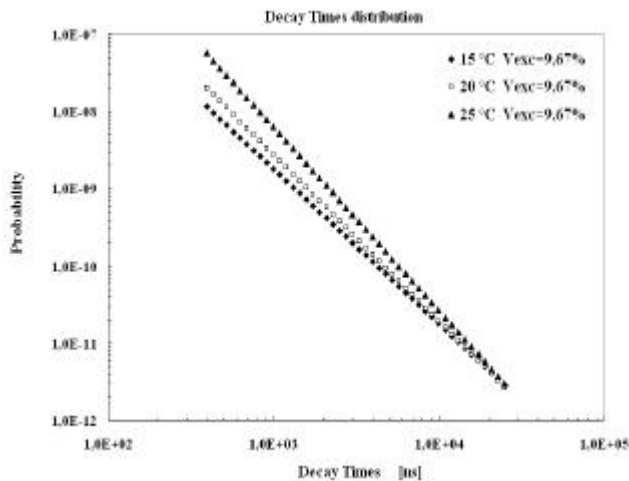


Figure 2: Decay times distributions of deep trap levels inside SPAD-STIM junction of 20 μm on diameter, at different temperature values and for a given value of the excess bias voltage.

3 SPAD-STIM 2-D ARRAY

The preliminary tests on the first 30 prototypes of identical 5x5 elements with an active diameter of 20 μm had been demonstrated a very good uniformity on both the breakdown voltage and the (low) dark counting rates values, respectively quoted by about: 31V with a dispersion of 0.8 V and 400 Hz with a dispersion of 50 Hz. Moreover, another figure of merit is fundamental in sight of the monolithic integration of many elements, that is noise arising by the induction from the adjacent detectors. During the avalanche processes some photons and electrons may reach someone of the adjacent elements and give beginning to their ignition; this phenomenon, which contribute to the detector noise, is respectively called optical and electrical *Cross Talk*. Here the results arising from its deep and complete investigation is synthetically introduced. Once that the absence of both the optical and a measurable electromagnetic contribution, which is due to the vicinity of the connection tracks, had been observed, the presence of spurious avalanches between adjacent elements was related to that one of the charged carriers lying into the substrate. This carriers trapped into the material are ready to initiate an avalanches process every time a variation on the electrical field condition occurs. Experiments in dark conditions, which tested the dependence of this Cross Talk effect to the distance between the detectors of the same array, and the analysis of data had been demonstrated, first of all, that the cross-correlation wasn't distance-dependent (inside the experimental errors) and a very low total probability per event of about 10^{-3} . In order to study this effect, a start (dark) signal had been chosen and sent on a Time Digital Converter (TDC Multi-Hit), as trigger for the

acquisition, while signals from other detectors (Cross Talk) representing the alternative stops. The collection time was 50 μs and the bin 100 ps per channel. Moreover, a comparison between the dynamics of Cross Talk and Afterpulsing effects, as presented in figure 3, has concurred to distinguish two different categories of trap levels; in particular, dynamics of Cross Talk appears faster, demonstrating that in such case the carriers trapping happens in less deep levels than those connected to the Afterpulsing effect.

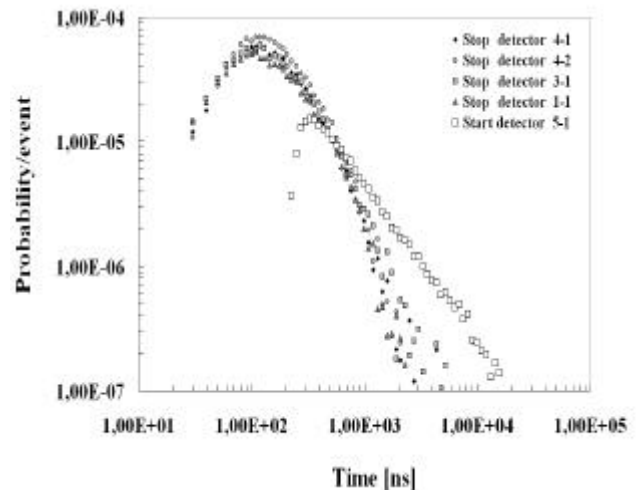


Figure 3: Extrapolated Cross Talk and Afterpulsing probability per event. Both the effects show similar trends but different dynamics.

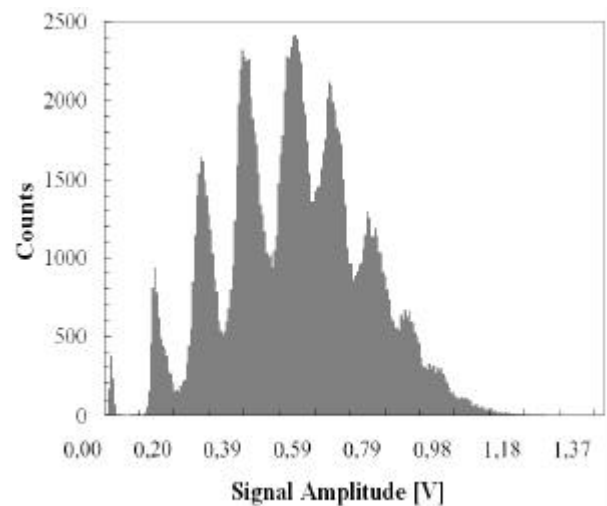


Figure 4: Amplitude distribution of events, when the array of 5x5 elements, with a diameter of 20 μm , (in SiPM configuration) was illuminated by a laser source at different intensity, rate of 2kHz, $\lambda=408$ nm and FWHM=50 ps.

Due to the uniformity on the detector response and the very low Cross Talk probability, the output SiPM signal is

expected to be a distribution characterized by a high degree of symmetry and a high peak resolution [6].

Finally, the device response in SiPM configuration as the amplitude distribution of events had been analyzed, here reported in figure 4 [6]. The 5x5 array had been illuminated, as in the previous work [9], with a laser source at different intensity, rate of 2kHz, $\lambda=408$ nm and FWHM=50 ps. The output signal had been analyzed by an Amplitude Digital Converter.

Compared to the previous result obtained by a charge integration (QDC) [9], as expected, a better resolution in terms of both peak resolution and symmetry is clearly observed.

4 CONCLUSION AND PROSPECTS

The use of high quality material and the CMOS process have been permitted the fabrication of devices characterized by a very high photon detection efficiency in a wide band and good linearity on the response, very low thermal dark counting rate and afterpulsing probability, also at room temperature. The comparison between experimental results from passively and actively quenched SPAD-STM devices was done; towards the monolithic co-integration of many elements, special attention on the passive quenching mode was given. Besides the use of a passive quenching circuitry, STM devices shows a short dead time of about 20 ns, an ultra fast pulse formation time and a good promising high timing resolution both in conditions of many and single photons.

A device which join together both the advantages of the avalanche photodiodes and of the photomultipliers is not commercially available, but is one of the major goal in the field of photonics. A similar device results from the common readout of multiple SPAD detectors. Essentially limited by the very small dimensions and the number of single elements which have to be joined together, the technological challenge is far from trivial. This so-called Silicon Photomultiplier, besides the very small dimensions, should provide high sensitivity to the single photon counting, high quantum detection efficiency over a wide spectrum, up to the near infrared region, very low dark counting rate, no sensitivity to the magnetic field and very low bias voltage. Characterization on first prototypes of 2-D SPAD-STM arrays demonstrates high uniformity on detectors responses and a very low Cross Talk probability. These advantages make the SiPM amplitude spectrum of an illuminating source a quite symmetrical distribution of very well resolved peaks [6], as it was effectively obtained.

Thus, because SPAD-STM technology is suitable for monolithic integration of 1-D and 2-D arrays of elements together with their associated circuitry, the very good performances checked for passively quenched hybrid devices suggest a simple use and management, which is an important demand especially in case of a very large number of detectors.

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RESPONSE AND RADIATION DAMAGE OF SiC DETECTORS

M. De Napoli^{a,*}, G. Raciti^a, E. Rapisarda^a, C. Sfienti^b

a) Dipartimento di Fisica e Astronomia, Università degli studi di Catania and Sezione INFN, 64, Via S. Sofia I-95123 Catania, Italy.

b) GSI, Darmstadt D-64291, Germany

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

Abstract

In order to investigate the use of silicon carbide (SiC) detectors in nuclear physics applications, we have irradiated high-quality 4H-SiC Schottky diode 21 μm thick both with alpha particles and ^{12}C and ^{16}O ions at incident energies between 2 and 53 MeV. The diode active-region depletion-thickness, the linearity of the response, the energy resolution and the signal rise-time were measured for different values of the applied reverse bias. Moreover, the radiation damage on SiC diodes irradiated with 53 MeV ^{16}O beam has been explored. The data show that SiC material is radiation harder than silicon but at least one order of magnitude less hard than epitaxial silicon diodes. An inversion in the signal was found at a fluence of 10^{15} ions/ cm^2 .

1 INTRODUCTION

In the last years the silicon carbide (SiC) has received a lot of interest as new material to be used in extreme operating conditions such as elevated temperatures, high-power, high-frequency and high-radiation fields. Indeed, one of the most appealing properties of the SiC, as well as of the other wide bandgap materials such as GaAs and diamond, is their predicted radiation hardness with respect to silicon. This property, together with a very low reverse current, makes SiC diodes suitable for the construction of specific detector arrays operating in high radiation environments.

In spite of the notable development in growing, processing and producing good-quality and low-defect SiC diodes, work to date on the use of such diodes as detectors of particles and ions has been very limited [1-5]. We have therefore studied [6] the response signal of high-quality 4H-SiC Schottky diodes to ^{12}C and ^{16}O ions and to an alpha particle source at various incident energies, in order to investigate the use of SiC detectors also in nuclear physics application. Moreover, we have investigated the SiC deterioration as a function of the radiation fluence.

2 EXPERIMENTAL DETAILS

Fig. 1 shows the layout of the Schottky diodes fabricated by epitaxy onto high-purity 4H-SiC n-type substrate from the ETC-Catania [7]. The nominal nitrogen dopant concentration and thickness of the n⁻ epitaxial layer were, respectively, 1.5×10^{16} N/ cm^3 and 21 μm ; those of the n⁺ layer were, respectively, 7×10^{18} N/ cm^3 and 279 μm .

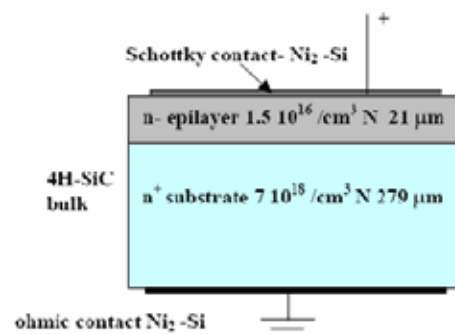


Fig. 1. The 4H-SiC diode layout. The Schottky junction is realized by the Ni_2Si layer, 0.2 μm thick, deposited at 600° C on the front surface, the ohmic layer by Ni_2Si deposited at 950° C [8].

The net doping and thickness have been measured [7], respectively, by C-V (Hg-probe) and FTR Biorad QS-500. The nominal defects mean value was 43 cm^{-3} as measured [7] by μRaman spectroscopy with Ar laser at 514.5 nm.

The active areas of the different SiC detectors were of 0.5 x 0.5, 1 x 1 and 2 x 2 mm^2 (see Fig. 2). The chips were glued on a brass foil, 1 mm thick, by a conductive glue and the single contacts between the Ni_2Si front surfaces and the pads of the board were realized by Al wire, 2 μm thick, bonding. Two boards with, respectively, six and five chips 2 x 2 mm^2 of surface were assembled, for a total number of 11 independent detectors. A third board was equipped with a Si detector 3 x 3 cm^2 of surface and 300 μm thick which was used as reference. The three boards were set up in the new scattering chamber FRIBs located at the end of the LS-20 beam line and operated under vacuum at 10^{-6} mbarn.

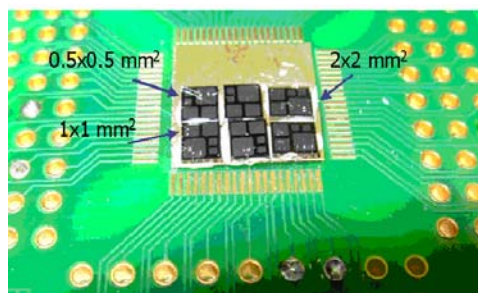


Fig. 2. Picture of the SiC detectors assembled on a board.

Standard electronics was used to process the signals: preamplifiers of 45mV/MeV gain and amplifiers with 0.5 μ s shaping time. Data acquisition was based on CAMAC ADCs read out through a GPIB standard National Instruments interface and a data-acquisition program built in the LabView 7 framework. Moreover, the preamplifier and amplifier signals were digitized by a Tektronix TDS 5104B digital oscilloscope.

The active samples were irradiated with both 5.48 MeV alpha particles from an ^{241}Am source and ^{12}C and ^{16}O beams accelerated by the Tandem at different energies and currents.

3 DETECTOR RESPONSE

The signal response to the alpha particles and the ^{12}C and ^{16}O ions was analysed in terms of linearity, energy resolution and rise-time as a function of the applied reverse bias. Indeed, we measured, at first, the correlation between the thickness of the depleted layer and the applied bias, which is expected to follow a square-root law [9]. By using four Al absorbers of 10, 13, 14.6 and 17.3 μm thicknesses, in front of the ^{241}Am alpha source, we scaled the incident energy from 5.48 to 3.76, 3.18, 2.72 and 2.19 MeV, respectively, as measured by the calibrated silicon detector.

The high degree of linearity observed in the correlation between the pulse height and the energy, shown in Fig. 3, for SiC detectors is consistent with previous measurements [1,2,4] and indicates the proportionality of the produced ionization charge to the deposited energy.

Using the SRIM code [10] calculations, the ranges of the alpha particles at the four incident energies in the SiC material were evaluated to be: 10.8 ± 0.4 , 8.5 ± 0.5 , 7.0 ± 0.6 and 5.4 ± 0.5 μm , respectively. For a given alpha energy we then searched for the value of the applied reverse bias at which the saturation of the pulse height signals is reached. The correlation between the evaluated range and the applied reverse voltage, shown in Fig. 4, is nicely reproduced by a square-root law [9].

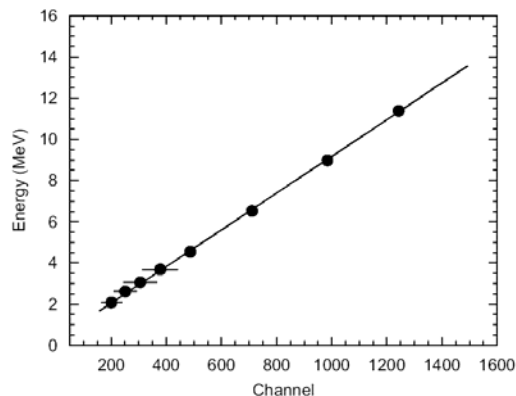


Fig. 3. Pulse height (channel) versus energy plot. Data points refer to the ^{12}C (5.06 (4.5) MeV) and ^{16}O (7.3 (6.5), 9.78 (9.0), 12.18 (11.4) MeV) beams and to the four alpha particles energies. The energy values in parentheses are the ones corrected for the energy lost in the Ni_2Si 0.2 μm thick front layer on the detector. The linear correlation coefficient R^2 from the fit has a value of 0.998.

Similar to the measurements performed with the alpha source, a number of spectra were taken over a range of bias voltages, from 0 to -450 V, for the ^{12}C beam at 17.68 MeV incident energy. In this case, no saturation has been observed in the peak centroid values, since the active region of the detector does not extend beyond the range of the ^{12}C at 17.68 MeV even at the maximum applied voltage. Therefore, we evaluated the thickness of the depleted region by comparing SRIM calculations to the energy loss measured at the different applied biases. Fig. 4 shows the results also for the ^{12}C .

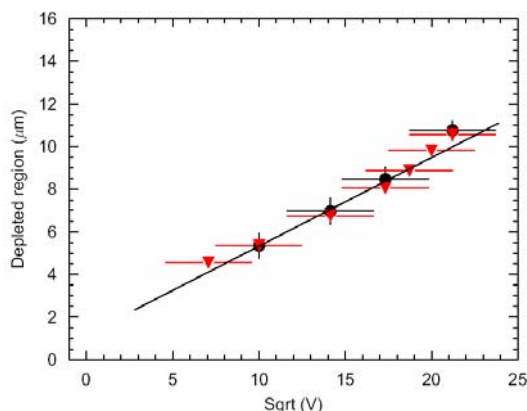


Fig. 4. Correlation between the square root of the applied bias and the SiC depletion layer thickness for alpha (circles) and the 17.68MeV ^{12}C beam (triangles).

In order to measure how the energy resolution behaves as a function of the thickness of the active region and therefore of the applied bias voltage, we have fitted the shape of the energy response spectra for the ^{12}C at 17.68 MeV with a Gaussian function. Fig. 5 shows the relative energy resolution (FWHM of the peak over the peak position) as a function of the applied bias voltage. Besides an initial enhancement from 0 to -50 V, the relative resolution increases slowly over the range of the applied bias voltages up to a value of 1.8%. The measured energy resolution values are in good agreement

with the ones observed in other measurements [2], although larger than the recently reported SiC energy resolution value of 0.34% [11,12].

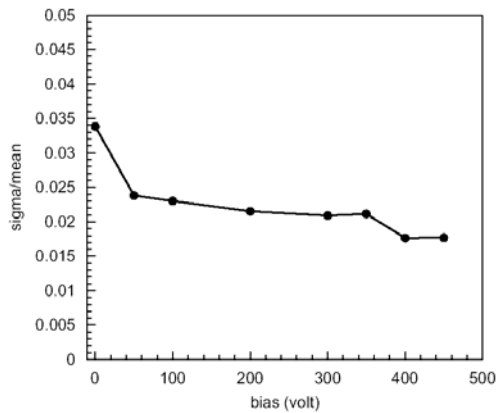


Fig. 5. Relative energy resolution versus applied reverse bias.

Moreover, by storing the waveforms of the preamplifier output in the Tektronix TDS 5104B digital oscilloscope we analyzed the behaviour of the pulses generated by the ^{12}C beam at 17.68 MeV. Typical pulses are reported in Fig. 6 for four different reverse bias values (V_{bias}). The decrease of the signal rise-time is related to the combined variations of the drift velocity of the ionization charges, proportional to V_{bias} , and of the depleted region thickness, proportional to $\sqrt{V_{\text{bias}}}$. Indeed, the rise-time varies from

97 at -100 to 68 ns at -200 V and reaches 46 and 44 ns at -400 and -450 V, respectively. As expected the ratios of the measured rise-time values scale as the inverse ratio of the square root of the applied bias voltages.

All the tested 11 detectors of identical configuration, showed, within the error bars, the same characteristics here reported.

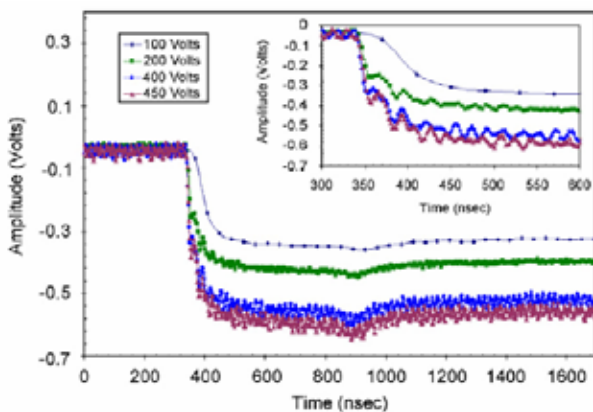


Fig. 6. Signals from the preamplifier generated by ^{12}C ions at 17.68 MeV incident energy for different applied bias values.

4 RADIATION DAMAGE

One of the main motivation of such study was to explore the radiation hardness properties of such SiC detectors. Five samples, polarized with a reverse bias of -100 V, were irradiated using 53 MeV ^{16}O ions provided

by the Tandem and their output signals were monitored during the irradiation time. Fig. 7 shows the peak centroid value of the ^{16}O spectrum as a function of the fluence. The amplitude dropped to 50% at a fluence of 6.5×10^{14} ions/cm² (see Fig. 7) in good agreement with results of Refs. [5,13]. At the same time, the reverse current increased by a factor of five and the noise by a factor of two (see Fig. 8).

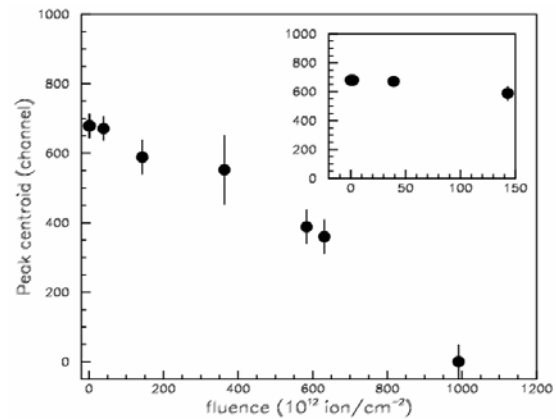


Fig. 7. Peak value of the spectrum of 53 MeV ^{16}O beam measured at increasing fluence. The plot at the lowest values of fluence is expanded in the insert.

The present SiC diodes are therefore around 10 times radiation harder than silicon diodes but a factor 10 less hard than thin epitaxial Si diodes for which the Charge Collection Efficiency (CEE) drops only to about 80% at 6×10^{15} protons/cm² at 24 GeV of incident energy [5]. However, it is not clear how to compare the damage produced by low-energetic ^{12}C or ^{16}O ions to the damage produced by protons, neutrons, gammas or pions and which kind of defects, among the known ones, are produced during irradiation.

A surprising inversion in the signal (Fig. 8) was found at the detector break point, corresponding to a fluence of 10^5 ions/sec. Therefore, we inverted both bias and amplifier polarities and we sent on the irradiated detectors an ^{16}O beam at 12 MeV, which releases in the depleted region of the SiC (5.4 μm) a different energy (8.3 MeV) with respect to the ^{16}O beam at 53 MeV (12 MeV). However, the pulse height of the signal was the same in both cases: the detector was sensitive to the charged ion but not to the deposited energy.

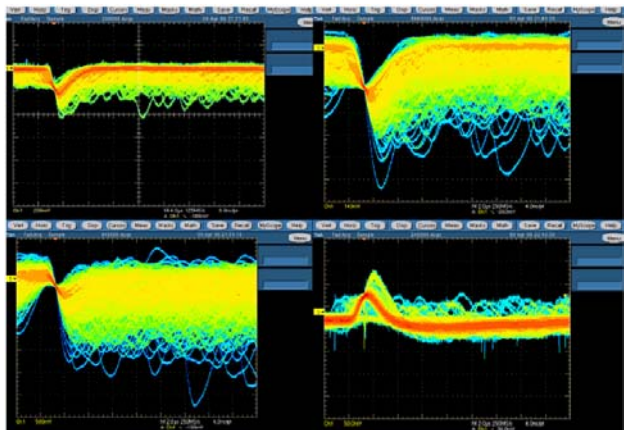


Fig. 8. Pulses from a SiC diode irradiated with the 53 MeV ^{16}O beam. Clockwise from top left: beginning of the irradiation, at fluence of $3.5 \cdot 10^{14}$ ions/sec, at a fluence of $7 \cdot 10^{14}$ ions/sec, and at a fluence of 10^{15} ions/sec: note the inversion of the signal.

5 CONCLUSION

SiC Schottky diodes 21 μm thick with small surfaces and high N-dopant concentration have been used to detect alpha particles and ^{12}C and ^{16}O beams at various incident energies. The signal response was analysed in terms of linearity, energy resolution and rise-time as a function of the applied reverse bias. Energy resolution of around 1.8%, rise time up to 44 nsec and the correlation between the square-root of the applied reverse bias and the thickness of the depletion region on the SiC diode have been measured. In particular, the maximum applied bias of -450 V depletes only 11.2 μm of the SiC active area.

The radiation damage vs dose measurements have been performed by irradiating the SiC samples with 53 MeV ^{16}O ions. The amplitude of the signal drops down to 50% at a fluence of 6.5×10^{15} ions/sec indicating more than one order of magnitude hardness to the radiation with respect to silicon diodes. A surprising inversion in the signal was found at a fluence of 10^{15} ions/sec and need to be further investigated to understand if it is produced by radiation damage or by the ^{16}O implanted in the material.

The good performances we have measured, are unfortunately balanced by the inconvenience of the high values of bias voltage needed to deplete the active region of the diode. However we expect a correlation between the depleting bias values and the N doping concentration in the epitaxial region [1]. We will investigate in the next future such a correlation, being aware of the negative influence on the ionization charge production and radiation hardness of a reduced doping concentration.

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CHARACTERIZATION OF SINGLE CRYSTAL CVD DIAMOND DETECTORS BY NUCLEAR DETECTION

Cristina Tuve^{a*}, R. Potenza^a, S. Costa^a, M. Chiorboli^a, A. Giusa^a, F. La Rosa^a, F. Mammoliti^b, F. Raimondo^a, G. Russo^a, M.A. Saizu⁺, C. Sutura^a, V. Bellini^b, G. Prestopino^c, M. Marinelli^c, E. Milani^c, A. Tucciarone^c, G. Verona-Rinati^c, M.G. Donato^d, G. Messina^d, S. Santangelo^d

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

d) Dipartimento di Meccanica e Materiali, Facoltà di Ingegneria dell'Università, 89060 Reggio Calabria, Italy

** Corresponding author, e-mail: cristina.tuve@ct.infn.it*

+ On leave from IFIN-HH, Bucharest, Romania

Abstract

Three-layer structures consisting of intrinsic/B-doped homoepitaxial CVD diamond grown onto commercial HPHT Ib substrates in the Laboratories of Roma "Tor Vergata" University by MicroWave Plasma Enhanced Chemical Vapor Deposition (MWPECVD) have been studied by means of Raman spectroscopy, photoluminescence (PL) and nuclear techniques.

The intrinsic layers have been deposited, at fixed methane to hydrogen ratio (1%), by systematically changing the substrate temperature (620-820 °C). Raman measurements pointed out the excellent crystalline quality and phase purity of the samples. Moreover, completely flat PL spectra in a wide energy range (1.7 eV-2.7 eV) indicated also their great purity. A clear correlation between excitonic emission and detector sensitivity was demonstrated. On the basis of these results, low methane concentrations (1% CH₄/H₂) in the deposition gas mixture and intermediate substrate temperatures (720 °C) have been identified as the best working conditions of our growth reactor.

Another important test of the film quality is based on the measure of the charge collection efficiency of the diamond. So the films were characterized through their response as nuclear detectors to ¹²C ions from 15MV Tandem accelerator of LNS. The energy resolution and the charge collection efficiency η of the specimens resulted very good, near to the best expected values. The reproducibility however and the influence of metal-diamond interfaces must be better investigated.

1 INTRODUCTION

Great effort is currently devoted all over the world to the optimization of the deposition process of high-quality

homoepitaxial single crystal CVD diamond (scCVD). In fact, encouraging results have been obtained for UV and particle detectors [1-8] based on homoepitaxial CVD diamond samples. However, such results suggest [3, 5, 9, 10] that further optimization of the material quality is necessary if one needs diamond-based detectors really competing with Si-based standard devices. In this regard, characterization techniques such as Raman spectroscopy, photoluminescence and nuclear detection, already successfully used to optimize the crystalline quality and detection properties of polycrystalline CVD (pCVD) diamond films [11-15], may provide precious hints also for the optimization of the deposition process of detector-grade scCVD diamond.

To this aim, we will report the results obtained bombarding scCVD diamond based detectors with ¹²C ions elastically scattered by ¹⁹⁷Au at various energies produced in the 15 MV Tandem accelerator of LNS.

2 EXPERIMENTAL SETUP

The studied samples consist of three-layer structures where the upper intrinsic layer has been deposited by CVD using a 1% CH₄/H₂ gas mixture. The intrinsic layer is separated from the commercial type Ib diamond substrate (Sumitomo) by a 15 μ m thick previously deposited and B-doped homoepitaxial layer.

Particle detectors have been realized by depositing Al contacts onto the intrinsic layer, whereas the B-doped layer has been used as the backing contact [17]. This configuration has been designed to avoid any contribution to the response of the device coming from the Ib substrate, whose mechanic removal is hard to obtain without damaging the homoepitaxial layer deposited on it.

At LNS the experimental setup allowed a ^{12}C collimated beam from the 15 MV Tandem accelerator to impinge on a $\sim 300 \mu\text{g}/\text{cm}^2$ thick gold target. The energy of the ions was varied between 27 MeV and 77 MeV. The scattered ions were detected through two scCVD diamond detectors (D3: $24 \mu\text{m}$ thick, $V = 120\text{V}$ and D4: $22 \mu\text{m}$ thick, $V = 132\text{V}$) placed at $\theta = 20^\circ$ with respect to the beam. The detectors were mounted on a single rotating holder in order that the penetration depth of the incident particles along the electric field applied to the detectors could be varied at the same incident energy. The detectors angle ϕ with respect to the direction of the impinging particles was varied in the $0^\circ \div 80^\circ$ range. Combining both the angle and energy scans, the penetration depth varied from few microns to the whole diamond thicknesses. We used also other two scCVD diamond detectors (D1: $25 \mu\text{m}$ thick, $V = 150\text{V}$ and D2: $43 \mu\text{m}$ thick, $V = 129\text{V}$) placed at $\theta = -20^\circ$ with respect to the beam and maintained at $\phi = 0^\circ$ with respect to direction of the impinging particles. In these other detectors the pulse heights were taken at different detector temperatures, varied in the $6.5 \div 60^\circ\text{C}$ range. The diamond detectors were placed in a copper support cooled with liquid Paraflu. The different temperatures were maintained using a programmable environmental chiller thermostat (Calora).

Beyond the measurements done varying penetration along electric field and varying sample temperature at the same penetration, we also detected pulse height spectra for a certain penetration and temperature at varying measurement time: that is we stopped the measurement during a given run at a given time interval, took the spectrum, continued the run for an equal time interval, stopped again and so on up to the chosen length of the run. The time intervals inside each run and the length of the run were also varied. Moreover, some data were taken also varying beam currents between 0.5 nA to 10 nA.

These measurements were made in order to confirm (or exclude) slow depolarization of diamond detectors. That is to investigate if the charge collection efficiency depends on measurement time at high beam currents and if this effect (if present) depends on the formation of a barrier at the contacts or if it depends on slow depolarization of the dielectric (the diamond).

The energy calibration was done with respect to Si detectors. Target and detectors were contained in a high vacuum scattering chamber. Pulses from Si and diamond detectors were amplified through conventional ORTEC charge preamplifiers followed by amplifiers, digitalized and registered on disc to be analyzed off-line afterwards.

3 RESULTS

3.1 Raman Spectroscopy

In Fig.1, typical Raman and photoluminescence spectra of homoepitaxial samples used in this work are shown. The narrow line width of the first order Raman spectrum points out a very high crystalline quality, which can compete with that of the best natural diamonds.

Moreover, the flat photoluminescence spectrum in the visible range witnesses the purity of the material obtained, as the most common nitrogen inclusions found in CVD diamond give PL features at 2.46 eV (N-V-N defect), 2.16 eV (N-V center) and 1.95 eV (N-V defect in a negative state of charge). A clear correlation between excitonic emission and detector sensitivity was demonstrated [18]. On the basis of these results, low methane concentrations (1% CH_4/H_2) in the deposition gas mixture and intermediate substrate temperatures (720°C) have been identified as the best working conditions of our growth reactor.

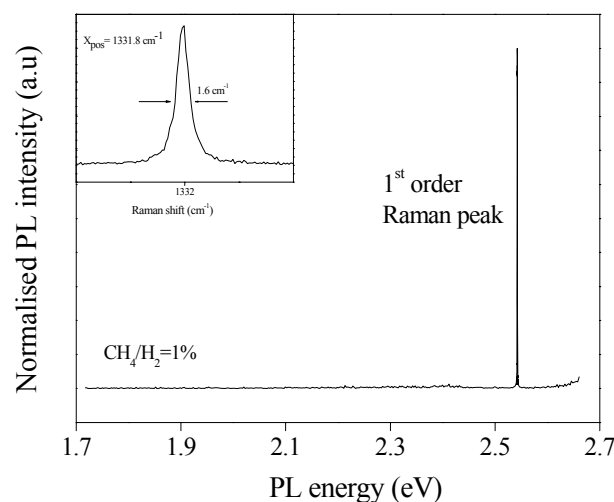


Fig.1 Typical photoluminescence spectrum of the homoepitaxial samples studied in this work. Exciting wavelength: $\lambda = 457.9 \text{ nm}$. In the inset: enlarged typical Raman spectrum of the same samples. Exciting wavelength: $\lambda = 514.5 \text{ nm}$.

3.2 Results of LNS measurements

3.2.1 Results for diamond detectors D1 and D2

We report the results for the detector D1: the detector D2 broke off during measurements. They depended on the beam energy. As a matter of fact for $E_{\text{beam}} = 45, 64$ and 77 MeV the ions crossed the whole thickness of the detector. For these energies we took data varying the temperature and the measurement time at fixed beam current. The charge collection efficiency versus the measurement time at same energy and beam current for different temperature show a charge collection efficiency η independent on measurement time later on 40 min, but for lower at higher temperatures. In Fig. 2 we reported η versus measurement time for different temperatures at $E_{\text{beam}} = 77 \text{ MeV}$ and beam current = 2 nA. The charge collection efficiency is about 85% at -6°C , 0.6°C and 25°C and 65 % at 60°C . The lower η seems to be ascribed to a larger recombination of the carriers in diamond at higher temperature.

At $E_{\text{beam}} = 27 \text{ MeV}$ the penetration depth for ^{12}C is $14 \mu\text{m}$. We took data at different beam intensity and also at different measurements time and temperatures of the

sample. Fig. 3 show η versus measurement time for different temperatures at a beam current = 2nA. In this case, with no dependence on temperature, the mean value of η is about 80%. If we look at the energy spectra we see the presence of double peaks at low temperatures (1°C, 25°C) but not a 60°C. The appearance of these spurious peaks decrease the measured charge collection efficiency at low temperature, so also at 27 MeV there could be a dependence on temperature similar to that found at higher energies. Why the double peaks appear is not clear. A hypothesis can be the formation of a barrier at the contacts (Schottky barrier) of the detector.

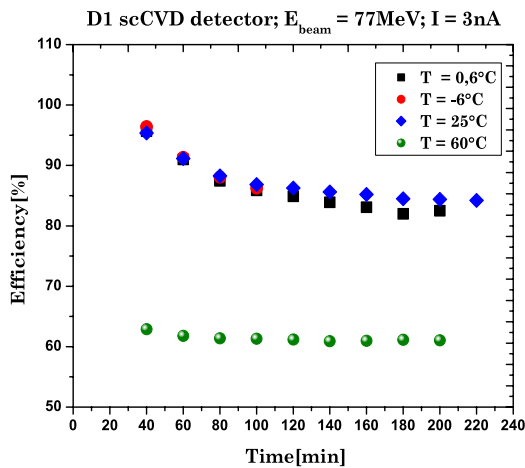


Fig. 2 Charge collection efficiency of the D1 scCVD diamond detector versus measurements time at $E_{\text{Beam}} = 77 \text{ MeV}$, at $I=3\text{nA}$ and at different temperature.

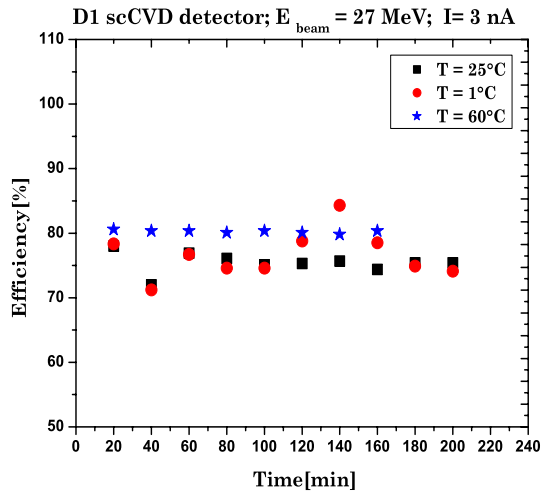


Fig. 3 Charge collection efficiency of the D1 scCVD diamond detector versus measurements time at $E_{\text{Beam}} = 27 \text{ MeV}$, at $I = 3 \text{ nA}$ and at different temperatures.

Contact effects arise from space charges that are present at the interface of two materials. The space-charge layer extends over a fraction of the sample thickness, which depends on the type and quality of the material. This barrier modifies the electric field where the

carriers are produced and so can modify the pulse heights: how much will depend on particle penetration. At high temperature the transport in CVD diamond seems dominated by fast recombination and trapping of carriers: this decreases the charge collection efficiency and this last effect blocks out, at 60°C and at 27 MeV, the formation of a double peak which is likely caused by the uniform electric field inside the diamond.

At high energy the carriers arise also near the substrate region, far from the metal contact so we don't see double peaks and the low value of charge collection efficiency is ascribable to the recombination effects at high temperatures.

3.2.2 Results for diamond detectors D3 and D4

Of the diamonds D3 and D4 we measured the charge collection efficiencies vs. measurement time and intensity of beam for all used beam energies. The results obtained for both detectors are about the same, so we discuss only those of D3 sample.

Fig 4 shows the measured energy versus the angle ϕ of incidence of the particles on the detector. The curves in the graph were calculated considering that: i) the charge collection efficiency was in the $0.92 \div 0.95$ range (so very high for all energies); ii) there is a systematic error of $\pm 5^\circ$ in the measured angle and iii) the effective thickness of the diamond was $20 \mu\text{m}$.

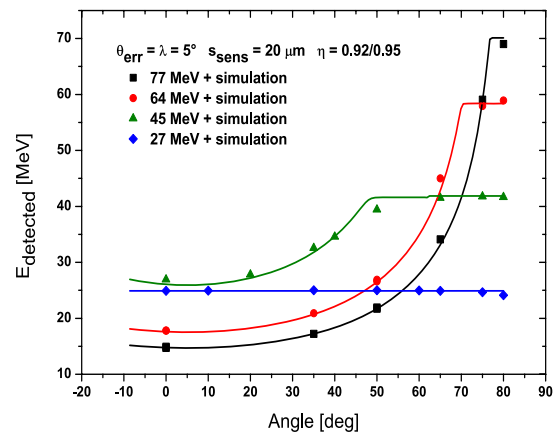


Fig. 4 Measured energy for ^{12}C ions of various incident energies vs. incidence angle on the detectors.

The energy resolution for D3 diamond detector at $E_{\text{beam}} = 27 \text{ MeV}$ and at $\theta = 0^\circ$ is about 1.5%. This value does not depend on measured time and penetration depth. It is very good and characteristic of these new detectors. For other energies a resolution of about 6% was measured. It seems that for this detector the space-charge layer extends over a fraction of the sample thickness smaller than that we have for diamond detector D1. This confirms that the layer depends on the type and quality of the material. It is possible that the worse energy resolution for high energies be ascribable to this space-

charge layer that modifies the pulse height produced by the diamond detector.

4 CONCLUSIONS

The results obtained for three-layer structures consisting of intrinsic/B-doped homoepitaxial CVD diamond showed that the charge collection efficiency is about 100% for all the detectors we used in the measurements at LNS. The energy resolution is $\sim 1.5\%$, when space-charge effects at contacts are not present. We didn't see effects of slow depolarization of the dielectric, the charge collection efficiency is in fact independent from measurement time and intensity of the beam. The charge collection η shows a small dependence on temperature of the device and on penetration depth. We suppose that this effects are due to the presence of the space-charge barrier at the contacts.

Further investigation should be done on this devices mainly modifying the contacts with different metals and measuring the I-V characteristics, in order to obtain true ohmic contacts.

In the next LNS measurements we will compare the diamond detectors growth at Roma Tor Vergata Laboratory with the diamond detectors realized by the Element Six Corporation, to compare their intrinsic and contact characteristics.

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Astroparticle physics



THE NEMO PROJECT: STATUS AND PERSPECTIVES

E. Migneco^{a,b} for the NEMO collaboration

a) INFN Laboratori Nazionali del Sud, Catania, Italy

b) Dipartimento di Fisica e Astronomia Università di Catania Italy

Abstract

The completion of the NEMO Phase-1 project that aims to validate the technologies for the km³ underwater detector was achieved with the construction of all the key elements of the underwater neutrino telescope and their deployment in the LNS Test Site at 2100 m depth. The NEMO Phase-2 project is in progress with the realization of an infrastructure on the candidate site at Capo Passero (Sicily, Italy) that will allow the test detector components at 3500 m depth and a long term monitoring of the site.

1 INTRODUCTION

High energy neutrino astronomy needs detector volumes of km³ scale to reveal the rare neutrino events producing tracks in the detector medium. Neutrino telescopes have to be shielded from the atmospheric muon background that would completely swamp the tiny effects due to neutrinos. For this reason, such detectors are deployed in deep sea or ice that act as radiator of Cherenkov light and as a screen for muon background. At the South Pole the IceCube km³ detector is under construction in deep antarctic ice. A km³-scale neutrino telescope in Mediterranean Sea, i.e. in the opposite hemisphere with respect to IceCube, will allow to achieve full coverage of the neutrino sky. In particular, a telescope in the Mediterranean Sea will allow to watch the Galactic Centre where interesting new phenomena were recently observed.

The construction of an underwater high energy neutrino telescope represents a remarkable challenge. Indeed, in deep sea instrumentation must be protected against corrosion and pressures as high as 350 bar. Moreover, the experiment reliability must be tuned to a life time of the order of ten years.

NEMO is an advanced R&D project that aims at the design, realization and validation of key technologies needed for the construction, deployment and maintenance of an underwater high energy neutrino telescope in the Mediterranean Sea [1].

2 NEMO PHASE-1

In December 2006, NEMO reached a major achievement with the successful deployment and connection of a technological demonstrator: NEMO

Phase-1. This system that includes prototypes of the critical elements of the proposed km³ detector: the junction box and the tower, was installed at the Underwater Test Site of the Laboratori Nazionali del Sud. It consists of a off-shore deep sea station and a on-shore station. Communication from and to shore is provided by a cable system composed by a 23 km main electro-optical cable. The cable, with 6 electrical wires and 10 monomode optical fibers, is split at the end in two branches, each one 5 km long. One branch is used for the NEMO Phase-1 experiment, while the other one provides connection for the SN-1 underwater seismic monitoring station, realized by the Istituto Nazionale di Geofisica e Vulcanologia (INGV) SN-1. SN-1 is the first European sea-floor real-time observatory and is in acquisition since January 2005. The SN-1 seismological data are integrated in the INGV land-based national seismic network and arrive in real-time to the Operative Centre in Rome.

The shore station, located inside the Catania harbor, hosts the power feeding system, the instrumentation control system, the landing station of the data transmission system and the data acquisition for both NEMO Phase-1 and the multidisciplinary experiments (SN-1, OvDE) hosted in the deep sea station.

The deep sea installation is composed by a Junction Box (JB) and a prototype detector structure called *mini-tower*.

The Junction Box is a key element of the detector. It provides connection between the main electro-optical cable and the detector structures assuring data transmission from and to shore for both physics and



Fig. 1- NEMO Phase-1 general lay-out.

control signals. The JB is designed to host and protect from the effects of corrosion and pressure the voltage transformer, the opto-electronic boards dedicated to the



Fig. 2 - The fully assembled Junction Box during the filling of the fiberglass vessel with silicone oil.

distribution and the control of the power supply and digitized signals. An innovative design with respect to the standard Titanium pressure vessels used for junction boxes operating in deep seawater for a long lifetime was developed. The idea is to decouple the pressure and corrosion resistance problems. The JB is made of four cylindrical steel pressure resistant vessels hosted in a fiberglass container that prevents contact between steel and sea water. The fiberglass container is filled with silicone oil and pressure compensated. All the electronics able to withstand high pressure is installed in oil bath, while the rest is located inside one pressure resistant container.

The tower is the structure that hosts the optical modules (OM) and the instrumentation. It is the basic element of the telescope for the detection, through the Cherenkov light, of the tracks induced by neutrinos. It is a three dimensional flexible structure composed by a sequence of storeys, hosting the instrumentation, interlinked by electro-optical cables and anchored on the seabed. The structure is kept vertical by a buoy on the top.

While the design of a complete tower for the km^3 consists of 16 storeys, for Phase-1 project a mini-tower of 4 storeys was realized. Each storey consists of a 15 m long structure hosting two optical modules (one down-looking and one horizontally-looking) at each end (4 OM per storey). The storeys are vertically spaced by 40 m. Each storey is connected to the following one by means of four ropes that are fastened in a way that forces each storey to take an orientation perpendicular with respect to the adjacent (top and bottom) ones. An additional spacing is added at the base of the tower,

between the tower base and the lowermost storey to allow for a sufficient water volume below the detector.

In addition to the 16 OM the instrumentation installed includes several sensors for detector calibration and environmental monitoring. In particular two hydrophones are mounted at the extremities of each storey for precise determination of the OM position by means of time delay measurements of acoustic signals provided by acoustic beacons placed on the seabed and one at the tower base.

The environmental sensors assembled in the mini-tower provide continuous monitoring of the deep sea environmental parameters.

The integration and tests of the whole mini-tower including mechanics, electronics and cabling system were completed in fall 2006.

The NEMO Phase-1 system was installed in December 2006 in a sea operation conducted with the cable layer vessel Teliri. The installation started with the

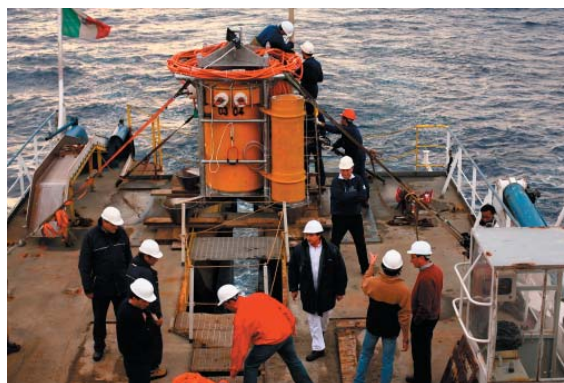


Fig. 3 – The Junction Box deployment procedure.

deployment of the JB at 2100 m depth (see Fig. 3). The JB was then connected to the main cable termination frame through a wet mateable hybrid connector operated by a underwater Remotely Operated Vehicle (ROV). After the JB connection Teliri came back to the harbor to take aboard the 15 m long mini-tower with the



Fig. 4 - The mini-tower with the 4 floors packed at the exit from the LNS shore station.

4 floor packed (see Fig. 4) on the tower base that is also the anchor of the structure. The mini-tower was deployed at about 200 meters from the JB and connected to the JB through a wet mateable hybrid connector. The use of ROVs for detector installation in deep sea is one of the distinctive technical strategies of the NEMO project. The connections of the NEMO JB and mini-tower, successfully operated by ROV, validated a viable procedure for the installation and maintenance of the future km^3 neutrino telescope in the Mediterranean Sea. Then the three acoustic beacons were deployed to define the field of the acoustic

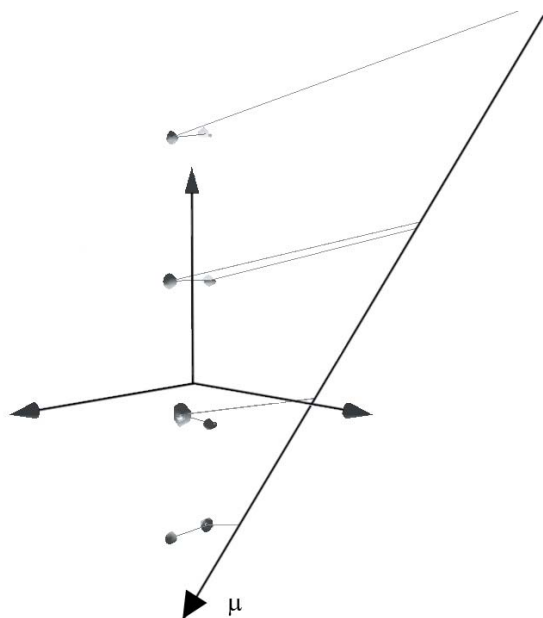


Fig. 5 – Reconstructed down-going muon track.

monitoring system. Eventually, the unfurling of the mini-tower took place, always using the ROV.

During the various stages of the installation, the apparatus was monitored from the shore station via the electro-optical cable.

The installation of NEMO Phase 1 ended on the 18th of December 2006 and the mini-tower is in data-taking since then. The data analysis concerning both the environmental parameters and the muon track reconstruction is in progress. Several muon tracks have been already reconstructed (see Fig. 5).

3 NEMO PHASE-2

NEMO Phase-2 aims to realize an infrastructure on the site of Capo Passero that is the Italian site candidate for the installation of the neutrino telescope in the Mediterranean Sea. NEMO Phase-2 will allow to test prototypes at the depth of 3500 m. Moreover, it will allow a continuous long term on-line monitoring of site properties that is essential for the installation of the full km^3 detector.

It consists of a 100 km cable, linking the 3500 m deep sea site to the shore, a shore station, located inside the harbour area of Portopalo di Capo Passero, and a full size tower of 16 storeys.

In this case the backbone cable is a DC cable, manufactured by Alcatel. The cable consists of a single electrical conductor, that can be operated at 10 kV DC allowing a power transport of more than 50 kW, and 20 single mode optical fibers for data transmission.

The bathymetry of the seabed to define the cable path was performed in 2006 and the cable has been already realized. The makeover of the shore station is in progress. The completion of this project is foreseen by 2008.

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ACOUSTIC BACKGROUND MEASUREMENTS WITH NEMO-ONDE

G. Riccobene^a, G. Cosentino^a, G. Pavan^b, F. Speziale^a, the NEMO Collaboration

a) INFN Laboratori Nazionali del Sud, Catania, Italy

b) CIBRA, University of Pavia, Via Taramelli 24, 27100 Pavia, Italy

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

ABSTRACT

The NEMO (NEutrino Mediterranean Observatory) Collaboration constructed and operated, 25 km E from Catania (Sicily) at 2000 m depth, NEMO Phase 1: an underwater test site to perform long-term tests of prototypes and new technologies for an underwater high-energy neutrino detector in the Mediterranean Sea. In this framework, on January 2005 the collaboration deployed and operated for 2 years, a pilot experiment for on-line monitoring of deep-sea noise. The station was equipped with 4 hydrophones operational in the range 30 Hz - 40 kHz. This interval of frequencies matches the range suitable for acoustic detection of high energy neutrino-induced showers in water. Hydrophones signals were digitized underwater at 96 kHz sampling frequency and 24 bits resolution. A custom software was developed to record data on high resolution 4-channels PCM file. Data are used to model underwater acoustic noise as a function of frequency and time, a mandatory parametre for future acoustic neutrino detectors. Results indicate that the average noise in the site is compatible with noise produced in condition of sea surface agitation (sea state) between 1 and 2. A test on the possibility to track acoustic source direction was also carried out successfully. Recorded data permitted also to monitor an unexpectedly abundant presence of marine mammals (sperm whales) in the region.

1 INTRODUCTION

An important issue in experimental astroparticle physics is the realization of underwater km³ neutrino telescopes for high energy neutrinos [1]. These apparatuses are arrays of large-area photomultipliers (typically about 10 inches diameter) designed to detect Cherenkov light radiated in water by charged leptons outgoing neutrino Charged Current interactions. The reconstruction of Cherenkov tracks allows the identification of the lepton direction and energy thus, to some extent, the neutrino ones. Proposed affordable detectors (NEMO [2], ICECUBE [3]), equipped with about 5000 PMTs, are expected to reach detection areas of km² at $E_\nu = 1\div 100$ TeV and to detect astrophysical point-like and diffuse neutrino fluxes originated by several astrophysical sources (AGN, GRB, microquasars, SNR). At higher energies (more than 10^{18} EeV) however, the expected neutrino fluxes are fainter and detectors with detection areas >10 km² are required. A different detection technique was suggested to build larger detectors [4]. At

these energies neutrino interactions in water produce showers, which release instantaneously a macroscopic amount of energy in a small volume of matter. Ionization and sudden heating of water produce a bipolar pressure pulse, which expands perpendicularly to the shower axis. The maximum wave amplitude, calculated with thermo-acoustic models, scales linearly with the density of energy deposition: for a 100 PeV hadronic shower it is about 400 mPa at a distance of ~ 1 km from the shower core [5]. The wave peak frequency is estimated to be in the range of ten kHz. The advantage of acoustic detection is the long absorption length of sound in water: in this frequency range, it is of the order of km. The knowledge of acoustic background is fundamental in order to carry out a feasibility study for an underwater acoustic neutrino detector. Noise in the sea has different origins: biological (fishes, marine mammals, crustaceans), mechanical (wind and surface waves, molecular thermal vibrations) and due to human activities (navigation, fishing, military operations, oceanographic instrumentation, oil exploration). Biological and human noises could reach very high pressure level, but they are, generally, produced by local and intermittent sources. In the frequency range of interest, noise is, in average, mainly due to surface agitation and to navigation that, in the Mediterranean Sea, can be assumed as constant acoustic background [6]. At present, only few measurements of acoustic noise have been carried out at depth larger than 2000 m, where acoustic detectors should be presumably located. At these large depths it is expected that surface noise should be strongly reduced, due to the change of sound refraction index with depth. On the other hand, it is not clear the value of sound emissions generated by cetaceans, animals that can immerse down to thousand meters depth [7]. In order to measure the level of acoustic noise in deep Mediterranean Sea, NEMO has developed a station that was installed at the Catania NEMO Test Site (TSS) for 2 years from January 2005 to December 2006.

2 THE ONDE ACOUSTIC STATION

The OvDE apparatus is designed to perform on-line monitoring of the acoustic noise at large depth. The station is equipped with four large bandwidth hydrophones (30 Hz - 40 kHz). Each hydrophone (hereafter H1, H2 H3 and H4) is mounted on an aluminum alloy vessel, pressure resistant, which also hosts the hydrophone preamplifier. The analog signals from preamps are transmitted, through underwater cables suitable for audio applications, to a glass housing that

hosts the digitization, data transmission and power distribution electronics. Analog signals are digitized, at 96 kHz sampling rate and 24 bits resolution, translated into optical and sent to shore through the optical fibers of the main cable. On shore, digital optical data are reconverted into electrical and recorded using a PC, in which a pair of professional PCI audio boards are mounted. The mechanical structure of OvDE is composed by: a commercial glass housing (which hosts the DAQ and power supply electronics), one electro optical (e.o.) cable that connects the station to the e.o. plug mounted on the NEMO underwater TSS frame [8] and, four electric cables that connect the housing to the hydrophone vessels, the hydrophone vessels. OvDE was designed to be deployed, in a single operation, together with the TSS frame, in order to avoid the use of ROV during the deployment. For this reason the station is hooked to the TSS titanium frame. The hydrophone vessels are hooked on the upper part of the frame, forming a tetrahedral antenna of about 1 m side. Hydrophones H1, H2, H3 lie in the same plane at about 2.5 m from the seabed, H4 is placed on the top at about 3.2 m from the seabed. Mechanical connections are made with plastic parts in order to decouple metals and to avoid sound propagation through the metal. We selected and used hydrophones coming from a special series, TC-4042C, manufactured by RESON for NEMO to operate at 250 bar pressure for long term deployment. The TC-4042C are piezoelectric sensors, having a nominal receiving sensitivity of -193 ± 3 dB re 1V/ μ Pa (at 1 atm pressure), linear over a wide range of frequencies: from few tens Hz to about 50 kHz. The selected hydrophones have also omni-directional sensitivity pattern, required for our ambient noise measurements. The differential output of the hydrophone is fed into a preamplifier, developed also by RESON, which have a gain of 20 dB. We modified two preamps (namely the ones of H2 and H4) applying a hi-pass filter (> 1 kHz, 6 dB per octave) to reduce most of the expected low frequency ambient noise, which has typically $1/f$ spectrum. This was done to better investigate the range of frequency more interesting for neutrino detection (> 10 kHz). On the other hand the use of a pair of unfiltered large-bandwidth hydrophones allows the comparison with bibliographic data, more abundant for low frequency measurements. The differential output of each preamplifier is sent to a pair of line input and line output transformers. The line-input transformer is hosted inside the aluminum vessel, the line output inside the glass housing. The electrical line between the transformers, 4 m long, is a shielded twisted-pair (AWG 24 size). Line transformers are used to galvanically insulate the line in case of shorts inside the hydrophone vessels. The hydrophone signals are then addressed to two commercial stereo A/D converter used for professional audio application. In particular channel H1 and H3 are respectively the left and right channel of one board, H2 and H4 (which have the 1 kHz frequency cut-off) the left and right channel of the other board. We used the Crystal CS5396 evaluation board which mounts a CS5360 sigma-delta stereo ADC. The sampling frequency is 96 kHz. The

output protocol is standard digital audio SPDIF (Sony Philips Digital Interface Format). This is a stereo protocol, thus it allows reduction of the number of channels to send to shore. The two ADCs are piloted by the same clock: the four hydrophone signals are, therefore, synchronized. The CS5396 samples the analog data at a rate of 96 kHz with a resolution of 24 bits, the nominal dynamic range of the ADC is 120 dB. The digital outputs of the two ADCs are sent to two fiber optic data transmitter ECT 100S-TM1 manufactured by Elcommtech. The use of stereo A/D boards permits to minimize the number of fibers used for data transmission. On shore, optical data from hydrophones are re-translated into electrical using fiber optic data receivers and, then, acquired and recorded on a PC (Pentium IV, 3 GHz) using two professional PCI audio boards, RME DIGI96-8 PAD, suitable for audio stereo data recording at 96 kHz and 24 bits. Data recording is performed with a 4 channels recording software (*SeaRecorder*, developed by CIBRA) that reads and keeps synchronized the two digital stereo streams coming from the underwater station. Data can be saved to standard Microsoft .wav files either in integer (16 or 32 bit/sample) or 32 bit float format (24+8 bit); float format is useful for importing data in Matlab for off-line analysis. Float format data files can be also converted to 16 bit format to reduce the storage space required. Recording to file can be programmed to be continuous, with automatic file splitting every hour or every 30 minutes, or scheduled for predefined file duration. During acquisition the envelope of the four channels is plotted in real-time to provide immediate feedback. A special filenames protocol was adopted to reduce the risk of data losses or data misinterpretation. Filenames include a date-and-time-stamp, number of channels, recording gain (linear), file format; sampling rate is omitted, as it is a hardware-locked parameter. For additional safety, for each recorded file a text file is generated with complete information of the hardware setup. A typical filename is: *Dati_fondo_20050827_161500_4CH1X_3200.wav*. Additional software was developed to browse and analyze the acoustic data off-line: the *SeaPro* code (developed also by CIBRA) was improved to read 32 bit file formats (integer and float) and 4 channels .wav files. The code can visualize on-line and off-line the spectrogram of the recorded audio files, and it is useful to highlight biological sounds, e.g. sperm whales' clicks, and to perform TDoA (Time Difference of Arrival) measurements to separate different sources and track their movement. During the initial period, a strategy of continuous data recording was chosen, this allowed the evaluation of the variability of detected sounds and to design a strategy for scheduled recording. As the continuous recording was not possible due to storage space constraints (recording float files requires 124GB/day) recording for five minutes every hour appeared to be a good compromise to get a representative sample of data. The software was, thus, programmed to record 5 minutes every hour thus reducing the storage space required daily to 10.2 GB.

3 DATA ANALYSIS AND RESULTS

Data analysis was distributed among INFN, mostly interested in analyzing the background noise, and CIBRA, interested in biological sounds (see G. Pavan in these proceedings). To date, systematic data analysis of background noise has been carried on for 6 months, from May to December 2005.

As described data from the four hydrophones are recorded as 4 channels .wav files. This permits data analysis using Matlab libraries. In order to recover the average noise in deep sea we calculate per each file (5' recording, taken every hour) the Power Spectral Density (PSD) of the recording. The PSD at each frequency f , is defined as:

$$PSD(f) = \frac{|X_{N_{DFT}}(f)|^2}{f_s L}$$

where f_s is the sampling frequency (96 kHz), L is the length of the recording (5 minutes) and X is the N^{th} component of the Discrete Fourier Transform corresponding to frequency f . In order to calculate the DFT we have divided the file into *blocks* of 2048 samples and we calculate the FFT of this data block. Each block is weighted using a Hanning window and the average FFT is calculated using an overlap of 50% between blocks [9]. In Figure 1 we present the average PSD of signals recorded by hydrophones H1 and H3 (not filtered) in July 2005 (about 300 files). The two dips present at about 10 and 27 kHz are attributed to intrinsic vibration of the system hydrophone-vessel. In the same figure we plot the average minima values of the PSD. Minima represent the electronic noise of the data acquisition system -white noise at $f > 10$ kHz- when sea noise is negligible (as expected for sea state zero in this range of frequencies). The noise produced by the ADC is negligible. At lower frequencies the white electronics noise adds up with noise induced by the power supply and diffuse acoustic background (not negligible at frequencies < 1 kHz). In figure 2 we show data recorded by H3 in the period May-December 2005 (about 3100 files).

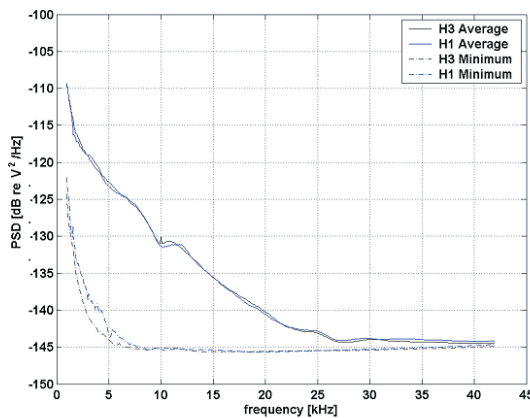


Fig. 1. Average and Minimum Power Spectral Density (in units of V^2/Hz) as a function of frequency measured by hydrophones H1 and H3 on July 2005.

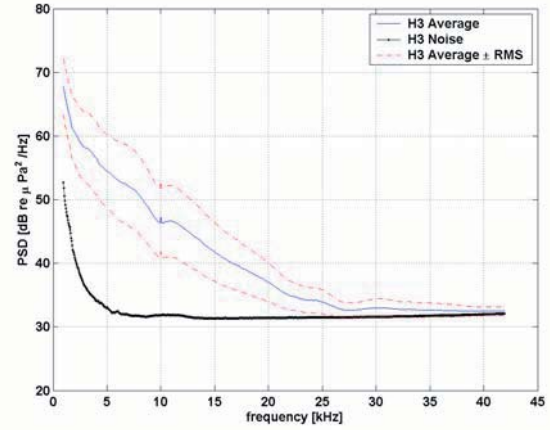


Fig. 2. Average Pressure Sound Density (in units of $\mu Pa^2/Hz$) as a function of frequency measured by hydrophone from May to December 2005. The black line indicates the equivalent noise pressure induced by the electronic noise of the station.

The equivalent sound pressure density is calculated using the measured hydrophone sensitivity (-177 ± 2 dB re 1 V/ μPa , $10 \text{ kHz} < f < 50 \text{ kHz}$) and assuming that it is constant over all frequencies. In the same plot the RMS of the distribution is also shown. Results indicated that between 20 and 40 kHz the equivalent sound pressure density (averaged in the whole period) is about $33 \pm 1_{stat} \pm 2_{syst}$ dB re $\mu Pa^2/Hz$ (corresponding to about $100 \mu Pa^2/Hz$). At lower frequencies the average noise and its RMS increase, due to biological, seismic and (mainly) navigation noise.

4 ACOUSTIC SOURCE TRACKING

Another characteristic of the station is the possibility to track acoustic sources. Thanks to the tetrahedral shape of the hydrophones antenna, recorded data can be used to localize the acoustic source direction using the TDoA (Time Difference of Arrival) technique. The source direction is recovered minimizing the functional $G(\vartheta, \varphi)$, defined as:

$$G(\vartheta, \varphi) = \sum_{i < j}^N [TDOA_{i,j}^M(\vartheta, \varphi) - TDOA_{i,j}^E(\vartheta, \varphi)]^2$$

where N is the total number of hydrophones, $TDOA^M$ is the measured time delay of the analyzed signal between the couple of hydrophones and $TDOA^E$ is the expected time delay of a signal coming from a source located in the direction (ϑ, φ) . In order to test the tracking capabilities of the station we performed a test with a known acoustic source operated from surface. Source positions were calculated using TDoA technique and compared to the known values. In figure 3 we report the obtained results. The bearing ϑ of the source is recovered with an error of about 2 degrees; the zenithal angle is recovered with an

error of about 10 degrees [10]. This error is attributed to the fact that we considered the propagation medium as homogenous and isotropic (while the sound refraction index changes with depth in the sea). In this way we recovered the apparent source direction, not the real one. Another source of error is the not-perfect knowledge of the station inclination with respect to the surface. The data received from a compass installed on the station indicates that OvDE lies coplanar to the seabed, the error in this measurement is about 3 degrees. Further analysis of these data is on-going.

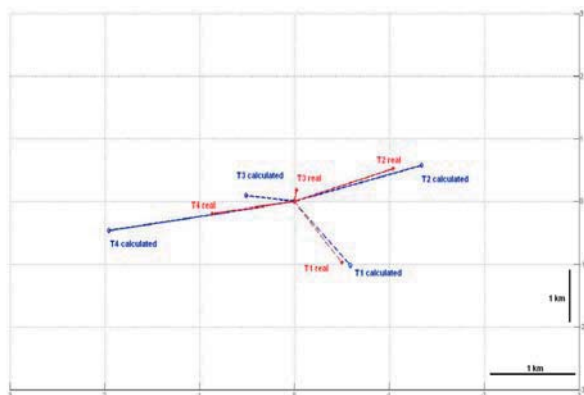


Fig. 3. Source tracking test performed with OvDE. Red and blue lines indicate the source real and reconstructed positions of the test source with respect to the position of OvDE. Source bearing is well reconstructed; the azimuth is recovered with an error of about 10 degrees.

5 CONCLUSIONS

The OvDE station operated at the NEMO Test Site of Catania from Jan 22nd 2005 to December 6th 2006. Data analysis is presently addressed to characterize the underwater noise level and its variations as a function of time. The analysis of data recorded in the time interval June- December 2005, shows that the average noise level is $33 \pm 1_{\text{stat}} \pm 2_{\text{syst}}$ dB re $\mu\text{Pa}^2/\text{Hz}$ in the frequency range of interest for acoustic detection (>20 kHz). A test of localization of noise sources using the 4 hydrophones data together was performed successfully, and will be the basis for marine mammals tracking. Recorded data set is also extensively used for interdisciplinary studies mainly addressed to search for cetaceans in the region.

6 ACKNOWLEDGMENTS

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A LONG TERM ACOUSTIC MONITORING OF SPERM WHALES OFF CATANIA (EAST COAST OF SICILY, ITALY)

G. Pavan^a, G. La Manna^a, F. Zardin^a, G. Cosentino^b, F. Speziale^b, the NEMO Collaboration

a) CIBRA, University of Pavia, Via Taramelli 24, 27100 Pavia, Italy

b) INFN Laboratori Nazionali del Sud, Catania, Italy

** Corresponding author, e-mail: gpavan@cibra.unipv.it*

ABSTRACT

Within the NEMO Project that addresses the underwater detection of high energy neutrino, an experimental deep station, named OvDE, has been deployed on the sea bottom 21 km offshore Catania (Sicily, Italy), at 2000 m depth. It is connected to the shore labs through electro-optical cables to provide real-time monitoring and data acquisition; deployed at the end of January 2005 it was operative till December 2006. Four calibrated broad-band hydrophones, sampled at 96 kHz, sent digital data to the shore lab 24/24h; data recording was made for 5 minutes every hour. The experiment provided long term data on the underwater noise and an unique opportunity to study the acoustic emissions of marine mammals living in the area or transiting during their movements within the Mediterranean basin. This reports concerns the analysis of sperm whales' detections made in year 2005. The detection of their characteristic clicks indicate a presence of sperm whales more consistent and frequent than previously believed. Against detections of whales in more than 50% of the recorded days, only few sightings are available for the whole year 2005.

1 INTRODUCTION

The OvDE (Ocean Noise Detection Experiment), was dedicated to the study of the acoustic noise. The OvDE station has been deployed on the sea floor 25 km offshore Catania (Sicily, Italy) at 2000 m depth [1]. It was connected to the shore labs through electro-optical cables to provide real-time monitoring; deployed in January 2005, it steadily sent data since the end of March 2005 till December 2006 when the acoustic module was replaced by the NEMO Phase 1 experiment [2]. The acoustic experiment hosted by the station concerned the study of the underwater acoustic environment to develop the strategies required for the detection of acoustic pulses generated by high energy neutrino interacting with water. The experiment was highly interdisciplinary and other than providing long term data on the underwater noise, it also provided an unique opportunity to study the acoustic emissions of marine mammals living in the area or transiting there during their movements within the Mediterranean basin.

2 EXPERIMENTAL SET-UP AND METHODS

The four calibrated broadband hydrophones on the OvDE acoustic module have -177 dB peak ref $1\text{V}/\mu\text{Pa}$ sensitivity and are connected to a 24 bit AD board with full scale level of $\pm 2\text{V}$; the system allows recording sound pressure levels up to 183 dB. The hydrophones were sampled at 96 kHz and 24 bit to send digital data to the shore lab 24/24h; as the continuous recording was not possible due to storage space constraints (uncompressed recording would require 124GB/day), recordings were made for periods of 5 minutes every hour. For additional technical details see Riccobene et al. (this issue). Data recording, totalling 2.5TB of scheduled recordings, and 1TB of free running recordings, was made with a custom developed 4 channels software recorder developed at CIBRA that reads and keeps in synch the two digital streams coming from the underwater station. Digital data arrives with 24 bit resolution and can be saved as standard Microsoft .wav files either in integer (16 or 32 bit/sample) or 32 bit float format (24+8 bit). Data for noise analysis at LNS was saved in 32 bit float format; copies for bioacoustic analysis at CIBRA were reduced to 16 bit to save space. Bioacoustic analysis was performed with SeaPro, the sound analysis software developed at CIBRA. The first phase was the classification of recorded sounds into known categories. The results have been arranged in excel tables to show, hour by hour, the occurrence of biological sounds and other relevant acoustic events such as sonars, echosounders, sparkers or other sound.

3 SPERM WHALE DETECTIONS

The most common sounds recorded are those produced by sperm whales, impulsive sounds named click, arranged in regular sequences (interclick interval in the range 0.5s to 2s), or in special patterned sequences (chirrup, codas, creaks). According to other studies in the Mediterranean Sea, sperm whales may dive to more than 1000 meters depth, but normally travel at 800-1000 meters depth. Their source level is greater than 200 dB at 1m on axis; the loudest clicks were received with sound pressure levels up to 170 dB. Clicks were often recorded with high SNR; by using a high-pass filter, the SNR can be further increased to improve the detection, count and analysis of the weakest click series.

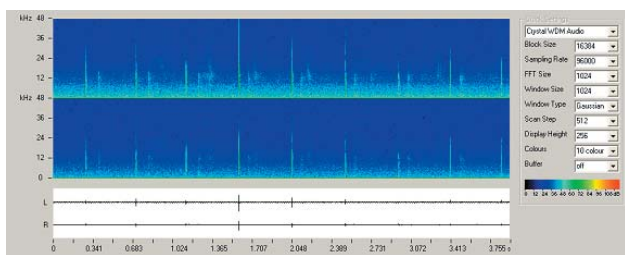


Fig. 1. Two channel spectrographic display of a series of sperm whales' clicks.

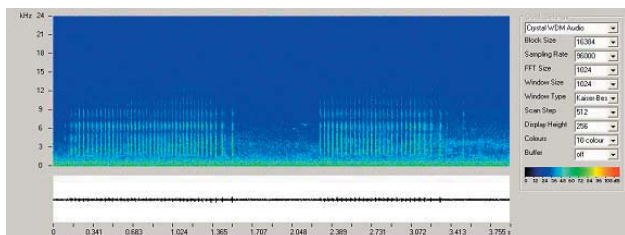


Fig. 2. Spectrographic display of chirrup.

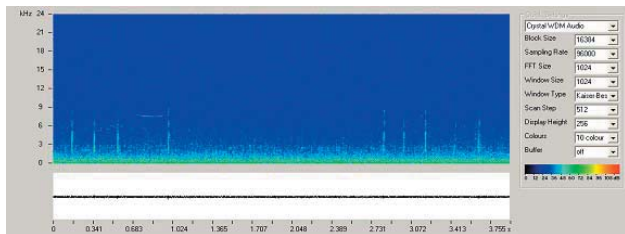


Fig. 3. Spectrographic display of two codas with the typical Mediterranean pattern 3+1 [7]. A weak dolphin whistle is also shown.

Detections indicate a presence of sperm whales more consistent and frequent than previously believed. Although the transiting of sperm whales is known since the end of XIX century [3], very few literature is available for the area. IFAW [4] reports a low sperm whale density in the Ionian basin with an encounter rate of 5.8 whale groups for 1000 km of transect. Lewis [5], based on the IFAW surveys, reports a total of 16 whales detected within the truncation distance of 20 km, along 3846 km of survey transects in the Ionian Sea. Panigada et al. [6] published a report about marine mammals presence in the area of the Strait of Messina and extending to south till 50km north of the OvDE Station. In the period from June 2005 to May 2006 they conducted 125 days of survey and sighted 80 marine mammals, of which 13.8% sperm whales and 1.2% Cuvier's beaked whales. With the OvDE station, in year 2005, sperm whales have been detected in 117 of the 231 (50.6%) recorded days (1186 out of 5147 recorded hours, 11.5%). The analysis of 2006 data is still in progress but seems to confirm 2005 data. Although several periods of consecutive days were characterized by the presence of sperm whales, solitary whales or groups of several individuals were often detected for few hours only and this means they were just in transit. In some cases the presence of whales was constant for more than one day.

In few occasions, other than clicks and creaks, chirrups and codas (the most common was the 3+1 type) [7], indicating socializing behaviours, were recorded.

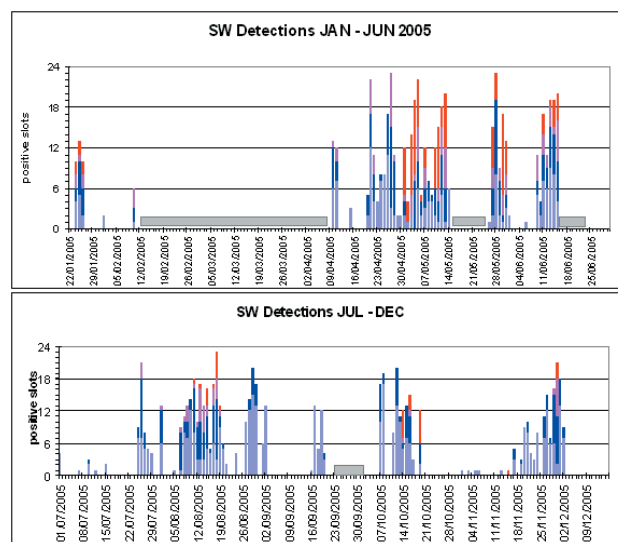


Fig. 4. Sperm whales' detections. Vertical bars indicate how many hours sperm whales have been detected each day. Grey bars indicate periods of recording inactivity. The longest one was due to a cable break. The stacked bars indicate how many animals were detected each hour: • 1 animal detected; • 2 animals detected; • 3 animals detected; • 3 or more animals detected.

4 WORK IN PROGRESS

New analysis algorithms are being developed to maximize the SNR ratio and to track the movements of impulsive acoustic sources to reveal the movement of sperm whales whilst in the detection range. By plotting TDOAs (Time Difference Of Arrivals) in a virtual 3D space it is easy to separate different sources and then, by projecting them in the real 3D space [8], to track the sources' movements. In some cases, when surface reflections are clearly linkable to individual clicks it is possible to exactly locate the animal, i.e. know the range and depth, instead of having only bearing and azimuth information. This will be important to assess the real detection range of the OvDE station. At the same time click details will be examined to measure the Inter Pulse Interval, i.e. the intervals among the pulses that constitute the sperm whale click [9]. According to the latest models on sound production [10] reliable IPI measures can be taken if on axis, either frontally or back, when a clean P0-P1-P2 structure is available. Otherwise, if SNR is high enough, it will be possible to assess the orientation of the whale. By measuring the IPI [11] it is possible to assess the whale size and, if size is greater than 13m, the sex. By combining TDOA and IPIs it will be possible to assess the number of transiting animals and the groups' composition to better estimate the population size and structure. The tracking of their movements will possibly reveal if their directions are seasonal and directed to/from the Strait of Messina as already suggested by Bolognari [3] or follow other rules, if any.

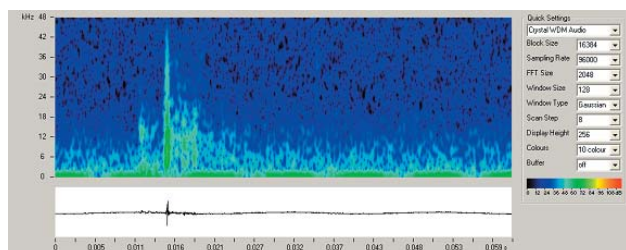


Fig. 5. Sperm whale click with clear multi-pulse structure: P0-P1-P2. In this recording the size has been estimated 9.94-10.27 meters, matching a young male or a female (females reach about 12 m, males reach 18 m).

5 OTHER BIOLOGICAL DETECTIONS

Sperm whale clicks are often loud as the animals dive at great depth, close to the receiving hydrophones; on the contrary, whistles and clicks from dolphins, which stay within few hundred meters from the surface, are recorded with much lower amplitude. Clicks similar to those emitted by Cuvier's beaked whales [9],[10] have been detected with amplitude much greater than that of dolphins; this indicate a deep source (work in progress) that match well with the known dive depths of beaked whales. Cuvier's beaked whales have been recorded to dive to more than 1800m. This species appears to be typical of sharp continental slopes, but it was never reported for the OvDE area; few stranding have been recorded on Calabria coasts and, recently, 10 km South of Messina [12]; Panigada et al. [6] report few encounters in the Messina Strait area in year 2005. Worthy to note, the amplitude of the received clicks is not constant but oscillating, as it could be expected by a directional source swimming and scanning the environment with left-right movements of the head. The hydrophones get the maximum amplitude when in the beam axis. Other than biological and unknown sounds, many man-made noises has been recorded and identified, including ship noise, sonars, echosounders, airguns (or sparkers), and explosions.

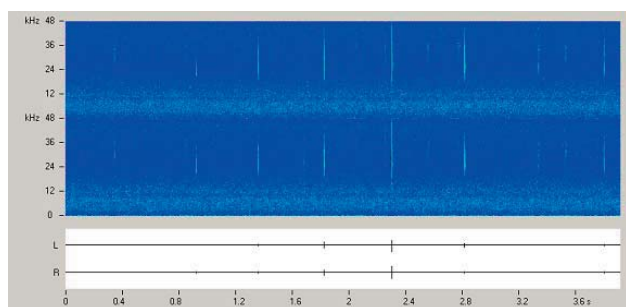


Fig. 6. Series of clicks spaced 460-480 ms, much louder than clicks from shallow dolphins, with oscillating amplitude.

6 ACKNOWLEDGEMENTS

A special thank to the whole NEMO team for having supported this interdisciplinary approach.

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Ion sources and accelerators



TANDEM AND SUPERCONDUCTING CYCLOTRON ACTIVITY

D. Rifuggiato on behalf of the LNS Accelerator staff

INFN Laboratori Nazionali del Sud, Catania, Italy

Abstract

The LNS Cyclotron and Tandem activity in 2006 is described with details on the beam time distribution and on the new role that the two accelerators are assuming as a primary and secondary one in the EXCYT facility for production of radioactive beams.

1 BEAM OPERATION

In 2006, an intense experimental activity with Tandem and Superconducting Cyclotron stable beams was carried out together with three test sessions of the EXCYT facility. At the end of these tests a ^8Li radioactive beam, produced in a graphite thick target by a ^{13}C beam, and ionized in a positive surface ionization source, was accelerated at the Tandem and transported to the experimental area hosting the set-up of the Big Bang experiment. Since the EXCYT sessions took about 6 weeks each, the overall time dedicated to experimental activity with stable beams amounts to 5.5 months. During this time interval, 2017 hours of Cyclotron beams and 1422 hours of Tandem beams were delivered. Therefore the good reliability level reached in the past four years can be confirmed, thanks to a careful improvement and replacement of many components, which allowed for a significant reduction of failures.

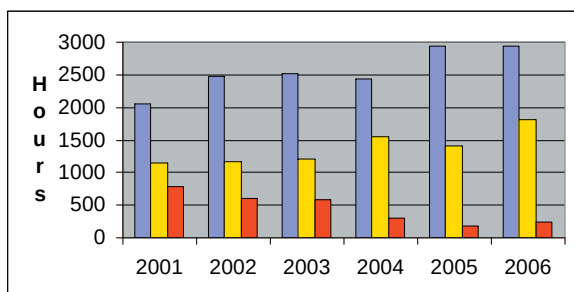


Figure 1: 2001-2006 Cyclotron beam statistics scaled to 8 months

Considering that 4.5 months were dedicated to EXCYT, about 50% of the experiments with stable beams approved by the Scientific Committee were performed in 2006, and the left experiments will be accomplished in the first 5 months of 2007.

In 2006 all the 3 new halls of the new experimental area were used for research activity of different kind:

Catana for proton-therapy and biological experiments, Magnex for preliminary tests, and the new Chimera scattering chamber for tests with in-flight radioactive beams. Only the 40° hall is not presently hosting any experimental set-up, also due to reasons related to the beam transport: Cyclotron beams have a too high rigidity to be bent by the old switching magnet, while delivering Tandem beams would prevent the Cyclotron beam to be contemporarily delivered to another hall. Therefore it was decided to include the 40° hall in the so-called by-pass area, reached by Tandem beams, together with the 60° and 80° beam lines. This operation will be accomplished by installing two additional dipole magnets, and is planned to be completed in 2008.

In 2006, 5 sessions of proton therapy of ocular tumors (Catana) were accomplished, using the 62 MeV proton beam from the Superconducting Cyclotron, for a total of 31 treated patients. In total the protontherapy activity took approximately 480 Cyclotron hours.

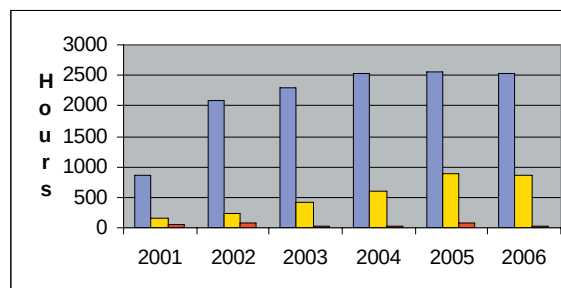


Figure 2: 2001-2006 Tandem beam statistics scaled to 8 months

In figures 1 and 2 the beam statistics for the years 2001 through 2006, scaled for a period of 8 months, are shown. The first column, in blue, displays the delivered hours, the second, in yellow, gives the preparation time, the third, in red, the number of failures. As evident from figure 1, the number of failures has a clearly decreasing trend, which demonstrates the achieved good reliability of the Cyclotron, quite important for the experimental activity as well as for the development of new projects. The amount of setting hours is still big, demonstrating that the Cyclotron is a quite complicated machine. As for the Tandem, the amount of delivered beam time is the same as in the previous years.

In both the figures, the beam time dedicated to EXCYT is not considered for sake of consistence.

2 SUPERCONDUCTING CYCLOTRON

In 2006 the Superconducting Cyclotron delivered beams in a quite reliable way and, if requested, with the usual good timing quality, i.e. FWHM 1 nsec and interburst separation 100-150 nsec, very much appreciated for nuclear physics experiments carried out with large array detectors. Table 1 shows the Cyclotron beam types delivered in 2006: 2017 hours for experiments and 1313 hours for EXCYT.

Table1: Cyclotron beams delivered in 2006

Beam	Time
Protons 62 MeV	664 h
Deuterons 62 MeV	38 h
^{12}C 62 AMeV	85 h
^{13}C 45 (EXCYT)	1313 h
^{20}Ne 20,45 AMeV	332 h
^{36}Ar 38 AMeV	80 h
^{40}Ar 20 AMeV	50 h
^{40}Ca 45 AMeV	120 h
^{48}Ca 45 AMeV	120 h
^{84}Kr 20 AMeV	60 h
^{112}Sn 35 AMeV	112 h
^{116}Sn 23 AMeV	130 h
^{124}Sn 35 AMeV	60 h
^{129}Xe 20,23 AMeV	110 h
^{197}Au 21 AMeV	58 h
Total	3330 h

In 2006 Cyclotron beams were used for Nuclear Physics experiments (29%), proton-therapy (15%) and interdisciplinary experiments (18%) mainly investigating on interaction of ion beams with biological matter and on new superconducting materials. The remaining part of beam time (38%) was used for EXCYT tests.

In figure 3 a plot of the experiments performed in 2006 with Cyclotron beams is presented, showing the beam time distribution among different experiments.

During the EXCYT tests, the Cyclotron delivered 1313 hours of an intense (150 watt) ^{13}C beam at 45 AMeV. Thanks to the upgrading of the electrostatic deflectors accomplished in the past years, with the use of new materials and new mechanics, and especially, thanks to the water cooling system implemented, the high intensity operations have been performed with a satisfactory reliability: the deflectors have proven to be able to sustain the intense (150 watt) beam mainly dissipated in the ground electrode, i.e. the septum, for several weeks. No replacement of the deflectors was necessary throughout the year 2006.

In Table 2 a list of the experiments performed at the Cyclotron in 2006 is given.

Table2: Experiments performed in 2006 at the Cyclotron

Experiment	Research field
Catana	Hadrontherapy
Staminal	Biology
Metabolic	Biology
High-Let	Biology
Apoptosis	Biology
TNT	Biology
DNA-Mech	Biology
Dopet	Biology
Discoli	Superc. material
Test 12C	Hadrontherapy
Test Rad. Hardn.	Rad. Hardn.
PRT	Targ. Ion source
EXCYT tests	Accelerators
Calibration	Nuclear physics
Panda-MVD	Nuclear physics
Test Electrons	Nuclear physics
Cecil II	Nuclear physics
Neutron	Nuclear physics
Quenching	Nuclear physics
Di-proton	Nuclear physics
New-FRIBS	Nuclear physics
Trequis	Nuclear physics

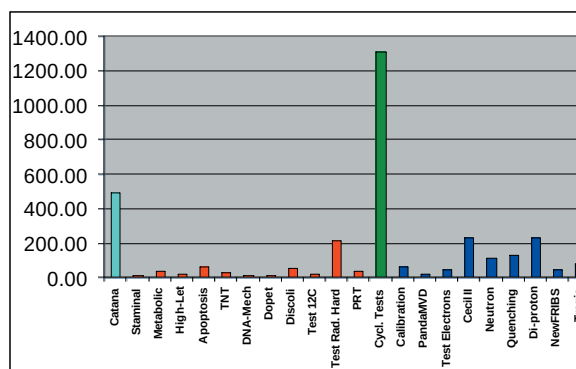
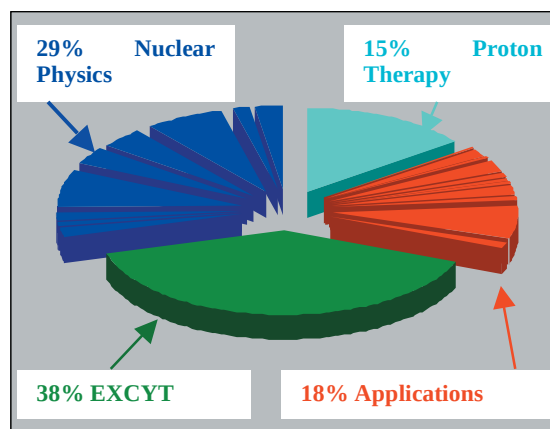


Figure 3: Cyclotron beam time distribution



3 TANDEM

As in the previous four years, in 2006 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.

Table 3 displays the Tandem beam types delivered in 2006: 1422 hours for experiments and 1217 for EXCYT.

Table 3: Tandem beams delivered in 2006

Beam	Time
Proton 22-26 MeV	100 h
⁶ Li 20-50 MeV	159 h
⁷ Li 20 MeV	50 h
⁸ Li (EXCYT)	1217 h
⁹ Be 10-40 MeV	81 h
¹² C 60 MeV	250 h
¹⁴ N 60 MeV	65 h
¹⁶ O 80 MeV	60 h
¹⁷ O 45 MeV	201 h
³² S 156 MeV	48 h
⁷⁹ Br 230 MeV	378 h
Total	2639 h

Tandem beams were used for Nuclear Physics experiments (27%) and applicative experiments (26%) covering several inter-disciplinary fields: ion lithography, radiation hardness, archaeology, and detector development. A big percentage (47%) of the total beam time, corresponding to 1217 hours, was dedicated to EXCYT test. In figure 4 a plot of the experiments performed in 2006 with Tandem beams is presented, showing the beam time distribution among different experiments.

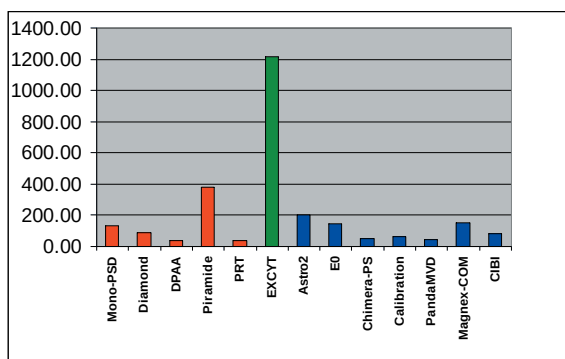
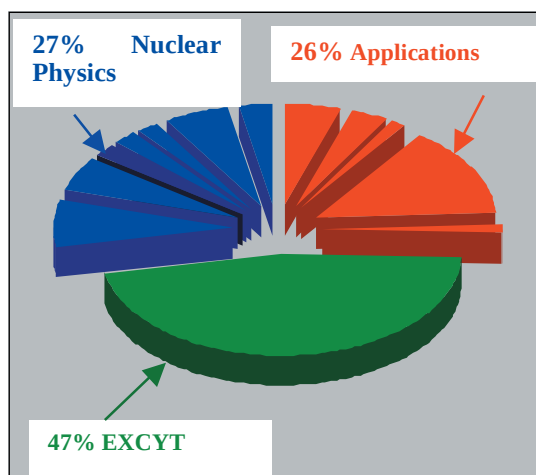


Figure 4: Tandem beam time distribution



In Table 4 a list of the experiments performed at the Tandem in 2006 is reported.

Table 4: Experiments performed at the Tandem in 2006

Experiment	Research field
Mono-PSD	Detectors
Diamond	Detectors
DPAA	Archaeology
Piramide	Rad. hardness
PRT	Targ. Ion Source
EXCYT tests	Accelerators
Astro2	Nucl. astrophysic
E0	Nucl. Spectrosc.
Chimera-PS	Nuclear physics
Calibration	Nuclear physics
Panda-MVD	Nuclear physics
Magnex-COM	Nuclear physics
CIBI	Nuclear physics

4 CONCLUSION

In 2006 the amount of delivered beams from accelerator confirms the high reliability level reached in the previous four years: a significant amount of experiments were performed in a reduced time, approximately 5.5 months. A big percentage of the total beam time was dedicated to complete the Excyt commissioning, at the end of which the 8Li radioactive beam was transported to the experimental set up. Proton-therapy was accomplished as usually with 31 patients treated in 5 sessions.

STATUS OF THE EXCYT FACILITY

G. Cuttone, R. Alba, L. Calabretta, L. Celona, F. Chines, L. Cosentino, P. Finocchiaro, D. Garufi, E. Messina, A. Pappalardo, G. Raia, M. Re, D. Rifuggiato, A. Rovelli, G. Schillaci, A. Amato, R. Avolio, F. Caruso, C. D'Amato, V. D'Amato, G. De Luca, B. Diana, S. Cavallaro, E. Furia, G. Gallo, A. Grmek, P. Maniscalco, G. Manno, R. Marletta, S. Marletta, G. Panasci, S. Passarello, M. Piscopo, S. Pulvirenti, P. Reina, S. Russo, S. Tringale, F. Tudisco, A. Varisano, V. Scuderi, D. Scuderi, E. Zappalà

INFN Laboratori Nazionali del Sud, Catania, Italy

Abstract

The aim of the EXCYT (EXotics with CYclotron and Tandem) facility is the production and acceleration of radioactive ion beams (RIBs). It is based on the two-accelerator method (ISOL technique): a primary beam accelerated by the K-800 Superconducting Cyclotron will produce, in a target-ion source complex, the required nuclear species which will be accelerated by a 15 MV Tandem. $^8,^9\text{Li}$ beams have been already produced and in the near future generation of oxygene, fluorine and chlorine beams have been planned, according to the experimental proposals, with beam intensities ranging between 10^4 to 10^6 pps and at the typical energies of our tandem. For some ion beam such as for Li, the highest extraction efficiency from the TIS is obtained by positive ionisation. Then the injection into the Tandem is suitable only after a charge exchange (CEC) to obtain negative

ions. The production of the radioactive ions were performed by injecting a $^{13}\text{C}^{4+}$ primary beam of 45 MeV/amu on a graphite target up to a beam power of 150W, while the ionisation was achieved by a Tungsten positive surface ioniser. The Li^+ has been produced at different energies to cross-check the transmission efficiency together with the charge exchange efficiency. The CEC consists of a cell containing Cs vapours which interact with the Li beam converting its charge from +1 to -1 by a two step reaction; it was already characterised off-line and the results obtained at the EXCYT facility confirm our previous observations and expectations such as the efficiency at different extraction energies and the isotopic shift effect. The nuclear experiments programme started in July 2006 with the experiments BIGBANG and RCS using the post-accelerated ^8Li ions.

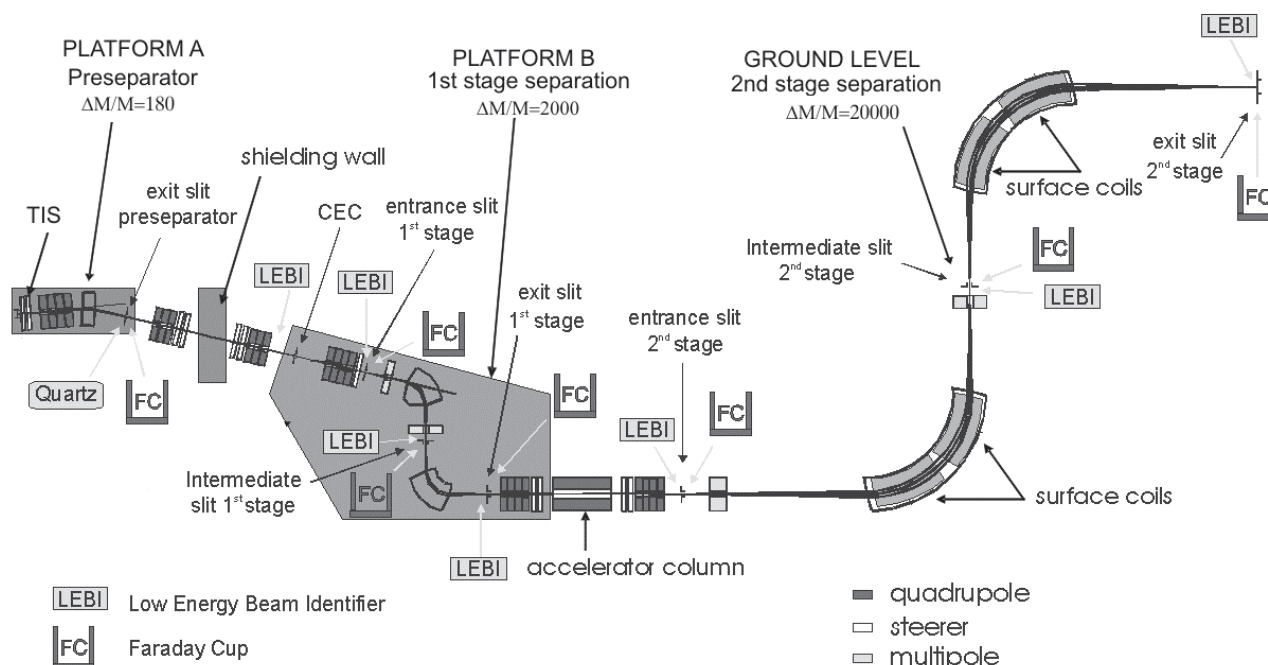


Fig. 1 – The layout of the isobaric mass separator

1 TOWARD THE FINAL EXCYT COMMISSIONING

The commissioning of the EXCYT facility started in the first months of 2005 and the detailed phases of commissioning with stable beams are reported in [1].

On June 2005 the first $^8\text{Li}^+$ beam was successfully produced and extracted from the TIS (fig.2). The TIS consisted on a 8.5 mm thick graphite (^{12}C) Target on a tantalum container and a Positive Ion Source (PIS) both heated up to 2100 °C. The PIS, being a surface ionisation source, is highly selective and efficient for alkaline atoms. The ^8Li beam was extracted at 25 keV from the TIS and transported through the two HV platforms, it was measured by mean of a LEBI device which detects the ^8Li beta decay emission. Taking into account the LEBI detection efficiency and subtracting the background, the ^8Li production yield was of 3×10^4 atoms/s [1]. The LEBI counts have been then fitted with an exponential decay equation which half-live time resulted to be 0.84 s in perfect agreement with the expected value for ^8Li .

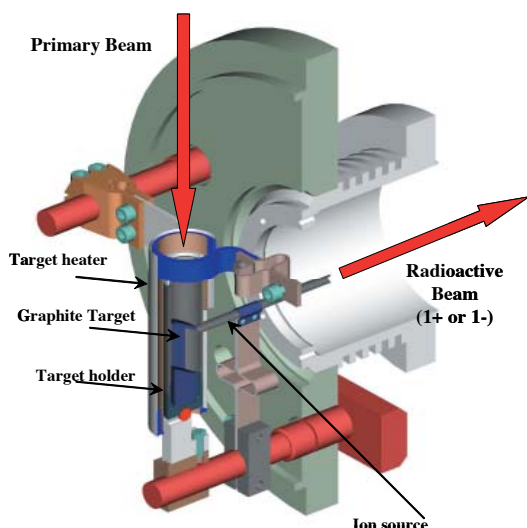


Fig. 2 – The TIS assembly.

At the end of 2005 a similar procedure was followed to find the optimal settings for the 2nd stage separator (fig.1) and for the coupling line with the Tandem. A ^7Li beam generated locally in the EXCYT Target-Ion-Source assembly as positive ion and transformed in negative ion in the charge exchange cell was successfully injected and accelerated by the LNS 15MV Tandem.

The first successful exotic beam production even with low yield and the commissioning of the whole facility with stable beams, permitted to focus our efforts in the maximization of the transport efficiency through the three stages of separation and through the coupling line with the tandem.

Since the CEC showed an increase of efficiency by decreasing the lithium beam energy, we decided to

lower the TIS extraction voltage. The best operating point was found experimentally at 10 kV permitting to obtain higher CEC efficiency with negligible beam losses over the HV platforms with respect to higher Li beam energy. In these condition, on March 2006, we increased the ^8Li production measured on LEBI1 up to 5.5×10^5 pps.

Moreover, in the July 2006, the increase of beam diagnostic reliability especially for the high energy ^8Li detectors (scintillating fibres and Si detectors), together with a meticulous campaign of debugging and checking of the electrostatic elements of the beam transport line, permitted a significant increase in the transmission efficiency as shown for ^7Li in table 1.

There are still losses in the preseparator and in the coupling line to the tandem which we are confident to still decrease matching the design calculations. The tandem transmission efficiency of 33% is strongly affected by the acceleration voltage. In this case we operated at the value of 7MV, lower values will strongly reduce the efficiency while higher operating voltage may increase this value up to 50-60% [2].

3 FIRST ^8Li BEAM DELIVERED TO USER

The design of a new target assembly which is mechanically more reliable, has a better thermal isotropic distribution and insulation, and which employs a different target geometry (graphite discs instead of a single pellet: see fig. 3), together with an increase of primary beam power and the mentioned improvement of beam optics make possible an increase of ^8Li production yield of more than one order of magnitude in a couple of months [3]. In table 2 a comparison of the results obtained is reported: all the production yields are measured by LEBI1.



Fig. 3 – New Target geometry, left side: picture, right side: CAD design

These values are strongly satisfactory, the TIS extraction voltage employed was 10keV while the injection energy to the tandem was 100keV.

The CEC efficiency for ^8Li was 3.4%, very close to the expected theoretical value of 3.6% at 10keV, this result also confirms the isotopic shift effect observed for the CEC efficiency.

From TIS to CEC $^7\text{Li}^+$	CEC eff. $^7\text{Li}^+ \rightarrow ^7\text{Li}^-$	Through 1 st stage sep. $^7\text{Li}^-$	Through 2 nd stage sep. $^7\text{Li}^-$	Through Tandem coupling line $^7\text{Li}^-$	Through tandem $^7\text{Li}^{3+}$
62%	2.7%	100%	100%	75%	33%

Table 1 – ^7Li transport, charge exchange and post-acceleration efficiencies

	Beam Energy	Beam Power	Target Temperature	^8Li Production yield	^9Li Production yield
March '06	45 MeV/u	75 W	2600 K	$5.5 \cdot 10^5$ pps	$1.8 \cdot 10^4$ pps
July '06	45 MeV/u	101 W	2600 K	$5.0 \cdot 10^6$ pps	$6.2 \cdot 10^4$ pps *
July '06	45 MeV/u	147 W	~2700 K	$9.0 \cdot 10^6$ pps	not measured

Table 2 – $^{8,9}\text{Li}$ production yields on LEBI1.

(* ^9Li yield on July was measured while the yield efficiency was not at the maximum).

CEC eff. $^8\text{Li}^+ \rightarrow ^8\text{Li}^-$	Through 1 st stage sep. $^8\text{Li}^-$	Through 2 nd stage sep. $^8\text{Li}^-$	Through Tandem coupling line $^8\text{Li}^-$	Through tandem $^8\text{Li}^{3+}$
3.4%	100%	90%	80%	10%

Table 3 – ^8Li transport transport, charge exchange and post-acceleration efficiencies

Table 3 reports the transmission efficiency for ^8Li beam up to the tandem entrance which are in good agreement with the ones obtained for ^7Li (see table 1).

The only remarkable difference was the anomalous decrease of the tandem acceleration efficiency with respect to stable beam operations down to 10%.

We believe that these beam losses are due to misalignments in the final part of tandem coupling line or in a not well tuned lens or steerer inside the accelerator itself. Further test are planned to overcome the problem and a new quadrupole quadruplets could be also installed just before the tandem to achieve a better focusing of the RIBs at terminal location. [4]

The maximum ^{13}C primary beam intensity was 1 eμA which corresponds to a beam power of 147W leading to a production yield of 9×10^6 pps of ^8Li , after the CEC the yield was 3.2×10^5 pps.

During the operational days we experienced a continuous increasing of the production efficiency, probably due to the target-ioniser conditioning and loss of impurities from the target.

Finally, on July 2006 the first EXCYT radioactive beam (^8Li) was injected in the 80° beam line of Laboratori Nazionali del Sud and there characterized in

terms of purity and intensity. The secondary $^8\text{Li}^{1-}$ beam was post-accelerated by the Tandem to a final energy $E_{\text{lab}} = 28.1$ MeV ($^8\text{Li}^{3+}$). The maximum ^8Li yield was about 9200 pps with a starting production of about $3.7 \cdot 10^6$ pps, the acceleration efficiency was even in this case about 10%. However, the users test required a maximum beam flux of 10^3 pps, therefore during the test the delivered beam intensity to the experimental cave was reduced to 800 pps.

The beam was analysed by using a ΔE-E silicon telescope. Its energy was such that alpha particles coming from the decay of ^8Li , after implantation on the E-stage, could not escape from the detector. Fig. 4 shows the calibrated ΔE-E 2d-spectrum. No beam contamination shows up from the spectrum.

Energy spectrum recorded on the E detector (Fig. 5) clearly shows the two contributions coming from the ^8Li beam and the alpha particles produced by the decay of the implanted ions. Integrated yield and average energy of the alpha particle contribution are fully consistent with ^8Li decay properties.

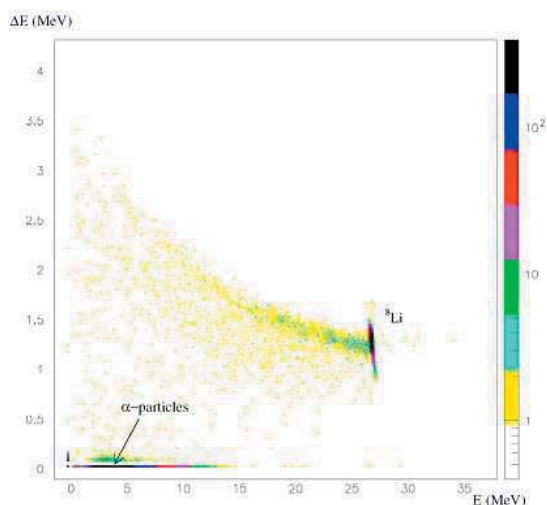


Fig. 4. ΔE -E matrix of ^8Li at $E_{\text{lab}} = 28.1$ MeV

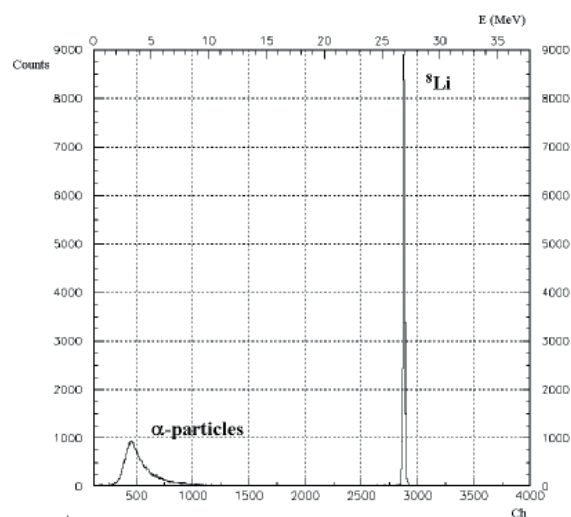


Fig. 5. Energy spectrum of E detector

4 DEVELOPMENTS

Following the successful production and post-acceleration of ^8Li the commissioning of the EXCYT facility is concluded. Further tests will be carried out to optimize the transport efficiencies in the preseparator and in the tandem coupling line, nevertheless the experimental program already approved by the LNS PAC with ^8Li have been already started.

The intensity will be not a limiting factor for this first experiments, however an R&D programme on TIS and ion sources is under way at LNS, to enhance the production yields for Lithium, Oxygen, Chlorine and Fluorine. The increase of primary beam power up to 500 W will also permit a further increase of the secondary beam.

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ECR AND MICROWAVE DISCHARGE ION SOURCES

S. Gammino^{a,*}, L. Andò^a, S. Barbarino^{b,a}, R. S. Catalano^b, L. Celona^a, G. Ciavola^a, F. Consoli^a,
F. Maimone^a, S. Manciangli^a, D. Mascali^{b,a}, G. Sorbello^{b,a}, L. Torrisi^{a,c}, L. Tumino^b, F. Chines^a,
G. Gallo^a, G. Manno^a, S. Passarello^a, E. Zappalà^a

a) INFN Laboratori Nazionali del Sud, Catania, Italy

b) University of Catania, Italy

c) University of Messina, Italy

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

Abstract

The activities of R&D of Ion Sources at INFN-LNS during the last few years have been focused on the development of 3rd generation ECRIS and these studies have taken to the construction of the MS-ECRIS source by means of a European collaboration led by INFN, within the frame of the EURONS/ISIBHI initiative. Significant results have been obtained in the deepening of different phenomena, with particular regards to the microwave coupling to the plasma, to the electron cyclotron resonance heating process and to the production of hot electrons inside ECR plasmas. Modelling of the plasma has become more precise, even though some parameters are not fully represented, and modelling of wave propagation inside the plasma chamber is now available. All these information have been relevant to the industrial design of MS-ECRIS components and to the preparation of the experimental programme to be carried out since the summer of 2007. The status of the MS-ECRIS project will be described along with the description of magnets and mechanical structure.

Despite the heavy burden of the industrial design of MS-ECRIS, other activities have been carried out in 2006. In particular the two sources to be installed at CNAO (Centro Nazionale di Adroterapia Oncologica) were commissioned and delivered to Pavia where the installation will be completed in 2007.

The Versatile Ion Source (VIS) design was modified with a new design of the microwave injection and magnet yoke and the source will be ready in the course of next year to fulfil all the specifications of the NTA-HPPA strategic project of INFN (New Technologies of Acceleration-High Power Proton Accelerators).

1 MS-ECRIS DESIGN

The production of intense beams of highly charged ions imposes the use of higher frequency (28 to 37 GHz) than it is used for the 2nd generation ECRIS (operating between 14 and 18 GHz) and it makes the use of superconducting magnets for the confining trap, B-minimum type, mandatory, as the resonance field B_{ECR} is 1 T at 28 GHz. According to the ECRIS standard model a radial

confinement with values at the chamber wall above 2.2 T is ideal, along with an axial confinement mirror with the two maxima respectively above 4 T and above 3 T. These values of field are close to the technological limits of NbTi superconductors nowadays. The MS-ECRIS source^[1,2], funded by the European Union in the framework of the EURONS JRA07-ISIBHI initiative, has been designed to fulfil all these requests. Its magnetic trap has the highest design values to date, to get an optimum confinement for 28 GHz or higher frequency. Its design is open to be adapted to the major accelerators in Europe; the main parameters are given in table 1 and compared to the ones of the SERSE source, which is the parent project.

Table 1. Main features of SERSE and MS-ECRIS.

Frequency	18 GHz	28 GHz
B_{radial}	1.55 T	2.7 T
B_{inj}	2.7 T	4.5 T
B_{ext}	1.6 T	3.2 T
Φ_{chamber}	130 mm	180 mm
L_{chamber}	550 mm	650 mm
Φ_{cryostat}	1000 mm	1100 mm
L_{cryostat}	1310 mm	1347 mm
V_{extr}	20-25 kV	40 to 60 kV
O^{8+}	~7 μA	~20 to 50 μA
Xe^{20+}	----	~50 μA
Pb^{27+}	----	40 μA

With respect to SERSE it will have the advantage of a LHe-free cryostat (served by two 1.5 W cryocoolers) and of a much more complex plasma chamber, designed for 60 kV insulation, for the management of 10 kW microwave power and including also a X-ray tantalum shield to prevent the LHe boil-off experienced in previous experiments. As for the case of SERSE, particular care was given to the design of the hexapolar coils, not only in terms of stability versus quench, but also in terms of uniformity for different azimuth, which is important to avoid preferential loss paths for the electrons and to keep the plasma stable. The possibility to get a last closed ECR surface inside the plasma chamber with a value close to 3

T may permit even the coupling of higher frequency microwave generators, up to 37 GHz, or even 56 GHz, with a modest confinement. The design of MS-ECRIS (fig. 1) has taken benefit of the experience with the SERSE source^[3] and of the GyroSERSE project^[4]. A description of the source design was presented in ^[2].

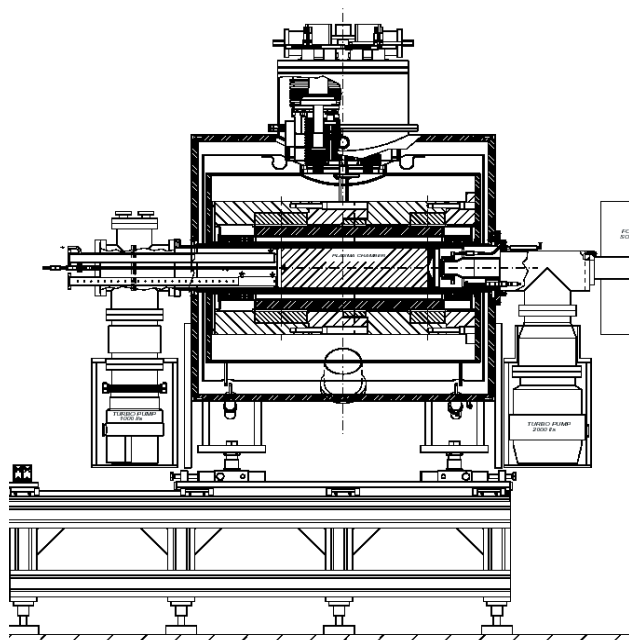


Fig. 1 – A layout of MS-ECRIS with cryostat and support.

The cryostat warm bore has a inner diameter of 202 mm, able to host a 180 mm plasma chamber. The plasma chamber size is relevant to increase the ion confinement time and finally the achievable charge states. Another key point is the magnets' reliability. The choice of small section wires (simple for the solenoid, ribbon-linked for the hexapole) permits to keep the current low for all the magnets (about 50% of the critical current for the hexapole and 40% for the solenoids). The quench detection system (QDS) is designed to switch off the magnets in case of a quench; cold diodes will keep a high level of safety. An additional heat load of 500 mW was considered to take into account the X-rays flux.

The microwave system will be based on a gyrotron (28 GHz-10 kW) followed by an arc detector, a bi-directional coupler and a mode filter before the TE₀₂ to TE₀₁ converter; then a 90° corrugated bend follows which avoids higher order mode excitation and also acts as an additional mode damper; a straight waveguide and a mechanical compensator takes close to the source where a dc break designed for 60 kV insulation is placed, followed by a watercooled vacuum window. The biased disk is located on the axis and the oven is placed on the lower part that is not much affected by electrons coming from the plasma. Room for plasma diagnostics is left on the right side, away from the plasma leakage path.

A 1000 l/s turbomolecular pump at the injection side and a 2000 l/s turbomolecular pump at the extraction side will be able to maintain the pressure in the order of 10⁻⁸ mbar.

The extraction system consists of the plasma electrode, fixed to the chamber and cooled by contact with the wall, and of a movable system made by the puller and ground electrode that may be shifted over 80 mm, to optimize the watercooled puller position.

2 ECR ION SOURCES FOR THE NATIONAL CENTER OF HADRON THERAPY (CNAO)

The Ion Sources R&D Team of INFN-LNS is taking care of the construction and installation of the ion sources at National Center of Hadron Therapy (CNAO) in Pavia in the frame of the agreement between INFN and CNAO.

The design of the sources was carried out in 2005 and it was decided that the best compromise between the reliability, the cost reduction and the low maintainance, consisted in the choice of two Supernanogan sources produced by the Pantechnik company, with some changes to permit the reduction of the emittance and of the beam ripple and the increase at the same time of the reliability and of the beam current (from 200 to 250 μ A for C⁴⁺ and from 600 to 900 μ A for H₃⁺).



Fig. 2 – A plot taken during reliability measurements (the red lines show the acceptable limits).

In 2006 the two sources have been completed and the factory tests were fully positive, either in terms of beam current and in terms of beam emittance (below 0.7 π for all species of interest). Additionally long reliability tests were carried out for each of the sources. The reliability was better than the required one, above 98% for the first ECR ion source (see fig. 2) and well above 99% for the second one, due to improvements of the microwave input system and of the gas valve. The implementation of the frequency tuning system improved the beam current and its ripple. The microwave injection was adapted to the load consisting of the chamber and of the plasma.

A new set of electrodes made the extraction process safer, reducing the number of sparks; the emittance now fulfils the requirements for all the species.

3 SOURCES FOR HIGH POWER PROTON ACCELERATORS

The request of high reliability for High Power Proton Accelerator triggered the decision to replace the solenoids

where a_g is the waveguide width, A is a constant related to the microwave power, ε_n the Neumann's factor (equal to 1 for $n = 0$, equal to 2 if $n = 1, 2 \dots$), x_{nv} is the ν -root of the Bessel function of n order

$$I_{nv}^{TM} = -\int_S \sin \left[\frac{\pi(x - x_A)}{a_g} \right] \left[e^{-i(n+1)p} J_{n+1} \left(\frac{x_{nv} \rho}{a} \right) + e^{-i(n-1)p} J_{n-1} \left(\frac{x_{nv} \rho}{a} \right) \right] dS \quad (3)$$

For the TE modes a similar functional dependence holds. In Fig. 6 the modulus of the electric field without the term $\{1/[1 - (\omega/\omega_{nv})^2]\}$ is shown in the xy plane for $z = L/2$, for the modes with resonance between 13991.15 MHz and 13995.993 MHz.

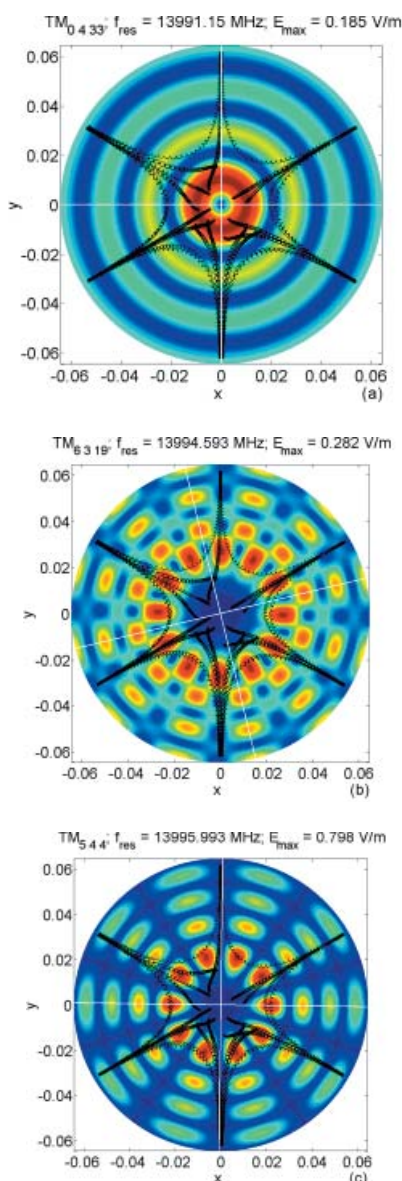


Fig. 6. Modulus of the electric field without the term $\{1/[1 - (\omega/\omega_{nv})^2]\}$ in the plane $z=L/2$ for modes close to 14 GHz. The star-shaped pattern represents the trajectory of an electron moving under the action of the magnetostatic field only.

For each of them the geometric degeneration is uniquely resolved by the exciting waveguide, and the related rotation is indicated by two normal white axes. The maximum modulus has been calculated for 1 W of the waveguide power; after a time interval large enough to neglect the second order terms. It is shown that the field distribution inside the cavity of an ECRIS can be changed significantly by means of small frequency variations, that have a huge effect both on the spatial distribution of minima and maxima, and on the amount of energy coupled from the waveguide to the cavity. Each mode has a different pattern, that has a direct effect on the rate of ionization and therefore on the source performances.

5 ACKNOWLEDGEMENTS

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INVESTIGATIONS ON LASER-DRIVEN PARTICLE ACCELERATOR AT LNS

**L. Torrisi^{1,2}, D. Margarone^{1,2}, L. Andò¹, S. Gammino¹, F. Caridi², A. Borrielli²,
L. Láska³, J. Krása³ and J. Wolowsky⁴**

¹*INFN Laboratori Nazionali del Sud, Catania, Italy*

²*Dipartimento di Fisica, Università di Messina, Italy*

⁽³⁾*Institute of Physics, A.S.C.R., Na Slovance 2, 182 21 Prague 8, Czech Republic*

⁽⁴⁾*Institute of Plasma Physics and Laser Microfusion, Hery St. 23, 00-908 Warsaw, Poland*

Abstract

A new generation of particle accelerators, based on pulsed laser-generated plasmas, is under study nowadays. These accelerators use, as an ion source, the hot plasma obtained by laser ablation of a solid and, as acceleration field, the equivalent voltage generated in the non-equilibrium charge distribution of the plasma. The high ion energy is obtained by the electric fields, of the order of tens MV/cm, developed on distances of the order of the Debye length. The high charge state of the produced ions, the high directivity of plasma plume and the presence of magnetic and electric fields, permit to extract intense energetic ion beams.

1 INTRODUCTION

High-power-laser irradiations of solids in vacuum permits to generate low volume of plasma with peculiar properties. Plasma has high temperature and density, high fractional ionization with high charge states, high plume directivity, high current and energetic particle emission. These characteristics suggest that a new method of ion acceleration can be defined with the goal to produce miniaturized particle accelerators.

At LNS laser intensities of the order of 10^{10} W/cm² generate plasmas at about 300 eV temperature, 10^{17} /cm³ density, 80% fractional ionization, charge states up to about 10+, ion currents of the order of 10 mA and ions with energies up to about 10 keV [1]. At PALS laboratory (Prague, Czech Republic) laser intensities of the order of 10^{16} W/cm² generate plasmas at about 30 keV temperature, 10^{21} /cm³ density, 99% fractional ionization, charge states up to about 50⁺ in heavy elements and ion energies up to about 1 MeV/amu [2].

Although the two experiments are different because in the case of very high laser intensity more complex and non linear phenomena occur, some plasma parameters, such as the equivalent temperature, the density, the equivalent ion acceleration voltage and so on, can be compared in the two cases.

The ions emission from plasma is directed mainly along the normal to the target surface, showing a directivity increasing with the ion charge state [3]. The ion energy

distribution follows a “Coulomb-Boltzmann-shifted” function indicating that thermal processes are responsible of the plasma temperature and of the adiabatic plasma expansion velocity in vacuum, and Coulomb processes are responsible of the high ion acceleration along the normal direction [4]. The ion acceleration is produced by an high voltage developed in the non-equilibrium charge state distribution of the plasma. Assuming it to be extended to a Debye distance, the electric field transient in the plasma is calculable of the order of some MV/cm for the LNS experiments and of the order of GV/cm for the PALS experiments [5].

2 EXPERIMENTAL SET-UP

At LNS a Nd:Yag laser operating at 1064 nm and 532 nm wavelength, 9 ns pulse duration and 900 mJ maximum pulse energy, is focused on solid metallic targets placed in vacuum. Ion collectors (IC) and an electrostatic ion energy analyzer (IEA) permit to measure the ion energies and the ion charge states through time-of-flight (TOF) technique measurements during irradiation at 10^{10} W/cm². Fig. 1 shows a photo of the laser laboratory at LNS.

At PALS an iodine laser operating at 1315 nm and 438 nm wavelengths, 300 ps pulse duration and 600 J maximum pulse energy, is focused on solid targets placed in vacuum. IC and IEA are used to measure the ion energies, charge states, current and angular distributions during irradiations at 10^{16} W/cm².

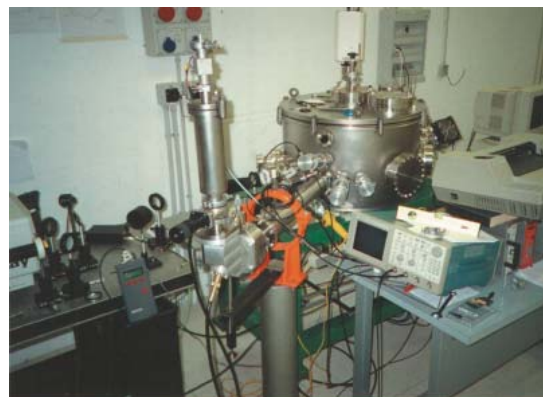


Fig. 1: Laser laboratory at LNS

IEA measures the energy-to-charge ratio by means of the electrostatic ion deflection provided by two biased plates, permitting to plot the ion energy distributions as a function of their charge state [6].

“In situ” plasma diagnostics using mass quadrupole spectrometer, optical spectroscopy and photon and electron detection, is employed with high temporal and spatial resolution, in order to investigate on the dynamic mechanisms of plasma generation and kinetics as a function of the irradiation conditions.

“Ex situ” diagnostics employees a surface profiler and a SEM in order to investigate on the crater and surface morphology of irradiated target surface.

For the post ion acceleration, deflection and focalization we used a bias supply of 40 kV, 100 mA, in order to polarize the metallic irradiated target, and a cylindrical permanent magnetic field of 0.1 Tesla intensity, which axis is directed along the normal to the target surface.

“Opera 3 D” code was used to simulate the path of ions and electron ion emitted from the target and deflected by the post electric and magnetic yields [7].

3 RESULTS

Fig. 2 shows two typical TOF spectra of tantalum target irradiation performed with the Nd:Yag at LNS (a) and with the iodine laser at PALS (b) at 500 mJ and 700 J pulse energy, respectively. The first spectrum shows characteristic peaks, detected by using a 430 eV/z energy/charge ratio, due to the production of eight charge states. The second spectrum features the production of fifty charge states detected by using a 400 keV/z energy/charge ratio.

In both experiments the ion emission is anisotropic and Ta ions are ejected approximately within $\pm 30^\circ$ around the normal to the target surface direction, although increasing the charge state this angular aperture decreases [3].

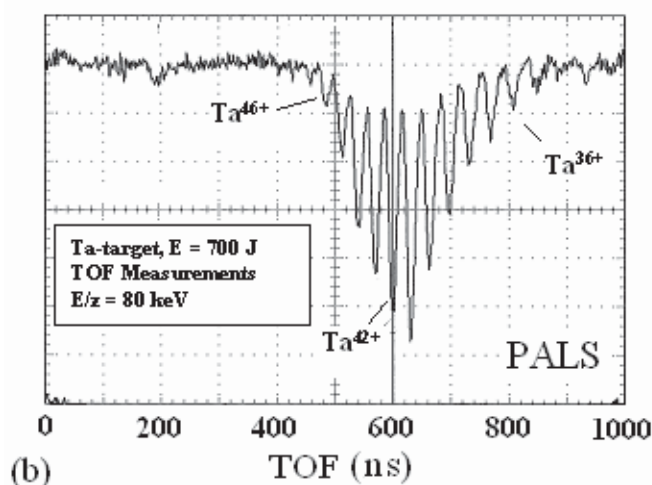
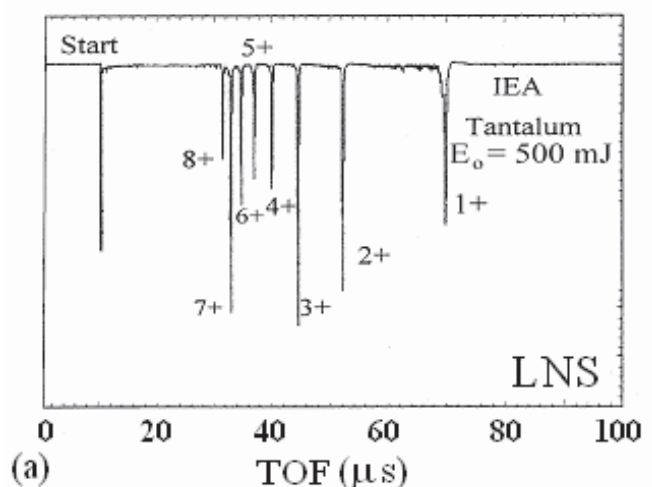


Fig. 2: Typical spectra of tantalum ablation at LNS (a) and PALS (b).

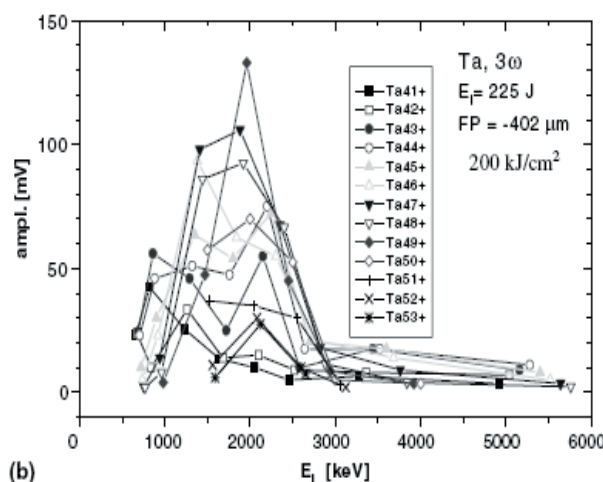
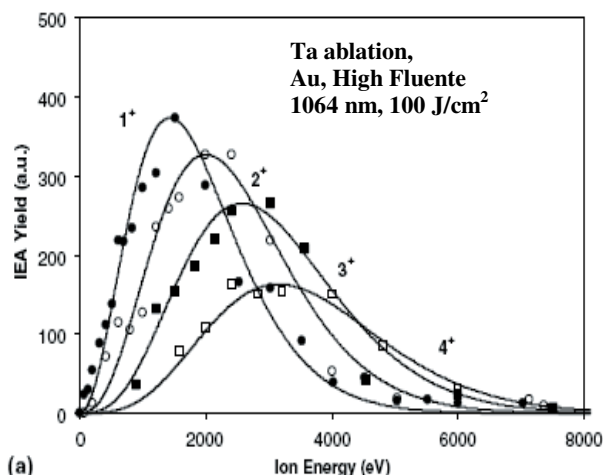


Fig. 3: Typical ion energy distributions obtained at LNS (a) and at PALS (b) laboratories

Fig. 3 shows some typical ion energy distributions for tantalum plasma obtained at the LNS (a) and at PALS (b) laboratories, respectively.

The experimental data (points), as a function of the ion energy and charge state, can be fitted with a Coulomb-Boltzmann-shifted function [1]:

$$f(v_T, v_k, v_c) = A(m/2\pi kT)^{3/2} v_T^3 e^{[-(m/2kT)(v_T - v_k - v_c)^2]}$$

where:

$v_T = (3kT/m)^{1/2}$ is the thermal velocity,

$v_k = (\gamma kT/m)^{1/2}$ is the adiabatic expansion velocity and

$v_c = (2zeVo/m)^{1/2}$ is the Coulomb velocity,

k is the Boltzmann constant, T is the temperature, ze is the ion charge and Vo is the equivalent acceleration voltage.

The fitting parameters determine the plasma equivalent temperature and the three components of the ion velocity. The equivalent temperatures obtained in the two experiments ablating tantalum are 300 eV at LNS and 30 keV at PALS, respectively.

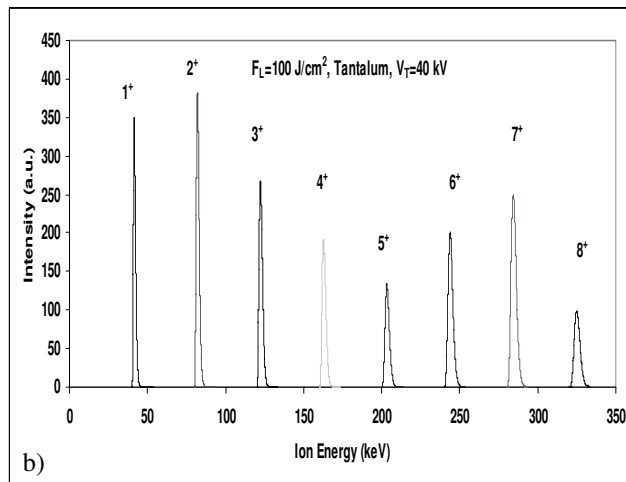
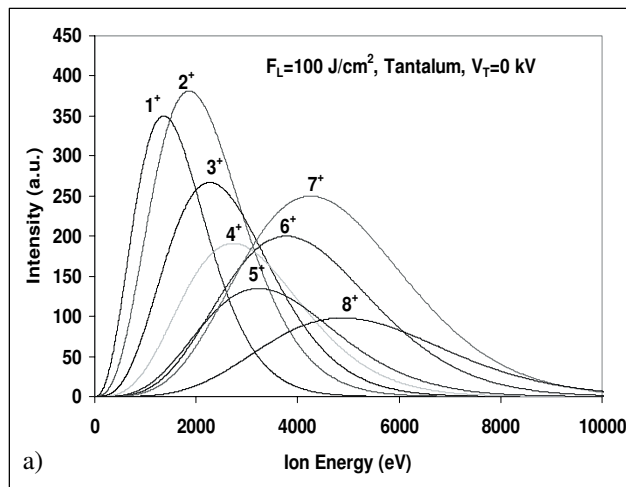


Fig. 4: Comparison of tantalum ion energy distributions without post acceleration (a) and with 40 kV post ion acceleration (b).

The regular shift of the ion energy distributions indicates that an electric field is generated in the non-equilibrium plasma producing an equivalent acceleration voltage Vo of the order of 600 V for plasmas generated at LNS and of the order of 10 kV for plasmas generated at PALS [8].

Assuming the plasma to be in near local thermal equilibrium (NLTE) conditions, and the equivalent voltage to be applied to distances comparable with the Debye length, of the order of 1 μ m, the obtainable electric field transient can reach values of the order of 6 MV/cm and 100 MV/cm for experiments at LNS and PALS, respectively.

Different geometries can be used to generate a post ion acceleration and an ion focalization. For example, the metallic target can be biased positively at 40 kV voltage and a cave cylinder, which axis is directed along the normal to the target surface, can be placed at ground. This geometry improves the ion directivity along the normal direction and accelerates the ion groups of 40 kV per charge state thus splitting the ion energy distribution.

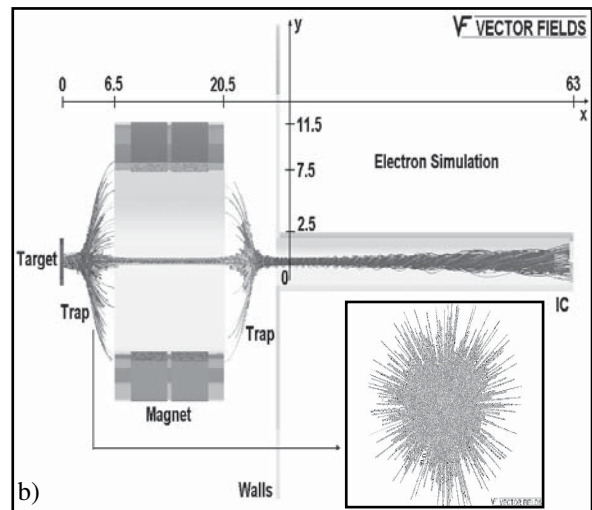
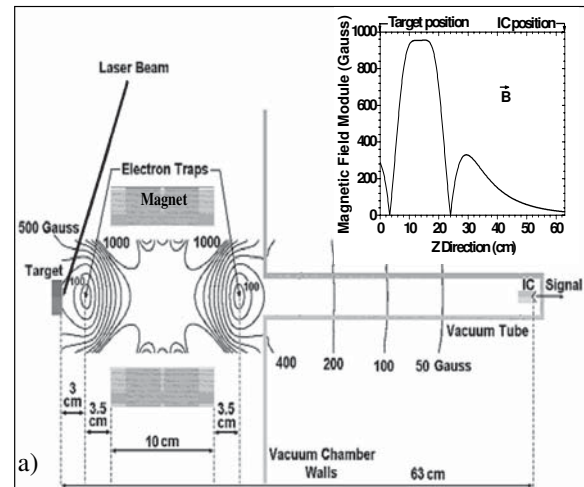


Fig. 5: Representation of the lines of the magnetic field in front of the target surface (a) and simulations of the electrons ejected from the plasma (b).

Fig. 4 reports a comparison of the tantalum ion energy distribution without the post acceleration (a) and with a 40 kV post acceleration (b), respectively.

This technique generates a multi-energetic ion beams, useful for many applications, such as that of ion implantation of different surfaces at high doses in order to modify their chemical and physical properties [9].

Advances in the laser-driven particle acceleration has been obtained also by using magnetic fields to influence the laser-generated plasma. Recent experiments at LNS used 0.1 Tesla permanent magnetic field directed along the target normal direction [10]. The lines of the magnetic field are reported in Fig. 5; they indicate the presence of two important zones along the normal to the target direction where the module of the field is minimum. The first minimum is placed at 3 cm distance from the laser irradiated target surface while the second minimum is located at 20 cm distance (see inset of Fig. 5a).

The first minimum produces an important effect for the electrons ejected from the laser-generated plasma. It generates an electron trapping in the position of minimum $|B|$, as reported in the simulation model of Fig. 5b calculated with "Opera 3D" code. This trapping modifies the spatial distribution of the electron density of the plasma in front of the ablated target. Due to the high electron mobility with respect to ions, the high negative electron density in the trap and the positive target surface, produce an electric field which accelerates further the ions ejected from the target and deflects the ions towards the axial direction. The main effects produced by the magnetic field application to the laser-generated plasma plume are: (i) the ions distributions become more energetic in presence of the magnetic field; (ii) the integral ion yield increases with the magnetic field application; (iii) the ion charge states increase with the use of magnetic field; (iv) the spectra are better TOF resolved with the use of the magnetic field.

Simulations indicate that the electron trap lasts about 300 ns, sufficient to accelerate ejected ions from plasma. This phenomenon is responsible of the increment of the electric field accelerating ions, of the increment of the electron-ion interactions and of the decrease of ion emittance. The electron trapping effect, due to the presence of the minimum of magnetic field, was confirmed by the Monte Carlo simulation of the electron trajectories in static electro-magnetic field performed by using the Opera 3D code. However other magnetic geometries and controls permitted to maintain the traps modifying their position and their lifetime so that an improvement in the ion acceleration can be obtained.

4 DISCUSSION

The results obtained at LNS and at PALS laboratories indicate that the goal to build a laser-driven particle accelerator is possible. Energetic ions are ejected from the laser-generated plasmas with low emittance and their energy can be increased by using a post acceleration or in presence of magnetic electron traps.

Recent measurements at LNS permitted to inject ions in ECR ion sources and to extract ions at a maximum charge state of the order of 40^+ and current densities up to about $50 \mu\text{A}/\text{cm}^2$, thus confirming the validity of the method and suggesting to use a laser ion source (LIS) with variable ion energy to adapt it to the needs of the following ECR ion source [11].

However many difficulties needs to be overcome to reach the goal because the produced ions are not mono-energetic, because the ion energy is not sufficiently high, ion deflection is necessary to eliminate neutrals, impurities ions and different energetic ions, the ion current density is still low and the plasmas are pulsed. This last problem can be resolved by using laser with repetitive pulses, of the order of 30 Hz, which energy cannot be too high and generally limited to the plasma density, to the order of $10^{12} \text{ W}/\text{cm}^2$.

Acknowledgements

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UPGRADING OF SCENT CYCLOTRON UP TO 300 AMeV

L. Calabretta, G. Cuttone, D. Campo, M. Maggiore, L.A.C. Piazza, M. Re, D. Rifuggiato
INFN Laboratori Nazionali del Sud, Catania, Italy

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

Abstract

The design of a superconducting cyclotron able to deliver protons and light ions has been upgraded to achieve the maximum energy of 300 AMeV. A preliminary isochronous field was simulated and the extraction trajectories have been studied and are presented here. An additional room temperature coil was also simulated to optimize the isochronous field for the different ions and to minimize the number of trimming rods.

1 INTRODUCTION

The characteristics of SCENT, a cyclotron able to accelerate particles having a charge to mass ratio $Q/A=0.5$ up to 250 A·MeV, has been already presented in the past years [1,2]. The IBA company has also demonstrated a serious interest to this project and has proposed a cooperation agreement to build together a SCENT cyclotron prototype to be installed in a future therapy center. The cooperation agreement between INFN and IBA was signed on July 2006. This cooperation agreement and the information exchange with IBA company stimulate us to upgrade the maximum energy achievable with SCENT cyclotron.

According to Fig. 1. it is evident that the percentage of treatable patients with carbon beam at energies of 250 AMeV and 300 AMeV are 45% and 74% respectively [3]. The spread between these two percentages is also larger if we consider the tumors located in the Head and Neck district, 46% to 94 %.

The reasons which convinced us to limit the maximum energy of the proposed cyclotron to 300 AMeV and not to reach the highest energy of 400 AMeV are shortly discussed here.

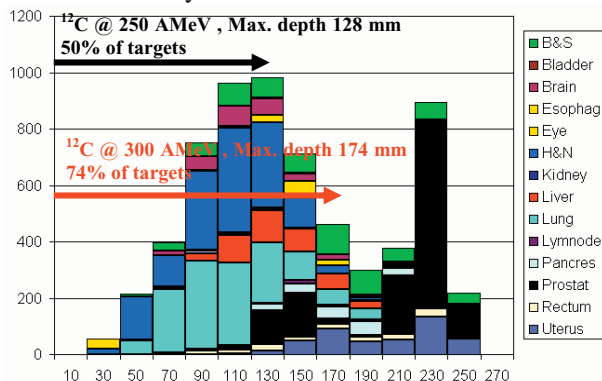


Fig. 1: Distribution of carbon treatment vs. depth of the target performed at CHIBA [3], 6323 targets. Two options are available to achieve the 400 AMeV: to increase greatly the spiral angle, proposed by Blosser

[4], or to increase the cyclotron diameter up to 6 m.

Both these solutions are very challenging for technical reasons and also for beam dynamic problem.

Increasing the maximum energy (E_{max}) of cyclotron means also to increase the minimum energy of proton beam extracted by the stripping method, which is about 0.8 E_{max} . That means that a Cyclotron able to accelerate carbon beam up to 400 AMeV is able to deliver a proton beam extracted by a stripper with a minimum energy of 300 AMeV. This is an additional problem because we prefer to have a cyclotron able to deliver both carbon and proton beam at useful energy

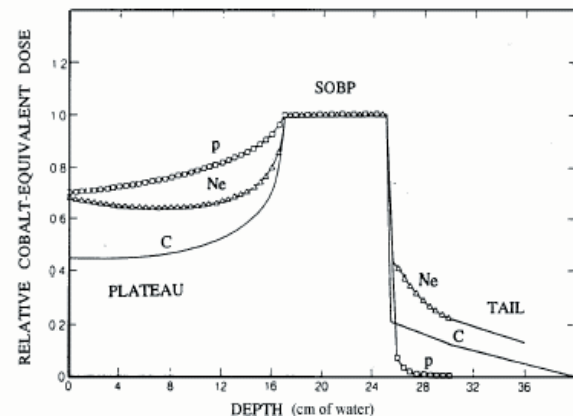


Fig.2: Dose distribution vs. Depth for different ion beam. Target thickness about 8 cm.

It is well known that carbon produces a dose also beyond the Bragg peak and the amount of this dose depends linearly from the depth of the treated tumour.

For targets located at 22 cm and with a thickness of ± 4 cm the amount of the dose at 5 cm beyond the target is $\geq 10\%$ the dose at the SOBP, see fig. 2. For this reason we believe that the use of carbon beam is more relevant for tumours not very deep.

According to these considerations we fix as higher energy limit for our cyclotron design the value of 300 AMeV. This goal was achieved maintaining the radius of the pole at 1.32 m and reducing the hill gap from the previous value of 50 mm to the new of 30 mm to have enough vertical focusing. The cyclotron main parameters are presented in table 1.

Table 1: Cyclotron main parameters

Sectors	4	RF Frequency	97 MHz
Hill gap	30 mm	Hill width	$34^\circ \div 44^\circ$
B at centre	3.07 T	<Max. Field>	4.2 T
Coil size: width	150 x	Current density	$<50 \text{ A/mm}^2$
height	210 mm ²		
Yoke diameter	5.1 m	Total weight	$<420 \text{ t}$

2 MAIN MAGNETIC FIELD

The preliminary magnetic field has been simulated by the 3D electromagnetic code OPERA. The beam dynamics properties have been evaluated by the code GENSPE, which calculates the equilibrium orbits using the magnetic field map produced by OPERA. The magnetic field was not optimized to save time and because we need a preliminary magnetic field just to investigate the extraction process by electrostatic deflector and by stripper. The magnetic field was achieved using the previous size of the superconducting coil cross section but increasing the current density up to 50 A/mm². Also some minor changes in the iron design were introduced: a larger hole in the valley, a larger spiral angle, and a larger return yoke diameter to reduce the stray field. Moreover in the perspective to build a superconducting coil with a current density as higher as 80 A/mm², we investigated if it is feasible to maintain the same iron configuration when a coil having a different cross section size and current density is used. The result of this study was positive. The differences between the magnetic field (vs. radius) produced by our nominal coil with a current density of 50 A/mm² and a smaller coil with higher density are shown in Fig. 3. The centre of the cross section of this smaller coil was shifted in x and y direction respect to the centre cross section of the nominal coil. The different curves show that it is possible to find out a proper position for the smaller coil which minimize the relative difference between the two curves at values below 10⁻³. The residual difference can be then properly compensated by a shimming of the iron.

3 ISOCHRONOUS MAGNETIC FIELD

The goal of SCENT project is to deliver both protons and light ions fully stripped. Despite the charge to mass ratio of H₂⁺ is quite similar to C⁶⁺ there is a small difference of about 0.7%. This small difference produce a different isochronous magnetic field for the two cases. In the previous design of SCENT cyclotron [5], we propose to optimize the required isochronous magnetic field using a set of Trim Rods (T.R.). An oil-dynamic system to move the T.R. and to switch from one setting to another in few seconds was also suggested. The use of T.R. is advantageous respect to trim coils because there are not coils inside the vacuum chamber of cyclotron and to avoid the use of many power suppliers. Anyway at least 20 T.R. for each hill are necessary and this increases the mechanical construction cost. The proposed energy upgrade needs also a more perfect isochronous field so probably the number of T.R. could be increased, so we find out a solution to avoid or at least to reduce the number of T.R. According to the method developed by Bellomo to design our k-800 cyclotron, we know that an additional coil can be used to minimize the contribute of magnetic field produced by trim coils.

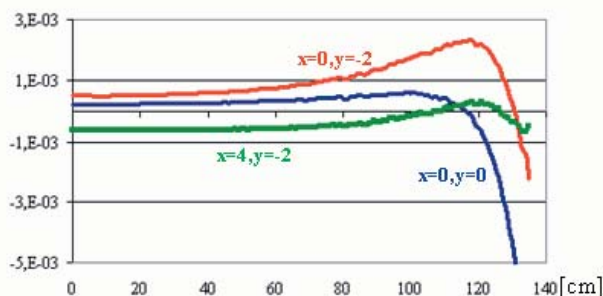


Fig. 3. Relative magnetic field differences vs. radius between two coils with a current density of 50 and 80 A/mm² respectively. The three curves are for different centre position respect to the initial position. The unit of the shift are mm. The nominal current was adjusted too.

To achieve the isochronous magnetic field for H₂⁺ and carbon beam a best fit code was done.

The code evaluates the mean magnetic field as the sum of three parts: the iron contribution which is fixed, the main coil form factor and the correction coil form factor. The best fit code finds out the current of the main and the correction coil which minimizes the difference between the isochronous field for the two desired ions in the radii range 13÷123 cm. Indeed, as it is described in the next session, the proton beam can be extracted at radius 122 cm at 246 MeV. So for radii larger than 122 cm we need an isochronous field just for carbon beam.

Our first tentative was to divide the main coil in two parts independently fed, but the result was not good, the difference being about 1%. So we simulated a room temperature coil and the fit was performed for different positions of this coil. In fig. 4 the different positions of the coil around the cyclotron are shown.

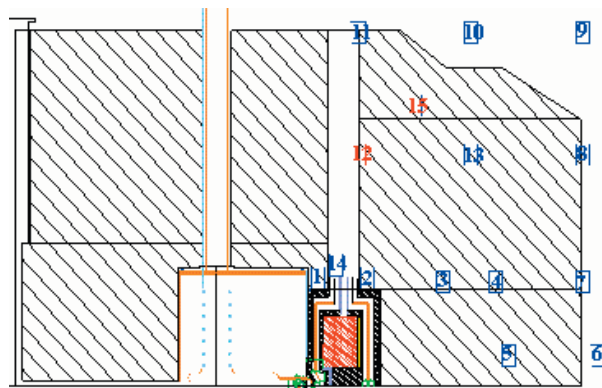


Fig. 4. Cross section of the cyclotron and the different position of the additional coil investigated.

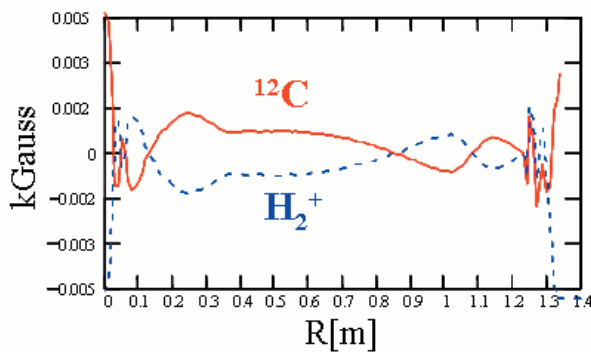


Fig.5. The curve are the relative difference between the isochronous magnetic field and the fitted magnetic field. The additional coil was in the position 15 of fig. 4.

The difference between the ideal isochronous magnetic field and the fitted real magnetic field vs. radius both for H_2^+ and carbon are shown in fig. 5. The average difference between the ideal isochronous field and the real one is around 0.1%. This was the best result among the different position shown in fig. 4. It was achieved with an additional coil in the position labelled 15. The result is very positive and we expect to reduce the number of T.R. below 10. If the additional coil has a size $12 \times 12 \text{ cm}^2$ the required current density is 3.3 A/mm^2 and the required power is 20 kW for each coil. For symmetry reason the additional coil consists of two symmetric coil around the median plane.

4 EXTRACTION

Despite the proton beam can be extracted by stripper of the H_2^+ molecular beam, the extraction of a fully stripped C must be done using an Electrostatic Deflector (E.D.). Due to the small gap of the hill (30 mm) it is not possible to install the E.D. inside the hill, so it is mandatory to place it in the valley. We first consider the option to install the two E.D. inside two RF cavities. Despite this solution works quite well for the beam extraction dynamic it is not convenient for the RF cavity power consumption. The large vertical size of the Dee in the region in front the inner wall of the cryostat produce a large capacitance which reduce greatly the Q of the cavity. Moreover the high power consumption and the high power density in the last stem and in the outer edge of the cavity suggested us to search out for an extraction based on just one E.D. to be placed in an empty valley. This solution allows to use an E.D. longer than the previous one and to design a more efficient RF cavity. Unfortunately this solution allows to use only two RF cavity for the acceleration. Both the two extraction solution with two E.D. inside the RF cavities or with just one in an empty valley allows us to extract the beam. The beam envelopes for both cases are shown in fig. 6A and B.

The main parameters of E.D. and M.C. used to simulate the extraction of C^{6+} beam are also shown in table 2. For both the two solutions the end point of

trajectory was the same. The effect of the lack of the second E.D. is compensated by the extra length of about 6° ($+23\%$) of E.D.1 and by its higher electric field. Anyway the Electric Field is lower than the reasonable value of 100 kV/cm. The electric field was selected to achieve a separation of 18 mm between the last accelerated orbit and the extracted orbit at the entrance of M.C.1. Also the 4 M.C. are longer and have an higher magnetic field, but anyway the proposed values are all feasible. Also the two beam envelopes are quite similar.

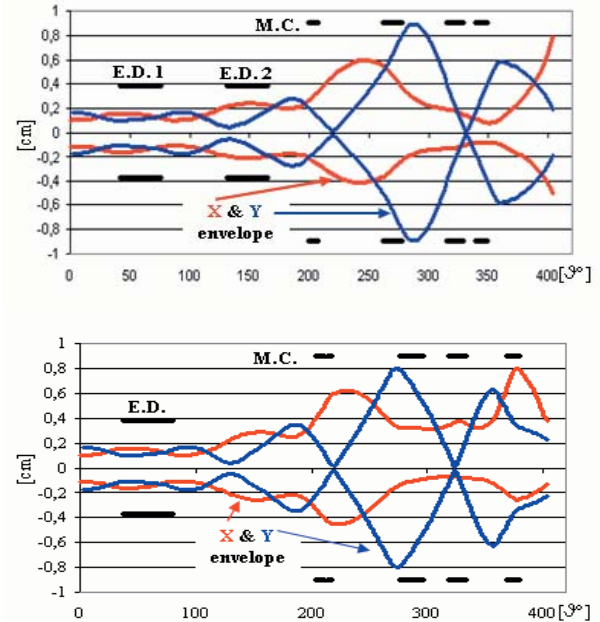


Fig. 6 A/B. Radial and vertical beam envelope along the extraction path. The position and length of the Electrostatic Deflector (E.D.) and of magnetic channels (M.C.) are also shown

The solution with one E.D. is also better both the vertical beam envelope is smaller and at the end of trajectory the beam is focusing in both the x and y planes. Unfortunately for the solution 1 the radial beam envelope inside M.C.1 is 10 mm, while is 6 mm for the solution with 2 E.D.

Table 2: Parameters of electrostatic Deflectors and magnetic channels for the two extraction path.

	Option 2 E.D.		Option 1 E.D.	
	Length	E.F.- M.F.	Length	E.F.- M.F.
E.D. 1	$42^\circ \div 76^\circ$	92 kV/cm	$38^\circ \div 80^\circ$	97 kV/cm
E.D. 2	$132^\circ \div 166^\circ$	92 kV/cm	---	---
M.C.1	$200^\circ \div 208^\circ$	1 kGauss	$206^\circ \div 218^\circ$	2.8 kGauss
M.C.2	$262^\circ \div 278^\circ$	1 kGauss	$278^\circ \div 298^\circ$	2.7 kGauss
M.C.3	$316^\circ \div 330^\circ$	1 kGauss	$324^\circ \div 334^\circ$	1.5 kGauss
M.C.4	$340^\circ \div 350^\circ$	1 kGauss	$370^\circ \div 380^\circ$	1.5 kGauss

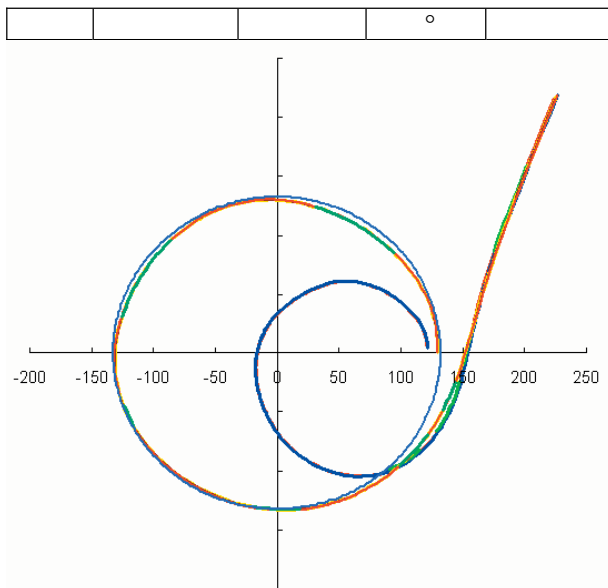


Fig. 7. Beam trajectory for carbon beam extracted with two electrostatic deflectors at 299 AMeV and for proton beam extracted by stripper at $E=246$ MeV.

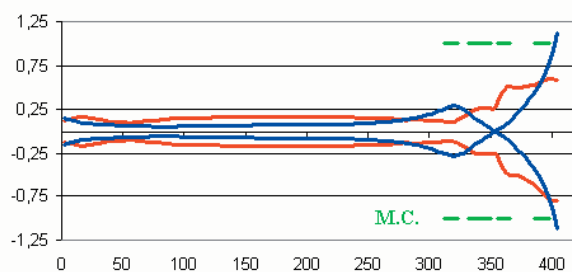


Fig. 8. Beam envelope of proton beam along the extraction path starting at $R=121.6$ cm and $\theta=2^\circ$.

Another goal which we have to achieve is to extract the proton beam at the inner radius as possible to reduce its energy at a value lower than 250 MeV. According to our simulation and using the preliminary magnetic field map the minimum energy which is possible to extract is 246 MeV; to extract this proton beam the stripper was placed at $R=121.6$ cm, $\theta=2^\circ$.

Using proper magnetic channels it is possible to deliver the proton beam along the same extraction channel of carbon beam and with a very similar direction, see fig 7. The beam envelope of proton beam along the extraction path and the position of the M.C. are shown in fig. 8.

5 CONCLUSIONS

The studies performed confirm that it is possible to upgrade the maximum energy of SCENT design to achieve the 300 AMeV. To overcome this limit means that it is not possible to extract the proton beam at energy lower than 250 MeV.

Unfortunately to maintain the radius of pole at 1.32 m we were forced to reduce the hill gap to 30 mm. This

small gap does not allow to install the Electrostatic deflector in the Hill. The decision to place the E.D. in one valley and to use only two RF cavities offers some advantages for the pumping system, for the cooling pipeline and for the diagnostic tools. Unfortunately, on the other hand, we have to use two RF cavities able to produce an high accelerating voltage of 200 kV or more at the extraction radii, to maintain the number of beam turn inside the cyclotron below the 1000.

A lot of work has to be done to optimize the isochronous magnetic field, to avoid the crossing of the dangerous resonance $\nu_x=4/3$, and to optimize the RF cavity design.

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NEW DESIGN TOOLS FOR A CYCLOTRON CENTRAL REGION

D. Battaglia, L. Calabretta, D. Campo M. Maggiore, L.A.C. Piazza, D. Rifuggiato,

INFN Laboratori Nazionali del Sud, Catania, Italy

Abstract

A code that allows us to design the spiral inflector and the central region of the SCENT cyclotron was implemented. The code integrates the main equations of motion of a particle in an electromagnetic field and provides an useful interface to describe the geometry and the physical constraints of the inflector and the central region to be simulated. The mechanical drawings of the inflector and the central region is made using a standard CAD. These drawings are then imported in OPERA 3D to produce the maps of the electric and magnetic field. An application interface allows us to enter the emittance and the particles' distributions to be transported through the inflector. An iterative process to design the central region was also developed and tested.

1 INTRODUCTION

A design study for a Superconducting Cyclotron for Exotic Nuclei and Therapy (SCENT) is in progress at LNS [1]. This is a four sectors cyclotron working in fourth harmonic which in his previous version had to accelerate light ions, with charge to mass ratio $q/A=0.5$, up to an energy of 250 AMeV. Recently a study to increase its maximum energy up to 300 AMeV has started.

The advantage to minimise the size of the cyclotron using high magnetic field has as a drawback the difficulty to design a very compact central region. The feasibility of the central region practically limits the value of the maximum magnetic field usable. Some new tools to help us in the design of the spiral inflector and of the central region were developed.

2 INFLECTOR DESIGN

Among the different types of cyclotron's inflectors known the spiral inflector has the main advantage to occupy a small space and for this reason it was selected as inflector for our project.

The properties of the spiral inflector are well known and described in historical references [2-3]. The free parameters of this inflector are the magnetic curvature and the slant angle. The first parameter is related to the value of the electric field while the second one is a mechanical parameter. Although the main parameters of the spiral inflector can be achieved by analytical equations of the central particles it is also very important for the design of a real device to evaluate the transmission efficiency for a beam with realistic emittance and the mechanical size of the inflector.

The main difference between the analytical solution

and the real case is due to the fringing field effects [4-5] which change the beam dynamics. At first order it is possible to compensate the fringing effects in two ways:

1. decreasing the inflector length;
2. changing the electric field between the electrodes.

We chose the second option because to change the electric field, it is only necessary to decrease the potential of the electrodes. This is also the usual operation made to tune the beam injection. Moreover two collimators, near the entrance and the exit of the inflector, connected to ground, allow us to reduce the extension of the fringing fields. All the mechanical parameters like the size of the holes, the distance between the collimators and the inflector, the gap and the aspect ratio of the inflector, affect the trajectories of the beam particles. So the beam particles' trajectories through the electric field have to be simulated to understand these effects.

A code to help us to design the model of the spiral inflector was developed in MATLAB [10]. The code produces an interface which asks us to fill in each field with the parameters of the inflector and of the cyclotron field and of the beam, see Fig. 1.

When all the parameters have been inserted, the code produces different files describing the central trajectory but also some input files for the mechanical drawing code which allows us to generate the mechanical model of the inflector and of its collimators. This model can be imported in the electrostatic simulator of OPERA code [9].

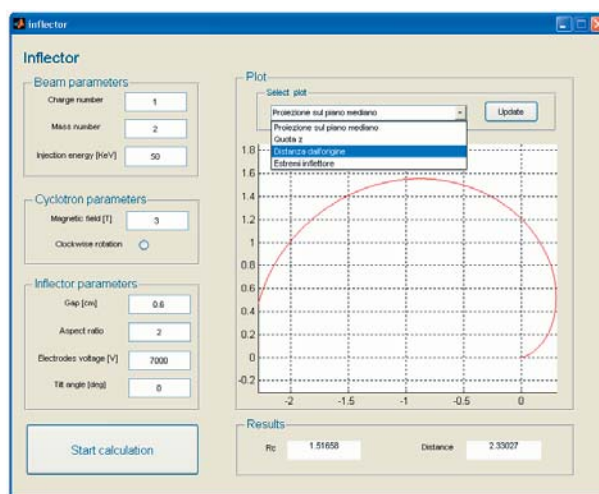


Fig. 1. Graphical interface to optimize the inflector design.

Then the boundary conditions to the geometrical structure have to be assigned to simulate the inflector by

the 3D code OPERA and to calculate the effective electric field distribution.

The tracking code of OPERA is used to simulate the trajectories of the ions inside the inflector. Fig. 2 shows the inflector and the particles' trajectories.

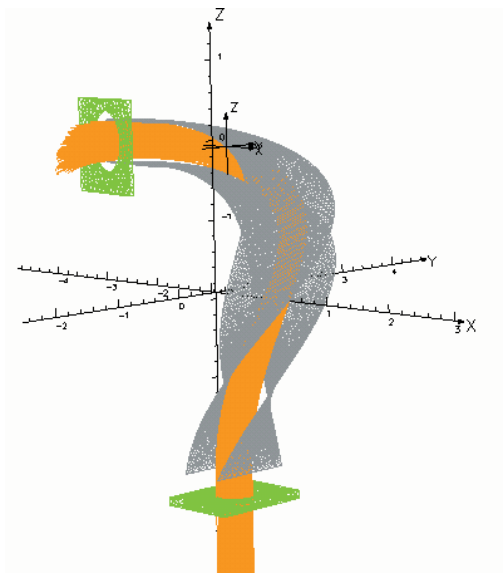


Fig. 2. Layout of the spiral inflector crossed by the beam. The electrodes surface are in grey, the collimators are in green and the beam particles in orange.

An additional code allows us to print easily the input file of the particle's coordinates in the phase space. Many parameters of the beam distribution like the size and the position of the beam and also the kind of the distribution, uniform or gaussian, can be selected.

The output files of OPERA code are also handled by the interface code which shows the final beam position and the beam distribution in the transversal plane at the exit position of the inflector.

In Fig. 3 the axial beam emittance of the particles transmitted through the inflector is shown. The transmission efficiency of the simulated inflector is about 98.5%.

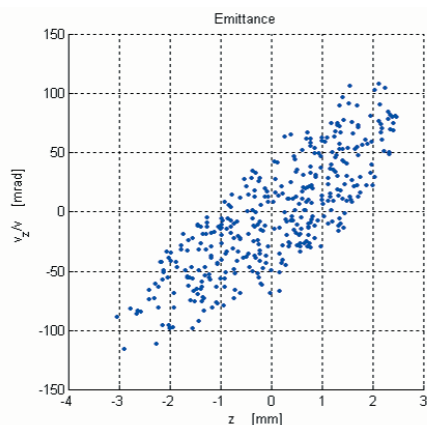


Fig. 3. Beam axial emittance at the exit of the inflector.

3 CENTRAL REGION DESIGN

The central region was designed to optimize the energy gain and the beam centering.

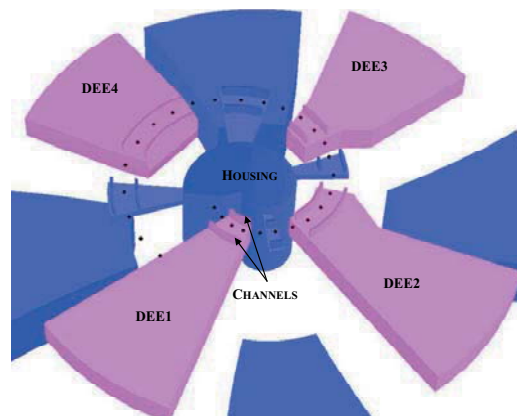


Fig. 4. Layout of the central region of SCENT.

The preliminary design of the central region begins with the construction of the reference trajectory. This is done using a CAD and assuming that the energy gain occurs in the middle of each acceleration gap. The coordinates of the particles and their velocity at inflector exit have to be entered too.

We supposed that the trajectory is the union of N arcs of circle, where N is the number of crossed gap. So we determined the position of the center of the arc and the new value of the radius for each crossed gap [6]. Around this trajectory a tentative profile of the dees and dummy dees is drawn. This structure is imported in a 3D electrostatic simulator code, like OPERA to achieve the electric field distribution. The magnetic field maps were evaluated also by the same code.

The electric and magnetic maps are then imported in a dedicated code to evaluate the real trajectory. This code, written in MATLAB environment, allows us to evaluate the beam dynamics integrating the Lorentz's equation $\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$ using the cartesian coordinates and time as independent variable of integration. An option using the angular azimuth as independent variable of integration is in progress. Looking at the trajectory the drawing of the central region electrodes are modified and a new simulation is restarted.

The code allows us to enter the coordinates, the velocity and the phase of a number of particles.

In the first turn, to improve the effects of the accelerating electric field a channel across each dee is used. These channels allow us to confine the electric field close to the gaps. A radial gap of 8 mm was selected to leave enough space for the beam inside the channel.

The electric field values along the vertical direction are lower than 60% of the Kilpatrick limit [8], because the magnetic field is just along this direction. Along the radial direction, where the magnetic field prevents the electrical discharge, the maximum electric field is up to 1.7 times the Kilpatrick limit.

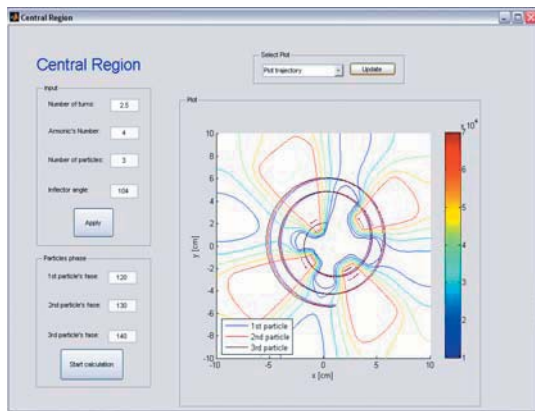


Fig. 5. Trajectory of three particles with different phase.

Fig. 5 shows the graphical interface of our code. The outputs of the code are the trajectories, the motion of the trajectories' center, the gain of energy for particle. In this figure the trajectories of three particles with phase ϕ of 120°, 130° and 140° respectively are plotted.

Fig. 6 shows the energy versus the RF phase while in Fig. 7 the motion of the curvature's center in the first turns are shown.

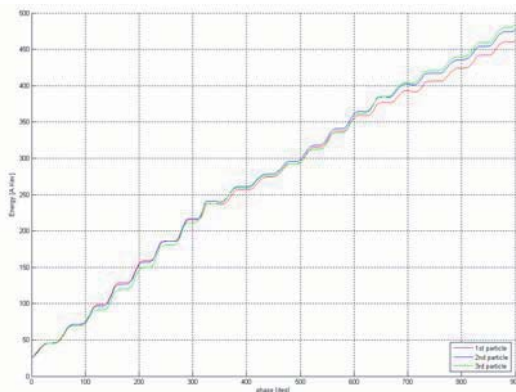


Fig. 6. Energy gain of three particles for the first turns.

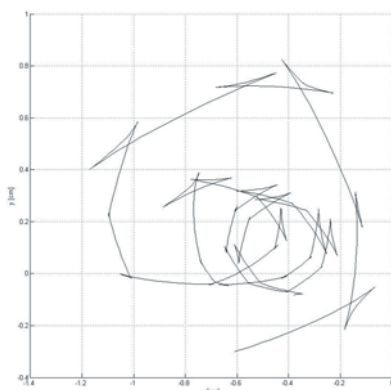


Fig. 7. Motion of the curvature's center of one particle.

4 NUMERICAL RESULTS

In order to check our code we simulated the beam dynamics of the central region of the K800 superconducting cyclotron.

We compared the results with the trajectory obtained from the code Z3CYCLONE [11].

In the Fig. 8 the red line shows the trajectory obtained with our code and the black one shows the result of the Z3CYCLONE simulation. A good matching of the results was obtained. The difference between the trajectories radii is lower than 0.6%.

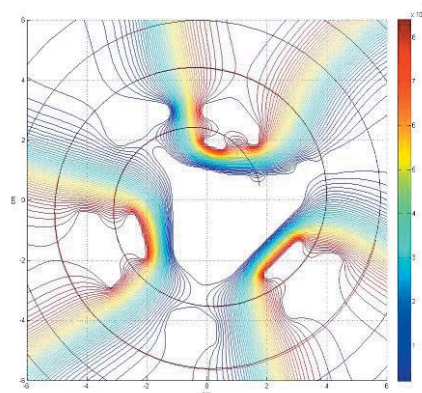


Fig. 8. Trajectory calculated with our code (red line) and Z3CYCLONE (black line).

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DESIGN OF THE FLAT-TOP ACCELERATION CAVITY FOR THE LNS SUPERCONDUCTING CYCLOTRON

L.A.C.Piazza, D.Battaglia, L.Calabretta, A.Caruso, F.Consoli, M.Maggiore, D.Rifuggiato, A.Spartà

INFN Laboratori Nazionali del Sud, Catania, Italy.

Abstract

A 3rd harmonic Flat-top acceleration system for the K800 Superconducting Cyclotron of the Laboratori Nazionali del Sud (LNS) was designed to reduce the energy spread of the accelerated particles and to improve the beam quality and the extraction efficiency.

The Flat-top effect is realized by the superposition of the 3rd harmonic to the fundamental acceleration frequency. The 3rd harmonic frequency is produced by an additional resonator, capacitively coupled to the K 800 cavities. The Flat-top cavity was designed with the 3D electromagnetic codes Ansoft HFSS and CST MicroWaveStudio.

1 INTRODUCTION

The LNS K800 Superconducting Cyclotron (CS), is a compact three-sector accelerator. The cyclotron, in operation since 1995, delivers ions in the energy range 8÷80 AMeV. The acceleration is provided by three $\lambda/2$ coaxial resonators, with a maximum acceleration voltage of 100 kV [1]. The tuning of the cavities, between 15 and 48 MHz, is allowed by a sliding short system, about 3 meters long. The cyclotron is now used also to deliver a primary beam for the Excyt project, a facility for the production of radioactive nuclei [2]. The introduction of a Flat-top system modifies the shape of the acceleration voltage from sine to square wave, reduces the energy spread of the accelerated beam and improves the beam quality and the extraction efficiency in the perspective of delivering a 500 W beam power. A brief description of the system is here presented.

2 FLAT-TOP SYSTEM

According to the Fourier analysis, a square waveform shape is the result of the sum of all the odd harmonics of the fundamental frequency. The superposition of the main frequency with the 3rd or 5th harmonic, gives a more uniform acceleration voltage in a phase range of $\pm 30^\circ$ around the phase of the reference particle [3].

If $V_0 = A_0 \sin(2\pi f_0 t)$ is the main resonance (f_0) acceleration voltage on the median plane and

$V_n = \frac{A_0}{n^2} \sin(2\pi(nf_0)t)$ ($n=3,5,7,\dots$) is the voltage of an odd n -harmonic frequency, the superposition of the fundamental and the harmonic n is:

$$V_{\text{FLATTOP}} = A_0 \sin(2\pi f_0 t) + \frac{A_0}{n^2} \sin(2\pi(nf_0)t).$$

If $n=3$ the Flat-top voltage has the shape shown in Fig.1.

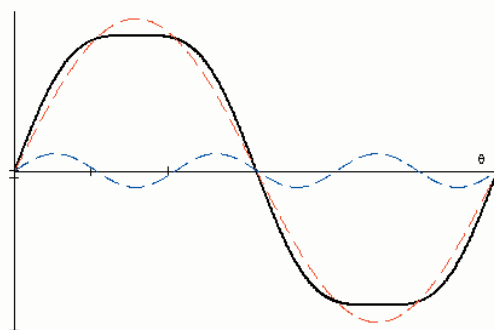


Figure 1: Main resonance (red line), 3rd harmonic (blue line) and flat acceleration voltage (black line).

As a general rule the result of the superposition between the fundamental frequency and a generic harmonic $n f_0$ produces a broader flattop region for lower harmonic number. On the other side the lower the harmonic mode, the higher the power dissipation, because the voltage amplitude is inversely proportional to the square of the harmonic number. According to the Fig.1 the energy gain for the particles inside a beam bunch with a length of about $10\text{-}20^\circ$ will be uniform. The Fig. 2 shows the flattop voltage achieved adding a 3rd or a 5th harmonic to the fundamental frequency.

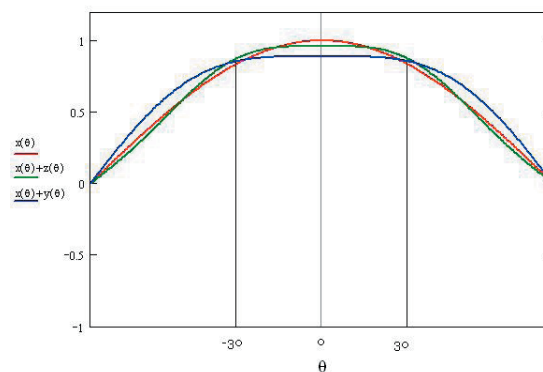


Figure 2: Not flat (red line), 3rd harmonic flat (blue line) and 5th harmonic (green line) acceleration voltage.

3 ELECTROMAGNETIC SIMULATIONS

The RF structures have been investigated with the 3D EM simulation codes CST MicroWave Studio[4] and Ansoft HFSS[5]. First of all the CS cavity was simulated to analyse its resonance modes and to evaluate its performances. The results of the simulation confirmed the $\lambda/2$ cavity behaviour in terms of electric and magnetic field distributions of the main mode and the higher modes

($3\lambda/2$, $5\lambda/2$...). Moreover further resonances identified as transverse resonance modes were found, see Fig. 3.

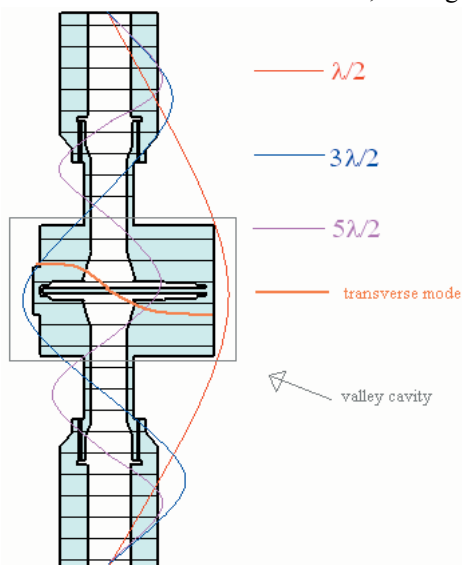


Figure 3: Electric field distribution of the main mode, the high harmonic resonances and transverse mode along a cross section of the cavity.

These further resonances occur ever at the same fixed frequencies (for example 98.0 MHz, 162.0 MHz, 220.0 MHz) and are not sensitive to the tuning change between 15÷48 MHz. So these frequencies are not related to the position of the sliding shorts of the cavities, but they are related to the geometry of the valley cavity, its shape and dimensions, which produces a transverse standing wave. The consequent modes are natural resonances of the cavity, which is confirmed by a simulation of the valley alone, without the coaxial structures. Due to the high frequency of these modes the usual operation of the cavity is not influenced, but a coupling between the transverse resonance mode and the 3rd or 5th harmonic of the fundamental ($n\lambda/2$) is possible. This coupling causes an energy transfer between these modes, thus in the frequency regions where transverse resonances are active it is not possible to generate a stable 3rd or 5th harmonic voltage to achieve a proper flat voltage distribution along the acceleration gap. A further effect related to the valley shape geometry is the electromagnetic distribution of the 3rd and 5th harmonic modes. The figure 4 shows the results of the simulations for three frequency regions. In the range 27.5÷30.0 MHz, the 3rd harmonic mode shows an electric field distribution on the median plane that allows to realize a flat-top effect at the extraction region. This frequency mode is a little higher than the right $3f_0$ value. In the range between 30.0 MHz and 33.5 MHz the 3rd harmonic mode is coupled to a transverse electric field, oscillating on the median plane, so the production of a flattop voltage is not possible. The values of the electric field at the injection and at the extraction are comparable but in opposite phase.

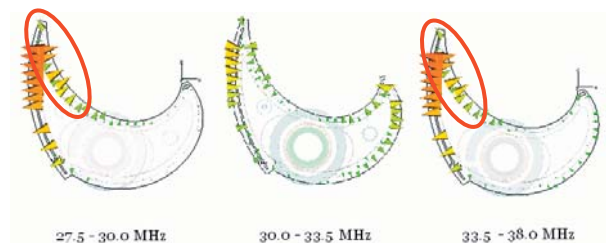


Figure 4: 3rd harmonic electric field distribution on the median plane for 3 frequency ranges. The red circled area is the region where the flat-top voltage is achieved.

A technical solution to overcome this problem, like a slotted Dee [6], has been studied without success. In the last range from 33.5 MHz to 38.0 MHz the transverse higher mode effect is attenuated. In this range it is always possible produce a Flat-top effect at the extraction region.

Unfortunately the 5th harmonic mode has an irregular distribution of the electric field on the median plane, for the whole frequency range due to the strong coupling with the transverse resonances, Fig. 5. So it is not allowed to use this mode to produce a flat-top effect.

Thus we analyzed a 3rd harmonic flat-top system only in the frequency range 27.5÷30.0 MHz and 33.5÷38.0 MHz. The figure 5 shows the resonance values of the 3rd and 5th resonant harmonic modes and of the transverse mode for the fundamental frequency range 22.0÷46.0 MHz.

4 DESIGN OF THE FLAT-TOP CAVITY

A $\lambda/4$ coaxial cavity with a plate has been chosen as Flat-top resonator. Only one additional cavity will be used to provide the flat-top effect for all the three CS resonators. The additional resonator will be installed inside an existing cylindrical hole in the top of the magnet which is connected with the valley of one RF Cavity. The RF cavity and the flat-top cavity are electrically connected by a capacitive coupling.

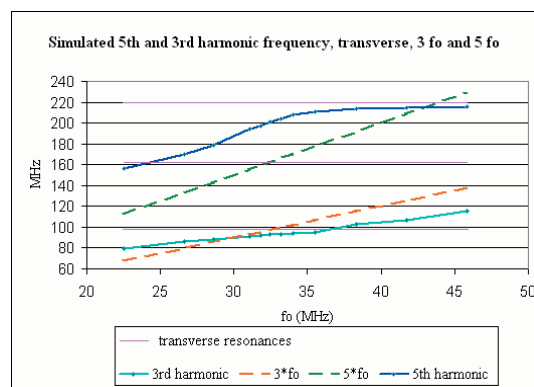


Figure 5: Simulated 3rd, 5th harmonic mode and transverse mode frequencies vs. frequency of the fundamental mode.

To tune the Flat-top cavity in all the frequency range, two different solutions have been investigated.

4.1 1st solution: fixed plate, sliding short circuit.

The first solution is a coaxial $\lambda/4$ cavity with a fixed distance plate from the median plane and a sliding short circuit system on the upper side of the cavity, as shown in Fig. 6. In this case the capacitance of the cavity is mainly due to the plate, while the inductance is adjustable by the sliding shorts. The geometrical main characteristics of the cavity are $\phi_{\text{ext}} = 90$ mm, $\phi_{\text{int}} = 24$ mm and the distance between the sliding short and the capacitive plate is in the range 587÷720 mm. The plate diameter and the distance from the dee are 180 and 100 mm respectively. This distance is enough to prevent electric discharges. The whole range of CS frequency is covered.

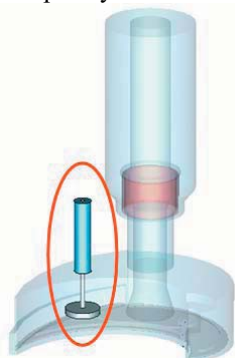


Figure 6: CS cavity and 1st Flat-top cavity.

The additional cavity is used to reduce the 3rd harmonic mode of the main cavity to the desired frequency value $3f_0$ in the frequency range 27.5÷30.0 MHz. While in the range 33.5÷38.0 MHz, we use the two cavities as one resonator where the frequency modes are the combination between the resonances of the original cavities. The positions of the sliding short of both the additional and the main cavity are used to find out the additional mode with the proper voltage distribution on the Dee and frequency $3f_0$.

To produce the Flat-top effect a maximum voltage of 40 kV is required at the extraction region. To achieve this voltage value a RF power of 13 kW and a current density on the short circuit of 76 Amps/cm are required. The Q factor value is about 5000. The perturbation of the additional cavity on the main resonator is about 90.0 kHz at higher frequencies. It is easily adjustable with a slight retuning of the CS cavity. The Q factor and the main resonance acceleration voltage distribution do not change.

Unfortunately the high value of the current density on the sliding contacts makes this solution not reliable.

4.2 2nd solution: variable capacitance plate

To avoid the previous problem a cavity with a fixed short circuit and a variable capacitance plate has been investigated. The tuning of this Flat-top cavity is allowed by a semicircular moveable plate system, as shown in Figure 7. The plate is composed by two symmetrical semicircular sections: one fixed, the other one rotating. The rotation from 0° to 180° of the moveable part allows to tune the capacitance of the Flat-top cavity.

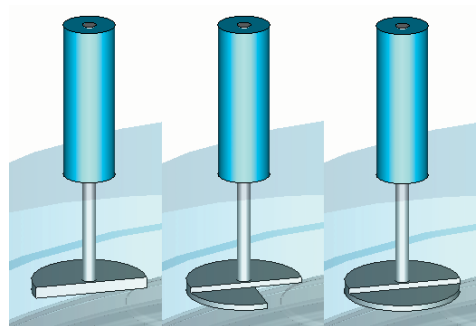


Figure 7: 2nd Flat-top cavity on detail.

It is possible to obtain a frequency variation of the flat-top cavity up to 8 MHz with half plates of ϕ 200 mm and 100 mm far from the median plane. So we chose the parameters of this cavity to achieve a flat-top effect in the frequency range from 33.5 MHz to 36.2 MHz because this range allows us to accelerate the primary beams requested to operate of the EXCYT facility.

To achieve the maximum voltage of 40 kV for the frequency mode $3f_0$ a power of 7 kW is required. An inductive excitation coupler is under study.

5 CONCLUSIONS

A preliminary Flat-top cavity has been investigated and designed at LNS with the aid of 3D electromagnetic simulators. A $\lambda/4$ coaxial cavity with a variable capacitance plate has been chosen to realize a Flat-top effect in the CS frequency range 33.5÷36.2 MHz. Despite its short frequency range this technical improvement should produce an increasing of extraction efficiency just for the beams required for the EXCYT facility. We are planning to make this cavity in order to check the expected improvement on the beam. After these tests we shall decide to build a second cavity with a different operational frequency range. The new cavity can be installed in another valley so allowing to use one or the other cavity according to the working frequency.

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RF FINGER CONTACTS - EXPERIMENTAL STUDY AS A RESULT OF A THEORETICAL INVESTIGATION ON THE SLIDING SHORT CURRENT OF THE CHOPPER-500 DEFLECTION SYSTEM

A.Caruso^{a,*}, L.Calabretta^a, F.Consoli^{a,*}, A.Spartà^a, J.Sura^b, E.Zappalà^a,

a) INFN Laboratori Nazionali del Sud, Catania, Italy

b) University of Warsaw, Heavy Ions Laboratori, Poland

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

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

Abstract

The frequency range of the Chopper-500 $\lambda/4$ coaxial resonator is between 65 and 110 MHz. The frequency tuning is obtained by the movement of a sliding short circuit connecting the inner and outer conductors of the resonator. The current flowing in the sliding short is a limiting factor to the maximum voltage applied to the Chopper electrodes. This junction between the two coaxial conductors is made by two circular strips of CuBe (Beryllium-Copper) sliding contacts. These finger contacts, like the whole cavity, are in a vacuum sealed environment. They can only sustain current densities lower than a certain threshold. For higher current densities, the “softening” temperature for the copper-CuBe junction may be reached and the contact surface may be damaged. It is possible to determine the current flowing in this contact region as a function of the electrodes voltage. Starting with the theoretical approach of the evaluation of the maximum current of the sliding short, a simple experimental set-up has been developed to test the RF finger contacts. The experimental results of these test bench measurements and the simulation by a proper electromagnetic solver will be provided in this work.

1 CHOPPER 500

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 $1.5 \div 2$ ns to 0.5 ns [1]. Now all the components of the system are ready. The $\lambda/4$ resonator, the coupling capacitor, the 3”1/8 coaxial line, the 50 kW final stage RF amplifier, the driver pre-amplifier, the low level control system and the DDS frequency synthesizer are on site. During 2006 several tests on the chopper-500 system have been done. All the low level control systems have been successfully tested at the maximum power of 1kW. The turn-on system, the protection circuits, the automatic tuning system, the coupling and trimmer capacitor electronic devices have been developed, assembled and tested on the chopper

resonator. The cooling system has been tested too with the cavity under vacuum. Long and strenuous tests have been performed on the sliding shorts from the mechanical point of view. This last test was done because a specific theoretical study on the single finger contact of the short circuits has shown up a possible bottle neck of the entire system. The Figure 1 shows respectively the connection between the inner and outer coaxial resonator and a portion of the finger contacts of the chopper-500.

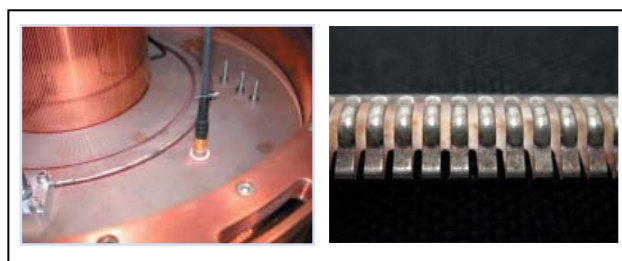


Figure 1: the sliding short connection between inner and outer coaxial on the left, the finger contacts on the right.

The schematic of Figure 2 depicts the Chopper-500 apparatus. The figure shows the basic components of the system, the chopper deflection plates, the distance a between the electrodes and the slits aperture, the direction along x of the beam.

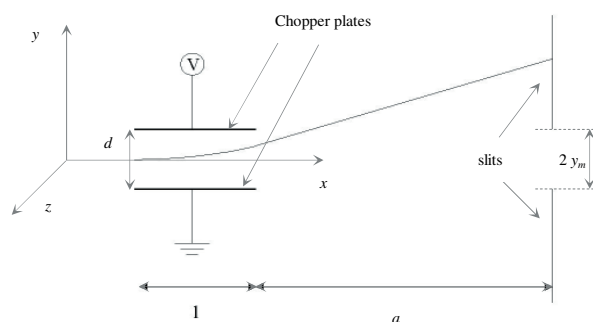


Figure 2: Chopper-500 system schematic drawing.

2 THEORETICAL INVESTIGATION

During the first operative test a parallel study was done to estimate the maximum power dissipated of the chopper-500, in terms of the maximum current density on the sliding short. The frequency range of the Chopper-500 $\lambda/4$ resonator is [65, 110] MHz, and the tuning within this interval is obtained by the movement of a sliding short circuit, connecting inner and outer coaxial conductors of the structure. The connection between inner and outer coaxial is made by two circular strips of CuBe (Berillium-Copper) finger contacts. A vacuum sealed cylindrical steel tank hosts the whole copper RF cavity. In this environment the short circuit can sustain only current densities lower than a threshold. For higher current values the “softening” temperature for the copper-CuBe junction may be reached and the contact surface may be damaged [2]. The current flowing in this sliding short is therefore a limiting factor of the maximum voltage applied to the Chopper electrodes, and a good estimation for safe working conditions is a max current density of 30 A/cm.

In some theoretical investigation is described the physical behaviour of the Chopper-500 system as bunch shaper (to achieve 500 ps) and beam suppressor (to increase the separation time). The theoretical minimum voltage $V_{M req}$ is necessary to obtain the request Δt_{req} when the beam passes through the Chopper-500 system. We also derived a formula for the current on the sliding short as function of the $V_{M req}$:

$$I_{SHORT} = iV_{M req} \sqrt{Y_0^2 + (2\pi n f_{CYCL} C_{cap})^2} \approx \quad (1)$$

$$\approx i \frac{m d y_m f_{CYCL} \sqrt{Y_0^2 + (2\pi n f_{CYCL} C_{cap})^2}}{q \Delta t_{req} \frac{l}{\beta \lambda_{CYCL}} \sqrt{\left(\frac{a^2}{l^2} + \frac{a}{l}\right) \sin^2\left(\frac{\pi l}{\beta \lambda_{CYCL}} n\right) + \frac{1}{4}}}$$

where Y_0 is the characteristic admittance of the coaxial resonator, C_{cap} is the plates capacitance, n is the ratio between the frequency of the sinusoidal voltages driving the Chopper and the Superconducting Cyclotron respectively; m and q are mass and charge of the particles in the beam delivered by the Cyclotron, $l = 0.4$ m is the length of chopper electrodes in the direction of the beam, $a = 3.5$ m is the drift length after the plates and $2 y_m$ is the distance between the slits (see Figure 1). The Superconducting Cyclotron works in 2nd harmonic and it has a radius at extraction equal to 0.87 m; therefore it follows that $\beta \lambda_{CYCL} = 2.733$ m.

Some particles are delivered by the Chopper-500 system to the following beam line also in the time intervals when in principle each one should be deflected. It is possible to define the *Deflection Ratio (DR)* [2] as the ratio between the maximum number of particles delivered by the Chopper-500 system during these time intervals and the number of particles during the first interval (the one properly intended for the bunch delivering). Sometimes this ratio can be referred also to

the total number of particles in one bunch coming to the Chopper from the Cyclotron. For bunches with given *FWHM*, *DR* is a function of the Chopper passing time window Δt , of the T_{CYCL} (period of the signal driving the Cyclotron) and of the frequency ratio n .

In Figure 3 the percentage *DR* is shown for the cases when respectively 1 over 2, 2 over 3, and 3 over 4 bunches are suppressed by the Chopper-500 system

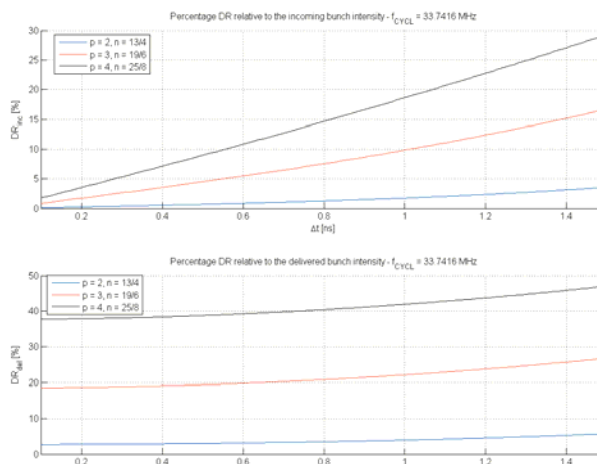


Figure 3: Percentage *Deflection Ratio (DR)* relative to the incoming and delivered bunch for $f_{CYCL} = 33.7416$ MHz.

The mentioned study has been applied to the various beams usually accelerated by the Cyclotron, leading to some tables of optimized conditions for the future use of the Chopper-500 system. The limits due to the threshold for the current flowing in the short circuit, together with the Chopper effect on the beam attenuation and the chopping efficiency have been considered. In order to estimate the required input power for the Chopper, the experimental measurements for the cavity R_{SHUNT} have been employed. In the tables 1-4 are summarized some results achieved when the frequency of the sinusoidal signal driving the Cyclotron is 33.7416 MHz, and the accelerated particles have A (atomic number) = 58 and q (charge respect to the unit) = 19. $V_{min-500}$ is the voltage to apply to obtain $\Delta t = 500$ ps and P_i is the related power. In the case when the current density flowing in the conductors is 30 A/cm, $V_{30A/cm}$ is the voltage applied to the Chopper and $P_{30A/cm}$ is the related supplied power, $y_{m,500}$ is the deflection for a $\Delta t = 500$ ps and $\Delta t_{3.5}$ is the deflection time when the slit aperture is 3.5 mm.

Table 1: $f_{CYCL} = 33.7416$ MHz, $A = 58$, $q = 19$, $y_m = 3.5$ mm; 3 bunches suppressed over 4 – Bunch separation time: 118.548 ns.

f_{CH} [MHz]	n	$V_{min-500}$ [kV]	P_i [kW]	I_{INNER} [A/cm]	I_{OUTER} [A/cm]
71.7009	2.125	210.390	35.416	67.303	25.239
80.1363	2.375	196.569	33.852	63.787	23.920
88.5717	2.625	186.783	35.347	61.553	23.082
97.0071	2.875	180.207	45.926	60.370	22.639
105.4425	3.125	176.339	50.993	60.106	22.540

Table 2: 1 bunch suppressed over 2 – Bunch separation time: 59.274 ns.

f_{CH} [MHz]	n	$V_{30A/cm}$ [kV]	$P_{30A/cm}$ [kW]	$y_m/\Delta t_{req}$ [mm/ps]	$y_{m,500}$ [mm]	$\Delta t_{3.5}$ [ps]
109.6602	3.25	87.228	11.418	$3.500 \cdot 10^{-3}$	1.750	1000.032

Table 3: 2 bunches suppressed over 3 – Bunch separation time: 88.911 ns.

f_{CH} [MHz]	n	$V_{30A/cm}$ [kV]	$P_{30A/cm}$ [kW]	$y_m/\Delta t_{req}$ [mm/ps]	$y_{m,500}$ [mm]	$\Delta t_{3.5}$ [ps]
106.848 4	3.167	87.753	12.397	$3.508 \cdot 10^{-3}$	1.754	997.750

Table 4: 3 bunches suppressed over 4 – Bunch separation time: 118.548 ns.

f_{CH} [MHz]	n	$V_{30A/cm}$ [kV]	$P_{30A/cm}$ [kW]	$y_m/\Delta t_{req}$ [mm/ps]	$y_{m,500}$ [mm]	$\Delta t_{3.5}$ [ps]
105.442 5	3.125	8.801	12.703	$3.510 \cdot 10^{-3}$	1.755	997.197

2.1 The sliding short circuit

The detailed study carried out for all the accelerated beams of the superconducting cyclotron has shown that the maximum RF power delivered from the final stage amplifier is theoretical enough to reach the goals of the Chopper-500 system (a separation time between two consecutive accelerated bunches between $100 \div 200$ ns and for the time length on the single bunch of 500 ps), but the shortcoming is the high current on the sliding short. All the simulations and the analyses, also summarized in the tables before included, show an intensity of the total current near the limit of the sliding short. A value reported in more than one study place 50 A/cm as the upper limit of the finger contact current density [3]. Several electromagnetic and temperature 3D simulations have been taken into account. In Figure 3 it is shown the current distribution on a couple of finger contacts at 30 MHz. The maximum distribution currents are localized on the finger bending side of the RF contact.

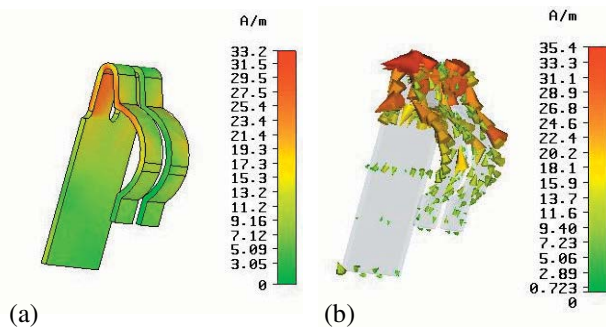


Figure 3: The current density distribution of the Cu-Be finger contact in a 3D electromagnetic simulation at 30 MHz, using the CST microwave studio. (a): contour profile; (b) vectorial visualization.

Moreover, a relation between temperature and current can be taken into account to work with the finger contacts in a safe area. The so-called “copper softening temperature” is the limit of this safe area. This is the

temperature at which the strain hardening in the highly stressed contact disappears. As the current increases, the contact resistance decreases. The softening temperature is about 187°C for a room temperature of 20°C.

3 RF FINGER CONTACTS TEST BENCH

A simple test bench has been developed to test the finger contacts. The weak point of the RF contact is the maximum temperature reached when the high frequency signal flows between both sides of the contact itself. With this test bench we focus our attention on the temperature. All the approaches, including our software study, show the increasing temperature to be a consequence of the high current flowing through the sliding shorts. In general, the number of finger contacts are many in this kind of approach, and the intensity current flowing in a single contact is a ratio between the total calculated current and the number of contacts. Let us try to invert this approach. If we reduce the number of finger contacts to one or two, without a proper cooling system, then a small RF power brings the contact near the so-called “copper softening” temperature, 460° K. In the Figure 4 the test set block diagram of the system is shown.

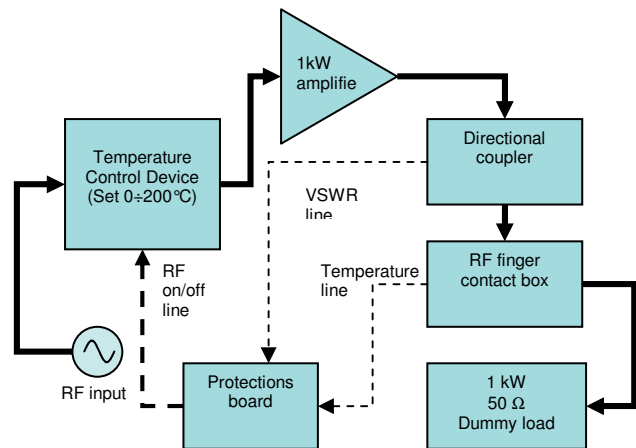


Figure 4: block diagram of the test bench system

3.1 Working principle of the test bench

The test has been carried out at the maximum power of 1kW CW (continuous wave) with a radio frequency of 30 MHz. According to the block diagram the input RF signal reaches the temperature control device. This device contains a voltage controlled amplitude modulator, based on the well-known Mini Circuits PAS-3, a differential amplifier (REF200 plus INA114 Burr Brown semiconductors) and an inverting operational amplifier. The differential stage compares the temperature value from the thermocouple attached to the finger contact and the set temperature value. The difference between the two signals drives the control gate of the RF modulator according to the maximum sensitivity of 10mV/°C. The modulated RF signal will be amplified by the 60dB gain, 1kW amplifier. The output amplifier stage, through a

directional coupler, is connected with the test box, where the finger contacts are placed to be tested. The output of the box is finally connected with the dummy load. The directional coupler supplies the VSWR, furthermore the attenuated forward and reflected signals are processed inside the protection board to prevent dangerous situations. This simple system is a controlled temperature test set. Once you set the maximum temperature, the system takes the RF contact to the desired temperature automatically.

Inside the finger test box the spring contacts being tested are placed. The contact is hosted between two copper bars. Next to the spring contact, in the bottom copper bar, a thermocouple (PT-100) reads the temperature reached. A particular internal view of the test box is shown in the Figure 5. The copper bars between the N-connector, the spring contacts, the thermocouple with the filter section are zoomed in the picture below.

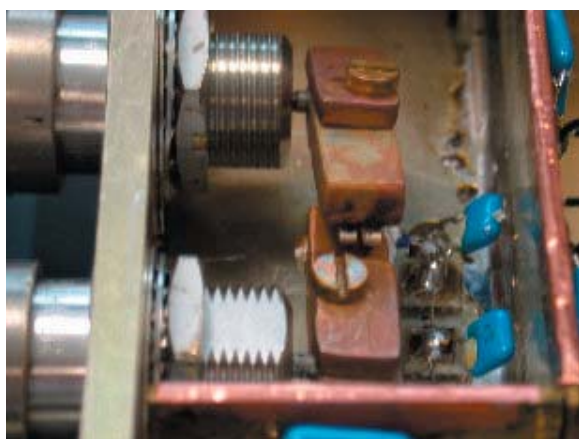


Figure 5: the internal view of the RF finger contact box

The small dimension and the elementary hardware of the box allow for a perfect agreement between the temperature of the contact and the PT-100 read-out.

3.2 Experimental results and measurements

The basic rules of thumb to run the finger contact test bench are resumed below:

- set the reference temperature;
- turn-on the RF power;
- increase the power up to 1kW maximum;
- wait until the finger contact temperature equals the reference one
- keep away from the softening copper temperature.

In the Figure 6 the graph shows an example of “softening copper temperature” reached at the frequency of 30 MHz with 1 kW CW. The finger contact loose the physical characteristics above 170°C.

The following graph of Figure 7 shows a test where a copper bar connects input and output N-connectors, no finger contact are used. The temperature gradually increases without the softening copper phenomenon.

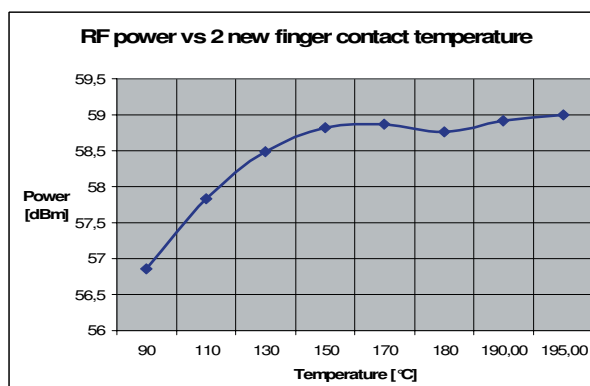


Figure 6: the two finger contacts damaged over 170°C

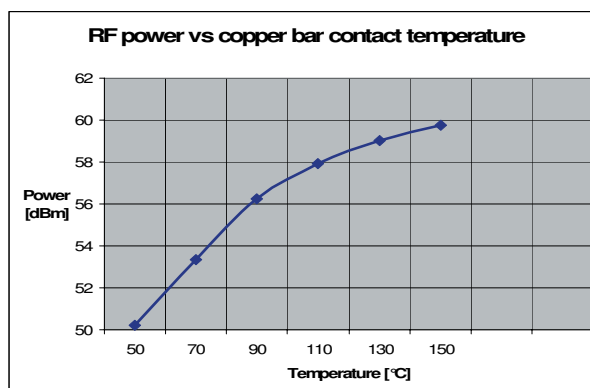


Figure 7: the copper bar temperature vs RF power

The experience of the thermocouple inserted in the test finger box can be replayed in the final version of the chopper-500 sliding short. We are planning to connect along the circular shape of the inner coaxial of the $\lambda/4$ resonator, as near as possible to the finger contacts, more than one PT-100 in order to check the working temperature of the RF contacts. The sliding short of the chopper-500 operates in a vacuum environment; a proper cooling system has been installed and already tested, but the high current can increase the temperature to a dangerous level. The continuous read-out of the heating effect through this simple system can avoid the copper softening temperature. The system can be fixed at a safe low working temperature far enough from the softening threshold. This finger contact test bench can easily be used to test all the finger contact types for any other future applications.

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Interdisciplinary physics



THE CATANA PROTON THERAPY FACILITY: FOUR 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)}, I.V. Patti^{a)}, S. Pittera^{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 92 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

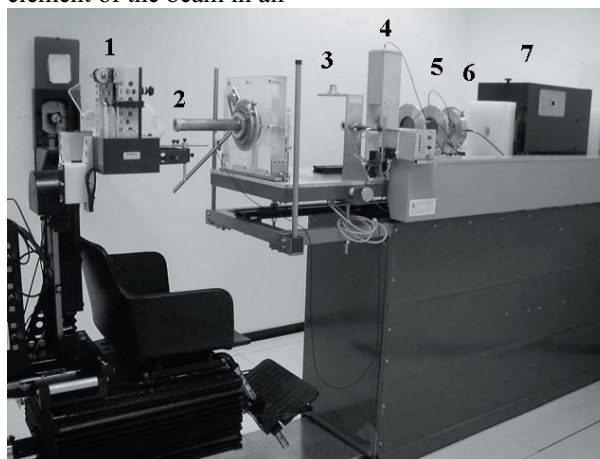


Figure 1: View of the CATANA beam line: 1. Treatment chair for patient immobilization; 2. Final collimator; 3. Positioning laser; 4. Light field simulator; 5. Monitor chambers; 6. Intermediate collimator; 7. Box for the location of modulator wheel and range shifter.

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).

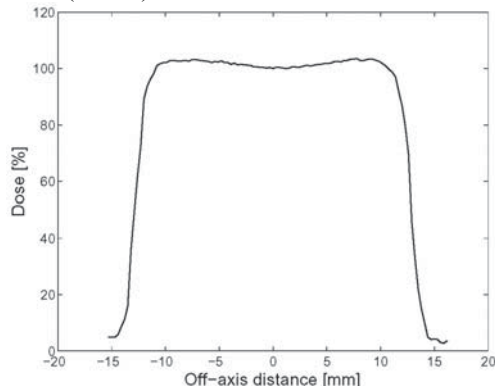


Figure 2: Lateral dose distribution for 62 MeV proton beam.

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%.

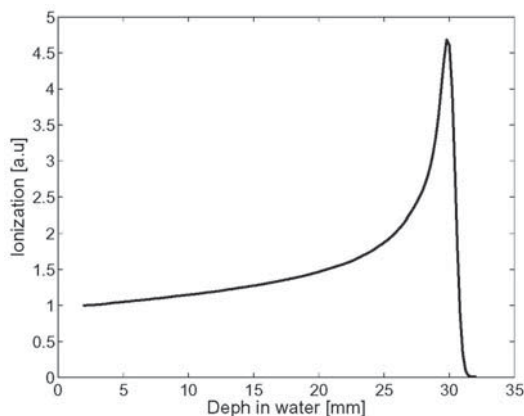


Figure 3: Bragg peak of 62 MeV proton beam acquired in a water-tank with the Markus ionization chamber at CATANA facility.

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 a 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].

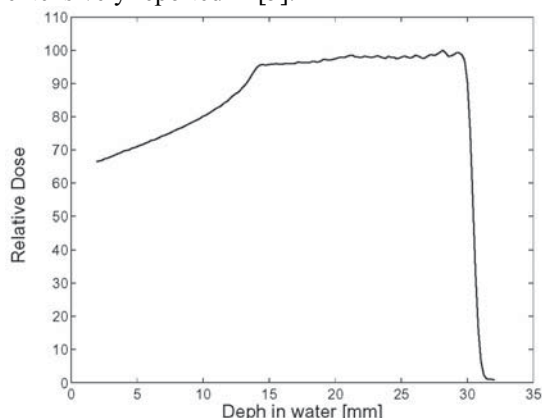


Figure 4: Spread Out Bragg Peak obtained with a modulator wheel.

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.

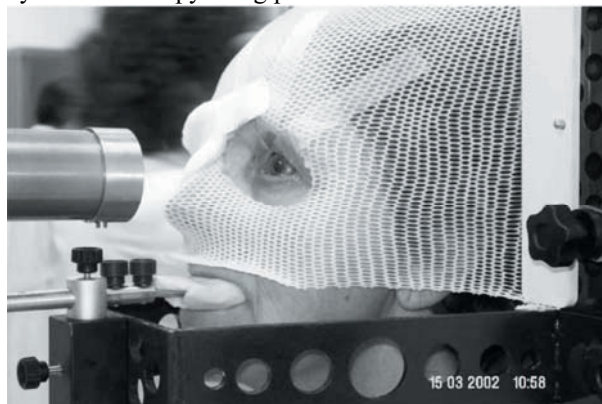


Figure 5: Thermoplastic mask and bite block.

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, 141 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 (4%), conjunctival rhabdomyosarcoma (1%), eyelid carcinoma (2%) and conjunctival Mucosa-Associated Lymphoid Tissue-Non Hodgkin Lymphoma (MALT-NHL) (1%). Among the 92 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 56 patients at 6-8 months, and for 36 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 the 75% of the patients, while the 25% maintain a stable dimensional lesion. An increased A-Mode ultrasound reflectivity was detected in almost all patients. These data clearly show a tumor control, particularly for those patients with 1 year follow-up. No major side effects requiring eye enucleation have been detected: an exudative 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

Physicists, medical physicists and medical doctors are continuing the improvement of the quality of the proton treatments at INFN-LNS either from a dosimetric point of view as well as from the transport beam line control. Regarding the latter, at the end of 2005, the new MOPI [7] microstrip detectors was installed as device for the control of the beam symmetry during the patient treatment. Its characterisation is actually in course. For the next year, the CATANA facility will continue its activity and 4/5 treatment sessions are programmed.

8 CONCLUSIONS

The preliminary results show an high percentage of local tumor control, despite the limited follow-up period, with a limited acute and subacute toxicity and visual outcome according to the previsions. The results are in agreement with those reported in the literature, regarding the treatment of uveal melanoma by means of hadrons.

Even if CATANA should not be the clinical answer for all the Italian patients affected by this kind of disease, it represents the first successfully Italian example of the collaboration between Nuclear and Medical Physicists together with Medical Doctors in fighting tumors with hadrons. CATANA is the first milestone in Italy through the extensive use of hadrontherapy in cancer treatment.

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PROTON THERAPY DETECTOR STUDIES UNDER THE EXPERIENCE GAINED AT THE CATANA FACILITY

G.A.P. Cirrone^{a,*}, G. Cuttone^a, F. Di Rosa^a, P.A. Lojacono^{a,b}, S. Lo Nigro^{a,b}, C. Marino^{a,b},
V. Mongelli^{a,b}, V.I. Patti^a, S. Pittera^{a,b}, L. Raffaele^{c,a}, G. Russo^{a,b}, M. G. Sabini^{a,d}, V. Salamone^{c,a},
L. M. Valastro^{a,c}

a) INFN Laboratori Nazionali del Sud, Catania, Italy

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

c) A.O.U. Policlinico, Università degli Studi di Catania, Italy

d) A.O. Cannizzaro, Catania, Italy

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

Abstract

Proton therapy represents, today, the most promising radiotherapy technique for external tumour treatments.

At Laboratori Nazionali del Sud of the Istituto Nazionale di Fisica Nucleare (INFN-LNS), Catania (I), a proton therapy facility is active since March 2002 and 140 patients, mainly affected by choroidal and iris melanoma, have been successfully treated. Proton beams are characterized by higher dose gradients and linear energy transfer as respect the conventional photon and electron beams, commonly used in medical center for radiotherapy. In this paper, we report the experience gained in the characterization of different dosimetric systems, studied and/or developed during the last ten years in our proton therapy facility.

1 INTRODUCTION

Proton therapy represents, today, the most promising radiotherapy technique for external tumour treatments. It exploits the physical and radiobiological properties of charged ions to deliver selectively the dose to the tumor sparing the neighboring healthy tissues. At INFN-LNS, a proton therapy facility is active since March 2002 and 140 patients, mainly affected by choroidal and iris melanoma, have been successfully treated. Actually, about twelve protontherapy centers are active around world and more the 9000 patient have been already treated in total. Nevertheless, radiation therapy with protons still represents a pioneering technique and improvements are yet required in the treatment clinical protocols as well as in the dosimetry procedures. Proton beams are characterized by higher dose gradients and linear energy transfer as respect the conventional photon and electron beams, commonly used in center for radiotherapy. For these reason, detectors and new materials are continually tested to find better solutions for relative and absolute proton dosimetry. In this paper, we characterization of different dosimetric systems, studied and/or developed during the last ten years in our proton therapy facility. Particular attention on the parallel plate ionization

chamber with the anode segmented in strips, and on relative dosimetry with natural, CVD and MOSFET dosimeters is done.

2 IRRADIATION CONFIGURATION

A proton beam is suitable for radiation treatment purposes if its distribution permits the irradiation of the whole tumors volume sparing, contemporarily, the healthy tissues surrounding the lesion. It must be spread in both longitudinal and transversal directions using energy and scattering systems, respectively. A proton beam longitudinally spread is obtained varying its energy and is called Spread Out Bragg Peak (SOBP). Dosimetry of a clinical proton beam implies determination of absorbed dose at the isocentre and reconstruction of dose distributions in a tissue-equivalent phantom. The choice of the dosimeter will depend on several factors, such as the accuracy, sensitivity and size of the detector's sensitive area with respect to beam spot size, as well as dose gradients involved. In the case of the absorbed dose determination the use of an "absolute" calibrated dosimeter is required.

2.1 Absolute dose determination

An extensive description of the CATANA proton therapy facility and its related main clinical results can be found in [1] and [2]. The absolute proton beam dosimetry is performed using a plane-parallel Advanced PTW 34045 Markus Ionization Chamber. 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 [3]. 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 [3].

2.2 Depth dose distribution

Depth dose curves and transverse dose distributions, either for full energy or modulated proton beams according with the most recent protocols, should be acquired with a water-tank system provided with three dimensional stepping motors fully controlled by computer. A software, entirely developed at INFN-LNS, controls this system and provides the acquisition and dosimetric analysis data. In collaboration with the Clatterbridge Center for Oncology (UK), wheel modulators to obtain therapeutic SOBP have developed. Proton beam energies lower than 62 MeV are obtained inserting PolyMethyl-MethAcrylate (PMMA) range shifters of different thickness along the beam path.

2.3 Lateral dose distribution

Also transversal dose measurements should be made in water or in a water-equivalent phantom with a detector having high spatial resolution in the scan direction. Silicon diodes, radiographic films and small ionization chambers may be used for reconstruction of lateral dose distributions [1].

3 DETECTORS FOR ABSOLUTE AND RELATIVE DOSIMETRY

As in conventional radiotherapy, clinical proton dosimetry requires the measurements of central-axis depth-dose distributions, transverse beam profiles and output factors.

3.1 Depth dose absolute detectors

Central-axis depth-dose measurements for unmodulated and modulated proton beams are performed with a PTW parallel-plate Advanced Markus chamber in a water phantom. It is a perturbation-free version of the classic Markus chamber, because of the wide guard ring and the smaller electrode spacing (1 mm) and, for the relative measurements, it is positioned at the center of a circular field 25 mm in diameter with the phantom surface located at isocentre. The high electric field strength ($4000 \text{ V}\cdot\text{cm}^{-1}$) provides a complete ion collection for dose rate up to $100 \text{ Gy}\cdot\text{min}^{-1}$.

3.2 Reference detectors for transversal dose

Transverse and diagonal dose profiles of the modulated proton beams are measured, in the middle of the SOBP, with radiochromic films oriented normal to the beam axis. They assure high resolution two-dimensional dosimetry in radiation fields with high dose gradients, such as clinical proton beams. The new Gafchromic™ EBT (ISP Corporation New Jersey) radiochromic film is used as reference detector for lateral distribution dose

measurements. It provides an optimal spatial resolution (of the order of $200 \mu\text{m}$) higher level of dose sensitivity with respect to the Gafchromic™ HS, extensively used in the last years for radiotherapy applications. Gafchromic™ EBT films were scanned with an Epson 1680 Pro™ flatbed color scanner in transmission mode and acquired with the Epson™ acquisition software. It permits the acquisition in the 48-bit RGB mode (16 bit per color) and a resolution of 127 dpi (0.2 mm). The film uniformity, evaluated according to AAPM report n. 63 [4], resulted to be smaller than 1.5% for the $5\times 5 \text{ cm}^2$ square EBT sheets. These EBT films are used for transverse dose profile measurements in the narrow collimated clinical proton beams. The EBT film calibration data in the normal orientation and in the range of 0.25 to 7 Gy results to be independent within 1% on the modulated proton beam quality, corresponding to residual ranges $[4 \div 15 \text{ mm}]$ in water. Therefore only one calibration file is needed to evaluate films exposed at the middle of SOBPs with different modulation depths. Off-axis profiles along the principal axis, for patient shaped collimators, are measured by irradiating the EBT film normally to the beam axis in a solid water phantom. The film is located at the depth of the middle of the SOBP representing the reference depth. In the Table I, beam penumbra (P), uniformity (H), symmetry (S_T (%)) and the useful treatment field ($W_{95\%}$ (mm)) (defined as the field width between the 95% points for 25 mm diameter collimator) data analysis as shown.

	EBT X	EBT Y
P (mm)	1.01	1.08
H	0.92	0.92
S_T (%)	103.0	102.3
$W_{95\%}$ (mm)	22.0	21.8

Table 1: Transverse performance of a proton beam profile with EBT Gafchromic™ films.

4 RELATIVE DETECTORS

4.1 Natural and CVD diamond

The properties of natural and synthetic diamond CVD (Chemical Vapor Deposition) as radiation detectors are now known [5]. These materials are tissue equivalent, non toxic, resistant to the radiation damage. They also show a high sensitivity, low leakage current and a good time resolution. In particular, synthetic CVD diamond presents the additional advantage that can be manufactured with a controlled amount of impurities at relative low cost. Our studies were focused on the dosimetric behaviour of natural and CVD diamonds. They confirmed the favorable properties of these detectors, not only for high energy photons and electrons therapy beams but also for a 62 MeV therapeutical proton beams. In particular, after a pre-irradiation, diamond detectors have an excellent time stability of sensibility.

All the results obtained in our study are reported in bibliography [6], [7].

4.2 MOSFET dosimetry

Recently, metal oxide semiconductor field effect transistor (MOSFET) detectors were proposed as clinical radiation dosimetry [9], [10] and the use of a dual bias dual MOSFET showed a better linearity, reproducibility and stability respect single MOSFET detector [11]. They are emerging as a versatile tool in various medical applications, particularly in patient dose verification [12] and in modern radiation oncology and diagnostic modality [13], [14]. The advantages of the MOSFET dosimeters include small size, immediate readout and reuse, facility of use, compactness, permanent dose storage. They are, isotropics, dose rate and temperature independent.

The details of the working principle of the MOSFET have been reported earlier [8], [15].

Considering this favourable dosimetric characteristics of the MOSFET dosimetry, a preliminary study (linearity, reproducibility, sensibility, energy dependence) on the use of the MOSFET dosimeters, using 62 MeV proton, beams is performed. In particular, in this work, the MOSFET and microMOSFET Output Factor (OF) for small radiation fields in proton therapy are presented. Their results are compared with those obtained with other detectors chosen for the same dosimetric test. The investigated devices are the commercially available MOSFET (TN-502RD) and microMOSFET (TN-502RDM), manufactured by Thomson and Nielsen Electronics Ltd (Ottawa, Canada). The microMOSFET is a commercial name for the MOSFET dosimeter with a small physical size of $1 \times 1 \text{ mm}^2$ and 1,5 mm thick. This physical size is about half the size of the standard MOSFET dosimeter. In order to verify the possibility to use the MOSFET and microMOSFET as dosimeters for small radiation fields in proton therapy, measurements of Output Factor $OF(\varphi)$, defined as $L(\varphi)/L(\varphi_0)$, where φ is diameter of the final collimator and φ_0 is diameter of reference collimator, are performed. The irradiation setup was the following: the MOSFET, or the microMOSFET dosimeter, was positioned at the centre depth of a SOBP and irradiated with a fixed dose of 200 cGy. The measurements were carried out with five different collimator diameters: 8, 10, 15, 20 and 25 mm. The results were compared with those obtained with TLD-100 microcubes, Scanditronix silicon diode (PFD) and radiochromic film MD55-2.

The results obtained with MOSFET and microMOSFET are reported in Fig 1 normalized to the reference collimator ($\varphi_0 = 25 \text{ mm}$), and compared with the $OF(\varphi)$ measured with TLD-100 microcubes, silicon diode and radiochromic film. As shown Fig. 1, the MOSFET $OF(\varphi)$ is, in every case, lower than OF silicon diode, radiochromic film and TLD microcubes.

The maximum difference found is about 9% respect radiochromic film, for 8 mm diameter collimator. The microMOSFET $OF(\varphi)$ are closed the results of the diode

and the radiochromic film. The maximum difference found is about 1.4% respect radiochromic film and silicon diode, for 8 mm diameter collimator.

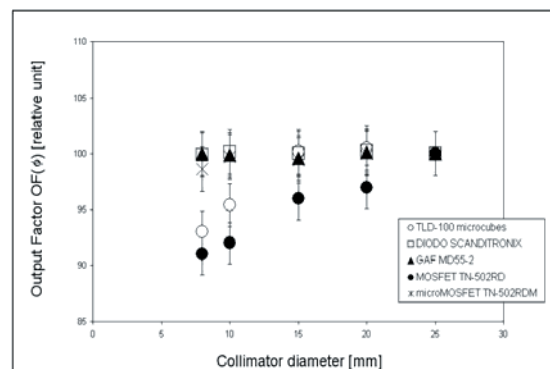


Figure 1. Comparison of the OF for MOSFET and microMOSFET with those obtained with other detectors.

This percentage difference is comparable with the experimental uncertainty of the measure of the Output Factor. The results of MOSFET $OF(\varphi)$ show the possibility to use the MOSFET dosimeter for field diameter from 15 to 25 mm. Instead, the microMOSFET results show that they can represent an alternative to the use of the silicon diode, currently used in dose measurements of the small radiation field, involved in proton therapy of uveal melanoma.

4.3 MOPI

Inside the CATANA facility particular care is devoted to the control of beam shape and symmetry during the patient irradiation. For these purposes, in collaboration with the INFN Section of Torino (I), a special transmission detector was developed [16]. The detector is composed by two strips ionization chamber, ortogonally disposed, and located along the beam axis. The detector consists of two contiguous gas cells, each cell being externally limited by an anode plane and having the cathode in common. The anode is made by a kapton foil 35 μm thick covered with a 15 μm thick aluminium layer. This layer has been engraved with a standard printed circuit board technique to obtain 256 conductive strips 400 μm wide interspaced with 100 μm of electrically isolated kapton. The detector sensitive area is $12.8 \times 12.8 \text{ cm}^2$ and is surrounded on three sides by a guard ring which is set to same voltage of the strips. On the fourth side the strips are narrowed and bent to reach the connector. The electric field is generated by polarizing the cathode to -500 V, while the other end of the field is provided by the strip polarization which is at +2 V (the same voltage of the input front-end). This detector permits us the on-line control of the beam shape and symmetry during the irradiation. We defined a specific parameter, mathematically defined as skewness [16].

It contains the desired informations on beam quality. The skewness monitoring during the irradiation represents a fundamental method to ensure the quality of proton treatment and provide high level check of the beam.

5 CONCLUSIONS

Then years of proton therapy activity has permitted the test of various detectors and materials. Many national and international collaboration have been established and a large amount of scientific papers have been published. These results permits us to affirm that our facility represents an ideal workbench for the test of dosimetric system in proton therapy and give an unique possibility in Italy for the improvement of the proton therapy technique.

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TEST RESULTS FROM AN IN-BEAM PET SYSTEM

F. Attanas^a, N. Belcar^a, M. Camarda^a, G.A.P. Cirrone^b, G. Cuttone^b, A. Del Guerra^a, F. Di Rosa^b, N. Lanconelli^c, V. Rosso^{a,*}, G. Russo^b, S. Vecchio^a

a) Dipartimento di Fisica "E. Fermi", Universita' di Pisa, e Sezione INFN di Pisa, Pisa, Italy

b) INFN Laboratori Nazionali del Sud, Catania, Italy

c) Dipartimento di Fisica, Universita' di Bologna, e Sezione INFN di Bologna, Bologna, Italy

** Corresponding author, e-mail: valeria.rosso@pi.infn.it*

Abstract

We report on the preliminary results obtained using a prototype of an in-beam PET system for the measurements of the dose delivered on phantoms by 62MeV protons at the CATANA beam line.

1 INTRODUCTION

The therapeutic effectiveness of conventional electromagnetic radiation for tumor treatment is intrinsically limited by its physical and radiobiological properties: heavy charged particles, like protons, can overcome these limitations due to the more selective energy deposition in depth and to an increased biological effectiveness.

Nevertheless the higher physical selectivity of ion therapy demands higher precision in the monitoring of the applied treatment, especially if the target volume is located close to critical organs, and a fractioned therapy is applied. In fact, minor inaccuracies in the positioning of the patient or local anatomical changes with respect to the information of the X-ray computed tomography (CT), that are the basis for the treatment planning, may produce unpredictable ion range deviations and consequently deviations from the planned dose.

For these reasons information on the effective ion range are desirable, but the complete stopping of the ions inside the patient prevents the application of electronic portal imaging methods used in conventional radiotherapy.

Heavy charged particles induce nuclear reaction in the irradiated material, generating β^+ emitters like ^{11}C , ^{15}O , ^{10}C from their stable isotopes: the measurements of the distribution of these activities, immediately after patient irradiation, lead to information on the effective ion range [1], [2] and [3].

In-situ measurements allow one to acquire the maximum statistics by detecting also the activity contribution provided by the very short half-life isotopes (e.g. ^{15}O), and to minimize blurring effects due to patient shifts during the transport to a clinical positron emission tomography (PET) system.

By using an iterative reconstruction algorithm the data acquired with the "in-beam PET" system produces a 3D image of the activity distribution. However, such a detected activity is not directly proportional to the delivered dose, because of the different nature of the physical processes that determine the β^+ activation and the energy deposition within the medium. Nevertheless

experimental results show that the distal dose fall-off is well correlated with the activity distal edge. This correlation is due to the threshold nature of the activation processes, that determines the fall-off of the corresponding cross section at energies approaching to the Bragg peak. As a consequence, the largest part of information about the beam range can be extracted by the distal edge of the activity distribution.

2 DESCRIPTION OF THE MEASUREMENTS

The DoPET (Dosimetry with a Positron Emission Tomograph) tomograph consists of two planar heads, with an active area of about 5 cm x 5 cm. Each head is made up of a squared position sensitive photomultiplier (Hamamatsu H8500) coupled to a matrix of LYSO scintillating crystals ($2 \times 2 \times 18 \text{ mm}^3$ pixel dimensions). A multiplexer system is chosen for acquiring only 4 signals from each head thanks to the resistive chain read-out of the multi-anodes photomultiplier [4].

A dedicated, electronic board is used for the signal amplification and digitization. The maximum count rate handled by the acquisition system is about 50 kHz coincidences (and 200 kHz events for each head).

In figure 1 all the components of the tomograph are shown. For each head the LYSO detector is visible wrapped with white tape and attached to the photomultiplier. The resistive chain, after the photomultiplier, is then connected to the electronic board through a flat cable. An USB cable brings the data to a PC for the acquisition.

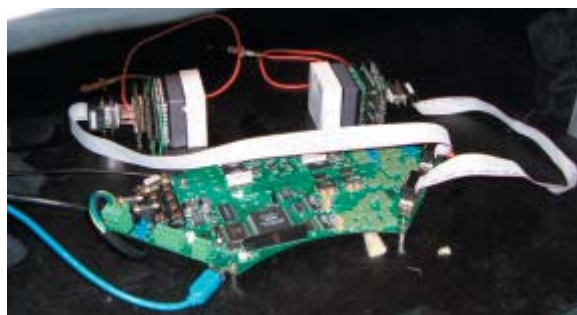


Figure 1: Components of the DoPET tomographic system: two heads and one electronic board.

The photomultipliers are sensible to day light, so a PVC cylindrical case was designed to shield each head, and the mechanical case layout is shown in figure 2.

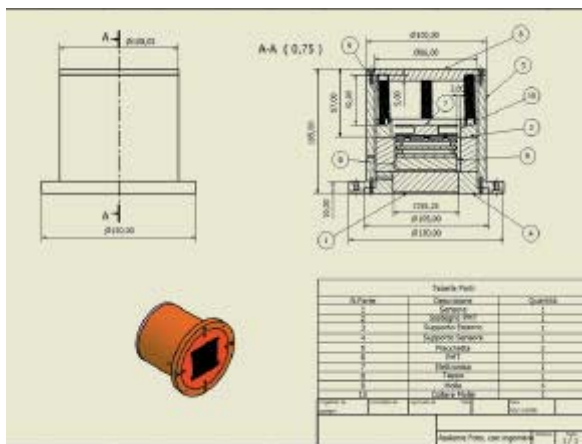


Figure 2: Detailed design of the cylindrical single head case

A data taking prototype was realized: it consists of a phantom holder placed in between the two heads, and the two anticorodal head holders. The distance between the heads holders can be set from 10 cm up to a maximum of about 20 cm also in an asymmetric configuration with respect to the phantom: a mechanical sketch is shown in figure 3.

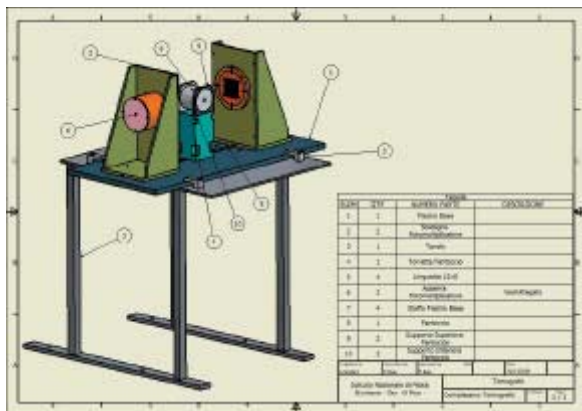


Figure 3: Mechanical layout of the DoPET tomographic prototype

A photograph of the prototype as positioned on the CATANA beam line is reported in figure 4: the last part of the 62 MeV proton beam line collimator is well visible on the left.

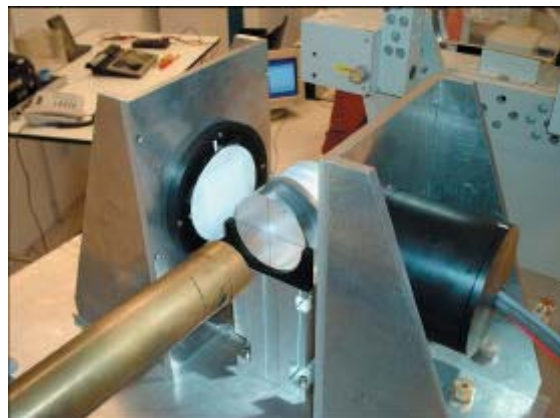


Figure 4: DoPET tomographic prototype positioned at the CATANA beam line.

The prototype is being validated through measurements on a cylindrical PolyMethylMethAcrylate (PMMA) phantom. The cylinder has a diameter of 7 cm and is 7cm long. The element composition of PMMA is close to soft tissue composition (8.05% H, 59.99% C and 31.96% O). The PMMA cylinder axis was positioned aligned to the proton beam line.

Preliminary measurements were performed with a symmetric distance of the two heads with respect to the cylinder axis : the distance between the heads was set at 14 cm. A 62MeV proton beam with a modulation of 12 mm eye-tissue equivalent matter, and four different range shifters was used. An irradiation time of 1 minute over the PMMA surface of 25 mm diameter was used; a total dose of 30 Gy was delivered for each irradiation.

With an acquisition time of about 30 minutes after the end of each irradiation the DoPET prototype provided about 10^5 coincidences on a irradiated volume of about 6 cm³.

The activity distributions were then reconstructed using a 3D iterative reconstruction algorithm [5]: each final image has a dimension of 42x42x130 voxels. The central slices of 5 reconstructed activities (one without range shifter and the other four with different range shifters) are reported in figure 5: the proton beam impinging from the left.

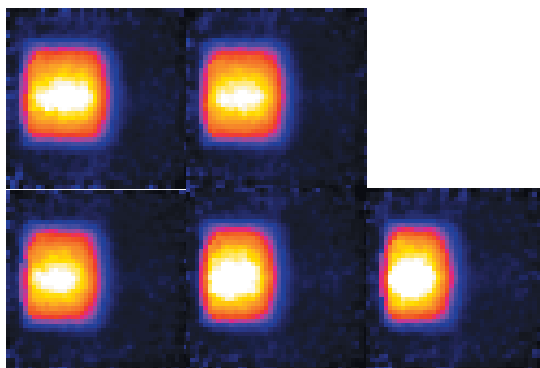


Figure 5: Central slices of the reconstructed activity images (42x42 pixels). From top left to bottom right: no range shifter, 1mm PMMA, 3 mm eye tissue equivalent matter, 4 mm eye tissue equivalent matter, 6 mm eye tissue equivalent matter.

Although the central slice activity images are extracted from low statistics 3D images, we were able to appreciate differences in proton-induced activity distribution down to 2 mm along the axial direction (i.e. along the proton direction). The same activities distributions reported in figure 5 are presented in figure 6: in this case the 75% contour activity profile of each activity is reported superimposing the 5 measurements for a better view of the profiles variations with increasing range shifter thickness.

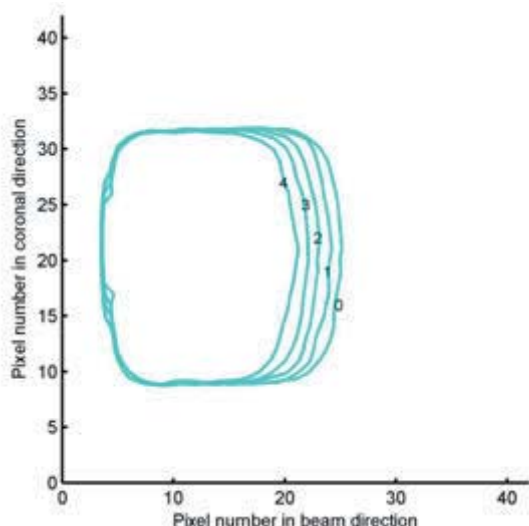


Figure 6: 75% contour activity profile of each activity (42x42 pixels; pixel dimension: ~1.1mm). Line 0: no range shifter; line 1: 1mm PMMA; line 2: 3 mm eye tissue equivalent matter; line 3: 4 mm eye tissue equivalent matter; line 4: 6 mm eye tissue equivalent matter.

3 CONCLUSIONS

The test of the DoPET prototype, was performed to demonstrate the feasibility of a dedicated PET system for dose monitoring in the case of proton therapy. By analyzing the activities induced by protons, it was possible to appreciate how the measured activity fall off follows the different range shifter. Steps in the range shifter thickness as small as 2 mm can be easily detected.

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MEDICAL PHYSICS APPLICATIONS OF THE GEANT4 MONTE CARLO TOOLKIT

G. Candiano^a, G. A. P. Cirrone^{a,*}, G. Cuttone^a, F. Di Rosa^a, G. Russo^a, F. Romano^a

a) INFN Laboratori Nazionali del Sud, Catania, Italy

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

Abstract

Monte Carlo (MC) method plays a very important role in medical physics applications. In many situations, the MC approaches are the only techniques that can be used in particular medical physics problems, like the predictions of the dose distribution using clinical proton and electron beams in non homogeneous material. In this report, we relate particular applications of MC method in different medical physics procedures following the experience we gained from the use of the GEANT4 Monte Carlo toolkit

1 INTRODUCTION

The subsequent first section is dedicated to the Geant4 MC toolkit used for all applications described in details in the second section. We dedicated at each developed application, a specific section in which, after a brief introduction, we describe the work realized.

1.1 Monte Carlo Geant4 Toolkit

Geant4 **Errore. L'origine riferimento non è stata trovata., Errore. L'origine riferimento non è stata trovata.** is an object oriented toolkit for the simulation of particle interactions with matter. It provides advanced functionality for all the domains typical of detector simulation: geometry and material modelling, description of particle properties, physics processes, tracking, event and run management, user interface and visualisation. The design as a toolkit and the adoption of the object oriented technology characterize Geant4 with respect to other general purpose Monte Carlo systems. The object oriented technology allows multiple implementations for any of the object interfaces in the toolkit. This powerful technological feature is at the ground of the wide set of physics processes and models available in GEANT4. As a toolkit, it consists of a set of compatible components where an user can build an application selecting the classes more usefull for his/her application. The flexibility of configuring a simulation application by selecting the physics processes to be activated, is a key feature for usage in different experimental fields. The accurate simulation of the energy deposit of protons in water plays also an important role in oncological radiotherapy and radiation protection: Monte Carlo methods are used for the optimisation of hadrontherapy beam line features and the verification of patients' treatment planning.

2 DEVELOPED MONTE CARLO APPLICATIONS

2.1 Hadrontherapy

The development of an hadron-therapy facility requires a long experimental work. This work concerns mainly the realization of the passive scattering system (to obtain an homogeneous lateral distribution of the beam), of the modulation (to perform a correct energy modulation) and of the collimators system. On the basis of this exigencies, we decided to realize a simulation work using the Monte Carlo, so-called "*Hadrontherapy*". Actually, this MC application is a continuously upgraded advanced example included in the official GEANT4 distribution. *Hadrontherapy* simulates a generic proton therapy beam line for eye treatment. It offers great flexibility: the user can easily change geometrical configuration of the beam line, the primary proton beam characteristics and different physic models without change the C++ code. The use of time-dependent geometries is also a standard feature within our application permitting us the simulation of the energy modulation system. Dose released by protons can be stored in a voxelized geometry of any material and shape. For our simulation proposed, we implemented different electromagnetic physics transport beam models, i.e. as the LowEnergy and Standard package. Moreover, we implemented different hadronic processes for proton and generic ions. For our purposes an eye structure was been simulated and dose distributions inside stored permitting the LET calculation (section 2.2 and section 2.6). *Hadrontherapy* application has been validated against experimental data acquired by us as reported elsewhere [3]. In Figure 1, the proton therapy beam line is shown, as it is simulated and displayed by our application.

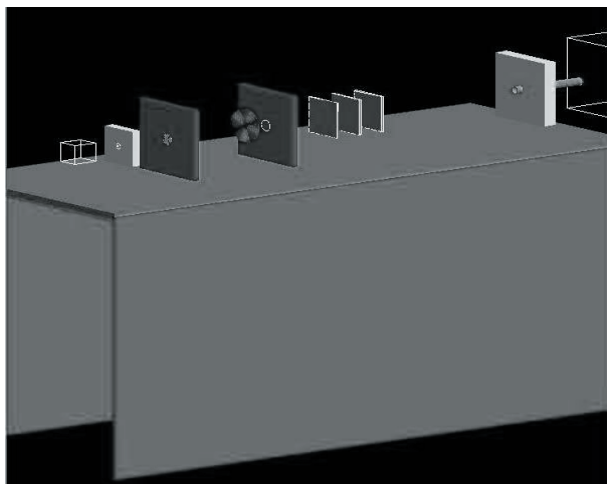


Figure 1 – Graphic view of GEANT4 beam line simulation displayed in Hadrontherapy

2.2 A proton TPS commissioning and verification

Many malignant tumour are localized near normal and delicate structures, i.e. serial organ. This circumstance is also the clinical case of intraocular malignancy. The ocular pathologies are successfully treated with radiation therapy, with preservation of the eye in almost all the surviving patients. Proton beam irradiation is the major employed modality of radiation therapy. Particularly, the proton therapy offers the dosimetric advantage of a highly conformal dose region with the possibility of covering the tumour volume with an elevated accuracy, sparing the surrounding healthy tissue. The external radiation treatment is a multi-step process involving the preliminary physical examination up to the treatment planning process and the plan verification. The radiotherapy treatment planning process is defined to be the process used to determine all features of the radiation beams used to deliver dose of radiation to a patient in order to control a cancerous tumour. Nowadays, treatment planning is performed with the assistance of a computerized Treatment Planning System (TPS), which helps the treatment planner and physician to define the target volume, determine beam directions and shapes, calculate the associated dose distribution, and evaluate the dose distributions. Nowadays, the most used dose distribution prediction algorithms for ocular proton therapy, are based on an analytical description of the proton energy deposition. These analytical beam transport models are often inherently limited by severe approximations and simplifications. Nevertheless, these algorithms are presently the technique most used because they offer the clinical advantage to calculate the real time dose distribution also in clinical and complex circumstances. Actually, EYEPLAN is the analytic standard tool in eye treatment with proton beam..

It is generally accepted that the true dose distribution can only be obtained from Monte Carlo simulations. Therefore, to verify the correct prediction of the EYEPLAN TPS dose distributions, a validation process has been performed using the Monte Carlo method

through the GEANT4 toolkit. The entire proton beam line and the geometric eye configuration are replaced in GEANT4 simulation toolkit. The validation procedure of our TPS is performed comparing the entire three-dimensional dose distribution calculated by analytical program to Monte Carlo dose distribution predictions. This comparison reveals that TPS resolution is not enough accurate to reproduce correctly the distal dose fall-off. Our studies demonstrate that Monte Carlo simulations are the best approach to validate an ocular proton therapy treatment planning. They are able, in fact, to predict the dose distributions for any geometry and to reveal any fails in the analytical calculations. Our experience also suggests that GEANT4 Monte Carlo code is suitable for treatment planning dose calculations once the simulation model is encapsulated and integrated into a treatment planning system. We expect that these techniques will be used for nozzle design work, dose-per-monitor-unit predictions and, eventually, routine treatment planning. The results also show how Monte Carlo approach is still time consuming for routine treatment planning but it provide the most accurate method to verify the dose distribution planned by TPS (Figure 2).

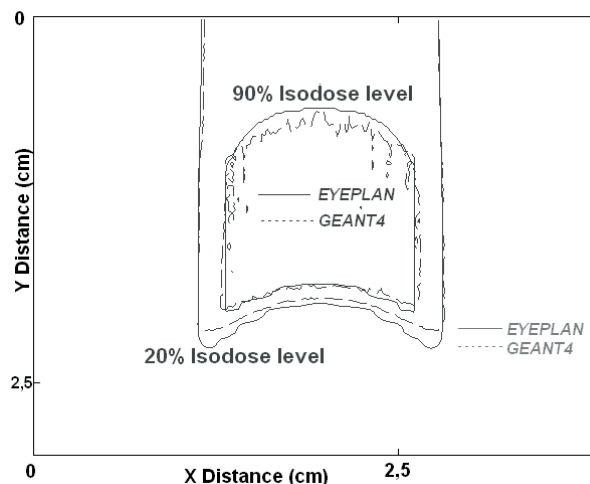


Figure 2 – Monte Carlo vs Geant4 dose distribution comparison

2.3 Gamma Knife® Stereotactic Radiosurgery

Today the Stereotactic Radiosurgery with devoted machine is the best clinical solution to the brain radiotherapy with external beams. In this field the Elekta Gamma Knife® is one of the better solutions thanks to its dosimetrical and geometrical precision. Gamma radiation from 201 ⁶⁰Co sources comes at the target area, traversing a collimator system and focusing on the isocenter [4]. The high precision demanded for this application and the high delivered dose need a very accurate treatment planning system (TPS). Our work has, as final purpose, the validation of the TPS GammaPlan, comparing its dose distribution with that of the Monte Carlo simulation, developed through the GEANT4 toolkit. The Monte

Carlo application reconstructs all the Elekta Gamma Knife features, from both a geometrical and physical point of view, so to simulate the real energy deposition (Figure 3).

The simulation has been validated for all available collimators in the standard configuration. Comparisons have been done between the calculated dose distributions and the experimental ones, obtained by radiochromic film dosimetry measurements inside a water phantom, equal to that used to quality assurance. In order to simplify the code, we simulated only one source and rotated the phantom at 201 angular positions, employing time-dependent geometries present in GEANT4. Once validated, we used Monte Carlo simulation to verify dose distribution calculated by the TPS, firstly in standard conditions (homogeneous phantom) and afterwards by introducing inside the phantom parts of different materials, better simulating the brain characteristics (inhomogeneous phantom). As regards the former configuration, results show that the TPS calculate in a correct way the dose delivered (Figure 4). As regards the latter, we found a discrepancy of about 4% between Monte Carlo and TPS outputs. It can be explained because the TPS GammaPlan considers the target as composed of unit density material (water) in order to calculate the dose distribution in a reasonable time. Obtained results let understand the importance of the application of Monte Carlo methods in radiotherapy, also from a clinical point of view.

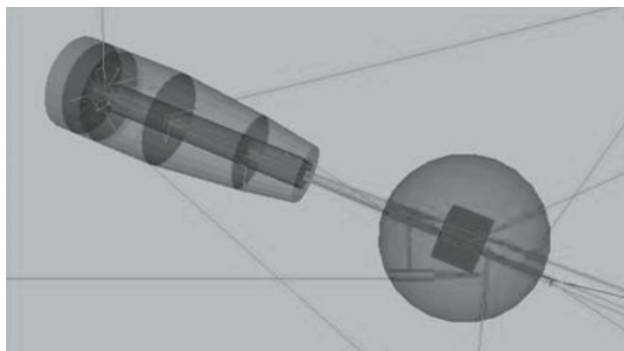


Figure 3 – Gamma Knife Geant4 application

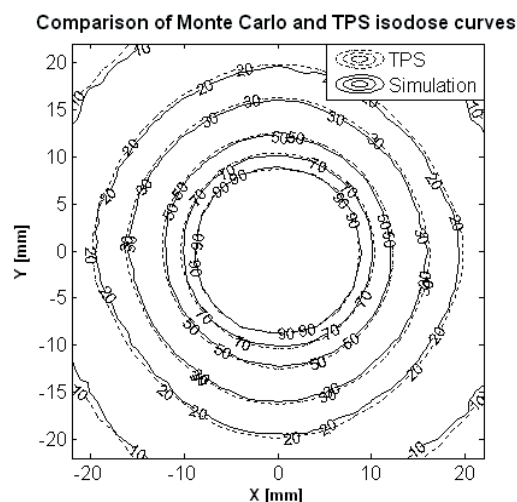


Figure 4 - Comparison of Monte Carlo and LGP isodose curves in the central plane (axial), for the 18 mm collimator. Monte Carlo voxel dimension: 1 mm; LGP voxel dimension: 1.6 mm.

2.4 Proton Computed Tomography (pCT)

Proton therapy is a precise form of radiation therapy that makes use of high energy proton in spite of the conventional, more commonly and less precise x-ray and electron beams. A precise radiation modality, it is the proton therapy, requires very accurate Quality Controls (QA) of the treatment procedures. In proton therapy, QAs are mainly related to the patient positioning and to the dose calculations with a treatment planning software. In existing proton treatment centers, positioning and dose calculations are currently based on x-ray radiographs and x-ray computed tomography (xCT), respectively. A new challenge, in the next years, could be the direct use of the proton beam for the tomographic imaging of the patient body developing a proton Computed Tomography (pCT) system. This will make the proton radiation procedure more precise by defining the position of the Bragg peak more accurately (enabling the verification of patient and tumor position with respect to the proton beam) and by permitting a direct measurement of the electron densities (and hence of the stopping powers values) of the involved tissues. Stopping powers, today, are in fact indirectly derived from the conversion of the linear attenuation coefficients, measured with a conventional x-tomography of the patient. This conversion is not error free and can produce, in many cases, an indetermination in the stopping power values and, consequently, in the calculated dose deposition. The main task for any imaging system, especially if devoted to critical applications, as medical diagnostic or dose calculation in a radiation treatment, is to obtain images with a sufficient density ($\leq 1\%$) and spatial ($\leq 1\text{mm}$) resolutions. Recent works, based on the analytical methods and Monte Carlo simulations, demonstrated the possibility to obtain proton tomographies of good density resolution and to realize, in the next years, a real pCT device. On the other hand many

limitations must be yet investigated. In our work we investigated the possibility to exceed the pCT more severe limitation: a poor spatial resolution due to the intrinsic presence of the Multiple Coulomb Scattering (MCS) inside the body of patient [5]. One possible solution for the spatial resolution improvement, is the use of the so-called ‘single tracking technique’ whose principle is tracking each single proton in coincidence as they enter and exit the imaged object. We studied and verify the single tracking approach both, using the Monte Carlo method as well as in an experimental measurement with a first prototype of a pCT system. In our work we realized also a possible schematic example of pCT device system (Figure 5).

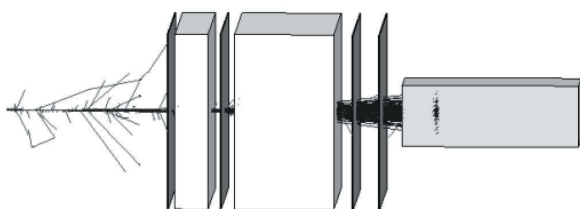


Figure 5 - The proton CT system as simulated with GEANT4

2.5 Radiobiological experiment

At the irradiation facility of Laboratory Nazionali del Sud, many radiobiological experiments are realized by national and international group. They are realized using the carbon and proton beams accelerated by the installed superconducting cyclotron. The experiments are mainly addressed to the study of the biological response of live matter when irradiated with charged high energy beams. Often the understanding of such processes cannot be fully realized without the help of Monte Carlo method. It provides information on the physical properties of the employed beams (like stopping powers, energy and fluence spectra, etc.) that cannot be, in many practical cases, experimentally derived. Using the GEANT4 toolkit we are able to derive such physical quantity and provide to the experimental groups, a fundamental support in their experiments.

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A RESISTANT MELANOMA CELL LINE AFTER COMBINED TREATMENT WITH PROTONS AND CHEMOTHERAPEUTIC DRUGS

A. Ristić-Fira^{a,*}, I. Petrović^a, L. Korićanac^a, L. Valastro^b, G. Privitera^c, G. Cuttone^b

a) Vinča Institute of Nuclear Sciences, Belgrade, Serbia

b) INFN Laboratori Nazionali del Sud, Catania, Italy

c) Institute of Radiology and Radiation Oncology, University of Catania, Italy

** Corresponding author, e-mail: aristic@vin.bg.ac.yu*

Abstract

Effects of fotemustine (FM) or dacarbazine (DTIC) in combination with proton irradiation on HTB140 human melanoma cell growth and proliferation were analyzed. Cells pretreated with 100 or 250 μM of FM or DTIC were irradiated with therapeutic doses of protons (12 and 16 Gy). Combined treatments with alkylating agents and protons, did not induce significantly different growth inhibition compared to single treatments, 48 h after irradiation. At the same time point, single treatments have shown better inhibitory effects on cell proliferation when compare to appropriate combined treatments. However, 7 days after irradiation, combined treatments of FM and protons have shown better inhibitory effects on cell viability and especially on cell proliferation, while treatments with DTIC and protons have shown increased level of inhibition of cell growth and proliferation than single DTIC application, but decreased inhibitory effects when compared to single proton irradiation.

1 INTRODUCTION

Melanoma cells are known to be resistant to radiation and commonly used chemotherapy agents. This resistance is associated with a poor prognosis for this metastatic disease [1]. The use of chemotherapeutic agents that could overcome the level of radioresistance of melanoma tumors might prove to be useful. To improve radiotherapy, it is important to understand the biological response that melanoma cells have to radiation [2].

Some forms of specially localized melanoma tumors, are treated with therapeutic proton beam successfully [3]. Physical properties of protons, well defined range, small lateral scattering and high energy deposition in the Bragg peak, make this type of therapy suitable for localized melanomas. In radiotherapy, in order to cover tumour volume, Bragg peak is spread out by modifying proton energy.

Chemotherapeutic drugs could theoretically target all metastatic sites, but current treatments do not provide a significant therapeutic benefit. Monochemotherapy with dacarbazine (DTIC), temozolomide, fotemustine (FM) and vindesine or its combinations with interferon-alpha are currently preferred [4].

Trying to improve therapeutic approaches, in this study we used cell viability and cell proliferation assays to compare the effects of combined treatment with FM or

DTIC and protons with single application of drugs or proton irradiation.

2 MATERIALS AND METHODS

2.1 Cell Culture and Irradiation Conditions

Human melanoma HTB140 cells were purchased from the American Tissue Culture Collection (Rockville, MD, USA) and routinely maintained in RPMI1640 media supplemented with 10% fetal bovine serum, penicillin-streptomycin and L-glutamine under standard conditions. Cells were irradiated within the spread out Bragg peak (SOBP) of the 62 MeV monoenergetic proton beam at the Centro di Adro Terapia e Applicazioni Nucleari Avanzati (CATANA) treatment facility. Applied doses were 12 and 16 Gy at the dose rate of 15 Gy/min. Irradiation position in the middle of SOBP was simulated by interposing 16.3 mm thick Perspex plate (Polymethyl methacrylate - PMMA) between the final collimator and cell monolayer, thus obtaining corresponding relative dose of $99.42 \pm 0.58\%$, with the mean energy of protons 34.88 ± 2.15 MeV. Reference dosimetry was performed by using plane-parallel PTW 34045 Markus ionization chamber calibrated according to IAEA code of practice [5].

2.2 Chemotherapeutic Drug Treatment

For single, as well as combined drug treatments, cells were treated with fotemustine (FM, Ital farmaco S.p.A., Milano, Italy) or dacarbazine (DTIC, Aventis Pharma S.p.A., Milano, Italy).

2.3 Experimental condition

Exponentially growing cells were treated with FM or DTIC (100, 250 μM). After 24 h cells were irradiated with protons (12, 16 Gy), replated in 96-well plates (3×10^3 cells/well) and grown for further 7 days, when cell viability and cell proliferation assays were performed. Effects of combined treatment were compared to those of single drug treatments or proton irradiation.

2.4 Viability Assay

Sulforhodamine B (SRB) assay is used for cell density determination, based on the measurement of cellular protein content. The assay was performed according to the method of Skehan and co-workers [6]. After an incubation period, cell monolayers were fixed with 10% trichloroacetic acid and stained with 0.4 % SRB for 30

min. The excess dye is removed by washing with 1% acetic acid. The protein-bound dye was dissolved in 10 mM Tris base solution for absorbance determination at 550 nm using a microplate reader (Victor, Wallac).

2.5 Proliferation Assay

To measure DNA synthesis and cell proliferation, a 5-bromo-2-deoxyuridine (BrdU) assay (Roche Diagnostics GmbH, Mannheim, Germany) was used. Cells were seeded into 96-well plates. After becoming adherent, cells were treated for 24 h with FM or DTIC and 24 h later were irradiated with protons (12, 16 Gy). BrdU labelling was performed after 48 h or 7 days according to the manufacturer's instructions. The absorbance was measured using microplate reader at 550nm.

3 RESULTS AND DISCUSSION

In our previous studies we analyzed effects of FM, DTIC or protons on HTB140 melanoma cell viability and cell proliferation [7, 8]. In order to improve level of inactivation of resistant cell line, the aim of this work was to compare the effects of combined treatment of FM or DTIC and protons to single drug treatment or single proton irradiation. For combined treatments chosen drug concentrations were 100 and 250 μ M. These concentrations are close to IC_{50} values and to those reported in literature [8, 9, 10]. Therapeutic doses of 12 and 16 Gy of protons were applied. These doses produce near 50% inhibition of HTB140 cells [7]. Time points of 48 h after treatment (appropriate for drug treatments) and 7 days after treatment (appropriate for irradiation) were chosen for the analysis of cell viability and proliferation.

3.1 Early effects of combined treatments with FM and protons

All analyzed treatments have shown significant decrease of cell viability at 48 h as compared to control. The level of cell growth inhibition after treatment with FM and protons was in the range of level of inhibition after relevant single drug treatment or proton irradiation (Figure 1). At the same time point, cell proliferation assay has shown better inhibitory effects of single irradiation and drug treatments as compared to combined. All combined and single treatments have shown significant decrease of cell proliferation comparing to untreated control (Figure 2).

3.2 Early effects of combined treatments with DTIC and protons

When using DTIC and protons, there was a significant decrease of cell viability after all analyzed treatments at 48 h, as compared to untreated control. Cell viability was in the range of 37 to 47 % of control. Combined treatments did not show better growth inhibition as compared to appropriate single treatments, except in the samples irradiated with 16 Gy protons, pretreated with 250 μ M DTIC ($p < 0.05$ as compare to 16 Gy proton irradiation) (Figure 3).

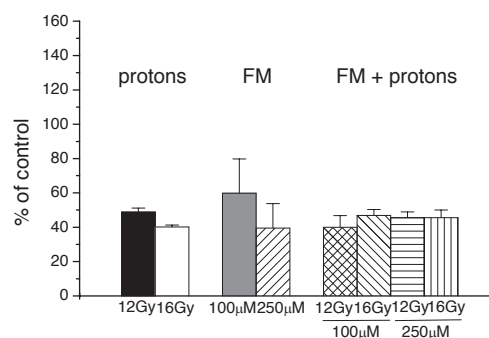


Figure 1. Viability of HTB140 cells estimated by SRB assay 48 h after single and combined treatments with protons and FM.

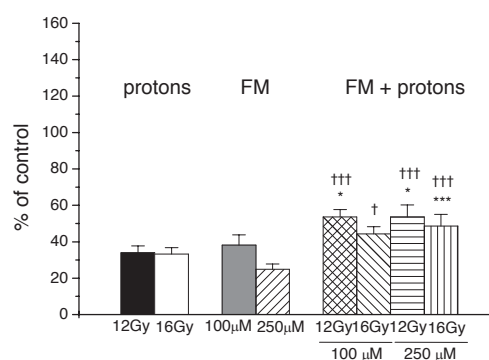


Figure 2. Proliferation of HTB140 cells estimated by BrdU assay 48 h after single and combined treatments with protons and FM. (* - combined treatments vs. FM, † - combined treatments vs. protons); * (†) - $0.01 < p < 0.05$, ** (††) - $0.001 < p < 0.01$, *** (†††) - $p < 0.001$

Single proton irradiation or DTIC treatment, as well as combined treatments of these agents, significantly decreased proliferative capacity of HTB140 melanoma cells with respect to untreated control. Level of cell proliferation in treated samples ranged from 43 to 61 % of control. Effects of DTIC and protons on cell proliferation were not significantly improved, regarding DTIC or proton treatment (Figure 4).

This relatively weak effect of combined treatment on cell growth inhibition and cell proliferation might be caused by the fact that melanoma cells are very radio and chemoresistant. HTB140 melanoma cells have shown very high level of radio resistance with surviving fraction at 2 Gy proton irradiation (SF2) being 0.931 ± 0.006 [7]. Melanoma cells showed constitutively activated nuclear factor kappa B (NF- κ B), a transcription factor activated by ionizing radiation [2]. Some evidence also indicates a link between the NF- κ B pathway and resistance of glioblastoma cells to O6-alkylating agents [11], such as FM and DTIC. Clarifying role of NF- κ B activation in future experiments might contribute to better

understanding of chemo and radio resistance of melanoma cells.

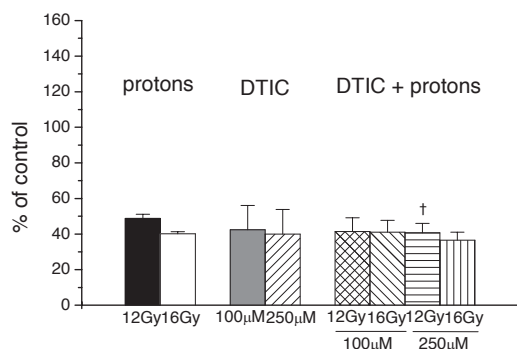


Figure 3. Viability of HTB140 cells estimated by SRB assay 48 h after single and combined treatments with protons and DTIC. (* - combined treatments vs. DTIC, † - combined treatments vs. protons); * (†) - $0.01 < p < 0.05$, ** (††) - $0.001 < p < 0.01$, *** (†††) - $p < 0.001$

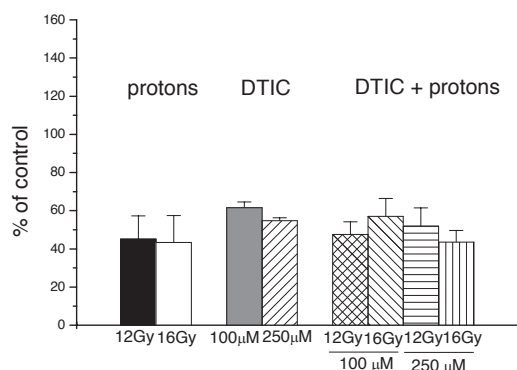


Figure 4. Proliferation of HTB140 cells estimated by BrdU assay 48 h after single and combined treatments with protons and DTIC.

3.4 Late effects of combined treatments with FM and protons

Taking into account that early effects of combined treatments did not show satisfied results, i.e. improved cell growth inhibition as compared to single treatments, in further experiments, late effects were analyzed. Late effects of combined treatments were estimated 7 days after irradiation, at the time point corresponding to the time appropriate for evaluation of irradiation damage.

Obtained results implicated that cell viability and proliferation of HTB140 cells exposed to single, as well as combined treatments with FM and protons, were significantly reduced, as compared to untreated control ($p < 0.001$). Cells exposed to combined treatments with FM and protons have shown improved cell growth inhibition, as compared to single proton irradiation. Combined treatments with FM and protons have shown significant growth inhibition, as compared to single proton

irradiation, but with different level according to statistical analysis. Treatments with FM and 12 Gy protons have shown very significant growth inhibition, as compared to single proton irradiation ($p < 0.001$ for both drug concentrations). Combined treatments of FM with 16 Gy protons have also shown significant growth inhibition, compared to adequate single proton irradiation ($p < 0.05$ for 100 µM FM, $p < 0.01$ for 250 µM FM). Effects of FM and protons on cell viability were not notably better, regarding FM treatment for both analyzed concentrations ($p > 0.05$) (Figure 5).

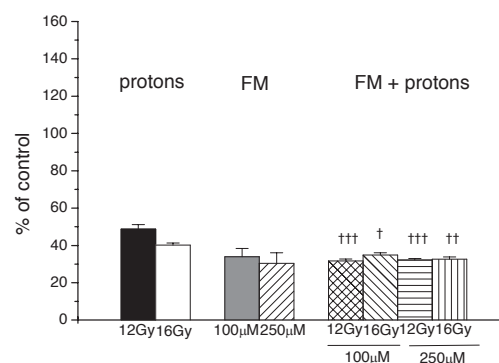


Figure 5. Viability of HTB140 cells estimated by SRB assay 7 days after single and combined treatments with FM and protons (* - combined treatments vs. FM, † - combined treatments vs. protons); * (†) - $0.01 < p < 0.05$, ** (††) - $0.001 < p < 0.01$, *** (†††) - $p < 0.001$

However, proliferation of these cells is markedly inhibited, comparing to relevant single drug treatments ($p < 0.001$ for all combined treatments) and applied doses of protons ($p < 0.001$ for all combined treatments) (Figure 6).

Obtained results have shown that FM and protons more efficiently inhibit cell growth 7 days after irradiation as compared to results obtained 48 h after irradiation. This might be caused by indirect effects of irradiation. Indirect action involves the production of reactive free radicals whose toxic damage on the key molecule results in different biological effects [7].

Viability of HTB140 cells after single DTIC treatment did not decrease. Cells exposed to combined treatments, as well as single proton irradiation have shown significant growth inhibition when compare to untreated control. Proton irradiation of cells pretreated with DTIC, have shown significant growth inhibition when compared to relevant single DTIC treatments ($p < 0.001$). However, cell viability after combined treatment was increased ($p < 0.001$) (Figure 7).

All analyzed treatments with DTIC significantly decreased proliferative capacity of HTB140 cells, when comparing to control. In all samples treated with both, DTIC and protons, cell proliferation was significantly decreased with respect to single DTIC application ($p < 0.001$). However, combined treatments have shown reduced level of inhibition than cells that were only irradiated with protons. Cells pretreated with DTIC and than exposed to proton irradiation (12 Gy), have shown

augmented proliferation capacity as compared to only irradiated cells (12 Gy protons; $p < 0.05$). Those irradiated with 16 Gy after being pretreated with 100 μM DTIC have also shown increased proliferation capacity ($p < 0.01$). However, the level of cellular response to 16 Gy protons after being treated with 250 μM DTIC was in the range of single 16 Gy proton irradiation ($p > 0.05$), reaching about 60 % of cell inactivation level (Figure 8).

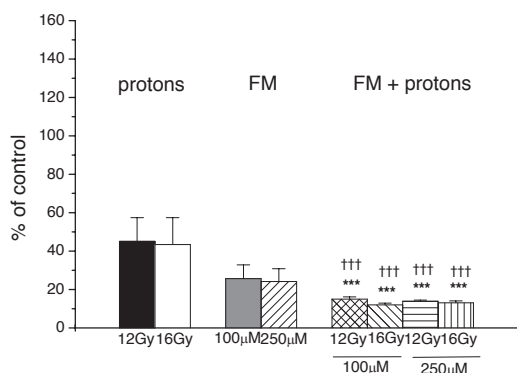


Figure 6. Proliferation of HTB140 cells estimated by BrdU assay 7 days after single and combined treatments with FM and protons. (* - combined treatments vs. FM, † - combined treatments vs. protons); * (†) - $0.01 < p < 0.05$, ** (††) - $0.001 < p < 0.01$, *** (†††) - $p < 0.001$

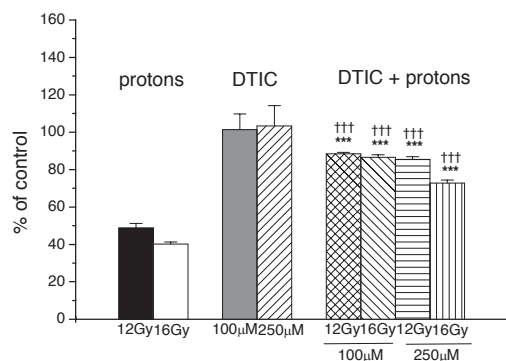


Figure 7. Viability of HTB140 cells estimated by SRB 7 days after single and combined treatments with DTIC and protons. (* - combined treatments vs. DTIC, † - combined treatments vs. protons); * (†) - $0.01 < p < 0.05$, ** (††) - $0.001 < p < 0.01$, *** (†††) - $p < 0.001$

This relatively weak effect of combined treatment with DTIC and protons on cell growth inhibition and proliferation might be explained through the activation of repair mechanism after DTIC treatment, because expression of DNA repair protein O⁶-alkylguanine-DNA-alkyltransferase is inducible by DNA damaging agents, such as DTIC and ionizing radiation [12].

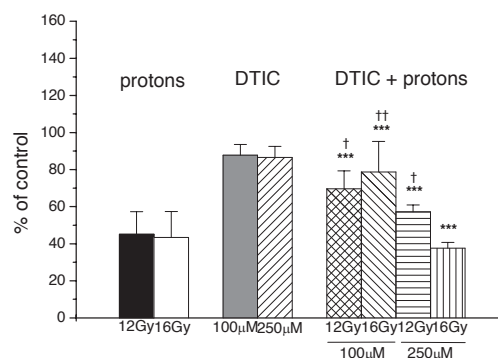


Figure 8. Proliferation of HTB140 cells estimated by BrdU assay 7 days after single and combined treatments with DTIC and protons. (* - combined treatments vs. DTIC, † - combined treatments vs. protons); * (†) - $0.01 < p < 0.05$, ** (††) - $0.001 < p < 0.01$, *** (†††) - $p < 0.001$

4 CONCLUSIONS

Treatments with FM and protons have shown better inhibition of HTB140 cell viability and proliferation, 7 days after irradiation, as compared to early effects. Combined treatments with DTIC and protons have shown better inhibitory effects on HTB140 melanoma cells after short time exposure. Molecular mechanisms induced by these treatments remain to be analysed.

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SPECTRAL ANALYSIS OF DELAYED LUMINESCENCE FROM HUMAN SKIN AS A POSSIBLE NON-INVASIVE DIAGNOSTIC TOOL

L.Lanzanò^{a,b,*}, A.Scordino^{a,b}, S.Privitera^{a,b}, S.Tudisco^{a,b} and F.Musumeci^{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: lanzano-l@lns.infn.it

Abstract

In vivo measurements of Delayed Luminescence (DL), have been performed on human skin, with the aim to develop a technique for optical biopsy. Preliminary tests have been performed on healthy volunteers, measuring the time decays of the spectral components ($\lambda_{\text{emiss}} = 400\text{-}800$ nm) starting 10 μsec after switching off the excitation ($\lambda_{\text{exc}} = 337$ nm). The modelling of experimental data has been examined in details in order to get parameters, characterizing the theoretical fit, whose changes may be correlated with age differences and seasonal variations.

diagnostic parameters were conducted to determine if optical techniques could be used as a tool for a preliminary selection of patients at increased risk of disease [10]. Anyway, up to now, a completely reliable analysis technique has not been developed yet, so we think that useful information could come by investigating the time resolved DL from skin.

In this paper we report the results of DL measurements performed on healthy human skin, showing how experimental data can be related to age dependence and season related variations.

1 INTRODUCTION

Recently several experimental studies [1-4] demonstrated that biological systems, once illuminated, emits a very weak luminescence prolonged in time. This phenomenon has been often called Delayed Luminescence (DL).

Due to its weakness, DL requires very sensitive (single-photon) detection systems to be observed. As a matter of fact instrumentation able to measure the DL from human cell cultures with adequate sensitivity has been built up only recently [5].

Results obtained with this new set up are quite interesting because they show that UVA induced DL can provide not only information about the functional state of the cultures but it is also able to discriminate between cell cultures of human fibroblasts and human melanoma [6]. This fact propose the DL as a possible candidate for the development of an optical biopsy technique able to give information on cultures of cells previously obtained from biopsy. Due to the importance of precocious diagnosis in the successful treatment of several pathologies, the extension of these results to a more direct analysis of tissues *in vivo* should be of great interest.

In this context skin is a suitable choice, because it has many important functions, is affected by several pathologies, and reflects the general health state of the whole organism. Moreover, it is easily accessible to optical analysis techniques.

Indeed, in the last years, several techniques have been proposed as non-invasive tools for *in vivo* examination of human skin. Among them two-photon excitation microscopy [7], infrared reflectance and fluorescence spectroscopy [8], excitation fluorescence spectroscopy [9] can be cited. In some case multicenter studies of the

2 MATERIALS AND METHODS

The properties of photo-induced DL from human skin *in vivo* have been investigated for two samples of healthy volunteers recruited from the staff in the Department of Physical and Chemical Methodologies in Catania University. They were all Caucasian, their age ranging from 26 to 59 years, and didn't present skin diseases or problems connected with the use of plasters. The following standard protocol has been observed for measurements in both groups. In particular, a region of the skin with no *naevi* has been individuated on the lower surface of the left forearm of every volunteer. Then, an adhesive tape stripping procedure [8] has been repeated four times on the same skin area before every measure, in order to remove impurities and the outer layer of the *stratum corneum*. Finally, the measurement was performed in a dark room and at room temperature.

The first group (Sample #1), consisting of two men (age 26,57) and two women (age 29,49), was chosen with the aim to test for the effective reproducibility of *in vivo* skin DL measurements, since most of the studies reported in Literature involve auto-fluorescence or other different spectroscopic techniques [7-10], while DL from human skin has been poorly investigated [4]. During each measure the time trends of four spectral components (460, 567, 645, 763 nm respectively) of DL emission were registered. The measurement was repeated ten times on every volunteer (all repetitions performed inside a maximum time interval of a few hours), and average and standard error have been evaluated. The whole group of measurements has been performed during three different periods of the year: winter (December 2005), spring (March 2006) and summer (August 2006), in order to check the behavior of DL during different seasonal

periods and testing in this way its sensitivity to natural changes in the physiological state of the skin [11].

The second group (Sample #2) consisted of 8 volunteers, five men (age: 26, 36, 37, 37, 58 years respectively) and three women (age: 35, 41, 49 years respectively), and measurements were performed only in summer with the aim to give complementary information about a possible sex-related dependence of DL on age, as reported for other skin spectroscopic analysis techniques [8].

All measurements have been performed with an improved version of the ARETUSA set-up, a sensitive instrument able to detect the photo-induced DL from cells in suspension, developed at Laboratori Nazionali del Sud in Catania [12]. The old set-up has been slightly modified in order to be able to perform DL measurements of skin tissue directly *in vivo*, by means of an optical fiber probe [13]. Indeed, the light from a high intensity pulsed nitrogen laser ($\lambda = 337$ nm, pulse width = 5 ns, max. energy = 100 μ J/pulse) was sent to the skin area of interest (about 25 mm²) through one branch of a bifurcated fiber bundle. The photo-induced emission, was collected by the inner part of the same bundle and carried up through a second branch to a single photon counting photomultiplier (Hamamatsu R-7206-1, multialkali, spectral response 300-850 nm) cooled down to -30°C. Due to the electronic control of the photomultiplier gate [12], the acquisition process is delayed with respect to the end of excitation. The whole data acquisition process was performed and controlled by a personal computer through a multi-channel scaler (Ortec MCS PCI) plug-in card. The low level of the emitted intensity did not allow to detect signals with a high spectral resolution. So the spectral analysis has been performed by a set of broad band (80 nm FWHM) Thermo-Oriel interference filters.

Raw data have been processed taking into account for the sensitivity factor of the apparatus, that is the product between the optical transmittance of the filtering system and the quantum efficiency of the photomultiplier [14]. A smoothing procedure has been used [15] in order to reduce random noise: experimental points have been sampled in such a way that it results $\Delta t_i/t_i = \text{constant}$.

The reproducibility of the measurement has been tested: percentage error on the DL intensity value $I(t)$ was less than 5% at shorter time and became larger, but less than 20%, at time $t > 1$ ms.

3 RESULTS AND DISCUSSION

The typical trend of the photo-induced DL intensity $I(t)$ from skin is reported in Fig. 1a, for one set of data (Sample#1, $\lambda_{em}=645$ nm, Age=26, Month=December).

For a great variety of biological systems [14-16] DL temporal trend can be modeled by a power law (hyperbolic) function as:

$$I(t) = I_0 / (1 + t/t_0)^m. \quad (1)$$

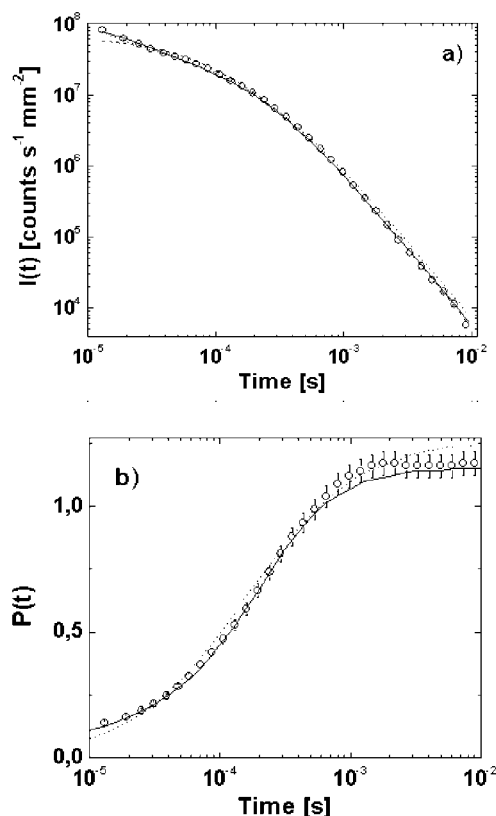


FIG. 1. (a) (○) Typical temporal trend of Delayed Luminescence from skin following UVA-laser induction at 337 nm, at 645 nm emission wavelength: (dashed line) hyperbolic fit according to Eq.(2) (reduced $\chi^2 = 0.82$), (dotted line) bi-hyperbolic fit according to Eq.(3) (reduced $\chi^2 = 0.86$), (solid line) fit according to Eq.(4) (reduced $\chi^2 = 0.33$). (b) (○) Experimental probability of decay $P(t)$ values corresponding to DL time trend shown in fig. 2a: (dotted line) theoretical $P(t)$ curve corresponding to hyperbolic fit; (solid line) theoretical $P(t)$ curve corresponding to Eq.(4) fit.

In figure 1a it is reported the fit according Eq.(1): it appears that this function failed to describe our data, especially at shorter times (where experimental uncertainty is lower). Neither a better accord it is obtained if one consider a bimodal behavior [17] according to the equation

$$I(t) = I_1 / (1 + t/t_1)^{m_1} + I_2 / (1 + t/t_2)^{m_2}. \quad (2)$$

In order to determine a more appropriate mathematical model, we consider the dimensionless function $P(t) = (-dn/n)/(dt/t)$ where $n(t)$ represents the total number of excited levels at time t . In our experimental condition (see M&M) $P(t)$ is related to the experimental probability that Δn_i levels of the n_i excited ones decay radiatively [6] and permits to evaluate how the decay probability changes in time along with the number of excited levels. Since the intensity $I(t)$ of luminescence is related to the number of excited level $n(t)$ by the expression $I(t) = -dn(t)/dt$, starting

from the experimental data of $I(t)$, the $P(t)$ function can be evaluated as

$$P(t) = \frac{I(t) \cdot t}{\int_t^\infty I(t) dt} \quad (3)$$

In Fig. 1b the $P(t)$ curve relative to the data of Fig. 1a are reported, along with the expected theoretical trend according to Eq.(1). It appears that the trend $P_{th}(t) = (m-1)t/(t+t_0)$, obtained by inserting Eq.(1) into Eq.(3), is different from $P_{exp}(t)$, obtained from the experimental points, which follows a slightly sharper transition and does not converge so rapidly to zero when time decreases, exhibiting a sigmoid-like trend. So, in order to accomplish to this behavior, another trial model function has been considered according to the following equation:

$$I(t) = \frac{I_0}{(t/t_0)^m} \frac{t^n}{t^n + t_0^n} \quad (4)$$

in such a way that the $I(t)$ trend reduces to a simple power law not only for times $t \gg t_0$ (as the hyperbolic decay does) but also for times $t \ll t_0$ (where a simple hyperbolic function goes toward a constant value). In fact, for $t \gg t_0$ it results $I(t) \rightarrow I_0/(t/t_0)^m$, while for $t \ll t_0$ it is $I(t) \rightarrow I_0/(t/t_0)^{m-n}$, which accounts for a lower but non-zero decay probability of the excited states. The solid line in Figs 1a and 1b shows the theoretical trend according to Eq.(4). The lowering of reduced χ^2 values, along with the decreased number of free parameters to be determined, with respect to the case of Eq.(2), encourages the use of a model curve Eq.(4).

Figure 3 shows the trend, as a function of the subject age, of the parameter m in Eq.(4) for $\lambda_{em} = 645$ nm. In winter m decreases with the age, assuming always values greater than 1. In the other periods of the year (spring and summer), when the skin pigmentation can become greatly influenced from climatic conditions, the monotonic trend appears less evident.

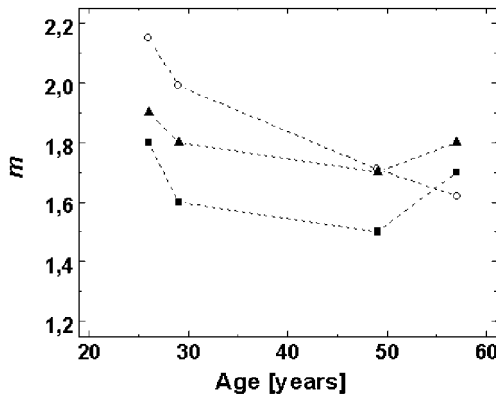


FIG.3. The parameter m in Eq.(4) as a function of the subject age and the season. Data refer to DL measurements performed at $\lambda_{em} = 645$ nm in different period of the year: (○)December, (■) March, (▲) August.

In order to take into account for the complex processes underlying luminescent phenomena, it is widely accepted to describe time-resolved luminescence decays as continuous distributions of decay times or rate constants by introducing a probability density function $H(\gamma)$ such that:

$$I(t) = A \int_0^\infty H(\gamma) \exp(-\gamma t) d\gamma \quad (5)$$

where γ denotes the rate constant and A is a normalising factor having the same units as $I(t)$.

According to Eq.(5) the distribution function $H(\gamma)$ can be determined by the inverse Laplace transform of $I(t)$. Such inversion can be easily performed if the observed data can be fitted by a function $I(t)$ that can be analytically Laplace inverted, as it occurs in the case of a pure hyperbolic decay trend [6] where $H(\gamma)$ is represented by a Gamma distribution. In our case the experimental data are well accorded by Eq.(4) whose analytical Laplace inversion is not known. However it must be noted that, if we operate a changes in the variables t and γ and introduce new “scaled” variables $\tau = t^n$ and $g = \gamma^n$, the theoretical trend $I(t)$ Eq.(4) becomes:

$$I(\tau) = I_0 \frac{\tau_0^{(m/n-1)}}{\tau^{(m/n-1)}} \frac{\tau_0}{\tau + \tau_0} \quad (6)$$

that can expressed as product of two functions whose analytical Laplace inverse transform in g -domain is known [18]. So the idea was to evaluate

$$I(\tau) = I_0 \int_0^\infty F(g) \exp(-g\tau) dg \quad (7)$$

or alternatively

$$I(t) = I_0 \int_0^\infty f(\gamma) \exp[-(\gamma t)^n] d\gamma \quad (8)$$

that is to consider the temporal trend Eq.(4) as a continuous distribution of stretched exponential decays. In Literature the stretched exponential function has been proposed as an alternative model [19-20] to fit luminescence decay of complex systems, in particular biological samples, characterized by decay rate that, instead to be constant as it occurs in the exponential relaxation, changes in time during the decay, that is our case. After determining $F(g)$ [18], the probability distribution function $f(\gamma)$ can be evaluated being:

$$f(\gamma) d\gamma = F(g) dg. \quad (9)$$

Figure 4 shows the distribution function $f(\gamma)$ for data obtained from measurements on Sample#1 in December at $\lambda_{em} = 645$ nm. It appears that the value γ_{max} corresponding to the maximum value for the $f(\gamma)$ function shifts towards slower decay rates for younger volunteers, especially if one distinguishes between women and men.

The necessity to separate the two classes of women and men before extrapolating any correlation with age appears evident in the data of the more populated Sample#2.

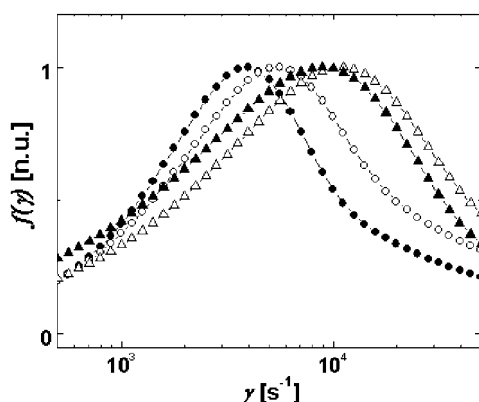


FIG. 4. Decay probability distribution function $f(\gamma)$, normalized to the maximum values, for the 645 nm emission spectral component. Data refer to DL measurements performed in December on different subjects. (●) Age=26 (man); (○) Age=29 (woman); (△) Age=49 (woman) (▲) Age=57 (man).

As a matter of fact Fig.5 shows the t_0 parameter values obtained by the fit of experimental data according to Eq.(4). Measurements have been performed in the summer period on the 8 persons constituting Sample#2 at $\lambda_{em} = 645$ nm. Both for men and women this parameter shows a monotonic decrease as a function of age. Moreover the experimental points related to the men-set can be well accorded to an exponential trend (reduced $\chi^2 = 0.5$) with a time-constant of 13 years, while the accord to an exponential trend for the data of the women-set is less significant (reduced $\chi^2 = 16.5$).

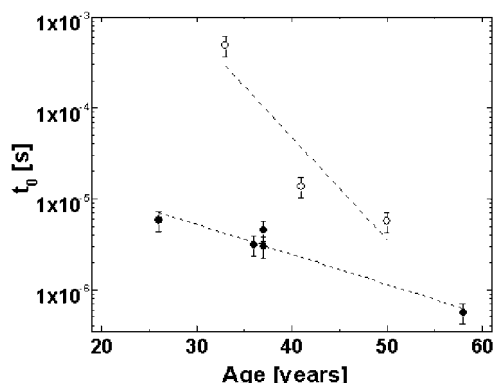


FIG. 5. Experimental values of parameter t_0 in Eq.(4) for different sex and age. (●) men, (○) women, (dashed line) theoretical fit to an exponential trend (reduced $\chi^2 = 0.5$ and 16.5, respectively).

4 CONCLUSIONS

Results reported in this paper constitute a preliminary test which permits us to assess that DL from human skin can be measured with good sensibility and reproducibility. Moreover experimental data can be modeled to a theoretical trend which represents a slight modification of the usual hyperbolic trend, and fitting parameters can be correlated to different characteristics of the sample (age of the subject, period of the year), showing in such a way the sensitivity of the technique to the physiological status of healthy skin.

Measurements on specified phototypes have been planned before extending the study to subjects healthy and affected by some skin pathologies in order to test the potentiality of the technique as a completely non-invasive diagnostic tool.

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EFFECTS OF IONIZING RADIATIONS ON BONE MARROW MESENCHYMAL STEM CELLS OF RAT: INVESTIGATIONS ON CLONOGENIC SURVIVAL AND EXPRESSION OF GROWTH FACTORS

D.Bronzi¹, D.Tibullo¹, C.Grasso¹, M.Barresi¹, M.Di Mauro¹, G.Palumbo², M.Bellia⁴, F.Licata¹, F.Santangelo¹, G.Bellia³, G. Li Volsi¹

¹Department of Physiological Sciences – University of Catania

²Department of Biomedical Sciences – University of Catania

³Department of Physics and Astronomy – University of Catania

⁴Department of Medicine and Systemic Pathology – Section of Work medicine

PRELIMINARY REPORT

Mesenchymal stem cells (MSCs) are multipotent cells in the bone marrow stromal line (Capián et al., 2001; Jiang et al., 2002; Reyes et al., 2002). The aim of this study was to verify whether low dose proton radiation (0,1 Gy or 1 Gy) can modify some functional characteristics of MSCs like vitality and differentiation into specific cellular phenotypes.

This study, performed on rat cells, demonstrated that MSCs, irradiated up to 1.0 Gy, exhibit the same vitality of controls and do not express caspases,

proteolytic enzymes which, cleaving strategic cellular proteins, are the effectors of apoptosis.

The comparison of expression of some functional proteins, markers of specific differentiation patterns, in cells irradiated at the lower doses (0,1 Gy) and in controls, gave evidence in the former of a marked increase of synapsin I and synaptophysin (Fig. 1A), a decrease of brain-derived neural factor (BDNF) and no significant variation of tyrosine kinase receptor B (trkB) (Fig. 1B), a receptor to which neurotrophins bind.

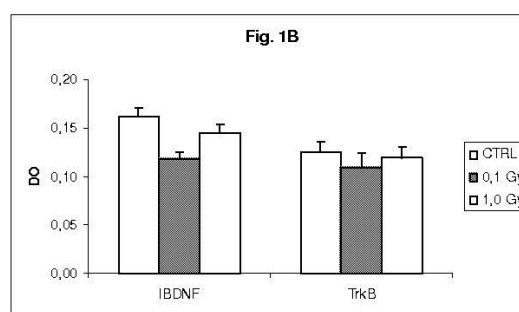
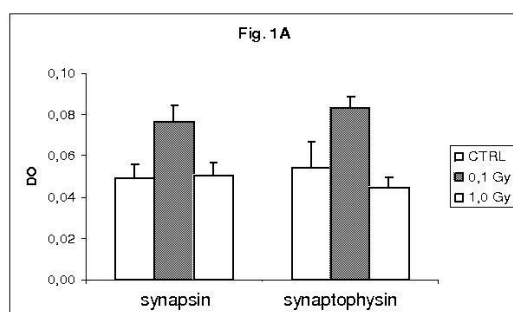


Fig. 1 – Synapsin , synaptophysin (1A), BDNF and TrkB (1B) antigens on MSCs by mean of optical density (DO). CTRL: control; G: Gray.

Furthermore, a dramatic enhancement of both clonogenic efficiency (Fig. 2A) and proliferative

capability (Fig. 2B) of MSCs appeared following proton irradiation at both doses applied (See Fig. 2).

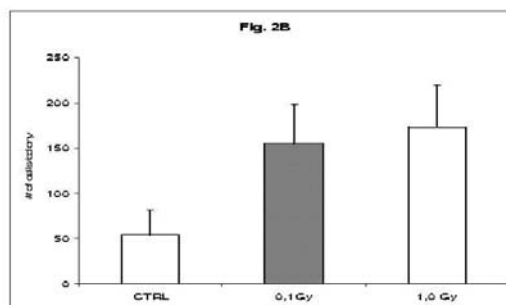
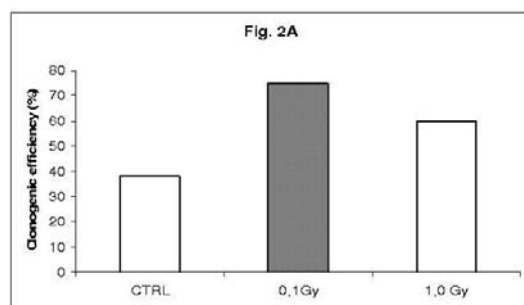


Fig. 2 – Effects of low doses of proton radiation on clonogenic survival and # of cells/colony. CTRL: control; Gy: Gray

On the whole, the analysis of these data demonstrates that MSCs, exposed to proton irradiation at doses up to 1.0 Gy, exhibit a great vitality. Furthermore, irradiation at low doses (0.1 Gy) induce a cellular differentiation to a specific phenotype, that has a low probability to be neural, but is secretory (Yaghoobi et al., 2006; Ballerini et al., 2002).

This last result suggest that further control experiments are needed to verify that the increase of proliferation following the exposure to low dose proton irradiation is a physiological response and to exclude a possible development into a tumor line.

The identification of parameters of irradiations able to start a well defined physiological differentiation in MSCs could have promising developments both in the basic as well as in the applied research.

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HUMAN FIBROBLASTS IRRADIATED WITH CARBON IONS: PRODUCTION OF SMALL DNA FRAGMENTS (1-23 kbp) AND HISTONE H2AX PHOSPHORILATION

F.Antonelli^a, M.Belli^{a,b*}, A.Campa^{a,b}, G.Cuttone^c, F.Di Rosa^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: mauro.belli@iss.it*

Abstract

Further results are here reported on DNA double strand breaks (DSB) induction and repair in human fibroblasts irradiated with 62 MeV/u carbon ions at the CS-LNS. This important biological endpoint is studied by DNA fragmentation and phosphorylation kinetics of histone H2AX. The pattern of DNA fragmentation is determined in the range 1 - 23 kbp completing the results previously obtained in the range 23 - 5700 kbp [1]. The measurement of this short DNA fragments is important to understand the degree of spatial correlation of DNA lesions induced by different types of ionizing radiation. The DSB yield measured after carbon irradiation is higher than that relative to gamma rays, giving an RBE of ≈ 1.3 in the size range studied. DNA DSB induction and repair data, obtained at 0.5 Gy using the H2AX phosphorylation assay, confirm the previous data obtained at 1 Gy in showing a higher persistence of H2AX phosphorylation, indicative of DNA DSB, after carbon irradiation compared with gamma irradiation. The overall results confirm that there are significant differences between carbon ions and γ -rays concerning the spatial distribution of DSB, and that they may be correlated with the different degree of their persistence. This finding is consistent with the hypothesis that clustered DSB play an important role in the induction of cellular effects by C-ions.

1 INTRODUCTION

There is a wide consensus in the recognition that DNA DSB can lead to relevant biological endpoints such as gene mutations, chromosome aberrations and cell death. Probably a very important factor for the fate of cells that have been irradiated is the spatial distribution of radiation induced DSB. In fact, spatial correlation of DSB is thought to affect their reparability. At the scale of the low level chromatin fiber organization, i.e. 1 kbp, DSB induced by radiation are correlated; it is expected that for carbon ions, like for all charged particles, the correlation is higher than for γ -rays.

In this work we measured the DNA fragmentation in the range 1 - 23 kbp induced by 62 MeV/u carbon ions in human fibroblasts in order to study the spatial correlation

of DSB. Moreover, we study phosphorylation-dephosphorylation kinetics of histone H2AX to detect DSB formation and repair in human fibroblasts irradiated with 0.5 Gy of carbon ions. In both cases, γ -rays were used as reference radiation.

The study here reported is part of a more comprehensive investigation aimed at evaluating the response to C ions of both targeted and non-targeted (bystander) cells.

2 MATERIALS AND METHODS

2.1 Cell culture

AG1522 normal human fibroblasts were grown as monolayers in alpha-Minimum Essential Medium (MEM), containing 1 mM glutamine, 20% foetal calf serum, 2% Hepes buffer solution (1 M) and antibiotics (all reagents from Gibco), at 37°C in 95% air and 5% CO₂ atmosphere.

2.2 Irradiation conditions

AG1522 diploid human fibroblasts were irradiated with fully stripped carbon ions at the Superconducting Cyclotron radiobiology facility of the LNS-INFN. The carbon ions energy at the cell entrance was 56 MeV/u corresponding to LET value of 40.5 keV/ μ m (in water). For DNA fragmentation experiments, confluent AG1522 human diploid fibroblasts were embedded in agarose plugs and irradiated at 4°C with several doses up to 200 Gy at a dose rate of about 30 Gy min⁻¹. For H2AX phosphorylation assay, the cells were irradiated as monolayers attached on to a mylar bottom of specially made Petri dishes with a dose of 0.5 Gy at a dose rate of about 1 Gy min⁻¹. ⁶⁰Co gamma-rays were used as reference radiation at the Istituto Superiore di Sanità at a dose rate of about 3.5 Gy min⁻¹ for DNA fragmentation and of about 1.0 Gy min⁻¹ for H2AX phosphorylation assay.

2.3 DNA fragmentation

Immediately after irradiation plugs were lysed by 1 hour treatment at 4°C followed by overnight incubation 50°C

in EDTA buffer containing Proteinase k (1.0 mg/ml) and Sarkosyl (1%). Calibrated Pulsed Field Gel Electrophoresis (PFGE) was performed to detect DNA fragments in the size range 9 – 23 kbp. Constant Field Gel Electrophoresis (CFGE) was used for the detection of the smaller fragments, in the size range 1 – 9 kbp [2]. The number of DNA DSB was evaluated by the number of fragment in many contiguous size intervals as already described [3].

2.4 H2AX phosphorylation

Phosphorylation of the serine 139 of the histone H2AX (γ -H2AX) represents one of the earliest response to the DNA DSB induction and can be used to study DSB induction and repair [4,5]. Phosphorylation-dephosphorylation kinetics of γ -H2AX were studied by measuring the number of phosphorylation foci at various times after irradiation. To this aim, cells were fixed and permeabilized for immunofluorescence analysis according to the method already described [6]. 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. Samples were then mounted using the Vectashield Mountin Medium (Vector Laboratories) for microscope analysis.

Cells were visualized using a Fluorescence Microscope System with a 100x immersion objective. About 200-300 foci were scored for each sample.

2 RESULTS AND DISCUSSION

3.1 DNA fragmentation

Both for γ -rays and for carbon ions the number of radiation induced fragments in the two size ranges 1 – 23 kbp (obtained by the measurements here reported) and 23 – 5700 kbp (obtained by previous experiments) can be well fitted with a linear function. Therefore, it is possible to define separate DSB yields in these two size ranges and, obviously, the total DSB yield for the size range 1 – 5700 kbp is given by the sum of these two separate values measured in the two regions. Fig 1 shows the number of DNA DSB in the size ranges 1 – 23 kbp and 23 – 5700 kbp (data obtained previously [4]) both for γ -rays and for carbon ions. The dashed lines represent the fitting lines and the slopes of these lines are DSB yields; moreover the slopes of the solid lines in Fig 1 represent total DSB yields for the size range 1 – 5700 kbp.

The DNA DSB yields in the size ranges 1 – 23 kbp, 23 – 5700 kbp and 1 – 5700 kbp, for both γ -rays and carbon ions, are reported in Table 1. Both DNA DSB yields in the regions 1 – 23 kbp and 23 – 5700 kbp are significantly greater for carbon ions than γ -rays especially in the range of small fragments. The RBE value, obtained from the ratio between the total DSB yield induced by carbon ions and that induced by γ -rays is 1.29 ± 0.11 . The RBE evaluated in the small fragment region is higher than that,

about 1.88. Indeed, by evaluating the fraction of small fragments in the range 1 – 23 kbp with respect to the total number of fragments in 1 – 5700 kbp, it turns out that for carbon ions the small fragments (1 – 23 kbp) represent about 21 % of the total, while for γ -rays they represent only about 14 % of the total. These results show that for carbon ions the sites of DNA damage are more spatially correlated than those for γ -rays in the size range studied.

The interplay between radiation track structure and the various levels of chromatin organization is crucial for the production of correlated damage in DNA. Some theoretical studies have found that the induction of DNA DSB by charged particles and by photons can be modulated spatially by the various levels of chromatin organization. In particular, an important modulation is predicted at the scale of some kbp [7]. The present study shows that carbon ions are more efficient compared to γ -rays in producing clustered DSB especially in the kbp region. Probably this feature contributes to increase DNA damage complexity, therefore decreasing repair capability by the cell.

Table 1: DSB DNA yields

Radiation type	y 1–23 kbp (Mbp ⁻¹ Gy ⁻¹) $\times 10^{-3}$	y 23–5700 kbp (Mbp ⁻¹ Gy ⁻¹) $\times 10^{-3}$	y 1–5700 kbp (Mbp ⁻¹ Gy ⁻¹) $\times 10^{-3}$
γ -rays	0.90 ± 0.18	5.27 ± 0.41	6.17 ± 0.45
¹² C ions	1.69 ± 0.23	6.30 ± 0.19	7.99 ± 0.30

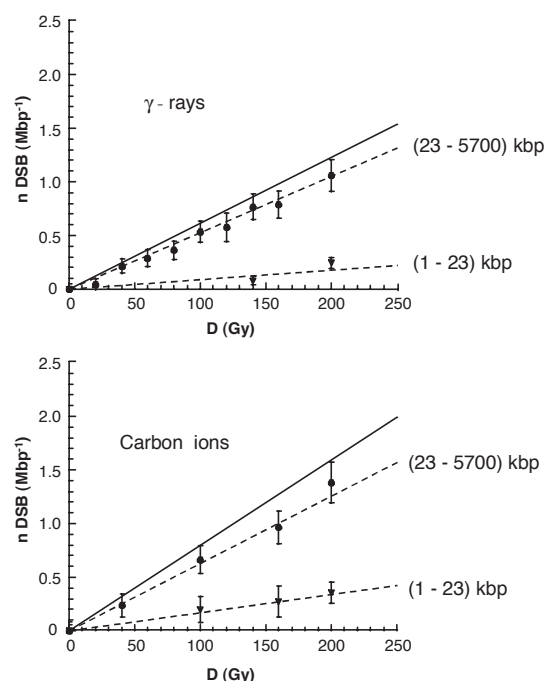


Fig. 1: Number of DNA DSB per Mbp induced by gamma-rays (upper panel) and carbon ions (lower panel).

in the size ranges 1 – 23 kbp and 23 – 5700 kbp. The mean and the standard error of the mean are computed from several plugs obtained in two experiments.

3.2 H2AX foci kinetics

Our results (fig.2) show several differences in the histone H2AX phosphorylation-dephosphorylation kinetics obtained after irradiation of AG1522 cells with a dose of 0.5 Gy of gamma rays or carbon ions. In particular, the number of γ -H2AX foci increase up to a maximum of about 14 foci/cell Gy^{-1} after gamma irradiation, while this number reaches a maximum of about 9 foci/cell Gy^{-1} when carbon ions were used. In both cases the maximum number of foci is reached at about 30 minutes after irradiation.

The difference in the maximum number of foci observed after irradiation with gamma rays or carbon ions could be explained by considering the differences in the energy deposition by the two kind of radiation used. During their traversal through the matter, carbon ions release energy in a more localized way comparing with photons and this could produce, with a given probability, DNA DSBs which are on the same track. If this is the case, it would not be possible to resolve multiple foci which are placed on top of each other by using a normal fluorescence microscope. Therefore the observed foci number would underestimate the actual number in a manner dependent on the probability to form more than one focus along the same track.

It is interesting to note that the maximum number of γ -H2AX foci observed at 30 min after irradiation is comparable to the calculated number of nuclear traversals giving one or more DSBs (data not reported).

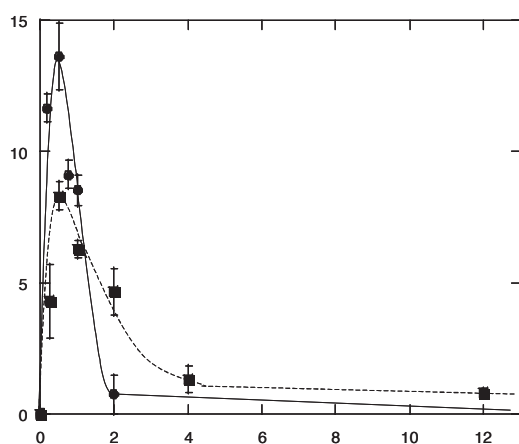


Fig. 2: Comparison between H2AX phosphorylation-dephosphorylation kinetics after irradiation with 0.5 Gy of gamma-rays (solid circles) or carbon ions (solid squares). The mean and the standard error of the mean are computed from at least two experiments.

Persistence of foci is dependent on the radiation used: the number of carbon ion-induced foci at 2 h after irradiation is about six times higher than that induced by

gamma rays and a difference in the foci persistence extends also at longer times after irradiation. This finding could reflect the occurrence of a damage induced by carbon ions that is more difficult to repair compared with gamma rays, consistently with the results obtained from the DNA fragmentation studies, although the latter were obtained using much higher doses.

The approach used in this study will be used in the future for investigations of response to C ions and γ -rays of non-targeted, bystander cells.

4 ACKNOWLEDGMENTS

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EFFECT OF 62 MEV PROTONS ON TELOMERES AND TELOMERASE IN NORMAL PRIMARY HUMAN CELLS

A. Sgura (a)* F. Berardinelli (a) A. Antoccia (a), G. Cuttone (b), L. Valastro (b), F. Di Rosa (b),
G. Russo (b) G.A.P. Cirrone (b) and C. Tanzarella (a)

(a) Dept of Biology, University "Roma Tre", V.le Marconi 446-00146 Roma and INFN-Roma3,

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

* Corresponding author, e-mail: sgura@uniroma3.it

Abstract

Telomeres are specialized nucleoprotein complexes that serve as protective caps of linear eukaryotic chromosomes. The loss of the ends of the chromosomes due to these un-rejoined DSBs may not be lethal to the cell, but may instead result in the loss of functional telomeres, chromosome fusion, and initiation of breakage/fusion/bridge cycle-induced chromosome instability.

In the present work we have tested the capability of low-LET radiations to affect telomere structure. X-rays and 62 MeV protons (CATANA facility, INFN-LNS), characterized by a similar LET were used to irradiate HFFF2 human primary fibroblasts. To evaluate radiation-induced alterations of telomere length, Q-FISH staining was performed on calyculin-A-condensed chromosomes and interphase nuclei with fluorescent PNA telomeric probe and telomere size was analysed with TFL-TELO software. To evaluate if this telomere elongation is a telomerase dependent mechanism, the telomerase activity will be analysed by means of TRAP assay in parallel samples.

1 INTRODUCTION

Telomeres, capping chromosome ends, are involved in maintaining chromosome stability; alterations of their length have been related to increased levels of chromosomal aberrations [1]. Increasing interest has recently been focused on the biological effects of protons for their clinical applications. It is well known that the different types of radiation may produce DNA DSBs characterized by a different degree of "complexity" associated with different biological consequences. The effect of radiation quality has been investigated for DNA damage endpoints, whereas other relevant aspects, such as telomere dysfunction and its role in chromosome aberrations, have not been studied so far, in particular for low-energy protons. With the aim of investigating these chromosome structures responsible of chromosome stability after X-rays and proton irradiation we have studied telomere length. Furthermore, as telomerase, the principal protein involved in telomere maintenance [2], is

activated by telomeres shortening and by other DNA-damage inducing factors [3], its activity will be analysed by means of TRAP assay technique at different time from treatment. In this paper we have confirmed our previous results in which different types of radiation as low-energy protons and sparsely ionizing radiation could be able to modulate telomere elongation at different time [4]. In addition, to evaluate if this telomere elongation is a telomerase dependent mechanism, the telomerase activity has been analysed by means of TRAP (Telomere Repeat Amplification Protocol) assay at the same harvesting times.

2 MATERIALS AND METHODS

Human primary fibroblasts (HFFF2) were irradiated with 4 Gy of 62 MeV of protons at the facility of Catania INFN-LNS. Experiments with X-rays (Gilardoni apparatus, 250 kV, 6 mA, 0.2 mm copper) were also carried out. Cells were fixed either 24 hours or 15 days after irradiation. To evaluate radiation-induced alterations of telomere length, Q-FISH staining was performed on interphase nuclei with fluorescent PNA telomeric probe and telomere size was analysed with TFL-TELO software kindly provided by Peter Lansdorp (British Columbia Cancer Center, Vancouver, Canada). The fluorescence intensity of telomeres was expressed in arbitrary units (a.u.f).

Telomerase activity was analysed in proton irradiated human fibroblasts using the PCR-based telomeric-repeat amplification protocol (TRAPEze ELISA Telomerase detection Kit). This procedure is separated in three steps:

1) Extract Preparation: protein extract of unirradiated and proton- irradiated cells was obtained by using 1X CHAPS lysis buffer.

2) TRAP extension/amplification: telomerase, if present in protein extract, adds a number of telomeric repeats (TTAGGG) to the 3' end of a biotinylated substrate oligonucleotide (b-TS); the extended products are then amplified by PCR.

3) Detection (ELISA): PCR products were analysed and the absorbance (A) was evaluated by the microplate reader. The difference between the absorbance for the sample and heat-treated sample was indicated as ΔA . When $\Delta A > 0.150$, the sample is defined telomerase positive.

3 RESULTS AND DISCUSSION

In the present study we confirm our previous results that showed that telomeres were not modified in their length as evaluated 24 h after exposure, whereas a significant increase in telomere length was detected in cells harvested 15 days later.

In order to better understand if this telomere elongation after irradiation is a telomerase-dependent or -independent mechanisms, we have analysed the telomerase activity after proton irradiation in human fibroblasts by means of TRAP assay at the same harvesting times of telomere Q-FISH analysis. Preliminary data, shown in Fig. 1, demonstrated no telomerase induction after irradiation.

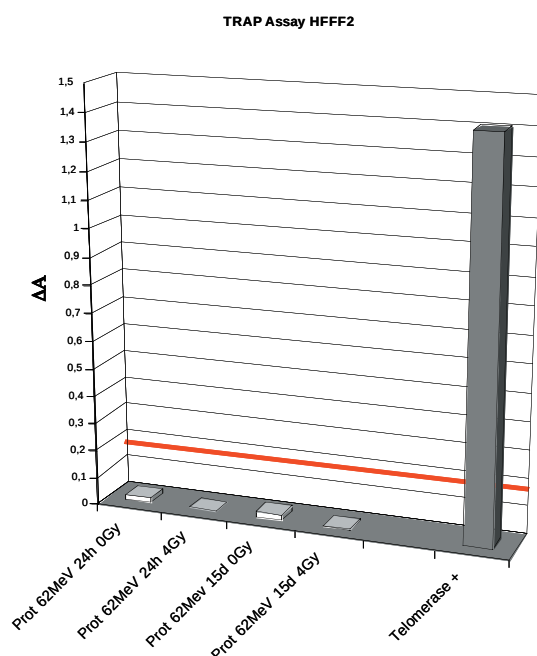


FIG. 1: Telomerase activity in HFFF2 cells expressed as ΔA . ΔA values > 0.150 are telomerase positive. Black bar represent a telomerase positive control.

These preliminary results seem to indicate that low LET sparsely ionizing radiation could be able to induce a delayed telomere instability through a telomerase-independent mechanism. Other experiments will be

carried out in order to understand if this delayed telomere lengthening could be the result of selection of cells characterized by longer telomeres. To this end the analysis will be performed on surviving cells. Furthermore, we can not ruled-out that the observed phenomenon is due to an Alternative Lengthening of Telomeres (ALT) based on recombinational mechanisms.

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A NOVEL EXPERIMENTAL SET-UP FOR DETECTING GATE LEAKAGE CURRENT INCREASE DURING HEAVY IONS EXPOSURE OF POWER MOSFETs

G. Busatto^a, F. Iannuzzo^a, A. Porzio^{a,*}, A. Sanseverino^a, F. Velardi^a,
A. Cascio^b, G. Curro^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

The results presented in this report are the continuation of an experiment started at LNS during 2004, that has the aim of investigating the failure mechanisms of power MOSFETs during the impact with an energetic particle as it frequently happens in the aerospace applications. The activity is devoted to understand the basic mechanisms that take place during the impact and may bring to permanent damages to the power MOSFET's both at its vertical structure (Single Event Burnout - SEB) and/or at its surface gate MOS structure (Single Event Gate Rupture - SEGR).

The experimental and simulative study have clarified 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. The studies regarding the dependences of this activation on the technological parameters have permitted us to improve the SEB/SEGR sensitivity of the studied Power MOSFET by a factor of about 2.5 and to develop four prototypes of radiation hardened power MOSFET.

However, these devices are still subject to SEGR phenomena for which the models proposed into the scientific literature do not seem to fully explain the device failure, probably due to the fact that SEGR failure mechanisms are strongly dependent on the device technology. Hence, in order to better understand the SEGR involved mechanisms, we have developed a new experimental set-up able to study the time evolution of the gate damage during the heavy ions exposure and to study the dependence of the damage amount both on the biasing conditions and the technological changes.

1 INTRODUCTION

Power MOSFETs are very important devices for aerospace applications, unfortunately their ability to safely operate in this radiation environment is drastically reduced by two failure mechanisms induced by single energetic particles impacts: the burnout (SEB) and the rupture of the gate oxide layer (SEGR) [1-9].

The experimental and simulative study have allowed us to demonstrate 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 [10-14].

The experimental results interpreted on the bases of 3-D finite element simulations have allowed us to identify surface regions in the lay-out of the devices where a large electric field develops after the impact. The contemporary presence of this electric field and the large amount of carriers generated during the impact can be likely invoked to be the cause of the accumulation of carriers into the gate oxide. The subsequent degradation of this oxide can explain the reduction of MOSFET SEGR capabilities.

The objective of this report is to present the experimental behaviour of gate damages induced by the impact of heavy ions on a power MOSFET. In order to better investigate these damages as a function of the bias conditions, we have developed a new experimental set-up that was used to study the time evolution of the gate damage during the heavy ions exposure and to study the dependence of the damage amount both on the biasing conditions and the technological changes.

2 THE GATE OXIDE DEGRADATION DUE TO HEAVY IONS IMPACTS

In the last years we presented an experimental set of SEGR data acquired in different bias conditions [15]. Unlike other experimental results [6-8], all the tested device have shown a strongly non linear relationship between the gate and drain bias voltages at which the gate rupture occurred. In addition, the gate damage observed at $V_{GS}=0V$ is quite dissimilar from what observed at negative gate-source voltages. At low gate-source voltage bias the gate damage mechanism is evidenced by a progressive increase of the gate leakage current like it happens in a cumulative effect, whereas at higher voltage biases an abrupt gate damage reveals a typical single event effect.

To obtain the experimental data, we assumed an initial value of V_{GS} and V_{DS} , exposed the device under test to the heavy ion beam, stopped the ion beam when the desired ion fluence was achieved and tested the leakage I_{GSS} with V_{GS} at $\pm 10V$ and V_{DS} at $0V$. If the gate damage didn't occur, the V_{DS} voltage was incremented and the test sequence was repeated. The experiment was stopped when the sample failed.

In Fig.1 a map of the MOSFET gate leakage I_{GSS} is

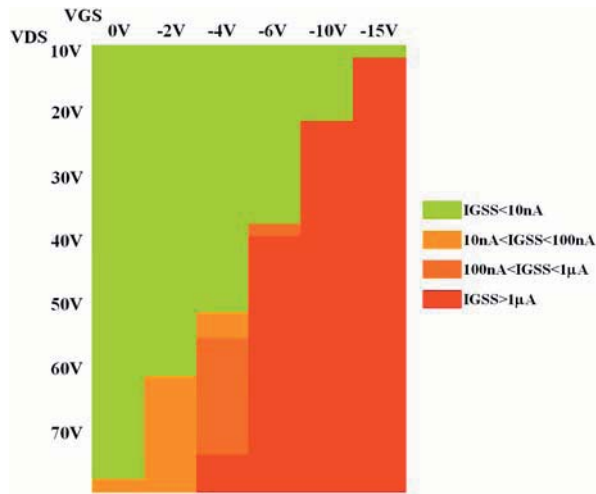


Fig.1 - The map of the I_{GSS} gate leakage.

reported. The green area represents the V_{DS} and V_{GS} bias conditions where the I_{GSS} , measured after the irradiation, is $< 10\text{nA}$. The red colour indicates the bias conditions that cause a SEGR where I_{GSS} is $> 1\mu\text{A}$. The light and dark orange regions indicate the bias condition which cause $10\text{nA} < I_{GSS} < 100\text{nA}$ and $100\text{nA} < I_{GSS} < 1\mu\text{A}$, respectively. Fig.1 points out that for low V_{GS} , the increase of I_{GSS} is proportional to the increase of the biasing voltages, whereas for larger V_{GS} a small variation of V_{DS} causes the change from the green to the red region and, then, the device failure.

For the samples which exhibits I_{GSS} lower than $1\mu\text{A}$ at the end of the irradiation (the green and orange regions of Fig.1), the value of I_{GSS} reduces with a time constant of about 10 minutes after the irradiation.

In Fig.2 the critical drain voltage at which the gate damage was detected ($I_{GSS} > 1\mu\text{A}$) is depicted for two different types of MOSFETs differing for their gate oxide thickness. The leakage transition, from a value $I_{GSS} > 100\text{nA}$ to a value $I_{GSS} > 1\mu\text{A}$, appears as a strong non linear function of the critical bias voltage.

Corresponding to the abrupt increment of I_{GSS} leakage a large drain and gate current pulses were detected. In Fig.3 the comparison between the drain current pulse related to the gate rupture and a typical drain current pulse recorded in the same bias conditions is presented. Further, the large amount of current measured at the gate terminal is depicted in the same figure.

The above results does not permit to have a clear picture of the time evolution of the gate damage formation during the irradiation. This problem was solved by developing the experimental set-up described in the following section.

3 THE EXPERIMENTAL SET UP

The schematic of the experimental circuit specifically developed to characterize SEB and SEGR of Power MOSFET is reported in Fig.4.

The DUT is biased at the drain and gate terminals by

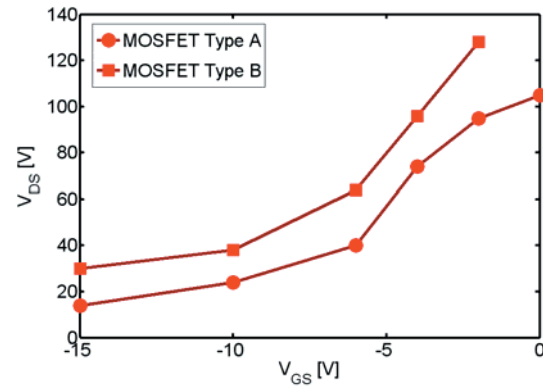


Fig.2 - The critical V_{DS} .

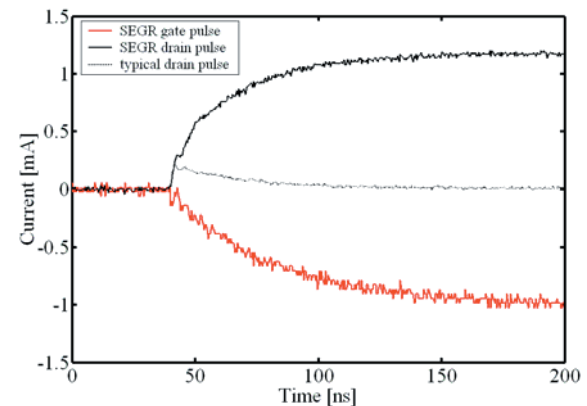


Fig.3 - The gate rupture current pulses.

means of external voltage sources in order to reverse biasing the N/epi-P+/body junction during irradiations at varying gate and drain biases.

The capacitors at the drain and gate terminals play a twofold role. At first they couple the gate and the drain to the input terminals of a fast sampling oscilloscope thus allowing us to collect the current pulses resulting from the impact of the energetic particles.

The second important role played by the two capacitors consists in the fact that they keep the voltage across the devices terminal practically constant during the impact and, because they are placed very close to the device leads, they ensures thereby a very low stray inductance into the biasing and measurement circuit.

Moreover, the construction of the experimental set-up is performed in order to have: 1) the best behaviour in terms of signal to noise ratio due to the very low levels exhibited by the measured signals, 2) the minimal effects of the stray elements like the parasitic inductance of the circuit, 3) the external terminations of the measurement circuit adapted to the impedance of the cables (50Ω) due to the very fast variations of the measured signal, that exhibits a rise time of about 1ns.

The drain leakage current and the gate leakage current of the DUTs were continuously monitored, in order to detect failure events.

Two $1\text{M}\Omega$ resistors (R_{GB} , R_{DB}) limit the current in short circuit circumstance in order to protect the instrumentation, furthermore, they consent the gate and

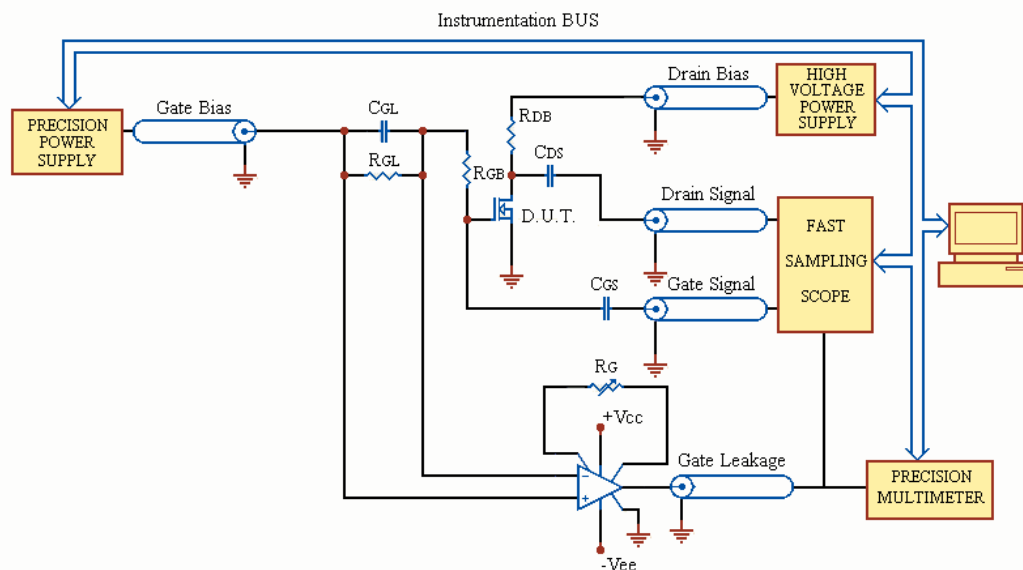


Fig.4 - The schematic of the experimental test circuit

drain leakage currents measurement during the experiment.

The charge generated during an ion impact produces a current transient that is detected by a fast sampling oscilloscope (LeCroy WavePro 7000 Series, a four trace scope with 10 Gsamples/sec and a 1GHz band width).

The time scale of the current pulses is of the order of a few nanoseconds hence the circuitry was adapted to the impedance of the cables (50Ω).

Besides the statistical analysis that we can perform on the current pulses acquired by the oscilloscope [12], the new experimental set-up includes a low noise operational amplifier that allows us to measure the gate leakage current, as the voltage drop across the $R_{GL}=1M\Omega$ resistor. Its output is monitored by a precision multimeter and recorded by the oscilloscope in order to follow the time evolution of the I_{GSS} leakage and to correlate its variations to the charge generated during the ion impact.

4 THE EXPERIMENTAL PROCEDURE

The experimental study of the reliability of power MOSFETs to be used in the outer space requires the choice of the radiation type and energy to best simulate the interaction with cosmic rays. The selection criterium employed had to ensure that the Linear Energy Transfer in the epitaxial region was sufficiently elevated to guarantee high energy depositions and the longitudinal range was sufficient to guarantee penetration into and through the active layers of the device.

The relation of the ion species and incident energy with the energy loss and range in the targets available was systematically studied using SRIM (The Stopping and Range of Ions in Matter) [16]. The SRIM simulations had been conducted on a typical device able to blocking 200V. Starting from the above criterium, we have chosen for the experiments ions of bromine ^{79}Br (236 MeV). With this choice the simulations had shown that the ionisation energy loss (LET) is high enough in the active

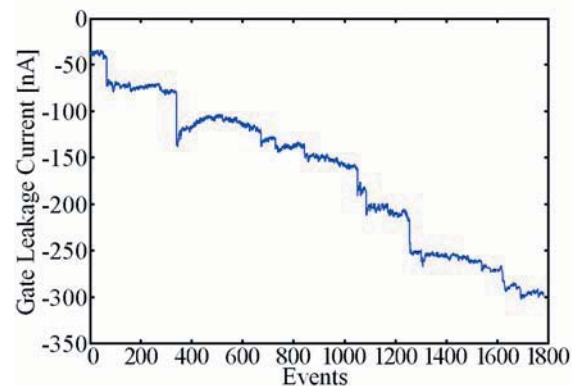


Fig.5 - The gate leakage current trend.

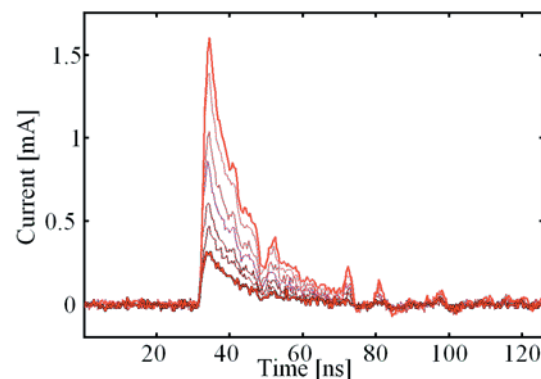


Fig.6 – Typical drain current waveforms.

layer of the structure under study.

In Fig.5 a typical gate leakage current evolution, recorded during exposure of the device by means of the new experimental set-up, is reported. During the experiment the gate bias was set to $V_{GS}=-2V$ in order to avoid the device SEGR that is typically observed for $V_{GS}>|-5V|$. In Fig.6 some typical drain current pulses related to ion impact on the structure are reported.

The gate leakage current for these test conditions

increases step by step and between two subsequent steps it tends to reduce. This behaviour is compatible with the interpretation according which only a limited number of impacting ions causes the increase of I_{GSS} . In fact, in Fig. 5, only about ten steps are observed over a total fluence larger than 10,000 (in the figure a large number of events are not registered).

To explain this behaviour we propose here that only a small area of the device lay-out is sensitive to the gate damage formation and only the ions that impact this area cause the oxide degradation. This sensitive area depends on the biasing conditions and on the technological parameters (i.e. gate oxide shape and thickness, cell pitch etc.).

5 CONCLUSIONS

We developed a new experimental set-up to study the time evolution of the gate damage during the heavy ions exposure and to study the dependence of the damage amount both on the biasing conditions and the technological changes.

Other studies are on the way trying to identify the actual extension of the sensitive area and its location on the device surface lay-out. The objective is to improve the SEGR performances of the future generation of radiation hardened power MOSFET.

6 ACKNOWLEDGMENTS

The authors wish to acknowledge Prof. Migneco, Prof. Lattuada and Dr. Rifuggiato of the INFN-Laboratori Nazionali del Sud for having permitted the experiments at the LNS tandem facility, and all the technicians of these laboratories for the precious assistance supplied during the experiments.

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EFFECTS OF CARBON-ION BEAM ON A RESISTANT MELANOMA CELL LINE

I. Petrović^{a,*}, A. Ristić-Fira^a, L. Korićanac^a, J. Požega^a, F. Di Rosa^b, P. Cirrone^b, G. Cuttone^b

a) Vinča Institute of Nuclear Sciences, Belgrade, Serbia

b) INFN Laboratori Nazionali del Sud, Catania, Italy

** Corresponding author, e-mail: ipetrov@vin.bg.ac.yu*

Abstract

Human HTB140 melanoma cells were irradiated along the Bragg curve of 62 MeV/u ^{12}C ions in the dose range from 2 to 16 Gy. Radiobiological parameters confirmed high radioresistance of the cells, showing also better effectiveness of ^{12}C ions, due to their higher linear energy transfer (LET), than protons. There was an important cell inactivation on the distal declining end of the Bragg peak. Proliferation capacity was lower at this position than close to Bragg peak maximum, due to ^{12}C fragmentation. It was shown that because of higher LET, ^{12}C ions caused more irreparable damage than protons.

1 INTRODUCTION

Good radiobiological response in killing malignant growth obtained by heavy ion beams has been commonly used in radiotherapy. When traversing matter, high energy charged particles lose their energy through interactions with atoms, with a large increase in energy loss at the end of their track - the Bragg peak. The energy deposited per unit of length along the particle track, which is the linear energy transfer or LET, explains induced biological effects to radiation damage. Since LET depends on particle energy, as well as on particle species, heavier particles have higher energy loss per unit length. It is assumed that these physical and biological properties might improve radiotherapy, particularly for radioresistant tumours. However, it has been shown that the largest biological effectiveness was achieved at intermediate LET values [1, 2].

A number of studies revealed that the relative biological effectiveness (RBE) depends on LET, but also on ion species and cell types. When analyzing biological responses to different ion species, it has been shown that their track structure of the energy deposition plays an important role and has to be taken into account. Different biological responses are caused by the different track structure for different atomic numbers with similar LET values [3].

In our previous research we have extensively analysed effects of proton irradiation, at the Bragg peak as well as along the plateau of SOBP, including the distal fall-off part of SOBP, on human HTB140 melanoma cells. Although rather high RBE values, with respect to γ -rays, were obtained in all cases, surviving fractions at 2 Gy (SF2) revealed that these cells are among most radioresistant cell lines reported [4, 5]. Being the limit case, due to its position on the wide scale of cellular

radiosensitivity, HTB140 cells were exposed to the beam of ^{12}C ions at three positions within the Bragg peak. Radiobiological effects corresponding to these different LET values were analysed.

2 MATERIALS AND METHODS

2.1 Cell Culture

Melanoma HTB140 cells were grown in RPMI 1640 medium supplemented with 10 % foetal calf serum (FCS), penicillin / streptomycin and L - glutamine in a 5% CO_2 incubator at 37 °C.

2.2 Irradiation Conditions

Exponentially growing cells were irradiated with 62 MeV/u ^{12}C ions produced by the superconducting cyclotron at the CATANA treatment facility, INFN – LNS, Catania. Three positions for irradiation (figure 1) were obtained by interposing Perspex plates (Polymethyl methacrylate - PMMA) of different thickness in front of the cell monolayer, thus providing corresponding dose levels (table 1).

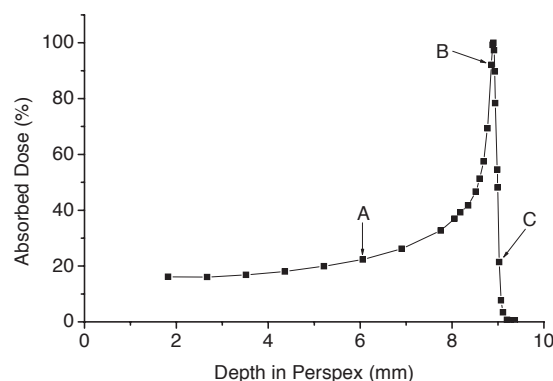


Figure 1. Depth dose distribution in Perspex of the 62 MeV/u ^{12}C beam produced at the CATANA treatment facility. Arrows correspond to irradiation positions.

Reference dosimetry was performed using plane-parallel PTW 34045 Markus ionization chamber calibrated according to IAEA code of practice [6, 7]. Single doses delivered to the cells were 2, 4, 8, 12 and 16 Gy, at dose rate of 11.03 ± 0.27 Gy/min. Irradiations with γ -rays, at the same dose levels, were performed using ^{60}Co source at the Vinca Institute of Nuclear Sciences in

Belgrade, at average dose rate of 1 Gy/min. All cell irradiations were carried out in air at room temperature.

Table 1: Irradiation position parameters.

Irradiation position	Depth in Perspex (mm)	Dose (%)
A	6.0	22.04±1.35
B	8.8	92.11±4.76
C	9.0	21.42±6.43

2.3 Clonogenic Assay (CA)

After irradiation cells were harvested by trypsinization and seeded into 25 cm² flasks at a suitable number for colony assay, and incubated at 37 °C for 7 days. Cells were then fixed with methanol and stained with 10 % Giemsa solution for evaluation of survival.

2.4 Cell Proliferation Assay

Cell proliferation capacity was estimated using Cell Proliferation ELISA, BrdU (colorimetric) Kit (Roche, Germany). Cells were irradiated, replated and maintained for 7 days under standard conditions, when the assay was performed according to the manufacturer's instructions. Absorbance was measured using microplate reader at a test wavelength of 450 nm and a reference wavelength of 690 nm. The inhibitory rates were calculated according to the following formula: inhibitory rate = (1-tested cell proliferation/mean of control cell proliferation) x100%.

2.5 Flow cytometric analysis

Cell cycle phase analysis was performed using propidium iodide (PI, Sigma-Aldrich Chemie GmbH Steinheim, Germany), added to cell samples prior to FACS analyses. 1x10⁶ cells per sample were washed in PBS, counted, fixed and permeabilized with 500 µL of 70 % ice-cold ethanol, overnight at 4 °C. Cells were then pelleted by centrifugation at 420 g for 10 minutes and stained 30 minutes prior to flow cytometric analyses with buffer containing 50 µg/mL propidium iodide and 50 µg/mL RNase A. The percentage of cells in SubG1, G0/G1, S and G2/M phases of cell cycle were calculated according to ModFit software program (Verity Software, Becton Dickinson, Heidelberg, Germany).

3 RESULTS

Response to irradiations with doses ranging from 2 to 16 Gy, were carried out at three positions within the depth dose distribution in Perspex of the 62 MeV/u ¹²C ion beam. Analyses were performed 7 days after irradiation, time corresponding to clonal survival. The numbers of viable cells were estimated from two duplicate experiments using clonogenic assay for each irradiation position. To fit survival curves the linear-quadratic model was used: $S = \exp(-\alpha D - \beta D^2)$. However, to obtain the best fit curves the model was reduced only to its linear term, implying that there is no shoulder which is commonly seen when cells are irradiated. The surviving fractions were evaluated from these best fit survival curves. All these results are given in figure 2.

The cell survival curve for irradiation position A, which belongs to the plateau region of the Bragg curve (figure 1), is flat and almost horizontal, showing practically no dose dependence (figure 2). At the position B, corresponding almost to the maximum of the Bragg peak, the survival curve is dose dependent with a rather good fall. When irradiation was carried out at the distal fall-off part of the Bragg peak, the position C, the survival curve was also dose dependent, but with a lower drop than at the position B.

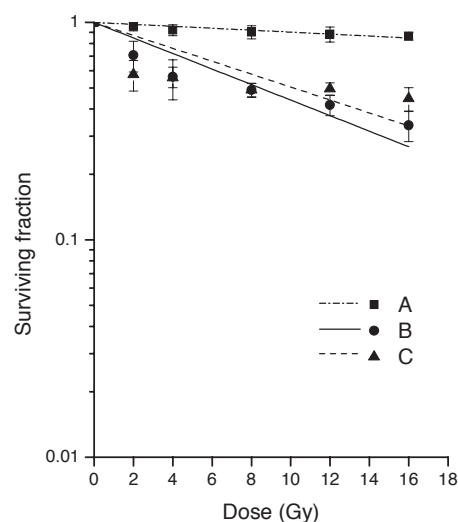


Figure 2. Dose dependent surviving fractions of HTB140 cells irradiated with ¹²C ions at three irradiation depths in Perspex.

Considering that surviving fraction at 2 Gy (SF2) represents the level of cellular radiosensitivity, rather high values were obtained for all three irradiation positions: 0.979±0.001 at A, 0.847±0.008 at B and 0.871±0.007 at C.

The attained biological effectiveness of carbon ions is estimated by RBE(2 Gy, γ), which represents the ratio of 2 Gy γ-ray dose and the proton dose generating the same inactivation level as that given by 2 Gy of the reference γ-rays. At the position A RBE(2 Gy, γ) was insignificant, while at positions B and C was quite high, having values of 3.99±0.44 and 3.69±0.38, respectively. With the increase of dose there was a modest decrease of RBE(Dose, γ) for the two positions, reaching for 16 Gy values of 2.47±0.04 and 2.06±0.02, respectively.

Effects of carbon ions on cell proliferation level were also assessed 7 days after irradiation and are presented as a percentage of control values (figure 3). For the same dose range, within the three irradiation positions along the Bragg curve, a dose dependent decrease of cell proliferation capacity was observed. At the position A, a moderate but dose dependent decrease of proliferation was observed. Moving the irradiation position close to the Bragg peak maximum (position B), BrdU incorporation capacity further decreased. At the distal

fall-off (position C) the highest inhibitory effects of irradiation regarding cell proliferation were obtained.

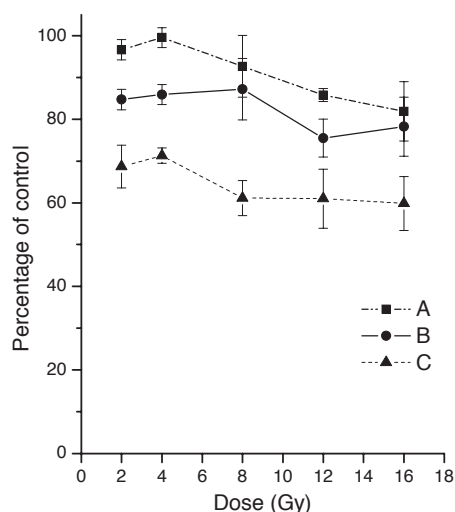


Figure 3. Dose dependent proliferation capacity of HTB140 cells 7 days after irradiation with ^{12}C ions at three depths in Perspex, estimated by BrdU.

Evaluation of apoptosis and analyses of cell cycle phase redistribution of HTB140 cells were performed in the presence of PI, 48 h after irradiation with ^{12}C ions.

Sub-G1 cell population, representing apoptotic cells, and corresponding apoptotic indexes are given in table 2. Carbon ions induced dose dependent apoptotic cell death, at the irradiation position close to the Bragg peak maximum. When irradiated at the plateau region or at the distal fall-off of the Bragg peak, the level of apoptosis was less, not exceeding 10 % (table 2).

Table 2. Dose dependent apoptosis in HTB140 cells 48 h after irradiation by ^{12}C ions at three depths in Perspex.

Irradiation position	Dose (Gy)	Sub-G1 (%)	Apoptotic Index
A	0	1.92±0.35	1
	2	3.70±0.19	2.02±0.46
	4	5.03±0.34	2.75±0.67
	8	7.04±1.50	3.66±0.13
	12	5.64±0.92	3.13±1.03
	16	6.53±0.36	3.49±0.44
B	0	1.92±0.35	1
	2	7.24±0.75	3.84±0.29
	4	8.20±1.80	4.26±0.17
	8	9.50±0.34	5.09±0.74
	12	10.8±0.80	5.75±0.62
	16	19.35±2.45	10.21±0.55
C	0	1.92±0.35	1
	2	9.09±1.41	4.77±0.12
	4	9.29±0.81	4.93±0.46
	8	8.91±0.97	4.90±1.39
	12	8.09±0.31	4.33±0.62
	16	10.99±2.11	5.73±0.07

Apoptotic index slightly increased when moving irradiation position, reaching its maximum of 10.21 ± 0.55 at position close to the Bragg peak maximum, when cells were irradiated with 16 Gy.

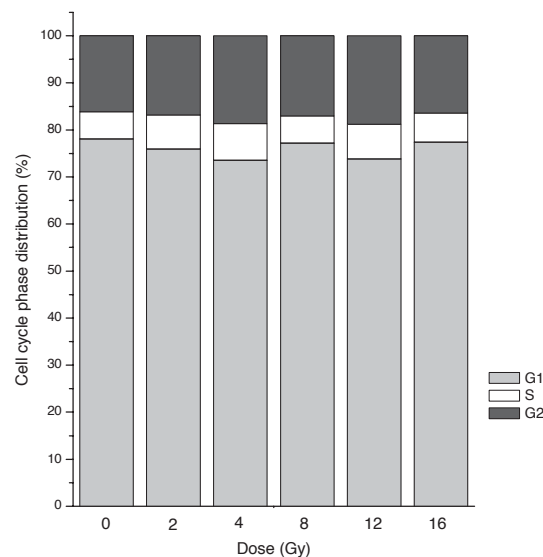


Figure 4. Cell cycle distribution of HTB140 cells 48 h after irradiation with ^{12}C ions at 8.8 mm in Perspex (position B).

Close to the Bragg peak maximum, cell cycle phase distribution has shown a significant number of cells in G1-S phase, while a modest G2-M arrest was detected. In both cases there was no dose dependent change in cell cycle distribution.

4 DISCUSSION

Carbon ion beam, produced at the CATANA facility was tested on a resistant human HTB140 melanoma cell line. A number of parameters describing level of cell radio-sensitivity, commonly used to analyse and predict the success of therapeutic irradiations, were presented. Irradiation position was moved along the Bragg curve of the 62 MeV/u ^{12}C ions, enabling investigation of the level of cell survival at different depths in Perspex. Chosen positions belonged to the plateau, the peak and the distal fall-off of the Bragg curve.

The obtained values of surviving fractions at 2 Gy (SF2), throughout the whole Bragg curve, indicated high level of radio-resistance of these cells [3, 8]. They moderately decreased when changing irradiation position from the proximal to the distal end of Bragg curve. Still these values, when compared to those obtained with 62 MeV protons, were lower [4]. This is the consequence of higher LET values in the case of ^{12}C ions than in the case of protons at the same irradiation positions.

The efficiency of carbon ions to inactivate cells with respect to conventional radiation (γ -rays) was analysed through relative biological effectiveness at 2 Gy (RBE).

Even though it was shown that HTB140 cells are among the most radio-resistant cells, yet the obtained RBE values indicated significant level of carbon induced cell inactivation, which was also higher than for protons. However, at the distal declining end of the Bragg curve, where the dose intensity was the same as in the plateau part, the killing ability of ^{12}C ions was close to that observed near to the Bragg peak maximum. Such behaviour, already identified, is very important in hadron therapy regarding the limits of the treated malignant tissue, especially if a crucial healthy tissue is in the close neighbourhood.

Proliferation capacity of cells slightly decreased with the increase of dose as well as when moving irradiation position along the carbon Bragg curve. Lower proliferation capacity at the position on the distal fall-off than at the position close to the Bragg peak maximum could be attributed to fragmentation of ^{12}C ions and contribution of its secondary particles [9]. When comparing the effects of γ -rays with protons and ^{12}C ions at the position close to the Bragg peak maximum, γ -rays and protons have shown lower dose dependent proliferation level [10]. This difference is due to the lower LET values of γ -rays and protons, with respect to ^{12}C ions, that produce reparable damage to affected cells provoking lower proliferation activity. In the case of ^{12}C higher LET values cause more irreparable damages, thus giving higher level of proliferation activity belonging mainly to the proliferation of unaffected cells.

The number of apoptosis detected was in the range already reported for the same cell line exposed to protons and γ -rays [10], thus confirming high radioresistance. The dose dependent increase of apoptotic cells at the Bragg peak maximum could be attributed to a more severe damage induced by higher LET of carbon ions, leading to the induction of late apoptosis or necroses. Slightly different values of apoptosis detected in the positions at the plateau and at the distal fall-off of the Bragg peak, being somewhat higher in the second position, might be explained by contribution of fractioning of ^{12}C ions. Corresponding apoptotic index at 48 h after irradiation, time point chosen for evaluation of programmed cell death, clearly showed the ability of ^{12}C ions to eliminate resistant HTB140 cells to a certain extent by inducing apoptosis. Although the range of apoptosis is insignificantly different from those reported for protons [10], the effect of irradiation with ^{12}C ions at the position close to the Bragg peak maximum is more pronounced.

The analysis of cell cycle phase redistribution, performed at the position close to the Bragg peak maximum, has shown a significant number of cells in G1-S phase indicating high metabolic activity of irradiated melanoma cells. This was followed by the modest G2-M arrest. In both cases there was no dose dependence in the cellular response. When comparing obtained results with those reported for the same cell line after proton irradiation no significant difference was observed [10]. According to the values obtained for control cells, which were close, cell cycle phase redistribution was not influenced by the position in the cell cycle at the time of

irradiation. It appears that results obtained are mainly influenced by the specific feature of HTB140 cells, which is melanogenesis [11].

5 CONCLUSIONS

Radiobiological parameters, evaluated after irradiations with ^{12}C ions, have revealed high resistance of human HTB140 melanoma cells. Still, these parameters, due to higher LET of ^{12}C ions, have shown better effectiveness compared to protons. Significant cell inactivation was observed on the distal declining edge of the Bragg peak. At the same irradiation position proliferation capacity, reflecting in a sense the cell life quality, was lower than close to the Bragg peak maximum because of ^{12}C ion fragmentation, i.e., contribution of secondary particles. When receiving maximum dose, cells irradiated with γ -rays or protons, having lower LET, have shown lesser dose dependent proliferation than for ^{12}C ions. This is correlated to different quality of damage produced in irradiated cells. Level of apoptosis induced by ^{12}C ions as well as cell cycle redistribution confirmed radioresistant character of cells. They were also in agreement with the specific nature of analysed cells related to their metabolic activity.

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FLUX DYNAMICS IN HIGH-TEMPERATURE SUPERCONDUCTORS WITH MODULATED NANOSTRUCTURING

E. Mezzetti^{a,*}, A. Amato^b, R. Gerbaldo^a, G. Ghigo^a, L. Gozzelino^a, F. Laviano^a, B. Minetti^a, A. Rovelli^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

In this paper, we investigate the electrodynamical properties of $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ strip-shaped films, which were locally modified by confined heavy-ion irradiation. The irradiations were made by means of 4.2 GeV gold ions. Quantitative magneto-optical imaging as well as in-field transport characterizations show how the irradiated regions locally react to an external electromagnetic perturbation, thus allowing its localization and measurement. Aiming at future applications, the main issues about the detector sensitivity, such as the role of interfaces between irradiated and pristine regions, are addressed.

of the HEHI lithography and aimed at working in a radiation-hard environment. The magneto-optical imaging (MOI) is used both to measure the local electromagnetic parameters and to promote the choice of the best electrical and patterning solutions for engineering the would-be sensors [8]. The MOI technique allows one to directly visualize and to quantify the magnetic field distribution across the contiguous irradiated/not irradiated regions, over the whole sample. In this way, both local and nonlocal phenomena, occurring in inhomogeneous superconductors, are readily investigated.

1 INTRODUCTION

Confined irradiation [1]-[4] by means of monochromatic particle beams with much higher flux than the one reached in typical radiation-hard environments, can modify the electromagnetic properties of high- T_c superconductors (HTSCs) on the micron-scale. Such micron-scale modulated HTSCs exhibit contiguous regions whose electric state reacts to external perturbations (e.g., steady-state magnetic fields and photons) in a discontinuous way over the same period of the micron-scale structural modulation [2],[5]. The local dissipative signal occurring across such modulated regions, under electrical current transport, is useful for high sensitivity measurement and mapping of time-dependent external excitations.

Along this study, it has been demonstrated how the implantation, by means of heavy-ion irradiation, of amorphous columns with nanometer-size diameter allows one to actually modify the electrodynamical properties throughout all the volume of the superconducting film [6],[7]. The spatial distance of these columnar nanostructures is characterized by a very peaked distribution that is finely controlled through the ion beam fluence. Thus, an high-energy heavy-ion (HEHI) lithography [1] is obtained by means of a dedicated beam facility suitably engineered for the micron-scale confinement of the beam and its movement, with nanometric resolution, over the sample surface, i.e., the (X-Y) plane [3],[4].

In this paper, we indicate the road-map towards new magneto-resistive devices, which are produced by means

2 EXPERIMENTAL DETAILS, RESULTS AND DISCUSSION

2.1 Film Growth Details

Superconducting thin films of $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ (YBCO) were grown by thermal co-evaporation on yttria stabilized zirconia (YSZ) substrates, with a 40 nm thick CeO_2 buffer layer [9]. The thermal co-evaporation technique ensures c-axis oriented films with very homogeneous properties over large areas (several square centimeters). The critical current density for as-grown films sets over $3 \times 10^{11} \text{ Am}^{-2}$ at $T = 4.2 \text{ K}$, for the film thickness of 300 nm [9]. The YBCO films were patterned in strip-shaped samples (80 μm wide) by UV photolithography and wet-etching in $\text{HCl}/\text{H}_2\text{O}$ (0.3%) solution.

2.2 Irradiation Details

The HEHI irradiations were performed with 4.2 GeV gold ions at the Superconducting Cyclotron (CS) accelerator facility of INFN-LNS, Catania, Italy. Gold ions cross the superconducting YBCO film and the CeO_2 buffer layer, where they release an almost constant energy density of $35 \text{ MeV ion}^{-1} \mu\text{m}^{-1}$, thus producing well correlated columnar defects [11]. Afterwards they implant in the YSZ substrate, around a depth of 120 μm , as estimated by means of SRIM simulations [12]. Transmission Electron Microscopy measurements revealed that the Au ion impacts on YBCO film create insulating columnar nanostructures with a diameter of about 5 nm surrounded by a larger amorphous zone [7]. The ion beam was collimated through a microsize pinhole (70 μm) on the (X-Y) moving target (see [3],[4] and references therein).

2.3 Optical, Magneto-Optical and Surface Characterizations

The MOI tool is a real-time magnetic microscopy technique that is able to visualize the magnetic field distribution with sub-micrometric spatial resolution on arbitrary large surfaces. The transduction of the local magnetic signal into the optical one occurs due to the magneto-optical Faraday effect [13]. The sub-micrometric spatial resolution (around $0.4 \mu\text{m}$) is practically limited by the used light wavelength. Such resolution is adequate and then necessary to study the local electromagnetic properties, i.e., to detect any kind of inhomogeneity, both chemical and electromagnetic, and to distinguish between local and nonlocal interactions among the microscopic current loops taking place in inhomogeneous HTSC's [2]. The relevant issue coming from the measurement of the local magnetic field density concerns the study of shape dependent effects in order to control the flux density in tailored micron-scale modulations [4]. In the present context, the critical currents of the contiguous regions are also measured, at least in the region of the (B, T) phase diagram that is accessible to MOI. These results are further used to establish electrical parameters as well as to check the correlation between irradiation fluence and the in-field response of the micron-scale modulated HTSC, at the suitable temperatures.

In Fig. 1, optical and MOI measurements of a linear array of micron-scale modulated regions in an HTSC film, are shown. The array was modulated by different 4.2 GeV Au-ion irradiation fluences, ranging from 0.25×10^{12} to 1×10^{12} ions/cm².

In Fig. 2, a topographic image of the irradiated/not irradiated interface achieved in non-contact mode Atomic Force Microscopy (AFM), in correspondence of the zone n.1 in Fig. 1c1), is shown. While in the optical image (in Fig. 1a)), local changes of the substrate refraction index label the irradiated parts, the AFM measurement does not allow one to distinguish any topographic difference between the irradiated and the not irradiated regions. For sake of clarity, the boundary between irradiated and not irradiated parts of the sample is enclosed in the dashed rectangle of Fig. 2.

It is noticeable that for lower HEHI energy, i.e., 0.25 GeV Au ions [5], it was found a stress-induced step of about 20 nm at the interfaces between irradiated/not irradiated regions of the HTSC film surface. These latter findings are consistent with our present results because the structural stress induced on the sample surface by the HEHI irradiation is inversely proportional to the implantation depth of the ions in the substrate.

2.4 Transport Measurements

As it is well known, when a transport current is applied to a homogeneous superconductor in the flux-flow state, vortex energy overcomes the pinning potential of crystal defects. Thus moving vortices generate a transverse electric field detectable as a voltage drop along the transport current direction [14],[15]. In a superconductor where the condensation energy is depressed over a

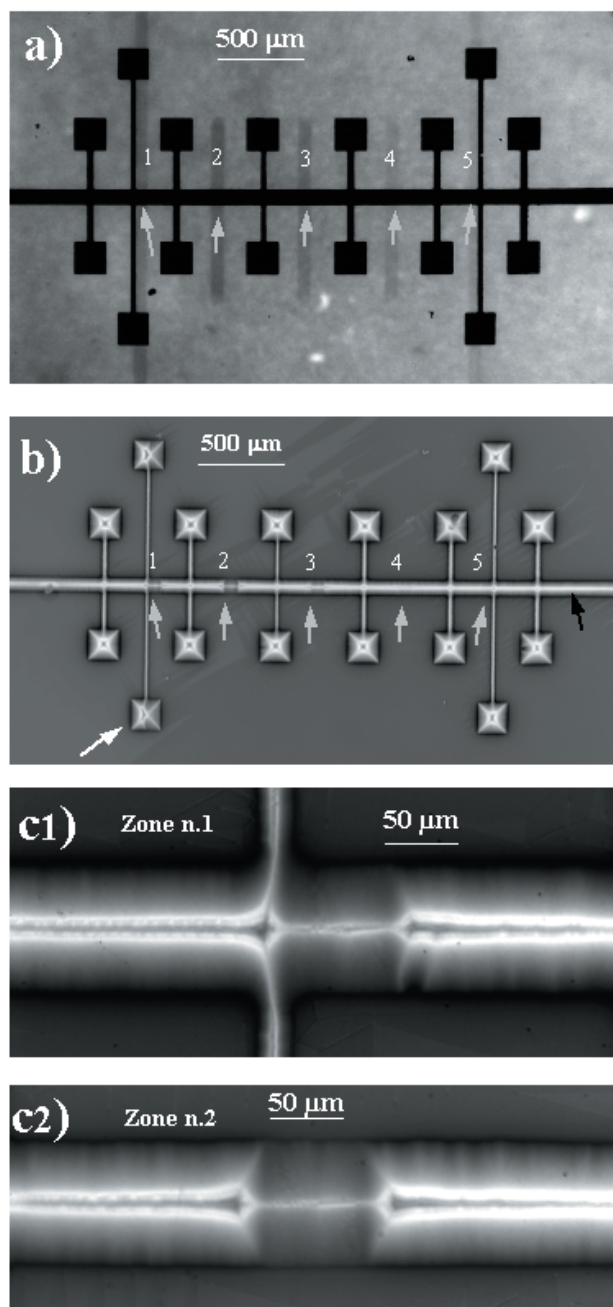


Fig. 1. (a) Optical image of a patterned sample with a linear array of micro-scale irradiated regions. Grey arrows and numbers indicate the irradiated regions which become magneto-resistive, with respect to the pristine ones, during electrical transport in magnetic field (HEHI energy: 4.2 GeV; irradiation fluences: 1×10^{12} ions/cm² (zone n. 1), 1×10^{12} ions/cm² (zone n. 2), 0.5×10^{12} ions/cm² (zone n. 3), 0.25×10^{12} ions/cm² (zone n.4), 0.25×10^{12} ions/cm² (zone n.5)). (b) MOI measurement of the same linear array taken at $T = 12$ K in remnant state (i.e., after the removal of the external magnetic field $B = 0.22$ T, applied perpendicular to the film plane). Bright regions inside the sample correspond to the regions where the trapped magnetic flux density is maximum (black arrow), dark zones around the samples correspond to negative stray-field (white arrow). (c) MOI frames of the zones n.1 (c1) and n.2 (c2), respectively, taken at $T = 20$ K in remnant state (after the removal of the external magnetic field $B = 0.18$ T applied perpendicular to the film plane).

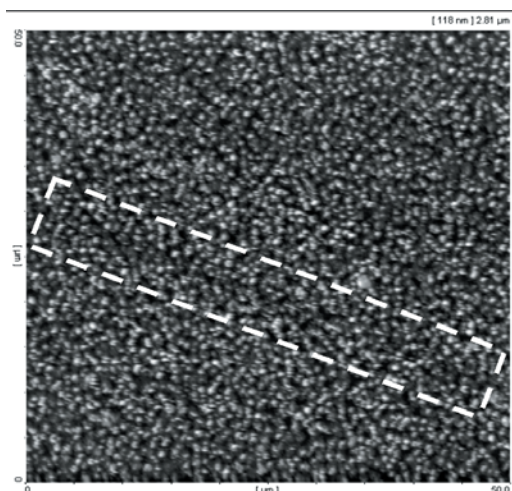


Fig. 2. AFM image (50 μm x 50 μm scan area) across the boundary between irradiated and pristine parts of the strip (zone 1 in Fig. 1). Such an interface corresponds to a slightly carved channel (width < 5 μm), enclosed inside the dashed rectangle.

micron-scale region due to the high density implantation of nanostructures, the electrical potential distribution is also tailored over the modulation length scale, because the flux flow state occurs in the damaged region much earlier than in the pristine ones. Therefore, under electric current transport, a sample with a micron-scale modulated region could be exploited for the magneto-resistive sensing of the external magnetic field.

The magneto-resistance characterization of the zone n.1 indicated in Fig. 1c1), was performed in the magnetic field range 0-0.7 T (Fig. 3 and Fig. 4). The nondissipative signal, picked up across the pristine region contiguous to the irradiated one, see Fig. 3, demonstrates the localization of the in-field dissipation inside the micron-scale modulated parts alone.

With respect to the magnitude of the magneto-resistive response, the ratio between the critical current density (J_c) of the pristine part and the J_c of the micron-scale modulated region has to be considered. The magnitude of the bias current (I_{bias}) has to be always negligible with respect to the weakest critical current, because the heating of the sample must be negligible too. On the contrary, higher I_{bias} means higher S/N ratio. The local J_c values, listed in Table I for several temperatures, were obtained by quantitative MOI measurements [17], both in the micron-scale irradiated region (zone n.1 of Fig. 1c2)) and in the pristine one. For $I_{\text{bias}} = 100 \mu\text{A}$ (corresponding to $J = 4 \text{ MA/m}^2 \ll J_c$), a good compromise between sensitivity and S/N ratio is obtained.

Another important issue to be addressed concerns the study of the detailed mechanism of dissipation occurring in the micron-scale modulated region, in order to exploit the magneto-resistive signal up to magnetic field as high as possible, while the pristine parts is still in a nondissipative state.

In the R vs. T curves of Fig. 4, a linear resistivity is always displayed by both the irradiated and the pristine regions near the normal state transition. The flux flow state in the bulk of the micron-scale modulated region

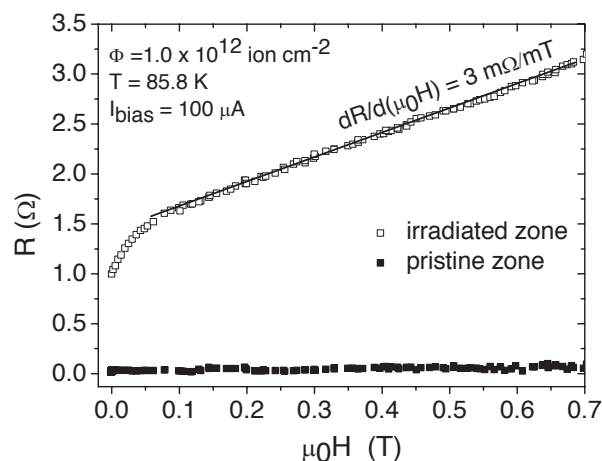


Fig. 3. Magneto-resistance response of the irradiated region (zone n.1 of Fig. 1; HEHI energy: 4.2 GeV; irradiation fluence: 1×10^{12} ions/cm²) (open symbols) and a pristine region (solid symbols).

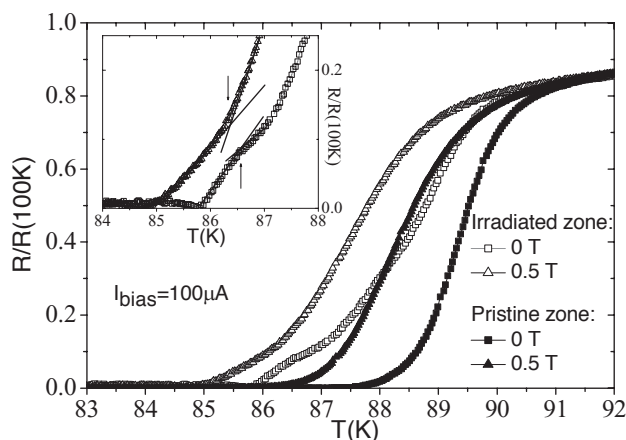


Fig. 4. Normalized resistance (vs. temperature) measurements of the irradiated region (zone n.1 of Fig. 1; HEHI energy: 4.2 GeV; irradiation fluence: 1×10^{12} ions/cm²) (open symbols) and a pristine region (solid symbols) at $B=0$ and $B=0.5$ T, respectively. Inset: zoom view of the resistance near the full superconductive transition.

covers a larger part in the (B , T) phase diagram with respect to the as-grown YBCO. In fact, the useful part of the (B , T) phase diagram, for the localization of the magneto-resistive signal in the micron-scale modulated region, must lay below the Irreversibility Field of the as-grown YBCO. Also the linear increase of the magneto-resistive signal in Fig. 3 accounts for the flux flow state of the micron-scale modulated region ($70 \times 80 \mu\text{m}^2$ area).

Thus, our approach can yield to an array of linear magneto-resistive sensing units with a spatial resolution of few tens of micron (here 70 μm).

Turning back to look at the initial nonlinear increase of the magneto-resistance in Fig. 3, it should be noted that, in such a range, the irradiated part displays higher sensitivity. This is also clear from the lower temperature part of the dissipative signal in the resistance curves in Fig. 4, because there is a second linear trend (indicated by the asymptotic lines in the inset of Fig. 4).

TABLE I
CRITICAL CURRENT DENSITY (J_c) VALUES OF THE PRISTINE REGION
AND THE IRRADIATED REGION FOR DIFFERENT TEMPERATURES.

T (K)	J_c (A/m ²) Pristine zone	J_c (A/m ²) Irradiated zone (zone n.2 of Fig. 1c2)).
4	$3.76 \cdot 10^{11}$	$1.91 \cdot 10^{11}$
20	$2.85 \cdot 10^{11}$	$1.56 \cdot 10^{11}$
30	$2.03 \cdot 10^{11}$	$1.12 \cdot 10^{11}$
50	$1.23 \cdot 10^{11}$	$6.49 \cdot 10^{10}$
70	$6.32 \cdot 10^{10}$	$3.43 \cdot 10^{10}$

The linear resistivity behavior corresponds to the dissipation state in the lowest J_c region, i.e., in the interface region between pristine and irradiated parts, where the magnetic flux is strongly confined and a ridge of the electric field distribution takes place [5],[14],[16],[18]. We note that the interface alone represents a downscaled magneto-resistive element [5], operating in the low-field range before both pristine and irradiated bulk regions start to dissipate during electrical transport in magnetic field.

3 CONCLUSIONS

The confined HEHI irradiation of HTSC strips by means of 4.2 GeV Au ions is a powerful tool to create micron-scale modulations that can be exploited to localize and to measure the external electromagnetic excitations, like a magnetic field. Such HEHI irradiation is indeed particularly suited for modulating the properties of HTSC, because the columnar nanostructure density can be finely controlled.

By means of MOI measurements, we provided the direct visualization of the tailored magnetic field pattern in such micron-scale modulated samples. Our approach leads to useful magneto-resistive elements embedded inside a nondissipative superconducting matrix.

By means of the electrical transport characterization, we discussed the main electrical constraints to be addressed to obtain the best performance. It turns out that the critical parameter is represented by the bias current for a given modulation strength of the electromagnetic properties.

We also discussed the role of the interfaces between pristine and modulated regions. We identified different working conditions of the would-be device, in order to exploit either the interface or the bulk properties of the micron-scale modulated region, while the localization of the dissipative signal is preserved.

It can be concluded that HTSC magnetic field detectors are suited for radiation-hard environments. Our approach can be further engineered to measure fast transients of the magnetic field with high spatial resolution.

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THE LANDIS ARCHAEOMETRIC PROGRAM OF OBSIDIAN CHARACTERIZATION TO ESTABLISH TRADE ROUTES IN THE PREHISTORY OF SICILY

G. Pappalardo^{1,2}, A. Massimino², L. Pappalardo^{2,3}, F. Rizzo^{1,2}, F.P. Romano^{2,3}

1. Dipartimento di Fisica e Astronomia, Università di Catania, Via S. Sofia 64, 95123 Catania

2. LANDIS, Laboratori Nazionali del Sud, INFN, Via S. Sofia 64, 95123 Catania

3. IBAM, Consiglio Nazionale delle Ricerche, Via A. Sangiuliano 62, 95100 Catania

Abstract

A program concerning the systematic study of obsidian from prehistoric Sicilian sites is presented.

Provenance determinations are established making use of the new instruments and methods realized by the LANDIS/LNS Laboratory.

Preliminary data on possible trade routes are presented.

INTRODUCTION

The obsidian is a vitreous material obtained by the volcanic rocks rich in Si [1]. This material has been largely used in the prehistoric times for its hardness and the ease to obtain cutting edges. A variety of tools (mainly blades, arrows), has been realised on times from Palaeolithic to the Bronze Age. Also enamels have been produced using the obsidian: the mask's eyes of Tutankhamon are made of obsidian [2].

In the Mediterranean few volcanic quarries exists: Lipari; Sardinia, Pantelleria and Palmarola. The various obsidians quarries have distinguishable chemistry both in the major and in some characterizing trace-elements (Rb,Sr,Y,Zr,Nb): this because the above elements are strictly related to the magma differentiation processes [3,4]. So, by measuring these elements in the obsidian tools it is possible to identify the production quarry of the bulk material.

Trade routes have been established by the measurements of the chemical elements. In the last decades a lot of work has been done and a map of the Mediterranean traffic has been suggested [5,6].

However, few data exist for the Sicily even if the presence of ancient people is established in the prehistoric times from Palaeolithic to Bronze age through Neolithic, Copper age [7].

The LANDIS laboratory has developed a method for non destructive quantitative determination of the above trace-elements by using the XRF (X-ray Fluorescence) mechanism. Radioactive X-ray sources [8,9] and, more recently, X-ray tubes with stability control [10] which the acquisition software developed at the LNS laboratory [11] have been used to obtain characteristic X-ray spectra. A

method based on the biparametric regression analysis [12, 9] has allowed to extract quantitative data.

A first analysis of an obsidian tool from Poggio Monaco - Paternò Ct (9) has established its provenance from Lipari island.

In the present work we describe a scientific program aimed to characterize, in a systematic way, the obsidians found in the excavations of prehistoric archaeological sites of Sicily.

Collaborations have been established with: the Soprintendenza ai BB.CC.AA. of Palermo; the Soprintendenza ai BB.CC.AA. of Caltanissetta; the Soprintendenza ai BB.CC.AA. of Catania; the Dipartimento S.A.Fi.St of the Catania University.

An agreement has been signed with the IBAM/CNR institute and with the Department of Physics and Astronomy of Catania University.

RESULTS

The research program started with the analysis in situ of 57 obsidians from Milena territory [13]; about 100 obsidians have been examined during two missions at Ustica [14]; more recently a series of measurements have been carried out on obsidians from Rocchicella (Mineo,CT) [15]; measurements are in progress on obsidian tools from the Neolithic site of Licodia Eubea (CT) (about 700 tools), S. Marco (Paternò, CT) and Poggio dell'Aquila.

Table 1 shows the sites and the archaeological periods of the present study.

SITE	PERIOD	N° OF ANALIZED SAMPLES
Milena (CL): Serra del Palco Mandria Fontanazza-Monte Grande Mezzebbi, Rocca dell'aquila. [Ref.13]	Copper age Neolithic	57
Ustica (PA): Villaggio dei Faraglioni [Ref.14]	Bronze age	95
Rocchicella (Mineo, CT) [Ref.15]	Neolithic Copper age Paleo- Mesolithic	53
Licodia Eubea (CT) [Ref.16]	Neolithic	691 *
Poggio dell'Aquila (CT) [Ref.17]	Copper age	48*
S. Marco (Paternò, CT) [Ref.18]	Neolithic	386*

Table 1. The obsidian samples of the present work
(* analysis are in progress).

Fig. 1 shows the archaeological sites

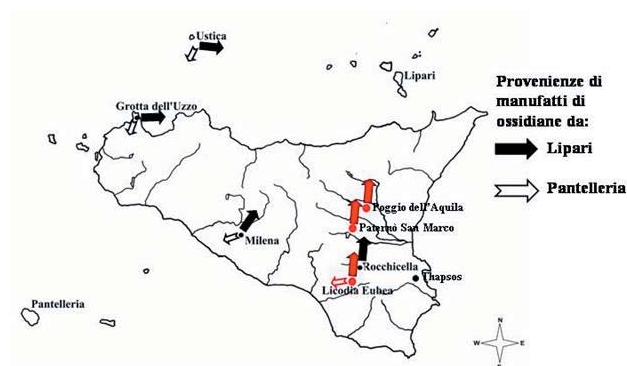


Fig. 1. The sites interested by the present analysis. Qualitative indication of the obsidians provenance are given.

CONCLUSION

The preliminary analysis suggests that the obsidians come essentially from Lipari and, at a less extent, from Pantelleria. (see also ref.19).

The ages range from Paleo-Mesolithic to bronze age.

Work is in progress to complete the present research program to extend it to other sites of Sicily and to perform the necessary typologic and archaeological analysis.

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ANALYSIS PIXE- α OF THE BLACK PIGMENTS OF CERAMICS FROM KAULONIA, A “MAGNA GRECIA” COLONY.

L.Pappalardo^{a,b,*}, V. Gagliardi^c, G. Pappalardo^{a,d}, F. Rizzo^{a,d}, F.P. Romano^{a,b}

a) Laboratori Nazionali del Sud, INFN, Catania

b) Istituto per i Beni Archeologici e Monumentali, CNR, Catania

c) Università di Pisa

d) Dipartimento di Fisica e Astronomia, Università di Catania

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

Abstract

During the excavation of the Kaulonia (a Greek colony near the Monasterace – Reggio Calabria – village) more than 1000 artefacts have been found whose study is in progress. Particular attention has been devoted to the black decoration present in the artefacts.

Morphological study and technical characteristics have allowed to classify the material in at least 4 groups corresponding to different provenance sites and workshops.

A quantitative non destructive analysis of the black pigments has been undertaken at LNS with the aims of evidence the difference on the chemical composition and consequently to individuate the provenance. Preliminary results are presented.

1 THE PIXE – α SPECTROMETER

PIXE (Particle Induced X-ray Fluorescence) is a non destructive method particularly suited for pigment analysis due to the well defined analytical depth. (5-10 μm for low energy particles). Quantitative analysis is allowed.

A portable spectrometer (PIXE- α) has been realized at the LNS laboratory of INFN; the spectrometer makes use of a ^{210}Po radioactive source as charge particles emitter [1]. To test the performance of the above spectrometer, in Table 1 the quantitative PIXE- α analysis on a black pigment of an original attic artefact is shown compared with typical values known for attic ceramics [2].

2 KAULONIA FRAGMENTS STUDY

25 ceramic sherds belonging to Kaulonia site have been analysed by means of the LNS PIXE- α . The aim is to individuate the differences in the chemical composition of the sherds black pigment in order to attribute the artefacts to different workshops.

Preliminary conclusions are reported:

A) The general chemical composition of the Kaulonia sherds black pigments suggests the use of the known technology of the “iron reduction” i.e. the firing in a

reducing atmosphere of a coating of fine clay rich on Al, Fe and K.

B) Large variations occurs: K_2O concentrations range from 1.2% to 8.1%; FeO from 10% to 22%; Al_2O_3 from 24% to 31%; SiO_2 from 30% to 45%.

As an example in Fig. 1 the X-ray spectra from VAN3 and VAN14 fragments are compared with a spectrum taken on an original attic fragment. The spectra are very similar suggesting the attic provenance of (VAN3 and VAN14), or, alternatively, the use of the “attic” recipe by the local workers.

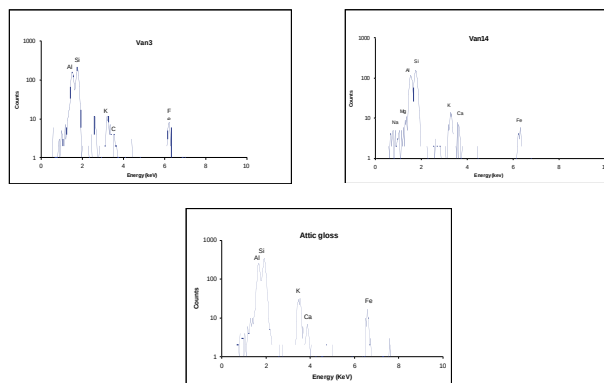


Fig. 1 – In Fig. 1 the PIXE-alpha energy spectra of VAN3 and VAN14 sherds compared with an attic pigment one.

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	MgO	Al ₂ O ₃	SiO ₂	K ₂ O	CaO	Fe ₂ O ₃ tot
ATT-1	1,9	31,7	46,8	4,1	0,9	13,5
ATT-2	1,8	31	46,7	5,5	0,3	13,1
ATT-3	2,2	29,8	43,4	6,1	0,9	15,4
ATT-4	1,9	19,2	45,6	4,7	0,6	15,3
ATT-5	1,9	30,9	45,3	6,5	n.d.	14,8
ATT-6	1,6	32,4	45,8	3	0,3	15,5
ATT-7	2 (1,5)	29 (2)	42(2)	3,3(0,2)	0,45(0,2)	13(1)

Table 1 – The quantitative results of PIXE- α non destructive measurements on an attic black pigment (ATT-7) compared with destructive results taken on attic sherds of various provenance.

THE NEW VERSION OF THE PORTABLE XRD SYSTEM OF THE LANDIS LABORATORY AND ITS APPLICATION FOR THE NON-DESTRUCTIVE CHARACTERISATION OF PIGMENTS IN ANCIENT ROMAN FRESCOES

F.P. Romano^{a,b,*}, G. Pappalardo^{b,c}, L. Pappalardo^{a,b}, F. Rizzo^{b,c}

a) CNR, Istituto per i Beni Archeologici e Monumentali, Catania, Italy

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

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

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

+ In press in Nuovo Cimento C

Abstract

A new version of the portable XRD system of the LANDIS laboratory of Catania is presented. The previous apparatus, a commercial portable diffractometer, was equipped with a new x-ray source realized by using a low power microfocus tube coupled to a polycapillary semi-lens optics. The new experimental set-up allowed to improve the angular resolution and to increase the intensity of peaks in the diffractograms respect with those measured with the previous version of the system. Finally, the application of the diffractometer for the non-destructive characterization of pigments present in some fragments of ancient Roman frescoes is discussed.

1 INTRODUCTION

It is well known that the XRD technique is successfully applied for the mineralogical characterization of materials in the Cultural Heritage field. Many studies have been performed in order to identify the pigments (or the mixtures of pigments) of ancient frescoes and wall paintings [1]; to obtain information on the clay pastes used to manufacture ancient potteries, to determine their cooking temperature and to characterize the pigments used for their colored decorations [2-3]; to study the nature of the corrosion patinas in ancient metallic objects [4-5].

Generally the XRD technique is applied with non-transportable instruments limiting its field of application only to small dimensions objects or requiring a destructive sampling (even if limited to few milligrams of material) in order to analyze artifacts that can not be transferred at the laboratories of analysis.

Recently many efforts have been dedicated to the development of portable systems even if with limited performance in terms of angular resolution and/or measurements time [6-7].

A commercial portable XRD system realized by the Italian ASSING company was previously installed at the LANDIS laboratory of the LNS/INFN of Catania for in-situ applications in the Cultural Heritage field. The system, based on a goniometric μ - μ geometry, was equipped with a Fe anode x-ray tube as source and with a Peltier cooled Si-PIN detector for collecting the x-rays diffracted by the samples under investigation. The ASSING XRD system presents some important analytical

capabilities: the sample can be positioned outside the goniometric circle allowing its use for non-destructive measurements of non-movable artifacts (for examples wall paintings or frescoes); it allows the simultaneous XRD and XRF measurements on the same area of the sample; the selection of the x-rays energy used to perform the diffraction on the samples is obtained by a digital filter that operates in the MCA analyzer of the detector; finally it presents compact dimensions and low weight and it is easily transportable in-situ.

However the commercial system evidenced some analytical limitations: it is necessary to operate long time measurements (about 3 hours) to have sufficient statistics in the collected diffractograms and it presents a low angular resolution reducing the capabilities to resolve peaks with similar diffraction angles.

Nevertheless the ASSING system was applied by the LANDIS laboratory for the non-destructive characterization of pigments present in ancient Roman frescoes [8] and for the in-situ characterization of the wall paintings at the Nestor Palace in Pylos (Greece) [9].

This paper presents the upgrade of the ASSING version of the XRD system operated by the LANDIS group. As described in the next section a new x-ray source, based on a low power microfocus tube coupled with a polycapillary optics, has been studied and installed on the diffractometer. In fact the recent development of such modular components for x-ray analysis enabled the possibility to use parallel x-ray beams of high intensity for XRD or micro-XRD investigations [10]. The improvements of the new experimental set-up of the system respect with the previous commercial version are also discussed.

Finally, the application of the diffractometer for the non-destructive mineralogical characterization of pigments present in some fragments of ancient Roman frescoes is shown.

2 THE NEW VERSION OF THE PORTABLE XRD SYSTEM OF THE LANDIS LABORATORY

The commercial version of the XRD system was upgraded by using a new x-ray source realised by the German IFG company. It consists of a 10 W microfocus x-ray tube with a Fe anode coupled to a polycapillary semi-lens optics. The use of the polycapillary optics allows to capture the most of the x-rays intensity produced in the 50 μm focal spot size of the tube Fe anode and, due to the semi-lens geometry, to obtain a parallel x-ray beam with a small divergence (only 0.26°) at the output of the source. The final beam spot size is 600 μm diameter. Additionally, in order to define the dimensions of the investigated area at the sample position (about 20 cm from the source and the detector), both the x-ray source and the Si-PIN detector are collimated by two slits with 1 mm aperture. The new experimental set-up of the XRD system was tested by performing measurements on a calcite standard. Results were compared with those obtained by using the previous version of the system operating at the same conditions (see Fig.1); diffractograms were collected in the angular range from 12° to 67° with a steps size of 0.05° and acquisition time/step of 5 seconds.

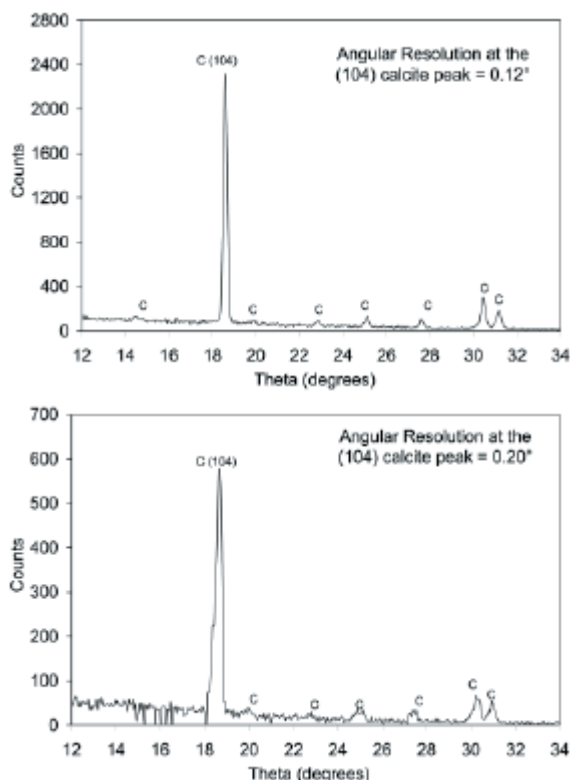


Fig. 1. The comparison of the calcite spectrum obtained with the new version of the XRD system (a) and the one measured with the previous version (b). Improvements in terms of angular resolution and intensity are evident.

The measured angular resolution at the (104) peak of calcite ($I\% = 100$) at $\theta = 18.62^\circ$ was respectively 0.12° and 0.20° for measurements performed with the new version of the system respect with the old one. The estimated improvement is about the 40%. Moreover the maximum intensity of the (104) calcite peak obtained with the new set-up was 4-5 times higher than the previous one, allowing to operate shorter measurements to obtain the same statistics in the diffractograms. Finally, the possibility to operate with a very high beam intensity was explored by enlarging the slit aperture of the x-ray source. Figure 2 shows the diffractogram obtained from the calcite standard; the intensity of the (104) peak is about a factor 10 higher respect with the one obtained with previous version of the system and the measured angular resolution is about the same.

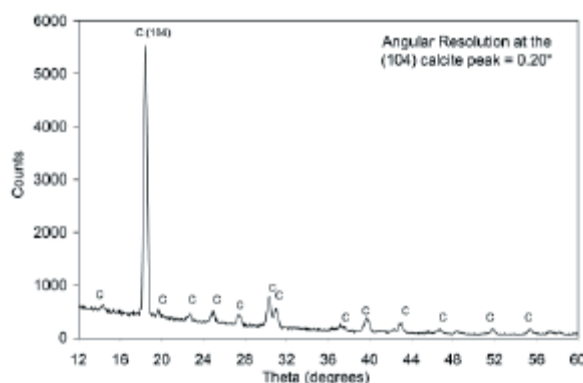


Fig. 2. Measurements of the calcite by using a 2 mm aperture slit to collimate the x-ray source. In this case angular resolution is about the same of that obtained with the commercial version of the system but the intensity of the (104) peak of calcite is about a factor 10 higher

3 THE NEW VERSION OF THE PORTABLE XRD SYSTEM OF THE LANDIS LABORATORY

The new XRD system of the LANDIS laboratory was applied in the non-destructive mineralogical characterization of pigments in some fragments of Roman frescoes excavated at the site of Monastero dei Benedettini in Catania by the Soprintendenza ai BBCCAA [9]. In particular a red pigment (sample AFF2), a red/brown pigment (sample AFF15) and a yellow pigment (sample AFF5) have been analyzed as first test of the system. Figure 3 shows the results obtained from sample AFF2 and AFF15. It is evident how the use of the system allows an accurate identification of the red hues of color; the samples labeled AFF2 was identified as cinnabar (Fig.3a) while, due to the presence of hematite, the sample labeled AFF15 was identified as a red ochre (Fig.3b). Finally, Fig.4 shows the diffractogram obtained by measuring the yellow pigment; the presence of the diffracted peaks of

goethite, quartz and kaolinite suggests the use of a yellow ochre.

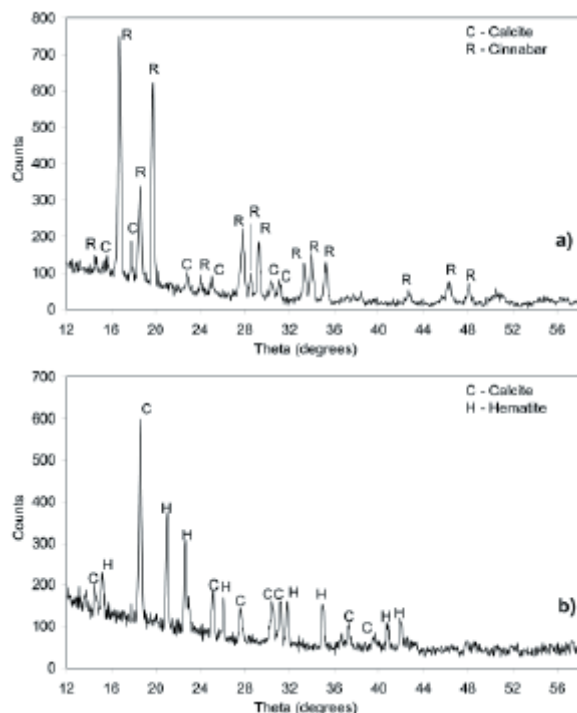


Fig. 3. The diffraction spectra of the red pigment of sample AFF2 (a) and the red/brown pigment of samples AFF15 (b). It is evident the use of cinnabar in AFF2 and of a red ochre in sample AFF15

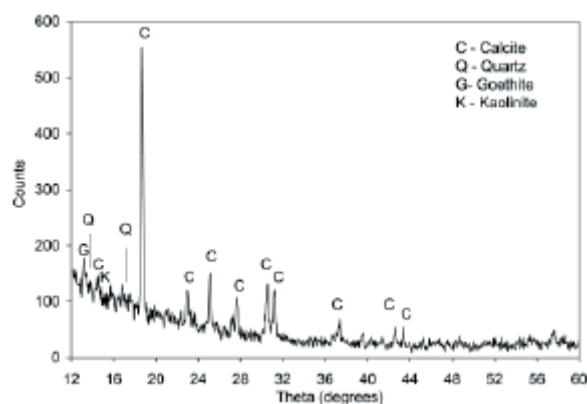


Fig. 4. The diffraction patterns of the yellow pigment in sample AFF5. The presence of goethite, quartz and kaolinite suggest the use of a yellow ochre

CONCLUSION

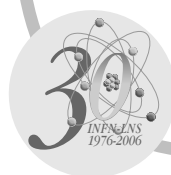
A new version of the portable XRD system of the LANDIS laboratory of Catania is presented. The previous commercial version was upgraded by a new x-ray source consisting of a low power microfocus x-ray tube coupled to a polycapillary semi-lens optics. The use of this source allows to operate with a quasi-parallel beam of high intensity. The preliminary test of the new set-up of the

system evidenced an improvement of about the 40% in the angular resolution and a factor 4-5 in the intensity of the peaks collected in the diffractograms. Also, the possibility to operate with very high intensity was explored by enlarging the slit aperture at the source exit; the intensity of the peaks obtained by measuring a calcite standard was about 10 times than the one measured by the previous apparatus. These improvements will allow a more efficient identification of the mineralogical phases present in the diffractograms in shorter measurement time. Finally, as first application of the new system a non-destructive mineralogical characterization of pigments in some Roman frescoes has been performed.

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| 2. DI ROSA Francesco | 5. PITTERA Salvatore |
| 3. MARINO Carmelo | 6. RUSSO Giorgio |

Personnel of other Institutions

- | | |
|--------------------------|----------------------------|
| 1. ANDO' Lucio | 11. MUSUMECI Francesco |
| 2. BARBARINO Sebastiano | 12. PAPPALARDO Ligneia |
| 3. CAPPUZZELLO Francesco | 13. PATTI Jolanda Valeria |
| 4. CATALIOTTI Francesco | 14. PAVAN Giovanni |
| 5. CHERUBINI Silvio | 15. RAFFAELE Luigi |
| 6. GUARINO Pietro | 16. ROMANO Francesco Paolo |
| 7. FICHERA Gabriele | 17. ROMANO Stefano |
| 8. FOSSATI Fabio | 18. SABINI Maria Gabriella |
| 9. MANCIAGLI Sebastiano | 19. SCORDINO Agata |
| 10. MUSUMARRA Agatino | 20. SORBELLO Gino |

Undergraduated Students

- | | |
|----------------------|------------------------|
| 1. CALANNA Ausilia | 10. PUGLIA Sebastiana |
| 2. CAMPO Daniela | 11. PUGLISI Donatella |
| 3. FAVETTA Marco | 12. RANDISI Giacomo |
| 4. FISICHELLA Maria | 13. RAPISARDA Giuseppe |
| 5. GASPARINI Luciano | 14. ROMANO Francesco |
| 6. LOMBARDO Ivano | 15. RIZZO Carmelo |
| 7. MAGGIO Angelo | 16. SACCONI Sergio |
| 8. MARINO Denis | 17. SCUDERI Alfio |
| 9. POLITI Giacomo | 18. STRANO Emanuele |

Scientific Guest

- | | |
|--|---|
| 1. ALVES-CONDE' Robert | Ganil, Caen - France |
| 2. BARAN Virgil | Dept. of Theoretical Physics, University of Bucharest - Romania |
| 3. BASRAK Zoran | Rudjer Boskovic Institute, Zagreb - Croatia |
| 4. BLICHARSKA Joanna | University of Silesia, Katowice - Poland |
| 5. BRENNER Marten Withmar | |
| 6. BARBOSA Marcel | IFUSP, São Paulo - Brasil |
| 7. BONNET Eric | IPN, Orsay - France |
| 8. BORELLO Lewin Thereza | IFUSP, São Paulo - Brasil |
| 9. BURJAN Vaclav | INP, Prague, Rez. - Czech Republic |
| 10. CERDONIO Massimo | INFN Padova - Italy |
| 11. CHATTERJEE Mihir Baran | Soha Inst. of Nuclear Physics, Kolkata - India |
| 12. DE LUCA Massimo | Università di Messina - Italy |
| 13. DESIATI Paolo | University of Wisconsin, Madison - USA |
| 14. DOBRESCU Serban | University of Bucharest - Romania |
| 15. FAN Hongmei | China inst.of atomic energy, Beijing - China |
| 16. FAN Hongsheng | China inst.of atomic energy, Beijing - China |
| 17. FILIPPOV Alexander | Joint Institute for Nuclear Research, Moscow - Russia |
| 18. GAUBERT Gabriel, Philippe, Nicolas, Michel | Ganil, Caen - Francia |
| 19. GORYUNOV Oleg | Inst.for Nuclear Research-Prospect Nauki - Ukraine |
| 20. GRZESZCZUK Andrzej | Universtisy of Silesia, Katowice - Poland |
| 21. GUINET Daniel | IPN, Lyon - France |
| 22. GUO Xiaohong | China inst.of atomic energy, Beijing - China |
| 23. GEISSEL Hans | GSI, Darmstadt - Germany |
| 24. GAITANOS Theodoros | Physics dep. University of Munich - Germany |
| 25. HAMMACHE Fairouz | IPN, Orsay - France |
| 26. INGUANTI Roberto | EGA Master |
| 27. JADU De | Saha Institute, Calcutta-India |
| 28. JEFFERY Wyss | University of Cassino - Italy |
| 29. KARIDAS Andreas-Germanos | Inst.of Nuclear Physics "Demokritos" - Greece |
| 30. KHLIBNIKOV Sergev | |
| 31. KIMURA Sachie | Physics Dept.Tohoku Universisty, Senday - Japan |
| 32. KISS | |
| 33. KOWALSKI Seweryn Cezary | University of Silesia, Katowice - Poland |
| 34. KRASA Josef | I-ASCR, Prague - Czech Republic |
| 35. KOIVISTO Hannu | Department of Physics,University of Jyvaskyla, Finland |
| 36. KUZNETSOV Viacheslav | INR, Moscow - Russia |
| 37. LAPIK Alexander | Institute of Nuclear Research, Moscow - Russia |
| 38. LARIONOV Alexei | St. Petersburg - Russia |
| 39. LE NEINDRE Nicolas | IN2P3-CNRS, Orsay - France |
| 40. LEJEUNE André Camille Ghislain | Inst.of Phisics, Liege - Belgium |
| 41. LEUNG Ka-Ngo | LBNL, Berkeley, California - USA |
| 42. LI Chen Bo | |
| 43. LI Xia | Inst.of atomic energy, Beijing - China |
| 44. LIU Bo | Chinainstitute of High Energy Physics, Beijing - China |
| 45. LALAZISSIS G. | University of Thessaloniki - Greece |
| 46. LI Zenghua | |
| 47. LIECHTENTHÄLER R. | Institute of Physics, University of São Paulo - Brazil |
| 48. LIVADARU Matilda Gabriela | |
| 49. LYAPIN Vladimir | University of Jyvaskyla - Finland |
| 50. LASKA Leos | I-ASCR, Prague - Czech Republic |
| 51. LOPEZ Olivier | |
| 52. MANGIONE A. | University of Messina and INFN - Italy |
| 53. MA Zhongyu | |
| 54. MAIDIKOV Vasyil | Jagiellonican University, Krakow - Poland |
| 55. MAJKA Zbigniew | JINR, Dubna - Russia |
| 56. MIKHAYLOVA Tatiana | |
| 57. MILJANIC Djuro | |
| 58. MILIN Matko | Rudjer Boskovic Institute, Zagreb - Croatia |
| 59. MUSENICH Riccardo | INFN, Sezione di Genova - Italy |

60. NIGGLI Hugo
 61. NIKOLAOS Nicolis
 62. NATOWITZ Joseph Bernard
 63. NOVOSEL Ivan
 64. OSTASHKO Volodymir
 65. OTTEVAERE Heidi
 66. PETRASCU Horia
 67. PFEIFER Miroslav
 68. PIASECKI Ernest
 69. PLANETA Roman
 70. PENG Guangxiong
 71. PETROVIC Ivan
 72. PICCIOTTO A.
 73. PRASSA Vaia
 74. PECELI Davorin
 75. POP Amalia
 76. RISTIC-FIRA Aexandra
 77. RODRIGUES Marcia Regina Dias
 78. RODRIGUEZ Gonzalo Sebastian
 79. SAMMADAR Santosh
 80. SCHACHTER Leon
 81. SCHUCK Peter
 82. SHEN Caiwan
 83. SIEMSEN Rudolf Hendrik
 84. SPADTKE Peter
 85. STIEBING Berward
 86. SWIDERSKI Eukasz
 87. SCHMIDT Katarzyna
 88. SCHROEDER Wolf Udo
 89. SKORODUMOV Boris
 90. SKWIRA-CHALOT Izabela
 91. SOULIOUTIS G.
 92. SOMORJAI Endre
 93. SUI Li
 94. SURA Jozef
 95. THIENPONT Hugo
 96. TIAN Wendong
 97. TRZASKA Wladislaw
 98. TUREA Aurelia
 99. TAKIGAWA Noboru
 100. TAN Zhiguang
 101. TOKE Jan
 102. TOKI H.
 103. TYPEL Stefan
 104. VERMA Shashi
 105. VISSAMI Francesco
 106. VAN GIAI Nguyen
 107. WIELECZKO Joan Pior
 108. WILCZYLSKI Sanusz A.
 109. WILCZYNSKA Siwek
 110. WOLTER Hermann Heinrich Hans Berthold
 111. WEISSER David C.
 112. YILDIRIM Gerbulent
 113. YIN Zhiguo
 114. ZADRO Mile
 115. ZIPPER Wiktor
 116. ZUO Wei
 117. ZHOU Daimei
 118. ZHANG Xin
 119. ZHANG Xuezheng
 120. ZIELINSKA - PFABE Malgorzata
- Texas A & M University - USA
Rudier Boskovic Institute, Zagreb - Croatia
Inst. for Nuclear Research-Prospect Nauki, Kiev - Ukraina
- NIPNE, Bucharest - Romania
I-ASCR - Czech Republic
University of Warsaw - Poland
Jagiellonian University, Krakow - Poland
China inst. of high energy physics, Beijing - China
VINCA Institute of Nuclear Sciences - Serbia E Montenegro
University of Messina and INFN - Italy
University of Thessaloniki - Greece
- IPNE, Bucharest - Romania
VINCA Institute of Nuclear Sciences - Serbia and Montenegro
IFUSP, São Paulo - Brasil
- Saha Institute, Calcutta - India
Inst. of Physics and Nucl. Engin, Bucharest - Romania
IPN Orsay - France
- KVI, Amsterdam - Holland
GSI, Darmstadt - Germany
- University Of Silesia, Katowice - Poland
Univ. Of Rochester - Rochester, NY - USA
University of Notre Dame, Indiana - USA
University of Hamernicka - Poland
A&M - Texas - USA
ATOMKI, Debrecen - Hungary
- Heavy Ion Laboratory - University of Warsaw - POLONIA
- Central China Normal University, Wuhan - China
University of Rochester - USA
Osaka University - Japan
GSI, Darmstadt - Germany
IUAC, University of Delhi - India
INFN-LNGS - Italy
IPN, Orsay - France
- Soltan Institute for Nuclear Studies, Swierk/Warsaw - Poland
- University of Munchen - Germany
Australian National University Canberra - Australia
- Institute "R. Boskovic", Zagabria - Croatia
University of Silesia, Katowice - Poland
Institute of Modern Physics, Lanzhou - China
Physics Dept., Beijing - China
- IMP, Chinese Academy of Sciences, Lanzhou - China
Smith College Northampton - USA

Journal Articles

This appendix lists journal articles describing work performed at LNS and also work conducted elsewhere by LNS personnel

W. Przygoda, C. Agakishiev, C. Agodi, H. Alvarez-Pol, A. Balanda, R. Bassini, G. Bellia, D. Belver, J. Bielcik, A. Blanco, M. Bohmer, C. Boiano, A. Bortolotti, J. Boyard, S. Brambilla, P. Braun- Munzinger, P. Cabanelas, S. Chernenko, T. Christ, R. Coniglione, M. Dahlinger, J. Diaz, R. Djeridi, F. Dohrmann, I. Duran, T. Eberl, W. Enghardt, L. Fabbietti, O. Fateev, P. Finocchiaro, P. Fonte, J. Friese, I. Frohlich, J. Garzon, R. Gernhauser, M. Golubeva, D. Gonzalez-Diaz, E. Grosse, F. Guber, T. Heinz, T. Hennino, S. Hlavac, J. Hoffmann, R. Holzmann, A. Ierusalimov, I. Iori, A. Ivashkin, M. Jaskula, M. Jurkovic, M. Kajetanowicz, B. Kampf, K. Kanaki, T. Karavicheva, D. Kirschner, I. Konig, W. Konig, B. Kolb, U. Kopf, R. Kotte, J. Kotulic-Bunta, R. Krucken, A. Kugler, W. Kuhn, R. Kulessa, S. Lang, J. Lehnert, L. Maier, P. Maier-Komor, C. Maiolino, J. Marin, J. Markert, V. Metag, N. Montes, E. Moriniere, J. Mousa, M. Munch, C. Muntz, L. Naumann, R. Novotny, J. Novotny, W. Ott, J. Otwinowski, Y. Pachmayer, T. Perez, V. Pechenov, J. Pietraszko, J. Pinhao, R. Pleskac, V. Pospisil, A. Pullia, N. Rabin, B. Ramstein, S. Riboldi, J. Ritman, P. Rosier, M. Roy-Stephan, A. Rustamov, A. Sadovsky, B. Sailer, P. Salabura, P. Sapienza, A. Schmah, W. Schon, C. Schroeder, E. Schwab, P. Senger, R. Simon, V. Smolyankin, L. Smykov, S. Spataro, B. Spruck, H. Strobele, J. Stroth, C. Sturm, M. Sudol, V. Tiflov, P. Tlusty, A. Toia, M. Traxler, H. Tsertos, I. Turzo, V. Wagner, W. Walus, C. Willmott, S. Winkler, M. Wisniewski, T. Wojcik, J. Wustefeld, Y. Zanevsky, P. Zumbach and HADES Collaboration

HADES experiment: Di-lepton spectroscopy in $p+p$ (2.2 GeV) and $C+C$ (1 and 2 A GeV) collisions

Acta Physica Polonica B 37 (1): 139-151

R. Planeta, F. Amorini, A. Anzalone, L. Auditore, V. Baran, I. Berceanu, J. Blicharska, J. Brzychczyk, B. Borderie, R. Bougault, M. Bruno, G. Cardella, S. Cavallaro, M.B. Chatterjee, A. Chbihi, M. Colonna, M. D'Agostino, E. De Filippo, R. Dayras, M. Di Toro, J. Frankland, E. Galichet, W. Gawlikowicz, E. Geraci, F. Giustolisi, A. Grzeszczuk, P. Guazzoni, D. Guinet, M. Iacono-Manno, S. Kowalski, E. La Guidara, G. Lanza, G. Lanzaone, J. Lukasik, C. Maiolino, Z. Majka, N. Le Neindre, N.G. Nicolis, A. Pagano, M. Papa, M. Petrovici, E. Piasecki, S. Pirrone, G. Politi, A. Pop, F. Porto, M.F. Rivet, E. Rosato, F. Rizzo, S. Russo, P. Russotto, M. Sassiv, K. Schmidt, K. Siwek-Wilczynska, I. Skwira-Chalot, A. Sochocka, M.L. Sperduto, L. Swiderski, A. Trifiro, M. Trimarchi, G. Vannini, Verde, M. Vigilante, J.P. Wieleczko, J. Wilczynski, L. Zetta, W. Zipper

Isospin effects studied with the chimera detector at 35 MeV/nucleon

Acta Physica Polonica B 37 (1): 183-191

E. De Filippo, F. Amorini, A. Anzalone, L. Auditore, V. Baran, I. Berceanu, J. Blicharska, J. Brzychczyk, B. Borderie, R. Bougault, M. Bruno, G. Cardella, S. Cavallaro, M.B. Chatterjee, A. Chbihi, M. Colonna, M. D'Agostino, R. Dayras, M. Di Toro, J. Frankland, E. Galichet, W. Gawlikowicz, E. Geraci, F. Giustolisi, A. Grzeszczuk, P. Guazzoni, D. Guinet, M. Iacono-Manno, S. Kowalski, E. La Guidara, G. Lanzaone, G. Lanzaone, C. Maiolino, Z. Majka, N. Le Neindre, A. Pagano, 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, K. Schmidt, K. Siwek-Wilczynska, I. Skwira, M.L. Sperduto, A. Sochocka, L. Swiderski, A. Trifiro, M. Trimarchi, G. Vannini, G. Verde, M. Vigilante, J.P. Wieleczko, J. Wilczynski, L. Zetta, W. Zipper

Isoscaling in neck fragmentation

Acta Physica Polonica A. Vol. 37, Pp. 199-206

E. De Filippo, F. Amorini, A. Anzalone, L. Auditore, V. Baran, L. Berceanu, J. Blicharska, J. Brzychczyk, B. Borderie, R. Bougault, M. Bruno, G. Cardella, S. Cavallaro, M.B. Chatterjee, A. Chbihi, M. Colonna, M. D'Agostino, R. Dayras, M. Di Toro, J. Frankland, E. Galichet, W. Gawlikowicz, E. Geraci, F. Giustolisi, A. Grzeszczuk, P. Guazzoni, D. Guinet, M. Iacono-Manno, S. Kowalski, E. La Guidara, G. Lanzaone, G. Lanzaone, C. Maiolino, Z. Majka, N. Le Neindre, A. Pagano, 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, K. Schmidt, K. Siwek-Wilczynska, I. Skwira, M.L. Sperduto, A. Sochocka, L. Swiderski, A. Trifiro, M. Trimarchi, G. Vannini, G. Verde, M. Vigilante, J.P. Wieleczko, J. Wilczynski, L. Zetta, W. Zipper

Isoscaling in neck fragmentation

Acta Physica Polonica B 37 (1): 199-205

W. Kühn for the Hades and Panda collaborations

Hadrons in dense matter: from Hades to Panda

Acta Physica Polonica B37 129

J. Beltrano, L. Torrisi, A.M. Visco, N. Campo and E. Rapisarda

Pulsed laser deposition (pld) technique to prepare biocompatible thin films

Adv. In Science and Technology 49 56-61

A.M. Visco, L. Calabrese, N. Campo, A. Bonavita, L. Torrisi
Pull-out strength analysis of quartz fibre posts in dental implants
Adv. In Science and Technology 49 (2006) 130-135

A. Mangione, L. Torrisi, A. Picciotto, A.M. Visco and N. Campo
Nanostructured Carbon Films Produced by Pulsed Laser Deposition for Bio-Medical Applications
Adv. In Science and Technology 49 (2006) 79-84

E. Migneco, A. Capone, P. Piattelli
Underwater laboratories for astroparticle physics and deep-sea science
Annals of Geophysics 49 (2-3): 643-658

C. Di Pietro, S. Piro, G. Tabbi, M. Ragusa, V. Di Pietro, V. Zimmitti, F. Cuda, M. Anello, U. Consoli, E.T. Salinaro, M. Caruso, C. Vancheri, N. Crimi, M.G. Sabini, G.A.P. Cirrone, L. Raffaele, G. Privitera, A. Pulvirenti, R. Giugno, A. Ferro, G. Cuttone, S. Lo Nigro, R. Purrello, F. Purrello, M. Purrello
Cellular and molecular effects of protons: Apoptosis induction and potential implications for cancer therapy
Apoptosis 11 (1): 57-66 Jan

L. Torrisi, A.M. Mezzasalma, S. Gammino, J. Badziak, P. Parys, J. Wolowski, L. Laska and G. Franco
Ion implantation induced by Cu ablation at high laser fluence
Appl. Surf. Sci. 252 (24) (2006) 8533-8538

L. Torrisi, F. Caridi, D. Margarone, A. Picciotto, A. Mangione and J.J. Beltrano
Carbon-plasma produced in vacuum by 532 nm-3 ns laser pulses ablation
App. Surf. Sci. 252 (18) (2006) 6883-6889

J.A. Aguilar, A. Albert, F. Ameli, M. Anghinolfi, G. Anton, S. Anvar, E. Aslanides, J.J. Aubert, E. Barbarito, S. Basa, M. Battaglieri, Y. Becherini, R. Bellotti, J. Beltramelli, V. Bertin, A. Bigi, M. Billault, R. Blaes, N. de Botton, M.C. Bouwhuis, S.M. Bradbury, R. Bruijn, J. Brunner, G.F. Burgio, J. Busto, F. Cafagna, L. Caillat, A. Calzas, A. Capone, L. Caponetto, E. Carmona, J. Carr, S.L. Cartwright, D. Castel, E. Castorina, V. Cavasinni, S. Cecchini, A. Ceres, P. Charvis, P. Chauchot, T. Chiarusi, M. Circella, C. Colnard, C. Compere, R. Coniglione, N. Cottini, P. Coyle, S. Cuneo, A.S. Cussatlegras, G. Damy, R. van Dantzig, C. De Marzo, I. Dekeyser, E. Delagnes, D. Denans, A. Deschamps, F. Dessages-Ardellier, J.J. Destelle, B. Dinkespieler, C. Distefano, C. Donzaud, J.F. Drogou, F. Druillole, D. Durand, J.P. Ernenwein, S. Escoffier, E. Falchini, S. Favard, F. Feinstein, S. Ferry, D. Festy, C. Fiorello, V. Flaminio, S. Galeotti, J.M. Gallone, G. Giacomelli, N. Girard, C. Gojak, P. Goret, K. Graf, G. Hallewell, M.N. Harakeh, B. Hartmann, A. Heijboer, E. Heine, Y. Hello, J.J. Hernandez-Rey, J. Hossli, C. Hoffman, J. Hogenbirk, J.R. Hubbard, M. Jaquet, M. Jaspers, M. de Jong, F. Jouvenot, N. Kalantar-Nayestanaki, A. Kappes, T. Karg, S. Karkar, U. Katz, P. Keller, H. Kok, P. Kooijman, C. Kopper, E.V. Korolkova, A. Kouchner, W. Kretschmer, A. Kruijjer, S. Kuch, V.A. Kudryavstev, D. Lachartre, H. Lafoux, P. Lagier, R. Lahmann, P. Lamare, J.C. Languillat, H. Laschinsky, Y. Le Guen, H. Le Provost, A.L. Van Suu, T. Legou, G. Lim, L. Lo Nigro, D. Lo Presti, H. Loehner, S. Loucatos, F. Louis, F. Lucarelli, V. Lyashuk, M. Marcelin, A. Margiotto, R. Masullo, F. Mazeas, A. Mazure, J.E. McMillan, R. Megna, M. Melissas, E. Migneco, A. Milovanovic, M. Mongelli, T. Montaruli, M. Morganti, L. Moscoso, M. Musumeci, C. Naumann, M. Naumann-Godo, V. Niess, C. Olivetto, R. Ostasch, N. Palanque-Delabrouille, P. Payre, H. Peek, C. Petta, P. Piattelli, J.P. Pineau, J. Poinsignon, V. Popa, T. Pradier, C. Racca, N. Randazzo, J. van Randwijk, D. Real, B. van Rens, F. Rethore, P. Rewiersma, G. Riccobene, V. Rigaud, M. Ripani, V. Roca, C. Roda, J.F. Rolin, M. Romita, H.J. Rose, A. Rostovtsev, J. Roux, M. Ruppi, G.V. Russo, F. Salesa, K. Salomon, P. Sapienza, F. Schmitt, J.P. Schuller, R. Shanidze, I. Sokalski, T. Spona, M. Spurio, G. van der Steenhoven, T. Stolarczyk, K. Streeb, D. Stubert, L. Sulak, M. Taiuti, C. Tamburini, C. Tao, G. Terreni, L.F. Thompson, P. Valdy, V. Valente, B. Vallage, G. Venekamp, B. Verlaat, P. Vernin, R. De Vita, G. de Vries, R. van Wijk, P.D.W. Huberts, G. Wobbe, E. de Wolf, A.F. Yao, D. Zaborov, H. Zacccone, J.D. Zornoza, J. Zuniga
First results of the instrumentation line for the deep-sea ANTARES neutrino telescope
Astroparticle Physics 26 (4-5): 314-324

L. Torrisi, S. Gammino, L. Laska, J. Krasa, K. Rohlena and J. Wolowski
Evaluations of electric field in laser-generated pulsed plasma
Czech J. of Physics 56, B580-586

F. Caridi, L. Torrisi, A. Picciotto, D. Margarone, A.M. Mezzasalma and S. Gammino
Energy distributions of particles ejected from laser-generated pulsed plasmas
Czech J. of Physics 56, B449-456

D. Margarone, S. Gammino, J. Krása, E. Krouský, L. Láska, P. Parys, M. Pfeifer, M. Rosinski, K. Rohlena, J. Skála, L. Torrisi, J. Ullschmied, A. Velyhan, J. Wołowski

Studies of Craters Produced by Laser on Solid Surfaces at Various Experimental Conditions

Czech J. of Physics, 56, B542-549

L. Torrisi, L. Ryc, D. Margarone and A. Borrielli

Soft x-ray radiation from metal targets at interaction of 9-ns laser pulses

Czech J. of Physics, 56, B571-579

A. Mangione, L. Torrisi, A. Picciotto and F. Caridi

Physical characterization of pulsed laser deposition of diamond-like nanostructures

Czech J. of Physics, 56, B534-541

S. Gammino, G. Ciavola, L. Torrisi, L. Celona, F. Consoli, S. Barbarino, D. Mascali and F. Maimone

High density ECR plasmas for the production of intense highly charged ion beams

Czech J. of Physics, 56 suppl. D, D1-D8

D. Miljanic, M. Milin, 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

He-6 quasi-free scattering off clusters in ^6Li

Europhysics Letters. vol. 76, pp. 801-807

Alderighi M, Amorini F, Anzalone A, Bassini R, Boiano C, Cardella G, Cavallaro S, Defilippo E, Guazzoni P, Laguidara E, Lanzano G, Lanzalone G, Maiolino C, Pagano A, Papa M, Pirrone S, Politi G, Porto F, F.Rizzo, Russo S, Sacca G, Sassi M, Sechi G, Zetta L.

Charge identification in large area planar silicon detectors, using digital pulse shape acquisition

IEEE Transaction on nuclear science, vol. 53, 279-285

E. Sciacca, S. Lombardo, M. Mazzillo, G. Condorelli, D. Sanfilippo, A. Contissa, M. Belluso, F. Torrisi, S. Billotta, A. Campisi, L. Cosentino, A. Piazza, G. Fallica, P. Finocchiaro, F. Musumeci, S. Privitera, S. Tudisco, G. Bonanno, E. Rimini

Arrays of Geiger Mode Avalanche Photodiodes

IEEE Photonics Technology Letters, vol. 18, n.15, August 1

P. Finocchiaro, A. Campisi, D. Corso, L. Cosentino, G. Fallica, S. Lombardo, M. Mazzillo, F. Musumeci, A. Piazza, G. Privitera, S. Privitera, E. Rimini, D. Sanfilippo, E. Sciacca, A. Scordino, S. Tudisco,

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Analisi delle provenienze di ossidiane del territorio di Milena (CL)

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RIBs in-flight production @ LNS

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Analisi delle provenienze di ossidiane del territorio di Milena (CL)

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RNB7 seventh international conference on radioactive nuclear beams, Cortina d'Ampezzo

Alessia Francesca Di Pietro

Reaction mechanisms in collisions induced by halo and/or weakly bound radioactive nuclei around the barrier

RNB7 Seventh international Conference on radioactive nuclear beams, Cortina d'Ampezzo

Pierpaolo Figuera

Reaction mechanisms in collisions induced by halo and/or weakly bound nuclei around the barrier : the $^{13}\text{N}+^9\text{Be}$ and $^6\text{He} + ^{64}\text{Zn}$ collisions

Fusion06: reaction mechanisms and nuclear structure at the Coulomb Barrier, Venezia

Alessia Francesca Di Pietro

Reaction mechanisms in collisions induced by halo nuclei around the barrier

IX international conference on nucleus nucleus collisions, august 28 2006, Rio de Janeiro Brasil

Pierpaolo Figuera

Structure effects on reaction mechanisms in collisions induced by halo and weakly bound nuclei around the barrier

International conference on actual problems of nuclear physics and atomic energy Kiev Ucraina

G.A.P. Cirrone, G. Cuttone, G. Candiano, N. Randazzo, V. Sipala, D. Lo Presti, S. Aiello, M. Bruzzi, M. Scaringella, M. Buccioli, D. Menichelli, C. Talamonti

The Prima Project: Development of a Proton Computed Tomography Device

RESMDD 2006, Florence October 2006

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An indirect Role of Monte Carlo in Radiation Treatment: Test and Development of a Proton Computed Tomography Device

IWORD 2006, Pisa July 2006

G.A.P. Cirrone, G. Cuttone, F. Di Rosa, G. Russo, M.G. Sabini

The Monte Carlo Geant4 Role in Radiation Therapy: the cases of Eye Proton Therapy and Gamma Knife Radiosurgery

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The Frontier on Imaging with Ionizing Radiations: Proton Computed Tomography and the Italian Prima Project

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Proton Therapy Detector Studies Under the Experience Gained at the Catania Facility

M. Maggiore

Design studied of the 300AMeV superconducting cyclotron for hadrontherapy

European Cyclotron Progress Meeting, Nizza (F), November 2-4, 2006

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Central region design of the 300AMeV superconducting cyclotron

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F. Amorini, C. Agodi, R. Alba, A. Anzalone, I. Berceanu, G. Cardella, M.B. Chatterjee, R. Coniglione, S. Cavallaro, M. D'Agostino, E. De Filippo, A. Di Pietro, E. Geraci, A. Grzeszczuk, P. Figuera, E. La Guidara, G. Lanzalone, N. Le Neindre, C. Maiolino, A. Pagano, M. Papa, S. Pirrone, A. Pop, G. Politi, F. Porto, F. Rizzo, P. Russotto, P. Sapienza

The reactions $^{40}\text{Ca}+^{40,48}\text{Ca}, ^{46}\text{Ti}$ at 25 MeV/A: isospin dependence of heavy residues formation

IX Int. Nucleus-Nucleus Conf. - August 28-September 1, 2006 - Rio - Brazil

E. La Guidara, F. Amorini, A. Anzalone, L. Auditore, V. Baran, I. Berceanu, J. Blicharska, J. Brzychczyk, B. Borderie, R. Bougault, M. Bruno, G. Cardella, S. Cavallaro, M.B. Chatterjee, A. Chbihi, M. Colonna, M. D'Agostino, R. Dayras, E. De Filippo, M. Di Toro, U. Emanuele, J. Frankland, E. Galichet, W. Gawlikowicz, E. Geraci, F. Giustolisi, A. Grzeszczuk, P. Guazzoni, S. Kowalski, G. Lanzañò, G. Lanzalone, N. Le Neindre, C. Maiolino, Z. Majka, A. Pagano, 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, K. Schmidt, K. Siwek-Wilczynska, I. Skwira, Ł. Swiderski, A. Trifirò, M. Trimarchi, G. Vannini, M. Vigilante, J.P. Wieleczko, J. Wilczynski, L. Zetta, W. Zipper

Dynamical aspects of fragment productions in the reaction $^{124}\text{Sn}+^{27}\text{Al}$ at 35 A.MeV, studied with the CHIMERA detector at INFN-LNS

IX Int. Nucleus-Nucleus Conf. - August 28-September 1, 2006 - Rio - Brazil

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Dynamical fission in the $\text{Sn}+\text{Ni}$ interaction at 35 A.MeV

IX Int. Nucleus-Nucleus Conf. - August 28-September 1, 2006 - Rio - Brazil

Seminars at LNS

The following seminars were presented at LNS this year

20-01-2006

Massimo Cerdonio

Ricerca di onde gravitazionali

INFN Padova

26-01-2006

Francesco Vissani

Teoria e fenomenologia delle oscillazioni di neutrini

INFN-LNGS

27-01-2006

Francesco Vissani

Masse e mixing di neutrini

INFN-LNGS

03-02-2006

V. Lyapin

Microchannel plate detectors: history, main principle, developing in JYFL

University of Jyväskylä, Finland

24-03-2006

David C. Weisser

Recent progress on superconducting resonators for the LINAC at ANU

Research School of Physical Sciences and Engineering
Australian National University Canberra - AUSTRALIA

24-03-2006

David C. Weisser

Beam pulsing techniques and ion source developments at ANU

Research School of Physical Sciences and Engineering
Australian National University Canberra - AUSTRALIA

03-04-2006

Joe Natowitz

Symmetry energy in low density nuclear gases

Texas A&M University

11-05-2006

Prof. J. Toke

Surface Entropy and first order phase transitions in finite nuclei - a new beginning for studies of nuclear multifragmentation?

University of Rochester, Usa

23-05-2006

A. Mangione - A. Picciotto

Carbon nanostructures produced by pulsed laser ablation - Temperatures characterization of plasmas generated by high power pulsed lasers

University of Messina and INFN

30-05-2006

Wyss Jeffery

Single event effects at SIRAD: from broad beam testing to ion electron emission microscopy

University of Cassino

31-05-2006

Prof. Hans Geissel

NUSTAR Experiments with the Present and Future Facilities at GSI-FAIR

GSI Darmstadt

07-06-2006

Santosh Sammadar

Statistical multifragmentation model: a critical assessment

Saha Institute, Calcutta-India

08-06-2006

Jadu De

Specific heat in finite nuclei

Saha Institute, Calcutta-India

23-06-2006

Riccardo Musenich

Applicazioni del superconduttore MgB2 per magneti di interesse per le attività di fisica nucleare

INFN, Sezione di Genova

27-06-2006

Angelo Campisi

Nuovi sensori a stato solido per la rivelazione di singoli fotoni e loro possibili applicazioni

INFN-LNS

10-07-2006

Shashi Verma

Elastic scattering measurements for ^7Be , $^7\text{Li} + ^9\text{Be}$ system and fusion measurements for $^7\text{Li} + ^9\text{Be}$ system using low energy Radioactive Ion Beam facility

Inter-University Accelerator Centre (IUAC) - University of Delhi, India

12-07-2006

Boris Skorodumov

The lowest excited states in ^{130}O . Astrophysical implications

Physics Dept, Univ. of Notre Dame, USA

14-07-2006

R. Liechtenthäler

The RIB facility in Brazil and the production of exotic secondary beams of ^6He , ^8Li and ^7Be

Institute of Physics, University of São Paulo, Brazil

18/19-07-2006

Massimo De Luca

Bioluminescenza in ambienti sottomarini profondi, impatto su strutture sommerse

Università di Messina e CNR - Istituto Talassografico di Messina

07-09-2006

Hannu Koivisto

Enhancement of magnetic field in B-min traps

Department of Physics, University of Jyväskylä, Finland

08-09-2006

Hannu Koivisto

Production of metallic ion beams

Department of Physics, University of Jyväskylä, Finland

19-09-2006

Paolo Desiati

Status of ICECUBE project

University of Wisconsin - Madison, USA

21-09-2006

H. Toki

Relativistic chiral mean field model for finite nuclei

Osaka University, Japan

25-09-2006

G. Lalazissis

Isospin properties of covariant density functional theory in nuclear physics

University of Thessaloniki, Greece

06-11-2006

Stefan Typel

Indirect Methods for Nuclear Astrophysics
GSI

14-11-2006

Fairouz Hammache

The $^{13}\text{C}(\alpha, n)^{16}\text{O}$ reaction in nuclear astrophysics

IPN-Orsay, GSI

2006-2006-2006

Roberto Inguanti

Utensili per meccanica e termoidraulica

EGA Master

01-12-2006

G. Soulioutis

Neutron-Rich Rare Isotope production at Fermi Energies and Application to the Texas A&M Radioactive Beam Upgrade Project

Texas A&M

14-12-2006

Eric Bonnet

Multifragmentation of heavy systems and signals of liquid-gas phase transitions

IPN-Orsay

Events

January 14	LNS users' group meeting
February 10	Olimpiadi di Fisica
March 6-7	LNS Scientific Committee
March 27	Ricerca, sperimentazione e didattica con Mathematica
March 29	EXCYT commissioning with stable and unstable Li beams
April 10-11-12-19-20	XVI Settimana Cultura Scientifica e Tecnologica
July 12	Connect - CST Workshop Series 2006
October 4-5	International Conference on Ettore Majorana's legacy and the Physics of the XXI century - in commemoration of the centennial of Majorana's birth
October 30-31	Il metodo Monte Carlo in radioterapia: pratica clinica e strumenti tecnologici
December 4	I primi 30 anni di attività dei LNS
December 5	INFN-IBA day

Degrees Theses

Student: A Esposito

La tecnica Dpaa (Deep Proton Activation Analysis): un innovativo metodo per la caratterizzazione del corpo delle monete antiche

Tutors: F Rizzo, G Pappalardo

Student: Enrico Mazzaglia

Codice Monte Carlo applicato alla simulazione di una tomografia computerizzata effettuata con protoni.

Tutors: F Rizzo, A Pagano

Student: Francesco Azzaro

Studio di un sistema di Imaging medico a protoni (pCT)

Tutors: F Rizzo, A Pagano

Student: Denis Marino

Simulazione di acceleratori lineari mediante tecniche Monte Carlo e confronto con i dati sperimentali

Tutors: F Rizzo, A Pagano

Student: M. Di Prima

Identificazione in massa e carica di frammenti emessi in collisioni nucleari ad energie intermedie tramite il multirivelatore CHIMERA

Tutors: F Rizzo, A Pagano

Student: Angelo Maggio

Studio di strutture a cluster del ^{14}C ad alta energia di eccitazione per mezzo della reazione $^6\text{He}+^{12}\text{C}$

Tutors: M. Lattuada A. DiPietro

Student: Elisa Rapisarda

FRIBs: tagged intermediate energy Radioactive Ion Beams at Laboratori Nazionali del Sud

Tutors: A. Pagano and F. Porto

Student: P. Russotto,

Dynamical emission of heavy fragments in the $^{112,124}\text{Sn}+^{58,64}\text{Ni}$ reactions at 35 AMeV as seen with CHIMERA

Tutors: A. Pagano and F. Porto

