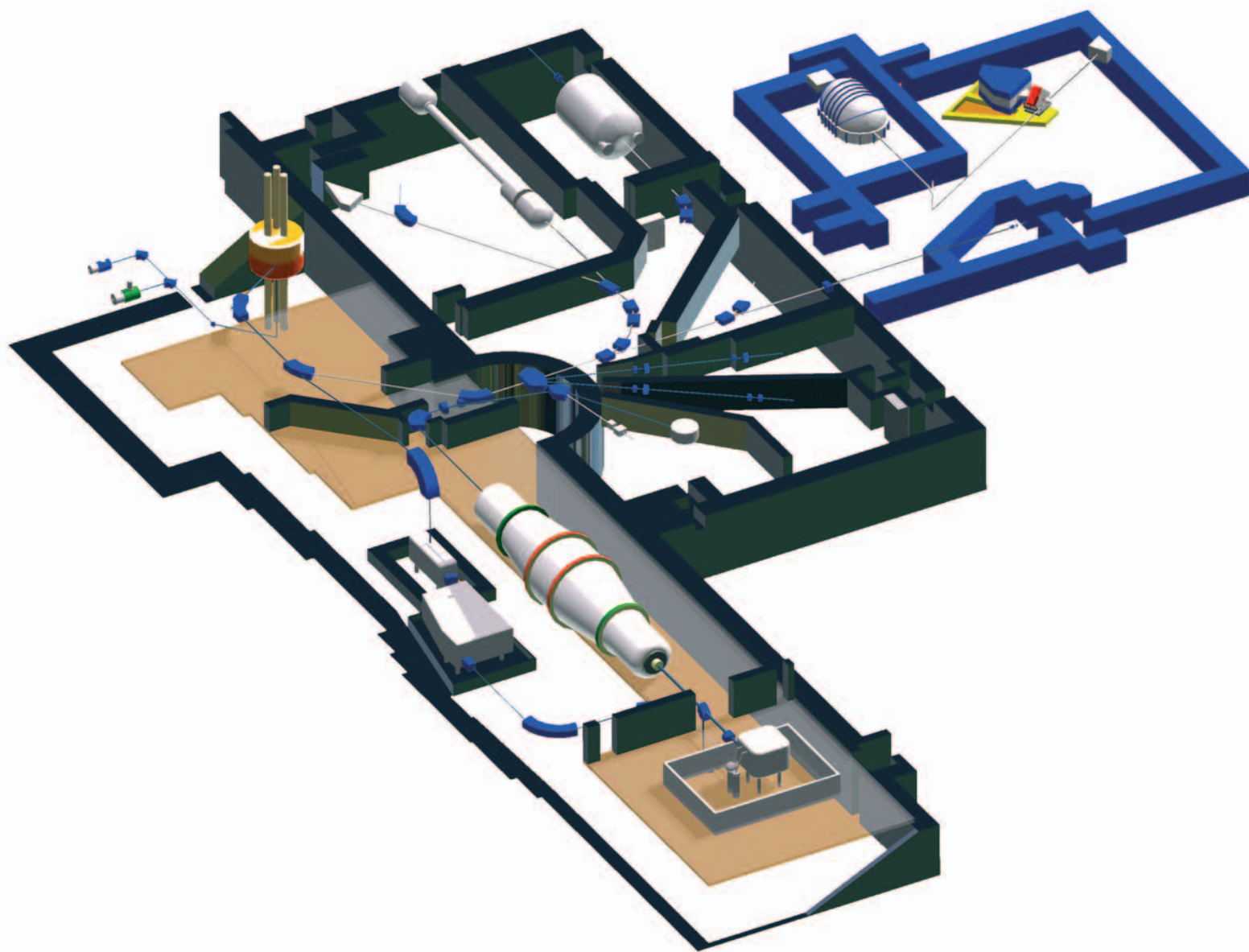




LABORATORI NAZIONALI DEL SUD



ACTIVITY REPORT 2003

Foreword

As in previous years, during 2003 the choice was made to share the time between experiments at the accelerators and activities related to the development of EXCYT project. As it is well known these two tasks are indeed conflicting since beam acceleration prevents working in the area where the EXCYT elements have to be mounted and tested.

The installation and connections of the main parts of EXCYT (platforms, target-source system, mass separator, etc.) were completed. Tests of high intensity primary beam were performed, allowing extraction of 100 W ^{13}C beam from the Cyclotron. The target-ion source assembly was realised and successfully tested at Ganil, confirming the expected production rates of Lithium isotopes. This result enforced the choice of ^8Li as first radioactive beam to be produced and accelerated at LNS. Nuclear astrophysics and nuclear structure experiments, already approved by the LNS Scientific Committee, are ready to run with this beam even with intensities lower than the one expected on the basis of the Ganil test.

An intense work around the spectrometer MAGNEX was also carried out, with the aim of getting the device fully operating at the same time when the EXCYT beams will be ready. The focal plane detector was tested and mounted, the design of the scattering chamber was completed and its realisation started.

Even with the interruptions demanded by the development of EXCYT, many intermediate energy experiments, proposed by large international collaborations and approved by the Scientific Committee, were performed with the Cyclotron beams. They could take advantage of the full configuration of the detector CHIMERA, whose 1200 telescopes were installed inside the large reaction chamber CICLOPE. At the same time further improvements of the detector performances have been considered giving place to a new technological research aimed at identifying the low energy products stopped in the first stage of the telescopes by a pulse shape analysis method.

Also Tandem beams were used for fundamental research, mainly concerning nuclear astrophysics and nuclear structure studies. Among them the completion of the BigBang experiment has to be mentioned, that led to the first measurement with unstable beams realised at LNS.

Beams from both accelerators continued to be widely used for applications and technical tests, mainly in the field of studies of irradiated biological samples, radiation hardness and development of new detection devices. The innovative technique of ion beam micrometric lithography was further refined, allowing to predict interesting industrial applications.

CATANA, the proton therapy facility, is now steadily operating. At the end of 2003 the patients suffering of ocular pathologies that were treated by CATANA exceeded the number of sixty. And there are clear signals that the success of CATANA is triggering the growth of new, wider initiatives in the area of Catania, that will benefit of the experience acquired at LNS in the field of proton therapy.

The NEMO activity in 2003 has been mainly focused on the design of the Phase 1 subsystems, that will allow to test all the critical components of the km^3 neutrino detector in the deep sea environment. At the same time, in the frame of the search for the best location of the underwater neutrino observatory, the results of the characterisation of water transparency and optical background of the site at 3500 depth, located about 80 km East of Capo Passero, indicated this site as highly suitable for the telescope installation.

In conclusion, the progress made during this year both in the development of new projects and in the successful exploitation of existing facilities, allows us to state that today LNS can look at its future with a renewed, well founded confidence.

Emilio Migneco
LNS Director

A - EXPERIMENTAL NUCLEAR PHYSICS

U.Abbondanno, L.Bardelli, S.Barlini, M.Bini, C.Birattari, R.Bougault, M.Bruno, G.Casini, M.Cavinato, F.Cerutti, A.Clivio, M.D'Agostino, J.De Sanctis, S.Fabbri, E.M.Fabrizi, E.Gadioli, E.Gadioli Erba, E.Geraci, F.Gramegna, A.Giussani, B.Guiot, V.Kravchuk, N.Le Neindre, A.Mairani, G.V.Margagliotti, A.Moroni, A.Olmi, S.Piantelli, G.Poggi, G.Vannini, L.Vannucci (NUCL-EX Collaboration) F.Amorini, A.Anzalone, G.Cardella, S.Cavallaro, E.DeFilippo, F.Giustolisi, E.La Guidara, G.Lanzanò, L.Lanzalone, C.Maiolino, A.Pagano, M. Papa, S.Pirrone, G.Politi, F.Porto, F.Rizzo for CHIMERA/ISOSPIN Collaboration

Charge and mass distributions of IMF's produced in the interaction of $^{58,62}\text{Ni}$ with $^{40,48}\text{Ca}$ at an incident energy of 25 A. Mev

J.Blicharska, M.Alderighi, A.Anzalone, L.Auditore, R.Barna, V.Baran, I.Berceanu, M.Bartolucci, A.Bonasera, B.Borderie, R.Bougault, M.Bruno, J.Brzychczyk, G.Cardella, S.Cavallaro, A.Chibihi, M.Colonna, M.D'Agostino, R.Dayras, E.De Filippo, D.De Pasquale, M.Di Toro, W.Gawlikowicz, E.Geraci, F.Giustolisi, A.Grzeszczuk, P.Guazzoni, D.Guinet, M.Iacono Manno, A.Italiano, S.Kowalski, E.La Guidara, G.Lanzanò, G.Lanzalone, N.Le Neindre, S.Li, S.Lo Nigro, C.Maiolino, Z.Majka, G.Manfredi, A.Pagano, M.Papa, M.Petrovici, E.Piasecki, S.Pirrone, R.Planeta, G.Politi, A.Pop, F.Porto, M.F.Rivet, E.Rosato, R.Russo, P.Russotto, K.Schmidt, G.Sechi, V.Simion, M.L.Sperduto, J.C.Steckmeyer, A.Trifirò, M.Trimarchi, G.Vannini, M.Vigilante, J.P.Wieleczko, J.Wilczynski, H.Wu, Z.Xiao, L.Zetta, W.Zipper

Calibration of CsI(Tl) scintillators for light charged particles (Z=1) in the first campaign of REVERSE experiment

M.Brenner, M.Lattuada, S.V.Khlebnikov, W.H.Trzaska, L.Krasnov, S.E.Belov, M.Gulino, V.V.Lazarev, Li Chengbo, M.Mutterer, G.Prete, G.P.Tiourin, M.Zadro

Search for condensates of alpha-particles in ^{32}S by alpha-particle transfer

F.Cappuzzello, M.Cavallaro, A.Cunsolo, A.Foti, C.Nociforo, S.E.A.Orrigo, J.S.Winfield, D.Beaumel, S.Fortier

Excited states of ^{19}O

G.Cardella, U.Abbondanno, C.Agodi, R.Alba, A.Anzalone, F.Amorini, L.Auditore, L.Bardelli, I.Berceanu, J.Blicharska, R.Bougault, S.Cavallaro, M.B.Chatterjee, A.Clivio, R.Coniglione, M.D'Agostino, E.De Filippo, J.De Sanctis, S.Fabbri, E.Geraci, A.Grzeszczuk, B.Guiot, C.Iacono Manno, E.La Guidara, G.Lanzanò, G.Lanzalone, N.Le Neindre, C.Maiolino, A.Pagano, M.Papa, S.Pirrone, G.Politi, A.Pop, F.Porto, F.Rizzo, P.Russotto, D.Santonocito, P.Sapienza, K.Schmidt, M.L.Sperduto, A.Stefanini, P.Staccioli, A.Trifirò, M.Trimarchi, M.Vigilante, W.Zipper

The analysis of the 2003 calibration campaign of the CHIMERA 4π detector

S.Cherubini, C.Agodi, R.Alba, C.Bonomo, L.Calabretta, L.Cosentino, A.Del Zoppo, A.Di Pietro, P.Figuera, M.Gulino, M.La Cognata, L.Lamia, A.Musumarra, L.Pappalardo, M.G.Pellegriti, R.G.Pizzone, A.Rinollo, C.Rolfs, S.Romano, C.Spitaleri, F.Strieder, S.Tudisco, A.Tumino

Production of a ^8Li radioactive beam and the $^8\text{Li}(\alpha, n)^{11}\text{B}$ reaction at big bang temperatures

E.De Filippo, M.Alderighi, F.Amorini, A.Anzalone, N.Arena, L.Auditore, V.Baran, M.Bartolucci, I.Berceanu, J.Blicharska, J.Brzychczyk, A.Bonasera, B.Borderie, R.Bougault, M.Bruno, G.Cardella, S.Cavallaro, M.B.Chatterjee, A.Chibihi, J.Cibor, M.Colonna, M.D'Agostino, R.Dayras, M.Di Toro, W.Gawlikowicz, E.Geraci, F.Giustolisi, A.Grzeszczuk, P.Guazzoni, D.Guinet, M.Iacono Manno, S.Kowalski, E.La Guidara, G.Lanzanò, G.Lanzalone, N.Le Neindre, S.Li, S.Lo Nigro, C.Maiolino, Z.Majka, G.Manfredi, T.Paduszynski, A.Pagano, M.Papa, M.Petrovici, E.Piasecki, S.Pirrone, R.Planeta, G.Politi, A.Pop, F.Porto, M.F.Rivet, E.Rosato, F.Rizzo, S.Russo, P.Russotto, K.Schmidt, G.Sechi, V.Simion, K.Siwiek-Wilczynska, I.Skwira, M.L.Sperduto, J.C.Steckmeyer, L.Swidorski, A.Trifirò, M.Trimarchi, G.Vannini, M.Vigilante, J.P.Wieleczko, J.Wilczynski, H.Wu, Z.Xiao, L.Zetta, W.Zipper

Fragment production in the reaction $^{124}\text{Sn} + ^{64}\text{Ni}$ and $^{112}\text{Sn} + ^{58}\text{Ni}$ at 35 A. MeV

A.Di Pietro, M.Lattuada, F.Pansini, D.Vinciguerra, M.Zadro, O.Yu.Goryunov, V.V.Ostashko, Li.Xia, F.Cappuzzello, A.Cunsolo, A.Foti, J.Winfield, T.Lonnroth, V.Lyapin, M.Mutterer, W.H.Trzaska
Using the resonance scattering method to study Li-He cluster states in boron exotic isotopes

Di Stefano

Simulation and rejection of atmospheric muon background for neutrino point-like sources with the NEMO - km³ neutrino telescope

P.Figuera, F.Amorini, C.Angulo, G.Cardella, S.Chherubini, A.Di Pietro, J.Lu, C.Marchetta, M.Papa, M.G.Pellegriti, R.G.Pizzone, R.Raabe, F.Rizzo, J.L.Sida, W.Tian, S.Tudisco

Formation and decay of ²²Na in the collisions ¹³N + ⁹Be and ¹²C + ¹⁰B

M.La Cognata, A.Musumarra, C.Spitaleri, S.Chherubini, D.Miljanic, M.G.Pellegriti, R.G.Pizzone, C.Rolfs, S.Romano, A.Tumino, S.Typel

The ³He (d, p) ⁴He reaction studied via the Trojan Horse Method

M.La Cognata, C.Spitaleri, S.Blagus, S.Chherubini, D.Miljanic, A.Musumarra, M.G.Pellegrini, R.G.Pizzone, S.Romano, A.Tumino, M.Zadro

Study of quasi-free ²H(t, tp) reaction at E_t=35.5 MeV as a validity test of PWIA for THM application

L.Lamia, C.Li, R.G.Pizzone, C.Spitaleri, S.Chherubini, A.Del Zoppo, P.Figuera, M.Gulino, M.La Cognata, A.Musumarra, L.Pappalardo, M.G.Pellegriti, A.Rinollo, C.Rolfs, S.Romano, S.Tudisco, A.Tumino

Astrophysical S(E)-factor for ⁹Be (p, α) ⁶Li reaction extracted via the Trojan Horse Method

G.Lo Bianco, D.L.Balabanski, N.Biasi S.Nardelli, C.M.Petrache, A.Saltarelli

A ns isomer in ¹³⁹Nd

G.Lo Bianco, N.Biasi, C.M.Petrache, A.Saltarelli

Gamma-ray and conversion-electron spectroscopy of ¹³⁹Nd

F.Mudò, C.Spitaleri, A.Mukhamedzanov, R.Tribble, C.Bonomo, S.Chherubini, Del Zoppo, P.Figuera, M.Gulino, M.La Cognata, L.Lamia, A.Musumarra, M.G.Pellegriti, R.G.Pizzone, S.Romano, S.Tudisco, A.Tumino

ANC method applied to the ³He (α, γ) ⁷Be capture reaction

S.E.A Orrigo, H.Lenske, F.Cappuzzello, A.Foti, A.Lazzaro, C.Nociforo, J.S.Winfield

On the resonance line shape in light neutron rich nuclei

M.G.Pellegriti, C.Spitaleri, A.M.Mukhamedzanov, S.Blagus, L.D.Blokhintsev, M.Bogovac, L.Calabretta, C.Chherubini, A.Di Pietro, A.Del Zoppo, P.Figuera, D.Miljanic, M.Milin, A.Musumarra, L.Pappalardo, R.G.Pizzone, D.Rendic, S.Romano, S.Tudisco, A.Tumino

Investigation on the off-energy shell effects in ²H (p, pp) n reaction

L.Pienkowski, Jun Lu, Jan Toke, W.Udo Schroeder, W.Gawlikowicz, C.Agodi, R.Alba, G.Bellia, R.Coniglione, A.Del Zoppo, P.Finocchiato, C.Maiolino, E.Migneco, P.Piattelli, D.Santonocito, P.Sapienza, M.Di Toro, M.Colonna, V.Baran, A.Moroni, P.Milazzo, N.Colonna

Projectile splitting in ⁶²Ni+¹¹²Sn reactions at e/a=35mev

R.G.Pizzone, C.Spitaleri, S.Chherubini, P.Figuera, M.La Cognata, L.Lamia, D.Miljanic, A.Musumarra, M.G.Pellegrini, S.Romano, S.Tudisco, A.Tumino, S.Typel

Influence of the ⁶Li momentum distribution on Trojan Horse Method applications

R.Planeta, J.Blicharska, J.Brzychczyk, J.Cibor, A.Grzeszczuk, P.Hachaj, S.Kowalski, Z.Majka, N.G.Nicolis, K.Schmidt, W.Zipper

Search for hyperheavy toroidal and bubble nuclei formed in the Au + Au collisions

A.Rinollo, C.Bonomo, S.Romano, C.Spitaleri, S.Chherubini, A.Del Zoppo, P.Figuera, M.Gulino, M.La Cognata, L.Lamia, A.Musumarra, L.Pappalardo, M.G.Pellegriti, R.G.Pizzone, S.Tudisco, A.Tumino

Improved measurement of cross-section and astrophysical factor of the d(d, p)t reaction using the trojan horse method

D.Santonocito, Y.Blumenfeld, P.Piattelli, F.Delaunay, N.R.Alba, G.Bellia, R.Coniglione, A.Del Zoppo, P.Finocchiario, P.Sapienza

Disappearance of collective motion in hot nuclei

S.Tudisco, C.Spitaleri, S.Blagus, D.Miljanic, M.Milin, A.Musumarra, M.G.Pellegrini, R.G.Pizzone, S.Romano, N.Soić, A.Tumino

Quasi-free reaction around the Coulomb barrier

A.Tumino, C.Spitaleri, C.Bonomo, S.Cherubini, P.Figuera, M.Gulino, M.La Cognata, L.Lamia, A.Musumarra, M.G.Pellegriti, R.G.Pizzone, A.Rinollo, S.Romano

Quasi-free ${}^6\text{Li}(n, \alpha){}^3\text{H}$ reaction at low energy from ${}^2\text{H}$ break-up

B - THEORETICAL NUCLEAR PHYSICS

V.Baran, M.Colonna, M. Di Toro

Isospin in nuclear fragmentation

S.Kimura, A.Buonasea

Electron screening effects on nuclear reactions at extremely low energies

U.Lombardo, C.W.Shen, P.Schuck, W.Zuo

Screening effects on ${}^1\text{S}_0$ pairing in neutron matter

U.Lombardo, C.W.Shen, N.Van Giai, W.Zuo

Neutrino mean free path in neutron stars

S.Terranova, A.Buonasea

Microscopic simulation of the quark-gluon plasma

D.Zhou, S.Terranova, A.Buonasea

A new microscopic approach to relativistic heavy ion collision

C - INSTRUMENTATION AND RELATED TECHNIQUES

G.Agakishiev, C.Agodi, H.Alvarez-Pol, A.Balanda, R.Bassini, G.Bellia, D.Belver, J.Bielcik, A.Blanco, M.Böhmer, C.Boiano, A.Bortolotti, J.L.Boyard, S.Brambilla, P.Braun-Munzinger, P.Cabanelas, S.Chernenko, T.Christ, R.Coniglione, M.Dahlinger, J.Díaz, R.Djeridi, F.Dohrmann, I.Durán, T.Eberl, W.Enghardt, L.Fabbietti, O.Fateev, P.Finocchiario, P.J.R.Fonte, J.Friese, I.Fröhlich, J.A.Garzón, R.Gernhäuser, M.Golubeva, D.González-Díaz, 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.Kämpfer, K.Kanaki, T.Karavicheva, D.Kirschner, I.Koenig, W.Koenig, B.W.Kolb, U.Kopf, R.Kotte, J.Kotulic-Bunta, R.Krücken, A.Kugler, W.Kühn, R.Kulesa, S.Lang, J.Lehnert, L.Maier, P.Maier-Komor, C.Maiolino, J.Marin, J.Markert, V.Metag, N.Montes, E.Moriniere, J.Mousa, M.Münch, C.Müntz, L.Naumann, R.Novotny, J.Novotny, W.Ott, J.Otwinowski, Y.C.Pachmayer, L.M.Pant, V.Pechenov, T.Pérez, J.Pietraszko, J.M.A.Pinhao, R.Pleskac, V.Pospíšil, W.Przygoda, 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.Schön, C.Schroeder, E.Schwab, P.Senger, R.Simon, V.Smolyankin, L.Smykov, S.Spataro, B.Spruck, H.Stroebele, 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.Wisniowski, T.Wojcik, J.Wüstenfeld, Y.Zanevsky, P.Zumbrich

Particle identification at HADES

M.Alderighi, A.Anzalone, R.Bassini, C.Boiano, G.Cardella, S.Cavallaro, E.De Filippo, E.Geraci, F.Giustolisi, P.Guazzoni, E.LaGuidara, G.Lanzanò, G.Lanzalone, A.Pagano, M.Papa, S.Pirrone, G.Politi, F.Porto, S.Russo, M.Sassi, G.Sechi, L.Zetta

Digital signal processing from CHIMERA: generalities and pulse shape acquisition of (ΔE , Fast) scatter plots

M.Alderighi, A.Anzalone, R.Bassini, C.Boiano, G.Cardella, S.Cavallaro, E.De Filippo, E.Geraci, F.Giustolisi, P.Guazzoni, E.Laguidara, G.Lanzanò, G.Lanzalone, A.Pagano, M.Papa, S.Pirrone, G.Politi, F.Porto, S.Russo, M.Sassi, G.Sechi, L.Zetta

Digital signal processing from CHIMERA: pulse shape acquisition of (fast, slow) scatter plots

M.Alderighi, A.Anzalone, R.Bassini, C.Boiano, G.Cardella, S.Cavallaro, E.De Filippo, E.Geraci, F.Giustolisi, P.Guazzoni, E.Laguidara, G.Lanzanò, G.Lanzalone, A.Pagano, M.Papa, S.Pirrone, G.Politi, F.Porto, S.Russo, M.Sassi, G.Sechi, L.Zetta

Digital signal processing from CHIMERA: pulse shape acquisition for charge discrimination in reversed silicon detectors

A.Cunsolo, F.Cappuzzello, A.Foti, A.Lazzaro, C.Nociforo, S.E.A.Orrigo, J.S.Winfield, H.Petrascu, M.Piscopo, G.Schillaci, V.Campagna, S.Salomone, A.Distefano, C.Cali, P.Litrico

Status of the MAGNEX Spectrometer

G.Cuttone, R.Alba, L.Calabretta, L.Celona, F.Chines, L.Cosentino, P.Finocchiaro, M.Menna, E.Messina, G.Raia, M.Re, D.Rifuggiato, A.Rovelli, G.Schillaci, A.Amato, R.Avolio, S.Cavallaro, C.D'Amato, E.Furia, A.Grmek, P.Maniscalco, G.Manno, R.Marletta, S.Passarello, M.Piscopo, S.Pulvirenti, P.Reina, S.Russo, S.Tringale, A.Varisano, V.Scuderi, E.Zappalà

The EXCYT facility towards its commissioning

W.Gawlikowicz, J.Blicharska, J.Brzychczyk, J.Cibor, A.Grzeszczuk, S.Kowalski, Z.Majka, R.Planeta, W.Zipper

The software replica of CHIMERA multidetector

E.Migneco, S.Aiello, E.Amato, M.Ambriola, F.Ameli, G.Andronico, M.Anghinolfi, M.Battaglieri, R.Bellotti, A.Bersani, A.Boldrin, M.Bonori, A.Capone, L.Caponnetto, F.Cafagna, M.Circella, R.Cocimano, R.Coniglione, M.Cordelli, M.Costa, S.Cuneo, A.D'Amico, V.D'Amico, C.De Marzo, R.De Vita, C.Distefano, A.Gabrielli, E.Gandolfi, A.Grimaldi, R.Habel, A.Italiano, M. Leonardi, L.Lo Nigro, D.Lo Presti, A.Margiotta, A.Martini, M.Masetti, R.Masullo, R.Mosetti, T.Montaruli, M.Musumeci, C.A. Nicolau, R.Occhipinti, R.Papaleo, C.Petta, P.Piattelli, G.Raia, N.Randazzo, S.Reito, G.Ricco, G. Riccobene, M.Ripani, M.Romita, A.Rovelli, M.Ruppi, G.V.Russo, M.Russo, P.Sapienza, J.P.Schuller, M.Sedita, M.Spurio, I.Sokalski, M.Taiuti, L.Trasatti, L.Ursella, V.Valente, P.Vicini, G.Zanarini, S.Zavatarelli

Status of the NEMO Project

E.Migneco, S.Aiello, E.Amato, M.Ambriola, F.Ameli, G.Andronico, M.Anghinolfi, M.Battaglieri, R.Bellotti, A.Bersani, M.Bonori, A.Capone, L.Caponnetto, F.Cafagna, M.Circella, R.Cocimano, R.Coniglione, M.Cordelli, M.Costa, S.Cuneo, A.D'Amico, V.D'Amico, C.De Marzo, R.De Vita, C.Distefano, A.Gabrielli, E.Gandolfi, A.Grimaldi, R.Habel, A.Italiano, L.Lo Nigro, D.Lo Presti, A.Margiotta, A.Martini, M.Masetti, R.Masullo, T.Montaruli, M.Musumeci, C.A. Nicolau, R.Occhipinti, R.Papaleo, C.Petta, P.Piattelli, G.Raia, N.Randazzo, S.Reito, G.Ricco, G. Riccobene, M.Ripani, M.Romita, A.Rovelli, M.Ruppi, G.V.Russo, M.Russo, P.Sapienza, J.P.Schuller, M.Sedita, M.Spurio, I.Sokalski, M.Taiuti, L.Trasatti, V.Valente, P.Vicini, G.Zanarini, S.Zavatarelli

The NEMO Phase-1 Project

D - ION SOURCES AND ACCELERATORS

L.Calabretta, L.Celona, G.Cuttone, S.Gammino, M.Maggiore, G.Raia, M.Re, D.Rifuggiato, S.Farinon, P.Fabbricatore, R.Musenich

A superconducting cyclotron as a primary accelerator for exotic beam facilities

S.Gammino, L.Torrisi, G.Ciavola, L.Andò, L.Celona, S.Manciagli, L.Laska, J.Krasa, M.Pfeifer, G.Shirkov, J.Wolowski

The ECLISSE method: comments and perspectives

M.Menna, F.Chines, G.Cuttone, D.Garufi, E.Messina, M.Re, M.-G.Saint-Laurent, A.C.C.Villari, R.Alves-Condé, M.Dubois, G.Gaubert, C.Huet-Equibec, P.Jardin, N.Lecesne, R.Leroy, J.Y.Pacquet

The experiment E435 at GANIL

M.Re, G.Sarta, E.Zappalà, G.Cuttone

Cathode field electron emission inhibition by gas treatment

M.Re, D.Garufi, M.Menna, G.Raia, G.Cuttone

Thermal simulation for EXCYT target assembly

Rifuggiato and LNS accelerator staff

Tandem and superconducting cyclotron activity

L.Torrisi, E.Amato, S.Gammino, D.Margarone, G.Bonanno, S.Scuderi

Study of photon emission from plasma generated by fast pulsed laser

E - INTERDISCIPLINARY PHYSICS

L.A.Applegate, F.Musumeci, H.J.Nigli, G.Privitera, A.Scordino, S.Tudisco

DL spectral analysis of epithelial cells

I.Baran, V.Baran, F.Musumeci, G.Privitera, A.Scordino, S.Tudisco

Relation between delayed luminescence and sytoskeleton state in yeast cells

L.Calabretta, G.Cuttone, G.A.P.Cirrone, M.Maggiore, L.Raffaele, G.Schillaci, S.Lo Nigro, L.Biagioni, M.G.Sabini

Proposal for the construction of an hadrontherapy center in Catania

G.A.P.Cirrone, G.Cuttone, P.A.Lojacono, E.Mongelli, S.Lo Nigro, J.Ott, V.I.Patti, G.Privitera, L.Raffaele, M.L.Rallo, A.Reibaldi, G.Russo, V.Salamone, M.G.Sabini, C.Spatola, L.Valastro

The CATANA proton therapy facility: two years of clinical and dosimetric experience

L.Cosentino, P.Finocchiario, A.Hermanne, H.Ottevaere, A.Pappalardo, H.Thienpont, P.Tuteleers, M.Vervaeke, B.Volckaerts, P.Vynck

Beam monitoring enhances deep proton lithography: towards high-quality micro-optical components

S.Gammino, G.Ciavola, L.Celona, L.Andò, M.Presti, A.Galatà, F.Consoli, S.Passarello, XZhang, L.Schachter, S.Dobrescu, K.Stiebing, M.Winkler, P.Spadtke, R.Gobin

Innovative ion sources at LNS

S.Grande, P.A.Lojacono, A.M.Luciana, A.Palma, V.I.Patti, L.Raffaele, A.Rosi, L.M.Valastro, V.Viti, L.Guidoni

Effects of proton beams on intact tumour cells examined by MRS

A.Karydas, V.La Rosa, P.Militello, G.Pappalardo, L.Pappalardo, F.Rizzo, F.P.Romano

Provenance of obsidian artefacts from different archaeological layers of Phaistos and Hagia Triada

L.Manti, G.A.P.Cirrone, G.Grossi, M.Durante, P.Lojacono, M.Pugliese, M.G.Sabini, P.Scamporrì, L.Valastro, G.Gialanella

Measurements of transmissible chromosome aberrations in human lymphocytes exposed to high-energy protons and ^{12}C ions

E.Mezzetti, D.Botta, A.Chiodoni, R.Gerbardo, G.Ghigo, L.Gozzelino, F.Laviano, B.Minetti, A.Rovelli, A.Amato

A new facility for heavy ion micro lithography

S.Passarello, F.Caruso, G.De Luca, G.Gallo, A.Grmek, G.Manno, F.Musarra, E.Zappalà, M.Maggiore.

Activity report of devices design group

A.Ristic-Fira, I Petrovic, D.Todorovic, L.Valastro, P.Cirrone, G.Cuttone

Cell cycle phase redistribution and apoptosis of HTB 140 melanoma cells exposed to 62 MeV protons

A.Ristic-Fira, I Petrovic, D.Todorovic, L.Valastro, P.Cirrone, G.Cuttone

Survival of HTB 140 Melanoma cells after exposure to 62 MeV protons

F.Rizzo, G.A.Cirrone, G.Cuttone, A.Esposito, S.Garaffo, G.Pappalardo, L.Pappalardo, F.P.Romano, S.Russo

The deep proton activation analysis: a new non-destructive method for the determination of chemical elements in the body of ancient coins

C.Tuvè, R.Potenza, C.Sutera,V.Bellini, A.Bonanno, F.Mammoliti, G.Pucella, M.Marinelli, E.Milani, A.Paoletti, A.Tucciarone, G.Verona-Rinati

Investigation of defect density as a function of growth temperature and thickness in CVD diamonds

F.Velardi, F.Iannuzzo, G.Busatto, A.Porzio, A.Sanseverino, G.Currò, A.Cascio, F.Frisina, A.Candelori

An original approach to study the charge generation mechanisms in power mosfets during heavy ions exposure

B.Volckaerts, L.Cosentino, A.Pappalardo, P.Vynck, M.Vervaeke, P.Finocchiario, A.Hermanne, H.Thienpont

Fabrication of micro opto-mechanical components with highly energetic heavy ion beams

F – GENERAL INFORMATION

List of publications

Seminars

Experiments at LNS Accelerators

Organization and Personnel

PhD Students

Under graduate students

Scientific guests

Events

CHARGE AND MASS DISTRIBUTIONS OF IMF'S PRODUCED IN THE INTERACTION OF $^{58,62}\text{Ni}$ WITH $^{40,48}\text{Ca}$ AT AN INCIDENT ENERGY OF 25 A MEV

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

F. Amorini^{h)}, A. Anzalone^{h)}, G. Cardellaⁱ⁾, S. Cavallaro^{h)}, E. De Filippoⁱ⁾, F. Giustolisi^{h)}, E. Laguidara^{h)}, G. Lanza^{h)}, L. Lanzalone^{h)}, C. Maiolino^{h)}, A. Paganoⁱ⁾, M. Papaⁱ⁾, S. Pirroneⁱ⁾, G. Politiⁱ⁾, F. Porto^{h)}, F. Rizzo^{h)}
for CHIMERA/ISOSPIN Collaboration

a) Dipartimento di Fisica, Università di Trieste and INFN Sezione di Trieste, Italy

b) Dipartimento di Fisica, Università di Firenze and INFN Sezione di Firenze, Italy

c) INFN Laboratori Nazionali di Legnaro, Italy

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

e) LPC Caen, IN2PS-CNRS/ENSICAEN et Université, F-14050 Caen cedex, France

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

g) Institut de Physique Nucleaire, IN2P3-CNRS, F-91406 Orsay Cedex, France

h) Dipartimento di Fisica, Università di Catania and INFN Laboratori Nazionali del Sud, Italy

i) Dipartimento di Fisica, Università di Catania and INFN Sezione di Catania, Italy

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

Abstract

Studies of nuclear dynamics and thermodynamics have been performed by the NUCL-EX group with the 4π array CHIMERA at LNS, measuring the systems $^{58,62}\text{Ni}$ on $^{40,48}\text{Ca}$ at 25 A MeV. The production of light charged particles (LCP) and intermediate mass fragments (IMF) are being investigated as they can provide useful information about the properties of hot nuclear matter. A procedure to identify these products in charge and mass has been tuned. The analysis is still in progress, but preliminary comparisons of theoretical calculations to experimental elemental and isotopic spectra, already obtained for selected angular regions corresponding to a few CHIMERA rings, are presented.

1 INTRODUCTION

The existence of different phases for finite nuclear matter has been confirmed by several experimental signals [1]. The systematic investigation of the phase coexistence region, starting from the liquid side up to some A MeV of available energy is one of the aims of NUCL-EX collaboration. These studies will be performed through experiments both at INFN Laboratories in Legnaro (LNL) and Catania (LNS).

The first experiment has been performed at LNS using the CHIMERA apparatus in the final configuration (1192 detection cells) [2], with beams of $^{58,62}\text{Ni}$ at 25 MeV/A accelerated on $^{40,48}\text{Ca}$ target.

Basically, the production of light charged particles (LCP) and intermediate mass fragments (IMF) are being

investigated as they can provide useful information about the properties of hot nuclear matter.

In order to identify the reaction products several identification methods are used. The ΔE -E method is applied to identify the charge of particles that punch through the silicon detectors. Moreover, an extension of this method to the high gain codified Silicon signals allows the isotopic identification for fragments with charge $Z \leq 9$ [3]. The mass of the fragments stopped in the silicon detectors can be extracted by using the time of flight technique. Finally, the light charged particles that punch through the silicon detector will be identified applying the pulse shape method to the CsI(Tl) fast and slow components [4].

2 LIGHT FRAGMENT IDENTIFICATION

In order to identify fragments in charge and mass, the ΔE -E method is used. For a particle that punches through the first stage of the telescope, the signal coming from the silicon detector can be used as ΔE signal while the CsI signal is used as residual energy signal.

As described in the procedure introduced in [3], sampling on the ΔE -E scatter plot some points on the lines of well defined isotopes, as ^1H , ^4He , ^7Li , ^9Be , ^{11}B , ^{12}C , a set of parameters of a Bethe-Bloch like formula were obtained for each detector so that a minimization routine determines, from the ADC channels, the atomic number and mass of the detected charged products. A one-dimensional mass spectrum (Fig. 1) is thus obtained for each charge with a very good resolution. Beryllium, Boron, Carbon isotopes up to Oxygen and sometimes Fluorine isotopes are clearly separated, as in previous measurements [3]. In addition, also the Hydrogen and Helium isotopes are identified by this procedure, having kept the acquisition thresholds as low as possible.

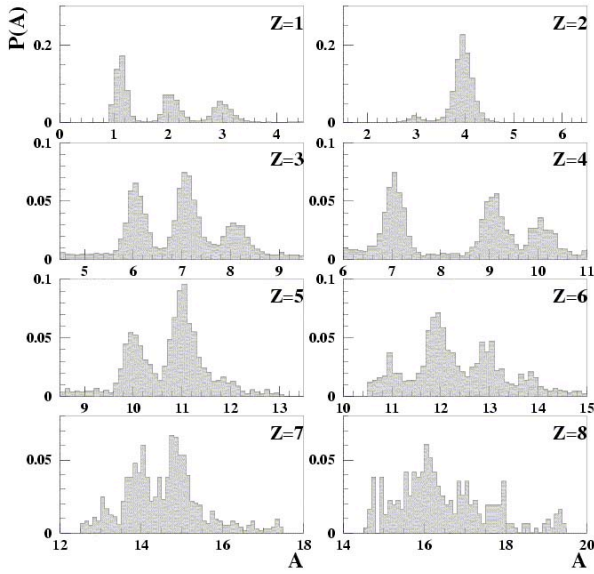


Figure 1 Mass distributions for fragments with $1 \leq Z \leq 8$ obtained for a detector of the sphere (ring10) for $^{58}\text{Ni} + ^{48}\text{Ca}$ system at 25 A MeV.

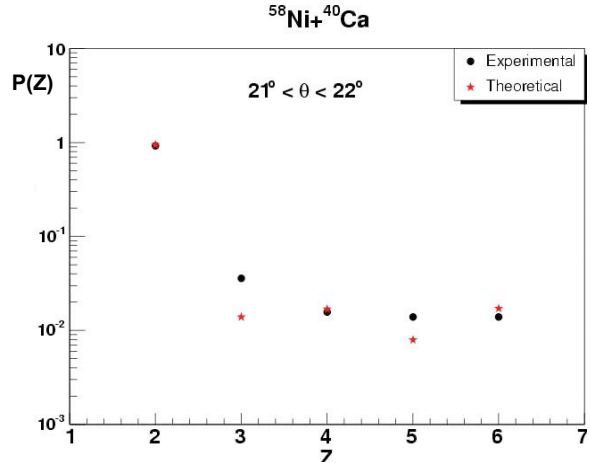
At variance with previous measurements [5], where a particle identification function customised for CHIMERA detectors was used in order to linearize the ΔE -E matrix, the same procedure of mass identification is adopted to obtain the charge identification for all the products that punch through the silicon detector. This is obtained adding to the above mentioned sampled isotopes, some points for the lines $Z=10$, 15 , 20 , 25 . Even if the whole analysis is in progress, some preliminary comparisons with theoretical predictions can be done using the mass and charge identification

obtained for an ensemble of calibrated detectors of 8° and 9° rings.

3 COMPARISONS WITH THEORETICAL CALCULATIONS

On the theoretical ground, calculations were made, for central collision of the two ions, with the Boltzmann Master Equation (BME) Theory [6]. The results obtained for the reaction $^{58}\text{Ni} + ^{40}\text{Ca}$ are compared with data in Figs. 2 and 3 and show that they reproduce quite reasonably the experimental values. In particular, Fig. 2 shows the charge distributions of ejectiles between Helium and Carbon and Fig. 3 their isotopic distributions (up to $Z=5$) for collisions of ^{58}Ni and ^{40}Ca at 25 A MeV in the angular range $21^\circ - 22^\circ$. The large angle fragment emission roughly selects rather central collisions.

Figure 2 Relative charge distributions of the particles



with $2 \leq Z \leq 6$ emitted between 21° and 22° in the interaction of ^{58}Ni with ^{40}Ca at 25 A MeV. The experimental data are given by black full circles, the predicted values by red stars.

However, the contribution of peripheral collisions to the production of IMF cannot be neglected and calculations are in progress to include these mechanisms. This is made according to a model proposed long time ago by Karol [7], which evaluates the reaction cross section for a nuclear collision within a geometrical approach considering the interactions of individual nucleons of the colliding ions in the overlapping region formed once they come into contact. Since this model, among the approaches which have been proposed to evaluate heavy ion reaction cross sections, seems to be the one that best fits with the formalism underlying BME theory, we did improvements and generalizations in order to apply it to the present measurements.

Present calculations predict the production of charged products with rather high kinetic energies exceeding, in the considered polar range, about 70 MeV in the case of α -particles, 100 MeV in the case of Li and Be, and 150

MeV in the case of B and C. This suggests that the experimental thresholds should slightly affect the measured spectra. Within this model, the IMF's are found to be mainly produced by nucleon coalescence before thermalization, in contrast with the α -particles which are also emitted in the evaporation of hot equilibrated nuclei at the end of the nuclear thermalization phase.

This mechanism of dynamical clustering of IMF's is described in [8] and, as reminded above, allows to very satisfactorily reproduce the low energy component of IMF spectra measured in very asymmetric reactions induced by light ions on medium and heavy nuclei. For this latter case, the measured energetic forward emission of IMF's is described as the contribution of the projectile's break-up [8-9] which could be less relevant for heavier symmetric systems.

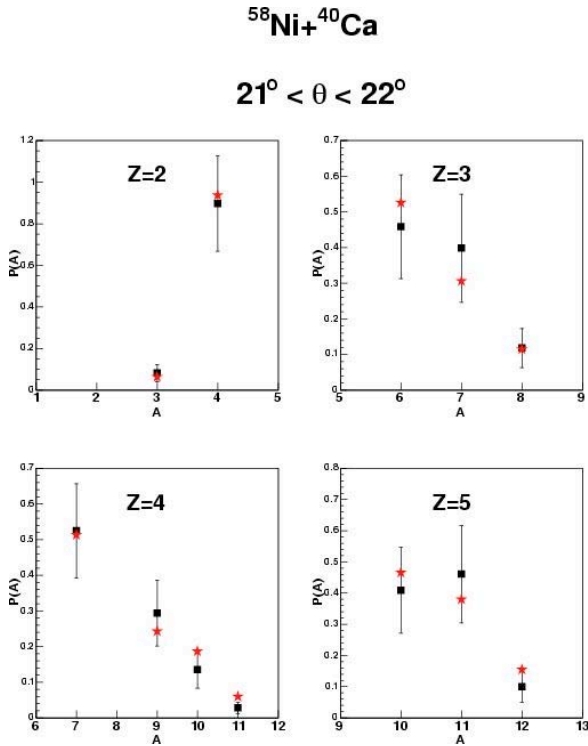


Figure 3 Relative mass distributions for ejectiles with $2 \leq Z \leq 5$ emitted between 21° and 22° in the interaction of ^{58}Ni with ^{40}Ca at 25 A MeV. The experimental data are given by full squares, the predicted values by stars.

These coalescence processes could also play a role in the midvelocity emissions in symmetric systems at the Fermi regime [10] and it is also in this perspective that the present study has been undertaken.

Even if present calculations must be considered very preliminary, the results of these comparisons are encouraging.

The analysis is still in progress. For the near future, on the theoretical side, we are studying in order to include mechanisms due to different impact parameters. Concerning the experimental data, we are tuning an

accurate selection of the events through refined statistical methods [11], in order to study very specific classes of reactions.

4 ACKNOWLEDGMENTS

The NUCL-EX Collaboration would like to thank CHIMERA-ISOSPIN Collaboration and the technical staff of INFN Catania and LNS, for skillful operating of the whole apparatus.

Special thanks are due to the Laboratori Nazionali del Sud Tandem and Cyclotron staff and particularly to D. Rifuggiato for having provided beams of very good quality for stability and timing.

5 REFERENCES

- [1] see for instance Ph. Chomaz, Proceedings of INPC2001, AIP proceedings Vol.610 (2002)167; M. D'Agostino *et al.*, Nucl. Phys. A734 (2004) 512
- [2] A. Pagano *et al.*, Nucl. Phys. A734 (2004) 504
- [3] N. Le Neindre *et al.*, Nucl. Instr. Meth. A490 (2002) 251
- [4] M. Alderighi *et al.*, Nucl. Instr. Meth. A489 (2002) 257
- [5] A. Pagano *et al.*, Nucl. Phys. A681 (2001) 331; M. Alderighi *et al.*, INFN-LNS Activity Report (2000) 41
- [6] M. Cavinato *et al.*, Nucl. Phys. A643 (1998) 15; Nucl. Phys. A679 (2001) 753
- [7] P. J. Karol, Phys. Rev. C11 (1975) 4
- [8] E. Gadioli *et al.*, Nucl. Phys. A708 (2002) 391; Eur. Phys. J. A17 (2003) 195
- [9] B. Becker *et al.*, Eur. Phys. J. A18 (2003) 639
- [10] S. Piantelli *et al.* Phys. Rev. Lett. 88 (2002) 052701; B. Davin *et al.* Phys. Rev. C65 (2002) 064614
- [11] E. Geraci *et al.*, Nucl. Phys. A732 (2004) 173

CALIBRATION OF CsI(Tl) SCINTILLATORS FOR LIGHT CHARGED PARTICLES (Z=1) IN THE FIRST CAMPAIGN OF REVERSE EXPERIMENT

J. Blicharska^{1,*}, M. Alderighi², A. Anzalone³, L. Auditore⁴, R. Barna⁴, V. Baran³,
I. Berceanu⁵, M. Bartolucci⁶, A. Bonasera³, B. Borderie⁷, R. Bougault⁸, M. Bruno⁹,
J. Brzychczyk¹⁰, G. Cardella¹¹, S. Cavallaro³, A. Chibihi¹², M. Colonna³,
M. D'Agostino⁹, R. Dayras¹³, E. De Filippo¹¹, D. De Pasquale⁴, M. Di Toro³,
W. Gawlikowicz¹⁰, E. Geraci³, F. Giustolisi³, A. Grzeszczuk¹, P. Guazzoni⁶, D. Guinet¹⁴,
M. Iacono Manno³, A. Italiano⁴, S. Kowalski¹, E. La Guidara³, G. Lanzano¹¹,
G. Lanzalone^{3,11}, N. Le Neindre^{8,9}, S. Li¹⁵, S. Lo Nigro¹¹, C. Maiolino³, Z. Majka¹⁰,
G. Manfredi⁶, A. Pagano¹¹, M. Papa¹¹, M. Petrovici⁵, E. Piasecki¹⁶, S. Pirrone¹¹,
R. Płaneta¹⁰, G. Politi¹¹, A. Pop⁵, F. Porto³, M. F. Rivet⁷, E. Rosato¹⁷, R. Russo⁶,
P. Rusotto³, K. Schmidt¹, G. Sechi², V. Simion⁵, M. L. Sperduto³, J. C. Steckmeyer⁸,
A. Trifiro⁴, M. Trimarchi⁴, G. Vannini⁹, M. Vigilante¹⁷, J. P. Wieleczko¹²,
J. Wilczyński¹⁸, H. Wu¹⁵, Z. Xiao¹⁵, L. Zetta⁶, W. Zipper¹

¹ *Institute of Physics, University of Silesia, Katowice, Poland*

² *Istituto di Fisica Cosmica, CNR and INFN, Milano, Italy*

³ *LNS and Dipartimento di Fisica, Università di Catania, Italy*

⁴ *INFN and Dipartimento di Fisica, Università di Messina, Italy*

⁵ *Institute for Physics and Nuclear Engineering, Bucharest, Romania*

⁶ *INFN and Dipartimento di Fisica, Università di Milano, Italy*

⁷ *IPN, IN2P3-CNRS and Université Paris-Sud, Orsay, France*

⁸ *LPC, ISMRA, Université de Caen, France*

⁹ *INFN and Dipartimento di Fisica, Università di Bologna, Italy*

¹⁰ *Institute of Physics, Jagiellonian University, Cracov, Poland*

¹¹ *INFN and Dipartimento di Fisica, Università di Catania, Italy*

¹² *GANIL, CEA, IN2P3-CNRS, Caen, France*

¹³ *DAPNIA-SPhN, CEA Saclay, France*

¹⁴ *IPN, IN2P3-CNRS and Université Claude Bernard, Lyon, France*

¹⁵ *Institute of Modern Physics, Lanzhou, China*

¹⁶ *Institute of Experimental Physics, University of Warsaw, Poland*

¹⁷ *INFN and Dipartimento di Fisica, Università di Napoli, Italy*

¹⁸ *Institute of Nuclear Studies, Otwock-Świerk, Poland*

* *Corresponding author, e-mail: jblichar@us.edu.pl*

Abstract

Two different function describing relation between energy value E and light output L were tested. The more useful of them was chosen to obtain energy calibration for light charged particles ($1 \leq Z \leq 3$). In this work the energy plots of hydrogen isotopes obtained for reaction $^{124}\text{Sn} + ^{64}\text{Ni}$ at 35 MeV/A are presented.

1 INTRODUCTION

The forward part of CHIMERA detector was built of 688 CsI(Tl)-Si telescopes. The telescopes were designed for detection of charged particles produced in heavy ion collisions.

The light isotopes lose a part of their energy in the Si detector, then they are stopped in CsI(Tl) crystal causing a pulse of light.

As we know [1, 2] the CsI crystal provides a light signal with two components: the fast decay component and the slow decay component.

The fast component depends on energy of the detected particle while the slow component varies with the particle type. This property of the CsI crystal is the base of the pulse shape analysis.

The discrimination technique applied for CHIMERA detector uses two gates method [3] adapted for photodiode readout [4].

As it is well known, the response of CsI(Tl) crystal is not linear with energy, especially for heavy ions and for low energy particles [1] Therefore a direct relation between energy value E and light output L is needed. It is preferable to elaborate the relation in the form of $E = f(L, Z, A)$ function.

2 THE FORMULA

As we reported previously [5] the simple function [6]:

$$E = f_1(L, Z, A) = kA^\alpha Z^\beta L^\gamma,$$

was tested, where the light output L is directly related to the fast component (named *fastpg*) by the equation:

$$L = \text{fastpg} - l_1$$

and k, α, β, γ and l_1 are the global fit parameters.

The plot of the function f_1 , fitted with experimental points is shown on the top panel of Fig. 1.

The points were obtained from reaction $^{124}\text{Sn} + ^{64}\text{Ni}$ at 35 MeV/A measured in the first campaign of REVERSE experiment (see Ref. [7]).

Unfortunately, the relation has not given satisfying results for hydrogen isotopes. Therefore it was necessary to find another function which gives better results.

From the literature [8] we know the function which was tested for protons:

$$E = aW(Z)L + bZ \ln(1 + cW(Z)L),$$

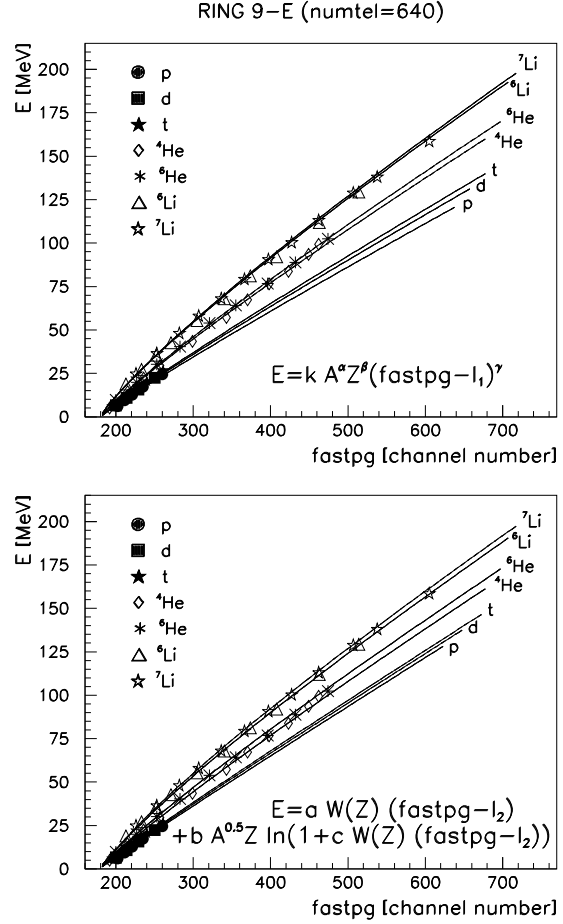


Figure 1: Light output of the CsI(Tl) as a function of energy for some ions. On the top panel the solid lines are result of fit with the function f_1 , and on the bottom panel – with the function f_2 .

investigated specially for the light charged particles, detected in plastic-CsI(Tl) telescopes, where:

$$W(Z) = p_1 \frac{\ln(1 + p_2 Z)}{Z} (1 - \exp - p_3 Z^{p_4}),$$

and $a, b, c, l_2, p_1, p_2, p_3, p_4$ are the global fit parameters.

To obtain the energy calibration for hydrogen isotopes we used the function in the form adapted for Si-CsI(Tl) telescopes:

$$E = f_2(L, Z, A) = aW(Z)L + bZ\sqrt{A} \ln(1 + cW(Z)L),$$

where:

$$L = \text{fastpg} - l_2.$$

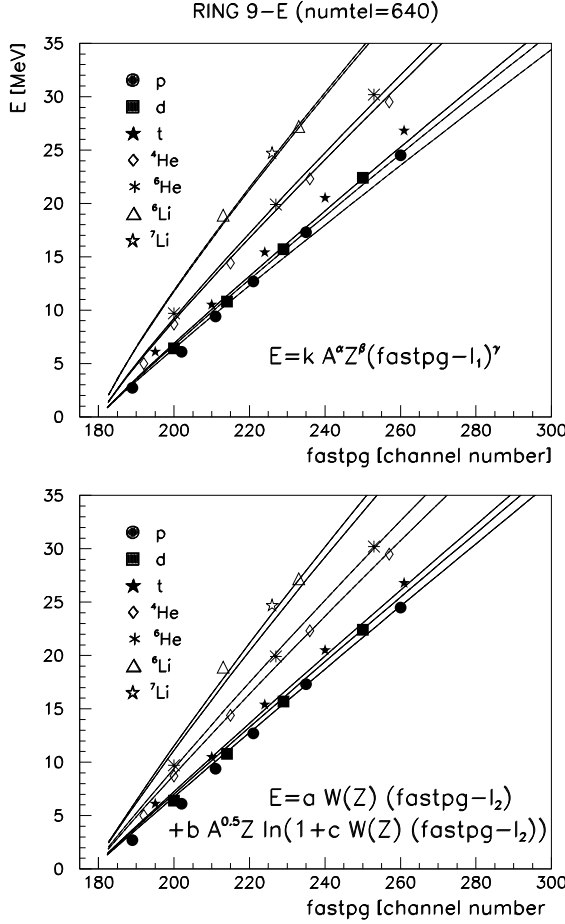


Figure 2: Light output of the CsI(Tl) as a function of energy for some ions. The plots are enlarged low energy regions of top and bottom panel shown on Fig. 1, respectively.

The plot of the function f_2 , fitted with the same experimental points, is shown on the bottom panel of Fig. 1.

One can see that lines corresponding to hydrogen isotopes are not consistent with analogous lines on the top panel.

The enlarged low energy regions for both functions are shown on Fig. 2.

3 RESULTS

For the helium and lithium isotopes, both functions: f_1 and f_2 , give very similar energy scaling. For hydrogen isotopes the function f_1 gives completely different energy scaling then the function f_2 .

In Figures 3, 4, 5 the energy plots obtained for ^1H , ^2H , ^3H using the function f_2 are shown,

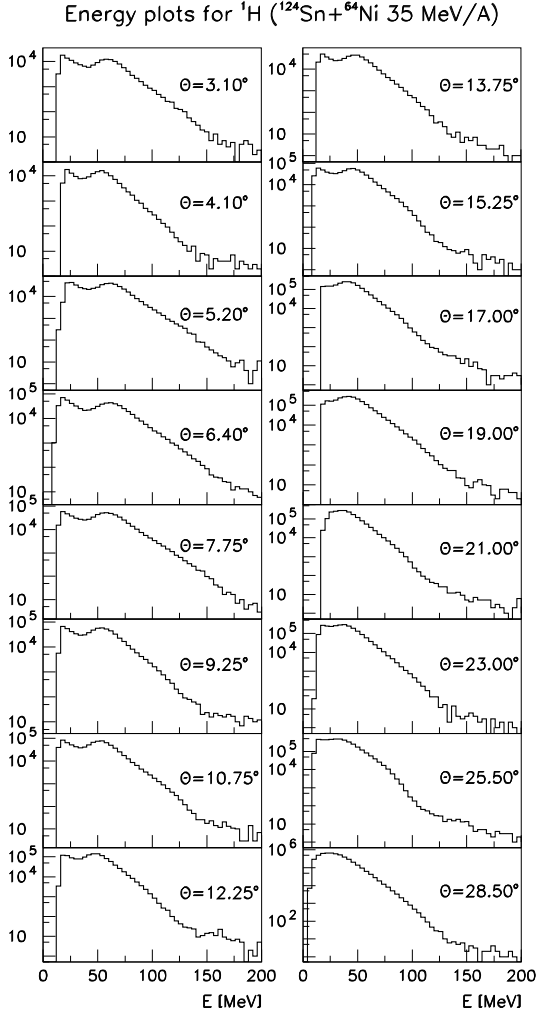


Figure 3: Energy plots for protons. For each angle θ the spectra was integrated over whole ring.

respectively. The vertical axes correspond to the number of counts. The results as an example are shown for the reaction $^{124}\text{Sn} + ^{64}\text{Ni}$ at 35 MeV/A.

4 CONCLUSIONS

One can see that for some rings results obtained using the function f_2 are not fully satisfying. Nevertheless they are much better then results obtained using the function f_1 , which for hydrogen isotopes can give improper energy scaling [9].

However the function f_2 for the global fit parameters gives proper energy scaling for helium

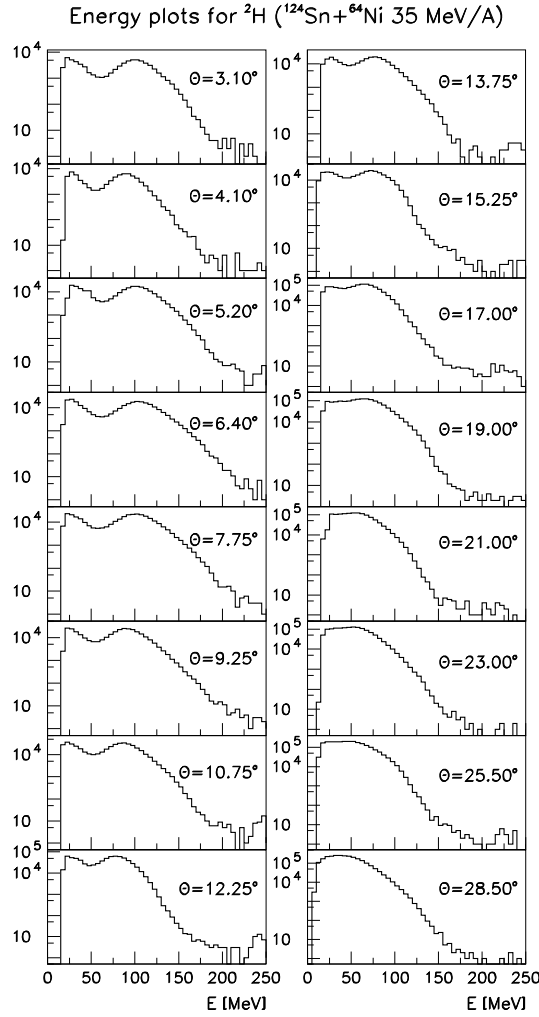


Figure 4: Energy plots for deuterons. For each angle Θ the spectra was integrated over whole ring.

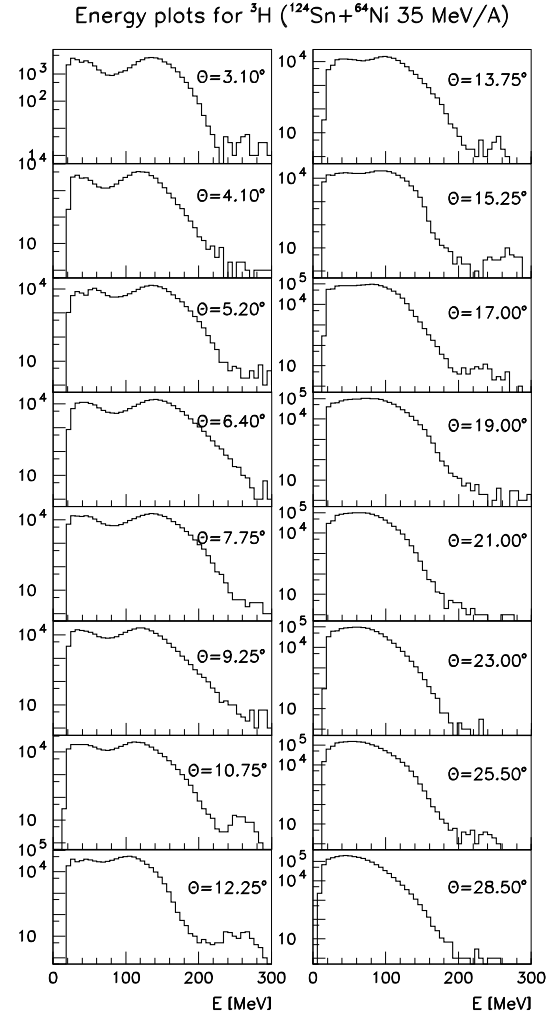


Figure 5: Energy plots for tritons. For each angle Θ the spectra was integrated over whole ring.

and lithium isotopes as well as for hydrogen isotopes.

The uncertainty of the energy scaling is estimated to be about 20% of the energy values.

REFERENCES

- [1] Y. Larochelle et al., Nucl. Instr. and Meth. **A348** (1994) 167.
- [2] D. W. Stracener et al., Nucl. Instr. and Meth. **A294** (1990) 483.
- [3] X. Alarja et al., Nucl. Instr. and Meth. **A242** (1986) 352.
- [4] D. Guinet et al., Nucl. Instr. and Meth. **A278** (1989) 614.
- [5] J. Blicharska et al., LNS Activity Report (2001) 113.
- [6] D. Cebra et al., Nucl. Instr. and Meth. **A313** (1992) 367.
- [7] J. Blicharska et al., Contribution for V-th Meeting of REVERSE Collaboration, Catania (2002).
- [8] W. Gawlikowicz et al., **UR-NCUR 01-04**, Rochester, New York (2001).
- [9] J. Blicharska, PhD thesis, to be published, Katowice (2004).

SEARCH FOR CONDENSATES OF ALPHA-PARTICLES IN ^{32}S

BY ALPHA-PARTICLE TRANSFER

M. Brenner^{a,*}, M.Lattuada^b, S.V. Khlebnikov^c, W.H. Trzaska^d, L.Krasnov^e, S.E. Belov^e, M.Gulino^b,
V.V. Lazarev^e, Li Chengbo^{b,f}, M.Mutterer^g, G.Prete^h, G.P.Tiourin^{c,d}, M.Zadro^{b,i}

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

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

c) V.G. Khlopin Radium Institut, St. Petersburg, Russia

d) Accelerator Laboratory, University of Jyväskylä, Finland

e) Faculty of Physics, St. Petersburg State University, Russia

f) University of Lanzhou, China

g) Institut of Physics, Technical University of Darmstadt, Germany

h) INFN, Laboratori Nazionali di Legnaro, Italy

i) Ruder Boškovich Institut, Zagreb, Croatia

Abstract

In order to search for cluster structure at high excitation of ^{32}S and its break up into four alpha particles and ^{16}O , the energy range above and below the break up threshold has been investigated. The preliminary results give evidence for the existence of excited levels that decay to excited states in ^{16}O . In agreement with expectations the yield goes low at the break up energy.

1 INTRODUCTION AND METHOD

The search for an alpha-particle condensate in nuclei was motivated by an interpretation of the observations of a mixed-parity rotational band in ^{32}S from alpha-particle scattering on ^{28}Si targets [1] and an indication of a sudden reduction in the scattering yield at the energy of break-up of ^{32}S at 31 MeV of excitation [2]. To look for states below and above that energy, the $^{28}\text{Si}(^6\text{Li},d)^{32}\text{S}$ was studied using the ^6Li beam of the LNS Tandem.

Five ΔE -E telescopes were mounted at angles between 15° and 65° in the scattering chamber to identify particles and measure their energy. The 5000 μm E-detectors were provided with a cooling system consisting in spirals around the detectors. To take advantage of the forward-backward angular correlation of the deuterons and the alpha-particles emitted in the decay of states in ^{32}S [3], alpha particles were detected by two position-sensitive detectors in the backward directions between 172° and 146° .

To calibrate the E-detectors, a 200 $\mu\text{g}/\text{cm}^2$ silicon target on a plastic backing of a few $\mu\text{g}/\text{cm}^2$ was bombarded with 22 MeV ^6Li . In the spectrum of protons two peaks show up, due to protons from the scattering of the beam particles from hydrogen, the stronger one due to elastic and the weaker due to inelastic scattering, by which the

first excited state of ^6Li was populated. The deuteron spectra exhibited peaks due to the population of states in ^{16}O and ^{20}Ne by alpha-particle transfer to carbon and oxygen in the target. Eight, in comparison to the last mentioned, weak peaks were assigned to states in ^{32}S , by the absence of a kinematic shift, when comparing excitation functions of states in ^{32}S as derived from the deuteron spectra taken at five angles. Since the energies of the oxygen and carbon peaks were well known, they were used for the calibration of the E-detectors. The energy calibration of the ΔE -detectors and the energy and angular calibration of the position sensitive detectors were carried out by an alpha- particle source.

2 EXPERIMENT AND RESULTS

A 370 $\mu\text{g}/\text{cm}^2$ self-supporting silicon target was bombarded by a 47 MeV ^6Li beam. Runs, in which both singles and d- α coincidences were collected, were followed by a 3000 mC exposure of only coincidence acquisition to allow for good statistics. So far only the latter has given interesting information about states assumed to exist at high excitation in ^{32}S . By a proper setting of the gain of the E-detector chains, an energy range of 27 to 41 MeV of excitation in ^{32}S by alpha-particle transfer was covered. No structure of excited

states can be observed in the ungated deuteron spectra. In different plots of the energies of the deuteron and alpha-particles versus the energy of ^{28}Si [4] or one pair of relative energies versus another [5], lines are observed. When events of the most conspicuous line were selected by geometrical cuts of the program PAW++ [6] the number of events was drastically reduced. This indicates that the yield of the transfer reaction is small in comparison to competing reaction channels. From the conservation of energy and momentum the q-values of the reaction were derived. Only ^{28}Si , out of the three final particles, can be excited. A peak near zero in the q-value spectrum corresponds to the ground state in ^{28}Si .

In the excitation functions for the ^{32}S by alpha transfer, peaks at 29 and 36 MeV are clearly observed, when events of populating the ^{28}Si ground state are selected. At the break up energy 31 MeV the yield falls to zero as shown in Fig. 1. Above that energy the broad peak hints at new reaction channels being opened.

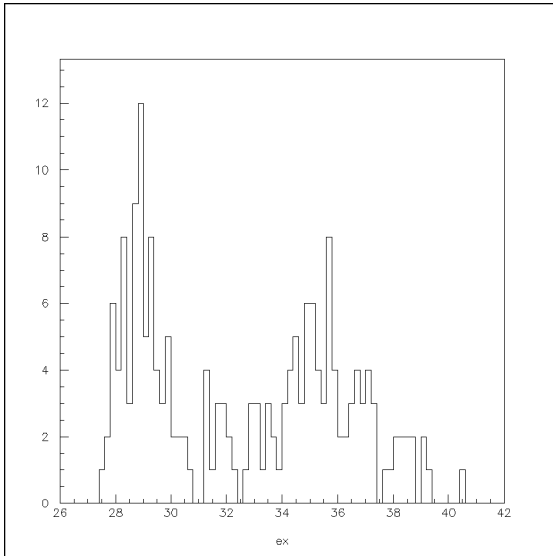


Fig.1 Transfer yield versus excitation energy in ^{32}S . Note the missing yield at the break up energy 31 MeV

So far only coincidences between deuterons in the telescope at 15° and the position sensitive detector between 162° and 171° are considered. The widths at half-maximum of the peaks are approximately 1.3 and 2.8 MeV. The number of events decreases with the increase in telescope angle. At 45° poor statistics do not allow for identification of excited states.

3 CONCLUSIONS

The above results are very preliminary. To search for structure of the broad peaks observed further investigation of the data is necessary. A recent experiment on the inverse reaction (^{28}Si beam on ^6Li

target) is expected to give additional evidence and support for the present results. Agreement with Fig.1 has been found in alpha-particle scattering from ^{28}Si [7].

In the region above break up the channel of decay into four alpha particles may open. The results encourage measurement of the multiplicity of the alpha-particles there. To allow for the detection of fast alpha-particles, a ^{28}Si beam on a ^6Li target is suggested.

4 REFERENCES

- [1] K.A. Gridnev et al., in Cond. Matter. Theor.15 (Nova Science Publishers IncNY, 2000).
- [2] M. Brenner et al., Proc. Symp. Nuclear Clusters: From Light Exotic to Superheavy Nuclei, edd R. Jolos and W. Scheid (EP Systema, Debrecen, Hungary, 2003).
- [3] A.P. Artemov et al., Sov. J. Nucl.. Phys. 55(1992)492.
- [4] E. Costanzo et al. NIM A295(1990)373.
- [5] A. Tumino et al., Eur. Phys. J. A12(2001)327.
- [6] wwwasd.web.cern.ch/cernlib/cernbin
- [7] K.-M. Källman, T. Lönnroth, M. Guttormsen, to be published.

EXCITED STATES OF ^{19}O

F.Cappuzzello^{a,*}, M.Cavallaro^{a,b}, A.Cunsolo^{a,b}, A.Foti^{b,c},
C.Nociforo^a, S.E.A.Orrigo^{a,b}, J.S.Winfield^a, D.Beaumel^d, S.Fortier^d

a I.N.F.N. - Laboratori Nazionali del Sud, Catania, Italy

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

c I.N.F.N. - Sezione di Catania, Catania, Italy

d Institut de Physique Nucléaire, IN2P3-CNRS, Orsay Cedex, France

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

Abstract

The $^{19}\text{F}(^7\text{Li}, ^7\text{Be})^{19}\text{O}$ reaction at 56 MeV incident energy was studied at forward angles in order to explore the ^{19}O excitation energy spectrum. The energy resolution (~ 50 keV) allowed the clear identification of the doublet composed of the ground and the state at 96 keV. Also populated is a known state at 1.472 MeV. All of these transitions are observed each for the ^7Be ground and first excited states at $E_x = 0.429$ MeV. Analysis is still in progress to ascertain other structures observed in the spectrum.

1 INTRODUCTION

In the last few years an increasing attention has been given to the study of both the structural properties of nuclei lying near the drip-lines and to the high isospin dynamics. Under these conditions the standard representation of nuclei, based on the assumption of mean field dynamics, turns out to be often inadequate. From a theoretical point of view the explanation of phenomena near the drip lines has been a valuable benchmark allowing a strong development of refined microscopic theories of structure and reaction mechanisms of nuclei. This has been due to the necessity to describe the increasing role of the nucleon nucleon pairing and of the coupling of the loosely bound nucleons to the excited states of the core. A microscopic description of this coupling (Dynamical Core Polarisation, see [1] and references therein), for example, has been demonstrated to be very important in order to explain the well known shell inversion between $2s_{1/2}$ and $1p_{1/2}$ in ^{11}Be ground state or that between $2s_{1/2}$ and $1d_{5/2}$ in the $N = 9$ isotones beyond ^{14}B and ^{15}C .

Other phenomena connected with that mechanism are observed in transfer or charge exchange (CEX) reactions. One of the most striking one is the appearance of narrow resonances embedded in the continuum (called BSEC) [2], showing that the valence nucleon remains bound to the core even when the energy transferred to the whole nucleus by the direct process would be enough to extract it. Examples of this are found in the ^{11}Be and ^{15}C spectra populated via the $^{11}\text{B}(^7\text{Li}, ^7\text{Be})^{11}\text{Be}$ and $^{15}\text{N}(^7\text{Li}, ^7\text{Be})^{15}\text{C}$ reactions at Tandem energies [3-6], or the tails of the parallel momenta distributions in the break-up experiments.

In previous experiments done at the Tandem laboratory of the IPN-Orsay, we have studied the response of ^7He , ^{11}Be and ^{15}C nuclei to the CEX probe

via the $(^7\text{Li}, ^7\text{Be})$ reaction at 57 MeV [3-6], by detecting the ^7Be ejectiles with the high resolution Split-Pole spectrometer. The three cases represent systems where a core constituting of an integer number of α particles is coupled to a system of three neutrons. Assuming that single particle excitations from the α clusters can be considered rather unlikely, the three neutron dynamics in the nuclear medium can be studied by exploring the excitation energy spectra of these nuclei. The pairing of two of the three neutrons to the core to form a more soft core is expected to be an important part of the three neutron phase space and phenomena directly associated to that are observed in the experimental results.

In the view of a systematic exploration of these phenomena for the $N\alpha + 3n$ systems as a function of the mass, the same technique, based on the $(^7\text{Li}, ^7\text{Be})$ reaction, has been applied to the study of ^{19}O , i.e. the $N = 4$ nucleus.

2 EXPERIMENTAL SET UP AND PRELIMINARY RESULTS

The experiment was performed at the IPN-Orsay Tandem laboratory using a 56 MeV $^7\text{Li}^{++}$ beam and a $100 \mu\text{g}/\text{cm}^2$ $^{27}\text{Al}^{19}\text{F}_3$ solid target on $30 \mu\text{g}/\text{cm}^2$ ^{27}Al backing, constructed at the LNS, Catania. The ^7Be ejectiles were detected by the IPN-Orsay Split-Pole magnetic spectrometer. The focal plane detector consisted of a proportional gas (pure propane at 300 mbar) counter with cathode strips read by delay-line and a stopping plastic scintillator. A silicon $\Delta E-E$ telescope, mounted in the scattering chamber at 30° , was used to monitor the elastic scattering, in order to normalize the data obtained in different runs. The ^7Be momentum spectra were measured at $\theta_{\text{LAB}} = 0^\circ$ and 2.7° . In Figure 1 the spectrum at $\theta_{\text{LAB}} = 0^\circ$ is presented.

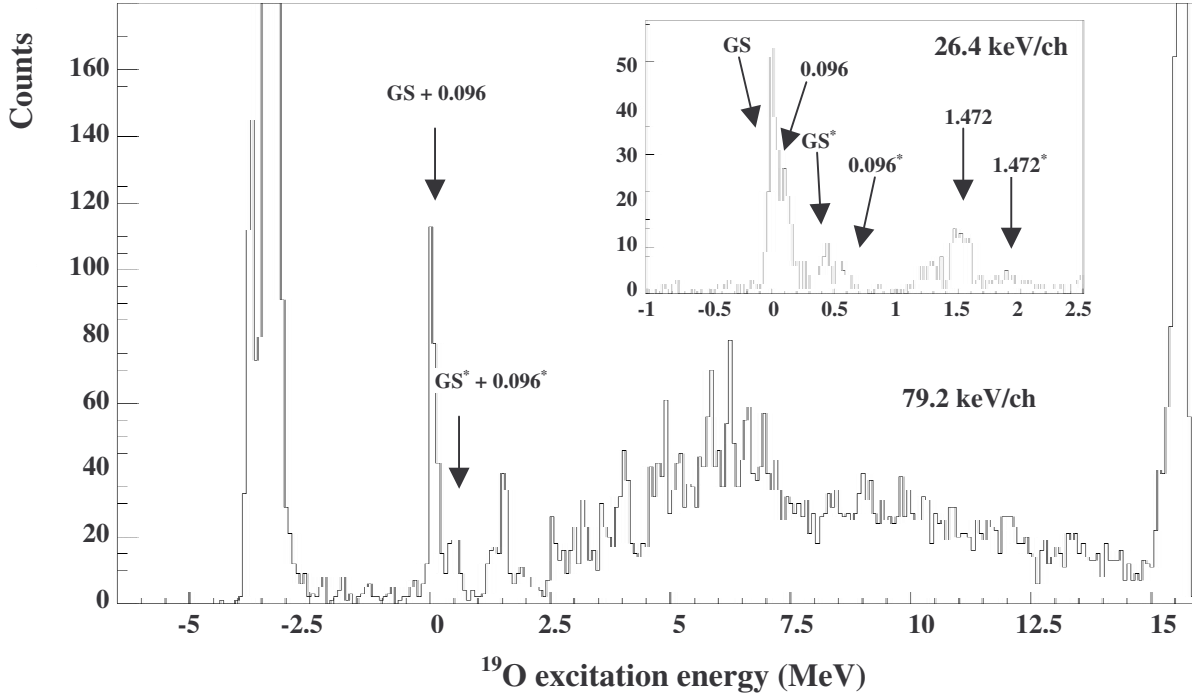


Figure 1. Excitation energy spectrum for the $^{19}\text{F}(^7\text{Li},^7\text{Be})^{19}\text{O}$ reaction at 56 MeV measured at 0° . In the plot the peaks marked with an asterisk are associated to the excitation of ^7Be at 0.429 MeV. In the insert a detail of the spectrum at a finer bin size is shown.

As shown in Figure 1 the $5/2^+$ ^{19}O ground state is separated from the $3/2^+$ first excited state as a consequence of the good energy resolution obtained (~ 50 keV). In addition the two bound ^7Be states populated by the $(^7\text{Li},^7\text{Be})$ CEX reaction, i.e. the $3/2^-$ ground state and the 0.429 MeV $1/2^-$ first excited state, are also well separated.

The four peaks associated to the transitions to the ^{15}C ground state and the known $E_x = 0.096$ first excited one, with and without excitation of ^7Be , and the peaks associated to the $^1\text{H}(^7\text{Li},^7\text{Be})n$ reaction were identified and used for the focal plane calibration, giving an overall error on the excitation energy of less than 50 keV for each spectrum.

The background from the ^{27}Al in the target and from possible ^{16}O and ^{12}C contaminants were estimated by means of supplemental run on a pure ^{27}Al target and a Mylar one. The analysis of these contributions is still in progress. In any case a preliminary inspection of these contaminant spectra shows that the ^{27}Mg states excited by the $(^7\text{Li},^7\text{Be})$ reaction are visible in the ^{19}O spectrum starting from -2.5 MeV in the scale of Figure 1. In particular we see that the peaks observed at 1.2 and 2.6 MeV in the ^{19}O spectrum are those mostly excited, corresponding to transitions to the 3.5 and 5 MeV of ^{27}Mg , while all the other have a minor influence. As regards the $(^7\text{Li},^7\text{Be})$ reaction on ^{16}O and ^{12}C , we see that the first plays a role beyond 5.8 MeV, while the

second has a much less influence and only starts from 8 MeV. This preliminary analysis shows that we observe the known state at 1.472 MeV together with other states at higher excitation energy of ^{19}O .

5 REFERENCES

- [1] S.Fortier et al., Physics Letters B461(1999)22.
- [2] G.Baur and H.Lenske, Nuclear Physics A282(1977)201.
- [3] F.Cappuzzello et al., Physics Letters B516(2001)21.
- [4] F.Cappuzzello et al., Nuclear Physics A, in press.
- [5] C.Nociforo Ph.D. thesis, Università di Catania, 2001.
- [6] F.Cappuzzello et al., EuroPhysics Letters 65(2004)766.

THE ANALYSIS OF THE 2003 CALIBRATION CAMPAIGN OF THE CHIMERA 4 π DETECTOR

G.Cardella^{a,*}, U. Abbondanno^d, C. Agodi^b, R. Alba^b, A. Anzalone^b, F. Amorini^{b,c}, L. Auditore^m, L. Bardelli^e, I. Berceanu^h, J. Blicharska^k, R. Bougault^g, S. Cavallaro^{b,c}, M. B. Chatterjee^h, A. Clivioⁱ, R. Coniglione^b, M. D'Agostinoⁱ, E. De Filippo^a, J. De Sanctis^j, S. Fabbri^j, E. Geraci^j, A. Grzeszczuk^k, B. Guiot^l, C. Iacono Manno^b, E. La Guidara^{b,c}, G. Lanza^a, G. Lanzalone^{b,c}, N. Le Neindre^l, C. Maiolino^b, A. Pagano^a, M. Papa^a, S. Pirrone^a, G. Politi^{a,c}, A. Popⁱ, F. Porto^{b,c}, F. Rizzo^{b,c}, P. Russotto^c, D. Santonocito^b, P. Sapienza^b, K. Schimdt^k, M. L. Sperduto^{a,c}, A. Stefanini^e, P. Staccioli^e, A. Trifiro^m, M. Trimarchi^m, M. Vigilanteⁿ, W. Zipper^k.

- a) INFN Sezione di Catania, Italy
- b) INFN-LNS, Italy
- c) Dipartimento di Fisica, Università di Catania, Italy
- d) Dipartimento di Fisica, Università di Trieste and INFN Sezione di Trieste, Italy
- e) Dipartimento di Fisica, Università di Firenze and INFN Sezione di Firenze, Italy
- f) Institute for Physics and Nuclear Engineering, Bucharest, Romania
- g) LPC Caen, IN2P3-CNRS/ENSICAEN et Université, F-14050 Caen cedex, France
- h) Saha Institute of Nuclear Physics Kolkata, India
- i) Dipartimento di Fisica, Università di Milano and INFN Sezione di Milano, Italy
- j) Dipartimento di Fisica, Università di Bologna and INFN Sezione di Bologna, Italy
- k) Institute of Physics, University of Silesia, Katowice, Poland
- l) Institut de Physique Nucleaire, IN2P3-CNRS, F-91406 Orsay Cedex, France
- m) Dipartimento di Fisica, Università di Messina and INFN Sezione di Messina, Italy
- n) Dipartimento di Fisica, Università di Napoli and INFN Sezione di Napoli, Italy

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

Abstract

The analysis of calibration data of the 2003 campaign of the CHIMERA detector is going on. We started with the analysis of the pulser runs to get a first mV/ch calibration. We can now convert such calibration in energy using as reference points elastic peaks obtained with beam. A problem of saturation of CsI detector was observed and understood. The solution to this problem was found increasing the bias of preamplifier.

1 INTRODUCTION

One of the main tasks in the analysis of a 4π detector is to produce a reliable detector calibration. In 2003 we performed the first experimental campaign of the complete CHIMERA detector[1]. We had to perform many runs dedicated to the energy calibration of the detector and now we are involved in the big task of extract good calibration parameters. In this report we outline the different steps we have to perform and the already obtained results.

2 THE CALIBRATION DATA

The standard CHIMERA calibration procedures were set during the 2000 REVERSE[2] campaign performed with the forward part of CHIMERA. A level zero calibration was given by the mV/ch conversion obtained by the pulser runs. After this step, using some physical points, the energy calibration was obtained. Also for the 2003 campaign we planned to use the same procedure. Many runs were dedicated to pulsers also in order to check for electronic gain shifts. The calibration physical points were obtained using both cyclotron and tandem beams. Tandem beams are very useful because they can be delivered at energy lower than coulomb barrier on gold target. In this way we are able to get elastic peaks also at the most backward angles of CHIMERA (176°). Higher energy Cyclotron beams can be used to get reference points for CsI(Tl) detectors. Beams of ^{12}C , ^{16}O , ^{19}F , ^{32}S , ^{64}Ni , were delivered at various energies. The lighter beams (^{12}C and ^{16}O) are now used as “physical points” to obtain the first step of the energy calibration, whereas the higher charge beams will be used to get correction factors to take into account pulse height defect [3]. In particular to have a direct comparison some runs were performed at a common energy of 100 MeV using beams of ^{16}O , ^{19}F , ^{32}S , ^{64}Ni .

3 THE PULSER ANALYSIS

Many runs were dedicated to pulsers also in order to check for shift of the electronics. During a typical pulser run a series of pulses of different amplitude is injected in the preamplifiers. In fig.1 it is shown a typical pulser run in a silicon detector. The two peaks with higher statistics are used as reference points for the millivolt value identification. An excellent stability was observed for silicon detectors. The peak position is maintained from the first run of February up to the last run of the campaign, in late July.

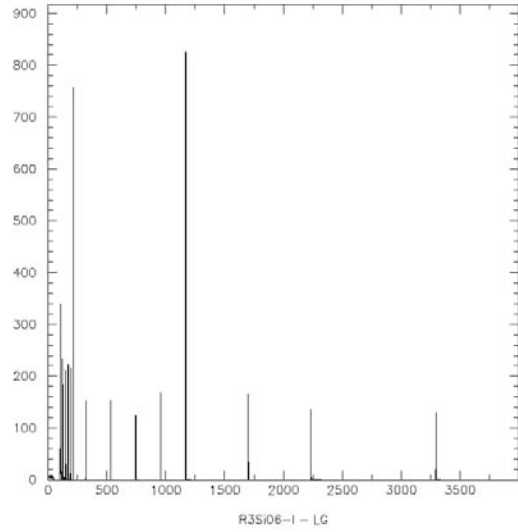


Fig.1 Typical pulser spectrum obtained for silicon detectors

The mV/ch conversion has been already obtained for all silicon detectors. Unfortunately for CsI detectors we had some different behaviors. In fig. 2 we show a comparison of two pulser runs for a detector of ring 8. The second reference peak is clearly shifted of about 300 channels and another peak appears near channel 4000 in run 577.

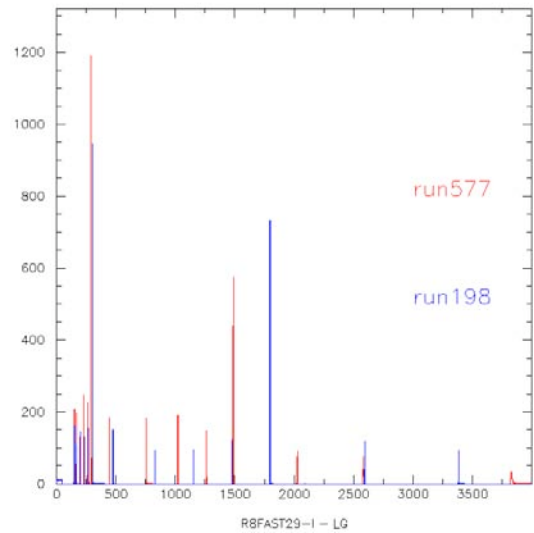


Fig.2 Comparison of CsI pulser run 198 and 577 for one detector of ring 8

The shift is due to a saturation of the preamplifier pulser. After some test we have discovered that the saturation was a consequence of the decrease of the imposed temperature of the cooling system used to

improve the performance of silicon detectors. Due to some problems of mother board components, at low temperature, the effective bias of CsI preamplifier was reduced generating the saturation of the pulses. Now the problem has been solved modifying the LV modules and increasing the maximum value of bias at which they can be operated. However we had to follow the behavior of CsI along all the runs of the last campaign to recover for this problem with a large increase of the calibration work.

4 OTHER ANALYSIS WORK

Other work is started to get the charge - mass identification through the ΔE -E scatter plots following the procedures outlined in ref.[4]. In a different way from the REVERSE campaign, for the 2003 lighter systems, as Ni+Ca, the charge identification for the fragments that punch through the silicon detectors, is performed using the procedure of [4] instead using a particle identification function.

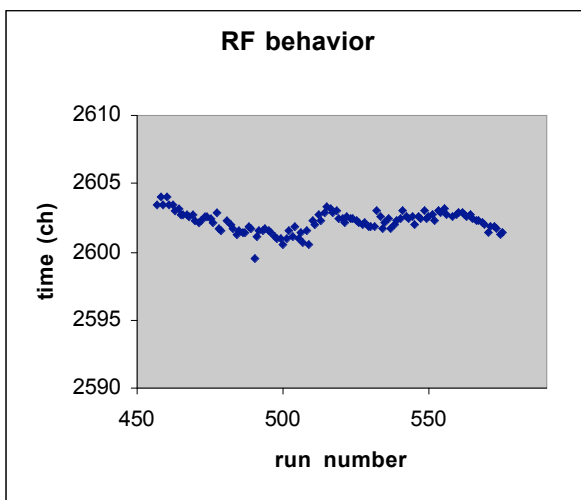
Similar work is going to get fast-slow identification for light particles in CsI(Tl)[5]. An analysis of the timing behavior along all the runs has been also performed to get a reference behavior for the time calibration procedure. In Fig.3 is shown the quite good stability of the RF observed along the beam of ^{112}Sn at 35 MeV/A, less than 5 ch (about 1.25 nsec) changes were observed during the whole beam time.

Fig.3 Behavior of the RF as a function of the time (^{112}Sn beam 35 MeV/A)

The new version of the analysis program is also ready to work. The main improvement with respect to old versions used for the REVERSE experiment is the possibility to read data directly from disk. All data of the 2003 campaign are now stored in two nas servers of LNS and Sezione di Catania allowing for a faster analysis work.

5 REFERENCES

- [1] S.Aiello et al., Nuclear Physics A583(1995)421.
- [2] A.Pagano et al Nucl.Phys. A734(2004)504
- [3] S.Aiello et al., NIM A427(1999)510.
- [4] N.Le Neindre et al.,NIM A490(2002)251.
- [5] M.Alderighi et al NIM A489(2003)257.



PRODUCTION OF A ^8Li RADIOACTIVE BEAM AND THE $^8\text{Li}(\alpha, n)^{11}\text{B}$ REACTION AT BIG BANG TEMPERATURES

S. Cherubini^{a,b}, C. Agodi^a, R. Alba^a, C. Bonomo^a, L. Calabretta^a, L. Cosentino^a, A. Del Zoppo^a, A. Di Pietro^a, P. Figuera^a, M. Gulino^{a,c}, M. La Cognata^a, L. Lamia^a, A. Musumarra^{a,c}, L. Pappalardo^a, M.G. Pellegriti^{a,c}, R.G. Pizzone^a, A. Rinollo^{a,c}, C. Rolfs^a, S. Romano^{a,c}, C. Spitaleri^{a,c}, F. Strieder^a, S. Tudisco^{a,c}, A. Tumino^{a,c}

- a) *Istituto Nazionale di Fisica Nucleare - Laboratori Nazionali del Sud, Catania, Italy*
- a) *Institut für Physik mit Ionenstrahlen, Ruhr-Universität Bochum, Bochum, Germany*
- a) *Dipartimento di Metodologie Fisiche e Chimiche per l'Ingegneria, Università di Catania, Catania, Italy*

Abstract

$^8\text{Li}(\alpha, n)^{11}\text{B}$ is a key reaction in the inhomogeneous Big Bang models. In order to study this reaction, a ^8Li radioactive ion beam was produced at the Laboratori Nazionali del Sud. The cross section of interest was measured using novel techniques that allowed for the tagging of the incoming ^8Li ions in combination with a ^4He gas cell and a 4π neutron detector. The obtained value is in fair agreement with previous work strengthening the model of inhomogeneous Big Bang nucleosynthesis.

1 INTRODUCTION

The remarkable agreement between the predictions of the primordial nucleosynthesis calculations with the observed primordial abundances of the light nuclides ^2H , ^3He , ^4He and ^7Li is considered a major triumph of the standard Big Bang model (SBBM) [1]. The SBBM assumes that during the phase of primordial nucleosynthesis the universe had a homogeneous density distribution. In view of the clumpiness of the universe on a large scale, theoretical studies ([2-4] and references therein) have taken into account possible inhomogeneities in baryon density arising from the quark-hadron phase transition of the universe. In these studies the universe is composed by high-density proton-rich regions and low-density neutron-rich ones. It is found that the observed abundances of the primordial nuclides can be explained equally well as in the SBBM, with the possible exception of ^7Li (see however [4]). A key prediction of the inhomogeneous Big Bang models (IBBM) is the production of significant amounts of $A \geq 12$ nuclides comparable to the abundances seen in the oldest metal-poor stars. Since the SBBM produces essentially zero metals, the presence of a “cosmic floor” of heavy elements in metal-poor stars would be a strong indicator of inhomogeneity at the time of primordial nucleosynthesis.

A key reaction in the inhomogeneous nucleosynthesis is $^8\text{Li}(\alpha, n)^{11}\text{B}$ ($Q = 6.63$ MeV). The thermal energy region is from 0.3 to 0.8 MeV for the relevant Big Bang temperature of 1×10^9 K. Thus, the cross section $\sigma(E)$ of this reaction must be known with high accuracy in this energy region. The cross section was inferred for the first time [5] using the inverse reaction $^{11}\text{B}(n, \alpha)^8\text{Li}$ with data over a wide range of energies including the thermal

region. However, this technique measures only the yield of $^8\text{Li}(\alpha, n)^{11}\text{B}$ to the ^{11}B ground state, while the reaction can proceed also to excited bound states of ^{11}B . Thus, the inverse reaction measured a lower limit of $\sigma(E)$. A direct $\sigma(E)$ measurement of $^8\text{Li}(\alpha, n)^{11}\text{B}$ requires the availability of a radioactive ^8Li ion beam ($T_{1/2}(^8\text{Li}) = 0.84$ s). Such experiments have been carried out [6-8]: the data with relatively large errors suggest an increase in cross section by about a factor 5 compared to that reported in [5]. Indirect methods as well as theory did not improve the situation [9]: e.g. a predicted enhancement factor of 1.3 [10] and 3.3 [11]. In order to improve this situation a new direct measurement implying the production of a radioactive ^8Li beam and the measurement of the $^8\text{Li}(\alpha, n)^{11}\text{B}$ were planned and carried out at the Laboratori Nazionali del Sud (LNS).

2 ^8Li BEAM PRODUCTION

Though a post-accelerated ^8Li beam will be soon available at the EXCYT facility at LNS [12], the present experiment used an in-flight produced beam. This was obtained by bombarding a deuterated target with a ^7Li primary beam that induced the $d(^7\text{Li}, p)^8\text{Li}$ reaction. The energy of the primary beam was $E_{\text{lab}} = 24.6$ MeV and its intensity was 100 pA.

The setup is shown schematically in Fig. 1. The beam was focused by a quadrupole doublet (QD1) onto a deuterated solid target, where ^8Li nuclides were produced via the reaction $d(^7\text{Li}, p)^8\text{Li}$. The ^8Li nuclides and the ^7Li projectiles left the production target predominantly in the 3^+ charge state. The ^8Li nuclides were filtered in momentum from the intense ^7Li primary beam by the 66° dipole magnet in combination with a quadrupole doublet (QD2) and focused onto a ^4He gas cell by 2

quadrupole doublets (QD3, QD4). In the gas cell, the ${}^4\text{He}({}^8\text{Li},n){}^{11}\text{B}$ reaction was initiated and identified by the produced neutrons.

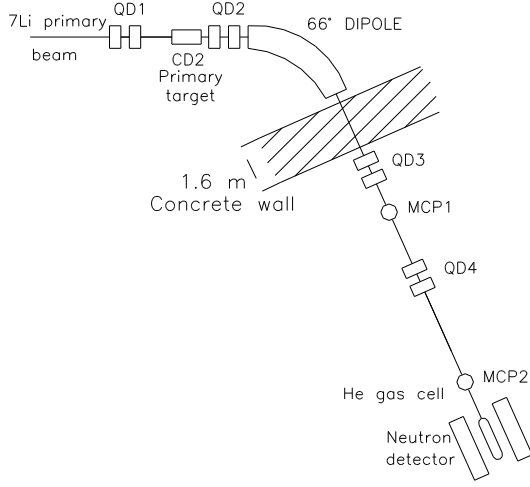


Figure 1. Schematic view of the experimental setup

The primary target was a 1 mg/cm^2 thick CD_2 foil sandwiched between carbon layers of $30 \text{ } \mu\text{g/cm}^2$ thickness. After this target, the ${}^7\text{Li}$ ion beam had an energy of 23.7 MeV . Since the forward kinematic solution in the ${}^8\text{Li}$ production kinematics was in momentum p too close to that of the ${}^7\text{Li}$ beam ($p({}^8\text{Li})/p({}^7\text{Li}) = 0.98$), we used the backward kinematic solution ($p({}^8\text{Li})/p({}^7\text{Li}) = 0.66$) for the momentum-filtering in the magnet. After the 66° dipole magnet, the ${}^8\text{Li}$ nuclides (backward kinematic solution) had an energy of $E_{\text{lab}}({}^8\text{Li}) = 10.3 \pm 0.4 \text{ MeV}$, where the quoted uncertainty reflects the momentum acceptance of the magnet.

2.1 ${}^8\text{Li}$ beam tuning

In a first step, a ${}^7\text{Li}$ beam emerging from the primary target with the same rigidity as the ${}^8\text{Li}$ nuclides was produced and tuned as a “pilot beam” through the beam line up to the gas cell using quartzes and Faraday cups as monitors, where the last quartz and the last Faraday cup were installed at a respective distance of 20 and 50 cm from the entrance foil of the gas cell. In the second step, the 24.6 MeV ${}^7\text{Li}$ primary beam was used and the associated ${}^8\text{Li}$ nuclides observed in the beam line using 2 micro-channel-plate detectors (MCP1 and MCP2). With a 5 m distance between the MCP’s, the ${}^8\text{Li}$ nuclides could be clearly identified by their time-of-flight (TOF) between the two MCP’s and resolved well from the leaky ${}^7\text{Li}$ projectiles. The ${}^8\text{Li}$ measured rate was used to perform a final fine tuning of the elements of the beam line. It turned out that the optimum parameters of the beam optical elements were nearly identical to the settings found with the ${}^7\text{Li}$ pilot beam. The measured ${}^8\text{Li}$ rate was on average about 150 nuclides/s consistent with expectation in view of the MCP restrictions. The

TOF spectrum allowed to measure absolutely the ${}^8\text{Li}$ energy which was consistent with the expected value of 10.3 MeV . The ${}^8\text{Li}$ energy was also verified by inserting a ΔE -E telescope (Si detectors) close to and upstream of MCP2.

2.2 ${}^4\text{He}$ gas cell

The gas cell had a 4 cm diameter, a 20 cm length. The entrance window was made of a $5 \text{ } \mu\text{m}$ thick Ni foil, which could sustain a ${}^4\text{He}$ gas pressure of 150 mbar. A Si detector was placed at the end of the gas cell to measure the energy loss of the ${}^8\text{Li}$ nuclides in the Ni foil and in the ${}^4\text{He}$ gas. For the Ni foil alone (no gas) the final ${}^8\text{Li}$ energy of 4.80 MeV was consistent within 1% with that calculated for the foil thickness. This energy is below the 2.06 MeV threshold of the ${}^8\text{Li} \rightarrow {}^7\text{Li} + n$ breakup as well as the thresholds of ${}^8\text{Li}(\alpha, 2n){}^{10}\text{B}$ and ${}^8\text{Li}(\alpha, np){}^{10}\text{Be}$. Including the ${}^4\text{He}$ gas, the energy at the end of the gas cell ($= 2.70 \text{ MeV}$) was also consistent with energy loss calculations. The mean ${}^8\text{Li}$ energy within the gas cell was therefore $E_{\text{lab}}({}^8\text{Li}) = 3.75 \text{ MeV}$ or $E_{\text{cm}} = 1.25 \text{ MeV}$.

2.3 Neutron detection

The neutron detection was performed by a 4π detector consisting of 12 ${}^3\text{He}$ -filled proportional counters embedded in a polyethylene moderator. This detector was provided by Caltech [13,14]. The moderator was in the form of a cube, 40 cm on a side, with an $11 \text{ cm} \times 11 \text{ cm}$ channel through the center, for insertion of the ${}^4\text{He}$ gas cell and the beam pipe. The neutrons created in the gas cell were moderated in the polyethylene material. Surrounding the 40 cm cube of polyethylene was a 4π layer of Cd shielding, which in turn was surrounded by a 4π passive layer of polyethylene and borated paraffin, approximately 10 cm thick. This passive shielding served to absorb externally created neutrons. The 12 ${}^3\text{He}$ proportional counters were positioned around the beam pipe channel. Each counter was characterised by a 100% detection efficiency for thermalised neutrons.

The cosmic background rate in the detector was observed to be 2 events/min, while the beam induced background was about 12 events/min.

Using a calibrated ${}^{252}\text{Cf}$ source, the neutron detection efficiency was found to be $\epsilon = 0.20 \pm 0.01$ consistent with previous work [12]. Since the neutrons emitted in ${}^4\text{He}({}^8\text{Li}, n){}^{11}\text{B}$ at $E_{\text{cm}} = 1.25 \text{ MeV}$ involve energies up to about 8 MeV, we have adopted a mean value of $\epsilon = 0.19 \pm 0.03$ according to Monte Carlo calculations [12].

A gate set on the ${}^8\text{Li}$ events in the TOF spectrum started a time-to-amplitude (TAC) converter, whereby the stop signals of the TAC (selected time range = 1 ms) were provided by the neutron detector (i.e. the events from the logic *or* of the 12 ${}^3\text{He}$ proportional counters). If neutrons were correlated with the ${}^8\text{Li}$ beam, one expected a coincidence time distribution $dN(t)/dt$ declining exponentially with time (or rising linearly with $\exp(-\lambda t)$) according to

$$dN(t)/dt = N_{\text{BG}} + N_0 \lambda \exp(-\lambda t), \quad (1)$$

where N_{BG} is the time-independent background contribution and N_o is the total number of time-correlated events, constant in time. This allows for disentangling the signal from the background. The results for this correlation are shown in Figure 2.

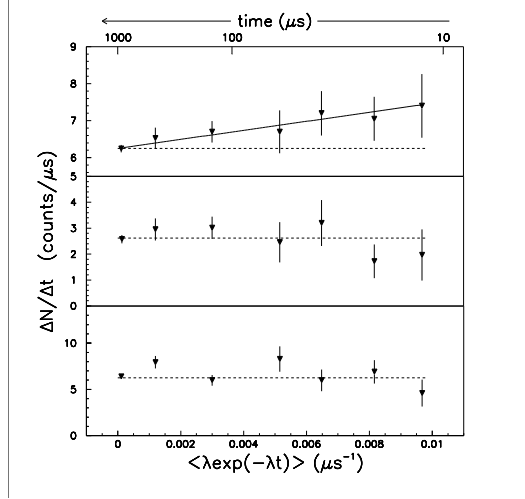


Figure 2. TAC-spectra shown as a function of $\langle \lambda \exp(-\lambda t) \rangle$: a) for ${}^8\text{Li}$ beam plus ${}^4\text{He}$ gas in the gas target, b) for ${}^8\text{Li}$ without Helium in the gas target and c) for ${}^7\text{Li}$ projectiles with ${}^4\text{He}$ gas in the gas target. The solid line represents a linear best fit to the data using the formula (1) while the dashed line is the time independent background contribution.

3 RESULT

The correlated neutron yield N_o is related to the number of incident ${}^8\text{Li}$ projectiles N_{Li} (as observed by the TOF), the number of ${}^4\text{He}$ target nuclides N_{He} (derived from the gas pressure and length of the gas cell), the neutron detection efficiency ϵ , and the cross section σ by the equation

$$N_o = N_{Li} N_{He} \epsilon \sigma. \quad (2)$$

The result for the cross-section is $\sigma = 500 \pm 170$ (statistic) ± 70 (systematic) mb at a mean energy of $E_{cm} = 1.25$ MeV, consistent with previous work within experimental uncertainties [6-8].

The present work with an enhancement factor of 12 compared to the results of the inverse reaction [5] strengthens the calculations of inhomogeneous Big Bang nucleosynthesis.

It should be noted that the present work is the first result of a radioactive ion beam experiment relevant to nuclear astrophysics carried out at Catania. Within the future EXCYT project at Catania [14], a ${}^8\text{Li}$ ion beam is expected to be available at the end of this year or in the

beginning of 2005 with an intensity several orders of magnitude higher than that obtained in the present experiment. With such a beam current, data with high precision can be obtained with the present setup over the full astrophysical energy range of ${}^4\text{He}({}^8\text{Li}, n){}^{11}\text{B}$ and also the related ${}^8\text{Li}$ destroying reaction will be studied.

4 REFERENCES

- (1) A.M.Boesgaard, G.Steigman, *Ann. Rev. Astr. Ap.* 23 (1985) 319
- (2) R.A.Malaney, W.A.Fowler: *Ap.J.* 333 (1988) 14 and *Ap. J. Lett.* 345 (1989) L5
- (3) T.Kajino, R.N.Boyd: *Ap.J.* 359 (1990) 267
- (4) K.Jademzik, G.M.Fuller, H.J.Mathews, T.Kajino: *Ap. J.* 422 (1994) 423
- (5) T. Paradellis, S. Kossionides, G. Doukellis, X. Aslanoglou, P. Assimakopoulos, A. Pakau, C. Rolfs, K. Langanke: *Z. Phys. A* 337 (1990) 211
- (6) R.N. Boyd, I. Tanihata, N. Inabe, T. Kubo, T. Nakagawa, T. Suzuki, M. Yonokura, X.X. Bai, K. Kimura, S. Kubono, S. Shimoura, H.S. Xu, D. Hirata: *Phys. Rev. Lett.* 68 (1992) 1283
- (7) X. Gu, R.N. Boyd, M.M. Farrell, J.D. Kalen, C.A. Mitchell, J.J. Kolata, M. Belbot, K. Lamkin, K. Ashktorab, F.D. Becchetti, J. Brown, D. Robers, K. Kimura, I. Tanihata, K. Yoshida, M.S. Islam: *Phys. Lett. B* 343 (1994) 31
- (8) Y. Mizoi, T. Fukuda, Y. Matsuyama, T. Miyachi, H. Miyatake, N. Aoi, N. Fukuda, M. Notani, Y.X. Watanabe, K. Yoneda, M. Ishihara, H. Sakurai, Y. Watanabe, A. Yoshida: *Phys. Rev. C* 62 (2000) 065801
- (9) R.N. Boyd, T. Paradellis, C. Rolfs: *Comm. Nucl. Part. Phys.* 22 (1996) 47
- (10) T. Rauscher, K. Grün, H. Krauss, H. Oberhummer: *Phys. Rev. C* 45 (1992) 1996
- (11) P. Descouvemont: *Nucl. Phys. A* 596 (1996) 285
- (12) INFN - LNS Activity Report 2002, pages 147-151
- (13) P.R. Wrean: Thesis, California Institute of Technology (1998)
- (14) P.R. Wrean, C.R. Brune, R.W. Kavanagh: *Phys. Rev. C* 49 (1994) 1205

Fragment production in the reaction $^{124}\text{Sn}+^{64}\text{Ni}$ and $^{112}\text{Sn}+^{58}\text{Ni}$ at 35 A.MeV

E. De Filippo^{1,*}, M. Alderighi², F. Amorini³, A. Anzalone³, N. Arena¹, L. Auditore⁴, V. Baran³, M. Bartolucci⁵, I. Berceanu⁶, J. Blicharska⁷, J. Brzychczyk⁸, A. Bonasera³, B. Borderie⁹, R. Bougault¹⁰, M. Bruno¹¹, G. Cardella¹, S. Cavallaro³, M.B. Chatterjee¹², A. Chbihi¹³, J. Cibor¹⁴, M. Colonna³, M. D'Agostino¹¹, R. Dayras¹⁵, M. Di Toro³, W. Gawlikowicz⁸, E. Geraci¹¹, F. Giustolisi³, A. Grzeszczuk⁷, P. Guazzoni⁵, D. Guinet¹⁶, M. Iacono Manno³, S. Kowalski⁷, E. La Guidara³, G. Lanza¹, G. Lanzalone^{1,3}, N. Le Neindre⁹, S. Li¹⁷, S. Lo Nigro¹, C. Maiolino³, Z. Majka¹⁵, G. Manfredi⁵, T. Paduszynski⁶, A. Pagano¹, M. Papa¹, M. Petrovici⁵, E. Piasecki¹⁶, S. Pirrone¹, R. Planeta⁸, G. Politi¹, A. Pop⁶, F. Porto³, M. F. Rivel⁹, E. Rosato¹⁸, F. Rizzo³, S. Russo⁵, P. Russotto³, K. Schmidt⁷, G. Sechi², V. Simion⁶, K. Siwek-Wilczynska¹⁹, I. Skwira¹⁹, M.L. Sperduto³, J. C. Steckmeyer¹⁰, L. Swiderski¹⁹, A. Trifirò⁴, M. Trimarchi⁴, G. Vannini¹¹, M. Vigilante¹⁸, J.P. Wieleczko¹³, J. Wilczynski²⁰, H. Wu¹⁷, Z. Xiao¹⁷, L. Zetta⁵, W. Zipper⁷

¹ INFN Catania and Dipartimento di Fisica e Astronomia, Università di Catania, Italy

² INFN Milano and Istituto di Fisica Cosmica, CNR, Milano, Italy

³ INFN-LNS and Dipartimento di Fisica e Astronomia, Università di Catania, Italy

⁴ INFN and Dipartimento di Fisica, Università di Messina, Italy

⁵ INFN Milano and Dipartimento di Fisica, Università di Milano, Italy

⁶ Institute for Physics and Nuclear Engineering, Bucharest, Romania

⁷ Institute of Physics, University of Silesia, Katowice, Poland

⁸ M. Smoluchowski Institute of Physics, Jagellonian University, Cracow, Poland

⁹ IPN, IN2P3-CNRS and Université Paris-Sud, Orsay, France

¹⁰ LPC, Ensi Caen and Université de Caen, France

¹¹ INFN Bologna and Dipartimento di Fisica, Università di Bologna, Italy

¹² Saha Institute Of Nuclear Physics, Kolkata, India

¹³ GANIL, CEA, IN2P3-CNRS, Caen, France

¹⁴ H. Niewodniczanski Institute of Nuclear Physics, Cracow, Poland

¹⁵ DAPNIA-SPhN, CEA Saclay, France

¹⁶ IPN, IN2P3-CNRS and Université Claude Bernard, Lyon, France

¹⁷ Institute of Modern Physics Lanzhou, China

¹⁸ INFN and Dipartimento di Fisica, Università di Napoli, Italy

¹⁹ Institute of Experimental Physics, Warsaw University, Warsaw, Poland

²⁰ Institute for Nuclear Studies, Swierk/Warsaw, Poland

Abstract

The forward part of the 4 π CHIMERA detector is used to study the intermediate mass fragments (IMF) production in semi-peripheral collisions. A method is presented to disentangle intermediate mass fragments produced in the initial dynamical stage of the collision from the ones coming from sequential decay of a projectile-like or target-like sources. For these dynamical produced fragments an isoscaling analysis is presented.

1 INTRODUCTION

The characterization of the IMFs emission pattern is fundamental in order to disentangle between fast non equilibrium emission and statistical decay of a hot and equilibrated nuclear matter. In this energy regime the predominance of a binary scenario, i.e. the presence in the outgoing channel of the remnants of projectile and target fragments produced in a wide impact parameter range, has been stated [1]. However, the occurrence of

mid-rapidity emission of IMF's and light charged particles modifies the binary character of the reaction: in particular dynamical emitted fragments at mid-velocity can arise from processes as "neck formations" [2-4], or "fast fission" [5-7].

We present data relative to IMFs production in semi-peripheral $^{124}\text{Sn}+^{64}\text{Ni}$ and $^{112}\text{Sn}+^{58}\text{Ni}$ reactions at 35 A.MeV studied with the forward part ($1^\circ \leq \theta_{\text{LAB}} \leq 30^\circ$) of the CHIMERA detector. Analysis is focused to light fragments ($3 \leq Z \leq 15$) emitted at mid-rapidity and their properties are presented and compared with theoretical

* E-mail: defilippo@ct.infn.it

predictions based on stochastic Boltzmann-Nordheim-Vlasov (BNV) transport theory [8]. A preliminary analysis of isospin effects in fragment production is also shown.

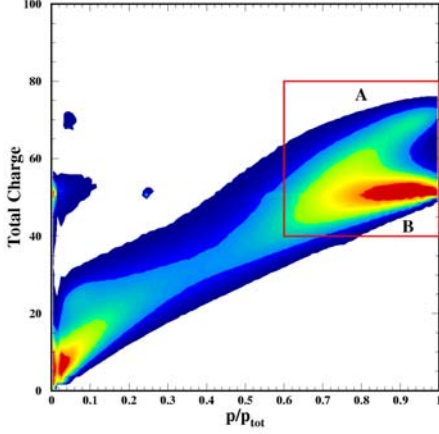


Fig. 1: Distribution of the total charge as a function of the total linear momentum (normalized to the initial projectile linear momentum) for the reaction $^{124}\text{Sn} + ^{64}\text{Ni}$ at 35 A.MeV. The box indicates the initial event selection. (Color online)

2 EXPERIMENTAL SETUP

Sn projectiles delivered by the Superconducting Cyclotron at LNS, Catania, at beam energy of 35 A.MeV, were used to study the neutron rich $^{124}\text{Sn} + ^{64}\text{Ni}$ and neutron poor $^{112}\text{Sn} + ^{58}\text{Ni}$ reactions on thin (200-300 $\mu\text{g}/\text{cm}^2$) targets. Typical beam intensity was $\sim 5 \times 10^7$ pps. The forward part of the CHIMERA array [9], covering the angular range between 1° and 30° , for a total of 688 telescopes was used. Each telescope is constituted by a 300 μm silicon detector followed by a CsI(Tl) acting as a stop detector. The time-of-flight technique is extensively used to measure the velocity and the mass of particles stopping in the silicon detectors. The ΔE -E method permits complete charge identifications up to $Z=50$. Light charged particles, which are stopped in the scintillator crystal, are identified by applying the pulse-shape discrimination method. Data acquisition system was triggered by requiring a multiplicity threshold of 2 or 3 in the silicon detectors.

3 RESULTS

Fig. 1 shows the bi-dimensional plot for the total detected charge Z_{TOT} as a function of the total momentum evaluated as $P_{\text{TOT}} = \sum Z_i V_{\text{par}}$ normalized to the projectile linear momentum. Complete events are selected requiring total charge reconstruction ($Z_{\text{TOT}} \geq 40$) and total linear momentum greater than 60% of the projectile momentum. In the selected zone two loci can be easily seen: the zone B corresponding to the reconstruction of the projectile charge and the zone A in which an almost complete reconstruction, including the target charge, is

achieved. This selection corresponds to a relatively broad charged particles multiplicity. In the following of the analysis we put attention on semi-peripheral collisions, selected requiring a total charge multiplicity $M < 7$. Assuming a geometrical correspondence between M_{TOT} and the impact parameter [10] this selection corresponds roughly to an impact parameter bin greater than 7 fm as deduced from the total multiplicity distribution.

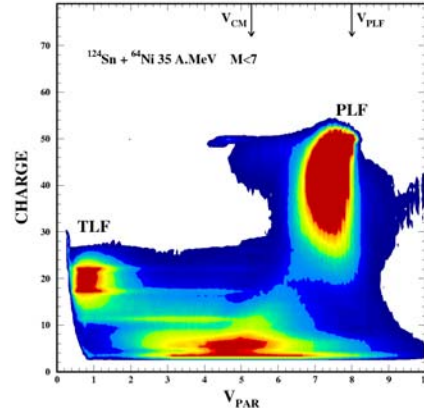


Fig. 2 Charge of the fragments as a function of the parallel velocity for a total multiplicity $M < 7$. The projectile velocity V_{PLF} (8.0 cm/ns) and center-of-mass velocity V_{CM} (5.3 cm/ns) are indicated by an arrow. (Color online)

In Fig. 2 the charge of the fragments is plotted as a function of their parallel velocity for the selected events with $M_{\text{TOT}} < 7$. Evidences for fast projectile like (PLF) residues as well as for very slow target like residues (TLF) are clearly visible in the charge spectrum. To illustrate the basic properties of the selected events we have plotted in Fig. 3 for ternary events, as a significant example, the invariant cross section contours for intermediate mass fragments (IMF) with charge $Z=4$, together, in the same plot, with the coincident projectile-like and target-like fragment.

The $Z=4$ fragments populate mainly the velocity region between projectile-like and target-like source.

To get insight on the mechanism of IMF production and the time scale of these processes we have selected, as a sharp approximation, in the plot shown in Fig. 2 three regions enclosing PLFs ($Z > 28$, $V_{\text{PAR}} > 6$ cm/ns), TLFs ($Z > 10$, $V_{\text{PAR}} < 1.5$ cm/ns), IMFs ($3 \leq Z \leq 15$, $2 < V_{\text{PAR}} < 8$ cm/ns) and we have analyzed them by studying relative velocity and angular correlation as well as isotopic yield ratio. We have calculated in an event-by-event procedure for the three fragments defined in the previous paragraph, the relative velocities $V_{\text{REL}}(\text{PLF-IMF})$ and $V_{\text{REL}}(\text{TLF-IMF})$. Fig. 4 shows correlation between these two quantities, both normalized to the velocity corresponding to the pure Coulomb repulsion energy as given by the Viola systematics [11].

Correlations have been considered for different windows in the parallel velocity spectrum: Fig 4 a) fast IMFs ($V_{\text{PAR}} > 5$ cm/ns), slow IMFs ($1.5 \text{ cm/ns} < V_{\text{PAR}} < 3$

cm/ns) and Fig 4 b) intermediate velocities IMFs ($3 \text{ cm/ns} < V_{\text{PAR}} < 5 \text{ cm/ns}$). In Fig 4a) the reduced relative velocity in IMF-PLF and IMF-TLF correlation are close to the ones obtained from Viola systematic (respectively $r_x \approx 1$ and $r_y \approx 1$) thus suggesting sequential decay from a primary PLF or TLF (SE). In Fig. 4b) reduced relative velocities are simultaneously larger than one (DE).

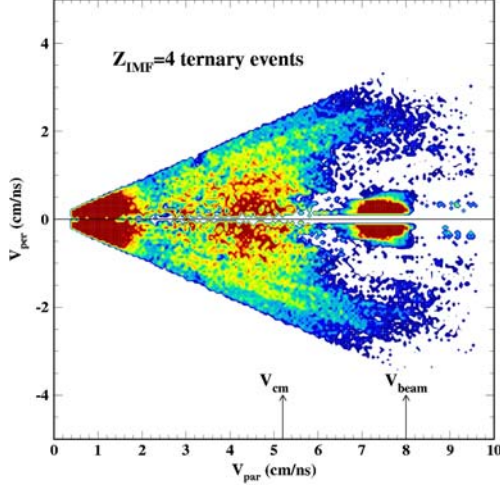


Fig. 3: (Color online) Invariant velocity plot for $Z=4$ particles in coincidence with the projectile-like and target-like fragments in ternary events.

We notice that, simple arguments based on three bodies Coulomb dynamics suggest to interpret this simultaneous violation of the Viola systematic as the result of Coulomb proximity effects produced in a time scale of the same order of the collision time [12].

Recently we have shown [13] that theoretical calculations for semi-peripheral collisions ($b \sim 5 \div 7 \text{ fm}$) made within Boltzmann-Nordheim-Vlasov (BNV) transport equations [9,14] and within a Molecular Dynamics code [15] for the reactions $^{124}\text{Sn} + ^{64}\text{Ni}$ and $^{112}\text{Sn} + ^{58}\text{Ni}$ at 35 A.MeV reproduced very well the basic features (for example V_{PAR} vs. Z correlation plot of Fig. 2) of the PLF, TLF and IMF groups. In particular, in ref. [13] it was shown the consistency between experimental data with the predicted formations of a neck-like structure inducing fast ($\sim 150 \text{ fm/c}$) emission of IMFs in a mid-velocity zone ($V_{\text{PAR}} \sim 4 \text{ cm/ns}$).

In order to test the dynamical origin of these selected IMFs with respect to the statistical decay we have studied the alignment configuration between PLF, IMF and TLF looking at their angular distributions. A useful representation of data is to define the “in-plane” angular distribution generally adopted in fission or in ternary break-up studies [16-17].).

A ϕ_{PLANE} angle with a strong maximum around 0° corresponds to a high degree of alignments along the separation axis while a more isotropic and flat distribution is expected for a pure statistical fission process.

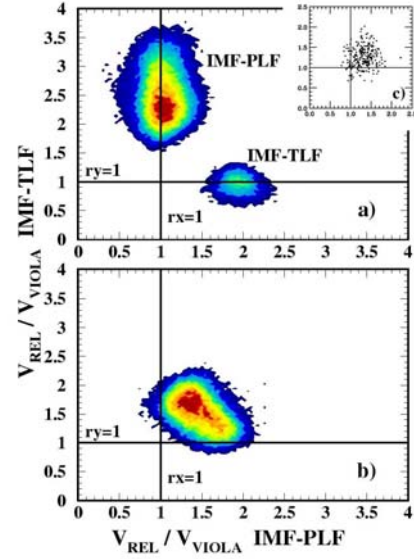


Fig. 4 Correlation of the reduced relative velocity for the PLF-IMF and TLF-IMF for different conditions of the IMFs velocities (see text for explanations). The insert c) shows results of BNV calculations taken from Ref. [14]. (Color online)

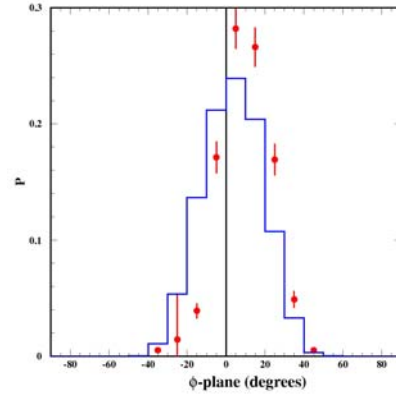


Fig. 5: ϕ -PLANE angle distribution (histogram) for intermediate velocity IMFs. Data have been plotted as a probability distribution P and grouped to 10 degrees bins in order to compare them with results of BNV calculations (circles).

Fig. 5 shows the ϕ_{PLANE} distribution for the “prompt” part of IMFs emission where a full alignment configuration is observed. This is also well reproduced by the BNV calculation done from 6 to 8 fm impact parameter (solid circles). We notice that fast IMFs ($V_{\text{PAR}} > 5 \text{ cm/ns}$) with relative IMF-PLF velocity close to the Viola systematics (SE) show a flatter and more isotropic ϕ_{PLANE} distribution (not shown here).

4 ISOSPIN EFFECTS

Isospin effects can be studied comparing the same observable for two reactions that differ essentially in isospin asymmetry [18]. The ratio of isotope yields emitted from two reactions is an example of this kind of observable. Isoscaling, observed mainly in multifragmentation

reactions [19], occurs when the ratio of isotope yields for neutron rich and a neutron poor reactions scales with an exponential behavior as a function of neutron and proton number:

$$R_{12} = Y_1(N,Z)/Y_2(N,Z) = C \exp(\alpha N + \beta Z)$$

where C , α and β are parameters extracted by fitting the experimental data. Isoscaling analysis has been recently done for central collision events in the reactions $^{124}\text{Sn}+^{64}\text{Ni}$ and $^{112}\text{Sn}+^{58}\text{Ni}$ at 35 A.MeV studied with the Chimera detector [20] and results interpreted in the frame of a grand-canonical statistical approach where the parameter α and β are related to the relative neutron and proton densities of a free nucleon gas.

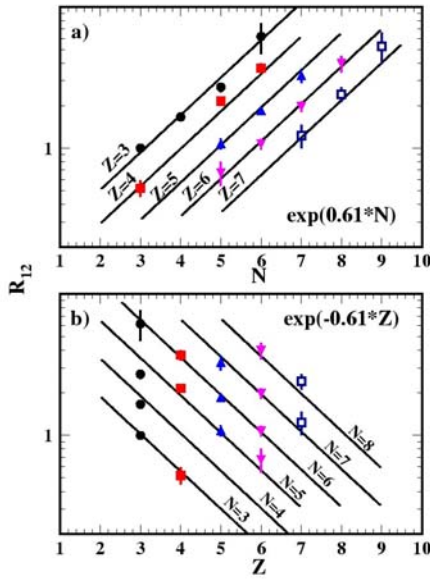


Fig. 6: Yield ratios for semi-peripheral $^{124}\text{Sn}+^{64}\text{Ni}$ and $^{112}\text{Sn}+^{58}\text{Ni}$ at 35 A.MeV for light IMFs selected with parallel velocity $V_{\text{PAR}} > 5$ cm/ns (SE, as in Fig 4a) as a function of neutron number N a) and proton number Z b). Lines are fit to the data giving rise to a common exponential slope.

However it is interesting to investigate possible isoscaling properties in semi-peripheral collisions. So, following our previous analysis, we have distinguished the two cases of a “prompt or dynamical” IMFs component (DE, as in Fig. 4b) and “sequential” IMFs component (SE, as in Fig 4a) where the reduced velocity ry is near to 1. In order to normalize the two set of data we have divided, as in Ref. [20], the isotopic ratio for fragment X to this ratio for ^6Li , i.e $R(X) = R_{12}(X)/R_{12}(^6\text{Li})$ where R_{12} is the isotopic ratio yield for fragment X between the neutron rich reaction 1 and the neutron poor reaction 2. Fig 6 shows results relative to the “sequential” IMFs component selection. A very nice isoscaling behaviour can be observed with values of the α and β parameters equal respectively to 0.61 and -0.61 . However, we have observed the persistence of an isoscaling signal for the “prompt” IMFs component (DE). In this latter case we obtained values of 0.53 and -0.40 respectively for the α and β parameters, but we

noticed a poorer quality of the fits respect to the SE component. If the two components were mixed together, then the well shaped isoscaling signal vanished and no reasonable fits were produced. Systematic evaluations of isoscaling parameters with proper source selection are important quantities for testing symmetry energy density dependence of Equation of State (EOS) in asymmetric nuclear matter.

5 CONCLUSIONS

Fragments produced in semi-peripheral reactions have been characterized in order to disentangle statistical emission from projectile-like and target-like fragments from dynamical IMFs emission in the intermediate rapidity region. The experimental data give evidence for fast dynamical neck-like emission of IMFs. BNV simulations are in agreement with our data for light IMFs ($Z < 15$) and supports the scenario of production of IMFs in the overlapping zone (neck) between target and projectile nuclei. Calculations predict that these fragments are produced in the first stage (≈ 150 fm/c) of the nucleus-nucleus interaction. An isoscaling signal is also present for typical fast reaction processes where the notion of statistical equilibrium emission can not be asserted.

REFERENCES

- [1] J. Lukasik et al., Phys. Rev. C55, 1906 (1997).
- [2] C.P. Montoya et al. Phys. Rev. Lett. 73 (1994) 3070.
- [3] P.M. Milazzo et al., Nucl. Phys. A703 (2002) 466.
- [4] S. Piantelli et al., Phys. Rev. Lett. 88 (2002) 052701.
- [5] F. Bocache et al., Nucl. Phys. A676 (2000) 391.
- [6] E.Piasecki et al. Proceedings of the IWM2001 international workshop on *Multifragmentation and related topics*, Catania, November 2001, pag. 187 (2002).
- [7] J. Colin et al., Phys. Rev. C67 064603 (2003).
- [8] V.Baran et al. Nucl. Phys. A703 603 (2002).
- [9] A. Pagano et al. Nucl. Phys. A681 (2001) 331.
- [10] C. Cavata et al. Phys. Rev. C42 (1990) 1760.
- [11] V. Viola, Phys. Rev. C31 (1985) 1550.
- [12] *The notion of reduced velocity plot as a clock for the IMFs emission time was given by J. Wilczynski in REVERSE data meeting held at LNS on April 2002.*
- [13] A. Pagano et al., *Proceedings of the VIII International Conference on Nucleus-Nucleus collisions, Moscow (Russia) 19-21 June 2003*, Nucl. Phys, in press (2004).
- [14] V. Baran et al., Nucl. Phys. A730 (2004) 329.
- [15] M. Papa et al., Phys. Rev. C64, 024612 (2001).
- [16] E.Piasecki et al. to be published.
- [17] A. Stefanini et al., Z. Phys. A351 (1995) 167.
- [18] M.B. Tsang et al., Phys. Rev. C64 (2001) 041603.
- [19] H.S. Xu et al., Phys. Rev. Lett. 85 (2000) 716.
- [20] E. Geraci et al., Nucl. Phys. A732 (2004) 173.

USING THE RESONANCE SCATTERING METHOD TO STUDY Li-He CLUSTER STATES IN BORON EXOTIC ISOTOPES

A. Di Pietro^a, M. Lattuada^{a,b}, F. Pansini^{a,b}, D. Vinciguerra^{a,b}, M. Zadro^c, O.Yu. Goryunov^d, V.V. Ostashko^d, Li Xia^e, F. Cappuzzello^a, A. Cunsolo^{a,b}, A. Foti^{b,f}, J. Winfield^a, T. Lonnroth^g, V. Lyapin^h, M. Muttererⁱ, W.H. Trzaska^j

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

b) Department of Physics and Astronomy, University of Catania, Italy

c) Institut Rudjer Boskovic, Zagreb, Croatia

d) Institute for Nuclear Research, Kiev, Ukraine

e) China Institute of Atomic Energy, Beijing, China

f) INFN - CT, Catania, Italy

g) Department of Physics, Abo Academy, Turku, Finland

h) Helsinki Institute of Physics, Helsinki, Finland

i) Technical University of Darmstadt, Germany

j) Department of Physics, University of Jyväskylä, Finland

Abstract

Work is in progress to study the experimental conditions needed for the measurement of ${}^{8,9}\text{Li} + \alpha$ scattering excitation functions using the forthcoming radioactive beam facility EXCYT at LNS. The aim of the experiments is to search evidence for excitation of ${}^{8,9}\text{Li}-\alpha$ cluster states in Boron isotopes.

1 INTRODUCTION

Exotic clustering [1] is acknowledged as one of the most promising research fields that can be investigated by radioactive beams induced reactions. It consists in the description of unstable nuclei as di-nuclear structures where at least one of the components can be unstable itself. Thus one of the basic prescriptions of the standard cluster models, namely the bound structure of the components, that baptized the α -particle as the ideal cluster, may not be satisfied in this framework. The presence of extended sub-structures leads to a high moment of inertia of the nucleus and rotational bands of states associated with deformed configurations may show up.

Recent examples of experimental as well as theoretical studies of this aspect of nuclear structure concerns the neutron rich isotopes of Beryllium and Boron [1-2].

As far as Boron is concerned, calculations [2] performed in the framework of Antisymmetrized Molecular Dynamics are able to describe the ground state of its very neutron-rich isotopes in terms of two substructures with $Z=2$ and $Z=3$ respectively. Rotational bands of excited states associated with the same structure are predicted as well. Of course the higher is the number of neutrons of the isotope, the more exotic are its clusters. For instance in the extreme case of ${}^{19}\text{B}$, its ground state can be described as having ${}^8\text{He}-{}^{11}\text{Li}$ and ${}^{10}\text{He}-{}^9\text{Li}$ components.

By decreasing the number of neutrons the structure of Boron isotopes in the ground state becomes more and more compact and accordingly the ground state of ${}^{13}\text{B}$ shows mainly single particle characteristics.

Nevertheless He-Li cluster configurations of its excited states are not ruled out. If still the threshold rule is valid even for these unstable systems, the states associated to such di-nuclear configurations are to be searched in the excitation energy region close to or larger than the decay threshold of the nucleus into the two components under consideration. For ${}^{13}\text{B}$ decaying into ${}^4\text{He}+{}^9\text{Li}$ this energy is around 10 MeV.

Similar predictions also concern ${}^{12}\text{B}$, for which two rotational bands of different parity, associated to a ${}^4\text{He}-{}^8\text{Li}$ configuration, are expected to start around the threshold for α -decay [3].

Some experimental results on selected α -decaying states of ${}^{12}\text{B}$ are reported in ref. 4, even if their cluster nature can only be speculated, since no information on their spins and thus on their rotational characteristics is deduced from that experiment.

The usual way to investigate the presence of such di-nuclear configurations is to study the excitation function of nuclear processes where the two clusters are present in the entrance and/or in the final state. Indeed elastic and inelastic scattering have been widely used in this kind of studies. An alternative tool is represented by three-body reactions producing the nucleus under consideration in an intermediate step, with a following decay into the relevant final state. For instance the ${}^{12}\text{C}-{}^{12}\text{C}$ rotational bands of ${}^{24}\text{Mg}$ have been widely investigated in the past as well as in recent years by measuring both the ${}^{12}\text{C}-{}^{12}\text{C}$ scattering excitation function and the energy correlation of two ${}^{12}\text{C}$ produced in three body reactions like ${}^{12}\text{C}({}^{16}\text{O}, {}^{12}\text{C} {}^{12}\text{C}) {}^4\text{He}$. Of course in the case of scattering the cross section is expected to be more sensitive to the nuclear structure when measured at large angles.

The choice is to measure the ${}^8,9\text{Li}-{}^4\text{He}$ scattering cross section at backward angles to study the ${}^8,9\text{Li}-{}^4\text{He}$ cluster structure of ${}^{12,13}\text{B}$ using the beams of the forthcoming EXCYT facility. In consideration of the poor intensities expected at the beginning for these unstable beams, the method of inverse kinematics resonance scattering on an infinite ${}^4\text{He}$ gas target seems specially suited, since it allows to measure the whole scattering excitation function in a wide energy range in a single experiment at a single beam energy.

2 THE EXPERIMENT PLANNING

The method [5] consists in filling the scattering chamber with a gas (${}^4\text{He}$ in the present case) acting as target and beam degrader at the same time and detecting the recoil particles thanks to their lower stopping power with respect to the beam. The gas pressure and the beam energy are chosen in such a way that the beam is completely stopped before it reaches the end of the chamber where detectors are mounted. In the hypothesis that elastic scattering is dominant over the other possible nuclear processes, the relation between the energy of the detected particle (α -particle in the present case) and the point of interaction along the beam path (and thus the interaction energy, too) is unique. If inelastic scattering events are also present, they can be separated from the elastic ones by measuring the total time of flight from the entrance of the beam into the chamber to the detection of the recoil particle. It was calculated, for instance, that a ${}^9\text{Li}$ beam energy of 36 MeV and gas pressure of 0.75 atm will allow to span the ${}^{13}\text{B}$ excitation energy region approximately from 3 MeV (threshold due to the ΔE thickness) to 11 MeV.

The LNS CT2000 scattering chamber is specially suited for this kind of experiments, thanks to its size and versatility. A window will separate the gas-filled chamber from the beam line and a MCP will be placed just before the entrance window, to give a start signal for TOF measurement.

The detection set-up will be mounted at the other end of the chamber and will consist of a number of ASPED arrays as E-detectors and 65 μm thick ΔE -detectors segmented into 4 quadrants. Each ASPED array is made of 12 silicon position sensitive detectors, 500 μm thick. TOF is of course different for the different points of interaction. A rough estimate of the average difference in time of flight for particle coming from elastic and inelastic scattering to the first excited state (2.7 MeV) gives values around 6 ns for α energies above the threshold.

From optical model calculations one can deduce values of 30 – 50 mb/sr for the non-resonant 180° potential scattering cross section, that represents here a kind of background. Resonant scattering cross section is expected to be much higher.

A test of the set-up and of the reliability of the method will be performed in the first half of 2004, using stable tandem beams. The choice is to deliver ${}^{18}\text{O}$ and ${}^9\text{Be}$ beams on ${}^4\text{He}$ target. The first beam will allow to test

the experimental set up, by comparison of its response with existing data.

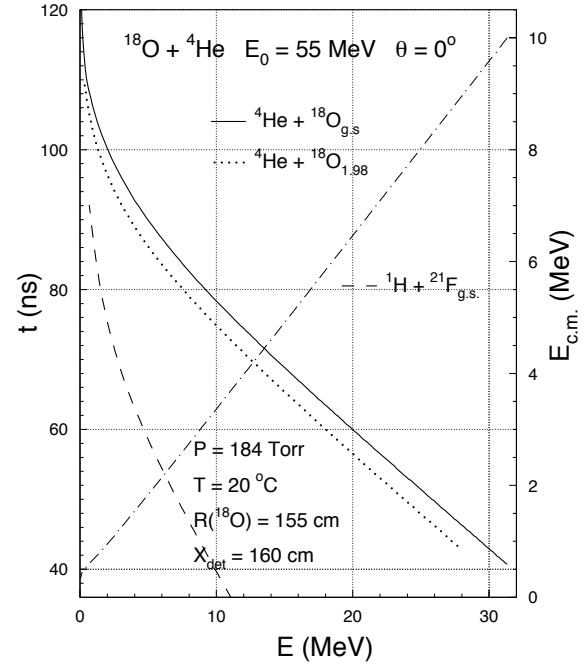


Fig.1 Kinematics for the ${}^{18}\text{O} + {}^4\text{He}$ experiment

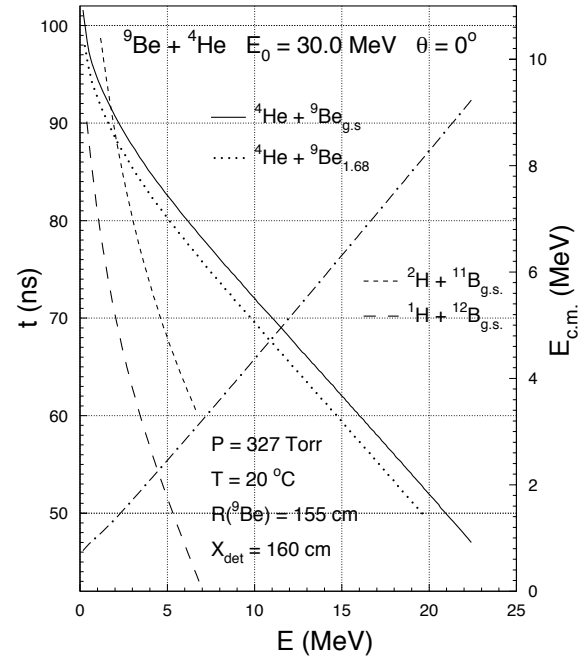


Fig.2 Kinematics for the ${}^9\text{Be} + {}^4\text{He}$ experiment

Fig.1 shows the kinematics for this system. The time of flight from the MCP before the entrance window to the ΔE detector is shown as a function of the detected energy of the recoil α -particle (continuous line). The

dotted line concerns the inelastic scattering to the first ^{18}O excited state whereas the dashed one refers to protons from the (α, p) reaction. The corresponding center of mass energy is represented by the dot-dashed line (scale on the right).

^9Be was chosen as second beam for the test experiment because of its mass that allows for a kinematics very similar to the one of the exotic beam experiments. The meaning of the curves in Fig. 2 is the same as in Fig. 1.

3 REFERENCES

- [1] H. Horiuchi, Europ. Phys. J. A 13(2002)39 and refs. therein
- [2] Y. Kanada En'yo and H. Horiuchi, Phys. Rev. C 52(1995)647
- [3] P. Descouvemont, Nucl. Phys. A 596(1996)285
- [4] N. Soic et al., Europhys. Lett. 63(2003)524
- [5] V.Z. Goldberg et al., Phys. Rev. C 69 (2004) 024602; G.V. Rogachev, PhD thesis, Kurchatov Institute (1999)

SIMULATION AND REJECTION OF ATMOSPHERIC MUON BACKGROUND FOR NEUTRINO POINT-LIKE SOURCES WITH THE NEMO-km³ NEUTRINO TELESCOPE

C. Distefano^a
for the NEMO Collaboration

a) INFN Laboratori Nazionali del Sud, Catania, Italy

Abstract

In this work we simulate the response of the future NEMO-km³ neutrino telescope to the passage of the atmospheric muon flux, studying the possibility to reject the background due to mis-reconstructed events. We also evaluate the background in a narrow sky region around a point-like source. In particular we study the case of microquasar SS433, suggesting its possible identification with the NEMO telescope in a time interval of few months.

1 INTRODUCTION

The NEMO (NEutrino Mediterranean Observatory) Collaboration [1] is conducting an intense activity to develop technical solutions and to select an optimal marine site for the construction of a km³ scale neutrino telescope in the Mediterranean Sea (for details see [2]).

Underwater (as well as under-ice [3]) neutrino telescopes are designed to track high-energy (>TeV) neutrinos and possibly measure their energy. These apparatuses are arrays of ~5000 optical sensors (PMTs) displaced in a lattice of about 1 km³, capable to track the Cerenkov light wavefront radiated in seawater by muons originated by CC interactions of astrophysical ν_μ [4].

For such a telescope atmospheric muons give a significant contribution to the background in the detection of astrophysical neutrinos, being their signals indistinguishable from muons induced by these neutrinos. Although at a depth of about 3.4 km (as in the case of the site of Capo Passero, selected by the NEMO Collaboration [5]) the muon flux is suppressed by several orders of magnitudes [6], it still exceeds any expected neutrino signal. Since the range of atmospheric muons is, at any energy, much shorter than the Earth radius, only *down-going* atmospheric muons reach the detector. Neutrinos, on the contrary, may cross the Earth and interact in the proximity of the detector producing clear signatures of *up-going* muons. For these reasons neutrino telescopes designs are optimized to search for up-going muon tracks. A *downward looking* muon neutrino telescope suffers, anyway, the presence of atmospheric muon background: the low PMT density and the present track reconstruction algorithms (at this stage, still not fully developed) determine the direction reconstruction capabilities of the detector. The result is that a fraction of down-going atmospheric muons is reconstructed as up-going tracks. Although this fraction is small ($\sim 10^{-5}$), the intense atmospheric muon flux produces a significant background of *fake* upward going muons.

In this work we carry out a preliminary study of the response of the future underwater NEMO-km³ neutrino telescope to atmospheric muons. The background due to mis-reconstructed atmospheric muons (*fake* upward going tracks) is then evaluated and noise rejection techniques are studied. Eventually we evaluate the atmospheric background expected in a narrow sky region around the coordinates of a point-like astrophysical neutrino source and we set a time-scale for the identification of this source above the background with the NEMO-km³.

2 SIMULATION OF ATMOSPHERIC MUON BACKGROUND

In order to evaluate the atmospheric muon background with respect to the signal produced by a point like neutrino source, we generated a sample of atmospheric muons reaching the NEMO-km³ detector. The propagation of muons inside the detector, the production, propagation and detection of Cerenkov photons are simulated using the *km3* software code developed by the ANTARES Collaboration [7]. The geometry of the NEMO-km³ telescope, simulated in this work, is a squared array of 9×9 towers *a la* NEMO [8] equipped with 5832 optical modules (10" diameter PMTs). The towers, moored at a seabed of 3400 m depth, have an instrumented height of 680 m, with a storey-storey distance of 40 m, and are arranged with a distance of 140 m. The *ANTARES-modk40* and *ANTARES-reco* tools are used, respectively, to simulate background optical noise (due to ⁴⁰K and bioluminescence) and to reconstruct the simulated muon tracks.

We generated an atmospheric muon sample, corresponding to 50 hours of detector live time, according to the formula given by Okada [9]. The latter parameterizes the integral energy spectrum of muons reaching a given depth D in seawater, as a function of the muon energy and direction.

A weighted sample generation procedure was used. Muons energies were generated with spectral index $X = 3$ within the range $1 \text{ TeV} \div 1 \text{ PeV}$, muons directions were randomly generated in 2π solid angle (only downward oriented) and the application points of their trajectories were randomly extracted on the surface of a volume of water containing the detector sensitive volume (a *box* having dimensions $L_x = L_y = 1480 \text{ m}$, $L_z = 880 \text{ m}$ and moored at 3400 m depth). The effect of the height of the *box* on the muon spectrum was also taken into account. For each generated event a weight W_{event} was calculated multiplying the corresponding Okada spectrum, derived from [9], times the generation weight W_{gen} , defined as:

$$W_{\text{gen}} = \frac{e_m^X I_E I_J A_{\text{geom}} t_{\text{gen}}}{N_{\text{total}}}, \quad (1)$$

where I_E and I_J are the energy and the angular space factors, A_{geom} is the geometrical area of the *box*, t_{gen} is the generation time and N_{total} is the total number of generated events. The weight W_{event} represents the probability that a generated muon reaches the *box*. A *hit-or-miss* muon event selection procedure was then applied to the muon sample.

To simulate a time interval of 50 hours, a number of $N_{\text{total}} = 5 \cdot 10^8$ muons was generated, only $\sim 1.8 \cdot 10^7$ survive the *hit-or-miss* selection. The energy spectrum and angular distribution of the muons reaching the *box* surface are plotted in Figure 1.

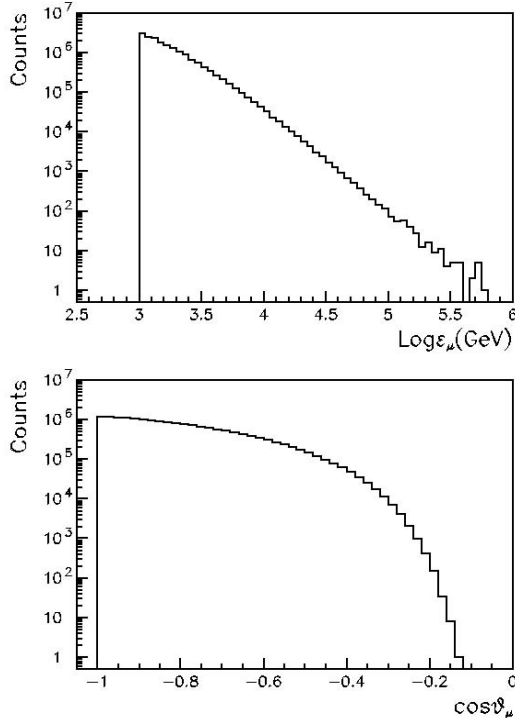


Figure 1: Energy spectrum and angular distribution of the simulated $\sim 1.8 \cdot 10^7$ muon events reaching the detector *box* in a time interval of 50 hours.

The generated atmospheric muons were, then, propagated inside the detector using the *ANTARES-km3* tool. In this simulation we have imposed seawater light absorption length of $\sim 70 \text{ m}$ (for blue wavelengths), which is the value measured in the site of Capo Passero [5]. The generation of spurious hits on PMTs (bioluminescence and ^{40}K optical noise) was performed using the *ANTARES-modk40* tool, imposing an optical noise rate of 20 kHz . This value is close to the one measured with $10''$ PMTs ($0.35 \text{ s.p.e. threshold}$) in the site of Capo Passero [5]. Eventually, the reconstruction of muon tracks, starting from the recorded PMT hits, was carried out using the *ANTARES-reco* code.

The results of the simulations are reported in Table 1: the total number of reconstructed muon events is about $\sim 1.1 \cdot 10^6$ and the number of mis-reconstructed up-going ($\cos \theta_\mu > 0$) events is 41117.

Table 1: Results of atmospheric muons simulation carried out with Okada parameterization for $t_{\text{gen}}=50$ hours, $\epsilon_\mu > 1 \text{ TeV}$ and NEMO-km3 detector moored at seabed depth of 3400 m .

	N_m
Muons at the detector <i>box</i>	17686147
Reconstructed muons	1079011
Up-going like rec. muons	41117

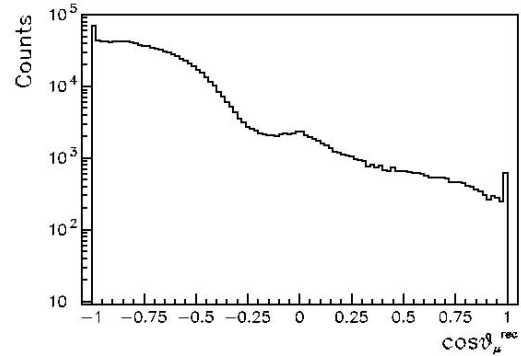


Figure 2: Angular distribution of the reconstructed atmospheric muons in a detector live time interval of 50 hours.

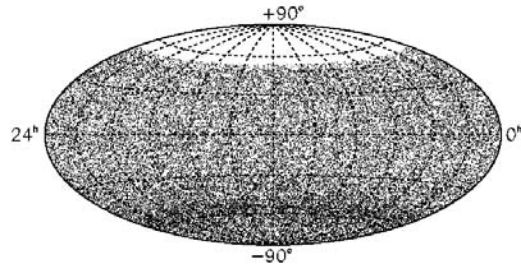


Figure 3: Full sky map in equatorial coordinates of mis-reconstructed atmospheric muons during a detection live time of 50 hours ($N_\mu=41117$).

The angular distribution of reconstructed muon events is reported in Figure 2. The distribution of the $N_\mu = 41117$ mis-reconstructed events, in the equatorial coordinates plane, is shown in Figure 3. It was found that the distribution of mis-reconstructed atmospheric muons is strongly dependent on declination (δ) while it is isotropic in Right Ascension (RA).

3 ATMOSPHERIC BACKGROUND FOR A POINT-LIKE NEUTRINO SOURCE

In order to evaluate the contribution of background with respect to the signal of a point-like neutrino source, we have to simulate longer time intervals (several months of data taking) to collect a significant statistics in a narrow sky region around the source coordinates. This task may be prohibitive due to large CPU time and the disk space consumption. However, it was shown that, for a given declination, the distribution of mis-reconstructed muons is isotropic in RA. This consideration allows us to project the sample of simulated events (having the same δ) in a single bin of RA. This is also equivalent to generate the Local Sidereal Time, related to the detection of a muon event, in a given interval. The corresponding “detector data taking time interval” is a function of the bin-width ΔRA and of the declination, due to the dependence of ΔRA on δ in the used system of coordinates. As an example we present the case of microquasar SS443 ($\delta = +04^\circ 58' 58''.0$, $RA = 19^h 11' 49''.6$). Considering an angular bin of $3^\circ \times 3^\circ$ around SS433, the generated sample of atmospheric muon events corresponds to a detector live time of about 250 days.

The theoretical neutrino flux estimated for SS433 is $1.72 \cdot 10^{-9}$ erg/cm² s [10]. Figure 4 shows (for the $3^\circ \times 3^\circ$ bin and 250 days detector live time) the reconstructed neutrino events from SS433 ($N_\mu = 60$ [11]), the background due to mis-reconstructed atmospheric muons (1079 events) and the background due to reconstructed atmospheric neutrinos (2 events [11]). In a smaller circular sky region, centered in the source and having radius of 1° , the reconstructed events are $N_\mu = 58$ from SS433, $N_\mu = 1$ atmospheric neutrinos and $N_\mu = 353$ fake upgoing (atmospheric) muons.

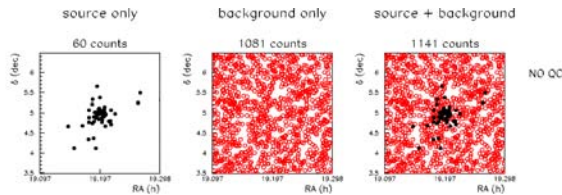


Figure 4: Distribution of neutrino events from SS433 and mis-reconstructed atmospheric muons (angular bin of $3^\circ \times 3^\circ$ centered on the source position, 250 days of detector live time).

At this level of the reconstruction procedure, the fraction of mis-reconstructed muons is very high and it could wash out the signatures of astrophysical neutrino fluxes. For this reason quality cuts are applied after the reconstruction procedure in order to make the event selection more stringent.

4 REJECTION OF THE ATMOSPHERIC MUON BACKGROUND

As shown in the previous section, the atmospheric muon background may exceed the neutrino signal also in the case of intense sources as SS433. Therefore, it is mandatory, during data analysis, to reduce this background applying quality cuts to the reconstructed event sample. Event quality cuts (QCs) can be based on several criteria, e.g. topology of PMT hits distribution, PMT hits charge, track fit quality... And they must be studied in order to reject muons with a minor effect on neutrino event detection.

The used muon reconstruction procedure is based on the sequential use of several fitting algorithms: linear pre-fit, L1-L2 M-estimator, Maximum likelihood. In particular the value of the logarithm of the likelihood function, $\log(L)$, at the fitted maximum, divided by the number of degrees of freedom $\log(L)/NDOF$ is used as a *goodness of fit criterion* [12]. Several tests performed by the ANTARES Collaboration shows that, imposing cuts on the value of $\log(L)/NDOF > -7.2$, almost all of the events passing the cut are well reconstructed.

In order to reject the atmospheric muon background we have applied likelihood quality cuts to our event sample. In Figure 5, we show the distribution of mis-reconstructed muons directions, in equatorial coordinates, for different values of $\log(L)/NDOF$.

The effect of QCs applied to the sample of events plotted in Figure 4 is shown in Figure 6. As QC level increases atmospheric muons are rejected with more efficiency than source neutrino events. The result is very satisfactory: for $\log(L)/NDOF > -9$ the source events are about 4σ above the background in the $3^\circ \times 3^\circ$ and dominate the sample in the 1° circular bin, as shown in Table 2.

Table 2: Number of events reconstructed in a circular sky region centered in the SS433 position and having a radius of 1° , as a function of quality cuts.

source	bkg	source+bkg	cut level
58	354	412	NO QC
58	195	253	QC -10
57	115	172	QC -9
53	15	68	QC -8

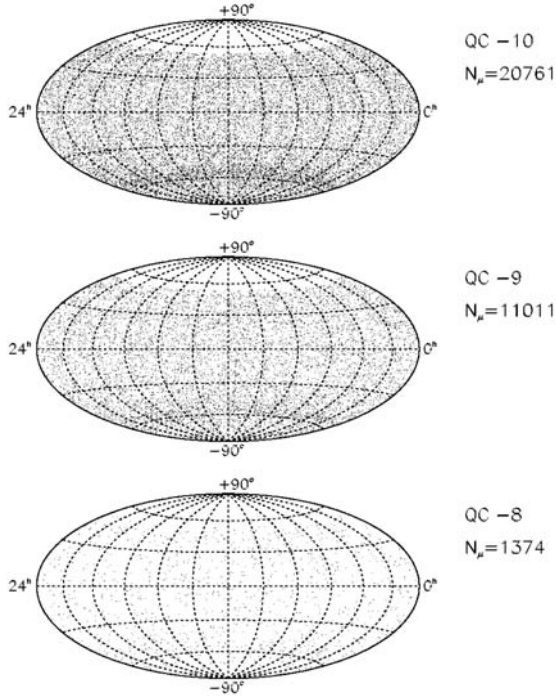


Figure 5: Full sky map in equatorial coordinates of misreconstructed atmospheric muons surviving different QCs (for a detection live time of 50 hours). For $\log(L)/NDOF > -7$ all atmospheric muons in the simulated sample are rejected.

5 CONCLUSIONS

We simulated an atmospheric muon background equivalent to 50 hours detector live time for the future NEMO-km3 neutrino telescope. We studied the possible quality cuts for background rejection. We studied, in particular, the signal to noise ratio for microquasar SS433. Preliminary results of simulations indicate that this source may be identified with a km^3 neutrino telescope within few months of observation.

6 REFERENCES

- [1] NEMO web page: <http://nemoweb.lns.infn.it/>.
- [2] E. Migneco et al., 2003, Proc. of VLVT Workshop, Amsterdam, October 5-8 2003, <http://www.vlvnt.nl/proceeding>.
- [3] IceCube web page: <http://icecube.wisc.edu/>.
- [4] T.K. Gaisser et al., Phys. Rep. 258(1995)173.
- [5] *Study and characterization of a deep sea site for a km^3 underwater neutrino telescope*, The NEMO Collaboration, <http://nemoweb.lns.infn.it/sites/sitereport>
- [6] E.V. Bugaev, Phys. Rev. D58 (1998) 054001.
- [7] D.J.L. Bailey, *Monte Carlo tools and analysis methods for understanding the ANTARES experiment and predicting its sensitivity to Dark Matter*, PhD dissertation, University of Oxford, United Kingdom, <http://antares.in2p3.fr/>.
- [8] M. Musumeci, for the NEMO collaboration, 2003, Proc. of VLVT Workshop, Amsterdam, October 5-8 2003, <http://www.vlvnt.nl/proceeding>.
- [9] A. Okada, Astrop. Phys. 2 (1994) 393.
- [10] A. Levinson & E. Waxman, Phys. Rev. Lett. 87.171101(2001); C. Distefano et al., ApJ 575(2002)378.
- [11] C. Distefano, *Sensitivity of the NEMO underwater Cerenkov telescope to TeV neutrinos from Galactic Microquasars*, PhD thesis, University of Catania.
- [12] A. Heijboer, 2003, Contribution to the INTERNATIONAL WORKSHOP ON Ultra High Energy, Neutrino Telescope July 29-30, 2003, Chiba University, Chiba, JAPAN, http://www-ppl.s.chiba.jp/nu_chiba2003/nu2003_presen_files/

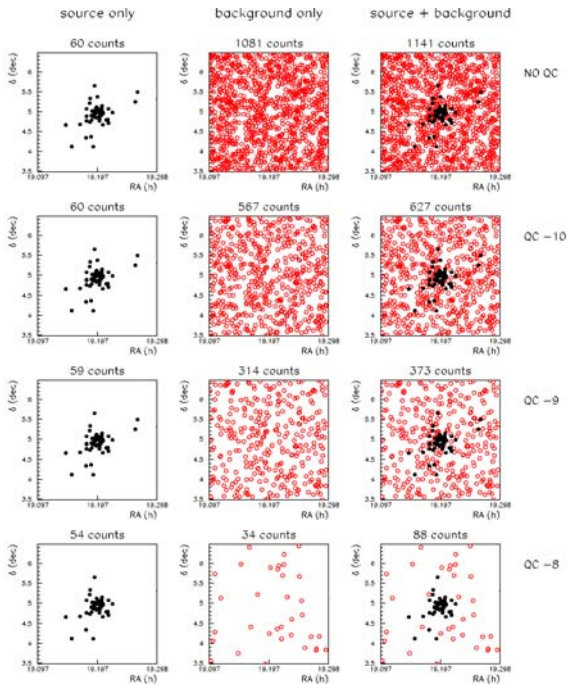


Figure 6: Distribution of neutrino events and total background events for microquasar SS433 as a function of applied quality cuts. The number of reconstructed events in the considered sky region is reported on top of each map.

FORMATION AND DECAY OF ^{22}Na IN THE COLLISIONS $^{13}\text{N}+^9\text{Be}$ AND $^{12}\text{C}+^{10}\text{B}$

P.Figuera^{a,*}, F.Amorini^{a,c}, C.Angulo^e, G.Cardella^b, S.Cherubini^{a,g}, A.DiPietro^a, J.Lu^a, C.Marchetta^a, M.Papa^b,
M.G.Pellegriti^{a,d}, R.G.Pizzone^{a,d}, R.Raabe^{ft}, F.Rizzo^{a,c}, J.L.Sida^f, W.Tian^a, S.Tudisco^{a,d}.

a)INFN Laboratori Nazionali del Sud, Catania, Italy

b)INFN Sezione di Catania, Catania, Italy

c)Dipartimento di Fisica ed Astronomia Universita' di Catania,Catania, Italy

d)Dipartimento di Metodologie Fisiche e Chimiche per l'Ingegneria

Universita' di Catania, Catania, Italy

e)Centre de Recherches du Cyclotron, Louvain la Neuve,Belgium

f)CEA, Saclay,France

g)Ruhr-Universitaet Bochum, Bochum, Germany

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

+Present address Instituut voor Kern-en Stralingsfysica University of Leuven, Belgium

Abstract

Recent results suggest that an inhibition of the fusion cross section could be present in collisions above the barrier between weakly bound participants. In order to further investigate this problem, we studied the fusion reactions $^{13}\text{N}+^9\text{Be}$ (weakly bound projectile and target) and $^{12}\text{C}+^{10}\text{B}$ both leading to the same compound nucleus ^{22}Na . The preliminary results of the data analysis, discussed in the present report, do not show a strong inhibition of the $^{13}\text{N}+^9\text{Be}$ fusion cross section compared to the one for the $^{12}\text{C}+^{10}\text{B}$ system.

1 INTRODUCTION

In the past few years, a great effort has been devoted to studying fusion reactions in collisions induced by radioactive ion beams in order to understand the effects of the nuclear structure on this reaction mechanism. As an example, both theoretical and experimental papers have investigated the effects of projectiles having a neutron halo structure, on the fusion reaction mechanism below and around the Coulomb barrier (see e.g. [1] and references therein).

Another interesting aspect, which can be investigated by using radioactive beams, concerns the study of fusion reactions above the barrier in collisions induced by weakly bound nuclei. In fact, in the study of stable beam induced fusion reactions, there are hints indicating a suppression of the fusion cross section in collisions between weakly bound nuclei. As an example, in [2] fusion excitation functions in colliding systems involving the least bound stable nuclei in nature (^6Li , ^7Li , ^9Be) show suppressed values of the fusion cross section above the barrier. For the system $^6\text{Li}+^9\text{Be}$ the authors find values of the fusion cross section which are about 50% lower than the expected calculated ones. The obtained results have been interpreted by assuming that the competition between fusion and breakup may lead to the dissociation, during the collision, of the weakly bound partners thus reducing the fusion cross section. It is suggested in [2] that the fusion probability is correlated to a parameter ϵ defined as $1/\epsilon=1/\epsilon_{\text{targ}}+1/\epsilon_{\text{proj}}$. Here ϵ_{targ} and ϵ_{proj} are the minimum energies needed to

break up into two fragments the target or the projectile respectively, and one should observe suppression of the fusion cross section for small values of ϵ ($\epsilon < 1.5$ MeV).

With the motivations discussed so far, we decided to compare fusion cross sections above the barrier for the systems $^{12}\text{C}+^{10}\text{B}$ and $^{13}\text{N}+^9\text{Be}$ leading to the formation of the compound nucleus ^{22}Na . The two colliding systems, leading to the same compound nucleus, are very similar. Therefore, in absence of structure effects, one would expect similar fusion excitation functions. However, in the collision $^{13}\text{N}+^9\text{Be}$ one has a weakly bound radioactive projectile ($S_p(^{13}\text{N})=1.9$ MeV) impinging on a weakly bound target ($S_n(^9\text{Be})=1.6$ MeV). Therefore, according to the above discussion, one may expect to observe a suppression of the fusion excitation function for $^{13}\text{N}+^9\text{Be}$ when compared to $^{12}\text{C}+^{10}\text{B}$.

2 EXPERIMENTAL RESULTS

The reaction $^{12}\text{C}+^{10}\text{B}$ has been studied using the stable beams accelerated by the tandem of the Laboratori Nazionali del Sud. The $^{13}\text{N}+^9\text{Be}$ reaction has been studied at the radioactive beam facility of Louvain la Neuve using ^{13}N beams at 30 and 45 MeV having currents between 10^7 and 10^8 pps. For this last experiment, we used thin ($200\mu\text{g}/\text{cm}^2$), self supporting targets of ^9Be which have been developed by the target laboratory of the Laboratori Nazionali del Sud. Special care was taken in the realization of these targets due to the problems connected to the toxicity of Berillium and

the fragility of the foils. Charged particles emitted in the studied collisions have been detected, and charge identified using monolithic silicon strip telescopes [3,4], in the angular range $\sim(3^\circ\div45^\circ)$. In both collisions the fusion cross section has been extracted by integrating the evaporation residue angular distributions. To obtain the absolute normalization factors for the cross section, we normalized to 1 the ratio between elastic and Rutherford cross sections at small scattering angles.

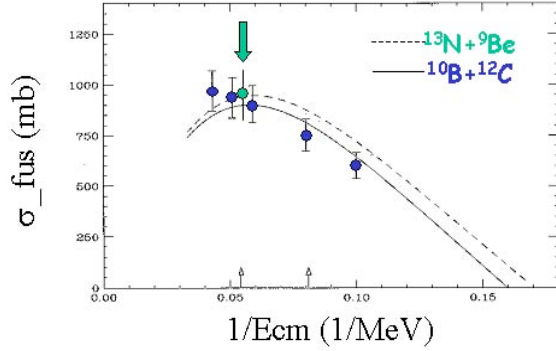


Figure 1. Measured fusion cross sections for $^{13}\text{N}+^9\text{Be}$ (marked by the arrow) and $^{12}\text{C}+^{10}\text{B}$ (other points). The continuous and dashed lines represent the fusion excitation functions for $^{12}\text{C}+^{10}\text{B}$ and $^{13}\text{N}+^9\text{Be}$ calculated with a phenomenological model which does not take into account structure effects of projectile and target.

In the preliminary results shown in figure 1, the extracted fusion cross sections for $^{12}\text{C}+^{10}\text{B}$ are compared with the one at $E_{\text{lab}}=45$ MeV for $^{13}\text{N}+^9\text{Be}$. The dashed and continuous lines represent the $^{13}\text{N}+^9\text{Be}$ and $^{12}\text{C}+^{10}\text{B}$ fusion excitation functions calculated with a simple phenomenological model [5] which does not take into account structure effects of projectile and target. As one can see, our data do not show any evident suppression of the fusion cross section for the weakly bound $^{13}\text{N}+^9\text{Be}$ system. In fact, the cross section for such system appears to be the same (within the experimental error) than the one for $^{12}\text{C}+^{10}\text{B}$. Moreover, the experimental data for both systems are in good agreement with the predictions of a simple phenomenological formula which does not take into account the structure of projectile and target.

The experimental relative yields of the different evaporation residue for the two reactions are compared with the predictions of the statistical model Cascade in figures 2 and 3. Such comparison is made at a fixed excitation energy of the compound nucleus $E^*(^{22}\text{Na})\approx 40$ MeV which corresponds to $E_{\text{lab}}(^{13}\text{N})=45$ MeV for the $^{13}\text{N}+^9\text{Be}$ reaction and $E_{\text{lab}}(^{10}\text{B})=42$ MeV for the $^{12}\text{C}+^{10}\text{B}$ system. As one can see, the experimental relative yields for the two reactions are very similar and in good agreement with the predictions of the statistical model. This excludes the possibility to have a strong incomplete fusion contribution in the ^{13}N induced reaction due to the presence of the weakly bound proton.

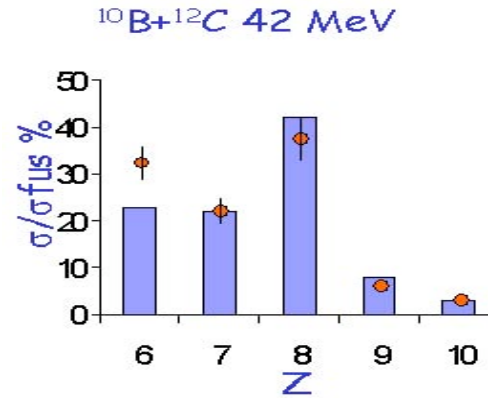


Figure 2. Experimental relative yield of the different evaporation residues for the collision $^{12}\text{C}+^{10}\text{B}$ (points) at $E_{\text{lab}}(^{10}\text{B})=42$ MeV ($E^*(^{22}\text{Na})\approx 40$ MeV) compared with the predictions of the statistical model Cascade (histog.).

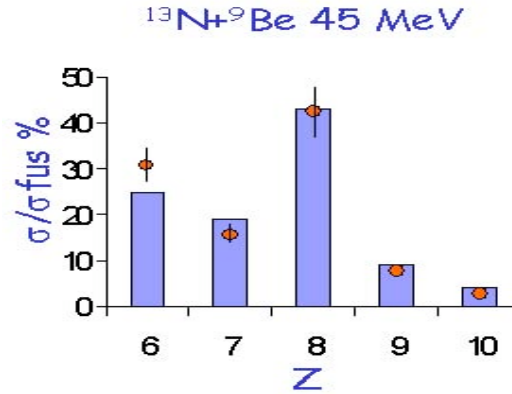


Figure 3. Experimental relative yield of the different evaporation residues for the collision $^{13}\text{N}+^9\text{Be}$ (points) at $E_{\text{lab}}(^{13}\text{N})=45$ MeV ($E^*(^{22}\text{Na})\approx 40$ MeV) compared with the predictions of the statistical model Cascade (histogram).

In summary, our preliminary results do not show strong suppression effects of the fusion cross section for the weakly bound system $^{13}\text{N}+^9\text{Be}$. Moreover the comparison with the statistical model calculations appears to confirm that the reaction proceeds via complete fusion followed by particle evaporation. Work is in progress to perform a systematic comparison of the residue energy spectra with the predictions of the statistical model, and to analyze the $^{13}\text{N}+^9\text{Be}$ data at $E_{\text{lab}}(^{13}\text{N})=30$ MeV.

5 REFERENCES

- [1] A. Di Pietro et al. :Phys.Rev. C69,044613(2004).
- [2] J.Takahashi et al .Phys Rev. Lett. 78,30,(1997).
- [3] F.Amorini et al.: LNS activity report 2002.
- [4] A.Musumarra et al.: NIM A409,414,(1998).
- [5] F.Porto et al.: Il Nuovo Cimento A83,339,(1984).

The ${}^3\text{He}(d,p){}^4\text{He}$ reaction studied via the Trojan Horse Method

M. La Cognata^{1,2}, A. Musumarra^{1,2}, C. Spitaleri^{1,2}, S. Cherubini³, Đ. Miljanić⁴,
M.G. Pellegriti^{1,2}, R.G. Pizzone², C. Rolfs³, S. Romano^{1,2}, A. Tumino^{1,2}, S. Typel⁵
¹*Dipartimento di Metodologie Fisiche e Chimiche per l'Ingegneria - Università di Catania, Catania, Italy*
²*Laboratori Nazionali del Sud - INFN, Catania, Italy*
³*Ruhr-Universität, Bochum, Germany*
⁴*Ruder Bošković Institute, Zagreb, Croatia*
⁵*GSI, Darmstadt, Germany*

Abstract

The ${}^3\text{He}(d,p){}^4\text{He}$ reaction has been studied by means of the Trojan Horse Method (THM) at 5 MeV and 6 MeV beam energies. The bare astrophysical S(E)-factor has been extracted both in Plain Wave Impulse Approximation and in Distorted Wave Born Approximation. The experimental data are compared to the direct astrophysical factor and the results discussed.

I. INTRODUCTION

The improved accuracy of cross section measurement at astrophysical energies has allowed a better understanding of many astrophysical phenomena. However, the energies characterizing nuclear processes in several astrophysical contexts are so low that the presence of atomic electrons must be taken into account. Their effect is usually referred to as electron screening, since atomic electrons shield nuclear charge, determining a steep rise of cross sections at ultra-low energies [1]. In order to parameterize the cross section rise due to the screening effect, an enhancement factor is usually introduced [1]:

$$f_{lab}(E) = \sigma_s(E)/\sigma_b(E) = \exp(\pi\eta U_e/E) \quad (1)$$

where $\sigma_s(E)$ and $\sigma_b(E)$ are respectively the cross section of shielded and bare nuclei, η is the Sommerfeld parameter and U_e is the electron screening potential energy. Since the astrophysical S(E)-factor for bare nuclei is not available experimentally, extrapolation, usually supported by theoretical arguments, is needed in order to evaluate the bare S(E)-factor, which is the useful nuclear input to astrophysical models.

The Trojan Horse Method (THM) has been introduced [2] as a complementary and independent method to obtain the bare nucleus astrophysical S(E)-factor and therefore the electron screening potential, without extrapolation. The basic assumptions of the THM have already been discussed elsewhere [2]; in this work the THM has been applied to the study of the reaction ${}^3\text{He}(d,p){}^4\text{He}$, whose importance is connected to primordial nucleosynthesis (both homogeneous and inhomogeneous) and with the analysis of electron screening [3].

In order to extract the astrophysical S-factor for the ${}^3\text{He}(d,p){}^4\text{He}$ reaction the THM has been applied to the study of the ${}^6\text{Li}({}^3\text{He}, p\alpha){}^4\text{He}$ three body reaction because the presence of the quasi-free mechanism at low energies in such a three body reaction had been reported in a previous work [4].

Furthermore, this study has allowed an effective val-

idation of THM below the Coulomb barrier as the ${}^3\text{He}(d,p){}^4\text{He}$ reaction also proceeds through a resonance associated with the 16.87 MeV level of ${}^5\text{Li}$. It is also important to stress that ${}^6\text{Li}$ nucleus represents the Trojan horse, as the cluster configuration ${}^6\text{Li}=d+{}^4\text{He}$ presents a high probability; deuteron is the participant to the virtual reaction while ${}^4\text{He}$ constitutes the spectator of the reaction.

Experimental procedures and data analysis are discussed in the following sections.

II. EXPERIMENTAL APPARATUS

The experiment was performed at Dynamitron Tandem Laboratorium in Bochum (Germany). The 4 MV tandem accelerator provided a ${}^3\text{He}$ beam with an average intensity of 10 nA. In the first run the beam energy was set to 6 MeV while in the second run a beam energy of 5 MeV was chosen in order to study the low energy behaviour of the astrophysical S-factor.

The ${}^3\text{He}$ beam impinged onto an isotopically enriched (${}^6\text{Li}\approx 95\%$) lithium fluoride target (300 mg/cm² thick, carbon backing 30 mg/cm² thick), placed at 90° with respect to the beam axis.

The detection set-up consisted of two symmetrical couples of PSD's in coincidence (PSD_{p1} and PSD_{α1}, PSD_{p2} and PSD_{α2}), arranged in the same plane on opposite sides of the beam direction, and placed at the quasi free angles [2].

In particular, the first proton detector is a telescope made up of a 502 μm and 992 μm position-sensitive silicon detectors, centered at 146.0°, covering an angular interval of 19.1°. Similarly, the second proton detector is a 1004 μm PSD, centered at -145.2°, and spans an angular range equal to 22.3°; in front of this detector is located a 200 μm thick aluminium degrader, in order to slow down high energy protons.

The first and the second α-particle detectors are placed in the forward direction, at -16.4° and 16.5° respectively. They are both 502 μm thick PSD, covering an angular

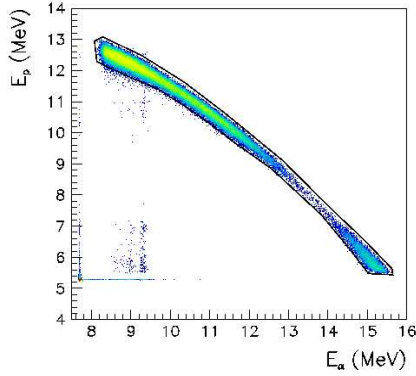


FIG. 1: ${}^6\text{Li}({}^3\text{He}, p\alpha){}^4\text{He}$ reaction kinematical locus in the E_p - E_α plane. The graphical cut adopted in the following analysis is also shown.

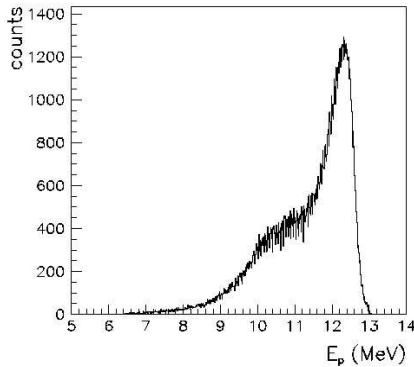


FIG. 2: Proton energy spectrum showing the large background from ${}^8\text{Be}$ sequential decay.

range of 15.0° and 14.4° . A $40\ \mu\text{m}$ aluminum degrader was placed in front of the two detectors, in order to stop ${}^3\text{He}$ nuclei elastically scattered by Fluorine and Carbon at small angles.

The selected angular range corresponds to kinematical conditions under which the momentum of the undetected α particle ranges from $-100\ \text{MeV}/c$ to $100\ \text{MeV}/c$. This assures that the bulk of the quasi-free contributions of the breakup process falls within the experimental phase space region.

The trigger for event acquisition is given by the logical OR of the coincidence between PSD_α and PSD_p . In this way background coming from other reaction and electronic noise is further reduced. Energy and position signals of the PSD's were processed by standard electronic chains together with the time coincidence signal, and sent to the acquisition system for on-line monitoring and data storing.

III. DATA ANALYSIS AND RESULTS

After detector calibration, the first step of the analysis is the selection of events corresponding to the ${}^6\text{Li}({}^3\text{He}, p\alpha){}^4\text{He}$ three body reaction. This is accomplished by means of a selection of the kinematical locus of this reaction. As the Q-value is very high (16.88 MeV), the kinematical locus (E_p - E_α) is well separated from other spurious contributions. Figure 1 shows the kinematical locus of the reaction ${}^6\text{Li}({}^3\text{He}, p\alpha){}^4\text{He}$ in the E_p - E_α plane and the graphical cut introduced in order to select only the events corresponding to the reaction channel of interest.

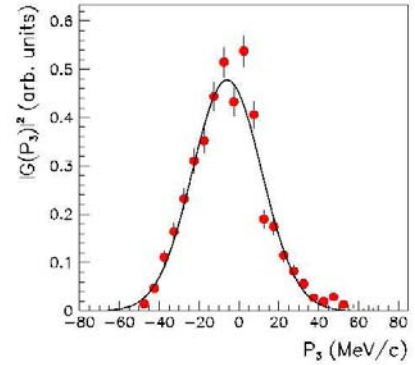


FIG. 3: Spectator momentum distribution extracted through the TH method. The width of the distribution agrees with the expected value from literature.

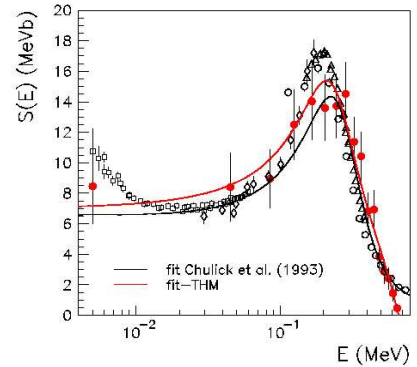


FIG. 4: THM astrophysical $S(E)$ -factor (full dots) compared with direct data from [6, 7, 8, 9]. The resonant behavior is well reproduced in spite of the low statistics.

The E_p spectrum obtained introducing the cuts mentioned above is shown in fig. 2. The presence of two reaction mechanisms is evident: at lower energy the quasi-free contribution shows up, while at higher energy the sequential decay from the first excited state of ${}^8\text{Be}$ ($J^\pi=2^+$, $E_x=3.04\ \text{MeV}$ and $\Gamma=1.5\ \text{MeV}$) appears to be very important.

The last contribution constitutes a large background that has to be subtracted before going on with the extraction of the $S(E)$ -factor of the two body reaction. In order to remove the ^8Be background, for each pair of quasi free angles the ^8Be contribution is subtracted by fitting the level with a Breit-Wigner in the $E_{\alpha-\alpha}$ spectrum. For establishing whether the contribution of the quasi-free mechanism is present and separable from other reaction mechanisms (e. g. sequential decays), angular correlation spectra are extracted from the data [2]. These spectra show an enhancement in the coincidence yield approaching the condition of nearly zero p_3 momentum; then coincidence yield decreases while moving far from this condition. This is an evidence for a quasi-free mechanism taking place, since it reflects the behavior of the momentum distribution of the deuteron inside ^6Li . As a further test, the quasi-free p_3 momentum distribution has been reconstructed and compared with that from literature [5]. In the present case, the extracted FWHM was ≈ 40 MeV/c, in agreement with the value expected from literature [5] (fig. 3).

Since the presence of the quasi-free contribution was clearly demonstrated, $S(E)$ has been deduced. In the framework of Distorted Wave Born Approximation (DWBA), the three body cross section can be written as in [2]. According to [2] the $S(E)$ -factor has been extracted dividing the three body cross section (in arb. units) for a Monte Carlo simulation containing the product of the kinematic factor and $|G(p_3)|^2$. The momentum distribu-

tion adopted in the analysis of the data is the Hankel function, whose FWHM is chosen to be 40 MeV/c, as already discussed. The deduced THM $S(E)$ -factor is then normalized to direct data at high energy to get $S(E)$ in absolute units. By fitting indirect THM data with the sum of a second order polynomial and a Breit-Wigner for the resonant behavior, we got $S(0)=7.0\pm 2.2$ MeV**·**b, in good agreement with direct data (figure 4) [6, 7, 8, 9].

IV. CONCLUDING REMARKS

In the last step of the analysis the screening potential has been extracted from the comparison of direct data with the THM $S(E)$ -factor. In fact, as the ^6Li break-up takes place in ^3He nuclear field due to the high energy of the projectile, THM $S(E)$ -factor is free of electron screening effect [2]. In the present case, low statistics allow only a rough estimate of the screening potential, $U_E \approx 150$ eV, in agreement with data from direct measurement [6, 7, 8, 9].

V. ACKNOWLEDGMENTS

The authors would like to thank Prof. M. Lattuada for his helpful collaboration during the course of the experiment.

-
- [1] G. Fiorentini, R. W. Kavanagh, C. Rolfs, Z. Phys. **350** (1995) 289.
 - [2] C. Spitaleri et al., Phys. Rev. **C63** (2001) 055801.
 - [3] F. C. Barker, Nucl. Phys. **A707** (2002) 277.
 - [4] M. Zadro et al., Nucl. Phys. **A474** (1987) 373.
 - [5] S. Barbarino et al., Phys. Rev. **C21** (1980) 1104.
 - [6] M. A. Aliotta et al., Nucl. Phys. **A690** (2001) 790.
 - [7] W. H. Geist et al., Phys. Rev. **C60** (2001) 054003.
 - [8] A. Krauss et al., Nucl. Phys. **A465** (1987) 150.
 - [9] G. S. Chulick et al., Nucl. Phys. **A551** (1993) 255.

Study of the quasi-free ${}^2H(t, tp)n$ reaction at $E_t=35.5$ MeV as a validity test of PWIA for THM application

M. La Cognata^{1,2}, C. Spitaleri^{1,2}, S. Blagus³, S. Cherubini⁴, Đ. Miljanić³, A. Musumarra^{1,2},
M.G. Pellegriti^{1,2}, R.G. Pizzone², S. Romano^{1,2}, A. Tumino^{1,2}, M. Zadro³

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

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

³*Ruder Bošković Institute, Zagreb, Croatia*

⁴*Ruhr-Universität, Bochum, Germany*

Abstract

The $t + p \rightarrow t + p$ and $t + p \rightarrow d + d$ channels have been investigated in indirect way through the three body ${}^2H(t, tp)n$ and ${}^2H(t, dd)n$ quasi-free reactions ($E_t = 35.5$ MeV). Coincidence spectra measured in a kinematically complete experiment show the presence of the quasi-free $t + p$ scattering. The excitation function $\sigma(E_{cm})$ and the angular distribution $\sigma(\theta_{cm})$ are extracted in the energy range $4.5 \div 9$ MeV from the three-body reaction cross section at low neutron momentum and compared with the behavior of the free two-body reaction excitation function. $t + p \rightarrow d + d$ quasi free reaction angular distributions at 8. MeV are also reported.

I. INTRODUCTION

The Trojan Horse Method (THM) represents a powerful tool to extract information on charged particle two-body cross sections at astrophysical energies [1, 2, 3, 4] from suitable three body reactions.

The application of the method requires:

- a preliminary investigation of the presence of the quasi-free (QF) contribution to the reaction cross section of the chosen three-body reaction;
- the close agreement between direct data from literature and indirect cross section extracted via the THM.

This procedure has been applied to a number of reactions [5], in particular ${}^7Li(p, \alpha){}^4He$ [6], ${}^6Li(p, \alpha){}^3He$ [7], ${}^6Li(d, \alpha){}^4He$ [2], ${}^{12}C(\alpha, \alpha){}^{12}C$ [8], as it constitutes a necessary condition for the applicability of the THM.

In the present paper results of a revisited data analysis of reactions induced by tritons on deuterons (see [9, 10]) are discussed; angular distributions and excitation functions for $t + p \rightarrow t + p$ and angular distribution for $t + p \rightarrow d + d$ are deduced above the Coulomb barrier in the simple PWIA approach [11, 12], by using deuteron as Trojan Horse nucleus. The present investigation constitutes a validity test necessary for a subsequent study of these reactions at sub-Coulomb energies via THM and a confirmation of the validity of polar approximation in the analysis of light particle reactions.

II. THE EXPERIMENT

The experiment was performed at the NSF Tandem Laboratory in Daresbury which provided a 3H -ion beam at energy 35.5 MeV and intensities up to 25-100 nA. The experimental set-up is described in [9, 10], so hereafter

only the essential details about data reduction are reported.

Concerning ${}^2H(t, dd)n$, after identification of the d ions in ΔE - E 2d-plot the locus of events in the $E_{d_1} - E_{d_2}$ plot due to such three body reaction is defined by the corresponding kinematics. Other three-body reactions occurring in the target were identified in the same way. The kinematic loci for different reactions do not overlap with the one of interest [9, 10].

In order to select the coincidences due to ${}^2H(t, dd)n$ reaction, constraints on the time-to-amplitude converter (TAC) parameter and a graphical cut on $E_{d_1} - E_{d_2}$ plot have been introduced. The Q-value spectrum for these coincidences events is also obtained and events below this peak have been selected for further analysis in order to reduce the contribution from random coincidences.

By using a Monte Carlo simulation the three body kinematic locus is calculated and compared with the experimental one corresponding to the region where the coincident events $E_{d_1} - E_{d_2}$ are present.

A similar procedure is followed to extract data from the ${}^2H(t, dd)n$ reaction, selecting the kinematical locus corresponding to $p - t$ coincidences.

III. EXPERIMENTAL EVIDENCE AND SELECTION OF QUASI-FREE MECHANISM

After the selection of the $d - d$ and $p - t$ coincidences, the next step of data analysis is to assure that in the considered experimental kinematic regions the contribution of the quasi-free process to the overall cross section is evident and well separated from others. As already mentioned, the analysis of the experimental results is in general complicated by the presence of other reaction mechanisms feeding the same particles in the final state, e.g. sequential decay (SD) and direct break-up (DBU). In the present case, *noise* contribution connected to SD

from the 3.1 MeV state of ^4H (FWHM=1.9 MeV), whose presence has been shown in a previous work [10], must be discriminated. Thus, from overall $t-p$ coincidence events corresponding to the quasi-free condition has to be selected.

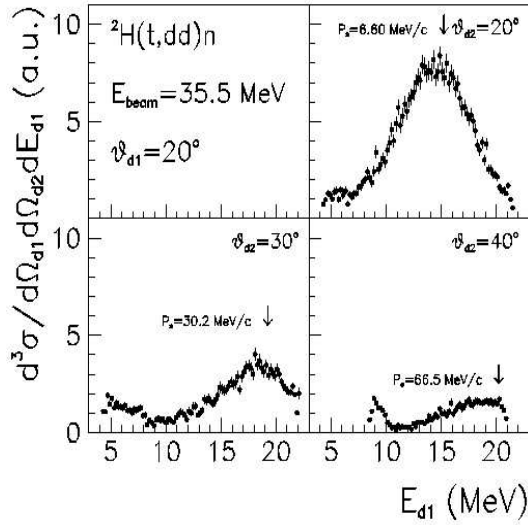


FIG. 1: Typical coincidence spectra projected on the E_{d1} axis for a fixed θ_{d1} and different θ_{d2} , within the angular ranges of $\pm 0.3^\circ$. The condition corresponding to minimum neutron momentum is marked with an arrow.

In order to investigate the reaction mechanisms and to separate quasi-free contribution from SD and kinematical effects, the angular correlation analysis is performed on the data. Fig. 1 shows typical coincidence spectra projected on E_{d1} axis for a fixed θ_{d1} and for different θ_{d2} angles within the experimental angular range, corrected for the detection efficiency. This is fulfilled dividing experimental spectra by simulated spectra obtained imposing only momentum and energy conservation.

From the comparison of these figures it can be observed that the coincidence yield attains a maximum when the neutron momentum approaches zero value (minimum $p_s = 6.6$ MeV/c). This condition is marked in each case with an arrow in the figure. This feature is expected for a quasi-free reaction because the momentum distribution of $p-n$ system in the ^2H nucleus has a maximum for $p_n = 0$ MeV/c, since $p-n$ relative motion essentially takes place in s-wave. This represents a first necessary check for the existence of the quasi-free mechanism in the $^2\text{H}(t, dd)n$ reaction.

The $(\theta_{d1}, \theta_{d2})$ angles corresponding to the condition of zero spectator momentum represent the so called quasi-free angles.

Similar results have been obtained for other quasi-free angle pairs and in the case of $t-p$ coincidence events.

A complementary way to test the presence of QF and/or SD mechanisms is to investigate the behavior of the coincidence yield as a function of the *spectator* particle momentum p_n , at the quasi-free angular pairs; in fact

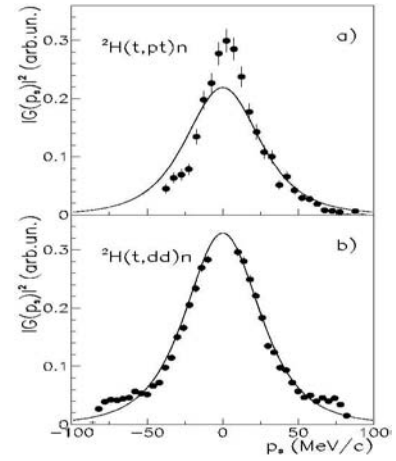


FIG. 2: Experimental momentum distribution (full dots) compared with the theoretical momentum distribution described by H  nkel function (full line) for $^2\text{H}(t, pt)n$ (a) and $^2\text{H}(t, dd)n$ (b).

the shape of the experimental momentum distribution turns out to be more sensitive to the reaction mechanism. In order to reconstruct the experimental p_n distribution, the energy sharing method [13] is therefore applied to each pair of detectors at QF angles.

Dividing the resulting quasi-free coincidence yield by the kinematic factor, a quantity which is proportional to the product of the p_n momentum distribution and of the differential two-body cross section [4] is left out. Anyway within such restricted angular ranges, the differential two-body cross section of the $t-p$ scattering can be considered almost constant.

Thus the quantity defined above and reported in Fig. 2a and 2b represents the experimental p_n momentum distribution in arbitrary units for the $^2\text{H}(t, tp)n$ and $^2\text{H}(t, dd)n$ channels. The error bars include only statistical errors. The extracted experimental momentum distribution (Fig. 2a and 2b) is then compared with the theoretical one, given in terms of a Hulth  n wave function in momentum space:

$$\Phi(\vec{p}_s) = \frac{1}{\pi} \sqrt{\frac{ab(a+b)}{(a-b)^2}} \left[\frac{1}{a^2 + p_s^2} - \frac{1}{b^2 + p_s^2} \right] \quad (1)$$

with parameters $a = 0.2317 \text{ fm}^{-1}$ and $b = 1.202 \text{ fm}^{-1}$ [6] for the deuteron ground state. The theoretical distribution is superimposed to the data of Fig. 2a and 2b, after being normalized to the experimental maximum. Eq. 1 with parameters a and b from [6] reproduces quite well the shape of experimental data.

IV. FROM THE EXPERIMENTAL THREE-BODY TO THE INDIRECT TWO-BODY CROSS SECTION

In order to select the region where the QF mechanism is dominant and PWIA approach is valid, coincidence events for neutron momentum ranging between -40 MeV/c and 40 MeV/c are considered in the further analysis.

According to the method already discussed, a Monte Carlo calculation has been performed to extract the $(KF \cdot |\Phi(\vec{p}_s)|^2)$ product; the momentum distribution entering the calculation is that given in Eq. 1. The geometrical efficiency of the experimental setup as well as the detection thresholds of the detectors have been fully taken into account.

Following the PWIA prescription [4], the two-body cross-section $d\sigma/d\Omega_{cm}$ is derived dividing the selected three-body experimental coincidence yield by the result of the Monte Carlo calculation.

As already mentioned, since this approach provides the off-energy-shell two-body cross section, it is necessary to perform the appropriate validity tests for the adopted IA.

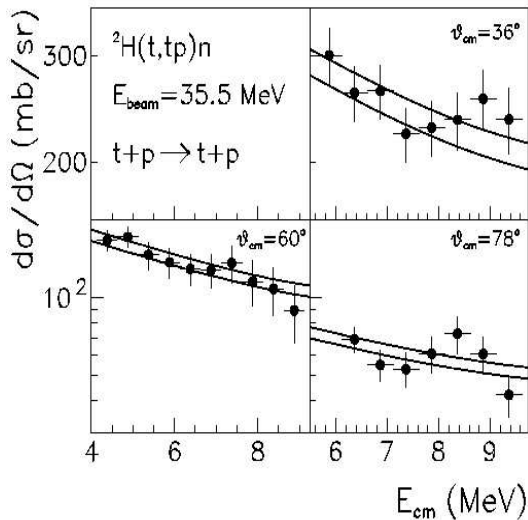


FIG. 3: Comparison between the obtained indirect excitation functions (full dots) for the $t+p$ elastic scattering, evaluated in correspondence of $\theta_{cm} = 36^\circ, 60^\circ, 78^\circ$, and the direct behavior (the two solid lines determine the range covered due to experimental errors and fitting uncertainties) [14, 15, 16, 17, 18, 19].

Once the presence and separability of quasi free mechanism is established, the next test to be carried out concerns the behavior of the indirect excitation function of the two-body quasi-free reaction.

It has to be verified that the behavior of the off-energy-shell two-body cross-section, integrated over a suitable θ_{cm} range, is consistent with that of direct data within the same angular region. Since direct data are not available in the full range determined by the present experimental conditions, a two-dimensional fit of direct data

from [14, 15, 16, 17, 18, 19] for $t+p$ elastic scattering has been performed, using as a minimizing function the product of a third order polynomial describing the energy behavior, with a linear superposition of the first five Legendre polynomials to account for the angular dependence.

The resulting two-body excitation functions for three different angles ($\theta_{cm} = 36^\circ, 60^\circ$ and 78°) are shown in Fig. 3 (full dots), where direct data are also reported (solid lines). The two solid lines show the minimum and maximum value of direct data including experimental errors and the uncertainty coming from the fitting procedure.

The normalization to the direct excitation functions has been performed at a fixed energy value for each data set. Two-body cross-section has been integrated over 6° ; moreover indirect data are averaged in energy intervals of 0.5 MeV to clearly evidence the energy behavior. Error bars take into account both statistical and normalization uncertainties.

Fig. 3 entails a very good agreement between direct and indirect data extracted through PWIA approach; this test confirms that the PWIA analysis is able to correctly describe the studied process at high energies. Moreover, it has to be stressed that this agreement is indeed a necessary condition for the further extraction of the astrophysical $S(E)$ factor by means of THM [2, 4, 8], as discussed in the Introduction.

Excitation functions have not been extracted for $t+p \rightarrow d+d$ reaction because they present a very small number of points due to low statistics.

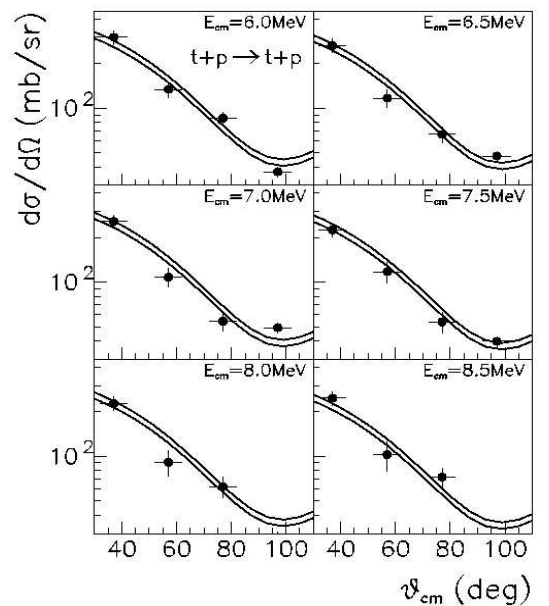


FIG. 4: Comparison between the indirect angular distributions (full dots) for the $t+p \rightarrow t+p$ scattering, evaluated in the energy range $4.5 \div 9$ MeV, and the direct differential cross section (solid lines) [14, 15, 16, 17, 18, 19].

By using an equivalent procedure, angular distributions for $t+p$ elastic scattering and $t+p \rightarrow d+d$ reaction

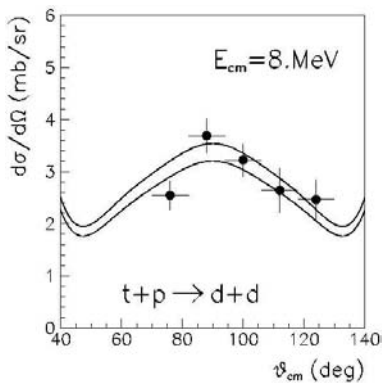


FIG. 5: Comparison between the indirect angular distributions (full dots) for the $t + p \rightarrow d + d$ reaction, evaluated at 8. MeV, and the direct behavior (solid lines) [20, 21, 22].

have been deduced.

Concerning $t + p$ elastic scattering (Fig. 4), angular distributions, integrated over 0.5 MeV and averaged over 10° , are shown for energies ranging from 4.5 MeV to 9. MeV and superimposed to direct data; normalization is accomplished in the way discussed before. The good agreement between direct and indirect data means that different waves contribute with the same weight to the measured differential cross section and to the one extracted through PWIA.

The same conclusion holds for $t + p \rightarrow d + d$ reaction, as it is shown Fig. 5. In this case angular distributions are re-

ported for a single energy, $E_{cm} = 8$. MeV, integrated over 1. MeV energy interval because of statistics; data are also averaged over 10° to evidence the overall behavior.

Direct cross section is obtained by converting data from [20, 21, 22] related to $d + d \rightarrow t + p$ reaction by detailed balance principle and fitting them by means of the product of a third order polynomial (to reproduce the energy dependence) with a linear combination of the first four even Legendre polynomials.

V. RESULTS AND CONCLUSIONS

The obtained results for the ${}^2H(t, tp)n$ reaction establish the presence of the quasi-free mechanism around the region of spectator momentum close to zero. The mechanism proceeds through a virtual two-body reaction in which a virtual proton within the deuteron reacts with the incident triton.

The $t + p$ scattering and $t + p \rightarrow d + d$ reaction have been indirectly studied over a wide range of relative energy from 4.5 MeV up to 9. MeV. The present work is a further validity test for the pole approximation above the Coulomb barrier and confirms that a positive result is obtained applying PWIA when a neutron is the spectator to the virtual reaction, that is, the three body cross section can be factorized as shown in [4] under selected conditions.

-
- [1] G. Baur, Phys. Lett. B **178**, 135 (1986)
 - [2] S. Cherubini et al., Ap. J. **457**, 855 (1996).
 - [3] S. Typel and G. Baur, Ann. Phys. **305**, 228 (2003)
 - [4] C. Spitaleri et al., Phys. Rev. C (2004), in press
 - [5] C. Spitaleri et al., Proceedings of the Omeg2003 conference, Riken (Japan), World Scientific (2004), in press
 - [6] M. Zadro et al., Phys. Rev. C **40**, 181 (1989)
 - [7] G. Calvi et al., Phys. Rev. C **41**, 1848 (1990)
 - [8] C. Spitaleri et al., Eur. Phys. J A **7**, 181 (2000)
 - [9] S. Blagus et al., Z. Phys. A-Atomic Nuclei **337**, 297 (1990)
 - [10] S. Blagus et al., Phys. Rev. C **44**, 325 (1991)
 - [11] G.F. Chew, Phys. Rev. **80**, 196 (1950)
 - [12] M. Jain et al., Nucl.Phys. **A153**, 49 (1970)
 - [13] N. Arena, D. Vinciguerra, F. Riggi, C. Spitaleri, Nuovo Cimento **45**, 405 (1978)
 - [14] A. Hemmendinger, G.A. Jarvis, R.F. Taschek, Phys. Rev. **76**, 1137 (1949)
 - [15] R. S. Claassen et al., Phys. Rev. **82**, 589 (1951)
 - [16] J.E. Brolley et al., Phys. Rev. **117**, 1307 (1960)
 - [17] M. Ivanovich, P.G. Young, G.G. Ohlsen, Nucl. Phys. **A110**, 441 (1968)
 - [18] J.L. Detch, R.L. Hutson, N. Jarmie, J.H. Jett, Phys. Rev. C **4**, 52 (1971)
 - [19] R. Kankowsky et al., Nucl. Phys. **A263**, 29 (1976)
 - [20] J.C. Allred, D.D. Phillips, L. Rosen, Phys. Rev. **82**, 782 (1951)
 - [21] J.E. Brolley, Jr., T.M. Putnam, L. Rosen, Phys. Rev. **107**, 820 (1957)
 - [22] A.D. Bacher, T.A. Tombrello, Nucl. Phys. **A113**, 557 (1968)

Astrophysical $S(E)$ -factor for ${}^9\text{Be}(p,\alpha){}^6\text{Li}$ reaction extracted via the Trojan Horse Method

L. Lamia^{*,1,2}, C. Li¹, R.G. Pizzone¹, C. Spitaleri^{1,2}, S. Cherubini^{1,3}, A. Del Zoppo¹, P. Figuera¹, M. Gulino^{1,2}, M. La Cognata^{1,2}, A. Musumarra^{1,2}, L. Pappalardo⁴, M.G. Pellegriti^{1,2}, A. Rinollo^{1,2}, C. Rolfs³, S. Romano^{1,2}, S. Tudisco^{1,2}, A. Tumino^{1,2}

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

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

³*Ruhr-Universität Bochum, Germany.*

⁴*Texas A&M University, College Station, Texas, USA.*

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

Abstract

In the last twenty years particular interest was devoted to the study of light element abundances (lithium, beryllium and boron). These elements can be seen as possible diagnostics between different scenarios in primordial or stellar nucleosynthesis. LiBeB are mainly destroyed via (p,α) reactions in both astrophysical environments and therefore precise measurements of their burning cross-sections are needed. In this short paper a recent study of the ${}^9\text{Be}(p,\alpha){}^6\text{Li}$ via the Trojan Horse Method in the astrophysical energy range $0 < E_{\text{cm}} < 0.7 \text{ MeV}$ is presented. Preliminary results are discussed and a comparison with direct data is made.

1 INTRODUCTION

In recent years the abundances of light elements lithium, beryllium and boron (LiBeB) have been increasingly used as diagnostics between different scenario for primordial or stellar nucleosynthesis. As reported in [1], beryllium primordial abundances can provide a powerful test to discriminate between homogeneous and inhomogeneous primordial nucleosynthesis. Moreover, as reported in [2], the study of beryllium abundances in young stars, together with lithium and boron, can provide a strong test for understanding stellar structure and discriminate between possible non-standard mixing processes in stellar interiors.

In both stellar and primordial environments, however, LiBeB are mainly destroyed by proton-capture reactions via the (p,α) channel with a Gamow energy E_G ranging from $\sim 10 \text{ keV}$ (for stellar nucleosynthesis) to $\sim 100 \text{ keV}$ (for primordial nucleosynthesis). These energies are low if compared with the Coulomb barrier E_C , usually of the order of MeV's, thus implying the reactions take place via tunnel effect with an exponential decrease of the cross section,

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

(where η is the Sommerfeld parameter). Due to the exponential suppression, the behavior of the direct cross sections at astrophysical energies are usually

extrapolated from that at higher energies by using the definition of the astrophysical factor

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

which varies smoothly with energies. Nevertheless this extrapolation procedure can introduce some uncertainties due, for example, to the presence of unexpected sub-threshold resonances or electron-screening effects [3].

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

In the present paper, we present the results of the study of two-body ${}^9\text{Be}(p,\alpha){}^6\text{Li}$ reaction, obtained through the application of the THM to the three-body ${}^2\text{H}({}^9\text{Be}, {}^6\text{Li})n$ reaction.

2 EXPERIMENTAL SETUP

The aim of the present experiment was to extract the information about the ${}^9\text{Be}+p \rightarrow {}^6\text{Li}+\alpha$ reaction after selecting the QF-contribution of

${}^9\text{Be}+d\rightarrow{}^6\text{Li}+\alpha+n$ reaction. The deuteron was used like “trojan horse nucleus”, having an high probability to be described like $d=p\oplus n$ [6]; in this framework the proton acts like *participant* while the neutron is the *spectator* to the virtual two-body reaction.

The experiment was performed at the LNS in Catania. The SMP Tandem Van de Graaf accelerator provided a 22 MeV ${}^9\text{Be}$ beam with a spot size on target of about 2 mm and intensities up 2-5 pnA. A deuterated polyethylene target (CD_2) of about $190\text{ }\mu\text{g}/\text{cm}^2$ was placed at 90° with respect to the beam axis direction. For a continuous monitoring of the target thickness during the experiment, a silicon ΔE -E telescope was placed at about 70 cm from the target with an angle of about 45° . The particle detection was performed by using two standard ΔE -E telescopes, where the second stadium was a PSD. The telescopes were placed at opposite sides with respect to the beam direction at a distance from the target $d=25\text{cm}$, covering the angular ranges 11.5° - 25.5° (telescope devoted to ${}^6\text{Li}$ detection) and 14.5° - 28.5° (telescope for ${}^4\text{He}$ detection). The displacement of the experimental setup was chosen in order to cover the whole QF-angular range, known “a priori” from a Montecarlo simulation. The trigger for the event acquisition was given by the coincidence between the two telescopes. Energy and position signals for the detected particles were processed by standard electronics and sent to the acquisition system for on-line monitoring of the experiment and data storage on magnetic tape for the off-line analysis.

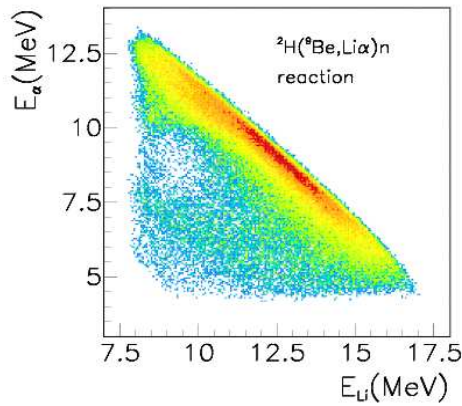


Figure 1.: Experimental kinematical locus for the three-body reaction ${}^9\text{Be}+d\rightarrow{}^6\text{Li}+\alpha+n$.

4 DATA ANALYSIS AND RESULTS

4.1. Three-body reaction identification.

After the energy and position calibration of the two PSD's in telescopes, performed by using the reaction data from ${}^{12}\text{C}({}^6\text{Li},\alpha){}^{14}\text{N}$ and ${}^{12}\text{C}({}^6\text{Li},{}^6\text{Li}){}^{12}\text{C}$, ${}^6\text{Li}$ and α particles were selected with the standard ΔE -E technique. After the particle identification and with the assumption of mass number 1 for the *undetected* third particle, the kinematical locus of events (E_{Li} vs. E_{α}) (fig.1) was reconstructed in very good agreement with the simulation. Moreover the experimental Q-value spectrum (fig.2) for the three-body reaction is centered at about -0.1 MeV, according to the expected theoretical value. Events below this peak were selected for the further analysis.

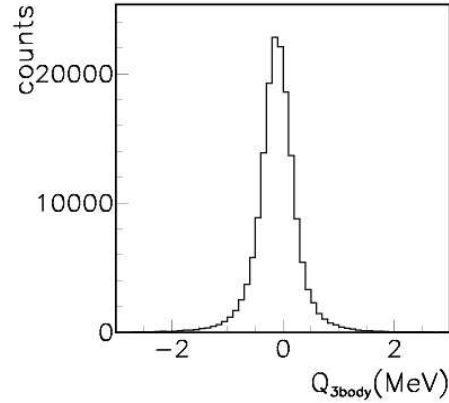


Figure 2.: Experimental Q-value spectrum for the three-body reaction ${}^9\text{Be}+d\rightarrow{}^6\text{Li}+\alpha+n$, with cuts in telescopes and kinematical locus in fig.1.

4.2. QF mechanism identification: neutron momentum distribution.

According to the PWIA description [7], the differential three body cross section can be factorized like

$$\frac{d^3\sigma}{dE_{\text{cm}}d\Omega_{\alpha}d\Omega_{\text{Li}}} \propto KF \cdot G^2(P_s) \cdot \left(\frac{d\sigma^N}{d\Omega} \right)_{\text{cm}} \quad (2)$$

where KF is the kinematic factor and $G^2(P_s)$ is the neutron momentum distribution inside the deuteron. According to the theory of the THM as described in [5,8], the energy of ${}^9\text{Be}$ in the entrance channel of the three-body reaction was

chosen to overcome the Coulomb barrier. This means that both Coulomb and electron screening effects are negligible in the two-body reaction data.

With this formalism, the term $(d\sigma^N/d\Omega)_{\text{cm}}$ in eq.2 represents the “nuclear part” of the differential cross section for the virtual two-body reaction ${}^9\text{Be}(p,\alpha){}^6\text{Li}$ that, in post-collision prescription, occurs at an energy $E_{\text{cm}}=E_{\text{Li}\alpha}-Q_{2b}$, where $E_{\text{Li}\alpha}$ is the ${}^6\text{Li}-\alpha$ relative energy and Q_{2b} is the two-body Q -value.

In order to reconstruct the neutron momentum distribution $G^2(P_s)$, a small energy window in ${}^6\text{Li}-\alpha$ relative energy (about 100 keV) was selected. By dividing the three-body coincidence yield by the kinematic factor and assuming that $(d\sigma^N/d\Omega)_{\text{cm}}$ can be considered constant in the chosen energy window, the experimental $G^2(P_s)$ distribution was extracted and compared with the theoretical one (fig.3). The agreement between experimental and theoretical data represent a very strong check for the existence of the QF-mechanism in the present data.

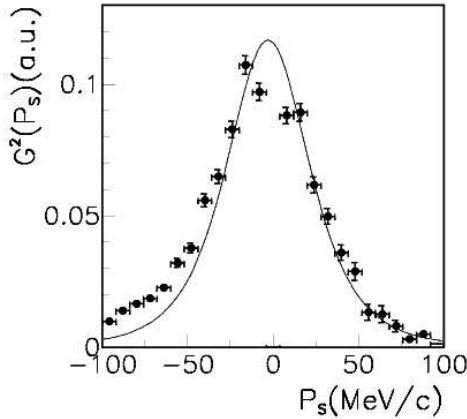


Figure 3.: Comparison between experimental (points) and theoretical Hulthén function (solid line) for the neutron momentum distribution. Error bars are due to the statistical error.

4.3. Indirect $S(E)$ -factor and comparison with direct data.

After the identification of the QF-mechanism, it was possible to apply the THM to the data and extract the behavior of the $S(E)$ -factor for the virtual two-body reaction ${}^9\text{Be}(p,\alpha){}^6\text{Li}$. In order to do this, only events with spectator momentum

$|P_s| < 30$ MeV/c, for which QF-mechanism is dominant, were considered. Therefore, by using the equation (2), it was possible to extract $(d\sigma^N/d\Omega)_{\text{cm}}$. It has to be emphasized that in the present case the obtained cross section is the nuclear part, the Coulomb barrier being already overcome in entrance channel. In order to get the “usual” two-body cross section that must be compared with the directly measured one, it is necessary to multiply $(d\sigma^N/d\Omega)_{\text{cm}}$ by the penetrability function through the Coulomb barrier, given in terms of regular and irregular Coulomb functions. By introducing this penetrability function P_l , as described in [5], it was possible to extract the two-body cross-section $\sigma(E)$ and therefore the bare-nucleus $S(E)$ -factor, defined in equation (1). It is worthwhile to stress that the comparison with direct data can be performed only after normalization, because the THM does not provide absolute value for the bare nucleus cross section (see eq. 2). For this reason, the indirect data from the present measurement have been normalized to the direct ones [8]. The final results are shown in fig.4 and with the comparison with direct data.

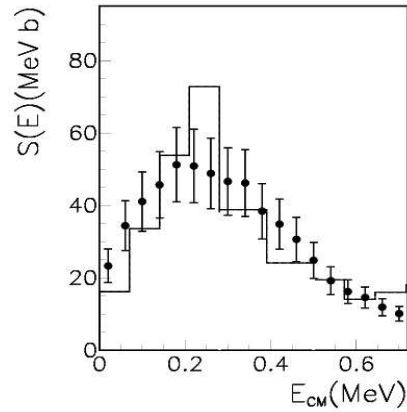


Figure 4.: Comparison between indirect (points) and direct experimental data (histogram line) for the $S(E)$ -factor. The error bars include both statistical and normalization error.

5 DISCUSSION AND CONCLUSION

The indirect study of the ${}^9\text{Be}(p,\alpha){}^6\text{Li}$ reaction was performed in the astrophysical energy region by applying the THM to the ${}^2\text{H}({}^9\text{Be}, {}^6\text{Li}\alpha)n$ three-body break-up process. The results obtained represent an additional validity test of the method at sub-Coulomb energies as well as [9]. In particular the behavior of the indirect $S(E)$ -factor (fig.4) show the presence of the expected low-energy resonance at $E_{\text{cm}} \sim 0.270$ keV, corresponding to the 6.87 MeV $J=1^-$ level of ${}^{10}\text{B}$. It should be noticed that the resonance width in the indirect data is larger than in direct ones. This is connected with the energy resolution (around ± 40 keV) of the present experiment which is much poorer than that of direct data. This means that presently it is not possible to extract any information about screening effects. An upgraded experimental set-up might improve the present results and give useful information for astrophysical applications.

6 REFERENCES

- [1] Boyd R.N. and Kajino T., APJ, **336**, L55-L58, 1989.
- [2] Stephens A. and Boesgaard A.M. et al., APJ, **491**, 339-358, 1997.
- [3] Rolfs C. and Rodney W.S. “*Cauldrons in the cosmos*”, University of Chicago Press, Chicago, 1988.
- [4] Baur G., Phys. Lett. B, **178**, 135, 1986.
- [5] Spitaleri C. et al., PRC, **60**, 055802, 1999.
- [6] Zadro M. et al., Phys. Rev. C, **C40**, 181, 1989.
- [7] Jain M. et al., Nucl. Phys., **A153**, 49:81, 1970.
- [8] Spitaleri C. et al., PRC, **69**, 1, 2004.
- [9] Zahnnow D. et al., Z.Phys. **A359**, 211, 1997.

GAMMA-RAY AND CONVERSION-ELECTRON SPECTROSCOPY OF ^{139}Nd

G. Lo Bianco^{a,b,*}, N. Blasi^c, C.M. Petrache^{a,b}, A. Saltarelli^{a,b}

a) Dipartimento di Fisica, Università di Camerino, Italy

b) INFN Sezione di Perugia, Italy

c) INFN Sezione di Milano, Italy

*Corresponding author, e-mail: giovanni.lobianco@unicam.it

Abstract

The nucleus ^{139}Nd has been studied at Laboratori Nazionali del Sud using the $^{125}\text{Te}(^{18}\text{O}, 4n)$ reaction at 73 and 68 MeV. γ - γ coincidence measurements usefully complemented data previously obtained by the $^{94}\text{Zr}(^{48}\text{Ca}, 3n)$ reaction. A mini-orange electron spectrometer was used to measure conversion coefficients that allowed parity assignments to be made.

1 INTRODUCTION

In a measurement of high-spin states in $^{138,139}\text{Nd}$ at the Lawrence Berkely National Laboratory [1] we found evidence for new bands (four in ^{138}Nd and two in ^{139}Nd) which are characterized by a low and nearly constant moment of inertia, whose value is about one third of the moment of inertia of a rigid rotor with a quadrupole deformation of $\beta_2 = 0.25$ [1]. Cranked-Nilsson model calculations suggest that these bands should be associated with a stable triaxial minimum in the potential energy surface.

A proper interpretation of these bands requires that the particle configuration is identified and that, in turn, can not be obtained without a detailed knowledge of the low-spin and low-excitation-energy part of the level scheme.

While in the case of ^{138}Nd the level scheme at low spin is well known thanks to an extensive study that has been published by de Angelis et al. [2], the only information that is available in the literature on ^{139}Nd is more than twenty years old and quite meager, especially so as far as the spin and parity assignments are concerned [3, 4]. We performed, therefore, an experiment at Laboratori Nazionali di Legnaro in which the GASP spectrometer was used to investigate the γ decay of levels in ^{139}Nd populated by the $^{94}\text{Zr}(^{48}\text{Ca}, 3n)$ reaction and we attempted to interpret the high-spin states in terms of the IBFM + broken pair model. Preliminary results of the calculations were encouraging [3], but some points of the experimental level scheme needed to be clarified.

To this purpose it was important to complement the data that were obtained using the $^{48}\text{Ca} + ^{94}\text{Zr}$ reaction by information resulting from reactions induced by lighter projectiles, that are less selective in populating the yrast states and provide cleaner data thanks to the smaller number of reaction channels that are open. It was also

important to supplement the results of γ -ray spectroscopy by conversion-electron measurements, that are particularly useful in the parity assignments.

In the present paper we summarize the results obtained over a number of years at Laboratori Nazionali del Sud using a ^{18}O beam provided by the tandem accelerator.

2 EXPERIMENTAL PROCEDURE

In all measurements levels in ^{139}Nd were populated by the $^{125}\text{Te}(^{18}\text{O}, 4n)$ reaction and the target was a tellurium foil (enriched to more than 90% in the isotope ^{125}Te) on a thin carbon backing.

In a first experiment γ - γ coincidences were measured at beam energy of 73 MeV. The target thickness was $500 \mu\text{g}/\text{cm}^2$ and we used three high-purity germanium (HPGe) coaxial detectors that were Compton suppressed by BGO shields. Two of the detectors had an efficiency of 90% (with respect to a $3'' \times 3''$ NaI[Tl] scintillator) and were positioned in a plain containing the beam line forming an angle of $\pm 45^\circ$ with respect to it; the third detector was smaller (25% efficiency) and was positioned perpendicular to that plain.

A second experiment had the purpose of determining conversion coefficients for transitions in ^{139}Nd . The beam energy was 68 MeV and the target thickness was $290 \mu\text{g}/\text{cm}^2$. Conversion electrons were measured by a mini-orange spectrometer, consisting of a Si(Li) detector cooled by liquid nitrogen and of a set of permanent magnets. The magnetic field configuration could be adjusted by choosing the type and the number of the permanent magnets. In the experiment on ^{139}Nd two

different configurations were used, that had maximal efficiency for electrons of ~ 200 keV and ~ 480 keV, respectively.

The electron spectrometer was used in conjunction with a HPGe detector and with two large-volume NaI[Tl] scintillators. Conversion-electron and γ -ray spectra were measured independently but simultaneously; in order to reject radiation that was not associated with the nuclear reaction a coincidence was required between the the NaI [Tl] scintillators and the HPGe detector or the Si(Li) detector.

The dependence of the efficiency of the HPGe detector

on energy was determined using ^{152}Eu and ^{133}Ba radioactive sources.

In the course of the experiment γ rays and conversion electrons emitted following the $^{150}\text{Sm}(^{18}\text{O},4n)^{164}\text{Yb}$ reaction were measured using the same experimental setup. The efficiency of the electron spectrometer as a function of energy in the two magnetic configurations could then be deduced from the known conversion coefficients of transitions in ^{164}Yb (figures 1 and 2).

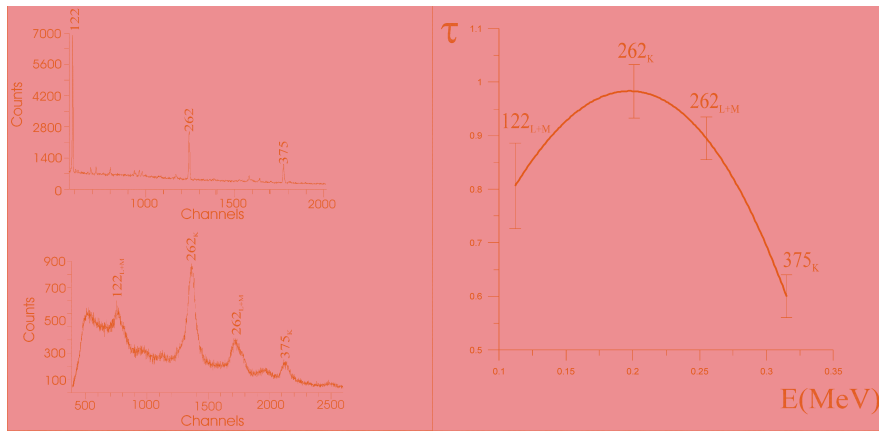


Fig. 1. Left panels: γ rays and conversion-electron spectra [$^{150}\text{Sm}(^{18}\text{O},4n)^{164}\text{Yb}$, 1st magnetic configuration].
Right panel: relative efficiency of the spectrometer at lower energies.

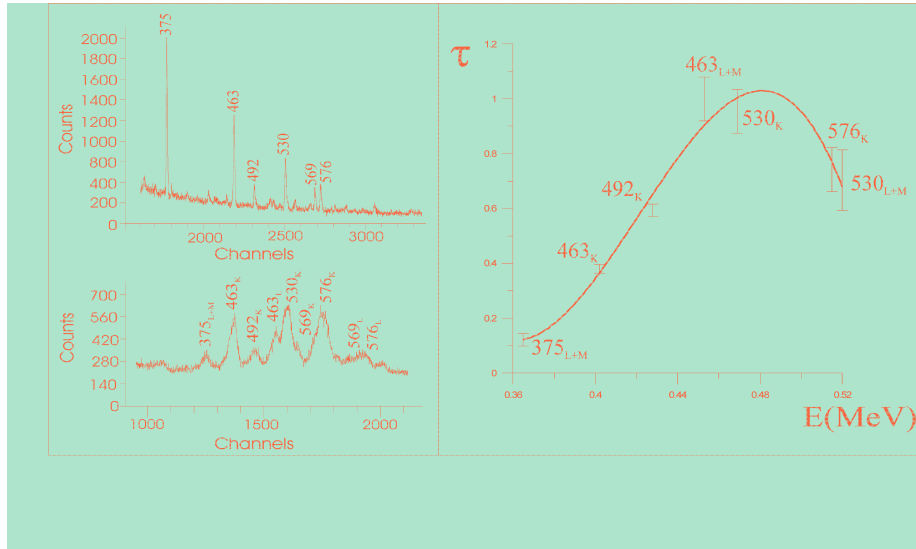


Fig. 2. Left panels: γ rays and conversion-electron spectra [$^{150}\text{Sm}(^{18}\text{O},4n)^{164}\text{Yb}$, 2nd magnetic configuration].
Right panel: relative efficiency of the spectrometer at higher energies.

3 RESULTS

Figure 3 shows a partial level scheme of ^{139}Nd , which only includes levels that could be identified from the coincidence data collected at Laboratori Nazionali del Sud following the $^{125}\text{Te}(^{18}\text{O}, 4n)$ reaction at 73 MeV. All transitions included in the scheme had already been seen in the Legnaro experiment; the new data was nevertheless invaluable, because it allowed several ambiguities to be removed.

Figure 4 shows the electron spectra that were measured following the $^{125}\text{Te}(^{18}\text{O}, 4n)$ reaction at 73 MeV and the corresponding γ -ray spectra.

K-shell conversion coefficients for transitions in ^{139}Nd (figure 5) could be obtained from the areas of the γ -ray and conversion-electron peaks and from the measured relative efficiencies of the γ -ray detector and of the electron spectrometer, taking as a reference the

known conversion coefficient and the areas of the γ -ray and electron peaks of a suitable line. Since γ -ray and electron spectra following the $^{125}\text{Te}(^{18}\text{O}, 4n)$ and the $^{150}\text{Sm}(^{18}\text{O}, 4n)$ reactions had been measured in identical experimental conditions we found it more convenient to utilize as a reference a transition in ^{164}Yb . In the case of transitions of energy <150 keV, for which conversion electrons could not be measured, total conversion coefficients were obtained by intensity balance.

The spin assignments that are shown in figure 3 are based on angular correlation and angular distribution data obtained at Legnaro and, in the case of transitions below 610 keV, were confirmed by the conversion coefficients measured at LNS. The latter information was essential for the parity assignments; it was particularly important to recognize the E1 character of the 605 keV transition.

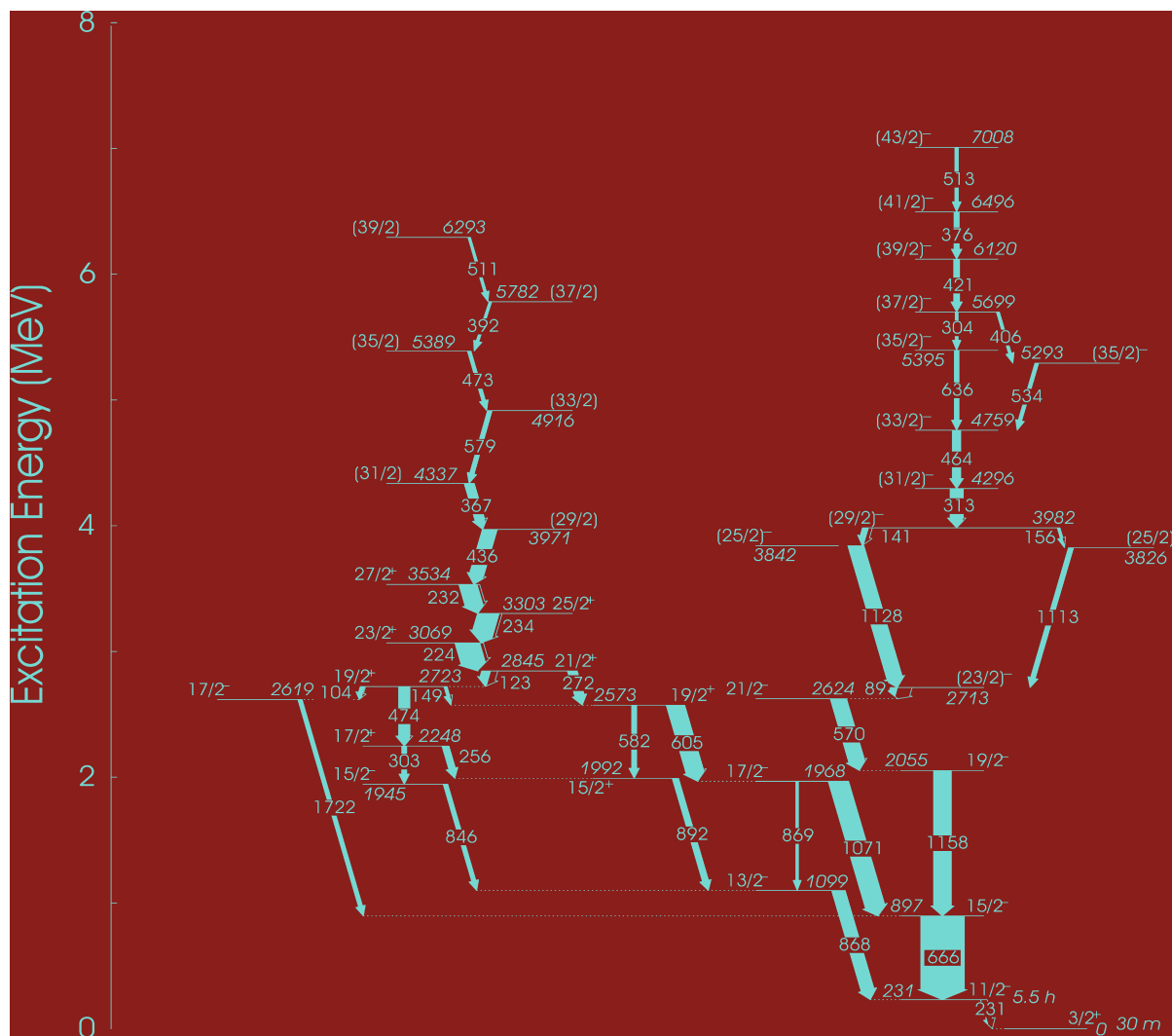


Fig. 3. Partial level scheme of ^{139}Nd , including levels that were populated in the $^{125}\text{Te}(^{18}\text{O}, 4n)$ reaction at 73 MeV.

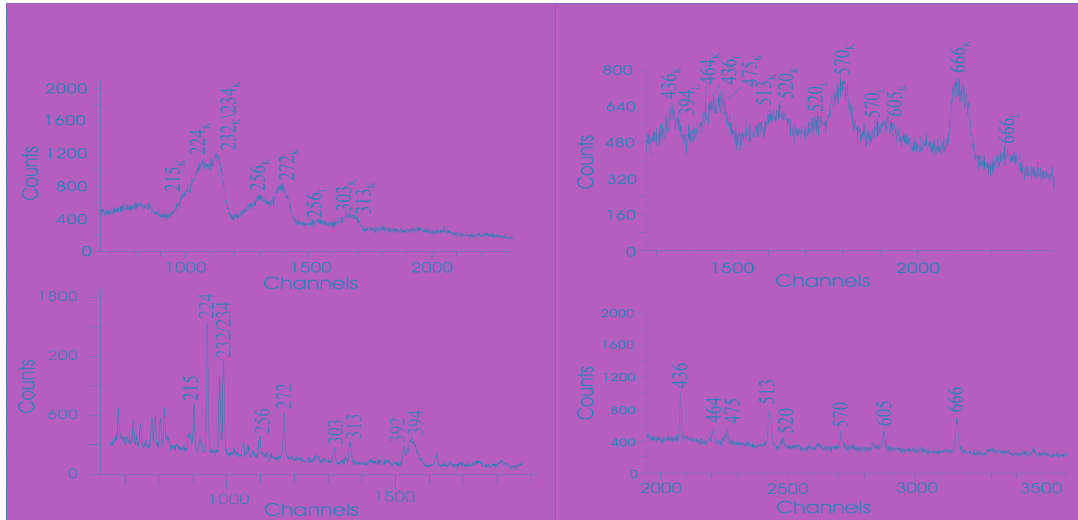


Fig. 4. Electron and γ -ray spectra measured following the $^{125}\text{Te}(^{18}\text{O}, 4n)^{139}\text{Nd}$ reaction at 68 MeV. The two sets of spectra correspond to different magnetic configurations in the electron spectrometer.

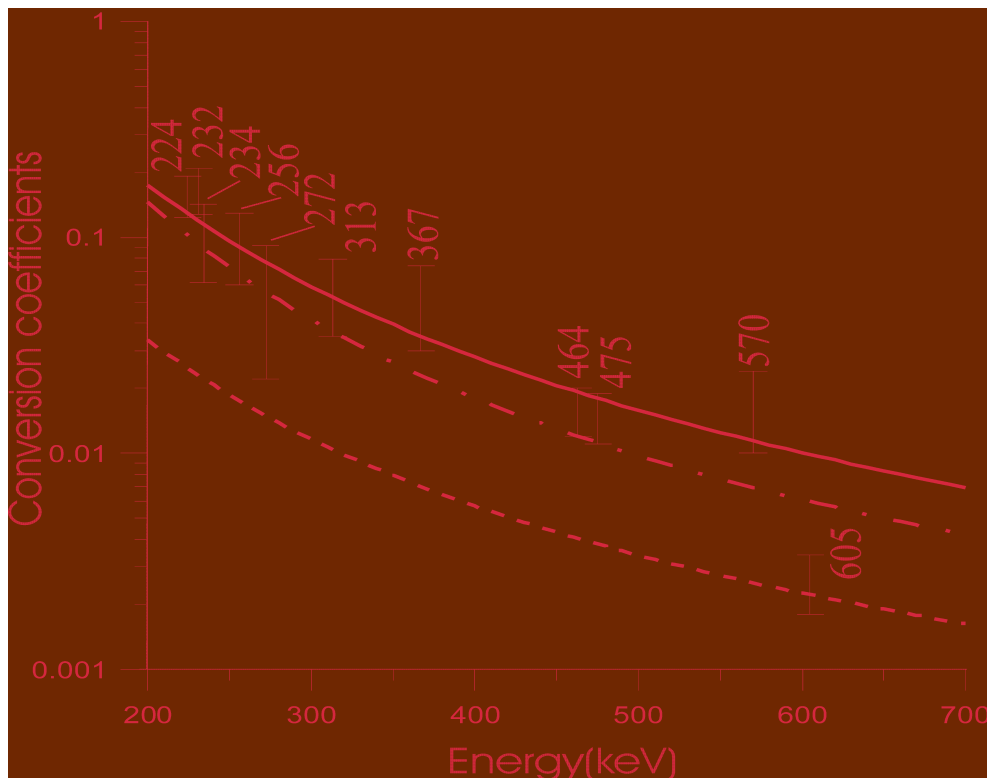


Fig. 5. K-shell conversion coefficients for transitions in ^{139}Nd as a function of transition energy. The solid, dot-dashed and dashed lines correspond to the theoretical values for M1, E2 and E1 transitions, respectively.

4 REFERENCES

- [1] C.M. Petrache et al., Phys. Rev. C61, 011305 (2000).
- [2] G. de Angelis et al., Phys. Rev C 49, 2990 (1994)
- [3] J. Gizon et al., J. Phys. G 4, L171 (1978)
- [4] M. Mueller-Veggian et al., Nucl. Phys. A344, 89 (1980)

A ns ISOMER IN ^{139}Nd

G. Lo Bianco^{a,b,*}, D.L. Balabanski^{a,b,+}, N. Blasi^c, S. Nardelli^{a,b}, C.M. Petrache^{a,b}, A. Saltarelli^{a,b}

a) Dipartimento di Fisica, Università di Camerino, Italy

b) INFN Sezione di Perugia, Italy

c) INFN Sezione di Milano, Italy

*Corresponding author, e-mail: giovanni.lobianco@unicam.it

+On leave from IRNE, Bulgarian Academy of Sciences, Sofia, Bulgaria

Abstract

A search for ns isomers in ^{139}Nd has been performed by the electronic method following the $^{125}\text{Te}(^{18}\text{O}, 4n)$ reaction at 68 MeV. An isomer was found having a mean life of 5.5 ± 0.8 ns. The centroids of the time spectra of transitions that de-excite the 3971 keV level are found to be shifted with respect to prompt transitions.

1 INTRODUCTION

Recently the Nd nuclei were intensively studied using powerful arrays of γ detectors, like GASP and Euroball, with an emphasis on the high-spin states. In $^{138,139}\text{Nd}$, in particular, several high-spin rotational bands were identified and considered to be an indication of a stable triaxiality ($\gamma \approx +30^\circ$) up to the highest observed states [1].

It should be noted that a detailed knowledge of the low-spin part of the level scheme of nuclei is a prerequisite for the understanding of the high-spin structures, whose excitation energy, spin and parity can only be determined from those of the low-spin states. In the case of ^{139}Nd the information that can be found in the literature dates back to the early 80's and we made an effort to establish a complete level scheme, based on γ -ray data from GASP and conversion-electron data obtained at LNS. The results that were obtained are reported elsewhere [2].

An important complement to the construction of detailed level schemes is the identification of isomers, that are to be expected in this mass region because of the proximity of the N=82 shell closure, and whose excitation energy can give information on the position of particular single-particle orbitals with respect to the Fermi surface

In the experiment that is described in the present paper we performed a search for ns isomers in ^{139}Nd by the electronic method.

2 EXPERIMENTAL PROCEDURE

Levels in ^{139}Nd were populated by the $^{125}\text{Te}(^{18}\text{O}, 4n)$ reaction at 68 MeV. The target was a 400 $\mu\text{g}/\text{cm}^2$ tellurium foil (enriched to more than 90% in the isotope ^{125}Te) on a 15 mg/cm^2 lead backing.

The target was surrounded by three large-volume BaF_2 detectors and by two high-purity germanium (HPGe) counters, that included a coaxial detector (having 25% efficiency with respect to a 3"x3" NaI[Tl] scintillator) and a low-energy photon spectrometer (LEPS) of planar geometry, having a resolution of ~ 600 eV at 122 keV. The two HPGe detectors were Compton suppressed by BGO shields.

Signals from the photomultiplier anodes of the three BaF_2 detectors were fed through wide-band amplifiers to constant-fraction discriminators that were connected to the inputs of a logic unit used in the OR mode. The output of the logic unit provided stop signals to two time-to-amplitude converters (TAC's), which were started by logic signals from the suppressed HPGe detectors.

The outputs of the two TAC's and those of the linear amplifiers connected to the HPGe detectors were digitalized and the data was stored in list mode on magnetic tape.

3 RESULTS

In the data analysis two time-energy matrices were produced, from which time spectra relative to selected transitions in ^{139}Nd could be obtained.

A partial level scheme of ^{139}Nd is shown in figure 1. In figure 2 the time spectrum of the 436 keV line, that de-excites the 3971 keV level having a tentative spin-assignment of 29/2, is compared to that of the 367 keV transition, that feeds that level. The former spectrum is visibly displaced, indicating the presence of a ns isomer. A similar shift is present in the time spectra of the 605 and 1071 keV transitions.

It should be noted that also in the time spectra of the 232/234 (unresolved), 224 and 272 keV transitions the centroids are very clearly shifted, but it is difficult to tell to what extent the observed shift is due to delayed

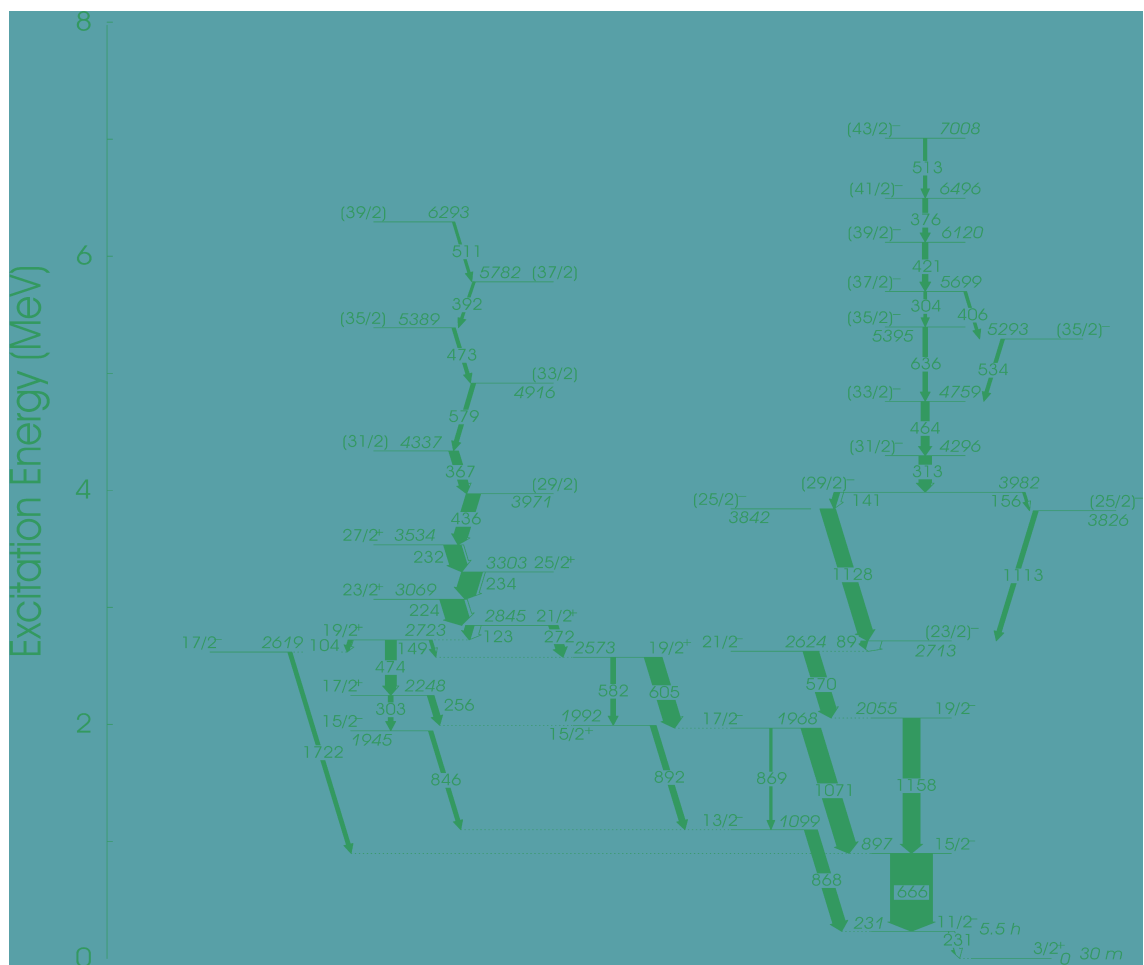


Fig. 1. Level scheme of ^{139}Nd from the $^{125}\text{Te}(^{18}\text{O}, 4n)$ reaction [2].

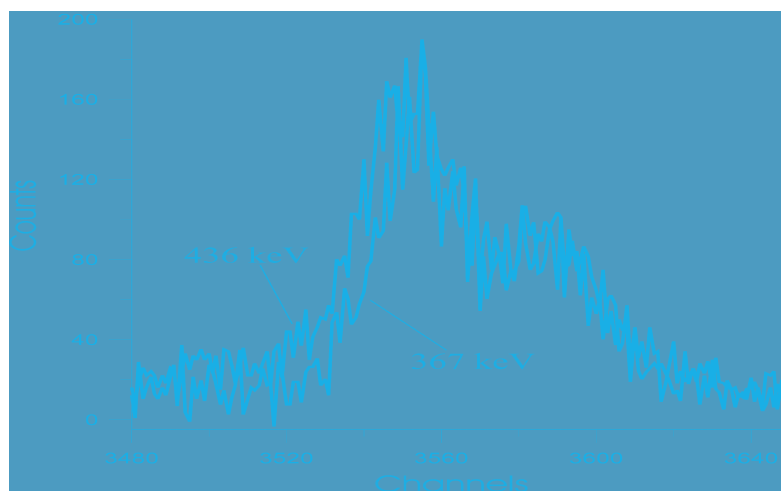


Fig. 2. Time spectra of the 367 keV and 436 keV transitions.

feeding of the levels and to what extent it is due to the time walk associated with the low energies of these transitions.

In order to evaluate the lifetime of the isomer we could not utilize an analysis of the shape of the time spectrum, that does not show a single time peak, because the stop pulse to the TAC's was given by any one of the three BaF₂ detectors, that were not perfectly time matched.

Energy [keV]	Centroid (coax HPGe) [channels]	Centroid (LEPS) [channels]
367	3568.3	3754.9
436	3556.1	3745.6
463	3566.1	3758.4
570	3569.3	3757.5
605	3559.3	----
1071	3567.4	----
1158	3576.0	----

Table 1. Centroids of time spectra for prompt and delayed transitions.

Delayed line [keV]	Prompt line [keV]	Shift (coax) [chan]	Shift (LEPS) [chan]	Shift (coax) [ns]	Shift (LEPS) [ns]
436	367	12.2	9.3	5.9	4.7
605	570	10.0	----	4.8	----
1071	1158	8.6	----	4.13	----

Table 2. Centroid shifts of delayed lines with respect to prompt lines of similar energy.

We resorted, therefore, to an evaluation of the centroid shift, excluding from the analysis transitions below 300 keV, for the reason that has already been mentioned. The results are collected in tables 1 and 2.

Statistical errors on the measured centroids are of the order of 0.3 channels in the data collected by the coaxial detector and of the order 0.5 channel in the data of the LEPS, that have lower statistics. Systematic errors, related to the arbitrariness in the choice of the limits of the portion of spectrum that is analyzed, are however much larger, amounting to about one channel (0.5 ns) for the coaxial detector data and two channels (1 ns) for the LEPS data.

The tables show that transitions that de-excite the 3971 keV level have consistent centroid shifts, which slightly decrease as we descend along the cascade because of side feeding. Centroids for transitions with energies higher than 570 keV could not be reliably extracted from the LEPS data, that have in any case larger errors because the transitions of interest all have relatively high energies.

Taking into account the systematic errors the shift of the centroid of the time peak of the 436 keV transition with respect to that of the 367 keV line results to be 5.9 ± 0.7 ns from the coaxial-detector data and 4.7 ± 1.4 ns from the LEPS data. A weighted average gives 5.5 ± 0.8 ns for the mean life of the isomer.

The possibility that 3971 keV level is fed by a higher lying isomeric state through a low-energy unobserved γ ray can not be entirely ruled out. A comparison of the intensities of the 367 keV and 436 keV transitions, however, makes it unlikely that any unobserved delayed transition be parallel to the 367 keV γ ray.

4 REFERENCES

- [1] C.M. Petrache et al., Phys. Rev. C61 (2000), 011305 (R).
- [2] G. Lo Bianco et al., *Gamma-ray and conversion-electron spectroscopy of ¹³⁹Nd*, these proceedings.

ANC Method applied to the $^3\text{He}(\alpha,\gamma)^7\text{Be}$ capture reaction

F. Mudò^{a,b,*}, C. Spitaleri^{a,b}, A. Mukhamedzanov^c, R. Tribble^c, C. Bonomo^a, S. Cherubini^d,
Del Zoppo^a, P. Figuera^a, M. Gulino^{a,b}, M. La Cognata^{a,b}, L. Lamia^{a,b}, A. Musumarra^{a,b}, M.G. Pellegriti^{a,b},
R.G. Pizzone^a, S. Romano^{a,b}, S. Tudisco^{a,b}, A. Tumino^{a,b}

a) INFN Laboratori Nazionali del Sud, Catania, Italy

b) Università di Catania, Catania Italy

c) Texas A&M University, Texas, USA

d) Ruhr Universität Bochum, Bochum, Germany

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

Abstract

The $^3\text{He}+^6\text{Li}\rightarrow\text{d}+^7\text{Be}$ transfer reaction has been studied at the Dynamitron Tandem Laboratorium-Ruhr-Universität in Bochum with a 5 MeV ^3He beam. We have analysed this reaction in order to deduce the Asymptotic Normalization Coefficient (ANC) for the virtual reaction $^7\text{Be}\rightarrow^3\text{He}+\alpha$. In fact, this coefficient determines the amplitude of the tail of the ^7Be overlap function in the $^3\text{He}+\alpha$ channel and it is used to calculate the Astrophysical Factor for the direct $^3\text{He}+\alpha\rightarrow^7\text{Be}+\gamma$ capture reaction, important from an astrophysical point of view.

1 INTRODUCTION

The determination of the cross section of the $^3\text{He}+\alpha\rightarrow^7\text{Be}+\gamma$ reaction at astrophysical energies has a twofold importance [1].

Firstly it is involved in the network of nuclear reactions for big-bang nucleosynthesis, because it is one of the three important cross sections contributing to the determination of the primeval ^7Li abundance.

Moreover the produced ^7Be via the $^3\text{He}+^4\text{He}\rightarrow^7\text{Be}+\gamma$ reaction proceeds in the termination of p-p chain II in stellar environment via electron capture to ^7Li [4].

As a further possibility, ^7Be might be burned in the $^7\text{Be}(p,\gamma)^8\text{B}$ reaction, even if this is the weakest of the three p-p chains contributing to the determination of neutrino's flux induced by the positron decay of ^8B .

This last process is the greatest source of neutrinos in the Sun.

In this paper we analyse the $^3\text{He}+\alpha\rightarrow^7\text{Be}+\gamma$ capture reaction by means of a peripheral nucleon transfer reaction exhibiting a cross section orders of magnitude larger than that involved in the direct capture reaction.

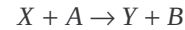
At solar energies direct capture reactions proceed through the tail of the nuclear overlap function [3]. At distances larger than the nuclear radius, the shape of this tail is determined mainly by Coulomb interaction. The ANC defines the amplitude of the ^7Be overlap function in the two body channel, where the ^3He and α particle are separated by a distance larger than the nuclear radius of ^7Be . One of the main advantages of ANCs is their

weaker model dependence than the Spectroscopic Factors.

2 THE METHOD

Our primary goal consists in the determination of nuclear capture cross sections at energies of stellar processes. However, since direct measurements of these cross sections are very difficult at energies of astrophysical interest, the ANC indirect method, which exploits transfer reactions between heavy ions, has been introduced.

In this framework the general transfer reaction can be written as:



where, $X=Y+a$, $B=A+a$ and a is the transferred particle.

The differential Distorted Wave Born Approximation (DWBA) cross section is parameterized by the Spectroscopic Factors S :

$$\frac{d\sigma}{d\Omega} = \sum_{J_B J_X} S_{AaI_B J_B} S_{YaI_X J_X} \sigma_{I_B J_B I_X J_X}^{DW}$$

where $\sigma_{I_B J_B I_X J_X}^{DW}$ are the reduced DWBA cross sections.

It is well known that Spectroscopic Factors are strongly model dependent and are defined in the inner part of the nucleus, while transfer reactions proceed in the external part.

For these reasons the DWBA formalism can be modified by using ANCs, that define the amplitude of

the tail of the overlap wave function of a generic bound state $\alpha=(\beta\gamma)$ [2,3]:

$$I_{\beta\gamma\alpha j\alpha}^{\alpha}(r_{\beta\gamma}) \xrightarrow{r_{\beta\gamma} > R_N} C_{\beta\gamma\alpha j\alpha}^{\alpha} \frac{W_{-\eta_{\alpha}l_{\alpha}+1/2}(2k_{\beta\gamma}r_{\beta\gamma})}{r_{\beta\gamma}}$$

where R_N is the nuclear interaction radius between β and γ , $W_{-\eta_{\alpha}l_{\alpha}+1/2}(2k_{\beta\gamma}r_{\beta\gamma})$ is the Whittaker function that describes the asymptotic behaviour of the bound state wave function of two charged particles, $k_{\beta\gamma} = \sqrt{2\mu_{\beta\gamma}E_{\beta\gamma}}$ is the wave number of the bound state $\alpha=(\beta\gamma)$, $\mu_{\beta\gamma}$ is the reduced mass, and $\eta_{\alpha} = Z_{\beta}Z_{\gamma}\mu_{\beta\gamma}/k_{\beta\gamma}$ is the Coulomb parameter of the bound state $(\beta\gamma)$.

The relation between ANC and Spectroscopic Factors is then given by:

$$(C_{\beta\gamma\alpha j\alpha}^{\alpha})^2 = S_{\beta\gamma\alpha j\alpha} b_{\beta\gamma\alpha j\alpha}^2$$

where $b_{\beta\gamma\alpha j\alpha}$ is the single particle ANC that defines the tail amplitude of the wave function of the bound state at large $r_{\beta\gamma}$. Inserting this definition in the DWBA cross section and paying attention to the asymptotic part of the wave function, the only model dependent quantity results $b_{\beta\gamma\alpha j\alpha}$:

$$\frac{d\sigma}{d\Omega} = \sum_{J_B J_X} \frac{(C_{Aa b j_B}^B)^2}{b_{Aa b j_B}^2} \frac{(C_{\gamma a k j_X}^X)^2}{b_{\gamma a k j_X}^2} \sigma_{l_B l_X}^{DW}$$

But for peripheral reaction the reduced DWBA cross section becomes proportional to single particle ANCs $b_{\beta\gamma\alpha j\alpha}$, removing their presence in the total cross section. So the only fit parameters are ANCs that guarantee the determination of the cross section independently from geometrical parameters.

We emphasize that the Spectroscopic Factors and ANCs are only intermediate steps in calculating quantities of astrophysical interest, such as cross sections for direct capture.

3 SET-UP AND EXPERIMENTAL RESULTS

Our capture reaction ${}^3\text{He}+\alpha \rightarrow {}^7\text{Be}+\gamma$ exhibits a peripheral behaviour and both ground state and first excited state of ${}^7\text{Be}$ contribute to the radiative process. So we have to deduce two ANCs to completely determine the cross section of interest. In order to measure these ANCs we are dealing with the α -transfer ${}^3\text{He}+{}^6\text{Li} \rightarrow \text{d}+{}^7\text{Be}$ reaction. In this transfer reaction the fitting parameters are the square product of the ANCs of ${}^6\text{Li}$ and of ${}^7\text{Be}$. So we need another reaction to obtain independently the ANC of ${}^6\text{Li}$, such as $\alpha+{}^6\text{Li} \rightarrow \alpha+{}^6\text{Li}$, considering the transfer and the elastic channels. The ${}^6\text{Li}$ ANC has been very well established by this reaction and its value is $C^2=0.41\text{fm}^{-1}$.

In order to measure the angular distributions of the transfer reaction with a 5 MeV ${}^3\text{He}$ beam the experimental set-up consisted of:

- Three solid state monitor detectors, two settled at 40 degrees (to check the beam alignment) and one at 150 degrees in the laboratory system (they have also been used in the normalization of the cross section with respect to the concurrent reaction ${}^3\text{He}+{}^6\text{Li} \rightarrow \text{p}+\alpha+\alpha$).

- Two ΔE -E telescopes, necessary for the discrimination of deuterons at different angles.

- A target made up of ${}^6\text{LiF}$ ($200\mu\text{g}/\text{cm}^2$) evaporated on a carbon backing ($30\mu\text{g}/\text{cm}^2$).

In the first run, we have used a PSD detector placed at forward angles, but in the second run we introduced pointlike detectors in order to minimize the uncertainties in the determination of the solid angle.

Degraders were settled in front of forward monitors in order to avoid intense elastic scattering.

In order to reduce beam spotsize and angular spread we have placed two collimators of 3mm and 1mm diameter, returning a spotsize of 3mm on the target.

The data have been normalized by considering protons coming from the ${}^3\text{He}+{}^6\text{Li} \rightarrow \text{p}+\alpha+\alpha$ reaction, so minimizing sources of errors.

As shown in fig.1 (a,b) the absolute center of mass cross sections obtained for the two final channels d_0 (${}^7\text{Be}$ G.S) and d_1 (${}^7\text{Be}$ 1st Excited State) in the full angular coverage are around 40mb and 20mb respectively.

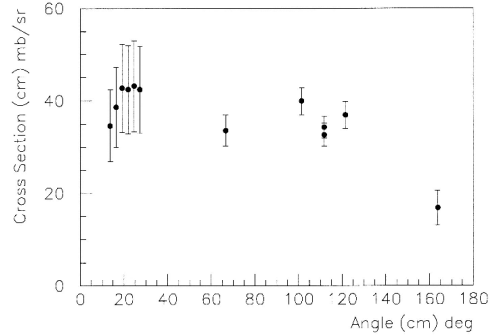


Fig.1a Angular Distribution of the ${}^6\text{Li}({}^3\text{He},\text{d}_0){}^7\text{Be}$ transfer reaction

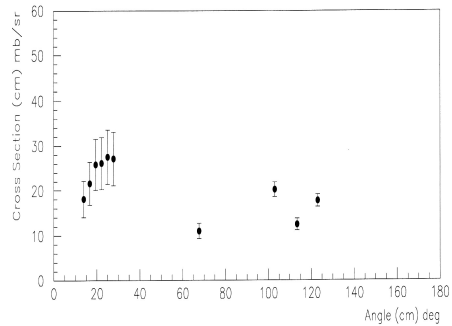


Fig.1b Angular Distribution of the ${}^6\text{Li}({}^3\text{He},\text{d}_1){}^7\text{Be}$ transfer reaction

At a beam energy of 5 MeV, corresponding to 3.3 MeV in the center of mass system, just above the

Coulomb barrier (2.19 MeV), we have preliminary reconstructed angular distributions spanning a region from 13 to 130 degrees. These angular distributions appear to be flat at this beam energy. This behaviour seems to imply that this reaction proceeds through a compound nucleus process rather than a transfer process at this energy. So in the next run we will decrease the ^3He beam energy in order to go below the Coulomb barrier and to get a larger contribution from the tail of the $^7\text{Be}(\alpha, ^3\text{He})$ overlap wave function, crucial to define in a better way the amplitude of ANCs.

4 REFERENCES

- [1] Rolfs C. and Rodney W.S. “Cauldrons in the cosmos” , University of Chicago Press, Chicago
- [2] A.M. Mukhamedzhanov et al., Phys. Rev. C 56, 1302 (1997)
- [3] A.Azhari et al., Phys. Rev. C 63, 055803 (2001)
- [4] A. Coc et al., Phys. Rev. D 65, 043510 (2002)

ON THE RESONANCE LINE SHAPE IN LIGHT NEUTRON-RICH NUCLEI

S.E.A.Orrigo^{a,b,*}, H.Lenske^c, F.Cappuzzello^a, A.Cunsolo^{a,b}, A.Foti^{b,d}, A.Lazzaro^a, C.Nociforo^a, J.S.Winfield^a

a) INFN Laboratori Nazionali del Sud, Catania, Italy

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

c) Institut für Theoretische Physik, Universität Giessen, Giessen, Germany

d) INFN Sezione di Catania, Catania, Italy

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

Abstract

On the basis of the Quasiparticle-Core Coupling model, a theoretical model is proposed to investigate the resonance line shape in the light neutron-rich nuclei as an effect of the interference between the 1-QP and 3-QP components. The preliminary calculations for the ^{15}C nucleus reproduce all the experimentally observed BSEC and the interference pattern.

1 INTRODUCTION

The phenomena observed when approaching the drip-lines constitute the new frontier of the modern nuclear physics. This new and interesting field has become accessible through the development of appropriate experimental techniques and theoretical models. Very peculiar conditions affect the structure and the reaction mechanisms involving light exotic nuclei: the large charge asymmetry and the low separation energy of the valence nucleon, approaching the continuum threshold. In such a picture, even the small energy contribution of residual interactions strongly influences the properties of the nuclei far from stability.

Thus, and especially for light neutron-rich nuclei, unusual phenomena can be observed, such as the formation of a thick superficial layer of neutron (skin) or the development of low density region (halo) with increasing of the neutron excess [1-3], the latter corresponding to narrower momentum distribution [4]. In these exotic systems, which in general can be represented as one or two weakly bound neutrons interacting with both an inert or excited core, the enhanced role of the isovector interactions and the coupling with the continuum lead to the dissolution of shell structures [5]. In fact there are evidence of effects like shell inversion and the presence of Bound States Embedded in the Continuum (BSEC) – for example in ^{11}Be [6] and ^{15}C [7-8] – for which the mean-field dynamics is no longer appropriate.

In particular, BSEC has been predicted theoretically some time ago in ref. [9] and observed for the first time in the stable $^{13}\text{C}(3/2^+, E_x = 7.677 \text{ MeV})$ nucleus [10]. These states appear as narrow resonances lying at energies well beyond the neutron emission threshold, therefore they can be only explained as quasi-bound core-excited configurations in terms of the Dynamical Core Polarization (DCP) model [9, 11]. Closer to the neutron drip line, the core itself is already neutron-rich thus an enhancement of BSEC structures is expected due

to the softer core and the increased polarizability of the system. The quadrupole polarizability increases, related to the presence of low-energy 2^+ core states, whose energy decreases with increasing mass. In particular, a strong enhancement of BSEC excitations is predicted in the low-energy continuum of the carbon isotopes with increasing the neutron number, in connection with the decrease of the first 2^+ core state from $E_x = 4.44 \text{ MeV}$ in ^{12}C to $E_x = 1.76 \text{ MeV}$ in ^{16}C and $E_x = 1.66 \text{ MeV}$ in ^{18}C [11, 12]. These arguments show the importance of a systematic study of such effects for carbon isotopes. An interesting case is ^{15}C which, with its small separation energy of the valence neutron ($S_n = 1.218 \text{ MeV}$), is intermediate between the well-bound $^{12,13,14}\text{C}$ nuclei and the more exotic ^{17}C ($S_n = 0.73 \text{ MeV}$) and ^{19}C ($S_n = 0.16 \text{ MeV}$).

^{15}C has been recently studied via ($^7\text{Li}, ^7\text{Be}$) Charge EXchange (CEX), where three narrow resonances were observed in the continuum at $E_x = 6.77, 7.30, 8.50 \text{ MeV}$ [7, 8]. Concerning the 8.5 MeV state, immediately before the peak a suppression of counts is evident. This suppression, recognized as a hole, is clearly seen in spectra at various angles, moving as expected by kinematic shift to different channels, i. e., to different positions on the focal plane showing that it is not caused by an anomalous behaviour of the detector. By analogy with the (p,p') inelastic scattering of nucleons on nuclei, where isolated resonances arising from the coupling of a single particle continuum to a BSEC have been found [9], this could be an interference between the non-resonant 3-body phase space and the 8.5 MeV BSEC. In general, interference phenomena give rise to typically asymmetric peaks in the spectra, with a non-trivial energy dependence.

2 THEORETICAL APPROACH

A simple theoretical model to investigate the resonance line shape is proposed. The general effective Hamiltonian of the Quasiparticle-Core Coupling (QPC) model [13] has the form:

$$H = H_{11} + V_{22} + V_{13}$$

where H_{11} represents the one-quasiparticle (1-QP) component that accounts for the single particle excitations of the valence neutron respect to the inert core. The residual interactions is split into two parts: V_{22} and V_{13} . The former accounts for the correlated one particle-one hole (i.e. 2QP) core excitations – usually described in terms of quasi-particle RPA (QRPA) theory – while the latter is the particle-core interaction which, acting between the two above-mentioned channels, leads to the coupling between the 1-QP states and the 3-QP core-excited configurations. The eigenstates $|\beta_j\rangle$ of the full Hamiltonian H will be therefore a superposition of the two components of 1-QP $|n_j\rangle$ and 3-QP $|(j' Jc)_j\rangle$, respectively without and with core excitation:

$$|\beta_j\rangle = \sum_n z_n |n_j\rangle + \sum_{j' Jc} z_{j' Jc} |(j' Jc)_j\rangle$$

where total spin and parity must be conserved ($\underline{J} = \underline{j} + \underline{Jc}$; $\pi_j = \pi_{j'} \pi_{Jc}$).

Projecting the Schroedinger equation into the 1-QP and 3-QP channels, the following set of coupled equations is obtained:

$$(H_{11} - \epsilon_1) z_n + \sum_{j' Jc} z_{j' Jc} \langle n_j | V_{13} | (j' Jc)_j \rangle = 0$$

$$(V_{22} - \epsilon_2) z_{j' Jc} + \sum_n z_n \langle (j' Jc)_j | V_{13} | n_j \rangle = 0$$

where ϵ_1 and $\epsilon_2 = \epsilon_1 - E_c$ are the eigenvalues of H_{11} and V_{22} respectively, and E_c being the excitation energy of the core states.

In a simplified model, we consider only two channels, the first representing the single particle continuum ($\epsilon_1 > 0$) and the second corresponding to a bound core-excited configuration ($\epsilon_2 < 0$). The choice of step-potentials (U_1, U_2) for both channels and also for the interaction V_{13} between them leads to a spherically symmetric problem, that admits analytic solutions. The obtained radial coupled equations are:

$$[d^2/dr^2 - l(l+1)/r^2 + K_1^2] u_{1,l}(r) - W u_{2,l}(r) = 0$$

$$[d^2/dr^2 - l(l+1)/r^2 + K_2^2] u_{2,l}(r) - W u_{1,l}(r) = 0$$

where $K_1^2 = 2m(\epsilon_1 - U_1)/\hbar^2$ in the internal region ($r < R$), $K_1^2 = 2m\epsilon_1/\hbar^2 \equiv k_1^2$ in the external region ($r > R$), $W = 2mV_{13}/\hbar^2 - m$ being the reduced mass between neutron and core – and $u_{i,l}(r)$ are the radial wave functions for the two channels ($i = 1, 2$). According to the Potential Scattering theory [14], in this particular case of square-well potentials the solutions are the spherical Bessel functions $j_l(k r)$ for $r < R$ and the spherical Hankel functions $h_l(k r)$ for $r > R$. So for $r < R$ we have:

$$u_{1,l}(r) = a [a_1 j_l(Q_+ r)] + b [a_2 j_l(Q_- r)]$$

$$u_{2,l}(r) = a [b_1 j_l(Q_+ r)] + b [b_2 j_l(Q_- r)]$$

where $Q_{\pm}^2 = 1/2 \{K_1^2 + K_2^2 \pm [(K_1^2 - K_2^2)^2 + 4W^2]^{1/2}\}$ and the coefficients a_i, b_i are determined solving the 2×2 matrix eigenvalue problem. For $r > R$ the solutions are:

$$u_{1,l}(r) = J_l(k_1 r) + C_{11} h_l(k_1 r)$$

$$u_{2,l}(r) = C_{12} h_l(k_2 r)$$

where the $h_l(k_2 r)$ of the second channel reduces to exponential decay due to the negative value of ϵ_2 . Imposing the matching conditions, that is the boundary conditions that both $u_{i,l}(r)$ and $du_{i,l}(r)/dr$ be continuous at $r = R$, it is possible to determinate the coefficients a, b, C_{11} and C_{12} and thus the wave functions. Moreover the knowledge of the scattering matrix elements $C_{ij} = [\exp(2i\delta_{ij}(k)) - 1]/(2i)$ enables one to obtain the phase shifts $\delta_{ij}(k)$ and the partial wave elastic cross sections $\sigma_{ij}(k)$:

$$\begin{aligned} \sigma_{ij}(k) &= (4\pi/k_i^2) (2l+1) |C_{ij}(k)|^2 \\ &= (4\pi/k_i^2) (2l+1) \sin^2 \delta_{ij}(k) \end{aligned}$$

3 RESULTS OF CALCULATIONS FOR ^{15}C

To perform these calculations, the potentials U_1, U_2 and the potential range $R = r_0 A^{1/3}$ have been taken from Hartree-Fock-Bogoliubov (HFB) calculations. To be precise, the second channel potential and the radius R have been obtained by fitting the HFB potential for the core nucleus, while in the first channel U_1 has been made state-dependant by imposing that the HFB single particle energy of the core states is reproduced. Finally, the particle-core interaction V_{13} has been left as a free parameter.

The preliminary results of the calculations for the ^{15}C nucleus are shown in Figure 1 and 2. In Fig. 1 the interference pattern related to one core-excited state ($E_x = 8.32$ MeV) is shown in detail for s, p and d-wave. The particular resonance line shape shown in the d-wave arises from the interference term V_{13} which couples the 1-QP and 3-QP channels, that is the single particle continuum and the resonant state.

In Fig. 2a the calculated elastic cross section σ_{11} for the d-wave – the one contributing to the resonance – is plotted with respect to the ^{15}C excitation energy, in comparison with the experimental spectrum taken at $\theta_{\text{lab}} = 14^\circ$ (Fig. 2b). The following core states have been included in the calculations: $E_x(J^\pi) = 6.09(1^-), 6.73(3^-), 7.01(2^+), 8.32(2^+)$ MeV. The interaction V_{13} has been set to 15 MeV and, for each ^{14}C state, it has been weighted through the experimental collective deformation amplitudes β [15]. σ_{11} has been then obtained by summing the contributions of all the above-mentioned core excitation. In the theoretical cross section three narrow resonances are evident, reproducing the existence of the three BSEC observed in the experimental spectra [7, 8].

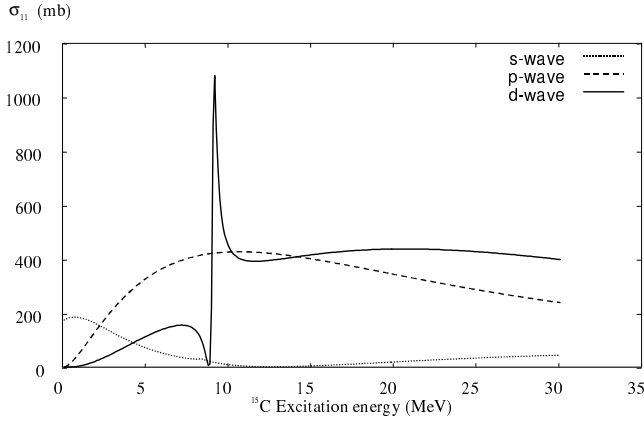


Figure 1: Calculated elastic cross section σ_{11} related to the core-excited state $E_x = 8.32$ MeV for s, p and d-wave. The particular resonance line shape shown in the d-wave arises from the interference term V_{13} between the 1-QP and 3-QP components.

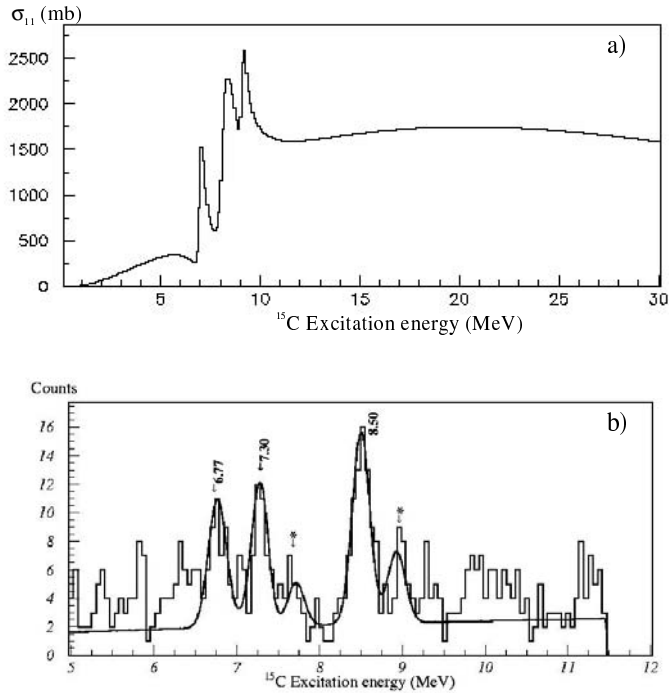


Figure 2: a) Calculated elastic cross section σ_{11} for the d-wave plotted with respect to the ^{15}C excitation energy. Core states included in the calculations: $E_x(^{15}\text{C}) = 6.09$ (1 $^-$), 6.73 (3 $^-$), 7.01 (2 $^-$), 8.32 (2 $^-$) MeV. b) Excitation energy spectra for the $^{15}\text{N}(^7\text{Li}, ^7\text{Be})^{15}\text{C}$ reaction at $E_{\text{inc}} = 55$ MeV and $\theta_{\text{lab}} = 14^\circ$. Peaks marked with an asterisk are associated to the excitation of ^7Be at 0.429 MeV. The continuous line is the sum of the background (the $^{15}\text{N}(^7\text{Li}, ^7\text{Be})^{15}\text{C}$ 3-body phase space) and the fitted peaks (dark gaussians).

4 CONCLUSIONS

The theoretical approach described here explains the resonance line shape as an effect of the interference between the 1-QP and 3-QP channels. Moreover the calculations succeed in reproducing all the experimentally observed BSEC, describing them in terms of core-excited configurations. Also this simple model allows an analytic form for the solutions.

Nevertheless, further analyses are in progress in order to improve the model, such as to develop multi-channel calculations, including at the same time the different core-excited states. In addition, calculations for the ^{17}C and ^{19}C have been started.

5 REFERENCES

- [1] I.Tanihata, Nuclear Physics A520(1990)411; I.Tanihata, Nuclear Physics A522(1991)275c.
- [2] K.Riisager et al., Nuclear Physics A548(1992)393.
- [3] P.G.Hansen et al., Annu. Rev. Nucl. Part. Sci. 45(1995)591 and refs. therein.
- [4] T.Kobayashi, Phys. Review Letters 60n.25(1988).
- [5] H.Lenske, J. Phys. G: Nucl. Part. Phys. 24(1998)1429.
- [6] F.Cappuzzello et al., Phys. Lett. B516(2001)21.
- [7] S.E.A.Orrigo et al., proc. of the 10th Int. Conference on Nuclear Reaction Mechanisms, 9-13 June 2003, Villa Monastero, Varenna, edited by E. Gadioli, Ricerca Scientifica ed Educazione Permanente (2003), Supplemento n. 122, p. 147.
- [8] F.Cappuzzello et al., Europhysics Letters, vol.65 n.6(2004)766.
- [9] G.Baur and H.Lenske, Nuclear Physics A282(1977)201.
- [10] H.Fuchs et al., Nuclear Physics A343(1980)133.
- [11] D.Cortina-Gil et al., Eur. Phys. J. A10(2001)49.
- [12] H.Lenske et al., Progress in Particle and Nuclear Physics 46(2001)187.
- [13] H.Lenske, Habilitationsschrift, University of Munich, 1987 (unpublished).
- [14] C.J.Joachain, Quantum Collision Theory, American Elsevier Pub. Co. (1975).
- [15] F.Ajzenberg-Selove, Nuclear Physics A523(1991)1.

INVESTIGATION ON THE OFF-ENERGY SHELL EFFECTS IN $^2\text{H}(\text{p},\text{pp})\text{n}$ REACTION

M.G. Pellegriti^{a,b}, C. Spitaleri^{a,b}, A. M. Mukhamedzanov^c, S. Blagus^d, M. Bogovač^d,
L. Calabretta^a, C. Cherubini^{a,e}, A. Di Pietro^a, A. Del Zoppo^a, P. Figuera^a, Đ. Miljanić^d, M. Milin^d, A. Musumarra^{a,b},
L. Pappalardo^d, R.G. Pizzone^a, D. Rendić^d, S. Romano^{a,b}, 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, Catania, Italy

c) Texas A&M University, College Station, USA

d) Institut-Ruđer Bošković, Zagreb, Croatia

e) Ruhr Universität Bochum, Bochum, Germany

Abstract

The present report investigates the half-off-energy shell effects on the shape of $^2\text{H}(\text{p},\text{pp})\text{n}$ cross section as a function of one of the outgoing proton energies. Two experimental runs were performed at Laboratori Nazionali del Sud (LNS), INFN, Catania and at Ruđer Bošković Institute, Zagreb by using a proton beam energy of 6 MeV. The shape of the cross section has been measured as a function of the outgoing proton energy. In the second run also the absolute cross section has been measured.

1 INTRODUCTION

The $^2\text{H}(\text{p},\text{pp})\text{n}$ reaction has been studied in the framework of the Trojan Horse Method that is an indirect method for the nuclear astrophysics, based on three-body reaction quasi-free mechanism. It allows cross section measurements at energy far below the Coulomb barrier [1-4] because the provided two-body cross section is free from Coulomb suppression. This method has been applied to the quasi-free pp scattering, the simplest case where the Coulomb suppression effects can be measured. The free pp cross section is well-known, its energy trend has been observed to be very similar to that of nn or pn systems except at low proton energies where it shows a deep minimum ($E_{\text{lab}} = 382.43$ keV, $\theta_{\text{cm}} = 90^\circ$) due to the interference between the nuclear and the Coulomb scattering amplitudes [5].

2 EXPERIMENTAL SET-UP

The $^2\text{H}(\text{p},\text{pp})\text{n}$ reaction was studied by choosing angular position of detectors and beam energy in such a way that the investigated pp relative energy is in the region sensitive to the interference. In particular it was studied at Laboratori Nazionali del Sud (LNS), INFN, Catania [6] and at Ruđer Bošković Institute, Zagreb by using a proton beam energy of 6 MeV impinging on a deuterated polyethylen film.

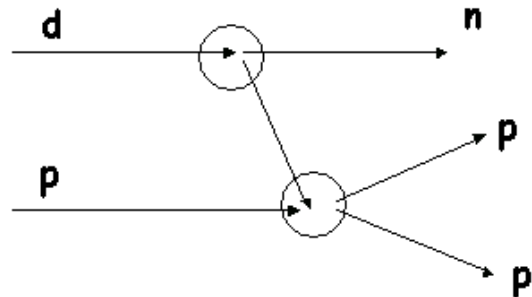


Figure 1: Break-up diagram for the $^2\text{H}(\text{p},\text{pp})\text{n}$ reaction

For the LNS set-up, proton-proton coincidences were measured by two Position Sensitive Detectors (PSD) placed at two different angular configurations with respect to the beam direction. The first configuration was: $16.2^\circ < \theta_1 < 24^\circ$ and $15.6^\circ < \theta_2 < 23.4^\circ$ and the final pp relative energy (E_{12}) was ranging from 0.3 to 0.8 MeV. The second one was: $26.2^\circ < \theta_1 < 34^\circ$ and $15.6^\circ < \theta_2 < 23.4^\circ$ and E_{12} was ranging from 0.5 to 1 MeV.

In the Zagreb set-up, detectors were placed at $8.7^\circ < \theta_1 < 22.5^\circ$ and $11.1^\circ < \theta_2 < 24.6^\circ$ and the investigated pp relative energy, E_{12} ranged from 0.2 to 0.7 MeV. The absolute cross section was also measured by normalizing with the p-d elastic scattering.

3 PWIA AND ON-SHELL HYPOTHESIS

The quasi-free mechanism for the ${}^2\text{H}(p,pp)n$ reaction was already studied in [7] at a beam energy ranging from 4.5 to 13 MeV and the Plane Wave Impulse Approximation (PWIA) was used to reproduce the data. The differential cross section for pp quasi-free scattering in PWIA is given by:

$$\frac{d^3\sigma}{d\Omega_1 d\Omega_2 dE_1} = KF \cdot |\psi(q)|^2 \cdot \left| \langle \vec{k} | t_{pp} | \vec{p} \rangle \right|^2 \quad (1)$$

where $\vec{k}$ and $\vec{p}$ are the momenta of relative motion of two protons in the initial and final state respectively, $\psi(q)$ is the Fourier transform of the deuteron internal wave function.

In reference [7] the half-off-shell pp-elastic cross section has been replaced by the on-shell one. Such an approximation is justified if the difference between the values of $|\vec{k}|$ and $|\vec{p}|$ is negligible and the Coulomb parameter is small. The 3-body cross section has been written in PWIA as a product of the kinematical factor, the square modulus of the Fourier transform of the deuteron internal wave function and the free two-body cross section [7]:

$$\frac{d^3\sigma}{d\Omega_1 d\Omega_2 dE_1} = KF \cdot |\psi(q)|^2 \cdot \left[\frac{d\sigma}{d\Omega} \right]_{free}^{c.m.} \quad (2)$$

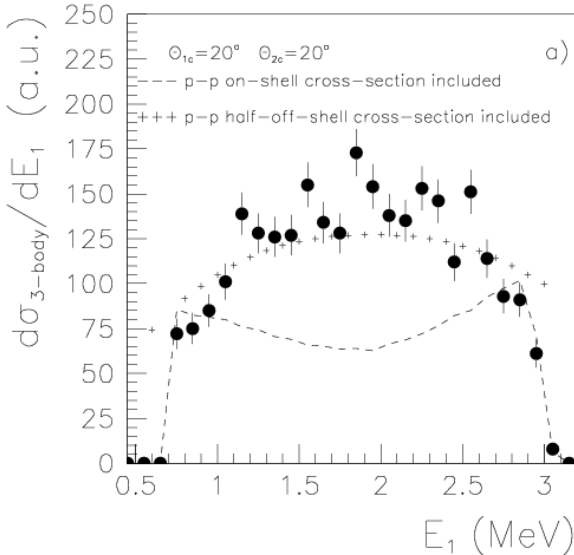


Figure 2 Dots are data from the 1st LNS set-up, the configuration with symmetrical angles centered at about 20° with respect to the beam direction. Dashed lines represents the calculation based on the PWIA and the free p-p cross section. Crosses are the half-off-shell calculation. The cross section is given as a function of the outgoing proton energy (arbitrary units).

These calculations [7] were normalized to the experimental data by using a factor 0.2. In this case the relative energy was almost constant so the p-p cross section did not modified the shape of the total cross section.

In the present case, due to the small relative angles, the relative energy varies over a wider range reaching also lower values than [7]. So the cross section starts to become sensitive to the interference behaviour of the free pp cross section.

A calculation based on eq. 2 is compared with data in Fig. 2, 3, 4 and does not reproduce data.

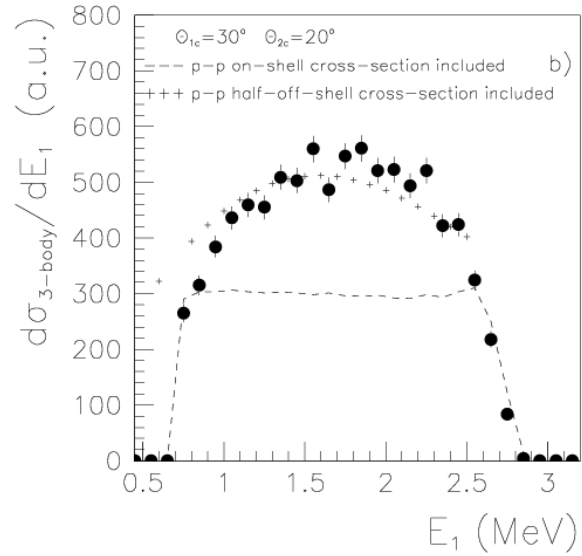


Figure 3: Dots are data from the 2nd LNS set-up, in this configuration detectors are centered at about 30° and 20° with respect to the beam direction. Dashed lines represents the calculation based on the PWIA and the free p-p cross section. Crosses are the half-off-shell calculation. The cross section is a function of the outgoing proton energy (arbitrary units).

3 PWIA AND HALF-OFF SHELL AMPLITUDE

In more accurate PWIA approach the T-matrix operator for the pp-scattering is given by the sum of the half-off-shell Coulomb T_C and the Coulomb-modified nuclear T_{CN} T-matrices:

$$T = T_C + T_{CN} . \quad (3)$$

To get the physical amplitudes we have to take the matrix elements:

$$\begin{aligned} \langle \vec{k} | T | \vec{p} \rangle &= \langle \vec{k} | T_C | \vec{p} \rangle + \\ &+ \langle \vec{k} | (1 + T_C G_0) t_{CN} (1 + G_0 T_C) | \vec{p} \rangle \end{aligned} \quad (4)$$

The expression for the half-off-shell Coulomb scattering amplitude $\langle \vec{k} | T_C | \vec{p} \rangle$ was derived by [8].

The second term can be evaluated by using a simple s-wave separable Yamaguchi nuclear potential [9].

So in this approach, the free pp cross section has been definitively replaced by the pp half-off-shell one. Note

that the propagator $\sigma = E_p - \frac{p_p^2}{2m_p}$ of the virtual

proton appearing between the three-ray vertex $d \rightarrow p+n$ and the pp scattering amplitude (E_p is the energy of the transferred proton and p_p is its momentum) is properly taken into account through the $|\psi(q)|^2$.

This kind of calculation has been compared with results of [7] and the shape of the cross section is in good agreement with the calculation.

The agreement with our experimental data is also quite good. In the case of the Zagreb set-up, where the absolute cross section also has also been measured, data are a factor two larger than the calculation.

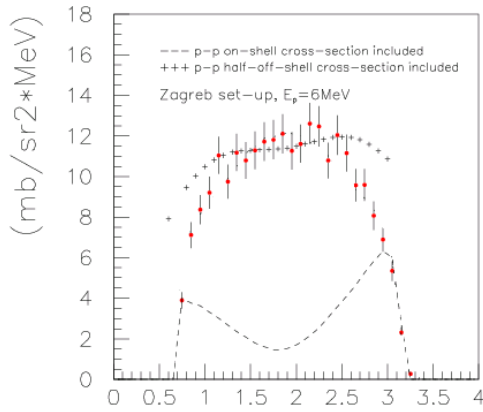


Figure 4: Cross section as a function of the outgoing proton energy. Dots are data from the Zagreb set-up, in this configuration detectors are centered at about 17° with respect to the beam direction. Dashed lines represents the calculation based on the PWIA and the free p-p cross section. Crosses are the half-off-shell calculation. The absolute cross section is a function of the outgoing proton energy.

4 REFERENCES

- [1] G. Baur, Phys. Lett. B178, 35 (1986).
- [2] S. Cherubini, Ap.J. 457, 855 (1996).
- [3] C. Spitaleri, Phys. Rev. C60, 055802 (1999).
- [4] C. Spitaleri, Phys. Rev. C63, 055801 (2001).
- [5] J.E. Brolley, Phys. Rev. 135, B1119 (1964).
- [6] M.G. Pellegriti, Proc. of Fusion03, Matsushima, Japan
- [7] V. Valković, Nucl. Phys. A166, 547 (1971)

- [8] Ė.I. Dolinskiĭ and A. M. Muckhamedzhanov, Soviet Journal of Nucl. Phys. 3 (1966) 180

- [9] H. Van Haeringen, Nucl. Phys. A253 (1975) 355

Projectile Splitting in $^{62}\text{Ni} + ^{112}\text{Sn}$ Reactions at $E/A = 35$ MeV

L. Pienkowski^a, Jun Lu^a, Jan Toke^a, W. Udo Schroeder^{a,*}, W. Gawlikowicz^b, C. Agodi^c, R. Alba^c, G. Bellia^c, R. Coniglione^c, A. Del Zoppo^c, P. Finocchiaro^c, C. Maiolino^c,
E. Migneco^c, P. Piattelli^c, D. Santonocito^c, P. Sapienza^c, M. Di Toro^c, M. Colonna^c, V. Baran^d,
A. Moroni^e, P. Milazzo^f, N. Colonna^g

a) Department of Chemistry, University of Rochester, Rochester, New York 14627

b) Jagellonian University, Cracow, Poland

c) INFN-Laboratori Nazionali del Sud, Via S. Sofia 44, I-95123, Catania, Italy

d) NIPNE Bucharest

e) INFN-Sezione di Milano

f) INFN-Sezione di Trieste

g) INFN-Sezione di Bari

** Corresponding author, e-mail: schroeder@chem.rochester.edu*

Abstract

Data reduction and evaluation were performed for the data collected by the Rochester-MULTICS-MEDEA collaboration. The present report focuses on a class of events in which both, the (forward) MULTICS array and the small-angle massive-product telescopes have detected fragments. The observed correlations between the atomic numbers of such coincident fragments reveal that the relatively light ^{62}Ni projectiles split quite frequently into two massive fragments.

An experiment was performed at the LNS-Catania aiming at studying isotopic effects in reactions between ^{62}Ni projectiles and two Sn isotopes at $E/A = 35$ MeV. The experimental setup included the MEDEA [1] and MULTICS [2] multi-detector systems, an array of 8 neutron detectors, two position-sensitive massive fragment detectors for the detection of projectile-like fragments, two 7-strip silicon detectors for massive target-like residues, and two high-resolution intermediate mass fragment telescopes. Selected experimental results obtained with the small-angle position-sensitive telescope and the (forward) MULTICS array are presented in Figs. 1 and 2.

Fig. 1 illustrates characteristics of the projectile-like fragments (PLF) and IMFs emitted at angles around the grazing angle for the Ni + Sn collisions. The left panels of this figure represent inclusive data, while the right ones represent events in which the MEDEA array detected from 3 to 10 particles. The top panels illustrate correlations between the fragment atomic number and a crude measure of fragment velocity and are seen to feature two distinct yield patterns, one for the projectile-like fragments and the other one (lower Z values) for intermediate-mass fragments. While the PLFs are abundant in the inclusive yields, showing a distinct reduction of velocity with increasing degree of kinetic energy or velocity damping, they are much less prominent for events "painting" the MEDEA detector.

Bottom panels of Fig. 1 illustrate correlations between the deflection angle of fragments and their atomic number. Since the latter constitutes a measure of kinetic energy damping, these bottom plots are to a certain extent equivalent to Wilczynski plots.

Similarly to what had been observed in many other reactions in this bombarding energy domain, these plots feature three segments of a yield ridge associated with dissipative orbiting - one running from small angles to the grazing angle at almost constant $Z=28$, the second one (less prominent) running from the grazing angle to small angles with decreasing Z value, and the third one running from small angles to larger angles with substantially reduced Z values. As seen in the bottom right panel, the latter segment of the yield ridge is associated with more strongly damped collisions selected by the coincident MEDEA array events.

Fig. 2 illustrates correlations between the atomic numbers of massive fragments detected at small angles using the small-angle telescope and the MULTICS array in coincidence. While MULTICS detects mostly small fragments, there is a considerable number of events seen in Fig. 2 where both detectors detect massive fragments. Considering that the MULTICS array detects preferentially fragments emitted from the PLF, the observed anticorrelation pattern for the coincident massive fragments is consistent with a scenario of a PLF splitting into two massive fragments. A rather fast splitting phenomenon has been reported by Glassel [3]

et al., who observed proximity influences by the target-like reaction partner in several heavy-ion reactions at slightly lower bombarding energies. Alternatively, the pattern in question could represent sequential emission of an intermediate-mass cluster from an accelerated PLF. In any case, observation of forward emission of intermediate-mass clusters kinematically correlated with a primary PLF offers significant constraints on the time scale for PLF decay and hence the stability of such nuclei. These observations suggest a future dedicated coincidence study to characterize the observed decay mode.

Figure 1: Characteristics of the fragment yield detected at forward angles. (See text)

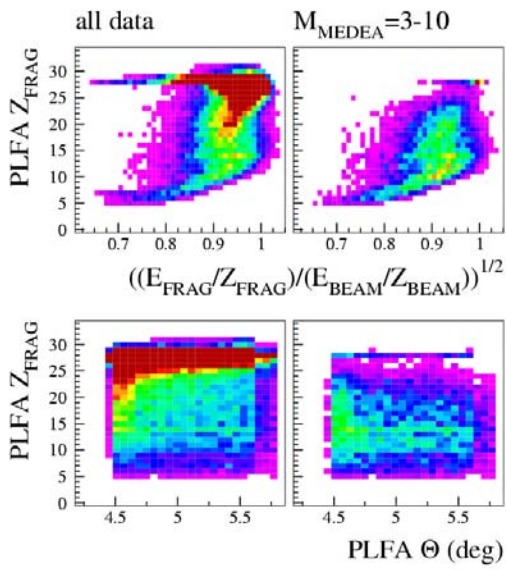
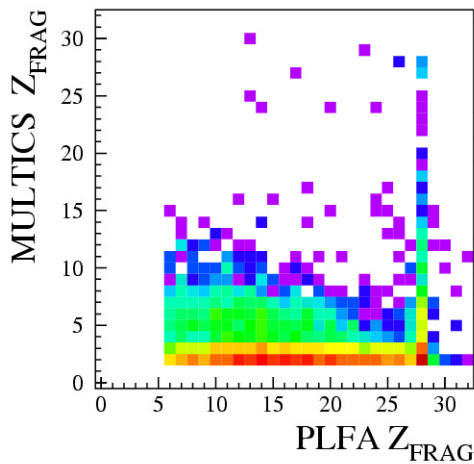


Figure 2: Correlations between atomic numbers of fragments detected by the small-angle telescope and the MULTICS array. (See text)



5 REFERENCES

- [1] E. Migneco et al., Nucl. Instr. and Meth. A 314 (1992) 31.
- [2] I. Iori et al., Nucl. Instr. and Meth. A 325 (1993) 458,
M. Bruno et al., Nucl. Instr. and Meth. A 311 (1992) 189,
N. Colonna et al., Nucl. Instr. and Meth. A 321 (1992) 529,
P.F. Mastinu et al., Nucl. Instr. and Meth. 338 (1994) 419.
- [3] P. Glassel et al., Phys. Rev. Lett. 43, 1483 (1979).

Influence of the ${}^6\text{Li}$ momentum distribution on Trojan Horse Method applications

R.G. Pizzone¹, C. Spitaleri^{1,2}, S. Cherubini³, P. Figuera¹, M. La Cognata^{1,2}, L. Lamia^{1,2}, D. Miljanić⁴,
A. Musumarra^{1,2}, M.G. Pellegriti^{1,2}, S. Romano^{1,2}, S. Tudisco^{1,2}, A. Tumino^{1,2}, S. Typel⁵

¹*Laboratori Nazionali del Sud-INFN, Catania, Italy*

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

³*Ruhr-Universität Bochum, Germany*

⁴*Institut Ruđer Bošković, Zagreb, Croatia*

⁵*GSI, Darmstadt, Germany*

Abstract

Indirect methods are nowadays a necessary tool for experimental nuclear astrophysics. Among them the Trojan Horse Method (THM) can be very important for studying the electron screening effect in charged particle induced reactions. For a better evaluation of the theoretical uncertainties of this method the role of the FWHM for the α - d relative motion inside ${}^6\text{Li}$ is investigated in this paper and compared with previous results from different experiments [1]. The behaviour of the FWHM as a function of the different radial wave function and transferred momentum q , is discussed in details and the implications for the Trojan Horse Method are also given.

I. INTRODUCTION

The presence of the electron screening effects at very-low energies ($1 < E_{cm} < 100$ keV) in nuclear reactions of astrophysical interest has triggered the development of many indirect methods for cross section measurements. Among them, the Trojan Horse Method (THM) has been extensively used in particular for reactions where light ions are involved, e.g. Li [2, 3, 4], since it allows to measure the bare nucleus two body cross section by means of a three body one, under suitable kinematic assumptions. The basic idea of this method has been extensively discussed elsewhere [5, 6, 7, 15, 16].

It has been pointed out [7, 15] that the study of the impulse distribution is important in order to evaluate and, if possible, to reduce, the errors introduced by the THM theoretical approach in the $S(E)$ -factor measurement. For its application THM requires a complete knowledge of the momentum distribution of the spectator particle inside the Trojan Horse nucleus and, therefore, it appears necessary to evaluate the impact on the extracted $S(E)$ -factor of the momentum distribution FWHM by varying:

- the radial part $R(r)$ of the most commonly used inter-cluster wave function $\chi(r)$, e.g. Hänkel function;
- the transferred momentum [1].

Their impact on the measured astrophysical factors will also be shown.

The choice of the ${}^6\text{Li} = d + \alpha$ system is related to its particular features:

- its low dissociation energy ($E_b=1.47$ MeV) into a deuteron and an alpha particle suggests a strong alpha-deuteron structure, ${}^6\text{Li} = \alpha + d$ [8]. In fact in the cluster model the ${}^6\text{Li}$ nucleus is well described by such a structure. Moreover the symmetric properties and

high binding energy of the α particle play a crucial role in this description;

- in the 70's and 80's, the ${}^6\text{Li}$ nucleus was probably the most studied nucleus thanks to large theoretical and experimental efforts since it is the simplest nucleus that can be described in the cluster model;
- over more than this two decades, the study of the relative $\alpha - d$ motion wave function has been determined through quasi-free scatterings and reactions.

In the present work an analysis of the experimental behaviour of the impulse distribution FWHM as a function of the radial part of the wave function for the $\alpha - d$ momentum distribution case is discussed. Moreover the dependence on the interaction energy will be investigated. We will also discuss the experimental measurements for the $\alpha - d$ momentum distribution in ${}^6\text{Li}$ extracted from the ${}^6\text{Li}({}^6\text{Li}, \alpha\alpha){}^4\text{He}$. In the final section the impact of FWHM variation on the extracted astrophysical factors for the ${}^6\text{Li}(d, \alpha){}^4\text{He}$ will be shown.

II. THREE BODY CROSS SECTION FOR THE QUASI-FREE MECHANISM

A typical three body reaction can be written as:

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

where, in the case of a quasi-free break-up process, a is the projectile, A the target, s the spectator, c and C the detected ejectiles. For simplicity's sake we will assume that the quasi-free break-up takes place in $A = x \oplus s$, with x participant to the $a(x, c)C$ reaction.

In the framework of the impulse approximation (IA) the theoretical triple-differential cross-section can be fac-

torized into two terms and it is given by [9, 10]:

$$\frac{d^3\sigma}{dE_1 d\Omega_1 d\Omega_2} = P \cdot (KF) \cdot \left(\frac{d\sigma^{off}}{d\Omega_{cm}} \right) \cdot |\Phi(\vec{p}_s)|^2 \quad (1)$$

where

1. P is a spectroscopic factor taking into account absorption effects and clustering probability;
2. $[(d\sigma/d\Omega)_{cm}]^{off}$ is the off-energy-shell differential cross section for the two body $B(x, c)d$ reaction at the center of mass energy E_{cm} given in post collision prescription by:

$$E_{cm} = E_{c-C} - Q_{2b} \quad (2)$$

with Q_{2b} the two body Q -value of the $a(x, c)C$ reaction and E_{c-C} the relative energy between the outgoing particles c and C ;

3. KF is a kinematical factor;
4. $|\Phi(\vec{p}_s)|^2$ is the momentum distribution of the spectator, $\vec{p}_s$.

When PWIA is used, the $|\Phi(\vec{p}_s)|^2$ factor in eq. 1 is simply the square of the Fourier transform of the inter-cluster wave function $\chi(\vec{r})$.

$$\Phi(\vec{p}_s) = (2\pi\hbar)^{-3/2} \int e^{-i\vec{p}_s \cdot \vec{r}/\hbar} \chi(\vec{r})_{rel} d\vec{r} \quad (3)$$

As a possible radial part of the intercluster wave function Hankel with cut-off radius as well as Eckart functions are commonly used [8].

In the standard THM approach the two body-cross section is obtained inverting eq. 1, where the product $KF \cdot |\Phi(\vec{p}_s)|^2$ is calculated by means of Monte Carlo simulations, after normalization to direct data.

III. DEPENDANCE OF THE FWHM FROM THE INTER-CLUSTER WAVE FUNCTIONS AND TRANSFERRED MOMENTUM

By considering only a s -wave motion between the two clusters, and neglecting antisymmetrization, the inter-cluster wave function can be written as

$$\chi(\vec{r}) = R(\vec{r}) Y_{00}(\theta, \phi) \quad (4)$$

The momentum distribution $|\phi(p_s)|^2$, especially its FWHM, Γ , and the top value $\phi(p_s = 0)$ have been calculated [8] for several functional dependences of $R(r)$, such as Hankel and Eckart functions. The general conclusions that can be drawn from this analysis, can be summarized as follows [8]:

- the FWHM of the momentum distribution is not particularly sensitive to the choice of the wave function for a cut-off radius $R_c > 3$ fm;
- the value of $|\phi(p_s = 0)|^2$ depends clearly on the choice of the intercluster wave function.

It has also been pointed out that, in order to take into account reabsorption effects, or even to simulate the inadequacy of the cluster model for small intercluster distances, a cut-off radius R_c can be introduced in the intercluster function, such that [8]

$$R(r) = 0 \quad \text{for} \quad r < R_c$$

Besides the PWIA approach the Distorted Wave Impulse Approximation (DWIA) treatment was sometimes applied in the analysis of quasi-free reaction and scattering experimental data.

It should be stressed that the main difference between the momentum distributions calculated in PWIA and in DWIA is twofold [11, 13, 14]:

- the shape of the $x - S$ momentum distribution tail. However for recoil momenta ($q < 100 \text{ MeV}/c$) the main features of the $|\phi(p_s)|^2$ are essentially the same in both procedures [12].
- in the absolute value of the cross-section.

However, PWIA has been widely used because, in spite of its simplicity, it predicts reasonably well the shape of the experimental momentum distribution, in region away from zeroes in $|\Phi(\vec{p}_s)|^2$ [13].

As regards the energy dependence of the FWHM, the transferred momentum in the three body reactions can be defined [1] as:

$$\vec{q} = \vec{p}_a - \frac{\vec{p}_c + \vec{p}_C}{2} \quad (5)$$

where $\vec{p}_a$, $\vec{p}_c$ and $\vec{p}_C$ are the momentum of the projectile and ejectiles c and C , respectively.

In several works [17] it has been shown that the FWHM for the α - d momentum distribution in ${}^6\text{Li}$ slowly increases with increasing transferred momentum. The asymptotic value, around 70 MeV/c is in good agreement with the value predicted by both the PWIA and the DWIA, only when values larger than 300 MeV/c are involved. The narrowing of the impulse distribution with decreasing transferred momentum is usually related to distortion or absorption effects [18].

One can assume that for the present case that A corresponds to ${}^6\text{Li}$ which can be described as ${}^6\text{Li} = \alpha \oplus d$. In this particular case the expression of $|\Phi(\vec{p}_s)|^2$ is given in PWIA by eq. 3 in terms of the intercluster wave function for the ${}^6\text{Li}$. To calculate $|\Phi(\vec{p}_s)|^2$ it can be assumed that the relative motion is described by the Hankel function [19].

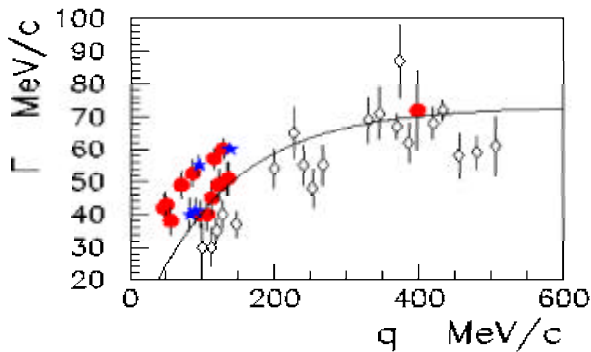


FIG. 1: FWHM for the α momentum distribution inside ${}^6\text{Li}$ as a function of the transferred momentum q (see text). Diamonds represent previous results by [1, 17], full dots new data for the ${}^6\text{Li}({}^6\text{Li}, \alpha\alpha){}^4\text{He}$ from the present work, black stars data from ${}^3\text{He}({}^6\text{Li}, p\alpha){}^4\text{He}$ (this work). The solid line represents an empirical fit described in the text.

The FWHM of the spectator momentum distribution has been extracted for ${}^6\text{Li}({}^6\text{Li}, \alpha\alpha){}^4\text{He}$ [2, 6] and in table 1, is reported the transferred momentum modulus calculated for some reactions and different beam energies according to equation 5. In figure 1 the trend of the FWHM for the α -d relative motion is reported as a function of the transferred momentum q : it seems clear how at low q the FWHM slowly increases until a “saturation” value is reached around 250-300 MeV/c. The correspondent FWHM at this q is 73 MeV/c as it was predicted by both the PWIA and the DWIA [13, 18].

The results reported in [1, 17] are plotted as diamonds; recent data extracted from ${}^6\text{Li}({}^6\text{Li}, \alpha\alpha){}^4\text{He}$ at different energies [2, 6] (full dots) and ${}^3\text{He}({}^6\text{Li}, p\alpha){}^4\text{He}$ [20, 21] (black stars) are also shown.

These data confirm the behavior already discussed in [1]. An empirical relation has been fitted to the present shape; in fact a function like

$$W(q) = f_0 \cdot (1 - e^{-q/q_0})$$

fits the experimental points if the parameters f_0 and q_0 are respectively set to 73 and 122.7 MeV/c. This allows useful applications for the Trojan Horse Method where low transferred momenta can be reproduced by using this FWHM as an important part of the spectator momentum distribution [2].

IV. IMPULSE DISTRIBUTION MEASUREMENT

In the PWIA it is possible to relate the three-body differential cross section to the impulse distribution of the spectator cluster inside ${}^6\text{Li}$ by using equation 1. This equation can be applied in order to derive $|\Phi(p_s = 0)|^2$ once the other quantities are known.

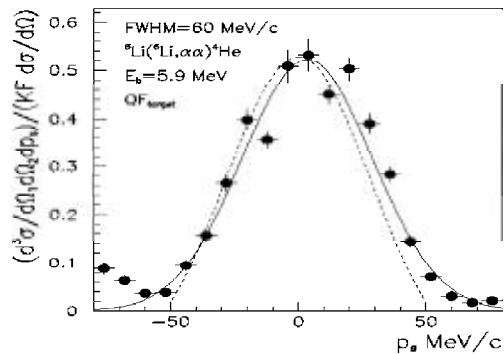


FIG. 2: Experimental momentum distribution for the α inside ${}^6\text{Li}$ derived according to the guidelines given in the text for the ${}^6\text{Li} + {}^3\text{He} \rightarrow \alpha + \alpha + p$ reaction (target break-up case).

TABLE I: Transferred momentum for the ${}^6\text{Li}({}^6\text{Li}, \alpha\alpha){}^4\text{He}$ reaction at different beam energies

E_b MeV	q MeV/c	reference
2.1	71	
2.7	87	
3.6	96	[22]
4.2	107	[22]
4.7	115	[22]
5.7	125	[22]
5.9	136	[2]
6.7	138	[22]
44	398	

In details the differential cross section for the ${}^6\text{Li} + {}^6\text{Li} \rightarrow \alpha + \alpha + \alpha$ reaction at 5.9 beam energy [2] has been extracted as a function of p_s for a narrow range (~ 100 keV) in E_{cm} , both for target and projectile break-up. Within this assumption one can assume that the nuclear-two-body cross section $\frac{d\sigma}{d\Omega_{cm}}$ is slightly varying with energy, or nearly constant. Thus dividing this quantity for the kinematical factor one obtains the shape of the impulse distribution of α inside ${}^6\text{Li}$ in arbitrary units. This is shown in figure 2 together with a Gaussian fit (solid line) as well as the appropriate Hankel function (dashed line). From this experimental impulse momentum distribution Γ can be easily derived; in our case the values of 60 ± 1 MeV/c (target break-up case) and 57 ± 1 MeV/c (projectile break-up) have been deduced. Other measurements for the ${}^6\text{Li} + {}^6\text{Li} \rightarrow \alpha + \alpha + \alpha$ reaction were also performed at lower beam energies ($E_b = 2.1$ and $E_b = 2.7$ MeV), by using the Tandem Accelerator located at the Ruder Boskovic Institute in Zagreb. The results are summarized in table 1 together with results for other beam energies.

In order to fit the experimental momentum distribution a cut-off radius is often introduced [18]. If the relative motion of the two clusters inside ${}^6\text{Li}$ is described by means of a Hankel function the momentum distribution

TABLE II: Results of the Hänckel fit for experimental data discussed in the text: beam energy, FWHM and cut-off radius

E_b MeV	FWHM MeV/c	R_c fm
2.1	49 ± 4	$6.5 \pm 2.$
2.7	53 ± 4	6.5 ± 0.5
3.6	40 ± 5	7.5 ± 1
4.2	40 ± 5	7.5 ± 1
4.7	45 ± 5	6.5 ± 1
5.7	49 ± 5	6.5 ± 1
5.9	61 ± 5	6.9 ± 0.2
5.9	63 ± 5	6.2 ± 0.2
44	72 ± 15	$5.2 \pm 2.$

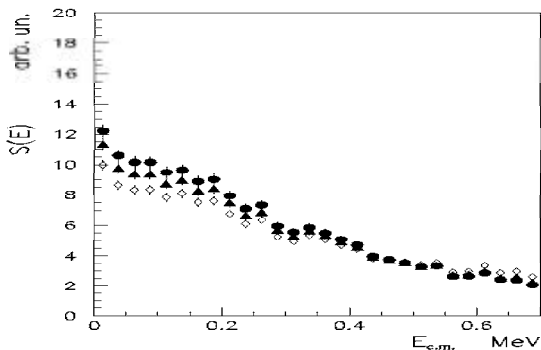


FIG. 3: ${}^6\text{Li}(d, \alpha){}^4\text{He}$ S(E)-factor energy trend in arbitrary units, extracted via THM, for different choices of the FWHM of the α momentum distribution inside ${}^6\text{Li}$. Full circles correspond to $\Gamma=70$ MeV/c, triangles to 60 MeV/c and diamonds to 50 MeV/c.

for the s-state is given by [19]:

$$|\Phi(p_s)|^2 = N \cdot \frac{1}{(p_s^2 + \beta^2)^2} \cdot \left[\frac{\sin p_s R_c}{p_s} + \frac{\cos p_s R_c}{\beta} \right] \quad (6)$$

with R_c the cut-off radius, and β which may be defined by means of the binding energy E_B of the $\alpha - d$ system

in ${}^6\text{Li}$ according to $\beta = (2\mu E_B/\hbar^2)^{1/2}$ where μ is the reduced mass.

The fitting procedure, applied to the experimental momentum distribution, gave results which are summarized in table 2.

V. APPLICATIONS TO THE THM

Reminding eq. 1 the factor $\text{KF} \cdot |\Phi(\vec{p}_s)|^2$ has been evaluated by means of a Monte Carlo simulation in PWIA approach. The simulation was performed in order to extract the S(E)-factor according to the THM prescriptions; as stated above it appears necessary to evaluate the impact of FWHM variations on the extracted THM S(E)-factor. This was done for the ${}^6\text{Li}(d, \alpha){}^4\text{He}$ reaction, which was studied via the ${}^6\text{Li}({}^6\text{Li}, \alpha\alpha){}^4\text{He}$ [2]. In figure 3 the different behaviors of the S(E)-factor are reported in arbitrary units for different choices of Γ , the FWHM of $\alpha - d$ intercluster momentum distribution in ${}^6\text{Li}$. Three values of Γ were chosen: $\Gamma=50, 60$ and 70 MeV/c; the variation of the S(E) coefficient, around 6%, is smaller than the normalization error (which is about 15%). Thus errors arising from momentum distribution knowledge are a minor error source for the S(E) determination at least for the ${}^6\text{Li}(d, \alpha){}^4\text{He}$ reaction.

VI. CONCLUSIONS

The FWHM for the momentum distribution of α -d inside ${}^6\text{Li}$ has been obtained from the ${}^6\text{Li}+{}^6\text{Li} \rightarrow \alpha+\alpha+\alpha$. Then its variation with the transferred momentum has been reviewed and updated.

Moreover the impact of FWHM variation on the S(E)-astrophysical factors obtained via THM has been investigated in the case of the ${}^6\text{Li}(d, \alpha){}^4\text{He}$ reaction. The errors arising from the uncertainties on Γ turned out to be comparable with the normalization errors, already taken into account in the THM application.

-
- [1] S. Barbarino et al., Phys. Rev., **C21**, 1104 (1980).
 - [2] C. Spitaleri et al., Phys. Rev. **C63**, 055801 (2001)
 - [3] M. Lattuada et al., APJ 562, 1076 (2001).
 - [4] F. Strieder, C. Rolfs, C. Spitaleri, P. Corvisiero, Naturwissenschaften 88, 461 (2001)
 - [5] C. Spitaleri, proc. of Folgaria meeting (1990).
 - [6] S. Cherubini et al., Ap. J. **457**, 855 (1996)
 - [7] C. Spitaleri et al., Phys. Rev. **C60**, (1999) 55802.
 - [8] M. Lattuada, et al., Il Nuovo Cimento, A83, 151 (1984)
 - [9] G.F. Chew, Phys. Rev., **80**, 196 (1950);
 - [10] G.F. Chew & G.C. Wick, Phys. Rev. **85**, 636 (1952);
 - [11] P.G. Roos et al., Nucl. Phys. **A257**, 317 (1976)
 - [12] R. Ent et al., Phys. Rev. Letters, **57** 2367 (1986)
 - [13] P. Roos et al., Phys. Rev., **C15**, 69 (1977)
 - [14] Jain, A.K., et al., Nucl. Phys. A, 153, 49 (1970)
 - [15] A. Tumino et al. Phys. Rev. C 67, (2003) 065803
 - [16] C. Spitaleri et al. Phys. Rev. C 69, (2004) 1
 - [17] M. Lattuada, et al., Il Nuovo Cimento, A71, 429 (1982)
 - [18] J.W. Watson et al, Nucl. Phys. A172, 513 (1971)
 - [19] J. Kasagi et al., Nucl. Phys. A239, 233 (1975)
 - [20] M. Zadro et al., Nucl. Phys., A474, 373 (1987)
 - [21] M. La Cognata, et al., proceedings of the 8th Cluster08 conference, Nara (Japan) (2003)
 - [22] M. Lattuada et al., Z. Phys. A, 330, 183 (1988)

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

^{a,*}, J.Blicharska^b, J.Brzychczyk^a, J.Cibor^c, A. Grzeszczuk^b, P.Hachaj^d,
S.Kowalski^b, Z.Majka^a, N.G.Nicolis^e, K.Schmidt^b and W.Zipper^b
for the ISOSPIN Collaboration

a) M.Smoluchowski Institute of Physics, Jagellonian University, Kraków, Poland

b) Institute of Physics, Silesian University, Katowice, Poland

c) Institute of Nuclear Physics, Kraków, Poland

d) Cracow University of Technology, Kraków, Poland

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

* Corresponding author, e-mail: ufplanet@cyf-kr.edu.pl

Abstract

We study the feasibility for an experimental observation of toroidal and bubble nuclei in Au + Au collisions. Preliminary data pertaining to Au+Au and Au+C collisions at 15MeV/A are analyzed. The beam time needed to accumulate a reasonable number of candidate events with at least five heavy fragments is estimated. The current status of reaction simulations, developed for this purpose, is presented.

Fifty years ago, Wheeler suggested the existence of nuclei with nonspherical shapes and investigated the stability of toroidal nuclei [1,2]. About 30 years ago, Siemens and Bethe showed that spherical bubble nuclei with a sufficiently large charge may be stable against a symmetry-preserving breathing deformation [3]. Later, Wong pointed out that probability of existence of such nuclei should depend on temperature [4]. As the nuclear temperature increases, the surface tension coefficient decreases and the Coulomb repulsion is pushing nuclear matter outwards leading to the formation of toroidal and bubble nuclei. Moretto [5] showed that the depletion of charge in the central cavity of nuclear bubbles stabilizes them against monopole oscillations. Such objects are however unstable with respect to quadrupole and octupole distortions. Generalized rotating liquid drop model calculations show that the minimum of the potential energy for toroidal shape occurs even at zero angular momentum for heaviest nuclear systems with masses greater than 300 atomic mass units [6].

Toroidal-shaped objects are also common in hydrodynamical collisions [7]. Simulations of nuclear collisions by means of transport equations show the possibility of ring-, disk-, or bubble-shaped nuclear configurations formation in central collisions [8-13]. It was found that different values of the incompressibility of nuclear matter leads to different exotic objects [9].

A number of observables were suggested as the signatures of noncompact nuclear system configurations breakup:

- (i) More of the intermediate mass fragments should be generated than would be expected for the decay of a compact object at the same temperature [8,14];
- (ii) Enhanced similarity in the charges of large fragments. Theoretical models have quantitatively predicted that the formation of noncompact geometries will result in increased cross section for emission of fragments with nearly equal masses [12, 15];
- (iii) Suppressed sphericity in the emission of heavy fragments [16];
- (iv) Two-body observables of the intermediate mass fragments should disentangle the emission from spherical sources and from ring- and disc-shaped sources [17].

The experimental evidence for the decay of nuclear matter noncompact geometries up to now is very limited. The article of Stone et al. [16] presents a systematic study of experimental results for the ⁸⁶Kr + ⁹³Nb system for incident energies ranging from 35 to 95 MeV/nucleon. The authors noticed a 5% enhancement of the intermediate mass fragments emission and similarity of these fragment charges. They also observe a 5% suppression in the mean value of the sphericity and suppressed flow angles of IMF emission. These

observations indicate the existence of exotic geometries for beam energies between 60 and 75 MeV/nucleon.

In this contribution, we present the feasibility study for the experimental observation of toroidal and bubble nuclei. This search is based on data collected by the CHIMERA collaboration for the Au + Au reaction at 15 MeV/nucleon. The experiment was performed at INFN – LNS in Catania using the 4 π CHIMERA multidetector [18].

In the first step of our analysis, we have established an identification method of heavy fragments using raw (uncalibrated) experimental data. In Fig.1 we present the raw energy spectra observed at several

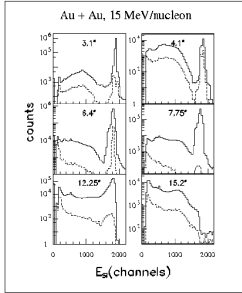


Fig. 1. Energy spectra for the Au + Au reaction (for details see text)

angles for all particles and fragments detected by silicon detectors (solid lines). The dashed curves correspond to particles that lose only part of their energy in the silicon detector and deposit the residual energy in the corresponding CsI detector. In each panel the ring polar angle is indicated. Inspection of the solid lines at smaller observation angles shows a relatively narrow peak related to quasielastic scattering and a broad bump of events at lower energy. With increasing angle of observation the narrow peak disappears. Similar spectra for the Au + C reaction at the same incident Au beam energy are shown in Fig. 2. For this reaction the cross section is dominated by fission of the Au-like nuclei after the inelastic collision with C target. Two fission fragments peaks are well visible in energy spectra while the quasielastic peak is practically not visible here due to the very small grazing angle for this reaction.

In order to get an approximate identification of heavy fragments for the Au + Au reaction we applied following criteria: (i) the energy deposited in a silicon detector is lower than energy of the quasielastic peak; (ii) the particle is stopped in silicon detector (associated CsI signal is not observed). Comparison between the solid and dashed curves in Figs 1 and 2 shows that the emission probability for light particles in both reactions

is relatively small in comparison to the heavy fragments (notice the logarithmic y axis scale on Figs. 1 and 2).

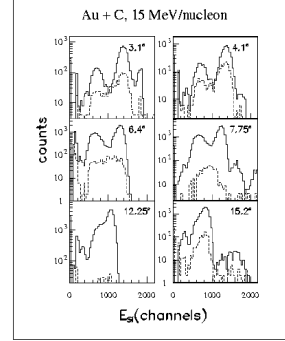


Fig. 2. Energy spectra for the Au + C reaction (for details see text)

To verify the quality of the heavy fragment identification procedure, the azimuthal correlation function, $\Delta\Phi_{ij}$, was studied. Such correlation functions are shown in Fig. 3 for Au + Au reaction (upper panels) and for Au + C system (lower panels). When

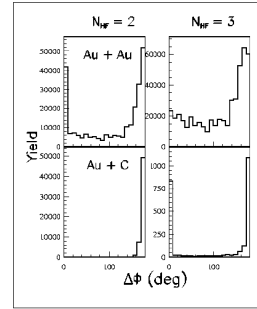


Fig. 3. Azimuthal correlation function for Au + Au (upper panels) and Au + C (lower panels) reactions

events with only two heavy fragments are considered ($N_{HF}=2$) for the Au + C we observe a peak at 180° corresponding to fission fragments of Au-like nuclei. In the case of Au + Au reaction additionally to the peak at 180° we observe a peak at 0° and some events with $\Delta\Phi_{ij}$ angles in between. These $\Delta\Phi_{ij}$ values are more abundant for the class of events with three heavy fragments.

The multiplicity distributions of heavy fragments for both reactions are presented in Fig. 4. This distribution is limited to multiplicities smaller than

4 and has a maximum at multiplicity 2 for the Au + C system. The distribution is much broader for the Au + Au reaction.

In order to distinguish between different nuclear geometries we need to accumulate a reasonable number of events with many heavy fragments. The beam time needed to achieve

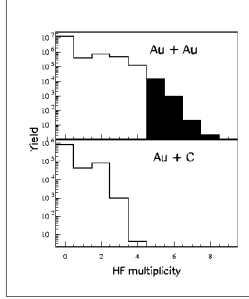


Fig. 4. The multiplicity of heavy fragments distributions for Au + Au and Au + C reactions (black area correspond to events with at least five heavy fragments).

this goal is calculated for events with at least 5 heavy fragments. We found that the fraction of such events among the accumulated data is equal to $8 \cdot 10^{-4}$. Assuming the Au beam intensity 0.03 pA and a target thickness of 0.3 mg/cm² we estimated that 450 hours of beam time is needed to record 10^6 multifragment events.

In order to examine the applicability of the CHIMERA multidetector for recognition of noncompact nuclear geometries we have developed the Monte Carlo simulation program ETNA (Expecting Toroidal Nuclear Agglomerations). This code allows us to simulate the decay of the nuclear system assuming ball, disk, toroidal and rod-like breakup geometries. First of all the number of participating nucleons is determined: for lower energies (e.g. 15 MeV/nucleon) all nucleons from the projectile and the target are assumed to be involved in the reaction, for higher energies some of them escape as prompt emitted particles. All the participants are assumed to form a composite system which breaks up into pieces. The number of resulting primary fragments is an input to the simulation program. The fragments are set in following procedure. The composite system divides into two with a bell curve probability of charge and mass distribution between them. The fragment to break next is selected with a probability equal to the portion of total system mass it carries. The process is repeated until the desired number of fragments is obtained.

All the fragments are then placed within a freezeout volume of density given by an input parameter. The shape of the freezeout volume in the current version of the ETNA code can be: a sphere, a disc, a toroid and

a rod. For non-spherical shapes the characteristic dimensions (e.g. the thickness of the disc) are of order of magnitude of the average diameter of the primary fragments to be put into. The fragments are placed randomly inside the freezeout volume. Then an overlap check is performed. If two or more fragments are to occupy the same location in space the placing procedure is repeated.

Energy conservation is then applied. The energy of the entrance channel (kinetic energy in the CM minus binding energy of the substrates) must not be less than the energy of the output channel (Coulomb energy minus binding energy of the products). If this does not happen – the event is discarded and the procedure starts from the beginning. The remaining energy is distributed among the fragments using Maxwell distribution. A center of mass shift is used to assure momentum conservation. Then the kinetic energies are multiplied by a common factor to guarantee energy conservation as well. Finally, a Coulomb acceleration subroutine is executed to obtain the final picture of the reaction.

As an example of simulation predictions we plot angular distributions of fragments in the laboratory system (Fig. 5). These calculations were performed for the case of five primary fragments. Here different lines correspond to different geometries of the decaying system. The differences between different geometries are visible.

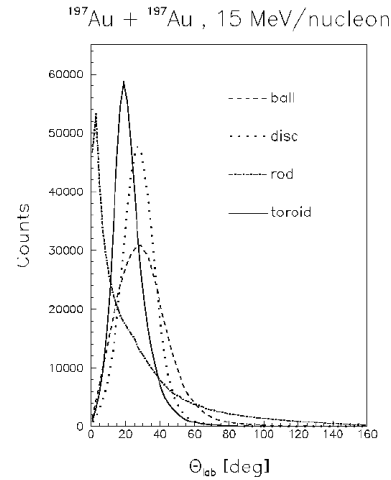


Fig. 5. The angular distributions for heavy fragments in the laboratory system for different geometries of the decaying system.

These simulations will be further refined with the inclusion of mass, charge and recoil corrections due to evaporation from the excited fragments. The relevant subroutines have been prepared [19]. The simulated events will eventually pass through the CHIMERA

software detector filter [20], in order to be compared with the experimental data.

In this contribution the feasibility study of experimental observation of toroidal and bubble nuclei in the Au + Au reaction is presented. The beam time needed to accumulate a reasonable number of events with at least five heavy fragments is estimated. Present status of the Monte Carlo simulation predictions is shortly discussed.

REFERENCES

- [1] J.A.Wheeler, "Nucleonic Notebook", 1950 (unpublished).
- [2] R.E.Euwema and J.A.Wheeler, unpublished.
- [3] P.J.Siemens and H.Bethe, Phys. Rev. Lett. 18 (1967) 704.
- [4] C.Y.Wong, Phys. Rev. Lett. 55 (1985)1937.
- [5] L.G.Moretto et al., Phys. Rev. Lett. 78 (1997) 824.
- [6] C.Fauchard and G.Royer, Nucl. Phys. A598 (1996) 125.
- [7] R. Adams et al. Appl. Phys. 39 (1968) 5173.
- [8] W.Bauer et al., Phys. Rev. Lett. 69 (1992) 1888.
- [9] L.G.Moretto et al., Phys. Rev. Lett. 69 (1992) 1884.
- [10] S.R.Souza and C.Ngo, Phys. Rev. C48 (1993) R2555.
- [11] B.Borderie et al., Phys. Lett. B302 (1993) 15.
- [12] H.M.Xu et al., Phys. Rev. C49 (1994) R1778.
- [13] D.O.Handzy et al., Phys. Rev. C51 (1995) 2237.
- [14] L.Phair et al., Phys. Lett. 314 (1993) 271.
- [15] C.Y.Wong, Ann.Phys. (N.Y.) 77 (1973) 279.
- [16] N.T.B.Stone et al., Phys. Rev. Lett. 78 (1997) 2084.
- [17] T.Glasmacher et al., Phys. Lett. B314 (1993) 265.
- [18] A.Aiello et al., Nucl. Phys. A583 (1995) 461.
- [19] N.G.Nicolis (private communication).
- [20] W.Gawlikowicz, The software replica of the Chimera multidetector, (<http://zefr.if.uj.edu.pl/catania>).

Improved measurement of cross-section and astrophysical factor of the $d(d,p)t$ reaction using the Trojan Horse Method

A. Rinollo^{a,b,*}, C. Bonomo^{a,b}, S. Romano^{a,b}, C. Spitaleri^{a,b}, S. Cherubini^{a,c}, A. Del Zoppo^a, P. Figuera^a, M. Gulino^{a,b},
M. La Cognata^{a,b}, L. Lamia^{a,b}, A. Musumarra^{a,b}, L. Pappalardo^a, M. G. Pellegriti^{a,b}, R. G. Pizzone^a, S. Tudisco^{a,b},
A. Tumino^{a,b}

a) INFN Laboratori Nazionali del Sud, Catania, Italy

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

c) Ruhr Universität Bochum, Bochum, Germany

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

Abstract

Reactions involving deuterium are of great importance in understanding stellar and primordial nucleosynthesis processes, and also in planning fusion reactors for energy production. We had already studied (see LNS Activity Report 2002) the $d(d,p)t$ reaction in the energy range from 1.4 MeV down to astrophysical energies by means of the Trojan-horse method applied to the three-body ${}^6\text{Li}(d,pt)a.$ reaction. In order to improve statistics and reduce the errors, the same experiment has been repeated. Protons and tritons have been detected in coincidence and identified, and the quasi-free events have been kinematically selected, in order to extract the cross-section and the astrophysical factor, and compare them with the values measured for the direct $d(d,p)t$ process.

1 INTRODUCTION

The d-d reactions have great relevance in nuclear astrophysics, being some of the thermonuclear processes which occurred during the first minutes of existence of the universe, immediately after the big bang. In particular, knowledge and modelling of the primordial abundance of deuterium, which is possible only having precise cross-section data at low energies, give important information about the baryon density of the universe and its geometry.

In order to overcome the problems (low rate, high background, presence of electron screening effects) connected with the cross-section measurements at low energies, which are suppressed by the Coulomb barrier, in recent years different indirect methods have been developed.

Among them, the Trojan-horse method (THM) has been successfully applied to study several astrophysically relevant two-body reactions by using appropriate three-body break-up reactions [2-5]. The method has proved to be particularly suitable for acquiring information on charged-particle induced cross-sections at astrophysical energies, since it allows to overcome the Coulomb barrier of the two-body entrance channel, and yields the bare-nucleus cross section without correction for electron screening effects.

Briefly describing the method, a projectile a strikes a target nucleus A , whose wave function has a large amplitude for a s - b cluster configuration. Under

appropriate kinematical conditions, the particle a interacts only with the cluster b of the target nucleus A , while s behaves as a spectator to the process

$$a+b(+s) \rightarrow c+d(+s)$$

In order to completely determine the kinematical properties of the spectator s , the other two particles must be detected and identified and their energies and angles measured. Since the bombarding energy is chosen to be above the Coulomb barrier in the incident channel for the $a+A \rightarrow c+d+s$ process, the particle b can be brought into the nuclear interaction region to induce the $a+b \rightarrow c+d$ reaction. Moreover, if the beam energy is settled on to be compensated for the $b+s$ binding energy and for the Fermi motion of b inside A , the two-body reaction can take place at very low a - b relative energy, e.g. in the region of astrophysical relevance.

To extract the two-body cross-section from the three-body data, different theoretical approaches have been developed (PWIA, DWIA, DWBA) [1,10]. In this work we used the simplest one (PWIA) [1]. Independently of the approach used, the deduced reaction cross-section $s^N(E)$ represents the nuclear part alone, the Coulomb barrier being already overcome in the entrance channel. In order to compare the two sets of data it is necessary to correct the $s^N(E)$ for the penetration probability function through the Coulomb barrier. Thus its energy dependence should be identical to that derived by the direct measurements, except at low energies where their behaviour should differ due to the effects of the electron

screening on the direct cross-section. The absolute scale for the cross-section is obtained by normalization to the direct data at energies where the effects of the electron screening on the direct data are still negligible. These considerations are of course valid also for the corresponding S-factors. Then, going at low energy, the THM allows to obtain an estimate of the screening potential U_e , by comparing the behaviour of the bare nucleus S-factor with the direct “screened” one.

2 THE EXPERIMENT

We have performed the $d+d \rightarrow p+t$ reaction applying the THM to the three-body ${}^6\text{Li}+d \rightarrow p+t+a$ break-up reaction (Fig.1).

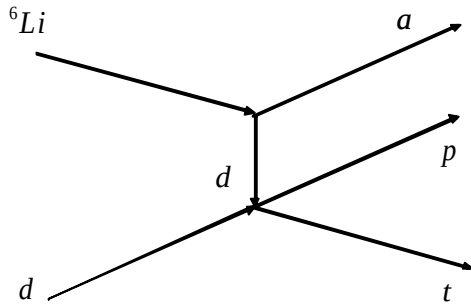


Fig.1: Pseudo-Feynman diagram of the break-up process

The ${}^6\text{Li}(d,pt)a$ experiment had been carried out for the first time at the Dynamitron-Tandem Laboratorium in Bochum (see LNS Activity Report 2002). Then, in order to obtain more precise results and improve statistics, we decided to perform this reaction once again.

The new experimental setup (scheme in Fig.2) was assembled into the “Camera 2000” scattering chamber at LNS. A $201 \mu\text{g}/\text{cm}^2$ CD_2 target was bombarded with a 14 MeV ${}^6\text{Li}$ beam, provided by LNS Tandem Van de Graaff accelerator, with a spot size on target of about 1 mm diameter. To detect the reaction products, we assembled four π E-E telescopes with 20 μm silicon detectors as π E- and 1000 μm Position Sensitive Detectors (PSD) as E-detectors. Two of the telescopes, identified by the letters A and B in the following, were put on the left side of the scattering chamber, with respect of the beam direction, covering laboratory-frame angles from 18° to 28° (telescope B) and from 43° to 53° (telescope A). The remaining two telescopes have been placed on the right side of the scattering chamber, covering laboratory-frame angles from 43° to 53° (telescope C, symmetric to A) and from 106° to 116° (telescope D, backwards).

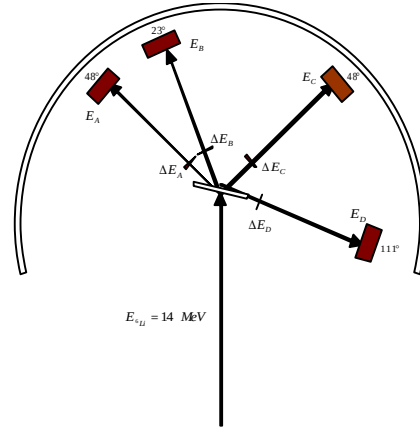


Fig.2: Scheme of the experimental setup.

These angular coverages were chosen in order to meet the quasi-free break-up conditions ($p_a=0$), which can be fulfilled in three different coincidence measurements:

1. Proton identified in A in coincidence with tritium in C;
2. Proton identified in C in coincidence with tritium in A;
3. Proton identified in D in coincidence with tritium in B.

When one of these three couples was fired in coincidence, then the system generated the trigger for the event acquisition. Energy and position signals for the detected particles were processed by standard electronics together with the delay between the time signals for each coincident event, and sent to the acquisition system for on-line monitoring of the experiment and data storage on magnetic tapes for the off-line analysis.

3 DATA ANALYSIS

The energy and position calibration of the π E-detectors and PSD's was performed using data acquired in preliminary runs of ${}^6\text{Li}({}^{197}\text{Au}, {}^{197}\text{Au}){}^6\text{Li}$, ${}^6\text{Li}({}^{12}\text{C}, {}^{12}\text{C}){}^6\text{Li}$ scattering and ${}^6\text{Li}({}^{12}\text{C}, {}^{14}\text{N})a$ reaction, also at 14 MeV. In order to perform the position calibration, a grid was mounted on each PSD throughout this preliminary phase.

Particle identification has been obtained by selecting the p and t loci in the π E-E matrices of the three telescopes.

The kinematics were reconstructed under the assumption of an a as third particle.

The Q-value spectrum obtained for the three-body reaction, correctly peaked on the theoretical value of 2.558 MeV, is plotted in Fig. 3.

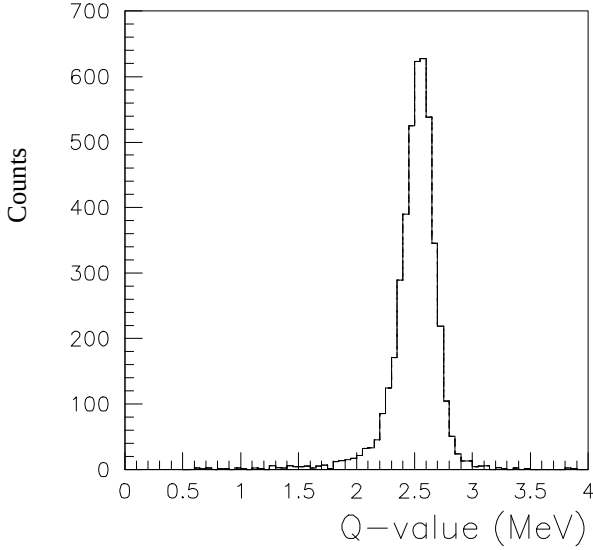


Fig.3: Q-value spectrum for the 3-body process. The theoretical value is 2.558 MeV.

The quasi-free events are selected by means of a cut in the spectator impulse, retaining the events with $-30 < p_a < 30$ MeV/c.

These events populate a region of p-t relative energy ranging from 75 KeV to 1.5 MeV, but we considered only events up to 1 MeV, because at higher energies an undesired background coming from a sequential process would affect the data.

Then the two-body cross-section has been extracted, following the PWIA approach: the coincidence yield, reported as a function of the p-t relative energy, was divided by a relative kinematical factor, obtained from a Monte Carlo simulation, and then corrected for the Coulomb barrier penetration probability factor, calculated from theory assuming a cut-off radius of 2 fm for the deuteron and a maximum value of relative angular momentum quantum number $l_{\max}=0$.

In this way, a relative value of the cross-section and then for the astrophysical factor $S(E)$ for the $d(d,p)t$ reaction has been obtained. This has later been normalized to the data taken in direct reaction measurements [6-9] and compared with them. The preliminary results are shown in Fig. 4. The data referred to all the three coincidences are here averaged together with the data from the former experiment performed in Bochum.

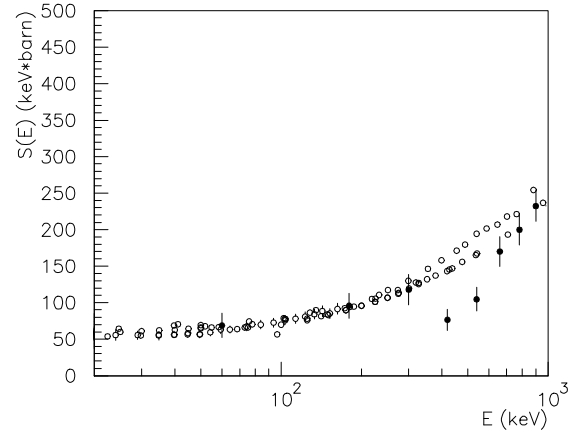


Fig. 4: The $S(E)$ factor obtained from our measurements (dots) compared with the data from direct reaction measurements (open circles).

ACKNOWLEDGEMENTS

The authors thank prof. M. Lattuada for his helpful collaboration.

4 REFERENCES

- [1] M. Jain et al., Nuclear Physics A153(1970)49.
- [2] C. Spitaleri et al., Phys. Rev. C60(1999)055802.
- [3] C. Spitaleri et al., Eur. Phys. J. A7(2000)181.
- [4] C. Spitaleri et al., Phys. Rev. C63(2001)055801.
- [5] M. Lattuada et al., Ap. J. 562(2001)1076.
- [6] R. L. Schulte et al., Nucl. Phys. A192(1972)609.
- [7] A. Krauss et al., Nucl. Phys. A465(1987)150.
- [8] R. E. Brown et al., Phys. Rev. C41(1990)1391.
- [9] U. Greife et al., Z. Phys. A351(1995)107.
- [10] S. Typel and G. Baur, Annals of Physics 305(2003)228.

DISAPPEARANCE OF COLLECTIVE MOTION IN HOT NUCLEI

D.Santonocito^{a,*}, Y.Blumenfeld^{b)}, P.Piattelli^{a)}, F.Delaunay^{b)}, N.Frascaria^{b)}, V.Lima^{b)}, J.Scarpaci^{b)}, C.Agodi^{a)}, R.Alba^{a)}, G.Bellia^{a,c)}, R.Coniglione^{a)}, A.Del Zoppo^{a)}, P.Finocchiaro^{a)}, F. Hongmei^{a)}, C.Maiolino^{a)}, E.Migneco^{a,c)*}, P.Sapienza^{a)}

a) INFN-LNS, Laboratori Nazionali del Sud, Catania, Italy

b) Institut de Physique Nucleaire, IN2P3-CNRS, F-91406, Orsay, France

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

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

Abstract

The evolution of the GDR γ yield for excitation energies between 160 and 300 MeV has been investigated in nuclei of mass $A \approx 126$ through the reactions $^{116}\text{Sn} + ^{12}\text{C}$ and ^{24}Mg at 17 and 23A MeV. Gamma-rays were detected with MEDEA array in coincidence with residues detected in MACISTE. The evolution of the GDR parameters has been investigated as a function of the linear momentum transferred to the fused system. This procedure allowed us to select hot nuclei produced in incomplete fusion reactions with different excitation energies. The analysis of the γ spectra and their comparison with CASCADE calculations is presented. Results suggest a saturation of the GDR yield between 200 and 300 MeV excitation energy

1 Introduction

Intermediate energy heavy ion collisions are a powerful tool to produce and investigate hot nuclei. Over the last decades the experimental investigation was strongly focused on studies performed with the aim of understanding the behaviour of nuclear matter under extreme conditions of density, temperature and excitation energy. Most of the available data was gathered by measuring light charged particles and intermediate mass fragments. Valuable information can also be obtained through the study of γ -ray emission.

Photons are emitted throughout the collision with different times scales and therefore their investigation allows to probe the nucleus-nucleus collisions at intermediate energies from the first stages to the equilibration. Recently the measurement of high energy γ -rays has yielded information on the role of 2-body collisions in the dissipation mechanism [1,2] and the study of thermal photons in coincidence with IMF has shown evidences for an onset of prompt IMF emission [3]. The study of the evolution of the Giant Dipole Resonance (GDR) properties in hot nuclei as a function of excitation energy has allowed to gain a deeper comprehension on collective properties of nuclear matter at extreme conditions. The most complete systematics have been obtained on medium mass nuclei with spherical ground state. in the region $A \approx 115$ [4] The results have clarified many features of the evolution of the GDR parameters as a function of excitation energy. In particular, while the centroid energy remains constant with excitation energy to a value of about 15 MeV, the γ multiplicity was observed

to increase up to $E^* = 300$ MeV in agreement with the 100% of the sum rule strength. Above this value a saturation of the γ yield was observed.

This problem was addressed by studying the evolution of the GDR in hot nuclei formed in incomplete fusion reactions induced by a 27A and 37A MeV beams on a ^{90}Zr and ^{98}Mo target at excitation energies in the range 300-550 MeV [5,6]. Gamma-ray spectra, measured in coincidence with a heavy residue, were compared with statistical model (CASCADE) calculations. In both cases it was concluded that only the assumption of a cut-off in the gamma-ray emission above about 200-250 MeV excitation energy allowed to reproduce the data.

This important result leads to the conclusion that a temperature of about 5.5 MeV represents a limit for the existence of the dipole vibration for $A \approx 110$ nuclei [5,6]. This can be qualitatively understood assuming that above a certain excitation energy the equilibration time of the collective oscillations becomes longer than the particle emission time leading to a progressive suppression of the GDR gamma emission.

The mechanism that suppresses the collective motion at high excitation energies is yet unclear. However, sizeable differences in the cut-off energy were observed between the 27A MeV and the 37A MeV data although nuclei in the same excitation energy region and with similar masses were populated in the two reactions. This suggests that dynamical effects could play a role in the hindrance of the collective motion [7].

Although these data give valuable information on the behaviour of the GDR at high excitation energies, they were all collected in an excitation energy region higher than the one where the saturation of the yield sets in. Therefore, the existence of a limiting excitation energy

for the GDR could only be inferred indirectly through statistical model simulations, in which a sharp cut-off for gamma emission was introduced.

The existence of a progressive quenching of the GDR yield is predicted by different models which show different energy dependences. The amount of reduction is therefore model dependent and it strongly affects the resulting GDR yield in a region between 150 and 300 excitation energy. If the parameter governing the GDR quenching is the excitation energy per nucleon of the composite system, in the case of $A \approx 110$ nuclei where a cut-off energy of $E \approx 250$ MeV was estimated, a value of $E^*/A \approx 2.2$ MeV can be deduced.

In order to map precisely the excitation energy dependence of the GDR disappearance we have chosen to investigate a region of excitation energies $1.3 < E/A < 2.5$ MeV. We have performed an experiment where hot nuclei in a mass region of $A \approx 125-135$ were populated in an excitation energy region between 160 and 300 MeV.

2 Experimental Method

The experiment was carried out at the Laboratori Nazionali del Sud - Catania using ^{116}Sn beams of 17A and 23A MeV, with an average intensity of 1.5 nA, impinging on $1\text{mg}/\text{cm}^2$ thick ^{12}C and ^{24}Mg targets. Light charged particles and gamma rays were detected using the MEDEA multidetector [8] which consists of a ball of 180 BaF_2 scintillators 20 cm thick covering polar angles from 30° to 170° . Fusion-like residues populated in the reactions and emitted at polar angle up to 3 degrees were focused by the magnetic field of superconducting solenoid SOLE on the focal plane detector MACISTE [9] placed 16 m from the target. Inverse kinematics reactions favoured the emission of a large fraction of outgoing residues inside the solenoid angular acceptance.

MACISTE consists of four telescopes, each with a useful area of $30 \times 40 \text{ cm}^2$ arranged on a $70 \times 70 \text{ cm}^2$ surface leaving a variable central hole for the beam transit. Each telescope consists, in turn, of a drift chamber used for the energy loss measurements, a wire chamber for the impact position and time of flight determination and, for the energy measurements, a 2 cm thick plastic scintillator coupled to a photomultiplier through a suitable light guide.

Particle and γ -rays identification in BaF_2 was performed using the combined information of time of flight and pulse shape analysis of the photomultiplier analog signal.

Residues were selected using their time of flight, measured with respect to the cyclotron RF. The trigger condition of the experiment was given by the coincidence between one of the MACISTE telescopes and at least one MEDEA detector.

Fusion-like events detected in the MACISTE wire chambers showed a distribution in time of flight whose width reflects the different linear momentum transfers in the reaction at a single bombarding energy. In particular, in the case of ^{24}Mg target a broader width is observed compared to ^{12}C one (see fig.1) reflecting the size of the distribution of nucleons participating to the incomplete fusion reaction which makes available a larger number of linear momentum transfer combinations. However, the use of very asymmetric reactions constrains the residues distribution favouring, at these bombarding energies, complete or close to complete fusion reactions. In the analysis events were sorted according to their time of flight and the evolution of the properties of gamma emission was investigated as a function of excitation energy. Events belonging to velocity windows corresponding to a region of $\pm 3\%$ of V_{CM} were selected for the three reactions (filled areas in fig.1) and the massive transfer

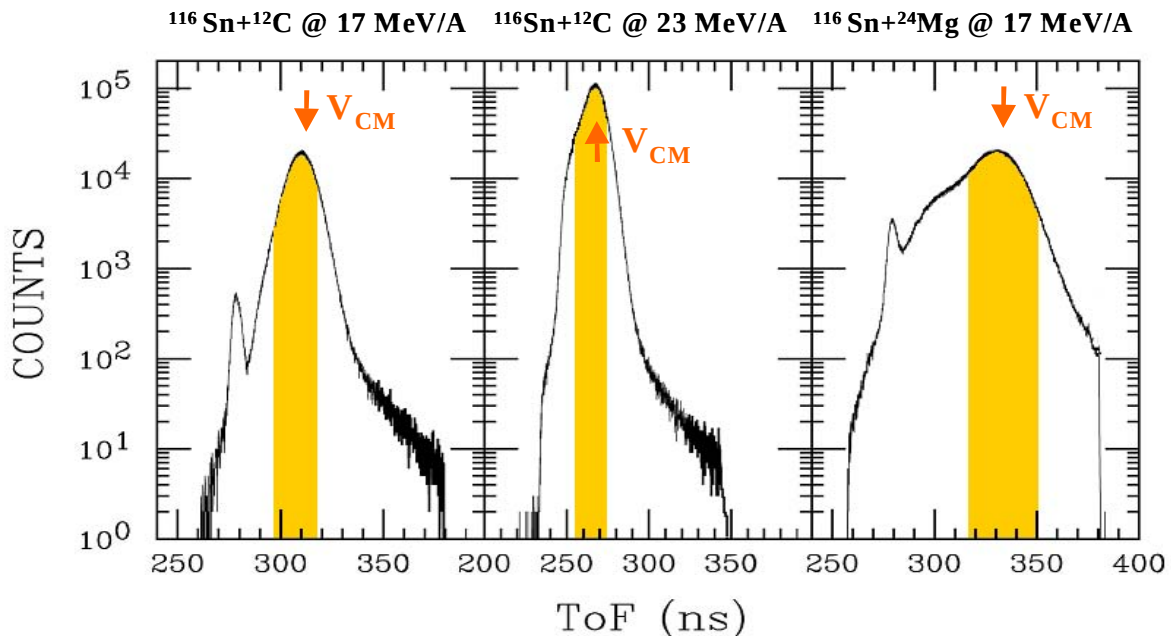


Fig.1: Velocity distributions of the residues detected in MACISTE for the three reaction studied. Filled areas correspond to the velocity regions used in the analysis.

model was applied to estimate the average excitation energy and masses from residue velocities (see tab.1).

Table 1

reactions	E_{beam}	E^* (MeV)	A	E^*/A (MeV)
$^{116}\text{Sn}+^{12}\text{C}$	17 MeV/A	160	126	1.27
$^{116}\text{Sn}+^{12}\text{C}$	23 MeV/A	200	126	1.59
$^{116}\text{Sn}+^{24}\text{Mg}$	17 MeV/A	300	136	2.20

This approach has been shown helpful in the determination of the excitation energy reached in incomplete fusion reactions which represents a fundamental issue when such a study is undertaken.

3 Data Analysis

The γ spectra measured at 90° in coincidence with fusion events were extracted for all the reactions. They show similar features: a pronounced bump around 15 MeV corresponding to the decay of the GDR and, above 35 MeV, an exponentially decreasing component due to the bremsstrahlung radiation arising from the np collisions in the first, not equilibrated, stages of the reaction (fig.2). The high energy part of the spectra was reproduced by an exponential function, fitted to the spectrum for energies above 35 MeV. The slope

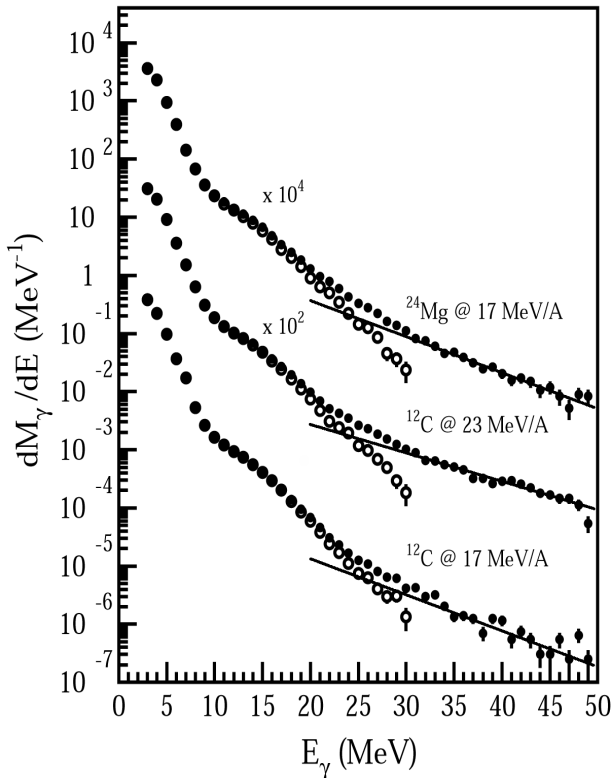


Fig.2: Normalized γ -spectra measured at 90° for the three reactions (full symbols). Open symbols represent the spectra subtracted from the bremsstrahlung contribution shown as full line.

parameter extracted from the fits are equal to 7.5 ± 0.8

and 8.8 ± 0.9 MeV for reactions at 17A and 23A MeV respectively, exhibiting a beam energy dependence in agreement with the systematics for nucleon-nucleon bremsstrahlung [10]. Besides in the case of the two reactions at 17 MeV/A the high energy gamma yield was observed to scale with the size of the target in agreement with the systematics [10].

The statistical gamma spectra obtained by subtraction of the bremsstrahlung component extrapolated down to low energies are shown in fig.2 as open symbols.

In order to investigate the evolution of the properties of the GDR as a function of the excitation energy we reproduced the gamma spectra using the statistical decay code CASCADE [11] which treats the statistical emission of γ -rays, neutrons, protons and alpha particles from an equilibrated compound nucleus with a given excitation energy and spin. In the calculation a Lorentzian line shape was assumed for the GDR with a mass dependent centroid energy given by $E_{\text{GDR}} = 76.5 A^{-1/3}$ and a width $\Gamma = 12$ MeV. As input to the calculation the initial excitation energies and masses inferred from the massive transfer approach were used.

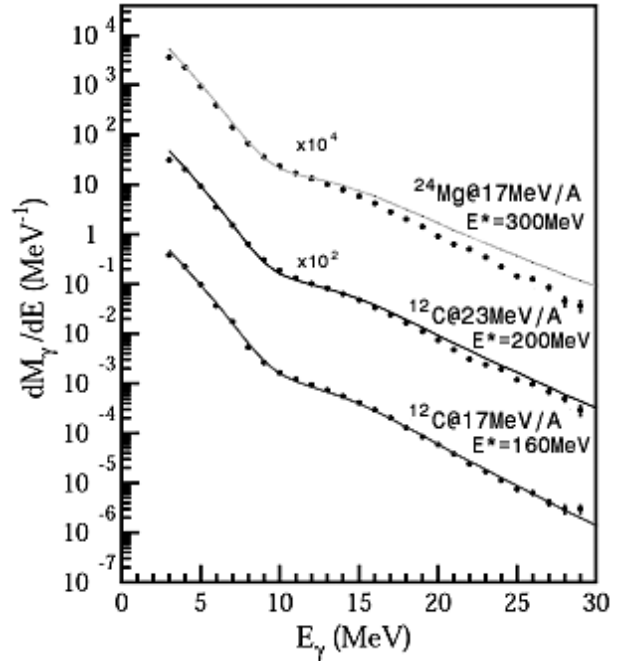


Fig.3: Bremsstrahlung subtracted gamma spectra measured for the three reactions. Full lines represent the results of CASCADE calculation at 160 MeV (lower), 200 MeV (middle), and 300 MeV (higher).

According to this assumptions the data of the reactions on ^{12}C target at 17A and 23A MeV were reproduced assuming a mass $A = 126$ and average excitation energies $E^* = 160$ and 200 MeV respectively while data on ^{24}Mg target were reproduced assuming $A = 136$ and $E^* = 300$ MeV. Preliminary results shown as full lines in fig.3 indicate a remarkable reproduction of the data at 160 and 200 MeV excitation energy over the all energy range examined while data at 300 MeV

excitation energy are not reproduced by CASCADE calculation whose prediction overshoots the data in the GDR region (fig.3).

The evolution of the GDR properties can also be studied extracting the gamma multiplicity in the GDR region for the different reactions. Gamma spectra, after bremsstrahlung subtraction, were integrated in a region between 12 and 20 MeV where the bulk of the yield is concentrated for the nuclei in this mass region. The extracted yields for the three reactions are $(3.3 \pm 3) \times 10^{-3}$, $(3.9 \pm 3) \times 10^{-3}$ and $(4.8 \pm 3) \times 10^{-3}$ respectively. The quoted errors include both statistical errors, an estimated error on the bremsstrahlung subtraction and a contribution related to uncertainties in the normalization. The comparison with CASCADE calculation integrated in the same energy region indicates a saturation of the gamma yield which seems to set in around 2 MeV/A excitation energy.

4 Conclusions

In this experiment the evolution of the GDR properties was investigated through the study of three different reactions. A selection of fusion events in terms recoil velocity was applied and the coincident gamma spectra were analysed. The gamma multiplicity was found to increase as a function of excitation energy. The comparison of the gamma spectra with CASCADE calculations suggests the rise of a saturation of the

gamma yield at about 2 MeV/A excitation energy. Some more refined calculation are needed to draw more definitive conclusions on the quenching of the GDR as a function of the excitation energy

References

- [1] P.Piattelli et al., Phys. Lett. B 442 (1998) 48
- [2] J.H.G.van Pol et al, Phys. Rev. Lett. 76 (1996) 1425
- [3] R.Alba et al., Nucl. Phys. A681 (2001) 339c
- [4] J.J.Gaardhøje et al, Ann. Rev. Nucl. Part. Sci. 42 (1992) 483
- [5] T.Suomijärvi et al. Phys. Rev. C53 (1996) 2258
- [6] J.B.Natowitz et al., Phys. Rev. C65 (2002) 034618
- [7] P.Piattelli et al. Nucl. Phys. A649 (1999) 181c
- [8] E.Migneco et al., NIM A 314 (1992) 31
- [9] G.Bellia et al., IEEE 43 (1996) 1737
- [10] H.Nifenecker and J.A.Pinston, Annu. Rev. Nucl. Part. Sci. 40 (1990) 113
- [11] F.Puhlhofer, Nucl. Phys. A280 (1977) 267

QUASI-FREE REACTION AROUND THE COULOMB BARRIER

S.Tudisco^{a,b,*}, C.Spitaleri^{a,b}, S.Blagus^c, D.Miljanic^c, M.Milin^c, A.Musumarra^{a,b}, M.G.Pellegriti^{a,b}, R.G.Pizzone^{a,b}, S.Romano^{a,b}, N.Soic^c, A.Tumino^{a,b}

a) INFN Laboratori Nazionali del Sud, Catania, Italy

b) Dipartimento di Metodologie Fisiche Chimiche per Ingegneria,
Univerisità di Catania, Catania, Italy

c) Institute Ruder Bokovic, Zagreb, Croatia

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

The ${}^6\text{Li} + {}^6\text{Li} \rightarrow 3\alpha$ reaction has been studied at 2.1 and 2.7 MeV incident beam energy; quasi-free reaction mechanisms with an α -particle spectator in target, in the projectile and in the CM-system were investigated. Momentum distribution and angular correlation are derived.

1 INTRODUCTION

Since a long time a different indirect approach based on the quasi-free reaction mechanism has been suggested for study nuclear reactions of astrophysical interest [1]. In order to establish the validity conditions of such approaches it is important to study quasi-free reaction mechanism under extreme condition.

In this work the ${}^6\text{Li} + {}^6\text{Li} \rightarrow 3\alpha$ reaction has been experimentally investigated around the Coulomb barrier. Direct processes due to quasi-free (QF) mechanism, in which an α -cluster (spectator of the ${}^6\text{Li}(d,\alpha){}^4\text{He}$ virtual reaction) either in the target or in the projectile have been observed. Moreover at these energies α - α coincidence measurements show a large peak where both ${}^6\text{Li}$ nuclei share one deuteron to make a third α particle.

2 BASIC FEATURES OF THE QUASI-FREE MECHANISM

The basic idea consists of the assumption that the quasi-free reaction mechanism is dominant at some particular kinematical conditions. At this conditions the target nucleus ${}^6\text{Li}$ is assumed to break-up in to the cluster α and d ; α is then considered to be a spectator to the ${}^6\text{Li}(d,\alpha){}^4\text{He}$ virtual reaction that proceeds within the region of the nuclear interaction. This description allows direct comparison of the triple differential cross section $d^3\sigma/(dE_1 d\Omega_1 d\Omega_2)$ of the ${}^6\text{Li}({}^6\text{Li}, 2\alpha){}^4\text{He}$ reaction with the cross section for the ${}^6\text{Li}(d,\alpha){}^4\text{He}$ nuclear process. By using the DWIA [2] we can express the triple-differential cross section, measured in a coincidence experiment, through the nuclear part of the two-body reaction cross section $d\sigma^n/d\Omega$ as:

$$\frac{d^3\sigma}{dE_1 d\Omega_1 d\Omega_2} = \text{KF} |\Theta(p_s)|^2 \frac{d^n\sigma}{d\Omega} \quad (1)$$

where KF is a Kinematical factor. The spectator momentum distribution, $|\Theta(p_s)|^2$ is related to the relative cluster motion inside the ${}^6\text{Li}$ nucleus.

3 EXPERIMENT

The experiment was performed at the 5MV Van de Graaf Tandem of the Rudjer Boskovic Institute of Zagreb (Croatia). A ${}^6\text{Li}$ beam with energy of 3.1 and 2.5 MeV was delivered on an isotopically enriched thin target of ${}^6\text{LiF}$. The outgoing α particles were detected in coincidence by means of four silicon position-sensitive detectors (PSD) placed at different angles (as reported in figure 1) in order to cover a region in which projectile and target break-up contributions were expected. Energy calibration was performed using the several peaks coming from an 8 MeV ${}^6\text{Li}$ beam sent on gold and CD2 targets; the obtained resolution was a few tens of keV; angular calibration of PSD's was performed using grids with several equally spaced vertical slits. The final resolution was 0.2° .

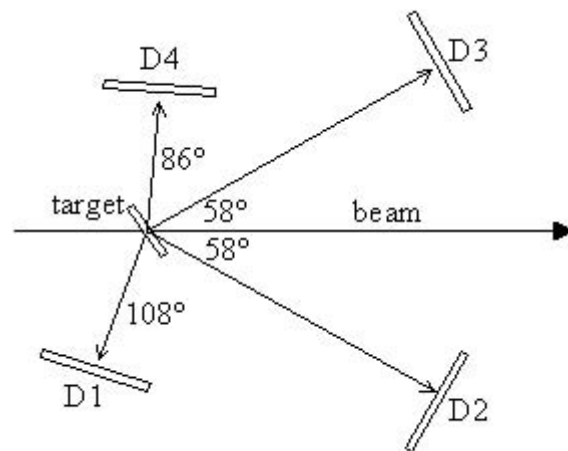


Figure 1. Experimental Set-Up

The final experimental set-up is able to cover an angular range of $58^\circ \pm 5^\circ$ for the detector D2-D3, $108^\circ \pm 12^\circ$ for the D1 and $86^\circ \pm 12^\circ$ for the D4.

To estimate the real incident energies and the ejectiles one, energy-loss correction were taken into account according to the measured target thickness.

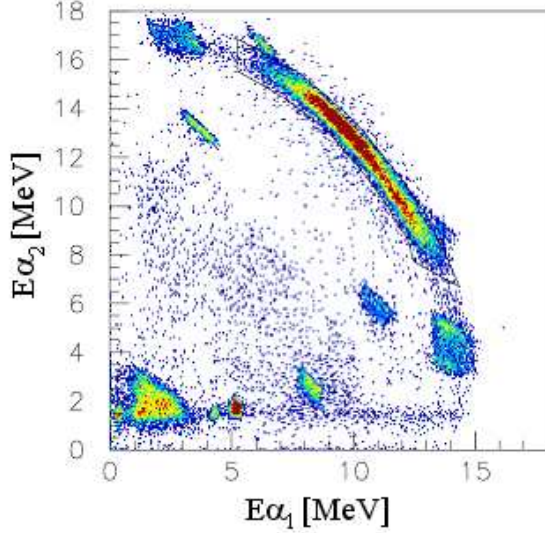


Figure 2. kinematical locus of the ${}^6\text{Li} + {}^6\text{Li} \rightarrow 3\alpha$

4 DATA ANALYSIS AND RESULTS

Energy and position signals, together with the time difference signal, were stored event by event on computer hard-disk for a subsequent off-line analysis. No particle identification technique was used during the experiment, since the high Q-value (20.9 MeV) of the reaction allows the α - α coincidence events to be easily identified. The rate of random coincidence after the off-line selection was found to be always of a few percent. In figure 2 we plot the kinematical locus of the ${}^6\text{Li} + {}^6\text{Li} \rightarrow 3\alpha$ reaction together with the appropriate graphical cut. The picture shows how this locus can be easily discriminated from other reaction channels.

In order to check the presence and correct energy and angular position of the QF contribution, one-dimensional spectra have been created by plotting data versus $E\alpha_1(E\alpha_2)$ for a given angle $\theta_1(\theta_2)$ and for different angles of the second detector, in step of $\Delta\theta = 1^\circ$ over the full angular range. In order to further verify the nature of the peaks, projections have been performed on the variables $E_{\alpha i \alpha j}$ (relative energy between any two particles) to investigate the presence of possible contribution from the formation and decay of ${}^8\text{Be}$. Such analysis confirms that in these selected energy and angular ranges ${}^6\text{Li}({}^6\text{Li}, 2\alpha){}^4\text{He}$ proceeds through the QF mechanism. Momentum distribution of the α -cluster in ${}^6\text{Li}$ can be extracted, in the framework of the plane wave impulse approximation, using the same procedure previously mentioned.

According to (1) the values of $d^3\sigma/KF$ were extracted from the experimental data and reported in figure 3 as a function of spectator momentum. The two-body cross section was taken as a constant.

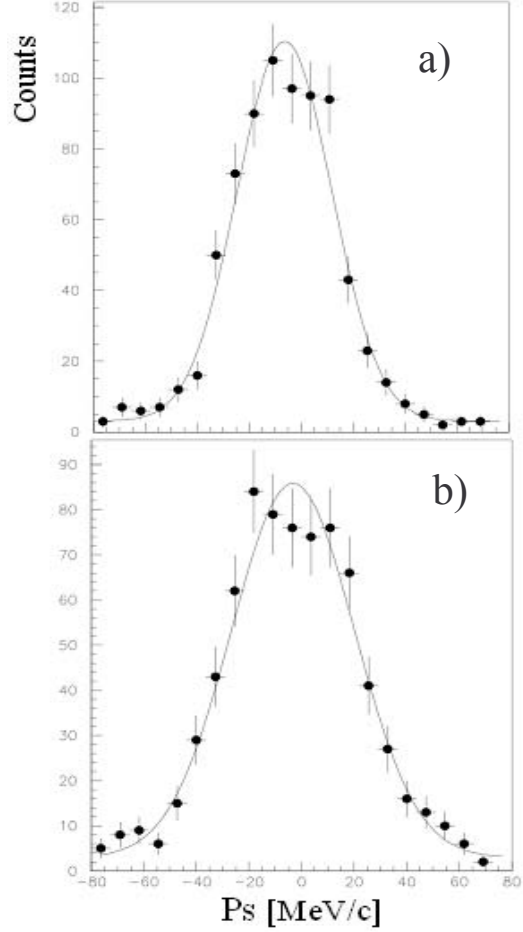


Figure 3. Momentum distribution for the α inside ${}^6\text{Li}$ a) projectile b) target, at 2.7 MeV of incident energy.

In the figure 3 and 4 the momentum distribution derived from the experimental data at the two energies (2.1 and 2.7 MeV) for α inside ${}^6\text{Li}$ are reported. In order to extract the FWHM, Gaussian fit has been performed. The results are summarized in table 1.

Table 1: FWHM of momentum distribution in target and projectile for different beam energy.

E_b MeV	FWHM _T MeV/c	FWHM _p MeV/c
2.1	42 ± 4	49 ± 4
2.7	43 ± 4	53 ± 4

These results agree quite well with previous ones reported in literature [3-4-5].

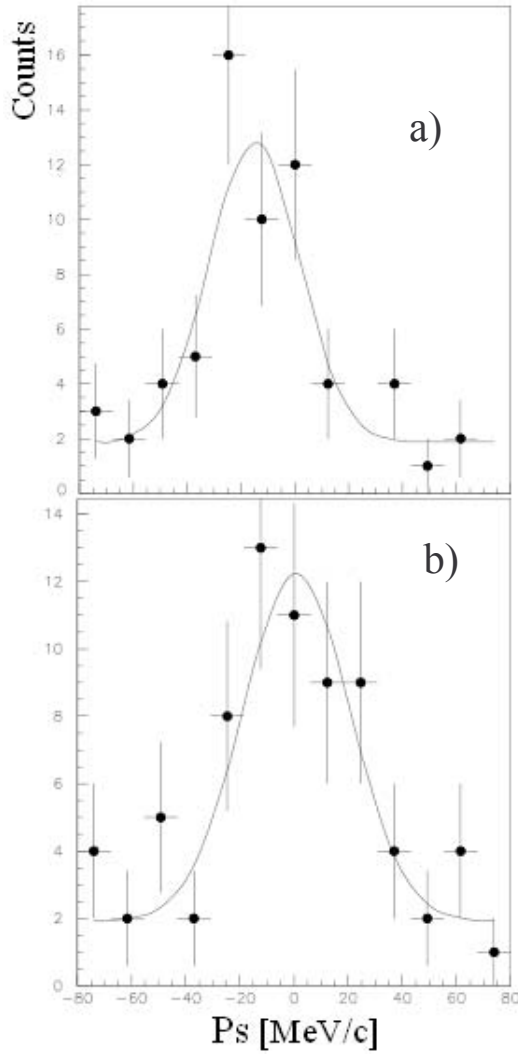


Figure 4. Momentum distribution for the α inside ${}^6\text{Li}$ a) projectile b) target, at 2.1 MeV of incident energy.

5 ANGULAR CORRELATION

To follow the angular and energy behavior of the cross section corresponding to the three processes, the angular correlations were extracted from data at 2.7 MeV, according to the following procedure. The differential cross section was averaged over a 1 MeV wide $E\alpha_1$ energy bin. The centroid of this bin was selected for each spectrum by imposing that the momentum of the undetected particle be parallel to the beam momentum. This allows the crossing of all three kinematical regions corresponding to the three processes, since whenever the spectator momentum is zero (either in the target, in the projectile or in the CM-system).

The results are shown in figure 5 where the two peaks corresponding to the QF contribution in the target

(around 80°) and projectile (around 105°) are clearly visible. A large bump corresponding kinematically to the QF process with the α -particle spectator in the CM-system, is seen where the other two contributions almost disappear.

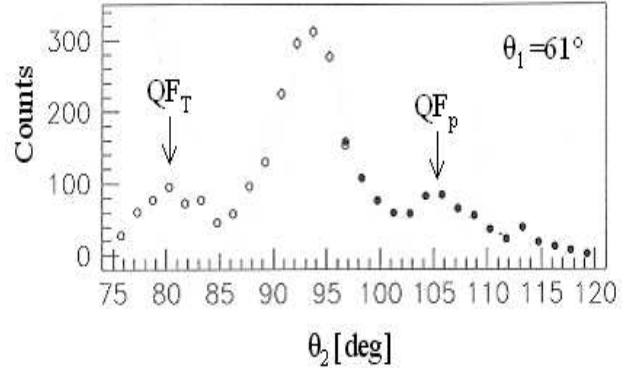


Figure 5. Angular correlation at 2.7 MeV.

6 CONCLUSION

The ${}^6\text{Li} + {}^6\text{Li} \rightarrow 3\alpha$ reaction was studied in a kinematically complete experiment at two different incident energies below the Coulomb barrier. At these energies quasi-free processes where an α -particle acts as a spectator either in the target or in the projectile has been observed. On the other hand appears a third appears which is a consequence of a direct process which leaves an α -particle at rest in the CM-system.

7 ACKNOWLEDGMENT

The authors would like to thank Prof. M. Lattuada for his helpful collaboration during the course of the experiment.

7 REFERENCES

- [1] Phys. Lett. B 178 (1986) 135
- [2] S. Cherubini et al. APJ 457 (1996) 855.
- [3] S. Barbarino et al. Phys. Rev C 21 (1980) 1104.
- [4] M. Lattuada et al. Z. Phys A 330 (1988) 183
- [5] C. Spitaleri et al. Phys. Rev C 63 055801

QUASI-FREE ${}^6\text{Li}(n,\alpha){}^3\text{H}$ REACTION AT LOW ENERGY FROM ${}^2\text{H}$ BREAK-UP

A. Tumino^{a,b)*}, C. Spitaleri^{a,b)}, C. Bonomo^{a,b)}, S. Cherubini^{c)}, P. Figuera^{b)}, M. Gulino^{a,b)}, M. La Cognata^{a,b)}, L. Lamia^{a,b)}, A. Musumarra^{a,b)}, M.G. Pellegriti^{a,b)}, R.G. Pizzone^{a,b)}, A. Rinollo^{a,b)}, S. Romano^{a,b)}

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

b) INFN Laboratori Nazionali del Sud, Catania, Italy

c) Ruhr Universität, Bochum, Germany

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

Abstract

The ${}^6\text{Li}+d$ interaction was studied in order to investigate the quasi-free ${}^6\text{Li}(n,\alpha){}^3\text{H}$ reaction, off the proton in ${}^2\text{H}$. A kinematically complete experiment was performed at a beam energy of 14 MeV. Coincidence spectra show the contribution of the quasi-free $n+{}^6\text{Li}$ reaction in the relative energy range from 1.5 MeV down to zero. The extracted ${}^6\text{Li}(n,\alpha){}^3\text{H}$ quasi-free cross-section was compared with the behaviour of direct data throughout the investigated energy range. No penetrability corrections were introduced on the quasi-free data, being the ${}^6\text{Li}(n,\alpha){}^3\text{H}$ direct reaction free of Coulomb suppression.

1 INTRODUCTION

Quasi-free scattering and reactions have been extensively studied in the past in order to investigate the cluster structure of light nuclei [1-4]. A number of theoretical approaches based on the Impulse Approximation were developed [5,6], which describe a quasi free $A+a \rightarrow c+C+s$ reaction (a having a strong $x\oplus s$ cluster structure) by a Pseudo Feynman diagram where only the first term of the Feynman series is retained. A pole of the diagram describes the break-up of the target nucleus a into the clusters x and s , and the other one contains the information on the virtual $A+x \rightarrow c+C$ two-body process, which leaves the cluster s as spectator.

Recently the quasi-free mechanism was successfully applied in the framework of the known Trojan Horse Method [7-10] to the study of charged particle two-body reactions relevant for astrophysics. In particular the Trojan Horse Method selects the quasi-free contribution of an appropriate three-body reaction performed at energies well above the Coulomb barrier to extract the relevant two-body reaction cross-section at astrophysical energies free of Coulomb suppression as well as electron screening effects.

The present paper describes an original application of the quasi-free mechanism to the neutron capture ${}^6\text{Li}(n,\alpha){}^3\text{H}$ reaction. This contribution was selected from the ${}^6\text{Li}+d$ interaction leaving the proton as spectator to the reaction. Practical aspects of the ${}^6\text{Li}(n,\alpha){}^3\text{H}$ reaction have also recently stimulated many studies. This reaction, whose cross-section resonates near a neutron energy of 240 keV, can be used to

monitor reactor neutron spectra as well as for breeding tritium in fusion reactors. In the present case, its importance relies on the chance to investigate possible off-energy-shell effects on the quasi-free data in a situation where the Coulomb barrier is absent. This represents an important test for the Trojan Horse Method, also in view of further applications to key astrophysical reactions using deuterons as source of a neutron beam.

2 THE EXPERIMENT

The ${}^2\text{H}({}^6\text{Li},\alpha){}^3\text{H}$ experiment was performed at the Laboratori Nazionali del Sud in Catania. The SMP Tandem Van de Graaf accelerator provided a 14 MeV ${}^6\text{Li}$ beam with a spot size on target of 1.5 mm and intensities up to 2-3 pA, that was delivered onto a CD_2 target of about $150 \mu\text{g}/\text{cm}^2$.

Two silicon ΔE -E telescopes, consisting of 20 μm ΔE - and 1000 μm position sensitive E-detector, were placed on opposite sides with respect to the beam direction covering the laboratory angles 18° to 28° and 43° to 53° . The angular ranges were chosen in order to cover momentum values P_s of the undetected proton ranging from about -100 MeV/c to about 100 MeV/c when α and ${}^3\text{H}$ are detected within 18° - 28° and 43° - 53° respectively. This assures that the bulk of the quasi-free contributions for the break-up process of interest falls inside the investigated regions, allowing also to cross check the method outside the relevant phase-space regions. The trigger for the event acquisition was given by the coincidences between the two telescopes. Energy and positions signals for the detected particles

were processed by standard electronics together with the coincidence relative times.

3 DATA ANALYSIS AND RESULTS

The ${}^2\text{H}({}^6\text{Li}, \alpha {}^3\text{H})\text{p}$ experiment was performed at the Laboratori Nazionali del Sud in Catania

The energy and position calibration of the telescopes was performed using data acquired in preliminary runs of the ${}^{12}\text{C}({}^6\text{Li}, \alpha){}^{14}\text{N}$ reaction, where many α peaks corresponding to well known excited states of ${}^{14}\text{N}$ were identified. A standard three-peak α source was also used.

In order to identify the channel of interest and to choose the kinematical conditions where the quasi-free process is dominant, α and ${}^3\text{H}$ loci were selected in the ΔE -E two-dimensional plots. An example of the ΔE -E plot where ${}^3\text{H}$ ions were selected, is shown in fig. 1.

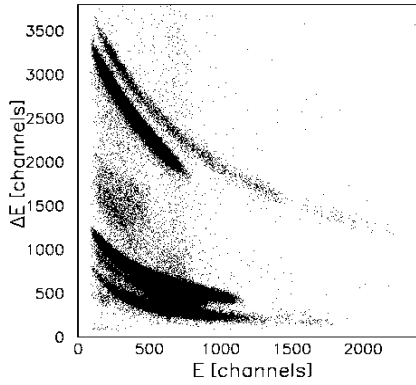


Fig.1: Example of ΔE -E plot referring to the telescope where the ${}^3\text{H}$ locus was selected

The kinematics were reconstructed under the assumption of a proton as third particle, leading to the Q-value spectrum shown in fig. 2. The spectrum shows a sharp peak between 2 and 3 MeV which corresponds to the channel of interest, i.e. $\alpha+{}^3\text{H}+\text{p}$, whose calculated Q-value is 2.59 MeV.

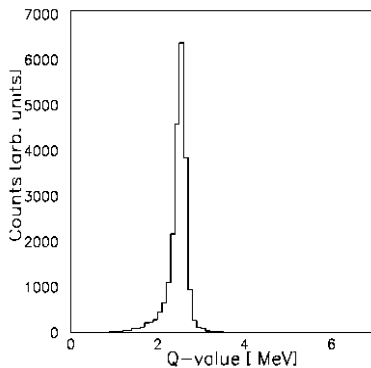
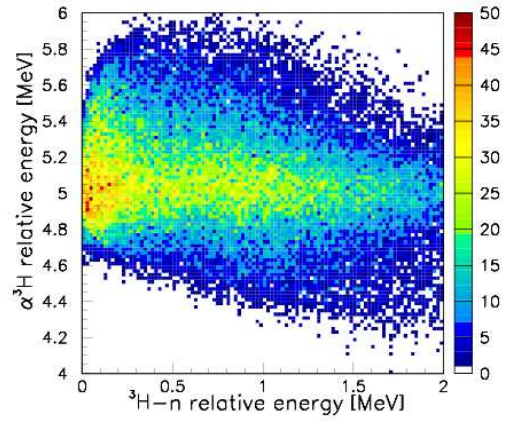


Fig.2: Q-value spectrum. The peak refers to the ${}^2\text{H}({}^6\text{Li}, \alpha){}^1\text{H}$ reaction of interest

The corresponding locus of events in the $E_{3\text{H}}$ vs. E_{α} plane reproduces very well the one calculated by using a three-body kinematical calculation. The resulting spectra make us confident on the quality of the performed calibration, and on the possibility to well identify the $\alpha+{}^3\text{H}+\text{n}$ channel. Sequential processes through the ground state of ${}^5\text{Li}$ or excited states ${}^4\text{He}$ or ${}^7\text{Li}$ can feed this channel. In order to evidence these possibilities, relative energies for any two of the three final particles were obtained. Coincidence events in the



α - ${}^3\text{H}$ vs. ${}^3\text{H}$ -p relative energy plane are shown in fig.3.

Fig.3: Coincidence events in the α - ${}^3\text{H}$ vs. ${}^3\text{H}$ -p relative energy plane

In this representation a very clear horizontal locus shows up, corresponding to the $5/2^-$ excited level at 7.45 MeV of ${}^7\text{Li}$.

Neither vertical nor diagonal loci associated to the excitation of ${}^4\text{He}$ and ${}^5\text{Li}$ respectively, seem to be present. The ${}^7\text{Li}$ excited state can be populated via quasi-free mechanism or via sequential decay.

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

The experimental momentum distribution was reconstructed by applying the energy sharing method [11] to our coincidence data selecting ${}^6\text{Li}$ -n relative energy windows of 100 keV. The ${}^6\text{Li}$ -n relative energy was calculated in post collision prescription in the standard way (for details see ref.[7-10]). The plane wave impulse approximation (PWIA) was employed, which factorizes the three-body cross-section into two

terms corresponding to the two poles mentioned in the introduction:

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

where $d\sigma/d\Omega$ is the off-shell differential cross-section for the two-body ${}^6\text{Li}(n,\alpha){}^3\text{H}$ reaction of interest, KF is a kinematical factor depending on masses, momenta and angles of the outgoing particles and containing the final phase-space factor [7-10], and $\Phi(\vec{p}_s)$ is the Fourier transform of the radial wave function for the p-n intercluster motion inside the deuteron, described in terms of a Hulthén function [10].

Dividing the three-body coincidence yield by the kinematical factor, we are left with a quantity proportional to the product of the momentum distribution with the differential ${}^6\text{Li}$ -n two-body cross-section. Since in the restricted relative energy ranges of 100 keV, the differential two-body cross-section can be considered constant, the quantity above reflects the behaviour of the experimental momentum distribution in arbitrary units. The result is reported in fig.4.

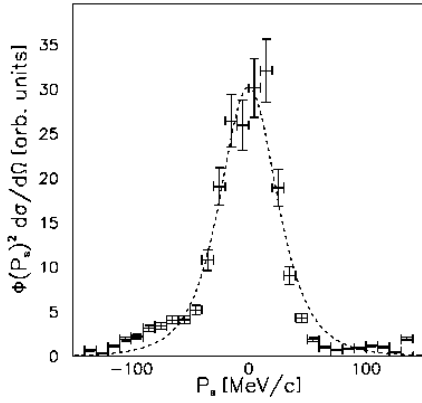


Fig.4: Experimental proton momentum distribution. The dashed line represents the shape of the theoretical Hulthén function in momentum space

The dashed line superimposed on the data gives the shape of the theoretical Hulthén function in momentum space, which is normalized to the experimental maximum. A quite good agreement shows up, making us confident that in the experimentally selected kinematical region, the quasi-free mechanism gives the main contribution to the ${}^6\text{Li}+d$ reaction and it can be selected without significant interference with contaminant sequential decay processes.

The further analysis was performed by considering coincidence events with a neutron momentum ranging

between -40 and 40 MeV/c. Following the PWIA approach the two-body cross-section was derived dividing the selected three-body coincidence yield by the result of a Monte Carlo calculation reproducing the

behaviour of the $KF|\Phi(\vec{p}_s)|^2$ product (see eq.(1)). The geometrical efficiency of the experimental setup as well as the detection thresholds were accounted for in the calculation. An error calculation for the ${}^6\text{Li}$ -n relative energy was also performed giving a value ranging from 80 to 120 keV, the minimum estimate corresponding to the phase space region where the lens effect is more efficient [12]. The extracted off-energy shell ${}^6\text{Li}$ -n two-body cross-section was then compared with direct data. In order to perform the comparison the two sets of data were integrated over the same $\theta_{\text{c.m.}}$ angular region, $\theta_{\text{c.m.}}$ being the emission angle for the outgoing α particle in the ${}^3\text{H}$ - α center-of-mass system [7-10]. The $\theta_{\text{c.m.}}$ covered in the present experiment was $40^\circ - 70^\circ$. Since the ${}^6\text{Li}$ -n direct data are not affected at low energy by Coulomb suppression, the comparison with our indirect cross-section can be performed throughout the investigated energy range without any further correction. The comparison is shown in fig. 5, where full dots represent our data while open triangles are direct data from ref. [13], both sets averaged out at the same energy bin of 120 keV comparable with the uncertainty.

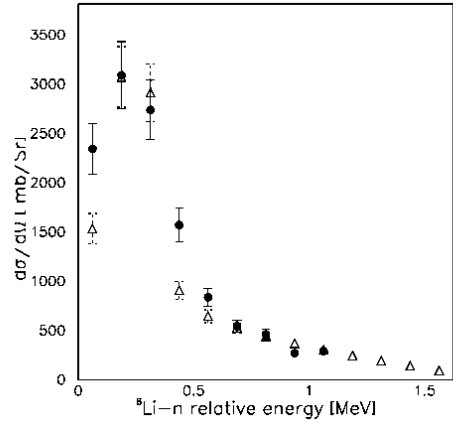


Fig5: Comparison between quasi-free data (full dots) and direct cross-section (open triangles) from ref. [13].

The two data sets agree quite well throughout the investigated range, including the resonant region around $E_{6\text{Li-n}} = 250$ keV. The good agreement validates the pole approximation for this experiment together with the PWIA approach and, importantly, the present results seem to exclude off-energy shell effects on the quasi-free cross-section other than the lack of the

Coulomb suppression at sub-Coulomb energies for reactions involving charged particles.

4 CONCLUSIONS

The ${}^6\text{Li}(n,\alpha){}^3\text{H}$ reaction was investigated by selecting the quasi-free contribution to the ${}^6\text{Li}(d,\alpha){}^3\text{H}p$ three-body reaction performed at 14 MeV. The two-body cross-section was deduced in PWIA approach and compared with the direct behaviour. The good agreement between the two sets of data suggests that no off-energy shell effects seem to be present in this case. It might be argued that they are important only when charged particle interactions at sub-Coulomb energies are involved, since they are responsible for the suppression of the Coulomb barrier on the quasi-free data.

Further studies at higher energy resolution are necessary to better understand this important aspect.

4 REFERENCES

- [1] Dj. Miljanić et al., Nucl. Phys. A215 (1973) 221.
- [2] J. Kasagi et al., Nucl. Phys. A239 (1975) 233.
- [3] M. Lattuada et al., Nucl. Phys. A458 (1986) 493.
- [4] M. Zadro et al., Nucl. Phys. A474 (1987) 373.
- [5] G.F. Chew, Phys. Rev. 80 (1950) 196.
- [6] N.S. Chant and P.G. Roos, Phys. Rev. C15 (1977) 57 and references therein.
- [7] C. Spitaleri et al., Phys. Rev. C 60 (1999) 055802.
- [8] C. Spitaleri et al., Phys. Rev. C 63 (2001) 055801.
- [9] M. Lattuada et al., ApJ 562 (2001) 1076.
- [10] A. Tumino et al., Phys. Rev. C 67 (2003) 065803.
- [11] N. Arena et al., Nuovo Cimento 45 (1978) 40.
- [12] G. Baur and H. Rebel, Ann. Rev. Nucl. Part. Sci. 46 (1996) 321.
- [13] J.C. Overley et al., Nucl. Phys. A221 (1974) 573.

ISOSPIN IN NUCLEAR FRAGMENTATION

V. Baran^{a,b}, M. Colonna^b, M. Di Toro^b

a) IFIN-HH and Bucharest University, Romania

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

Abstract

The isospin dynamics when we explore various reaction mechanisms at intermediate energies is discussed. We are concerned with its peculiarities in the nuclear liquid-gas phase transition, in mid-rapidity fragment formation for semicentral collisions as well as in the diffusion process in binary, peripheral reactions. The connection of these effects to the density dependence of symmetry energy is analyzed in detail.

1 INTRODUCTION

In the last decade, as a result of the continuous progress in the experimental techniques, an increased interest was devoted to the investigations of the role of symmetry term of the nuclear equation of state, EOS, on nuclear structure and dynamics [1]. Its behaviour is poorly known in regions beyond normal density. Here our goal is to present several possibilities offered by the reaction dynamics of dissipative heavy ion collisions to disentangle among various parametrizations of symmetry energy. In the following we will compare results obtained with forces that have the same saturation properties for symmetric NM. We will refer to a "asy-stiff/superstiff" EOS when we are considering a potential symmetry term with a linear/parabolic increase with nuclear density and to a "asy-soft" EOS when it shows a saturation and eventually a decrease above normal density [2].

2 CENTRAL COLLISIONS : NUCLEAR MULTIFRAGMENTATION

At Fermi energies, the process of multifragmentation following the collision of heavy nuclei is expected to show features analogous to usual liquid-gas phase transitions of water. Considering the time scales of various processes, the spinodal decomposition can be a possible kinetic mechanism leading to phase separation. In the phase diagram of asymmetric nuclear matter the relevant unstable regions can be defined in terms of instabilities against isoscalar-like and isovector-like fluctuations.

Maybe unexpected, since from the thermodynamical analysis the most extended unstable region is related to the chemical (diffusive) instability, the liquid-gas phase transition in asymmetric nuclear matter is driven by instabilities against isoscalar-like modes, when the proton and neutron densities fluctuate in phase [3]. The growth of such unstable modes will finally lead to the formations of the liquid and gas phases. During this process the isospin distillation takes place: the fragments with a lower isospin content will be surrounded by a more neutron rich gas. An intuitive picture, where the two features discussed above are evidenced, is presented in Fig 1.

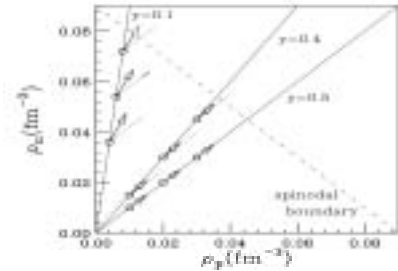


Figure 1: The mechanism of isospin distillation: the direction of unstable modes. The thick lines correspond to constant concentration direction and the short thin lines to a pure isoscalar mode.

The direction of unstable modes leading to the formation of liquid phase is indicated by the arrows. We observe how to an increase of neutron density relative to the initial value will correspond a proton density increase. The deviation from the line of constant proton concentration (thick lines) toward a less asymmetric matter indicates the isospin distillation effect. We also mention that the isovector-like modes, related to the segregation of protons from neutrons, remain stable at subsaturation densities and such fluctuations are never amplified.

3 FROM SEMICENTRAL TO SEMIPERIPHERAL COLLISIONS: NECK FRAGMENTATION

In the framework of a microscopic transport model, based on a stochastic extension of the BNV equation, we can investigate the "dynamical" IMF production observed experimentally in semicentral heavy ion collisions in the Fermi energy domain. We identify two main mechanisms responsible for the IMF emission that cannot be ascribed to the statistical decay of PLF or TLF:

- i) the neck fragmentation mechanism, a fast process, that takes place within first 200fm/c to 300fm/c from the reaction beginning;
- ii) the dynamical fission, triggered by the large deformations acquired during the interaction stage, expected to take place at longer times.

We have studied in detail the features of neck fragmentation, as a source of IMF emission in the

midrapidity region and the related peculiarities of isospin dynamics for the reaction $^{124}\text{Sn} + ^{64}\text{Ni}$ at 35~AmeV.

This system was extensively investigated experimentally at LNS Catania, in the framework of REVERSE collaboration.

In Figure 2 we report, for the ternary events, the probability distribution of the time interval between the moment of the scission of the dinuclear system and the moment when an IMF, neck originating fragment (NIMF), was observed.

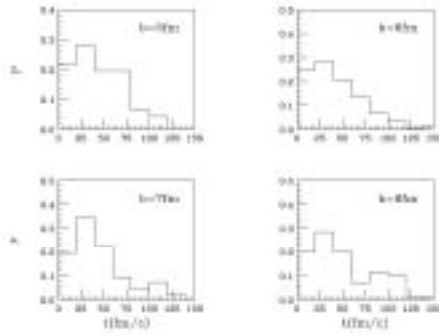


Figure 2: The probability distribution of scission-to-scission times in the neck fragmentation for various impact parameters.

This NIMF's appears largely decoupled from PLF or TLF. Indeed the relative asymptotic velocities IMF-PL(TL)F show deviations from the Viola systematics, r (r_1) in Figure 3, ranging from 25% to 70% [4]. We interpret this as the consequence of an early decoupling of the neck zone, where the IMF's are formed, from the PLF and TLF.

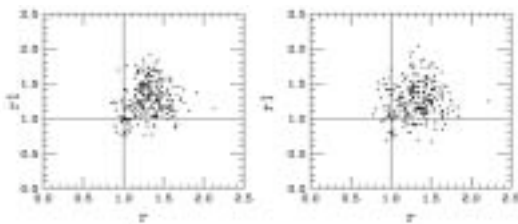


Figure 3: The correlation between deviations from Viola systematics for neck fragmentation mechanism.

Indeed, at the separation time, because of incomplete dissipation of their collective motion, PL and TL residues have relative velocities, with respect to the participant region, well above the values associated with a pure Coulomb repulsion. We observe that the neck region, due to expansion effects as well as to the contemporary PLF-TLF centrifugal motion, is quenched inside the spinodal instability region. Hence we identify the spinodal decomposition as the kinetic process driving fragment formation in the neck region. As a consequence, we find that the mean field compressibility is governing the neck fragmentation dynamics, while the nucleon-nucleon cross

section value shapes its properties [4]. Two conditions should be satisfied in order to optimize the observation of this new fragmentation mechanism:

- selection of not too peripheral events, since enough matter should be present in the interacting zone;
- selection of the beam energy, since we need a matching between the interaction and the instabilities time scales (see also [5]).

A consistent picture is emerging on the dynamical origin of fragment formation from central to peripheral collisions. In particular, as in the case discussed here, we can actually have an increase of the fragment production probability in semicentral reactions, since the rotational motion is inducing a better matching of the relevant time-scales. For the reaction studied here we have a typical rise and fall of mid-rapidity fast fragment production with increasing impact parameter. From a dominance of very dissipative binary events for central collisions to the NIMF formation at intermediate impact parameters, to come back to binary dominance in more peripheral reactions when the induced deformations may lead to dynamical fission mechanism [6].

We observe interesting effects in the isospin dynamics, related to the density and asymmetry gradients between participant and spectator regions. The IMF isospin content keeps track of an early neutron enrichment process. For the three asy-EOS introduced we plot in the Figure 4 the average isotopic composition, $I=(N-Z)/A$, of the NIMF's as a function of the PLF r-deviation from Viola systematics. At all impact parameters clear differences are evidenced. The average asymmetry does not depend strongly on r . We notice however that it increases proportionally to the slope of the symmetry potential as a function of density around and below normal density. The suprasystiff parametrization, i.e. with an almost parabolic increasing behavior around ρ_0 , produces systematically more neutron rich NIMF's.

We interpret this effect as due to a different neutron/proton migration at the interface between PL/TL "spectator" zone around normal density and the dilute neck region where the NIMF's are formed. In order to understand the details of this isospin diffusion dynamics we follow the time evolution of the average density and average asymmetry in the spatial cubic volume of 10fm side around the CM and containing mainly the neck zone.

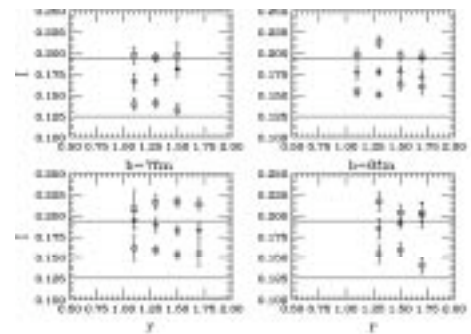


Figure 4: NIMF isospin content for asysoft (circles), asystiff (rhombs) and suprasystiff (squares) EOS as a function of r-deviation from Viola systematics at impact parameters from $b=5\text{fm}$ to 8fm .

The corresponding correlation is shown in Figure 5 for asysoft and superasystiff parametrizations. The numbers close to the each symbol indicate the corresponding time step. The density variations in the considered volume are very similar for the two asy-EOS, at each time the circle and square points are aligned roughly at the same mean density ρ_0 . This is not surprising since the density oscillations are due to the stiffness of the symmetric (isoscalar) part of the EOS which is kept exactly the same (soft choice here) for the two different asy-EOS parametrizations. Actually the overall compressibility in asymmetric matter is modified by the density dependence of the symmetry term, but the effect is not large and proportional to the square of the mean asymmetry I . This can explain the very tiny alignment shift between circles and squares in Figure 5. The initial average asymmetries have values close to that of the composite system ($I=0.17$). The differences until 80fm/c can be assigned to a different relative fast neutron to proton emission from the central region.

In this time interval we have a density oscillation and so neutrons are probing some more mean field repulsion in the superasystiff case (the circles slightly below the squares). After 80fm/c the dilute neck region is forming and a clear dependence on the used asy-EOS of the isospin dynamics is evident. A much larger neutron enrichment of the neck zone for the asysuperstiff EOS takes place. We can understand this results in simple terms. In presence of density gradients, as in the case of neck fragmentation, the nucleons will feel the superposed effects of the forces due to the isoscalar and isovector part of the mean field.

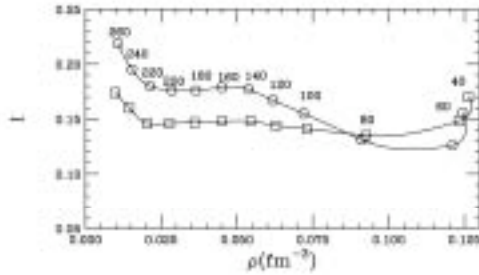


Figure 5: Mean asymmetry-density correlations in a cubic volume centered around the CM during the reaction evolution. The points are obtained by averaging over all events for asysoft (squares) and superasystiff (circles) EOS at $b=6$ fm.

In the asysuperstiff case the neutrons will be accelerated towards the neck region since the repulsion of the symmetry part of the mean field is sharply increasing around normal density. This migration from spectator to neck at the interface compensates in part the neutrons that moves out from the participant region in presence of the expansion causing finally the observed enrichment. This effect is largely reduced in the asysoft case due to the flatness of the density dependence of the symmetry mean field around ρ_0 , [10]. We see that the isospin content of NIMF carries important information on

the isovector part of the effective interaction and the related isospin dynamics in the early stages of the reaction. We expect a different isospin pattern for the IMF's resulting from induced and/or statistical fission of the more charge symmetric PLF's and TLF's.

Interesting enough, we observe isoscaling, [7], in the neck fragmentation, at the freeze-out, in spite of the short time scales of the IMF production. The isoscaling parameters, are sensitive to the density dependence of the asy-EOS, increasing in absolute values when going from asy-soft to asy-stiffer EOS [4]. We expect such behaviour from the larger "neutron migration" discussed before. An important confirmation of this EOS dependent isospin dynamics should come from secondary emission measurements from mid-rapidity sources.

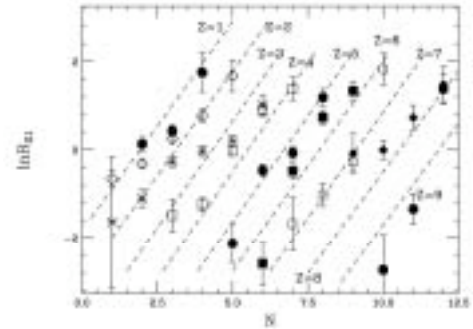


Figure 6: Isoscaling in neck fragmentation.

4 PERIPHERAL COLLISIONS: ISOSPIN DIFFUSION

In more peripheral collisions between nuclei with different N/Z ratio, isospin migration is expected to take place leading the system toward a uniform asymmetry distribution.

The degree of equilibration, correlated to the interaction time, may provide insights about transport properties of asymmetric nuclear matter, in particular on the diffusion coefficient of fermionic systems. In this section we inquire into the role of density dependence of symmetry energy and the effects of pre-equilibrium particle emission on isospin diffusion. Our analysis was also stimulated by recent discussions and experimental observations on this subject, see [8], [9]. We focus on charge asymmetric collision $^{124}\text{Sn} + ^{112}\text{Sn}$, at 50 AMeV bombarding energy, to which we refer as the mixed system, (M). A number of 400 events were achieved for each initial condition and asy-EOS.

The calculations were performed for impact parameters $b = 8, 9, 10$ fm when the reaction has mainly a binary character. In this case the isospin content of primary PLF and TLF may provide the essential information about the isospin equilibration rate. At $b=8$ fm, however, around 25 % of the events were ternary. An IMF was produced in the midvelocity region, through neck fragmentation. For even more central events this mechanism become dominant: at $b=6$ fm, one or two IMF's were found in more than 70 % of events, [10]. Their formation in the overlap region will influence the final isospin distribution, making more difficult the interpretation of the results. In the following, for the above initial

conditions, we select only the binary events. We define the average contact time, t_c , as the time elapsed between the initial touching and the moment when projectile (target)- like fragments, PLF (TLF), reseparate. From our simulations we obtain $t_c = 120, 100, 80$ fm/c for the three corresponding impact parameters.

From density contour plots we note the peculiar dynamics of the overlap region: after around 40 fm/c, concomitant to the fast motion leading to PL and TL prefragments, the formation of diluted interface is clearly evidenced. The isospin migration takes place during the transient contact between the two peripheral regions of higher density separated by the lower density neck. In contrast, in deep-inelastic collisions at low energies, the isospin equilibration is driven by the N/Z difference between the interacting nuclei with a quite uniform density profile until the separation.

We quantify the degree of equilibration through the isospin imbalance ratio defined as:

$$R_i = \frac{2I_i^M - I_i^{124+124} - I_i^{112+112}}{I_i^{124+124} - I_i^{112+112}}$$

Here i stands for projectile (target) and the quantities refer to the isospin content or, in general, to any isospin dependent quantity, as it results from the mixed reaction (M), from the reactions between neutron rich nuclei, (124+124), and between neutron poor nuclei, (112+112), respectively. As its value is more approaching to zero this is an indication of a larger degree of equilibration. The extreme case $R_T = -1$ and $R_P = 1$ show the absence of any isospin transfer. We report its dependence on the contact time for asysoft (squares) and asysuperstiff (circles) EOS in Figure 7. From our results we conclude that superasystiff EOS provide a better agreement to the experimental observations, see [8]. A clear difference between the two equations of state is evident for $b=8$ fm. A smaller values of isospin imbalance ratio for asysoft EOS points towards a faster equilibration rate. In ref. [8] a possible explanation was related to the observation that below normal density the asysoft EOS has a larger value of symmetry energy.

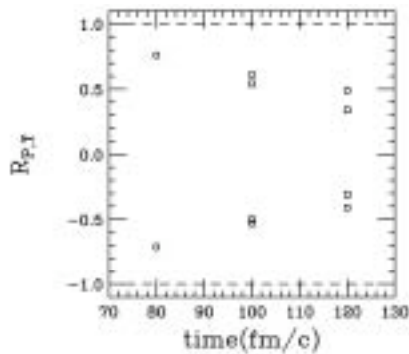


Figure 7: Isospin imbalance ratio as a function of the contact time for asysoft (squares) and superasystiff (circles) EOS.

Therefore an enhanced isospin equilibration has to be triggered if the diffusion take place at lower density. In fact the mechanism of charge equilibration is more complicated due to the reaction dynamics (fast particle emissions, density gradients). In Figure 8 we plot in left windows, for the two asy-EOS, the dependence on the interaction of: average projectile asymmetry (black circles), average gas asymmetry originating from projectile (crosses), asymmetry of the nucleons transferred from projectile to target (rhomb), asymmetry of the nucleons transferred from target to projectile (squares).

In the right panels we draw:

average target asymmetry (black circles), average asymmetry of emitted particles originating from target (crosses), asymmetry of the nucleons transferred from projectile to target (rombs) asymmetry of the nucleons transferred from target to projectile (squares).

In all figures the horizontal lines refer to the initial asymmetry of the projectile (target).

The projectile asymmetry deviates more from the initial value. Both preequilibrium and nucleon transfer drive the system towards a more symmetric configuration. The two effects tend to compensate for the target resulting in a smaller variation from the initial value. In the superasystiff case, the projectile, in spite of a more asymmetric matter passing to the target, has, at separation time, a larger asymmetry than in the asysoft case.

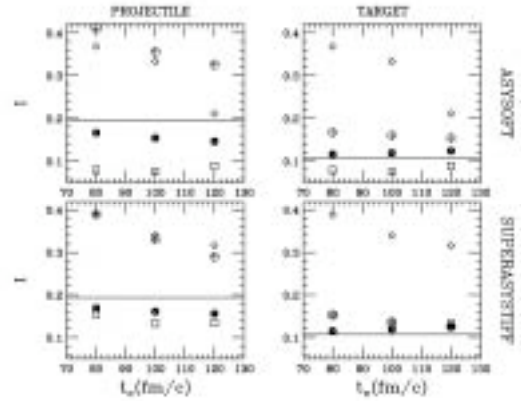


Figure 8: Isospin sharing at Fermi energy (see the text).

We see in fact that a lower asymmetry is removed by preequilibrium particles and to a neutron richer matter is also migrating from the target, an effect related to density gradients, as discussed above.

5 CONCLUSIONS

In this work we showed how various reaction mechanism at Fermi energies can provide complementary informations about the density dependence of symmetry term of EOS. In these reactions several observables are sensitive to the isovector channel:

- i) isospin distillation in multifragmentation,
- ii) isospin content of neck fragments,

- iii) isoscaling parameters,
- iv) isospin content of PLF and TLF in peripheral reaction

6 REFERENCES

- [1] Isospin Physics in Heavy Ion Collisions at Intermediate energies, Eds. Bao-An Li and W. Udo Schroeder , Nova Science Publishers (2001, New York).
- [2] M. Di Toro et al., Prog. Part. Nucl. Phys. 42 (1999).
- [3] V. Baran et al., Phys. Rev. Lett 86(2001)4492.
- [4] V. Baran, M. Colonna, M. Di Toro, Nucl. Phys. A730(2004)329.
- [5] M. Colonna, M. Di Toro, A. Guarnera, Nucl. Phys. A589(1995)160.
- [6] E. Piasecki and Reverse collaboration (to be published).
- [7] M.B. Tsang et al., Phys. Rev. Lett 86(2001)5023.
- [8] M.B. Tsang et al., Phys. Rev. Lett 92 (2004) 062701.
- [9] M.B. Tsang, Nucl. Phys A 734 (2004) 605.
- [10] V. Baran et al. Nucl. Phys. A703(2002) 603.

ELECTRON SCREENING EFFECTS ON NUCLEAR REACTIONS AT EXTREMELY LOW ENERGIES

Sachie Kimura*, Aldo Bonasera

a) INFN Laboratori Nazionali del Sud, Catania, Italy

Abstract

We perform molecular dynamics simulations to assess the screening effects by bound target electrons in low energy nuclear reactions in laboratories. Quantum effects corresponding to the Pauli and Heisenberg principle are enforced by constraints. We show that the enhancement of the average cross section and of its variance is due to the perturbations induced by the electrons. This gives a correlation between the maximum amplitudes of the inter-nuclear oscillational motion and the enhancement factor. It suggests that the chaotic behavior of the electronic motion affects the magnitude of the enhancement factor.

1 INTRODUCTION

The knowledge of the bare nuclear reaction rates at low energies is essential not only for the understanding of various astrophysical nuclear problems, but also for assessing the effects of host material in low energy nuclear fusion reactions in matter. This is currently a subject of great interest in nuclear physics, since Muenster group has reported that the experimental cross sections of the $^3\text{He}(d,p)^4\text{He}$ and of $\text{D}(^3\text{He},p)^4\text{He}$ reactions with gas target show an increasing enhancement with decreasing bombarding energy with respect to the values obtained by extrapolating from the data at high energies[1].

These observations have motivated many theoretical as well as experimental studies. Many of them attempted to attribute the enhancement of the reaction rate to the screening effects by bound target electrons.

In this context one often estimates the effect of screening by determining the so-called screening energy which is practically a constant decrease of the barrier height in the tunneling region. It is determined by making a fit to the data. A puzzle is that the screening energy obtained by this procedure exceeds the value in the so called adiabatic limit, which is given by the difference of the binding energies in the united atom and in the target atom and is theoretically thought to provide the maximum screening energy, for all systems so far studied experimentally.

For $^7\text{Li}(p,\alpha)\alpha$ reaction, in addition to the direct measurement, an indirect measurement of the cross section using the Trojan horse method has recently been made by the group in this laboratory. The comparison between the two methods indicates again that the screening energy in the direct method exceeds the adiabatic limit by a large factor[2].

There are already some theoretical studies performed taking into account the dynamical effects of the electronic wave function by the time-dependent Hartree-Fock(TDHF) scheme[3,4,5]. We examine the problem also in the very low incident energy region not reached experimentally yet. At such very low energies

fluctuations are anticipated to play a substantial role. In order to study the sources of such fluctuations, TDHF scheme which gives averaged values only is insufficient. We mention also that the understanding of the fusion dynamics and fluctuations has a great potential for the enhancement of the fusion probability in plasmas for the energy production.

2 NUMERICAL SIMULATION

In order to examine the problem theoretically, we use constrained molecular dynamics (CoMD) models. Molecular dynamics contains all possible correlations and fluctuations due to the initial conditions(events). In order to treat quantum mechanical system like target atoms and molecules, we use classical equations of motion with constraints to satisfy the Heisenberg uncertainty principle and the Pauli exclusion principle [6].

Notice that in the D+d case that we investigate here, since one electron is involved, only the Heisenberg principle is enforced and obtained -13.56 eV as the binding energy of deuterium atom and 0.5327 Angstrom as the mean square radius. These values can be compared with the experimental values of -13.61 eV and 0.5292 Angstrom, respectively. We found that the approach reproduces rather well the binding energies and the radii of atoms up to Be [7].

Using the ensemble of target atoms thus prepared as initial states, we perform the simulation of the reaction.

3 RESULTS AND DISCUSSION

As a result from the numerical simulations, we obtained that the enhancement factor deviates from 1 and becomes large, as the incident energy becomes smaller.

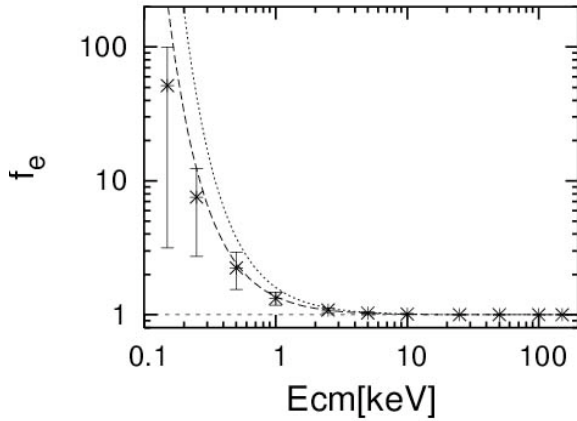


Fig.1 Enhancement factor as a function of the incident energy for D + d reaction.

Fig. 1 shows the incident energy dependence of the enhancement factor. The averaged enhancement factors from our calculation are shown with stars and its variance with error bars. The dashed and dotted line show the enhancement factors with are obtained by putting the screening energy $U_e = 25.0 \pm 5.0$ eV from experimental data. In the low energy region the enhancement factor is more than 50. However the averaged enhancement factor does not exceed the adiabatic limit. We performed also a fit of our data at beam energies higher than 1keV with eq. (4) and obtained $U_e = 15.9 \pm 2.0$ eV. This value, between the sudden and the adiabatic limit, is in good agreement with previous studies with TDHF scheme[3, 4]. Note that the variance is large and indicates that in some events the fusion probability exceeds the adiabatic limit in that region. We checked also that the contribution to the enhancement comes mainly from the interaction in the classical allowed region.

We found also that the behavior of the bound electron(s) becomes unstable, depending on the dynamics especially in the extremely low energy region. It can be explained by the association with the gravitational 3-body problem, which has the same form of the equation of motion and it is nonintegrable [8]. There is a famous example of the motion of asteroids around the sun perturbed by the motion of Jupiter; the motion of the asteroid becomes unstable, i.e., chaotic, depending on the ratio of the unperturbed frequencies of the asteroid and Jupiter.

In the case of the fusion with the atomic target, the events, in which we get large amplitude due to the resonances, give small enhancement of the cross section because of the contribution of the instability of the electronic motion during the reaction.[9]

4 SUMMARY

We performed of molecular dynamics simulations of the

electron screening problem. We calculated the penetrability of the Coulomb barrier by using molecular dynamics simulations with constraints and imaginary time. We have shown that both the enhancement factor and its variance increases as the incident energy becomes lower. However we obtained the averaged screening energy smaller than the value in the adiabatic limit, while from fluctuations some events clearly exceed such a limit. Relatively small enhancement is obtained because of the existence of resonances, i.e., instability of the bound electrons. It means that the chaoticity of the electron motion affects the enhancement factor of the cross section.

4 REFERENCES

- [1] H. J. Assenbaum et al. Z. Phys. A327 (1987) 461.
- [2] M. Lattuada et al. Astrophysical Journal, 562 (2001)1076.
- [3] T. D. Shoppa et al. Phys. Rev. C 48 (1993) 837.
- [4] S. Kimura et al, Phys. Rev. C 67 (2003) 022801(R).
- [5] S. Kimura et al. in Proc. of the International Conference of Fusion03, November 2003, to appear in Prog. Theor. Phys.
- [6] M. Papa et al. Phys. Rev. C 64 (2001) 024612.
- [7] S. Kimura, and A. Bonasera, in preparation.
- [8] H. G. Schuster, Deterministic Chaos (VCH, Weinheim, Germany, 1995) Chap. 7.
- [9] S. Kimura, and A. Bonasera, nucl-th/0403062, submitted

Screening effects on 1S_0 pairing in neutron matter

U. Lombardo^{a,*}, C.W. Shen^{b,†}, P. Schuck^c, W. Zuo^d

a) INFN Laboratori Nazionali del Sud, Catania, Italy

b) INFN Laboratori Nazionali del Sud, Catania, Italy

c) Institut de Physique Nucleaire, Orsay, France

d) Institute of Modern Physics, Lanzhou, China

Abstract

The 1S_0 superfluidity of neutron matter is studied in the framework of the generalized Gorkov equation. The vertex corrections to the pairing interaction and the self-energy corrections are introduced and approximated on the same footing in the gap equation. A suppression of the pairing gap by more than 50% with respect to the BCS prediction is found.

On the other hand, the vertex corrections due to the screening of nuclear matter are expected to restore the same magnitude of the gap as the non screened pairing

1 MEDIUM POLARIZATION IN THE NUCLEAR PAIRING

In the past the studies of pairing have mainly been concentrated on the influence of either dynamic self-energy corrections or vertex corrections to the neutron matter pairing problem, independently from one another [1]. All investigations in this direction invariably led to the conclusion that dynamic self-energy corrections yield a quite strong reduction of 1S_0 pairing in neutron matter. However, to be consistent, self-energy corrections have to be followed by vertex corrections on the same footing. This is the objective of the present investigation. It will be seen that the vertex corrections have tendency to further reduce the gap but to a lesser extent than that is the case from self-energy corrections. Our approach is based on the Gorkov Green's function formalism where we develop systematically self-energy and effective pairing interaction to lowest order in the particle-hole bubble insertion. Though intuitively quite reasonable and physically motivated, we should mention that this is neither based on an expansion in a small parameter nor does it rely on some variational principle. None the less our results will be quite comparable to those of other works, notably based on the correlated basis function approach which, to a large extent, is variational. The results of such an investigation are reported in Fig.1. But, when the protons are included to the n-n polarization (left side of Fig.2) one should add p-p polarization (right side of Fig.2) giving rise to a strong attractive contribution [2].

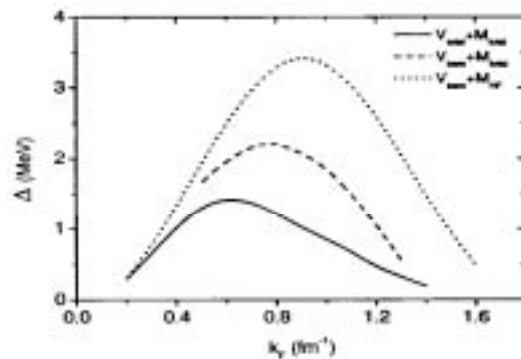


FIG.1 Energy gap vs Fermi momentum (density) in three approximations: bare potential plus BHF self-energy (dotted) and BHF+polarization (dashed), potential and selfenergy with polarization (solid).

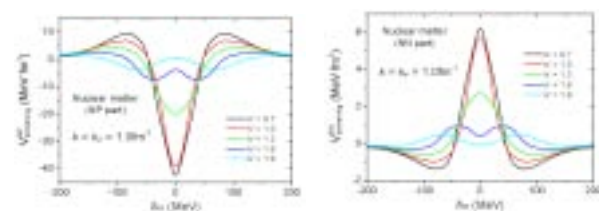


FIG.2. nn (left) and pp (right) polarization potential in One bubble approximation.

REFERENCES

- [1] U. Lombardo, P. Schuck and W. Zuo, Phys.Rev. C64, 021301 (2001).
- [2] C.W. Shen, U. Lombardo, P. Schuck, W. Zuo and N. Sandulescu, Phys. Rev. C67, 061302 (2003).

Neutrino mean free path in neutron stars

U.Lombardo^{a,*}, C.W. Shen^{b,†}, N.Van Giai^c, W. Zuo^d

a) INFN Laboratori Nazionali del Sud, Catania, Italy

b) INFN Laboratori Nazionali del Sud, Catania, Italy

c) Institut de Physique Nucleaire, Orsay, France

d) Institute of Modern Physics, Lanzhou, China

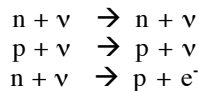
** Corresponding author, e-mail: lombardo@lns.infn.it*

+On leave from CIAE, Beijing, China

Abstract

The neutrino propagation in neutron stars is studied in the framework of the linear response theory. The medium effects are treated in the non-relativistic Brueckner-Hartree-Fock approach either in the mean-field approximation or in the RPA. The residual interaction is expressed in terms of the Landau parameter extracted from the equation of state of spin- and isospin-polarized nuclear matter. The Brueckner theory including three-body forces is used for determining the equation of state. Numerical predictions for the response function of nuclear matter in β -equilibrium and the neutrino mean free path are presented in a range of baryonic densities and temperatures. The main results are a dominance of the charge-exchange component over the scattering component and an enhancement of the neutrino mean free path induced by nuclear correlation.

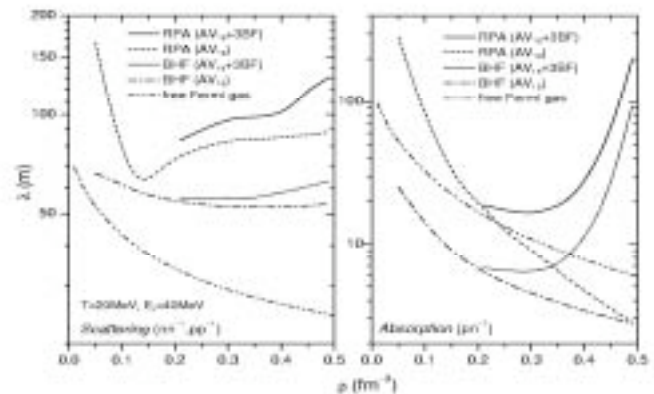
The neutron star opacity is mainly driven by the interaction of neutrinos with the baryonic matter, the main processes being



The neutrino opacity is governed by the neutrino mean free path λ . The calculation here reported goes beyond the Fermi-gas model, taking into account the strong nucleon correlations. They reduce the phase space in the final state and then an enhancement is expected for the mean free path. The present prediction is based on the linear nuclear response to weak interactions and on the Brueckner theory including relativistic effects and nucleonic resonances. The figure summarizes the calculations of the neutrino mean free path performed in three different models: free Fermi gas, mean field (BHF) and mean field plus RPA. Increasing the amount of correlations λ also increases. The effect of three body force at high density produces an additional enhancement. These features are common to both neutrino nucleon scattering and charge exchange processes.

REFERENCES

- [1] U. Lombardo, C.W. Shen, N. Van Giai and W. Zuo, Nucl. Phys. A 722, 532c (2003).
- [2] U. Lombardo, C.W. Shen, N. Van Giai and W. Zuo, Phys. Rev. C 68 055802 (2003).



MICROSCOPIC SIMULATION OF THE QUARK-GLUON PLASMA

S.Terranova^{a,*}, A.Bonasera^{a,*}

a) INFN Laboratori Nazionali del Sud, Catania, Italy

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

Abstract

We calculate the Equation of State of a quark system interacting through a phenomenological potential: the Richardson's potential, at finite baryon density and zero temperature. We solve molecular dynamics with a constraint due to Pauli blocking and find evidencies of a phase transition from "nuclear" to "quark matter", which is analyzed also through the behaviour of the J/Ψ embedded in the quark system.

1 INTRODUCTION

The production of a new state of matter, the Quark-Gluon Plasma (QGP), is one of the open problems of modern physics. Experimentally such a system can be obtained through ultra-relativistic heavy ion collision (RHIC) at Cern and at Brookhaven [1], QGP is formed in the first stages of the collisions, and can be studied through produced secondary particles.

In this work we propose a semiclassical model which has an EOS resembling the well known properties of nuclear matter and predictions to the QGP. We simulate the nuclear matter composed of nucleons (which are by themselves composite three-quark objects) and its dissolving into quark matter. An important ingredient of our approach is a constraint to satisfy the Pauli principle. The approach dubbed Constraint Molecular Dynamis (CoMD) as been successfully applied to relativistic and non relativistic heavy ion collision [2] and plasma physics as well [3]. In addition, for our system of colored quarks, we will show how the color screening is related to the lifetime of a particle J/Ψ in the medium.

In particular we will see that lifetime of the J/Ψ as function of density behaves as an order parameter. Having a model which simulates the QGP might be useful when dealing with finite and, possibly, out of equilibrium systems. Infact dynamics and finite size effects might wash completely or hide a phase transition.

2 NUMERICAL METHOD

We use molecular dynamics with a constraint for a Fermi system of quarks with colors.

The quarks interact through the Richardson's potential [4], in which we have a Coulomb and a linear term, the second one is responsible of the confinement.

The color degrees of freedom of quarks are taken into account through the Gell-Mann matrices and their dynamics is solved classically, in phase space, following the evolution of the distribution function [5].

Initially we distribute randomly the quarks in a box of side L in coordinate space and in a sphere of radius p_f in

momentum space, p_f is the Fermi momentum [5] related to the density of quarks with colors ρ_{qc} in this way:

$$\rho_{qc} = \frac{3n_s}{6\pi^2} p_f^3 \quad (1)$$

We generate many events and take the average over all events in each cell on the phase space and for each particle we calculate the occupation average, i.e. the probability that a cell in the phase space is occupied.

To describe the Fermionic nature of the system we impose that average occupation for each particle is less or equal to 1 ($\bar{f}_i \leq 1$). At each time step we control the value of average distribution function and consequently we change the momenta of particles by multiplying them for a quantity ξ . ξ is greater or less than 1 if $\bar{f}_i$ is greater or less than 1 respectively; which is the *constraint* [2]. With this procedure the basic quantities describing the system like: total energy, average occupation and order parameters (they will be described in this section below) after a given time will reach stationary values. We can see this in Fig1 in a typical case with $\rho_B = 5.995 \text{ fm}^{-3}$. We have repeated the calculations, in the same conditions, but two different starting points, i.e. from quarks with colors randomly distributed, i.e. QGP (left) and from quarks condensed in clusters of three with different colors, i.e. nucleons (right), respectively.

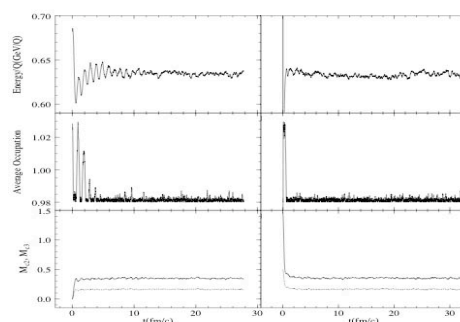


Fig 1: Time evolution starting from QGP (left) and nucleon (right)

In both conditions, the system will reach the same saturation values, though at different times. We stress that this behaviour is independent of the density.

We define an order parameter to check the order of a phase transition if any. It is defined through the Gell-Mann matrices as [4]:

$$M_{c3} = \frac{1}{N} \sum_{i=1}^N \sum_{a=3,8} \lambda_j^a \lambda_k^a + \lambda_i^a \lambda_j^a + \lambda_i^a \lambda_k^a =$$

$$M_{c2} + \frac{1}{N} \sum_{a=3,8} \lambda_j^a \lambda_k^a + \lambda_i^a \lambda_k^a \quad (2)$$

where $j(i)$ and $k(i)$ are the two quarks closest to the quark i . M_{c2} is the reduced order parameter which gives the color of the particle j closest to particular quark i .

To better understand the clusterization of colored quarks we also define an higher order parameter M_{c4} related to the colors of the 4 closest quarks:

$$M_{c4} = \frac{1}{N} \sum_{i=1}^N \sum_{a=3,8} \lambda_j^a \lambda_k^a + \lambda_i^a \lambda_j^a + \lambda_j^a \lambda_l^a +$$

$$\lambda_i^a \lambda_k^a + \lambda_k^a \lambda_l^a + \lambda_i^a \lambda_l^a \quad (3)$$

We normalize the order parameters in this way:

$$\tilde{M}_{c2} = \frac{2}{3}[M_{c2} + 1] \quad \tilde{M}_{c3} = \frac{2}{9}[M_{c3} + 3] \quad \tilde{M}_{c4} = \frac{2}{15}[M_{c4} + 6] \quad (4)$$

From the properties of the Gell-Mann matrices [6] it is easy to derive the following results for the order parameters: if the three closest quarks have different colors then $\tilde{M}_{c2} = \tilde{M}_{c3} = \tilde{M}_{c4} = 1$, in this case we have isolated white nucleons. This case is recovered in the calculation at small densities, where the system is locally invariant for rotation in color space. If four closest quarks have the same color $\tilde{M}_{c2} = \tilde{M}_{c3} = \tilde{M}_{c4} = 0$, we have a condition that we call *EXOTIC COLOR CLUSTERING*. Also in this case the system is locally invariant for rotation in color space; the corresponding potential energy is very large and repulsive.

If the three closest quarks have two different colors, independently of the color of the two closest quarks, we have the Quark Gluon Plasma, hence: $\tilde{M}_{c2} = \tilde{M}_{c3} = 2/3$. In this state $\tilde{M}_{c4}$ can assume three different values according to the colors of the four closest quarks and number of pairs of different color: $\tilde{M}_{c4} = 4/5$ (ex: *rggr*), $\tilde{M}_{c4} = 1$ (ex: *rggb*), $\tilde{M}_{c4} = 3/5$ (ex: *rggg*). We note that in the QGP case the system is globally invariant for rotation in color space.

To test for a signature of the various states of matter we studied the behaviour of a pair of quarks c and $\bar{c}$ embedded in the system, with $m_c = m_{\bar{c}} = 1.37 \text{ GeV}$. For each density we calculate the lifetime of the J/ψ particle, through its survival probability in the system. The survival probability is related to the total number of pairs c and $\bar{c}$ that stay bound after they are inserted in the saturated system of u and d quarks.

We have fitted the J/ψ survival probability with the expression:

$$P_{sur}(t) = \exp[-(t - t_D)/\tau] \quad (5)$$

and

$$t_{sur} = t_D + \tau \quad (6)$$

where t_D is the delay time of the J/ψ before the probability begins its exponential decreasing, and t_{sur} is the lifetime of J/ψ in the system, similar to fission[7].

3 RESULTS WITH CUT-OFF

When quarks, objects of different colors, are embedded in a dense medium, such as in nuclear matter, the potential becomes screened in a similar fashion as ions and electrons in condensed matter. This is the *Debye screening* [8].

The screening can be obtained through the use of a Debye radius screening in the interaction, as will be discussed in the next section. In this section, the screening is produced directly, through the interaction of colored quarks. But the system is not infinite, like nuclear matter, and this screening is insufficient to screen the linear potential and avoid its divergence for $r \rightarrow \infty$, hence we introduce a cut-off for the potential. The cut-off is a free parameter, when quark distances are greater then the cut-off, the interaction is equal to zero.

In Fig 2 we plot some quantities related to the case with small quark masses, $m_u = 5 \text{ MeV}$, $m_d = 10 \text{ MeV}$ and a cut-off of 3 fm. The energy per nucleon and corresponding energy density in units of the ϵ_F (energy density for a Fermi gas (top figures) versus baryon density divided by the normal density ρ_0 , have a very irregular behaviour that we can explain through the order parameters (third figure).

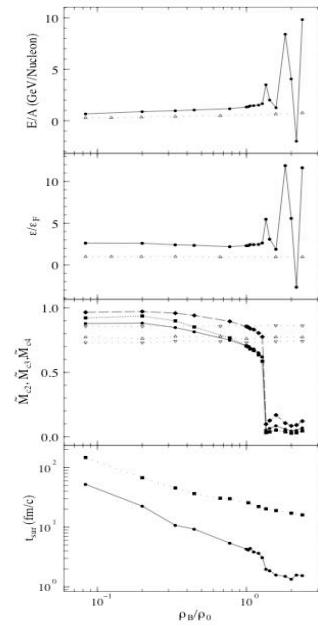


Fig 2: $m_u = 5 \text{ MeV}$, $m_d = 10 \text{ MeV}$ and a cut-off of 3 fm.

For small densities the quarks are condensed in clusters of three different colors, the system is locally white (isolated white nucleon). The normalized order parameters: $\tilde{M}_{c2}$ (circles), $\tilde{M}_{c3}$ (squares) and $\tilde{M}_{c4}$ (rombs)

are near to 1. At higher densities, the quarks are not in clusters but randomly distributed, $\tilde{M}_{c2} = \tilde{M}_{c3} = 2/3$ and $\tilde{M}_{c4} = 4/5$ and we have the QGP ($\rho_B / \rho_0 \approx 1.2$). But the system does not stay in this state, it prefers the exotic color clustering state where at least the four closest quarks have the same color. At density about 1.4–2.4 times the normal density $\tilde{M}_{c2} = \tilde{M}_{c3} = \tilde{M}_{c4} = 0$. The system reaches this state through a first order phase transition at about $1.3\rho_0$. In the figure relative to the energy per nucleon, the transition is signaled by a discontinuity at the same density. The other discontinuities at larger densities $\rho_B / \rho_0 > 1.5$, are probably due to the clusterization of more than four quarks of the same color. In these conditions, the linear term becomes very high and positive, hence the attraction between different clusters of quarks with different color distant in space prevails respect to repulsion between charges of the same color in each cluster, this explains the large values of the energy and consequently of energy density.

Repeating the same calculations with the Coulomb term only, triangles in Fig 2, we get a constant contribution, not only to the energy, but also to the order parameters. The Coulomb term produces a permanent clusterization among quarks which prevents them to reach the ideal QGP state. When the linear term is included it prevails respect to the Coulomb one and the system stays in exotic color clustering state, $\tilde{M}_{c2} = \tilde{M}_{c3} = \tilde{M}_{c4} = 0$. In Fig. 2(bottom) we plotted the behaviour of J/ψ particle (full line). When the density increases, the lifetime decreases because it is more probable that a particle of different flavour gets in between a $c\bar{c}$ pair and breaks the bond. t_{sur} behaves like an order parameter, infact it has a jump just where we found the phase transition ($\rho_B / \rho_0 \approx 1.3$). Turning off the interaction (squares in Fig 2 bottom), we can see a different behaviour, i.e. a monotonic decrease with density. The survival time in the medium is always larger than that with interaction, because the forces break more easily the bonds between particles ($c, \bar{c}$ quarks). After the jump we notice a saturation of the surviving probability, again similarly to the order parameter.

In order to study the sensitivity of the result to the input parameters, we have repeated the calculations with $m_u = m_d = 180 \text{ MeV}$ and a cut-off equal 1.26 fm. The quark masses are chosen to reproduce the energy per nucleon of nuclear matter at normal density.

In Fig 3 where we plot the same quantities of Fig 2 (symbols have the same meaning), we can see a behaviour more regular than previously. At very high densities (almost $45\rho_0$), in the figure relative to the energy per nucleon (top) we see a flex, probably indicating a second order phase transition, which becomes a change of slope in energy density (figure below). The normalized order parameters are always positive, i.e. it never happens that three equal quark color states are on average in the same region in r space. At low densities actually they never reach the value of 1 (nucleons). Which implies that our potential is

insufficient to get a good clusterization. Values of order parameters at high density are always larger than 2/3 for $\tilde{M}_{c2}$ and $\tilde{M}_{c3}$, and 4/5 (one the possible values of $\tilde{M}_{c4}$ to have QGP). This indicates a residual clusterization between quarks of different color, which we associate to the semiclassical counterpart of pairing. Infact residual attractive force especially due to the Coulomb term, couples quarks of different color.

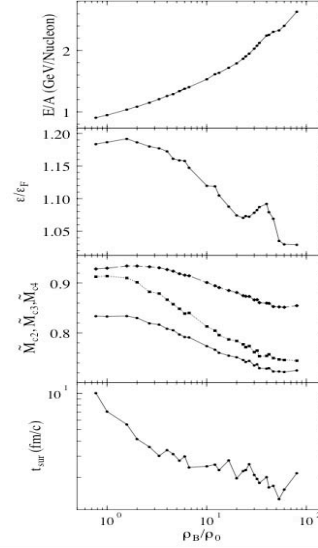


Fig 2: $m_u = m_d = 180 \text{ MeV}$ and a cut-off of 1.26 fm.

And if we study the behaviour of particle J/ψ in the medium we obtain a regular behaviour, Fig 3 (bottom), i.e. a fast decrease for small densities, and after about $7\rho_0$ a slow decrease with some fluctuation around 1–2 fm/c. The lifetime of J/ψ behaves again similarly to the order parameters.

In conclusion, we can see how changing quark masses and cut-offs we do not have the exotic color clustering and a first order phase transition, but a probable second order phase transition to QGP.

It is clear that the cut-off value changes the transition point from QGP to exotic color clustering, consequently, while if we analyze the reduced order parameters versus quark masses we find an almost constant behaviour.

3 DEBYE SCREENING

In this section, to have a good screening of the linear interaction we use a particular expression of the linear term obtained through the resolution of the Poisson equation in one dimension [8]:

$$\phi_{Lin} = \begin{cases} \frac{k}{\chi_l} \exp(-\chi_l r_{ij}) & \rho_q \neq 0 \\ kr_{ij} & \rho_q = 0 \end{cases} \quad (8)$$

χ_l is the linear Debye inverse radius [5,8] that for large densities goes to a constant. Also the linear

potential goes to a constant and not to zero like for a total screening, but for distance larger than the Debye radius the potential is screened. k is the string tension defined through the Λ parameter [6]. We stress that the confinement property is recovered in the zero density limit.

In Fig 4 we plot some results with this potential and $m_u = m_d = 324$ MeV. Also in this case we choose the masses of quarks to reproduce the energy per nucleon of nuclear matter at normal density.

In the top figure relative to energy per nucleon we found a minimum for low densities. The energy density, for large densities, shows some fluctuations, which can be due to numerical fluctuations. The order parameters are smooth functions of the density and also in this case they never reach the QGP values (dotted lines): $\tilde{M}_{c2} = \tilde{M}_{c3} = 2/3$ and $\tilde{M}_{c4} = 4/5$ (or other possible values), i.e. a residual clusterization remains. Probably it is an effect of the instability of quark pairs of different colors that produces the instability at large energy density. Also in this case the reduced order parameters are always positive and we never have exotic color clustering.

The calculated lifetime of J/Ψ in the medium versus density is shown in Fig 4 (bottom) and it behaves like the order parameters also in this case.

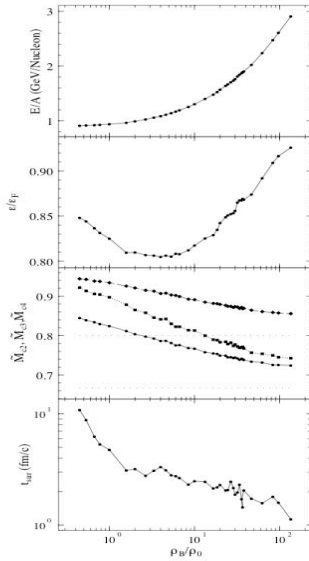


Fig 4 $m_u = m_d = 324$ MeV, screened linear potential

4 SUMMARY

In conclusion, in this work we have discussed a semiclassical molecular dynamics approach to infinite matter at finite baryon density and zero temperature starting from a phenomenological potential that describes the interaction between quarks with color. Pauli blocking, necessary for Fermions at zero

temperature, is enforced through a constraint to the average one body occupation function.

Color degrees of freedom for quarks are responsible for Debye screening, even though we have adopted some prescription mainly for numerical reasons to screen the linear term at large distances.

Depending on parameters for the quark masses and the potential, we obtain EOS which exhibit a first, second or a simple cross over to the QGP. We stress that these transitions are due to changes in the system symmetries. Infact we have a local invariance for rotation at low densities i.e. for nucleons. This means that we can rotate locally the color of the quarks with no change in the energy. The QGP displays a global invariance, i.e. we can change randomly the quarks colors anywhere in the system without changing the system properties.

Exotic clustering is also a local property, infact we can change the color randomly but only within a cluster of identical colors. It is the breaking of these symmetries which gives the phase transitions. A suitable physical observable for the phase transition could be the J/Ψ , in fact we have shown that for infinite systems it behaves like an order parameter and it is also able to distinguish between a first order and a second order (or a cross-over) phase transition. Finite size and dynamical studies within the model proposed will revail if such a property remains. Those studies could also give indications on the possibility that the phase transitions are washed by finite sizes effects. Also other indicators of a phase transitions such as intermittency can be easily studied in the framework of our model.

5 REFERENCES

- [1] C.Y.Wong, Introduction to High-Energy Heavy ion Collisions, World Scientific Co., Singapore, 1994.
- [2] M.Papa et al., Phys. Rev. C64(2001)024612.
- [3] A.Bonasera, Prog Theor Phys (in press).
- [4] A.Bonasera, Phys. Rev. C60(1999)65212.
- [5] S.Terranova and al., submitted.
- [6] R.Morpurgo, Introduzione alla fisica delle particelle, Zanichelli, Press 1987.
- [7] T.Maruyama and T. Hatsuda, Phys. Rev. C61(2000) 62201(R).
- [8] E.M.Lifshitz and L.P.Pitaevskii, Physical Kinetics, Pergamon Press 1991.

A NEW MICROSCOPIC APPROACH TO RELATIVISTIC HEAVY ION COLLISION

D.Zhou^{a,*}, S.Terranova^{b,+,}, A.Bonasera^{b,+}

a) Institute of Particle Physics, Huazhong Normal University, Wuhan, 430079 China

b) INFN Laboratori Nazionali del Sud, Catania, Italy

** Corresponding author, e-mail: zdm@iopp.ccnu.edu.cn*

+ Corresponding author, e-mail: Terranova@lns.infn.it , Bonasera@lns.infn.it

Abstract

A transport model for the ultra-relativistic nucleus-nucleus collisions based on the mean free path approach is proposed. The method is manifestly Lorentz invariant. We discuss some calculations for pp and AA collisions and compare to data. Comparison to data is reasonable and the model can be easily modified to take into account genuine many body effects and quantum statistics similarly to low energy heavy ion collisions.

1 INTRODUCTION

Relativistic heavy ion collisions (RHIC) offer a unique tool to explore matter states never explored before. In particular at high energy densities a transition from nuclear matter to the Quark-Gluon Plasma (QGP) is expected.

To have a complete picture of the AA collisions we need some inputs coming from elementary collisions in which we have a creation of new particles from the dynamics of quarks and gluons (partons). Hence the time evolution of the many body systems is extremely complicated due to the initial number of particles in AA collisions which largely increase during the time evolution, depending on the beam energy.

The purpose of this paper is to propose a new method of solution of the semiclassical transport equation which should describe (in some approximations which we will not discuss here [1]) the many body part of the process.

This is based on the concept of the mean free path approach and on a probability of collision (see below).

The mean free path method has been studied in detail at low energies and it has been shown to solve the Boltzmann equation in case where an analytical solution is known [2]. Here we have generalized the approach to keep into account relativistic effects. The particles move on straight lines during collisions since we have not implemented any force yet. For short we name the method proposed here as Relativistic Boltzmann equation (ReB).

For the discussion in this work we will base our consideration on a parton cascade model for ultra-relativistic heavy ion collision [1] generally composed of the parton initial state, the parton evolution, the hadronization, and the hadron evolution [3].

There are two ways of creating the parton initial state. In [4,5] the parton initial state was composed of partons from the mini-jets production in nucleus-nucleus collision and the HIJING multiple mini-jet generator [6] was specified in [4,5]. The parton initial state in [7,8] was created via probability distributions first for the spatial and momentum coordinates of nucleons in colliding nuclei and then for the flavor and spatial and momentum coordinates of partons in nucleons. Our parton cascade model follows the former way, however, the JPCIAE multiple mini-jet generator [9] is used instead of HIJING. The JPCIAE multiple mini-jet generator for ultra-relativistic nucleus-nucleus collision is based on PYTHIA [10], which is a well known event generator for hadron-hadron collision.

In this approach the partonic system is hadronized by JETSET [10], after the nucleon-nucleon collision ceated (freeze-out) and the hadronic final state is the consequence.

Quantum statistics (i.e. Pauli and Bose statistics) are not included at present but they have been considered explicitly in [11], for Bose and [12], for Fermi statistics.

In future works we plan to include the different statistics as well as the influence of many particle collisions [2], which could be very important because of the reached high densities.

2 FORMALISM

We follow the mean free path method as discussed in [2]. Briefly, for each event, at each time step dt and for each ion i we search for the closest ion $j(i)$ in phase space i.e. we define the quantity:

$$\Xi_{ij} = \frac{r_{ij}}{v_{ij}dt} \quad (1)$$

where r_{ij} , and v_{ij} are the relative distances and velocities (relativistic) and dt is the time step used in the calculations.

Define a collision probability as:

$$\Pi = \frac{v_{ij} dt}{\lambda} = \sigma \rho(r_i) v_{ij} dt \quad (2)$$

where $\rho(r_i)$ is the local density calculated at each time step.

Note that the quantities defined above are scalars and it is quite easy to show that they are Lorentz invariant.

The physical meaning of the equation (1) is simple, we search for particles that are close in coordinate and far away in velocity space, i.e. particles with opposite momenta. For instance at RHIC energies we have a relative velocity of the order of the speed of light c for particles of the target (T) and projectile (P) respectively, and zero for particles belonging to T or (P). The latter particles are automatically excluded from the first condition.

Once the two closest particles have been found, we calculate the local density knowing the relative distance and the number of particles near the colliding couple. From the relative energy and the particles type we know the elementary cross sections and thus the probability Eq.(2). A random number is taken and if it is smaller than the calculated probability, a collision occurs and it is modeled by Pythia, if $\sqrt{s} > 3.2 GeV$.

The time step is chosen such that the probability is always small compared to 1 and to minimize the CPU time. Once these conditions are fulfilled a further decrease of the time step dt will not change the results but will increase linearly the CPU time.

Notice that in our approach we have to pay the price of largely CPU time consuming calculations, proportional to $N(t)^2$, where $N(t)$ is the number of particles at time t . This calculation time might become prohibitive at LHC energies where many particles are produced.

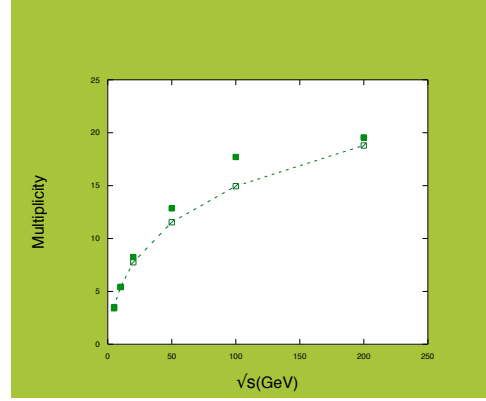
3 PP COLLISION

The essential input of all transport approaches are the elementary cross sections. Of course the used models Pythia and Jetset are tailored to reproduce that elementary process.

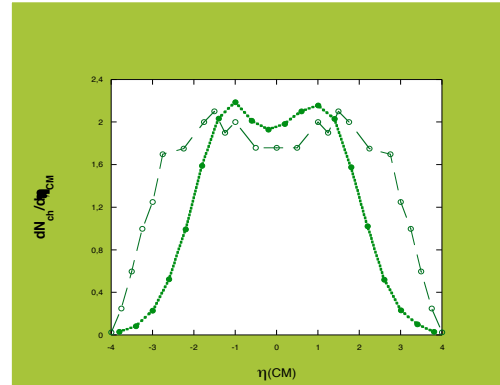
In this paragraph we will show what is the influence of the way the collision partners are chosen and we will fix the essential parameters which enter the calculations.

In Figure (1) we show the multiplicity of produced charged particles(full) in pp collisions vs CM energy from $\sqrt{s} = 5 GeV$ to $\sqrt{s} = 200 GeV$, compared with experimental result(open) [2].

The figure shows a good agreement.



For completeness we show in Fig.2 the pseudorapidity distribution of charged particles at $\sqrt{s} = 62.8 GeV$, in pp reactions. The results of the model(close circles) have the same shape then experimental data(open circles) with a similar plateau, only for a small interval of pseudorapidity, from -1.5 to 1.5 , central rapidity region.



4 AA COLLISION

We now discuss the nucleus-nucleus collision. In figure (3) we plot the multiplicity distribution in $^{197}Au+^{197}Au$ at C.M. energy of $200 GeV/A$. We plot with dashed lines, from right to left, the contribution to the multiplicity distributions at $b=1,3,5$ and $7 fm$.

We notice that for fixed impact parameter the multiplicity distribution has an almost gaussian shape. Dotted line refers to the multiplicity distribution of all impact parameters (from 0 to b_{max}).

Thus in order to make the same data selection as in the experiments one should not make a selection in b but directly in multiplicity. For instance a 5 percent most central multiplicity selection does not

really correspond to a $(b/b_{\max})^2=0.05$, i.e. $b=3.8\text{fm}$ for our system, but one should calculate say for all impact parameters and selection the multiplicity distribution.

The 5% most central collision events can selected with a multiplicity larger then say about 5000 in ReB.

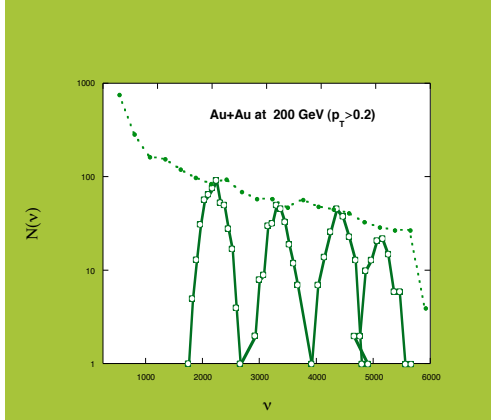


Fig 3: Multiplicity distribution

5 CONCLUSIONS

We proposed a new method, ReB, to solve the semiclassical transport equation, based on the mean free path.

We applied this method to pp and $^{197}\text{Au}+^{197}\text{Au}$ collisions, obtaining some result, fairly good agreement with data.

6 REFERNCIES

- [1] K.Geiger, B.Muller, Nucl. Phys.B 369, 600 (1992).
- [2] A.Bonasera, F. Gulminelli, and J. Molitoris, Phys. Rep. 243, 1(1994).
- [3] Ben-Hao Sa et al., Phys. Rev. C50, 2614 (1994).
- [4] B. Zhang, Comput. Phys. Commun. 109, 193 (1998).
- [5] D.Molnár and M. Gyulassy, Phys. Rev. C62, 054907 (2000).
- [6] M.Gyulassy and X.-N.Wang, Comput. Phys. Commun. 83, 307 (1994).
- [7] V.Börchers and al., Phys. Rev.C 62, 064903 (2000).
- [8] S.A.Bass,and al., nucl-th/0212103.
- [9] Ben-Hao Sa and al., Phys. Rev.C 59, 2728 (1999).
- [10] T. Sjöstrand, Comput. Phys. Commun. 82, 74 (1994).
- [11] Ben Hao Sa and A. Bonasera, PRC submitted.
- [12] K.Alpgard et al., Nucl.PhysB. 129, 365 (1977).

PARTICLE IDENTIFICATION AT HADES

G.Agakishiev⁷, C.Agodi², H.Alvarez-Pol¹⁹, A.Balanda⁵, R.Bassini¹⁰, G.Bellia^{2,3}, D.Belver¹⁹, J.Bielcik⁶, A.Blanco⁴, M.Böhmer¹⁴, C.Boiano¹⁰, A.Bortolotti¹⁰, J.L.Boyard¹⁶, S.Brambilla¹⁰, P.Braun-Munzinger⁶, P.Cabanelas¹⁹, S.Chernenko⁷, T.Christ¹⁴, R.Coniglione², M.Dahlinger⁶, J.Díaz²⁰, R.Djeridi⁹, F.Dohrmann¹⁸, I.Durán¹⁹, T.Eberl¹⁴, W.Enghardt¹⁸, L.Fabbietti¹⁴, O.Fateev⁷, P.Finocchiaro², P.J.R.Fonte⁴, J.Friese¹⁴, I.Fröhlich⁹, J.A.Garzón¹⁹, R.Gernhäuser¹⁴, M.Golubeva¹², D.González-Díaz¹⁹, E.Grosse¹⁸, F.Guber¹², T.Heinz⁶, T.Hennino¹⁶, S.Hlavac¹, J.Hoffmann⁶, R.Holzmann⁶, A.Ierusalimov⁷, I.Iori^{10,11}, A.Ivashkin¹², M.Jaskula⁵, M.Jurkovic¹⁴, M.Kajetanowicz⁵, B.Kämpfer¹⁸, K.Kanaki¹⁸, T.Karavicheva¹², D.Kirschner⁹, I.Koenig⁶, W.Koenig⁶, B.W.Kolb⁶, U.Kopf⁶, R.Kotte¹⁸, J.Kotulic-Bunta¹, R.Krücken¹⁴, A.Kugler¹⁷, W.Kühn⁹, R.Kulesa⁵, S.Lang⁶, J.Lehnert⁹, L.Maier¹⁴, P.Maier-Komor¹⁴, C.Maiolino², J.Marín¹⁹, J.Markert⁸, V.Metag⁹, N.Montes¹⁹, E.Moriniere¹⁶, J.Mousa¹⁵, M.Münch⁶, C.Müntz⁸, L.Naumann¹⁸, R.Novotny⁹, J.Novotny¹⁷, W.Ott⁶, J.Otwinowski⁵, Y.C.Pachmayer⁸, L.M.Pant⁹, V.Pechenov⁷, T.Pérez⁹, J.Pietraszko⁶, J.M.A.Pinhao⁴, R.Pleskac¹⁷, V.Pospíšil¹⁷, W.Przygoda⁵, A.Pullia^{10,11}, N.Rabin¹³, B.Ramstein¹⁶, S.Riboldi¹⁰, J.Ritman⁹, P.Rosier¹⁶, M.Roy-Stephan¹⁶, A.Rustamov⁶, A.Sadovsky¹⁸, B.Sailer¹⁴, P.Salabura⁵, P.Sapienza², A.Schmah⁶, W.Schön⁶, C.Schroeder⁶, E.Schwab⁶, P.Senger⁶, R.Simon⁶, V.Smolyankin¹³, L.Smykov⁷, S.Spataro², B.Spruck⁹, H.Stroebele⁸, J.Stroth^{8,6}, C.Sturm⁶, M.Sudol^{8,6}, V.Tiflov¹², P.Tlusty¹⁷, A.Toia⁹, M.Traxler⁶, H.Tsertos¹⁵, I.Turzo¹, V.Wagner¹⁷, W.Walus⁵, C.Willmott¹⁹, S.Winkler¹⁴, M.Wisniowski⁵, T.Wojcik⁵, J.Wüstenfeld⁸, Y.Zanevsky⁷, P.Zumbruch⁶

- 1) *Institute of Physics, Slovak Academy of Sciences, 84228 Bratislava, Slovakia*
- 2) *Istituto Nazionale di Fisica Nucleare - Laboratori Nazionali del Sud, 95125 Catania, Italy*
- 3) *Dipartimento di Fisica e Astronomia, Università di Catania, 95125, Catania, Italy*
- 4) *LIP-Laboratório de Instrumentação e Física Experimental de Partículas, Departamento de Física da Universidade de Coimbra, 3004-516 Coimbra, PORTUGAL.*
- 5) *Smoluchowski Institute of Physics, Jagiellonian University of Cracow, 30059 Cracow, Poland*
- 6) *Gesellschaft für Schwerionenforschung mbH, 64291 Darmstadt, Germany*
- 7) *Joint Institute of Nuclear Research, 141980 Dubna, Russia*
- 8) *Institut für Kernphysik, Johann Wolfgang Goethe-Universität, 60486 Frankfurt, Germany*
- 9) *II.Physikalisches Institut, Justus Liebig Universität Giessen, 35392 Giessen, Germany*
- 10) *Istituto Nazionale di Fisica Nucleare, Sezione di Milano, 20133 Milano, Italy*
- 11) *Dipartimento di Fisica, Università di Milano, 20133 Milano, Italy*
- 12) *Institute for Nuclear Research, Russian Academy of Science, 117312 Moscow, Russia*
- 13) *Institute of Theoretical and Experimental Physics, 117218 Moscow, Russia*
- 14) *Physik Department E12, Technische Universität München, 85748 Garching, Germany*
- 15) *Department of Physics, University of Cyprus, 1678 Nicosia, Cyprus*
- 16) *Institut de Physique Nucléaire d'Orsay, CNRS/IN2P3, 91406 Orsay Cedex, France*
- 17) *Nuclear Physics Institute, Academy of Sciences of Czech Republic, 25068 Rez, Czech Republic*
- 18) *Institut für Kern- und Hadronenphysik, Forschungszentrum Rossendorf, PF 510119, 01314 Dresden, Germany*
- 19) *Departamento de Física de Partículas. University of Santiago de Compostela. 15782 Santiago de Compostela, Spain*
- 20) *Instituto de Física Corpuscular, Universidad de Valencia-CSIC, 46100-Burjassot, Valencia, Spain*

Abstract

The HADES di-electron spectrometer, built at GSI by a large collaboration between 20 institutes from 10 European countries, has recently started to collect physics data. The complex data analysis is going on, and in this paper we report on the procedure we use for the particle identification.

1 INTRODUCTION

During last decade significant enhancements of dilepton yields in invariant mass spectra, as compared to an appropriate superposition of di-lepton contributions from freely decaying hadrons, were found both at relativistic (1-2 A.GeV) [1] and ultra-relativistic (160-200 A.GeV) heavy ion collisions [2]. In the intermediate mass range ($200 \text{ MeV}/c^2 < M_{\text{inv}} < 500 \text{ MeV}/c^2$) below the pole mass of the short lived ρ meson, the yield exceeds standard theoretical predictions up to a factor 5-7.

Presently most of the theoretical studies interpret these findings as a possible manifestation of the change of the vector mesons properties inside the nuclear medium. However, the underlying phenomenon could not be identified unambiguously and various interpretations have been proposed [3]. A new round of experiments aiming at better mass resolution and statistics is now under way to provide more precise data [4]. The High Acceptance Di-Electron Spectrometer (HADES) is a new second generation di-electron spectrometer designed to operate with proton, pion and heavy ion beams provided by the GSI accelerator facility in Darmstadt [5]. The spectrometer was built during 1997-2003 and is presently becoming operational. In this paper we present first results concerning the particle identification capabilities of the spectrometer.

2 THE SPECTROMETER

The HADES spectrometer is schematically depicted in Fig.1. A fast hadron-blind Ring Imaging Cherenkov (RICH) counter with gas radiator and solid CsI photocathode, placed around a segmented target, is used for electron identification [6]. Four Multi-wire Drift Chambers (MDC1-MDC4) together with a superconducting magnet, form the magnetic spectrometer for momentum measurement with an expected invariant mass resolution of 1-2% in the ρ/ω region [7]. A set of electromagnetic Pre-Shower detectors, together with a TOFINO ($18^\circ < \theta < 45^\circ$) and a Time-Of-Flight (TOF, $45^\circ < \theta < 85^\circ$) scintillator walls, constitute the Multiplicity and Electron Trigger Array (META) [8].

Each of above mentioned sub-detectors consists of six segments surrounding the target. A fast data acquisitions system is used as well as a two-level trigger scheme [9]: (a) LVL1- fast determination of the charged particle multiplicity (M_{ch}) in the META, in order to select central collisions and thus provide a first level trigger; (b) LVL2 – real time selection of electron pairs within a selectable invariant mass window, by correlating the impact position of each fast particle detected in the META with the center of a corresponding ring detected in the RICH.

In this report we present results from a commissioning run in November 2001, where the HADES detector was operated using only the following sub-systems: the RICH, the two inner MDC planes and the outer META. One of the studied reactions was C+C

at 2A.GeV. The intensity of the beam was $I_{\text{beam}} = 10^6$ particles/s and a 5% interaction length target was used. We collected 8×10^7 LVL1 triggered events with $M_{\text{ch}} > 3$. The MDC track segments were correlated with corresponding hits in the META after the magnetic field, in order to determine the momentum of particles. Simulation events were generated by a UrQMD code, while the propagation of particles and the detector response was simulated using a Geant 3 based package including the full HADES geometry. After digitization of the simulated information the resulting simulation data were analyzed in the same way as the experimental data.

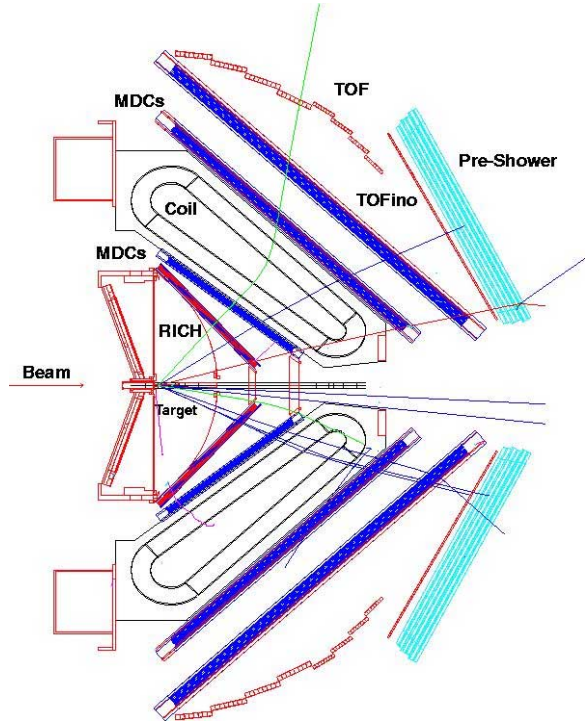


Figure 1 - Schematic cross section of the HADES spectrometer.

3 CHARGED HADRONS

Hadron identification is performed mainly on the basis of the measured momentum, velocity and energy loss in the TOF detector. The principle of the hadron identification is illustrated in fig. 2. Particles with different mass fill different regions in the velocity vs. momentum distribution. The pronounced maxima correspond to positive/negative pions and protons. One can also appreciate the effect of the superior time resolution of the TOF detector ($\sigma_{\text{tof}} \approx 150 \text{ ps}$) in comparison to the TOFINO ($\sigma_{\text{tofino}} \approx 350 \text{ ps}$)

The proton and pion yields were extracted and found to be in agreement within 10% with those values obtained by the analysis of the URQMD simulation data. The average correction factor, taking into account the geometrical acceptance of the detectors and the efficiency of the tracking method, is ~ 0.7 .

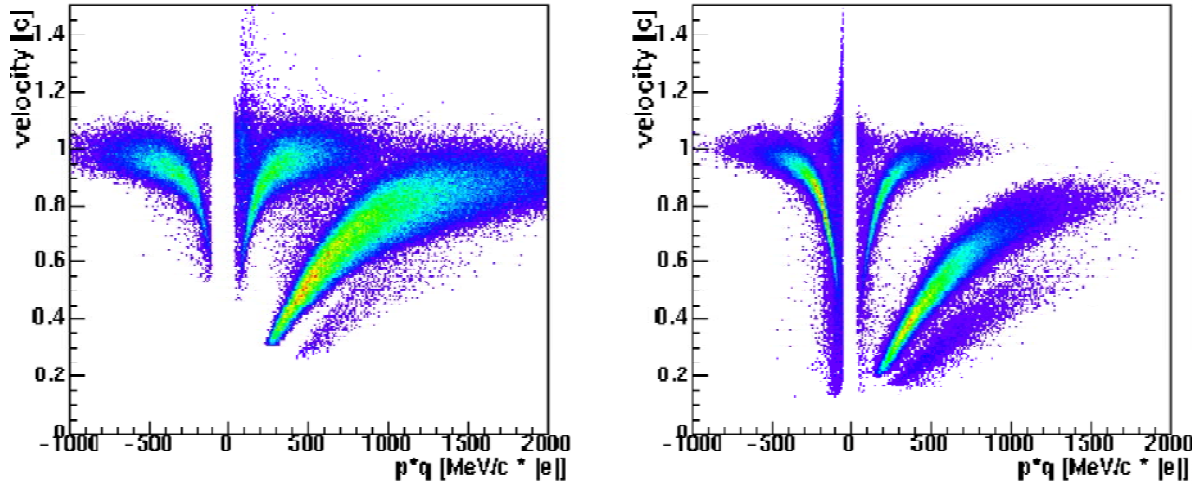


Figure 2 Velocity vs. charge*momentum of charged particles detected by HADES. Left: particles detected by the inner Pre-Shower/TOFINO detectors. Right: particles detected by the outer TOF detector.

4 ELECTRONS

For the analysis of electrons the key detector is the RICH. From all the minimum bias reconstructed rings we have chosen suitable quality criteria, in order to suppress fake rings produced for example by electronic noise or charged hadrons traversing the photon detector. The charged particle track segments in the inner MDC were matched with ring centres. The matching condition was $|\Delta\theta| < 1.7^\circ$ and $|\Delta\phi \cdot \sin(\theta)| < 1.8^\circ$ for the polar and the azimuthal angles, respectively. For additional electron identification, the following condition on the velocity of particles was applied: $0.8 < \beta < 1.2$ as determined by the TOF and $0.8 < \beta$ by the TOFINO. The β cut in TOFINO has been done only from one side because in case of more than 1 hit in a TOFINO paddle, the determination of time is not correct and leads to $\beta > 1.0$ for these cases. The multiplicity of the identified electrons per event in measured and simulated events differs by less than 30%. The shape of momentum spectra for electrons and positrons is in both cases very similar (Fig.3).

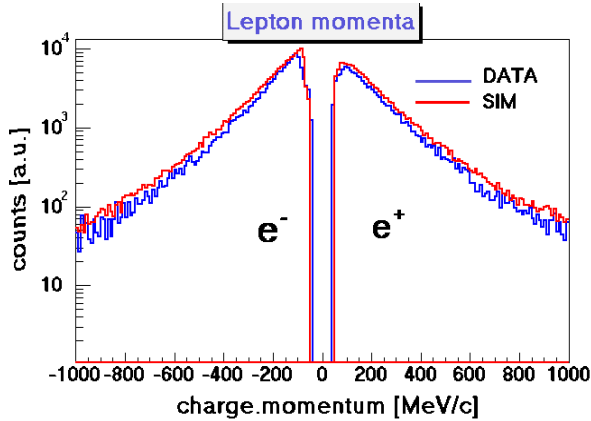


Figure 3 - Momentum spectra of electrons detected in C+C at 2 A GeV compared with results of simulation.

From identified unlike sign electrons we have constructed e^+e^- pairs. For further analysis we have used only pairs that contain electron candidates producing different hits in all detectors. Most of them are due to combinatorial background arising from photon conversion and Dalitz decay of π^0 mesons. In order to evaluate the combinatorial background we have used the like-sign pairs method [2]. By subtracting from the e^+e^- spectrum we can get a signal related to di-electron decays. The most dominant sources of e^+e^- pairs with opening angle larger than 4° are π^0 and, to a smaller extent, η Dalitz decays. After subtracting the combinatorial background, we observe indeed that the dominant signal is in the invariant mass region up to $150 \text{ MeV}/c^2$, as expected for π^0 Dalitz decay.

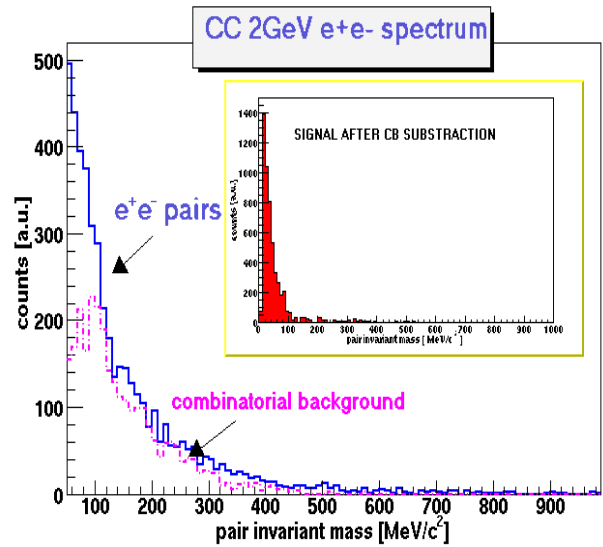


Figure - 4 Invariant mass spectrum of dilepton pairs detected in C+C at 2 A GeV.

5 SUMMARY AND OUTLOOK

The data analysis of the Nov01 run clearly demonstrated the capability of HADES to identify electron pair signals in the huge background produced by the high yield of charged hadrons, mainly protons and charged pions, in heavy-ion collisions. However, the lack of a second level trigger in this commissioning run manifested itself in the low statistics of observed electron pairs in the interesting region above 200 MeV/c², see inset in Fig.4. The second level trigger was put into operation, and tested, in May-September 2002. The first physics run was carried out in November 2002. We studied the C+C reaction at 2AGeV beam energy, storing about 213 million events. Their composition is 56% LVL1 trigger + 44% LVL2 trigger. Taking into account that such a LVL2/ LVL1 ratio gave rise to about a factor 9 in electron enrichment, this corresponds to a 20 times larger statistic in comparison to the Nov01 run. This data is currently being analyzed and with the results we expect to shed more light on the question of a possible di-electron pair yield excess in the invariant mass region below the ρ/ω vector mesons.

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

6 REFERENCES

- [1] R.J.Porter et al., Phys. Rev. Lett. 79 (1997) 1229.
- [2] Th.Ullrich et al., Nucl. Phys. A610 (1996) 317c, and A. Drees, Nucl. Phys. A610 (1996) 536c
- [3] E.L.Bratkoscaya et al., Nucl.Phys. A634 (1998) 168. and ref. cited in it
- [4] H.Appelhauser et al., Nucl.Phys. A698 (2002) 253c. and ref. cited in it
- [5] A.Kugler, Czech.J. Phys. vol. 50/S2 (2000) 72.
- [6] M.Böhmer, et al., Nucl. Instr. Meth. A471 (2001) 25
- [7] H.Bokemeyer, et al., Nucl. Instr. Meth. A477 (2002) 397.
- [8] C.Agodi et al., Nucl. Instr. Meth. A 492 (2002) 14.
- [9] J.Lehnert et al., Nucl. Inst. and Meth. A 502 (2003) 261 and A. Toia et al., Nucl. Inst. and Meth. A 502 (2003) 270

DIGITAL SIGNAL PROCESSING FROM CHIMERA: PULSE SHAPE ACQUISITION OF (FAST,SLOW) SCATTER PLOTS

M.Alderighi^a, A.Anzalone^b, R.Bassini^c, C.Boiano^c, G.Cardella^d, S.Cavallaro^b, E.DeFilippo^d, E.Geraci^f, F.Giustolisi^b,
P.Guazzoni^{c,*}, E.Laguidara^b, G.Lanzanò^d, G.Lanzalone^b, A.Pagano^d, M.Papa^d, S.Pirrone^d, G.Politi^d, F. Porto^b,
S.Russo^c, M.Sassi^c, G.Sechi^a, L.Zetta^c.

a) INFN and IASF-CNR, Milano - Italy

b) LNS and Dipartimento di Fisica Università di Catania - Italy

c) Dipartimento di Fisica Università di Milano and INFN - Italy

d) INFN and Dipartimento di Fisica Università di Catania - Italy

e) INFN and Dipartimento di Fisica Università di Bologna - Italy

** Corresponding author, e-mail: paolo.guazzoni@mi.infn.it*

Abstract

A 100 Msamples/s 14-bit Sampling Analog-to-Digital converter has been used to perform digital pulse-shape acquisition of signals collected from CHIMERA telescopes. The signals from a typical CHIMERA detection cell have been collected using a very simple analog front end, basically reduced to the preamplifier. The preliminary on-beam results for (Fast,Slow) scatter plot acquisition are presented in this contribution.

1 INTRODUCTION

Aim of this series of contributions is to present a digital signal processing method which is able to fully exploit the performance of last generation 4π -Detector Arrays, with an additional advantage of a possible big reduction of the realization costs. In order to simplify the electronic chain of multidetector telescopes, we have carried out some tests using commercial Sampling Analog-to-Digital Converter (SADC) modules to perform a real-time digital pulse-shape analysis of the signals coming from a standard detection cell of CHIMERA (i.e. a telescope of a 300 μm silicon detector and a 6x6x12 cm³ CsI(Tl) scintillator coupled to a photodiode), directly collecting signals from the preamplifier. The preliminary on-beam results for (Fast,Slow) scatter plot acquisition from CsI(Tl) detectors are presented in this contribution.

2 EXPERIMENTAL RESULTS

The pulse height of Silicon detectors is proportional to the incident-particle energy, independently of its type (neglecting the Pulse Height Defect). CsI(Tl) scintillators, on the contrary, emit light pulses whose shape varies with the type of incident radiation. As well known the decay of the light emitted by the CsI(Tl) is given by the sum of two exponential functions, called Fast and Slow components:

$$L(t) = (A/\tau_F) \exp(-t/\tau_F) + (B/\tau_S) \exp(-t/\tau_S) \quad (1)$$

where $L(t)$ is the light pulse amplitude at time t and τ_F and τ_S denote, respectively, the decay constant of the

Fast and Slow components of the light pulse. Typical values are $\tau_F \sim 0.4 - 0.7 \mu\text{s}$, $\tau_S \sim 7 \mu\text{s}$. Discrimination among LCP is possible essentially because the ratio between the amplitudes of Fast and Slow components is a function of mass, charge and energy of the detected product. Thus the use of scatter plots of Fast vs. Slow components is a useful method employed in multi-detector arrays for LCP Identification (LCP-Id). A value of Fast and Slow components of the light pulse may be obtained by integrating, over a Δt interval, the charge output of the photodiode at two proper times t_1 and t_2 . Using the same electronic chain and the same hardware platform and software procedure of the previous contribution, describing the $(\Delta E, \text{Fast})$ scatter plot acquisition, we have also evaluated the possibility to perform Light Charged Product (LCP) Identification, i.e. (Fast,Slow) scatter plots, by using digital pulse shape acquisition.

For CHIMERA, the classical two-gate method [1] based on the comparison between Fast and Slow components is applied to collect Fast and Slow signals from CsI(Tl) detectors. The scintillator is coupled to a Hamamatsu photodiode, connected to a charge preamplifier, and to a Silena 761F amplifier. Its shaping time (1.5 μs) is the same for Fast and Slow outputs. After the amplifier, the Fast signal enters a stretcher for holding the pulse at its maximum value up to the completion of the Slow signal. Then it enters the "Fast" QDC. The Slow signal, after the amplifier shaping, enters directly the "Slow" QDC. To obtain Fast and Slow components the two signals are simultaneously converted by the QDCs with a gate pulse (2 μs wide) delayed 8 μs from the beginning of the pulse.

With digital signal processing, we collected pulse shapes directly from the preamplifier of the CsI(Tl),

with an only sampling ADC. Later analyzing the shape of the collected signal we can extract both the Fast and Slow components of the light pulse emitted by the CsI(Tl).

To reconstruct the (Fast,Slow) scatter plots in order to perform LCP-Id we had to find a proper algorithm to apply the comparison method. Firstly, we tried to apply the two-gate method to the signals properly modifying width and position of the gates. The results were not fully satisfactory, as only charge and not isotopic identification was possible. In fact while the whole Fast information is still contained in the rising edge, the Slow component is spread out on both rising edge and beginning of the tail.

As heuristic approach we did some tests using a timing-filter amplifier with different time constants to differentiate the charge signal of the preamplifier. The results were better, thus we decided to work on the numerical derivative of the pulse and apply to it the two-gate method.

In Fig. 1 the shape of a typical output signal from the preamplifier of CsI(Tl) scintillator (*shape-a*) is shown together with the obtained shape of the pulse-derivative (*shape-b*). The two gates employed to calculate P1 and P2, the gated areas used for LCP-Id, are also shown.

In Fig. 2 the (P_1 , P_1+P_2) scatter plot (equivalent to the standard Fast-Slow scatter plot), obtained for the reaction $^{58}\text{Ni} + ^{27}\text{Al}$ at 25 AMeV incident energy and

$\theta_{\text{lab}} = 6^\circ$, is shown. The CsI(Tl) was used without Silicon in front.

In Fig. 3 (*left*) the zoomed area indicated in Fig. 2 is magnified. Fig. 3 (*right*) shows the LCP-Id spectrum obtained by projecting the properly linearized (P_1 , P_1+P_2) scatter plot.

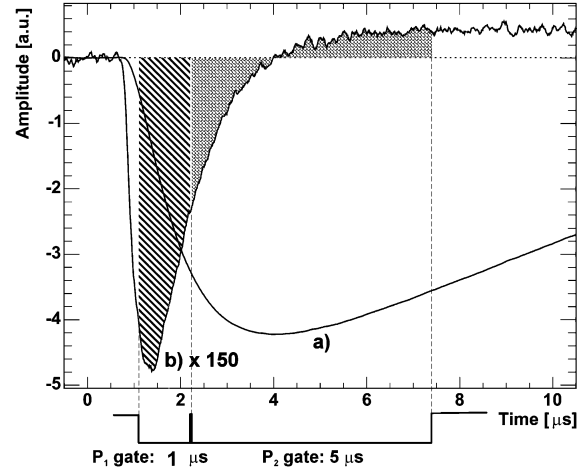


Fig. 1: Shapes of: a) unfiltered output signal from CsI(Tl); b) numerical derivative of the filtered signal, with highlighted the two gates used to calculate the P1 and P2 components (see text).

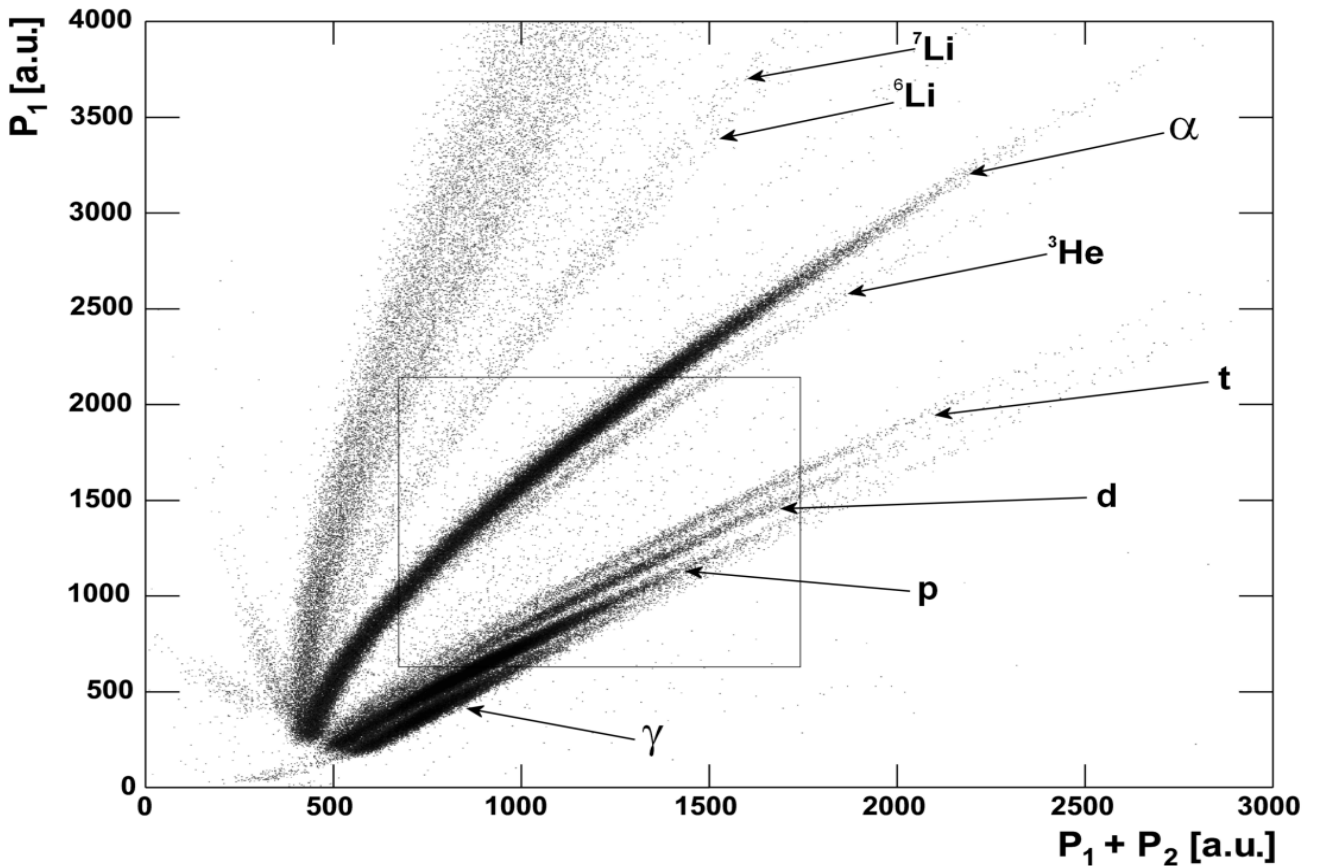


Fig. 2: Scatter plot of P1 vs. P1+P2 obtained in “digital way” for the $^{58}\text{Ni} + ^{27}\text{Al}$ reaction

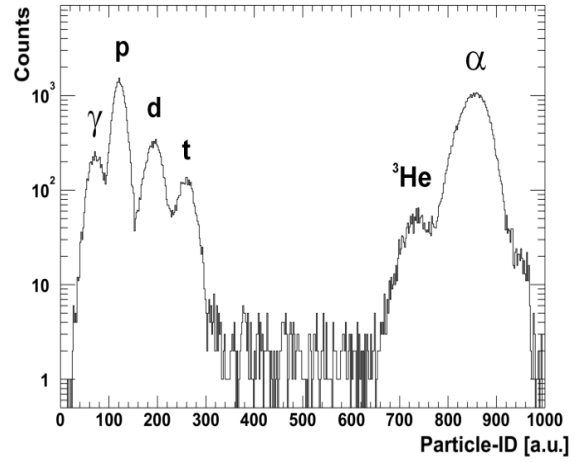
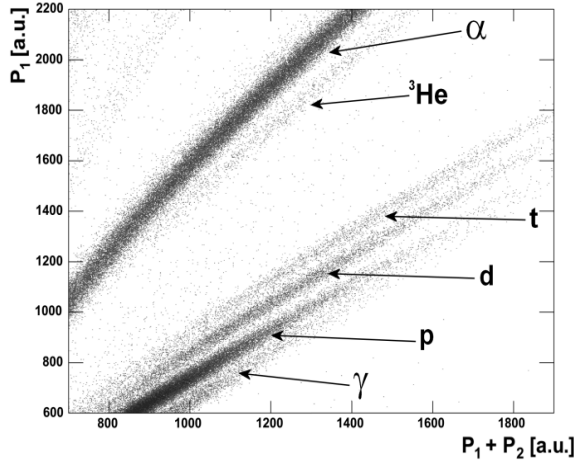


Fig. 3: (left) Zoom of the area of the scatter plot outlined in Fig. 2; (right) LCP-ID spectrum obtained by projecting the properly linearized scatter plot on particle-ID axis.

All quantitative comparisons between the results obtained in “digital way” and in “analog way” were performed by using the Factor of Merit (FoM) of the identification defined as the separation between two peaks (i.e. centroid distance) divided by the sum of their full widths at half maximum [2]. Fig. 4 shows the histogram of the factor of merit for the identification spectrum shown in Fig. 3 (digital), compared with similar results obtained with the standard CHIMERA electronic chain (analog). It has to be noted that the “digital” results are obtained with a trigger in *multiplicity one*, while the analog in *multiplicity two* (no gamma rays).

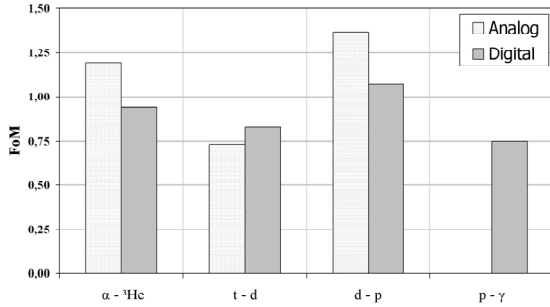


Fig. 4: The figure shows the factor of merit for the identification spectrum shown in Fig. 3 (digital), compared with similar results obtained with the standard CHIMERA electronic chain (analog).

Fig. 5 shows examples of pulse-form for different LCPs and gamma rays, collected for the reaction $^{58}\text{Ni} + ^{27}\text{Al}$ at 25 AMeV incident energy and $\theta_{\text{lab}} = 6^\circ$.

In order to facilitate comparison, the different pulse-forms were normalized to the same height at $t = 16 \mu\text{s}$, and their baselines were shifted to zero.

A pulse-form due to a photon conversion directly in the silicon photodiodes is also shown. It has to be noted its steep rise, as compared to all other pulse-forms.

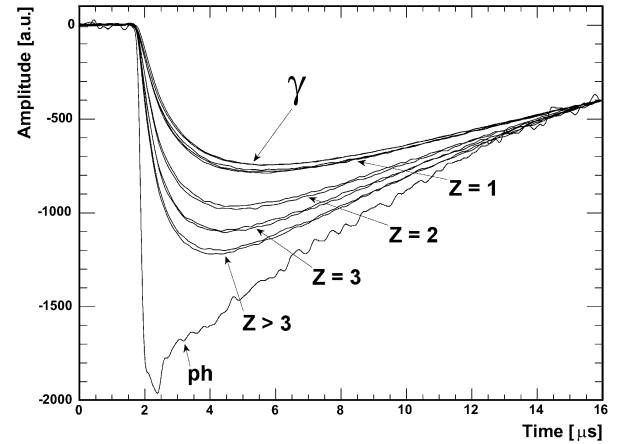


Fig. 5: Selected pulse shapes from CsI(Tl), due to gammas and products of different charge are shown. The ph-trace is due to a photon conversion directly in the silicon photodiode.

3 REFERENCES

- [1] D.Guinet, et al., NIM A278 (1989) 614.
- [2] R.A.Winyard, et al., NIM 95 (1971) 141.

DIGITAL SIGNAL PROCESSING FROM CHIMERA: GENERALITIES AND PULSE SHAPE ACQUISITION OF (ΔE ,FAST) SCATTER PLOTS

M.Alderighi^a, A.Anzalone^b, R.Bassini^c, C.Boiano^c, G.Cardella^d, S.Cavallaro^b, E.DeFilippo^d, E.Geraci^f, F.Giustolisi^b,
P.Guazzoni^{c,*}, E.Laguidara^b, G.Lanzanò^d, G.Lanzalone^b, A.Pagano^d, M.Papa^d, S.Pirrone^d, G.Politi^d, F. Porto^b,
S.Russo^c, M.Sassi^c, G.Sechi^a, L.Zetta^c.

a) INFN and IASF-CNR, Milano - Italy

b) LNS and Dipartimento di Fisica Università di Catania - Italy

c) Dipartimento di Fisica Università di Milano and INFN - Italy

d) INFN and Dipartimento di Fisica Università di Catania - Italy

e) INFN and Dipartimento di Fisica Università di Bologna - Italy

** Corresponding author, e-mail: paolo.guazzoni@mi.infn.it*

Abstract

A 100 Msamples/s 14-bit Sampling Analog-to-Digital converter has been used to perform digital pulse-shape acquisition of signals collected from CHIMERA telescopes. The signals from a typical CHIMERA detection cell have been collected using a very simple analog front end, basically reduced to the preamplifier. The preliminary on-beam results for (ΔE ,Fast) scatter plots are presented in this contribution.

1 INTRODUCTION

Aim of this series of contributions is to present a digital signal processing method which is able to fully exploit the performance of last generation 4π -Detector Arrays, with an additional advantage of a possible big reduction of the realization costs. In order to simplify the electronic chain of multidetector telescopes, we have carried out some tests using commercial Sampling Analog-to-Digital Converter (SADC) modules to perform a real-time digital pulse-shape analysis of the signals coming from a standard detection cell of CHIMERA (i.e. a telescope of a 300 μm silicon detector and a 6x6x12 cm^3 CsI(Tl) scintillator coupled to a photodiode), directly collecting signals from the preamplifier. The preliminary on-beam results obtained for (ΔE ,Fast) scatter plots are presented in this contribution.

2 SIGNAL PROCESSING

In view of new 4π -Detector Array projects [1,2] we have implemented an ad hoc system to digitally process data collected from a typical CHIMERA detection cell. This work has been motivated by both the increasing employment of digital pulse-shape analysis in γ -spectroscopy and our previous experience in on-line digital signal processing [3,4]. The advantages of using digital techniques in gamma-spectroscopy have been extensively proved. Digital pulse shape acquisition, among many other possibilities, can be used for correction of pulse distortion due to electronic noise and pulse pile-up [5], for efficient baseline correction,

allowed by post-triggering of the pulse, spurious pulse discrimination based on their shape analysis and pulse energy evaluation [6], or for pulse height analysis. More in detail, many advantages arise from the use of digital pulse shape acquisition: a) possibility to implement online computation of algorithms directly on the shape of collected pulses such as optimal filters which are hardly realized with analog techniques; b) insensitivity to pick-up noise, as soon as the signal has been digitized; c) flexibility and possibility to periodically recalibrate the system with software procedures.

The use of fast computers, such as new bi-processors with 2.4 GHz new generation CPU that allow for fast on-line real-time analysis on the digitized data, is another advantage with respect to the standard analog way.

The aim of the preliminary on-beam tests was to verify the feasibility of digital signal processing using typical detection cells of a multidetector with emphasis on achieving good identification over a very large dynamic range such as that of an experiment in the intermediate energy regime (10-40 AMeV).

In all tests, an acquisition rate of hundreds of Hz has been reached, fully compatible with CHIMERA acquisition rate.

For our sampling data acquisition system we have chosen to use commercial Sampling ADCs to save manpower. The only constraints we have complied in the choice have been that the digitizer resolution was good enough to cover the full reaction dynamics (up to GeVs) and its sampling rate satisfied the Nyquist frequency.

The ADC used is a SIS3301 [7], an 8-channel 6U VME digitizer/transient recorder with a sampling rate of up to 105 MHz for the individual channel and 14-bit resolution. It manages a dual memory bank, a multievent functionality and pre/post trigger capability.

SADC was located in a VME crate, together with an embedded CPU module, a VP7 by SBS Technologies [8]. The VP7 is a 6U all-in-one VME-bus CPU based on Pentium III processor (700 MHz).

In Fig. 1 the block diagram of the acquisition program is shown. It is written in Visual C++ and runs under Windows NT 4.0.

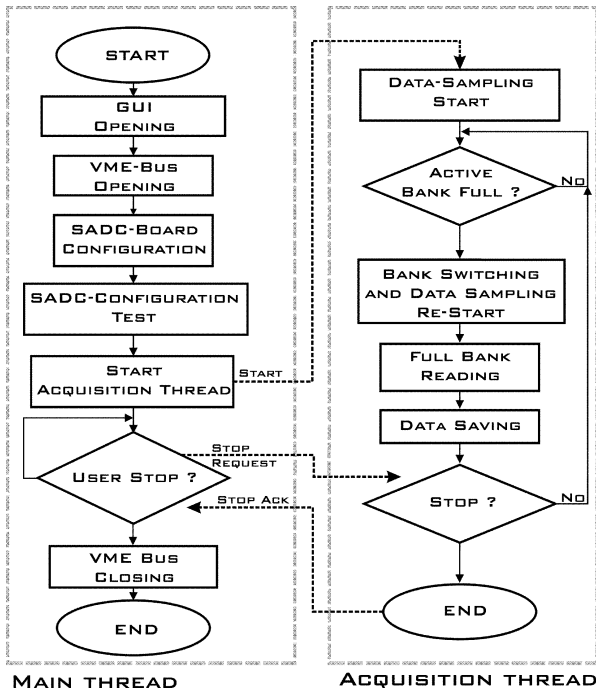


Fig. 1: Block diagram of the acquisition program running on VP7.

3 EXPERIMENTAL RESULTS

As previously said, we decided to collect signals directly from the preamplifiers of both Silicon and CsI(Tl) detectors. A two-stage preamplifier [9], developed by the Electronic Laboratory of the Sezione di Milano of the Istituto Nazionale di Fisica Nucleare, has been used instead of the standard CHIMERA preamplifier. Its first stage is a charge preamplifier; the second one an output buffer. Different sensitivities have been used for silicon detector (2.5 mV/MeV, gain 2) and CsI(Tl) scintillator (90 mV/MeV, gain 2).

For a square pulse (rise-time 5 ns, width 1 ms and frequency 100 Hz) the output signal of the preamplifier – properly modified to perform this test – has a rise-time of 30 ns and a fall time of 45 μ s. Constant fraction discriminators connected to the different detectors were used to trigger SADC.

In Fig. 2 the electronic chain used for digital pulse shape acquisition of (ΔE ,Fast) scatter plots is shown.

To perform Pulse Height Analysis (PHA) of the signals coming from the telescope in order to reconstruct the (ΔE ,Fast) scatter plot, the full pulse height (Maximum) of the signals from both Silicon and CsI(Tl) has been used as “true” signal-value.

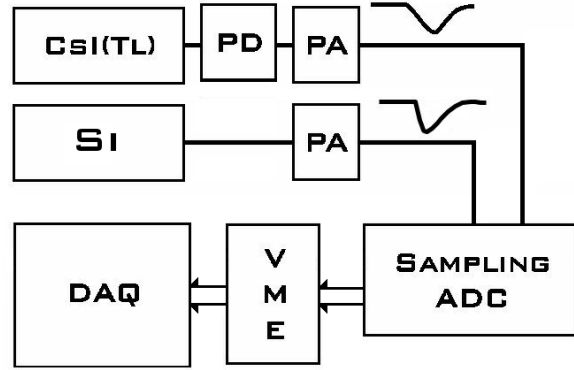


Fig. 2: Electronic chain used for digital pulse shape acquisition.

Each signal has been filtered digitally by means of a simple triangular filter [10], using a symmetric triangle with a time baseline of 11 samples (110 ns at 100 Msamples/s).

The use of post-trigger allowed for an accurate baseline restoring of each pulse, before the computation of pulse height and of Fast and Slow components.

Waveforms of 2048 consecutive ADC samples have been collected at 10 ns time intervals and stored in the SADC memory banks in wrap-around mode. For every event the sample collection is stopped by using a post-trigger. From this instant the pulse-form for each event parameter (ΔE and Light Pulse) is reconstructed and stored.

The samples before the beginning of the pulse have been used to determine the baseline value. In our case, baseline is defined as an average ADC value of these samples located in the “baseline window” ($\sim 1\mu$ s duration, positioned at the beginning of the waveform, i.e. 100 samples from sample #100 to sample #200). In the following we will no more mention filtering and baseline subtraction, always done for the shown results.

Digital constant fraction timing was used to compute the beginning of pulses and corresponds to the time at which the pulse-form cross 10% of the full pulse height relative to baseline.

A typical ΔE vs. Maximum of Light Pulse (MLP) scatter plot is shown in Fig. 3 for the reaction $^{40}\text{Ar} + ^{12}\text{C}$ at 20 AMeV incident energy and $\theta_{\text{lab}} = 3^\circ$.

In the same figure the back-trace of the pulses (both from Silicon and from CsI(Tl)) for different charges and energies is shown. In this way, specially in case of “debugging” of a multidetector, the digital pulse shape acquisition is a powerful tool that allows for a full control of the working mode of the array.

The particle-Id spectrum obtained by projecting the properly linearized (ΔE ,MLP) scatter plot on the ΔE axis is shown in Fig. 3b.

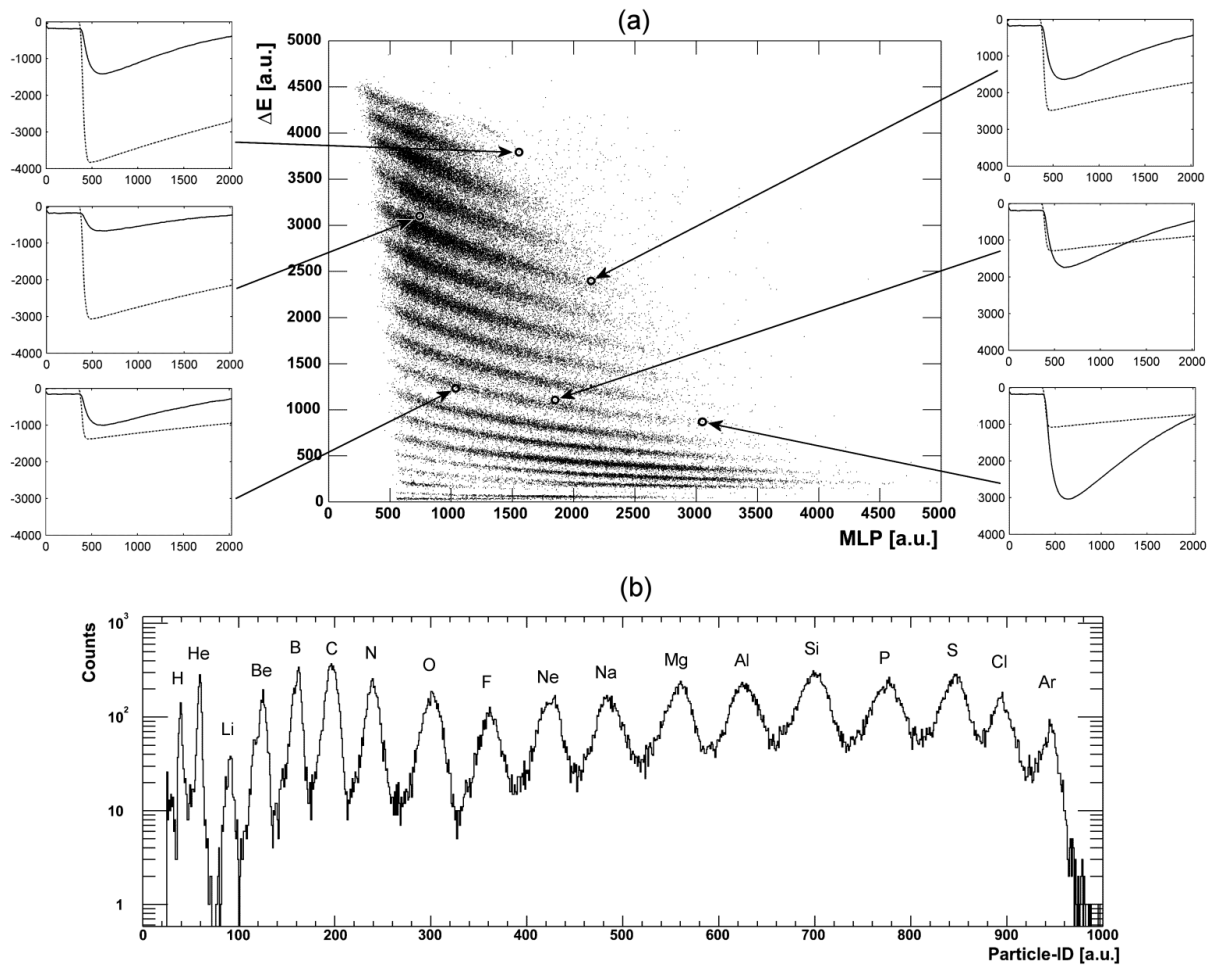


Fig. 3 (a): (ΔE , MLP) scatter plot for the $^{40}\text{Ar} + ^{12}\text{C}$ reaction. Examples of both Silicon and CsI(Tl) pulses for different charges, back-traced from the point in the scatter plot, are also shown. (b) Particle-Id spectrum obtained by projecting the properly linearized (ΔE , MLP) scatter plot on the ΔE axis.

The done tests demonstrate the feasibility of a full digital processing of multidetector signals, directly collected from the preamplifiers of a detection cell of a 4π -Detector Array, i.e. a telescope of a very high capacitance (1 nF) Silicon detector coupled to a very large volume ($> 400 \text{ cm}^3$) CsI(Tl) scintillator during a typical Intermediate Energy Nuclear Physics Experiment. The followed approach provides a discrimination for Light Charged Products and Intermediate Mass Fragments as good as the one obtained with the standard analog one over a large energy range.

Moreover this method implies simplified electronic setup in a cost-effective manner with respect to the standard setup presently used by multidetector arrays used in intermediate energy Nuclear Physics.

4 REFERENCES

- [1] http://www.ganil.fr/eurisol/instrumentationgroup/meetings/reaction-subgroup/Reactions_Legnaro_06-04-01.pdf.
- [2] http://www.finuphy.org/doc/New_Joint_Research_Projects_I3NS.pdf
- [3] S.Aiello, et al., IEEE Trans. Nucl. Sci. 47, (2000) 196.
- [4] M.Alderighi, et al., IEEE Trans. Nucl. Sci. 49 (2002) 432.
- [5] R.E. Chrien and R.J. Sutter, NIM A249 (1986) 421.
- [6] E. Cosulich and F. Gatti, NIM A321 (1992) 211.
- [7] SIS GmbH, Hamburg, Germany.
- [8] SBS Technology, Albuquerque, USA.
- [9] R.Bassini, et al., Proceeding of NSS2003 Conference, Contribution N36-45.
- [10] V.T.Jordanov and G.F.Knoll, NIM A345 (1994) 337.

DIGITAL SIGNAL PROCESSING FROM CHIMERA: PULSE SHAPE ACQUISITION OF (FAST,SLOW) SCATTER PLOTS

M.Alderighi^a, A.Anzalone^b, R.Bassini^c, C.Boiano^c, G.Cardella^d, S.Cavallaro^b, E.DeFilippo^d, E.Geraci^f, F.Giustolisi^b,
P.Guazzoni^{c,*}, E.Laguidara^b, G.Lanzanò^d, G.Lanzalone^b, A.Pagano^d, M.Papa^d, S.Pirrone^d, G.Politi^d, F. Porto^b,
S.Russo^c, M.Sassi^c, G.Sechi^a, L.Zetta^c.

a) INFN and IASF-CNR, Milano - Italy

b) LNS and Dipartimento di Fisica Università di Catania - Italy

c) Dipartimento di Fisica Università di Milano and INFN - Italy

d) INFN and Dipartimento di Fisica Università di Catania - Italy

e) INFN and Dipartimento di Fisica Università di Bologna - Italy

** Corresponding author, e-mail: paolo.guazzoni@mi.infn.it*

Abstract

A 100 Msamples/s 14-bit Sampling Analog-to-Digital converter has been used to perform digital pulse-shape acquisition of signals collected from CHIMERA telescopes. The signals from a typical CHIMERA detection cell have been collected using a very simple analog front end, basically reduced to the preamplifier. The preliminary on-beam results for (Fast,Slow) scatter plot acquisition are presented in this contribution.

1 INTRODUCTION

Aim of this series of contributions is to present a digital signal processing method which is able to fully exploit the performance of last generation 4π -Detector Arrays, with an additional advantage of a possible big reduction of the realization costs. In order to simplify the electronic chain of multidetector telescopes, we have carried out some tests using commercial Sampling Analog-to-Digital Converter (SADC) modules to perform a real-time digital pulse-shape analysis of the signals coming from a standard detection cell of CHIMERA (i.e. a telescope of a 300 μm silicon detector and a 6x6x12 cm³ CsI(Tl) scintillator coupled to a photodiode), directly collecting signals from the preamplifier. The preliminary on-beam results for (Fast,Slow) scatter plot acquisition from CsI(Tl) detectors are presented in this contribution.

2 EXPERIMENTAL RESULTS

The pulse height of Silicon detectors is proportional to the incident-particle energy, independently of its type (neglecting the Pulse Height Defect). CsI(Tl) scintillators, on the contrary, emit light pulses whose shape varies with the type of incident radiation. As well known the decay of the light emitted by the CsI(Tl) is given by the sum of two exponential functions, called Fast and Slow components:

$$L(t) = (A/\tau_F) \exp(-t/\tau_F) + (B/\tau_S) \exp(-t/\tau_S) \quad (1)$$

where $L(t)$ is the light pulse amplitude at time t and τ_F and τ_S denote, respectively, the decay constant of the

Fast and Slow components of the light pulse. Typical values are $\tau_F \sim 0.4 - 0.7 \mu\text{s}$, $\tau_S \sim 7 \mu\text{s}$. Discrimination among LCP is possible essentially because the ratio between the amplitudes of Fast and Slow components is a function of mass, charge and energy of the detected product. Thus the use of scatter plots of Fast vs. Slow components is a useful method employed in multi-detector arrays for LCP Identification (LCP-Id). A value of Fast and Slow components of the light pulse may be obtained by integrating, over a Δt interval, the charge output of the photodiode at two proper times t_1 and t_2 . Using the same electronic chain and the same hardware platform and software procedure of the previous contribution, describing the $(\Delta E, \text{Fast})$ scatter plot acquisition, we have also evaluated the possibility to perform Light Charged Product (LCP) Identification, i.e. (Fast,Slow) scatter plots, by using digital pulse shape acquisition.

For CHIMERA, the classical two-gate method [1] based on the comparison between Fast and Slow components is applied to collect Fast and Slow signals from CsI(Tl) detectors. The scintillator is coupled to a Hamamatsu photodiode, connected to a charge preamplifier, and to a Silena 761F amplifier. Its shaping time (1.5 μs) is the same for Fast and Slow outputs. After the amplifier, the Fast signal enters a stretcher for holding the pulse at its maximum value up to the completion of the Slow signal. Then it enters the "Fast" QDC. The Slow signal, after the amplifier shaping, enters directly the "Slow" QDC. To obtain Fast and Slow components the two signals are simultaneously converted by the QDCs with a gate pulse (2 μs wide) delayed 8 μs from the beginning of the pulse.

With digital signal processing, we collected pulse shapes directly from the preamplifier of the CsI(Tl),

with an only sampling ADC. Later analyzing the shape of the collected signal we can extract both the Fast and Slow components of the light pulse emitted by the CsI(Tl).

To reconstruct the (Fast,Slow) scatter plots in order to perform LCP-Id we had to find a proper algorithm to apply the comparison method. Firstly, we tried to apply the two-gate method to the signals properly modifying width and position of the gates. The results were not fully satisfactory, as only charge and not isotopic identification was possible. In fact while the whole Fast information is still contained in the rising edge, the Slow component is spread out on both rising edge and beginning of the tail.

As heuristic approach we did some tests using a timing-filter amplifier with different time constants to differentiate the charge signal of the preamplifier. The results were better, thus we decided to work on the numerical derivative of the pulse and apply to it the two-gate method.

In Fig. 1 the shape of a typical output signal from the preamplifier of CsI(Tl) scintillator (*shape-a*) is shown together with the obtained shape of the pulse-derivative (*shape-b*). The two gates employed to calculate P1 and P2, the gated areas used for LCP-Id, are also shown.

In Fig. 2 the (P_1 , P_1+P_2) scatter plot (equivalent to the standard Fast-Slow scatter plot), obtained for the reaction $^{58}\text{Ni} + ^{27}\text{Al}$ at 25 AMeV incident energy and

$\theta_{\text{lab}} = 6^\circ$, is shown. The CsI(Tl) was used without Silicon in front.

In Fig. 3 (*left*) the zoomed area indicated in Fig. 2 is magnified. Fig. 3 (*right*) shows the LCP-Id spectrum obtained by projecting the properly linearized (P_1 , P_1+P_2) scatter plot.

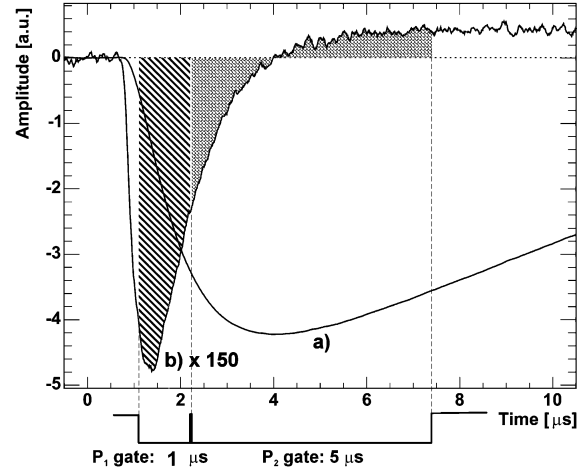


Fig. 1: Shapes of: a) unfiltered output signal from CsI(Tl); b) numerical derivative of the filtered signal, with highlighted the two gates used to calculate the P1 and P2 components (see text).

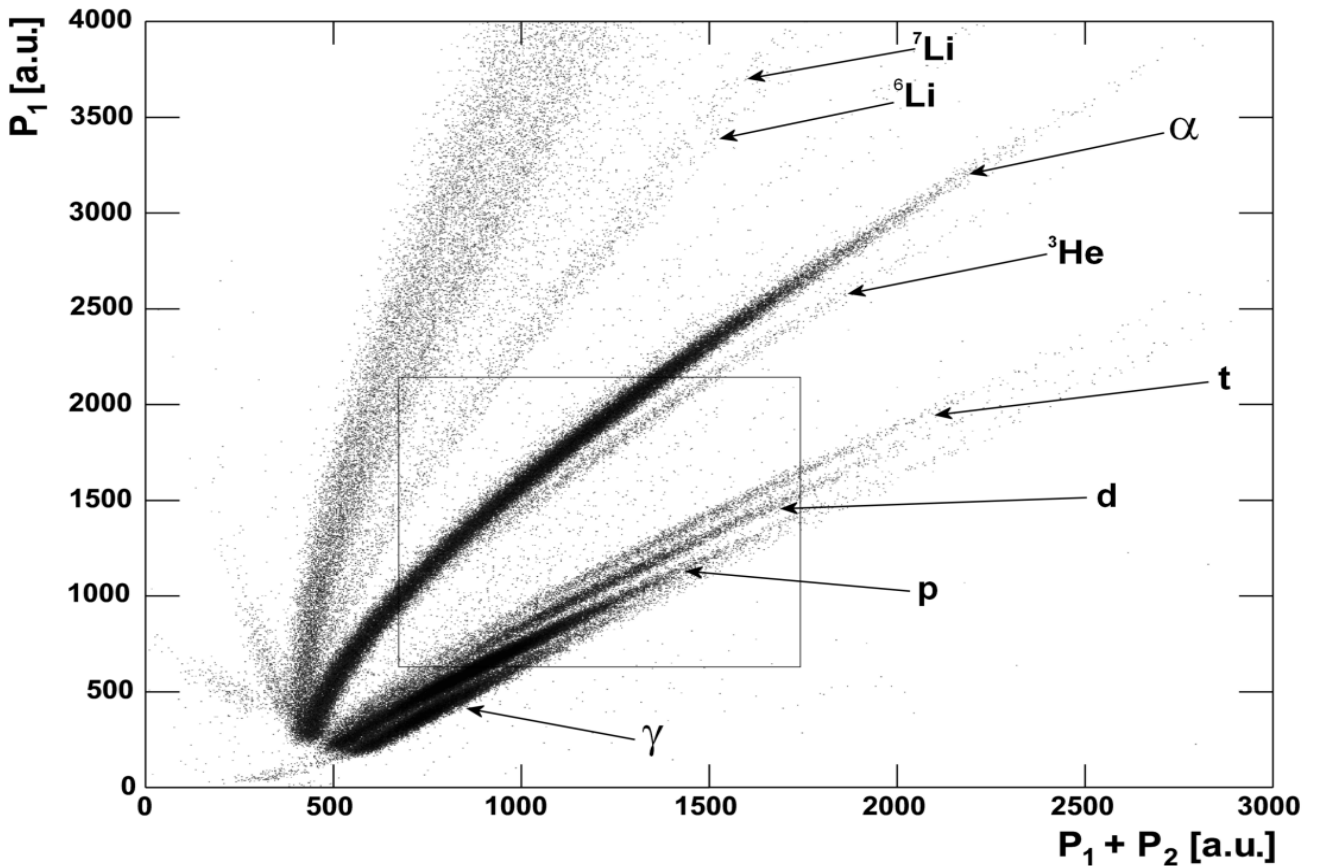


Fig. 2: Scatter plot of P_1 vs. P_1+P_2 obtained in “digital way” for the $^{58}\text{Ni} + ^{27}\text{Al}$ reaction

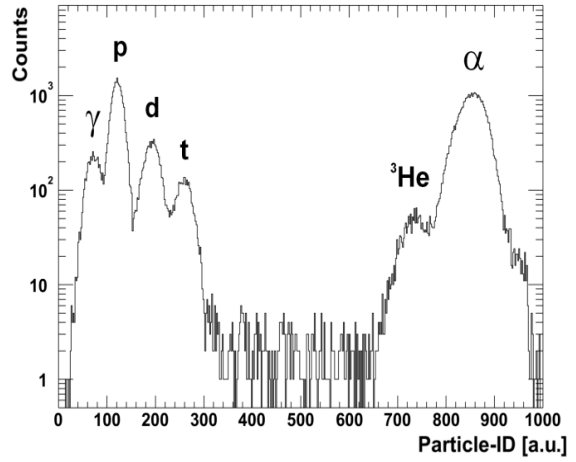
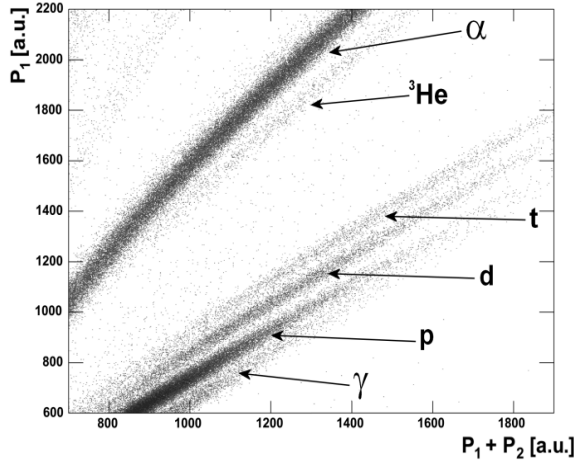


Fig. 3: (left) Zoom of the area of the scatter plot outlined in Fig. 2; (right) LCP-ID spectrum obtained by projecting the properly linearized scatter plot on particle-ID axis.

All quantitative comparisons between the results obtained in “digital way” and in “analog way” were performed by using the Factor of Merit (FoM) of the identification defined as the separation between two peaks (i.e. centroid distance) divided by the sum of their full widths at half maximum [2]. Fig. 4 shows the histogram of the factor of merit for the identification spectrum shown in Fig. 3 (digital), compared with similar results obtained with the standard CHIMERA electronic chain (analog). It has to be noted that the “digital” results are obtained with a trigger in *multiplicity one*, while the analog in *multiplicity two* (no gamma rays).

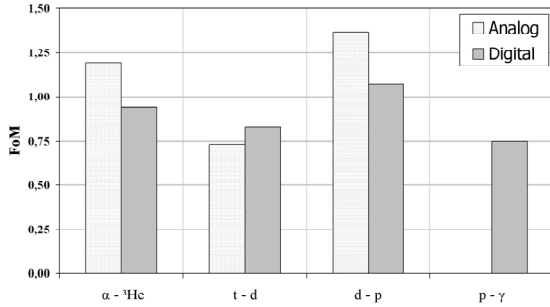


Fig. 4: The figure shows the factor of merit for the identification spectrum shown in Fig. 3 (digital), compared with similar results obtained with the standard CHIMERA electronic chain (analog).

Fig. 5 shows examples of pulse-form for different LCPs and gamma rays, collected for the reaction $^{58}\text{Ni} + ^{27}\text{Al}$ at 25 AMeV incident energy and $\theta_{\text{lab}} = 6^\circ$.

In order to facilitate comparison, the different pulse-forms were normalized to the same height at $t = 16 \mu\text{s}$, and their baselines were shifted to zero.

A pulse-form due to a photon conversion directly in the silicon photodiodes is also shown. It has to be noted its steep rise, as compared to all other pulse-forms.

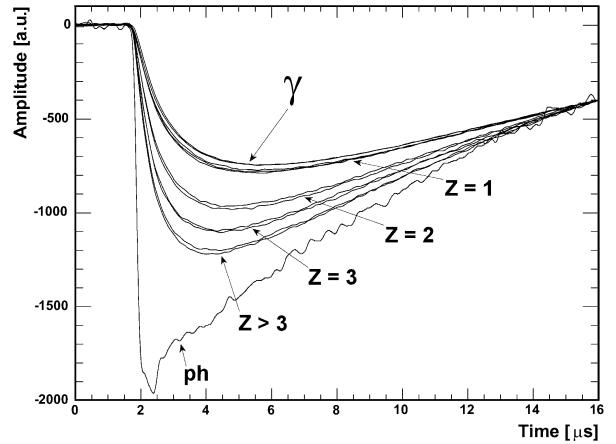


Fig. 5: Selected pulse shapes from CsI(Tl), due to gammas and products of different charge are shown. The ph-trace is due to a photon conversion directly in the silicon photodiode.

3 REFERENCES

- [1] D.Guinet, et al., NIM A278 (1989) 614.
- [2] R.A.Winyard, et al., NIM 95 (1971) 141.

DIGITAL SIGNAL PROCESSING FROM CHIMERA: PULSE SHAPE ACQUISITION FOR CHARGE DISCRIMINATION IN REVERSED SILICON DETECTORS

M.Alderighi^a, A.Anzalone^b, R.Bassini^c, C.Boiano^c, G.Cardella^d, S.Cavallaro^b, E.DeFilippo^d, E.Geraci^f, F.Giustolisi^b,
P.Guazzoni^{c,*}, E.Laguidara^b, G.Lanzanò^d, G.Lanzalone^b, A.Pagano^d, M.Papa^d, S.Pirrone^d, G.Politi^d, F. Porto^b,
S.Russo^c, M.Sassi^c, G.Sechi^a, L.Zetta^c.

a) INFN and IASF-CNR, Milano - Italy

b) LNS and Dipartimento di Fisica Università di Catania - Italy

c) Dipartimento di Fisica Università di Milano and INFN - Italy

d) INFN and Dipartimento di Fisica Università di Catania - Italy

e) INFN and Dipartimento di Fisica Università di Bologna - Italy

** Corresponding author, e-mail: paolo.guazzoni@mi.infn.it*

Abstract

A 100 Msamples/s 14-bit Sampling Analog-to-Digital converter has been used to perform digital pulse-shape acquisition of signals collected from CHIMERA telescopes. The signals from a typical CHIMERA detection cell have been collected using a very simple analog front end, basically reduced to the preamplifier. The preliminary on-beam results for Charge Discrimination in Reversed Silicon Detectors are presented in this contribution.

1 INTRODUCTION

Aim of this series of contributions is to present a digital signal processing method which is able to fully exploit the performance of last generation 4π -Detector Arrays, with an additional advantage of a possible big reduction of the realization costs. In order to simplify the electronic chain of multidetector telescopes, we have carried out some tests using commercial Sampling Analog-to-Digital Converter (SADC) modules to perform a real-time digital pulse-shape analysis of the signals coming from a standard detection cell of CHIMERA (i.e. a telescope of a 300 μm silicon detector and a $6\times 6\times 12\text{ cm}^3$ CsI(Tl) scintillator coupled to a photodiode), directly collecting signals from the preamplifier. The preliminary on-beam results for Charge Discrimination in Reversed Silicon Detectors are presented in this contribution.

2 EXPERIMENTAL RESULTS

Using the same electronic chain and the same hardware platform and software procedure of the previous contribution, describing the (ΔE ,Fast) scatter plots acquisition, we have also evaluated the possibility of charge identification for the reaction products stopping in the silicon detector of a CHIMERA cell, mounted in *reverse mode*, i.e. with the reaction products entering the back side of the silicon.

It is well known that the pulse shape of solid state detectors depends on the density and the spatial distribution of charge carriers generated by the detected

ions. The sensitivity of the pulse shape to length and density of ionization tracks – and thus to mass, charge, and energy of the detected ions – depends essentially on plasma and charge-carrier-drifting effects. By using charge-sensitive preamplifiers, the total charge-collection time (plasma erosion-time plus charge carriers drift-time) corresponds to the rise time of the output signals.

Consequently (see e.g. ref. [1] and references therein) the shape of the signals, and in particular their rise-time and height, can be used for particle identification by using proper analog modules, such as shaping and timing amplifiers and constant fraction discriminators. More recently Pagano et al. [2] applied the same method to CHIMERA large area (300 μm thick, $5\times 5\text{ cm}^2$ area) planar silicon detectors.

In this contribution we present the results for the pulse shape discrimination obtained by applying digital pulse shape acquisition techniques to the signals coming from totally depleted CHIMERA silicon detectors, in reverse mount and at realistic experimental conditions, in order to reconstruct their rise-time and pulse height, and consequently to obtain charge identification also for products stopping in the silicon detectors.

In a preliminary test experiment at the LNS Superconducting Cyclotron in Catania, with a 21.1 AMeV ^{20}Ne beam bombarding a ^{27}Al target, charge identification have been obtained for the reaction product both crossing (ΔE vs. E technique) and stopping in Silicon detector (Silicon-Energy vs. Rise-Time technique). The measurement has been done as parasitic test during an Intermediate Energy experiment with the

multidetector CHIMERA in its final 4π configuration (1192 telescopes).

One telescope in the 3rd wheel has been mounted in reverse mode and used for the present test. The studied pulse shape discrimination technique has been applied to the first detector of the Si-CsI(Tl) detection cell, while both Si and CsI(Tl) signals have been used for (ΔE -E) analysis. The full area of the silicon detector ($5 \times 5 \text{ cm}^2$) has been used with no collimator.

Each signal has been digitally filtered. Waveforms of 2048 consecutive ADC samples have been collected at 10 ns time intervals and stored in the Sampling ADC memory banks in wrap-around mode. For every event the sample collection is stopped by using a post-trigger. From this instant the pulse-form for each event parameter (Si and CsI(Tl)) is reconstructed and stored. The use of post-trigger allowed for an accurate baseline restoring of each pulse, before the computation of pulse height.

The rise time of pulses was calculated as the difference between the times at which the pulse-form crosses 10% and 90% of the full pulse height relative to baseline.

In Fig. 1 the result obtained for the previous reaction are shown. On the right side the (Silicon-Energy vs. Rise-Time) scatter plot is shown, while left side presents the (ΔE vs. E) scatter plot for products producing a signal in the CsI(Tl). A full charge identification up to $Z = 11$ has been obtained for the reaction product crossing the Silicon detector, while for the reaction products stopping in the Silicon detector charge identification has been reached in the range $4 \leq Z \leq 12$.

The quality of the obtained results clearly indicates that the digital signal processing approach is able to give excellent results in this application, too.

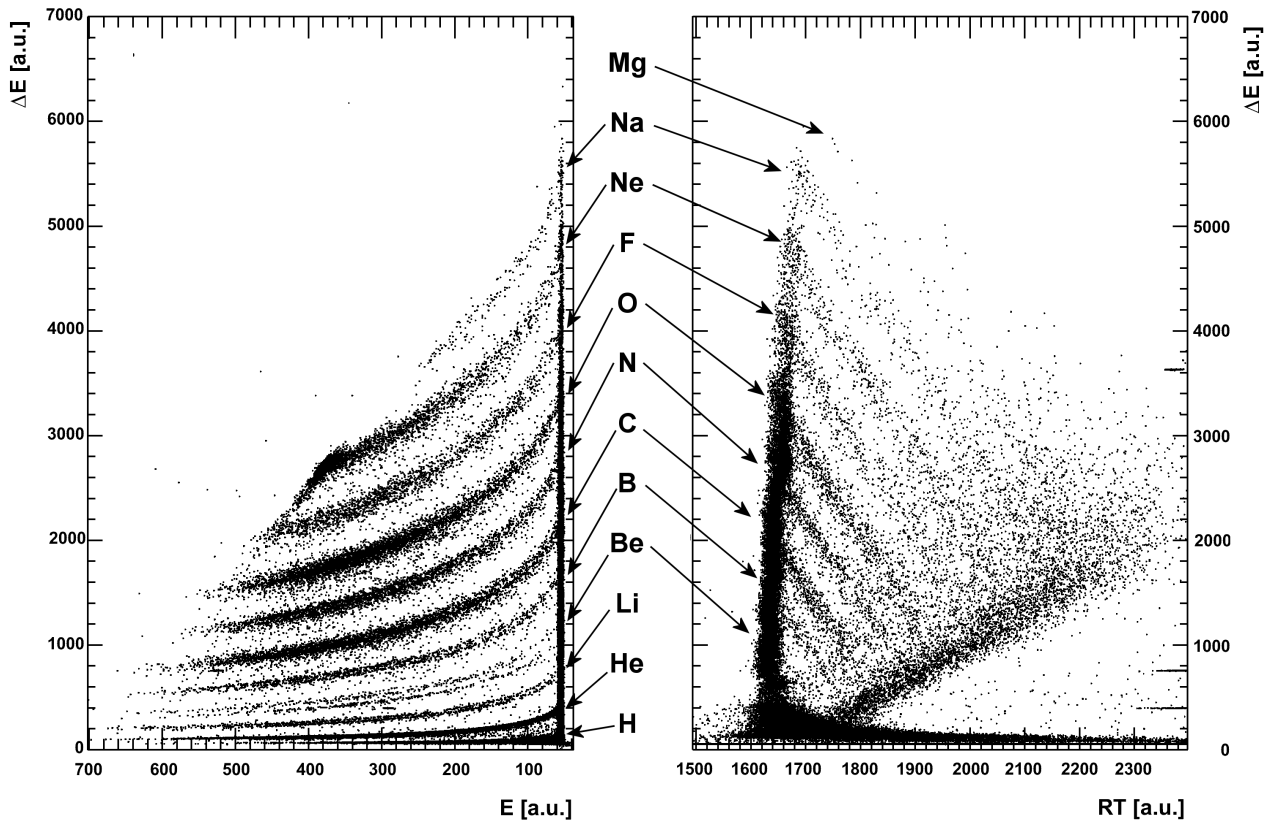


Fig.1: results obtained for the $^{20}\text{Ne}+^{27}\text{Al}$ reaction are shown. On the right side the (Silicon-Energy vs. Rise-Time) scatter plot is shown, giving charge identification for products stopping in the silicon detectors. Left side presents the (ΔE vs. E) scatter plot for products producing a signal in the CsI(Tl).

3 REFERENCES

- [1] G. Pausch et al., NIM A337 (1992) 573.
- [2] A. Pagano et al, Proc. of "The international Workshop on Multifragmentation and Related Topics - IWM2003", GANIL, Caen, November, 2003 – in press.

STATUS OF THE MAGNEX SPECTROMETER

A.Cunsolo^{a,b,*}, F.Cappuzzello^a, A.Foti^{b,c}, A.Lazzaro^{a,b}, C.Nociforo^a, S.E.A.Orrigo^{a,b}, J.S.Winfield^a, H.Petrascu^d,
M.Piscopo^a, G.Schillaci^a, V.Campagna^a, S.Salomone^a, A.Distefano^a, C.Cali^a, P.Litrico^a

a) INFN Laboratori Nazionali del Sud, Catania, Italy

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

c) INFN Sezione di Catania, Catania, Italy

d) NIPNE, Bucharest, Romania

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

Abstract

The status of the MAGNEX large-acceptance spectrometer at the LNS is described. The spectrometer itself (dipole, quadrupole and vacuum chamber) is essentially complete. The principal remaining “heavy” work (in progress) concerns the completion of the radiation shielding, the installation of the electric power and cooling water and the fabrication of the target chamber. The Focal Plane Detector is mounted on its support at the exit of the spectrometer. The new Position-Sensitive Start Detector has been completed and tests are underway. Also, the first “production version” of the data acquisition system is finished and has been used in tests. Last, but not least, a vital step has been made with the successful interpolation of the 3D measured magnetic field to the required precision for the software ray reconstruction.

1 INTRODUCTION

The interest of the international nuclear physics community in the use of the MAGNEX large acceptance spectrometer [1-3] was confirmed by a successful “Workshop on Forthcoming Facilities at the LNS” held during 20-22 March 2003. Many ideas for experiments with the spectrometer, both with stable and radioactive beams (the latter from the EXCYT facility), were proposed and discussed. Following this, three Letters of Intent for experiments were given to the LNS Scientific Committee in November, together with a request for beam time from the Tandem for the Commissioning of MAGNEX.

Unfortunately the final completion of MAGNEX has been rather delayed because of (i) the late arrival and placement of the concrete blocks for the radiation shielding walls in the new experimental area, and (ii) the consequent delay in the installation of the necessary services (electric power and cooling water) which is now in progress at time of writing. Nevertheless, considerable work has been done over the last year, as will be found in the following sections of this report. A photograph of the spectrometer in the new experimental area is shown in Fig. 1.



Fig. 1. View from the top of the shielding walls of MAGNEX with the recently-installed FPD on the right. The beam will come from roughly the top-left of the picture.

2 MECHANICAL AND VACUUM

- The vacuum system is mounted and tested, apart from that for the scattering chamber.
- The control system for the vacuum and the platform rotation is installed and tested.
- The scattering chamber has been designed and the company to construct it has been awarded the contract after a competition.
- A support above the platform for the Focal Plane Detector (FPD) has been made and installed. This allows the detector to move in order to compensate for kinematical shifts of the focal plane.
- An additional support (an extension of the above) has been made with rails to allow the FPD to be rolled back for dismantling or, e.g.,

for changing the entrance window foil. See photograph in Fig. 2.



Fig. 2. The FPD box installed at the exit of the spectrometer on the support that allows it to be rolled back for maintenance.

3 DETECTORS

The completed FPD has been delivered from GANIL and mounted in its actual position. It has been electronically tested and is ready for testing with an α -source. The gas handling system (shown in Fig. 3) is also mounted on the rotating platform and has been tested.



Fig. 3. The gas handling system for the FPD installed on the platform. An access port at the exit of the spectrometer (before the bellows) is seen on the left.

The new Position Sensitive Detector for the entrance to the spectrometer (as mentioned in last year's Report) has been completed with a 12×16 array of pads for the position readout. The electron shower leaving the microchannel plate of the detector induces charges on the nearest few pads. From the centroid of the charge distribution, an accurate (sub-millimeter) position measurement can be made, in a similar way to the technique used for the strip readout in the FPD.

4 DATA ACQUISITION SYSTEM

The front-end of the data acquisition system for MAGNEX is currently based on an SBS (Or Computer) VP7 board (Intel Pentium-III processor and Tundra Universe-II VME-PC/I bridge). This system with CAEN 6u-VME TDCs, ADCs, scalars, CFDs and C-RAMs is completed, fully tested and has been used for bench tests of the Gassiplex multiplexed-readout for the new PSD detector described above. The low-level software to interface with the Universe chip is from VMELinux Project [4], which has been easy to implement but is not a real-time system. We plan to upgrade to a Motorola MVME5500 CPU (also with a Universe chip) in order to have real-time interrupt handling as well as better serving the CAEN C-RAMs multiplexed ADCs. A large part of the software already developed for the VP7 can be reused for the Motorola CPU.

As regards the back-end acquisition system, two 1750 PowerEdge workstations have been ordered and received from Dell, together with a 770N PowerVault disk storage system. These have been mounted in a rack and the operating system and basic software have been installed. The analysis software developed on a Sun workstation has been transferred to one of these workstations (the other workstation being intended for the ray reconstruction analysis). A test of the CHIMERA-based analysis software has been done using simulated data from the full MAGNEX detection system (PSD + FPD) by GEANT.

The present back-end software for run control, histogram binning and display is essentially the CHIMERA acquisition software. This will have to be modified and extended in order to implement the software ray reconstruction described in the following section.

Extensive internal documentation has been written for the MAGNEX data acquisition system in html format and posted on the INFN-LNS web-site. In this way, the documentation can be made up-to-date as the project develops without incurring un-necessary paper reprints.

5 SOFTWARE RAY RECONSTRUCTION

The goal of the software ray reconstruction is the determination of the particle vector momentum at the target location, which in turn is the key element to ensure the high level of performance foreseen for MAGNEX [5]. One of the most delicate problems, solved this year, was the interpolation of the 3D measured field for the dipole and the quadrupole. This has been obtained via the image charge technique, whose basic principles are described in ref. [6]. For the application to the MAGNEX problem this technique has been strongly upgraded in order to treat sparse maps with about 80000 measured values, taking into account

the experimental errors. In particular, the problem of finding a precise representation of the 3D field (within 10 Gauss on average) through a proper image charge space distribution, requires the solution of very large linear systems of equations, for which only numerical approaches can be used. For that purpose a detailed study of all the possible mathematical approaches has been done, also showing that stable solutions exist for the case of MAGNEX. A detailed description of these findings will be submitted soon for publication.

6 REFERENCES

- [1] A.Cunsolo et al., proc. Workshop “Giornata EXCYT”, 1996, Catania, p.143; proc. Workshop “II Giornata EXCYT”, Catania (1997) p.71.
- [2] A.Cunsolo et al., Nucl. Instr. Methods, A481 (2002) 48.
- [3] A.Cunsolo et al., Nucl. Instr. Methods A484 (2002) 56.
- [4] John Huggins and Michael J. Wyrick, VMELinux Project, Chesapeake Research, Warrenton, Virginia, USA.
- [5] A.Lazzaro et al., proc. 7th Intl. Computational Accelerator Physics Conf., East Lansing, Michigan 15-18 October 2002. M. Berz and K. Makino, eds., IOP conference series 175 (2004) in press.
- [6] R.Degenhardt and M.Berz, Nucl. Instr. Methods A427 (1999) 151.

THE EXCYT FACILITY TOWARDS ITS COMMISSIONING

G. Cuttone, R. Alba, L. Calabretta, L. Celona, F. Chines, L. Cosentino, P. Finocchiaro, M. Menna, E. Messina, G. Raia, M. Re, D. Rifuggiato, A. Rovelli, G. Schillaci, A. Amato, R. Avolio, S. Cavallaro, C. D'Amato, E. Furia, A. Grmek, P. Maniscalco, G. Manno, R. Marletta, S. Passarello, M. Piscopo, S. Pulvirenti, P. Reina, S. Russo, S. Tringale, A. Varisano, V. Scuderi, E. Zappalà

INFN - Laboratori Nazionali del Sud, via S. Sofia 62, 95123 Catania, Italy

Abstract

The EXCYT facility (EXotics with CYclotron and Tandem) is based on a K-800 Superconducting Cyclotron injecting stable heavy-ion beams (up to 80 MeV/amu, 1 eμA) into a target-ion source assembly (TIS) to produce the required nuclear species, and on a 15 MV Tandem for post-accelerating the radioactive beams. In May 2003 the Target-Ion Source assembly (TIS) was successfully tested at GANIL under the same operational conditions that will be initially used at EXCYT. The commissioning of the facility and the start of the first experiment with ^8Li is foreseen by the end of 2004

1 SUPERCONDUCTING CYCLOTRON

Following the upgrading process of the Superconducting Cyclotron (CS) accomplished in the last few years [1], in 2003 an accelerator stop was scheduled to test the cooled deflector by shooting high-intensity beams on it. The tests were also aimed to the extraction of a light ion beam sufficiently intense to be used as a primary beam for EXCYT. When shooting a ^{20}Ne beam (45 MeV/amu), we found a power limitation at 40 W: the beam caused mechanical damages in the Ta septum of the electrostatic deflector. To solve this problem we designed and mounted:

- 1) A new septum modified to a V-notch for an improved power dissipation;
- 2) A small chopper installed in the injection line allowing to decrease the beam current in the longitudinal way;
- 3) Two internal current probes provided with a cooling circuit, to find the best conditions for minimum beam dissipation in the septum;
- 4) Phase slits to increase the extraction efficiency up to 60%.

New tests with ^{13}C , the prospective primary beam for the production of ^8Li , resulted in an extracted beam power of about 100 W corresponding to 680 e nA (fig. 1). This figure is estimated to be sufficient for an adequate production of ^8Li (10^4 - 10^6 pps on target) and at the moment is the maximum achievable for radioprotection issues.

2 PRIMARY BEAM LINE AND HV PLATFORMS

The vertical segment of the primary beam line has been redesigned and additional diagnostic elements have been introduced through the whole line. Since the TIS is at 50 kV with respect to the high-activity platform and its operating temperature is around

2000 °C, to check the correct beam positioning a remote-controlled linear actuator with one alumina disc and three collimators (diameter 6, 9, 12 mm respectively) had to be placed on the top of the platform (fig. 2, A). The disc can withstand 10 W maximum, thus it will be used only during the beam preparation and replaced with one of the collimators during target irradiation. The outer halo of the primary beam will constantly collide with the collimator and an increase or decrease of the relevant measured current outside the fixed thresholds automatically triggers the safety system to stop the beam.

During target irradiation, beam shape and positioning will be provided by a special diagnostic element placed at a few centimetres above the TIS (fig. 2, B): it consists of a 10-μm scintillating layer deposited on a 10-μm window, and of a second 6-μm window to shield the first one from the TIS thermal irradiation. Studies and tests on prospective windows indicated that -as for thermal dissipation, irradiation heating and radioactivation- Al has better properties with respect to

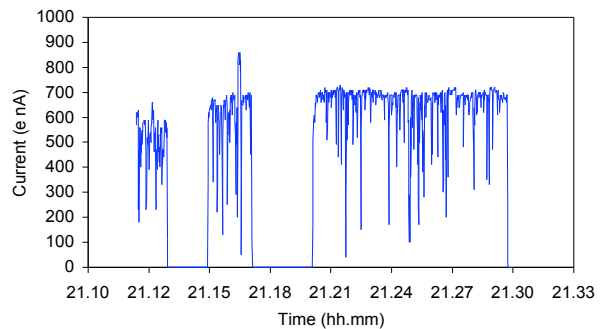


Fig. 1: ^{13}C (60 MeV/amu) intensity versus time. The extracted power was 100 W

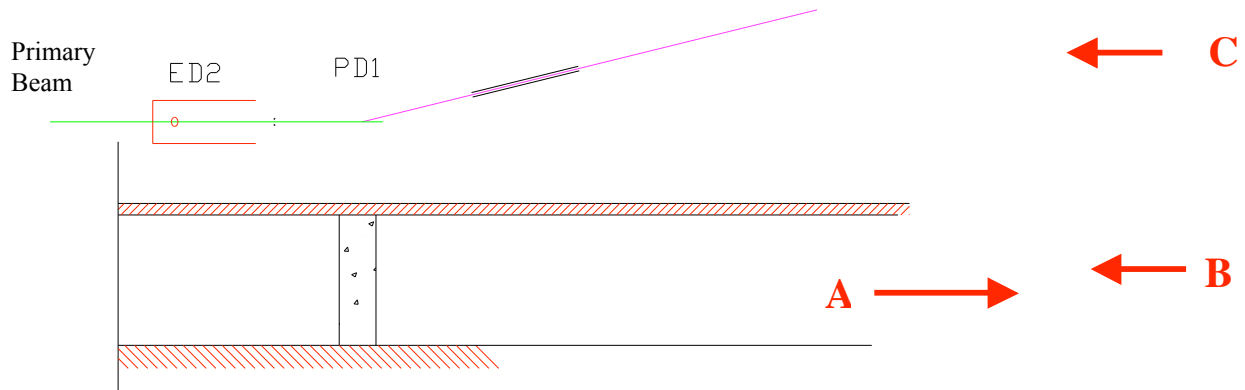


Fig. 2: Special diagnostic elements on the high-activity platform

graphite, Ti, Cu, Ag, Au. The scintillator must have good radiation hardness, therefore at LNS we deposited inorganic materials on the Al window: CsI(Tl) by thermal evaporation and $\text{Al}_2\text{O}_3(\text{Cr})$ by electron-gun bombardment. Alternative techniques like Ion Beam Assisted Deposition e Plasma Spray are currently under study. The thermal dissipation and the energy decrease on the windows are about 0.6 % of the primary beam power while the minimum detectable beam power is around 1W. Computer simulations show that the temperature increase is negligible under those conditions (fig.3).

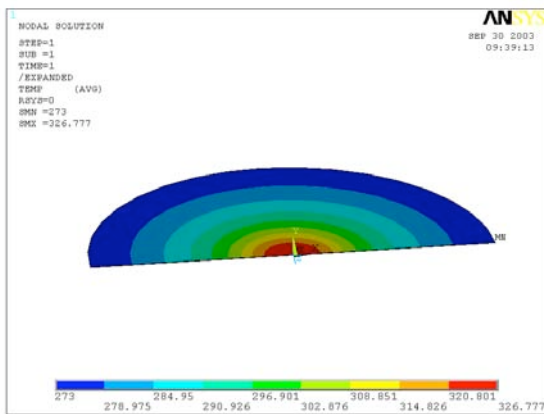


Fig. 3: Temperature distribution (in Kelvin) for a window made of $\text{Al}_2\text{O}_3(\text{Cr})/\text{Al}$ (10+10 μm) with $\varnothing=25\text{mm}$. The primary beam is ^{13}C , $\varnothing=5\text{mm}$, 100W

A video camera with zoom will be placed on the TIS vertical axis to look at both diagnostic elements through a dedicated view port on the 90° bending magnet (fig. 2, C). Finally, two linear actuators have been placed soon after the 18° magnetic dipole in the

secondary beam line: one at the 0° exit, the other at the 18° exit. Both actuators can host alumina discs for beam monitoring by means of video cameras connected to the video multiplexer on the low-activity platform

3 TARGET-ION SOURCE ASSEMBLY

This year signed a milestone for the EXCYT activity: in fact, the first radioactive beams ^8Li , ^9Li (fig. 4) were successfully obtained during an experiment at the SIRa test bench, GANIL; details may be found in [2]. Almost the whole year was entirely devoted to the preparation of the experiment, the experiment itself, the TIS post-mortem and the final dismounting.

We had to face a large number of different and time-consuming tasks: presenting the experiment at the GANIL Advisory Committee, designing and building an interface to match the SIRa's front-end, rotating our TIS and solving the subsequent problems of mechanical stability, obtaining radioprotection authorisations for the experimental activity, performing heating tests after temperature simulations at LNS [3], sending the TIS together with accompanying instrumentation and tools to GANIL, mounting and calibrating the assembly, running the experiment, performing the post-mortem analysis, arranging for radioactive transportation back at LNS.

In collaboration with PNPI-RAS, Gatchina, a new type of combined target-ion source unit has been developed for the on-line production of radioactive singly charged ions [4]. In this configuration the target is able to withstand high temperatures and acts also as an ioniser (ionising target), thus making the effusion delays shorter. Off and on-line experiments with the ionising target housing different target materials have been

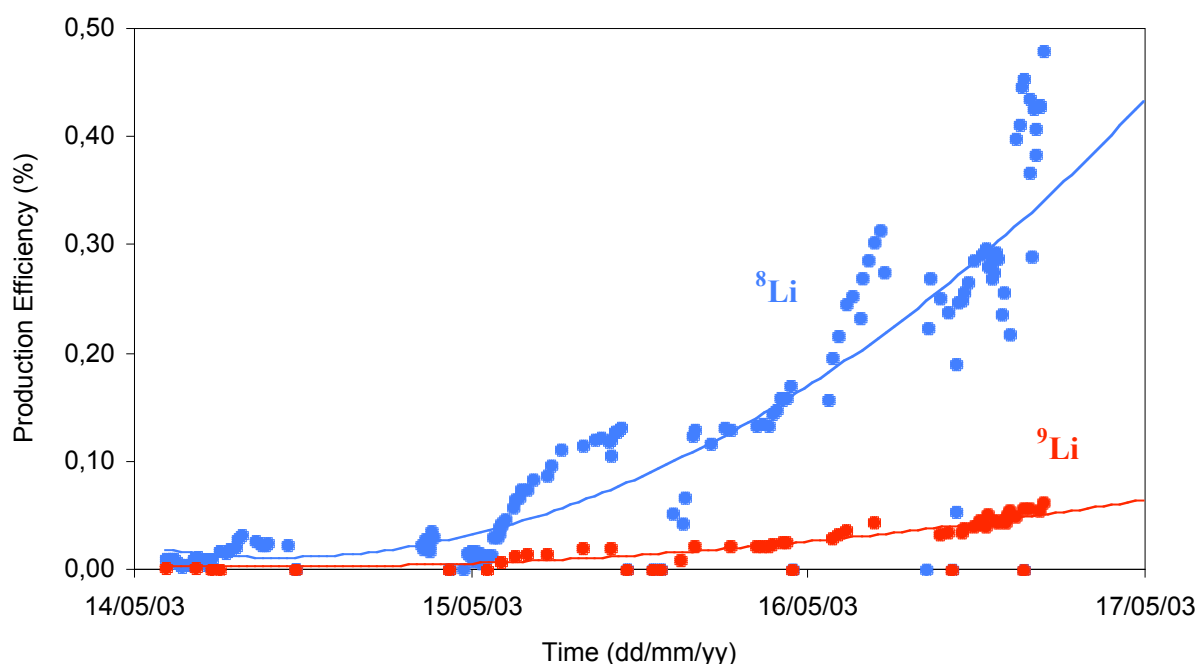


Fig. 4: Production efficiency for ^8Li , ^9Li versus time. The production efficiency is the ratio of the extracted radioactive ions to ones theoretically produced into the target (estimation by the EPAX code)

carried out. The off-line ionisation efficiency measured for stable atoms of Li and Mg varied between 0.14 and 5.4 %, while the on-line yields of neutron-deficient isotopes of Pm, Sm, Eu, Gd, Tm, Yb and Lu, which depend on the ionisation and on the release efficiencies, were within the interval 0.1 – 7%. Rather unexpectedly, we observed for the first time an axial magnetic field influence on the ionising efficiency of atoms with low potential of ionisation such as Li and neutron-deficient isotopes of Pm, Sm, Eu, Gd, Tm, Yb, Lu produced in on-line experiments

Other ancillary activities consisted in implanting stable isotopes of Li, F, Cl into LaB_6 and W specimens to be used for future tests on ionisation and charge-exchange efficiencies.

4 ISOBARIC MASS SEPARATOR AND BEAM DIAGNOSTICS

The isobaric mass separator has been mounted and aligned with the required precision. Tests to measure its mass resolving power are planned in 2004.

During 2003 we installed and aligned 4 LEBI (Low Energy Beam Imager/Identifier) devices on the low-intensity platform. In order to measure and monitor also the radioactive beams, the devices were modified by introducing a beta-detector with 50 % efficiency. The detector consists of a $6 \times 6 \times 5 \text{ cm}^3$ plastic scintillator coupled to a photomultiplier, both controlled via a pneumatic actuator. By using stable and collimated radioactive sources, the measured current sensibility

threshold was 10^6 pps for light stable beams up to 300 keV (fig. 5) and 10^4 pps for beta particles with average energy of 1 MeV [5, 6]. A graphic pattern superimposing to the beam image has been assigned to each LEBI: it contains all the information about the alignment and the relevant spatial calibration. The LEBI devices will be completely operated by means of two personal computers placed on the low-intensity platform and connected to Ethernet.

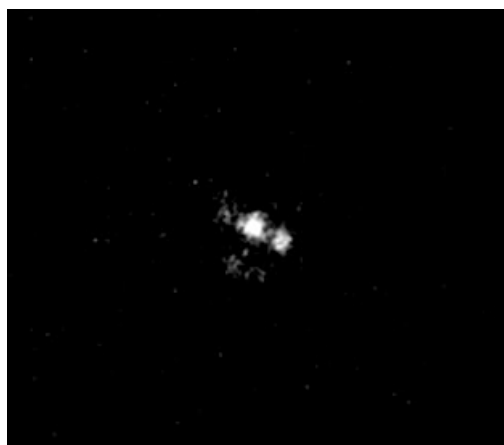


Fig. 5 Image on the LEBI of a proton beam with intensity = 0.03 pA and energy = 170 keV. The structure with different spots is due to the pepper pot grid

In addition, their video signals are input into a multiplexer and from there directly to the console through glass-fibre cabling.

Identification of radionuclides will be performed with a counter board (National Instruments 6601) and a multichannel analyser (Ortec MAESTRO) installed into a personal computer in the low-activity platform. As for the post-accelerated beams, currently we are purchasing ten Glass-Fibre Based Beam Sensors (GFIBBS); in addition telescopes and microchannel plates for identifying the radionuclides by time-of-flight techniques will be mounted in early 2004.

5 CONCLUSIONS

In conclusion, all the goals planned for this year have been successfully reached. In particular, we would like to stress the importance of two milestones: the production of radioactive ion beams at GANIL and the achievement at LNS of a primary beam power of 100 W. In 2004, EXCYT will be completed and authorised to work with a primary beam power of 500 W. The commissioning of the facility with stable beams is planned for September 2004, while the start of the first experiment with a radioactive beam of ^8Li is foreseen by the end of 2004

6 REFERENCES

- [1] D. Rifuggiato et al., Status report of the LNS Superconducting Cyclotron, Nukleonika Vol. 48 Supplement 2, 2003, pp. S131-S134
- [2] M. Menna et al., The experiment E435 at GANIL, this report
- [3] M. Re et al. , Thermal simulations for the EXCYT target assembly, this report
- [4] V. N. Pantelev et al., Off-line and on-line tests of ionizing targets, PNPI preprint 2511 (2003) 1
- [5] L.Cosentino and P.Finocchiaro, Ion beam imaging at very low energy and intensity, NIM B211 (2003) 443-446
- [6] L.Cosentino and P.Finocchiaro, Recent developments of the EXCYT radioactive beam diagnostics, Proceedings of the Dipac 2003, Mainz, Germany, May 5–7, 2003

The Software Replica of CHIMERA Multidetector

W.Gawlikowicz^{1*}, J.Blicharska², J.Brzychczyk¹, J.Cibor³,
A.Grzeszczuk², S.Kowalski², Z.Majka¹, R.Płaneta¹, and W.Zipper²

For ISOSPIN Collaboration

¹ *Institute of Physics, Jagiellonian University, 30-059 Kraków, Poland*

² *Institute of Physics, University of Silesia, Katowice, Poland*

³ *H.Niewodniczański Institute of Nuclear Physics, Kraków, PL-31342, Poland*

A complete software replica (filter) of the CHIMERA multidetector array has been constructed. All details of the CHIMERA multidetector geometry have been taken into account, including dead-zones, as well as detectors dead-layers. Detection thresholds for all charged-particles have been determined with respect to used detection technique (Time-of-Flight, CsI, and Si-CsI identification).

I. INTRODUCTION

The CHIMERA multidetector array [1, 2] is made of 35 rings in a cylindrical geometry around the beam axis (see Fig. 1).

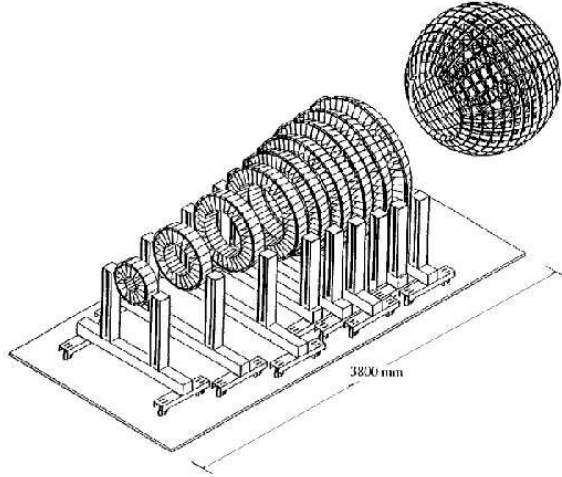


FIG. 1: A schematic view of CHIMERA multidetector. The forward part (from left) was used in REVERSE experiment.

It consists of total 1192 detectors. The forward 688 detectors in 18 rings are assembled in 9 wheels, covering the polar angles from 1° to 30° . The remaining 504 detectors in 17 rings are assembled in a sphere of 40cm radius, covering the polar angles from 30° to 176° .

The laboratory solid angle coverage is about 95%, taking into account dead-zones and detector dead-layers. A detail geometrical structure of the CHIMERA multidetector is presented in Table I.

The CHIMERA multidetector array is built from Si-CsI(Tl) telescopes. The thickness of the silicon detectors varies from 220 to $320\mu\text{m}$. The thickness of CsI(Tl) crystals varies from 12cm (rings 1÷16) to 3cm (rings 33÷35).

Such a thickness of CsI(Tl) crystals allows one to stop all charged-particles in the entire dynamical range.

RING	Dist.[cm]	$\theta_{min}[^\circ]$	$\theta_{max}[^\circ]$	$\Delta\phi[^\circ]$
1	350	1.0	1.8	22.50
2	350	1.8	2.6	22.50
3	300	2.6	3.6	15.00
4	300	3.6	4.6	15.00
5	250	4.6	5.8	11.25
6	250	5.8	7.0	11.25
7	210	7.0	8.5	9.00
8	210	8.5	10.0	9.00
9	180	10.0	11.5	9.00
10	180	11.5	13.0	9.00
11	160	13.0	14.5	7.50
12	160	14.5	16.0	7.50
13	140	16.0	18.0	7.50
14	140	18.0	20.0	7.50
15	120	20.0	22.0	7.50
16	120	22.0	24.0	7.50
17	100	24.0	27.0	7.50
18	100	27.0	30.0	7.50
19	40	30.0	38.0	11.25
20	40	38.0	46.0	11.25
21	40	46.0	54.0	11.25
22	40	54.0	62.0	11.25
23	40	62.0	70.0	11.25
24	40	70.0	78.0	11.25
25	40	78.0	86.0	11.25
26	40	86.0	94.0	11.25
27	40	94.0	102.0	11.25
28	40	102.0	110.0	11.25
29	40	110.0	118.0	11.25
30	40	118.0	126.0	11.25
31	40	126.0	134.0	11.25
32	40	134.0	142.0	11.25
33	40	142.0	150.0	11.25
34	40	150.0	163.0	22.50
35	40	163.0	176.0	45.00

TABLE I: Geometry of CHIMERA multidetector. For each detector in a ring, a distance from target, minimum and maximum polar angle, and azimuthal angle range are specified.

The dimensions and granularity of the CHIMERA apparatus allows one to identify particles via Time-of-Flight (TOF) technique using the cyclotron RF signal as a start.

*Corresponding author e-mail address: ufwgawli@if.uj.edu.pl

Using TOF technique, charged-particles stopped in the silicon detector can be identified, what lowers drastically the detection thresholds, especially for intermediate-mass fragments.

The CHIMERA filter is an exact software replica of the CHIMERA multidetector array. It takes into account all details of the CHIMERA apparatus geometry, including dead-zones, as well as detectors dead-layers. Detection thresholds for all charged-particles are determined with respect to used detection technique.

II. THE CHIMERA FILTER

The CHIMERA filter is a FORTRAN subroutine which can be *included* in any simulation program. As any “filter”, it gives information about detector being hit, and if a particle is above specified identification threshold or not.

If the particle escapes through detection system dead-zones (like beam-entry or beam-exit), or hit detectors dead-layer, the subroutine returns *detector number zero* (no active detector area has been hit). All dead-zones and detectors dead-layer of the CHIMERA apparatus has been taken into account. In particular, real detectors have a flat “face” part. Therefore, for all detectors, a transformation from cartesian to spherical coordinates is performed. It gives a realistic shapes of detectors in the $\theta - \phi$ space, and takes care of real dead-zones and dead-layers connected with their shape.

There are three possibilities of particle identification : (i) mass identification - TOF method; (ii) isotopic identification - particles are identified via pulse shape discrimination technique in CsI(Tl) element alone, or via Si vs. CsI(Tl) energy deposits; (iii) charge identification - Si vs. CsI(Tl) energy deposits. The particle identification sequence in CHIMERA filter is the same as in experiment. These particles which are stopped in Si element and are in a range of TOF identification are recognized as TOF particles. All particles below TOF energy thresholds are not detected. Note that not the entire CHIMERA apparatus is working with TOF method. In that case particles which give no pulse in CsI(Tl) element are not detected. Particles having enough energy to enter CsI(Tl) element can be identified with isotopic or charge resolution. It depends whether particles are within the isotopic identification range, and it can also depend on their energy. Some particles are identified with the isotopic resolution from certain energy. Below that energy they have charge resolution only.

The detailed information about the CHIMERA filter usage, and particular filter files can be found in Appendixes.

III. MODIFYING CHIMERA FILTER FOR A NEW EXPERIMENTAL SET-UP

The CHIMERA filter is written in a way to allow easy modification of detector parameters. They usually differ from experiment to experiment because of calibration procedure. Moreover, usually some detectors are not working and some are replaced. The current experimental set-up is defined in detectors definition file (see Appendix B and D). The detection thresholds are specified in TOF thresholds file - `Chimera_filter.E0TOF`, while the Si-CsI(Tl) thresholds are specified in `Chimera_filter.E0SI` file (see Appendix F). The idea is to have different detectors definition file for each experiment. Existing energy threshold files can be appended and used for all experiments. In this way, the current detectors definition file specifies which threshold function is used. The detectors definition file is an input argument during initialization - see Appendix B.

Acknowledgments

We wish to thank the entire LNS Catania group, and particularly Enrico De Filippo and Angelo Pagano, for their contribution in this work.

APPENDIX A: INCLUDING CHIMERA FILTER AS A SUBROUTINE

The CHIMERA filter consists of separate files included by `Chimera_filter.for`. This file has to be included in a *main* program. It will subsequently include all needed subroutines and read data input files during the initialization.

APPENDIX B: INITIALIZING AND CALLING SEQUENCE

The filter has to be initialized by following calling sequence:

```
CALL Chimera_filter_init
(E_TYPE,DEFINITION_FILE,TARGET_FILE) .
```

This subroutine is defined in `Chimera_filter.init` file. When called, reads all input data files.

The initializing parameters are:

- **E_TYPE** (0/1) - this variable defines the way of including target energy loss corrections; if **E_TYPE**=0, the energy loss in the target is taken into account during thresholds calculations, but the particle energies are as they come from simulation; if **E_TYPE**=1, the energy loss is taken into account during thresholds calculations, and the target energy loss is subtracted from the simulation data,

- **DEFINITION_FILE** - the name of the detectors definition file (see Appendix D),
- **TARGET_FILE** - the name of the file with the target energy losses parameterization (see Appendix E).

After initializing, the CHIMERA filter should be called in the event-by-event sequence. A template for event “filtering” would be as follows:

```
do i=1,Number_of_events
CALL Chimera_filter(M,Z,A,E,TH,PH,DET,ID)
enddo
```

The filter parameters are:

- M - multiplicity (integer)
- Z(M) - charge (integer)
- A(M) - mass (integer)
- E(M) - energy [MeV] (real) - LAB system
- TH(M) - polar angle [$^{\circ}$] (real) - LAB system
- PH(M) - azimuthal angle [$^{\circ}$] (real) - LAB system
- DET(M) - detector number (integer)
- ID(M) - particle ID (integer)

If the filter was initialized with **E_TYPE=1**, the **E(M)** values are corrected for the energy loss in target, if **E_TYPE=0**, the subroutine does not change the energies.

The subroutine **Chimera_filter** returns a number of detector for all particles which hit a detector, whatever they are above the threshold or not. Particles which escape through detection system dead-zones or hit the detectors dead-layer have detector number equal zero. In the filter the numbering of “real” detectors starts from 1, as we believe that a *bien être* is to give a number greater than zero for “real” devices (in the CHIMERA experimental files it usually starts from zero).

The particle ID numbers returned by filter are:

- ID=0 - particle is below identification threshold
- ID=1 - mass identification only (TOF method)
- ID=2 - isotopic identification (Si-CsI(Tl) or CsI(Tl))
- ID=3 - charge identification only (Si-CsI(Tl))
- ID=4 - “multi-hit” particle

In the present version of the Chimera filter most of the particle “multi-hits” are rejected (ID=0). Exception is made for events where one particle is stopped in Si element, and the another one enters CsI(Tl) crystal. Since the latter one can be identified using CsI(Tl) or Si-CsI(Tl) signals, it has ID=4 (particle stopped in the Si element has ID=0).

APPENDIX C: COMPILING AND LINKING

The CHIMERA filter is written in FORTRAN. Since it is using *structures*, a FORTRAN90 compiler is recommended. The source code is using long FORTRAN lines, so one should use *extended source* option during compilation. No special libraries are needed during linking.

APPENDIX D: DETECTORS DEFINITION FILE

The detectors definition file defines CHIMERA multi-detector geometry, energy threshold functions, and maximum values of charge for TOF, charge, and isotopic fragment identification. Such a file has to be written separately for each experimental set-up.

The file structure, for each detector, is as follows:

```
det ok F_TOF F_SI ZTOF Zmin Zmax ZminA ZmaxA  $\theta$ 
 $\phi$   $\Delta\theta$   $\Delta\phi$  R[cm] RING NAME
```

where:

- det - detector number
- ok (0/1) - dead/alive - switch off not working detectors (all particles have ID=0 for not working detector)
- F_TOF, F_SI - energy thresholds function number for TOF and Si-CsI(Tl) identification, respectively - some of detectors have the same energy thresholds, therefore one function can be used for a group of detectors (see Appendix F)
- ZTOF - maximum charge number for TOF method
- Zmin, Zmax - minimum and maximum possible charge identification
- ZminA, ZmaxA - minimum and maximum possible charge for isotopic identification
- θ , ϕ , $\Delta\theta$, $\Delta\phi$ - polar and azimuthal angle of detector center, and detector angle ranges, respectively
- R[cm] - distance from target
- RING - ring number
- NAME - detector name (optional)

APPENDIX E: TARGET CORRECTIONS FILE

The target corrections file gives target energy loss parameterization for each ring (θ) of CHIMERA apparatus. It has to be written separately for each target mass, charge, and thickness. We recommend here to use the same convention for all targets, e.g. $^{64}\text{Ni}.310$ - energy loss corrections for ^{64}Ni target having thickness 310

$\mu\text{g}/\text{cm}^2$. Of course, corrections for each target are made for half of its thickness, what is a good approximation for average value (the reaction can take place in any part of the target).

The file structure, for each ring, is as follows:

RING# a b power f1 f2 f3 f4,

where a, b, power, f1, f2, f3, and f4 are coefficients of energy loss, E_{loss} , parameterization, depending on particle charge, Z , mass, A , and energy, E :

$$E_{loss}(Z, A, E) = a \frac{AZ^2}{E} \ln \left(1 + b \frac{E}{A} \right) F_{low}(Z, E). \quad (\text{E1})$$

The function $F_{low}(Z, E)$ is a correction function for low energies, given by following formula

$$F_{low}(Z, E) = 1 - \frac{1}{1 + P1(Z)E^{P2(Z)}}. \quad (\text{E2})$$

The $P1(Z)$ and $P2(Z)$ are functions of charge, Z , only defined as:

$$P1(Z) = \left(f1 + \frac{f2}{Z} \right) / Z^{power}, \quad (\text{E3})$$

and

$$P2(Z) = f3 + \frac{f4}{Z}. \quad (\text{E4})$$

The energy loss formula might look difficult at first sight but has a simple explanation. The expression $a \frac{AZ^2}{E} \ln \left(1 + b \frac{E}{A} \right)$ approximates quite good the behavior of energy loss for high energies, for all particles. The remaining part of Eq.(E1) is governing a behavior of energy loss for low energies. It is varying very much with particle charge. As one can see from Eqs.(E3) and (E4), the low energy part of energy loss formula (E2) is changing rapidly with the decrease of charge of the particle.

APPENDIX F: ENERGY THRESHOLD FILES

The CHIMERA filter has two energy threshold files :

- `Chimera_filter.E0TOF` - TOF energy thresholds (mass identification only)
- `Chimera_filter.E0SI` - Si-CsI(Tl) energy thresholds for isotopic and charge identification.

The files structure, for each particle, is as follows:

FUNCTION# A_{id} Z A THRESHOLD,
where:

- FUNCTION# - identification function number for TOF identification (F_TOF) or Si-CsI(Tl) identification (F_SI) assigned in detectors definition file (see Appendix D)
- A_{id} (0/1) - mass identification;
if $A_{id}=0$, the threshold is for charge identification only;
if $A_{id}=1$, the threshold is for isotopic identification (in `Chimera_filter.E0SI` file) or for TOF identification (in `Chimera_filter.E0TOF` file)
- Z, A - charge and mass
- THRESHOLD - energy threshold.

Each identification function (of charge and mass) can be used for a set of detectors having the same thresholds. The maximum charge for particle identification is specified in detectors definition file (see Appendix D).

In the case of charge identification ($A_{id}=0$), only charge number is used.

[1] S. Aiello et al., Nucl.Phys. **A583** (1995) 461; Nucl. Instr. and Meth. **A369** (1996) 50; Nucl. Instr. and Meth. **A400** (1997) 469; IEEE Trans. on Nucl. Sci. **47**, No.2 (2000)

114.
[2] F. Porto et. al., Acta Phys. Pol. **B31** (2000) 1489.

STATUS OF THE NEMO PROJECT

E. Migneco^{a,*}, S. Aiello^e, E. Amato^h, M. Ambriola^b, F. Ameliⁱ, G. Andronico^e, M. Anghinolfi^f, M. Battaglieri^e, R. Bellotti^b, A. Bersani^f, A. Boldrin^k, M. Bonoriⁱ, A. Caponeⁱ, L. Caponnetto^e, F. Cafagna^b, M. Circella^b, R. Cocimano^a, R. Coniglione^a, M. Cordelli^g, M. Costa^a, S. Cuneo^f, A. D'Amico^a, V. D'Amico^h, C. De Marzo^b, R. De Vita^f, C. Distefano^a, A. Gabrielli^c, E. Gandolfi^c, A. Grimaldi^e, R. Habel^d, A. Italiano^h, M. Leonardi^l, L. Lo Nigro^e, D. Lo Presti^e, A. Margiotta^c, A. Martini^g, M. Masetti^c, R. Masulloⁱ, R. Mosetti^j, T. Montaruli^b, M. Musumeci^a, C.A. Nicolauⁱ, R. Occhipinti^a, R. Papaleo^a, C. Petta^e, P. Piattelli^a, G. Raia^a, N. Randazzo^e, S. Reito^e, G. Ricco^f, G. Riccobene^a, M. Ripani^f, M. Romita^b, A. Rovelli^a, M. Ruppi^b, G.V. Russo^e, M. Russo^e, P. Sapienza^a, J.P. Schuller^{i,+}, M. Sedita^a, M. Spurio^c, I. Sokalski^b, M. Taiuti^f, L. Trasatti^g, L. Ursella^j, V. Valente^g, P. Viciniⁱ, G. Zanmarini^c, S. Zavatarelli^f

(The NEMO Collaboration)

- a) INFN, Laboratori Nazionali del Sud, Catania (Italy)*
- b) Sezione di Bari & Dipartimento di Fisica e Politecnico dell'Università di Bari, (Italy)*
- c) INFN, Sezione di Bologna & Dip. di Fisica dell'Università di Bologna, (Italy)*
- d) INFN, Sezione di Cagliari & Dip. di Fisica dell'Università di Cagliari, (Italy)*
- e) INFN, Sezione di Catania & Dip. di Fisica dell'Università di Catania, (Italy)*
- f) INFN, Sezione di Genova & Dip. di Fisica dell'Università di Genova, (Italy)*
- g) INFN, Laboratori Nazionali di Frascati, Frascati (Italy)*
- h) INFN, Gruppo Collegato di Messina & Dip. di Fisica dell'Università di Messina, (Italy)*
- i) INFN, Sezione di Roma 1 & Dip. di Fisica dell'Università di Roma "La Sapienza", (Italy)*
- j) Istituto Nazionale di Oceanografia e Geofisica Sperimentale, Sgonico (TS), (Italy)*
- k) ISMAR-CNR, Sezione di Venezia (Italy)*
- l) IAMC-CNR, Sezione di Messina, (Italy)*

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

+ on leave from DAPNIA/SPP CEA Saclay, France

Abstract

The activities towards the realization of a km³ Cherenkov neutrino detector, carried out by the NEMO Collaboration are described. Long term exploration of a 3500 m deep site close to the Sicilian coast has shown that it is optimal for the installation of the detector. A complete feasibility study, that has considered all the components of the detector as well as its deployment, has been carried out demonstrating that technological solution exist for the realization of an underwater km³ detector. The realization of a technological demonstrator (the NEMO Phase 1 project) is under way.

1 INTRODUCTION

The realization of a km³ scale detector for astrophysical neutrinos is considered today one of the most important aims of the next decade. Up to now only smaller scale detectors have been realized or are under way [1-3], demonstrating the feasibility of the technique of Cherenkov detection of the secondary muons in deep waters or ice. However, the realization of a km³ scale detector needs a further improvement of the technologies by means of appropriate R&D studies.

The Mediterranean Sea offers optimal conditions, on a worldwide scale, to locate the telescope and several sites have been proposed by the European collaborations active in the field. Moreover, it has full complementarities, in terms of sky coverage, with the

ICECUBE detector [4] that is under construction at the South Pole.

The NEMO Collaboration aims to carry out the necessary R&D towards the km³ neutrino detector. The activity has been mainly focused on:

- search and characterization of an optimal site for the km³ installation;
- development of a feasibility study of the detector.

Since 2002, the realization of a small scale technological demonstrator, the so called NEMO Phase 1 project, started.

Further detail on the NEMO activities are reported in the proceedings of the first "Workshop on Technical Aspects of a Very Large Volume Neutrino Telescope in the Mediterranean Sea" (Amsterdam 5-8 October 2003) [5].

2 SITE SELECTION AND CHARACTERIZATION

The installation of the km³ detector needs a complete knowledge of the site physical and oceanographic characteristics over a long time period. Therefore, the NEMO Collaboration has performed, since 1998, a long term research program to select and characterize an optimal deep-sea site. This activity has demonstrated that the abyssal plateau in the Ionian Sea close to the southernmost cape of the coast of Sicily (Capo Passero) shows excellent characteristics to host the km³ underwater neutrino detector.

More than 20 sea campaigns have been performed, aiming at studying the seasonal and long term behavior of water optical characteristics and oceanographic properties (like currents, sedimentation and seabed geology) [6].

The location of Capo Passero site, at about 80 km from the coast and about 50 km from the shelf break, was chosen to ensure the best condition of stability in time of the water parameters and avoid any perturbation coming from the presence of the shelf break. A geological survey of the area verified the flatness and the absence of any evidence of recent turbidity events. The nature and structure of the seabed was studied in detail in order to design the mooring structures of the neutrino detector.

2.1 Light transmission properties

Water transparency can be parametrized in terms of light absorption (a), scattering (b) and attenuation (c), which is the combined effect of the first two. These quantities have to be measured *in situ*. We used a set-up based on a CTD probe (that measures water salinity and temperature as a function of depth) and on the AC9 transmissometer (that allows the measure of light absorption and attenuation in nine different wavelengths, from 412 to 715 nm).

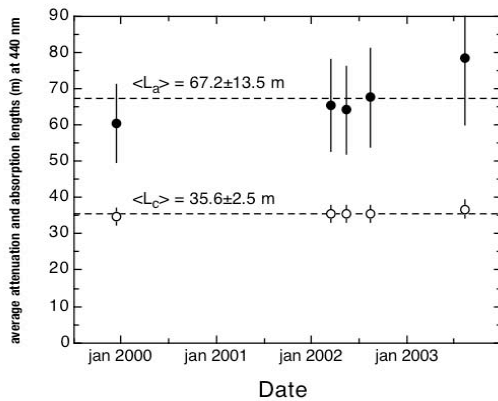


Figure 1: Values of the absorption and attenuation lengths in the blue region (440 nm) measured during five different campaigns. The reported values are the average in the depth region 2850-3250 m. Dashed lines represent average values over the five different campaigns.

In figure 1 we show the absorption and attenuation lengths in the blue region (440 nm) measured at the depths of interest for the telescope (more than 2500 m) in different campaigns. The measured values of the absorption length are about 70 m, close to the one of optically pure water. Seasonal variations are negligible and compatible with the instrument experimental error [6].

2.2 Optical background

Optical background in the seawater comes mainly from two natural causes: the decay of ⁴⁰K, which is present in seawater, and the so called *bioluminescence* that is the light produced by biological organisms. Of these two effects the first one shows up as a constant rate background noise on the optical modules (roughly 20-30 kHz on 10" PMT), while the second one, when present, may induce large fluctuations (both in the baseline and as presence of high rate spikes) in the noise rate. In Capo Passero an average rate of about 25 kHz of optical noise with rare high rate spikes due to bioluminescence has been measured in several sea campaigns. This results is in agreement with the vertical distribution of bioluminescent bacteria measured in Capo Passero, that shows a very low concentration of these bacteria at depths greater than 2500 m. This result is also consistent with measurements of bioluminescence in deep-sea carried out by Battle et al [7] in the north-east Atlantic ocean.

2.3 Oceanographic parameters

Deep sea currents have been continuously monitored in Capo Passero since 1998. The analysis points out that the behavior of the deep sea currents in the area is almost homogeneous on the part of the water column that has been monitored (at depths between roughly 2800 and 3400 m) with very low average values (around 3 cm/s) and peaks not exceeding 12 cm/s.

The downward flux of sediments has also been analyzed. The annual average value of material sedimenting at large depth in Capo Passero is about 60 mg m⁻² day⁻¹, a rather low value as expected for an oligotrophic environment such as the Ionian Plateau.

3 FEASIBILITY STUDY FOR A KM3 DETECTOR

A great deal of work has also been done to carry out a study of the technical feasibility of the km³ detector, taking into account all of its components and their deployment, that eventually yielded the preliminary project of the detector described in the following. The study was carried out in close contact with leading companies in the field of deep sea operations.

3.1 Definition of the detector architecture

It is clear that the architecture of the km³ detector should stem from a compromise between performances and technical feasibility of the detector. Of course cost is also an issue.

Computer simulations were undertaken in order to define a suitable architecture to be analyzed afterwards in terms of technical feasibility using the ANTARES software package [2,8]. For this purpose, muons were generated, with a E_μ^{-1} spectrum, at the surface of a cylinder surrounding the detector which represents the detector horizon. As a first approach one can consider filling up a volume of about one km^3 with a lattice of equally spaced sensors. The spacing should be of the same order of the absorption length of light in water. In our simulation horizontal and vertical distance between down-looking sensors is equal to 60 m. This turns out in a total number of 5600 sensors arranged in 400 strings. The performances of such a detector in terms of muon effective area and angular resolution are shown in figure 2 (solid line).

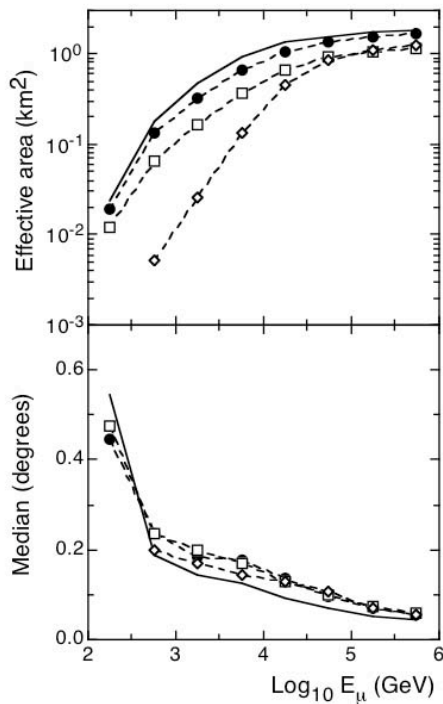


Figure 2: Effective areas and median angles between true and reconstructed muon tracks as a function of muon energy for different detector configurations. Regularly spaced (60 m) lattice of downlooking OM (5600 OM in total) with 20 kHz background (solid line); 9×9 array of “NEMO towers” (5832 OM in total) with different background rates: 20 kHz (full dots), 60 kHz (open squares) and 120 kHz (open diamonds). Quality cuts were applied in the NEMO array cases in order to achieve similar angular resolutions.

Although the solution of arranging the sensors along a string presents some advantages in terms of simplicity, this architecture can be difficult to realise due to the close distance between strings (60 m) compared with their total height (780 m). Moreover, the large number of structures to be moored and connected raises the cost of the detector.

Therefore, alternative solutions for the architecture, in which the number of structures is reduced by gathering a

relatively large number of sensors on each one of them, should be studied. In particular, constraints on the distance between structures (larger than about 120 m) and on their height (smaller than 1 km) were suggested by a preliminary feasibility study in terms of construction, deployment and maintenance operations of the detector within reasonable costs. Following these suggestions, we have proposed a structure (that is described in more detail in the following) composed by a square array of “NEMO towers”. The proposed architecture is “modular”, in the sense that it is expandable with the addition of extra towers, and configurable with different sea floor layouts. At present it should be considered as a reference for a deeper feasibility study. The performances of this architecture in terms of effective area and angular resolution were evaluated by means of computer simulations. In the top panel of fig. 2 effective areas after quality cuts are reported for different values of the optical background rate. At 20 kHz, which is close to the measured value in Capo Passero, the detector based on NEMO towers (full circles) exhibits an effective area only slightly smaller than the homogenous detector (solid line). With increasing background rate up to 120 kHz (open diamonds) a stronger and stronger reduction in the effective area is observed when quality cuts are applied to obtain a good angular resolution. The resolving power of a neutrino telescope is intrinsically limited by the angle between the neutrino and the muon, our simulations exhibit an angular resolution for the reconstructed track comparable with the intrinsic one up to about 100 TeV. This remarkable result is a peculiar feature of an underwater telescope (due to the large scattering length) which is well exploited in the point-like source search.

3.2 Mechanical structures

Optical modules and instrumentation will be mounted on a structure that we have called *tower*. It is a three dimensional structure composed by a sequence of storeys (that host the instrumentation) interlinked by a system of cables and anchored on the seabed. The structure is kept vertical by an appropriate buoyancy on the top.

The final features of the tower (number of storeys, number of optical modules per storey, distance between the storeys) can be optimized following the results of numerical simulations accordingly to the physics to be address. However, the modular structure of the tower will permit to adjust these parameters to the experimental needs.

In the preliminary design we have considered a 18 storey tower, where each storey is made with a 20 m long storey hosting two optical modules (down-horizontal) at each end (4 OM per storey). The vertical separation between storey is fixed at 40 m, giving a total active height of 680 m. An additional spacing of 150 m is added at the base of the tower, between the anchor and the lowermost storey to allow for a sufficient water volume below the detector. In its working position each storey will be rotated by 90° , with respect

to the up and down adjacent ones, around the vertical axis of the tower. One of the advantages of this structure is represented by the fact that it can be compacted, by piling each storey upon the other, to allow transport and deployment. The structure is unfurled, reaching its operating configuration, after its deployment on the seabed.

3.3 Data transmission

For a 5000-6000 OM neutrino telescope the expected data rate (essentially due to background and assuming a rate of about 30 kHz) is on the order of 20-30 Gbps, while the distance over which the data have to be transmitted can be of the order of 100 km. These considerations recommend the use of a fibre optics transmission system and a power consumption as low as possible.

Furthermore, a common timing must be known in the whole apparatus at the level of detection device to allow correlation in time of events. In this sense, a favorable choice is the use of synchronous protocols. For example, the Synchronous Digital Hierarchy (SDH) protocol, which embeds data, synchronism and clock timing in the same serial bit stream, allows an easy distribution of the clock signal to the whole apparatus.

Many devices are available off-the-shelf with present technology to implement a data transport suited to the km³ detector. Just few years ago data multiplex/demultiplex was realized with Time Division Multiplex (TDM) techniques acting on electric signals, with high power consumption and big processing complexity. Nowadays the same operations are carried out by Wavelength Division Multiplex (WDM) techniques using totally passive components.

Line termination devices, i.e. electro-optical transceivers, are the only active components needed for the connection. The great advantages in terms of power consumption, reliability, and simplicity recommend this technique as a perfect candidate for final km³ detector.

3.4 Power distribution

An evaluation of the total power budget needed for the km³ detector can be made considering an approximate load of 18 W at the level of each storey (four OMs plus some instrumentation with related electronics) plus some extra load at the level of the Tower Base (100 W) and of the Junction Boxes (200 W). This leads to a total amount of power required of about 27 kW.

Several solutions for the energy distribution system have been analyzed: in direct current, in alternate current mono phase and alternate current three phase. These

solutions have been compared in terms of voltage drops and Joule losses. A three phase AC system has been chosen since it presents some advantages in terms of losses and reliability. This system is used for the energy distribution up to the level of the local electronics module in each storey where a conversion to DC is made.

4 THE NEMO PHASE 1 PROJECT

The technological solutions proposed for the km³ detector and described in section 3 require an adequate process of validation. For this reason, we have undertaken a project, called NEMO Phase 1, for a technological demonstrator consisting in a subset of the proposed km³ detector and including some of its critical elements. The project will be realized at the Underwater Test Site of the Laboratori Nazionali del Sud in Catania, where a 28 km electro optical cable, reaching the depth of 2000 m, allows the connection of deep sea instrumentation to a shore station. The NEMO Phase 1 system will be composed by a network of Junction Boxes (a main one and two secondary) and two NEMO Towers. This will allow to test mechanical characteristics, data transmission and power distribution system of the whole apparatus. The project is completely funded, with a joint contribution of INFN and MIUR, and its completion is foreseen by the end of 2006.

5 REFERENCES

1. See AMANDA website at <http://amanda.uci.edu>
2. See ANTARES website at <http://antares.in2p3.fr>.
3. See NESTOR website at <http://www.nestor.org.gr>.
4. See ICECUBE website at <http://icecube.wisc.edu>.
5. See <http://www.vlvnt.nl/proceedings>
6. See <http://nemoweb.lns.infn.it/sites/sitesreport>
7. Battle et al. in <http://www.vlvnt.nl/proceedings>
8. D. Bailey, *Monte Carlo tools and analysis methods for understanding the ANTARES experiment*, Ph.D. thesis, Univ. of Oxford (2002).

THE NEMO PHASE-1 PROJECT

E. Migneco^{a,*}, S. Aiello^e, E. Amato^h, M. Ambriola^b, F. Ameliⁱ, G. Andronico^e, M. Anghinolfi^f, M. Battaglieri^e, R. Bellotti^b, A. Bersani^f, M. Bonoriⁱ, A. Caponeⁱ, L. Caponnetto^e, F. Cafagna^b, M. Circella^b, R. Cocimano^a, R. Coniglione^a, M. Cordelli^g, M. Costa^a, S. Cuneo^f, A. D'Amico^a, V. D'Amico^h, C. De Marzo^b, R. De Vita^f, C. Distefano^a, A. Gabrielli^c, E. Gandolfi^c, A. Grimaldi^e, R. Habel^d, A. Italiano^h, M. Leonardiⁱ, L. Lo Nigro^e, D. Lo Presti^e, A. Margiotta^c, A. Martini^g, M. Masetti^c, R. Masulloⁱ, T. Montaruli^b, M. Musumeci^a, C.A. Nicolauⁱ, R. Occhipinti^a, R. Papaleo^a, C. Petta^e, P. Piattelli^a, G. Raia^a, N. Randazzo^e, S. Reito^e, G. Ricco^f, G. Riccobene^a, M. Ripani^f, M. Romita^b, A. Rovelli^a, M. Ruppi^b, G.V. Russo^e, M. Russo^e, P. Sapienza^a, J.P. Schuller^{i,+}, M. Sedita^a, M. Spurio^c, I. Sokalski^b, M. Taiuti^f, L. Trasatti^g, V. Valente^g, P. Viciniⁱ, G. Zanmarini^c, S. Zavatarelli^f

(The NEMO Collaboration)

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

b) Sezione di Bari & Dipartimento di Fisica e Politecnico dell'Università di Bari, (Italy)

c) INFN, Sezione di Bologna & Dip. di Fisica dell'Università di Bologna, (Italy)

d) INFN, Sezione di Cagliari & Dip. di Fisica dell'Università di Cagliari, (Italy)

e) INFN, Sezione di Catania & Dip. di Fisica dell'Università di Catania, (Italy)

f) INFN, Sezione di Genova & Dip. di Fisica dell'Università di Genova, (Italy)

g) INFN, Laboratori Nazionali di Frascati, Frascati (Italy)

h) INFN, Gruppo Collegato di Messina & Dip. di Fisica dell'Università di Messina, (Italy)

i) INFN, Sezione di Roma 1 & Dip. di Fisica dell'Università di Roma "La Sapienza", (Italy)

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

+ on leave from DAPNIA/SPP CEA Saclay, France

Abstract

The NEMO Phase-1 project, which is now in course of realization at the LNS, aims at the realization of a technological demonstrator of the km³ underwater neutrino detector. The project consists in a network of three junction boxes and two instrumented detector structures and will be installed at a depth of 2000 m at the Underwater test Site of the LNS.

1 INTRODUCTION

The technological solutions proposed for the km³ neutrino detector require an adequate process of validation. For this reason it was decided to realize a technological demonstrator, at the Underwater Test Site of the Laboratori Nazionali del Sud in Catania, consisting in a subset of the proposed km³ detector and including some critical elements like junction boxes, towers, data and power transmission systems. This project is called NEMO Phase 1.

The NEMO Phase 1 system will be composed by a network of Junction Boxes (a main one and two secondary) and two Nemo Towers.

2 THE LNS TEST SITE

The Test Site of the Laboratori Nazionali del Sud (figure 1) consists of an electro-optical submarine cable, to connect the underwater installation at 2000 m depth to the shore, and a shore station.

The cable system is composed by a 25 km main electro-optical cable, split in two branches, each one 5 km long. One branch will be dedicated to the NEMO

Phase 1 experiment, while the other one will host the first underwater seismic monitoring station, called SN-1, realized by the Istituto Nazionale di Geofisica e Vulcanologia (INGV). The cable carries 6 electrical wires, 4 mm² in diameter, and 10 monomode optical fibres G-652.

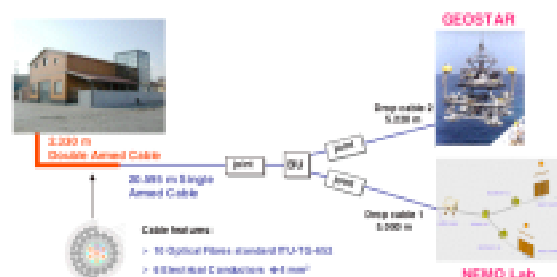


Figure 1: Layout of the LNS Underwater Test Site.

A shore station, located inside the port of Catania, will host the energy power system of the laboratory, the instrumentation control system, the landing station of the data transmission system and the data acquisition, as

well as a mechanics and electronics workshops for the assembly of the components.

The submarine cable has been deployed in 2001. In September 2004 the terminations of the two branches will be recovered to install on each one a frame with the wet mateable receptacles on which the underwater structures will be connected.

3 NEMO PHASE-1

The NEMO Phase-1 project (fig. 2) will consist of three junction boxes, a primary and two secondary ones, plus two towers. The system includes a high speed and high bandwidth data transmission system and the power distribution system for the underwater installation.

The project has been completely funded, with joint contributions of INFN and MIUR, and its realization is foreseen in 2006.

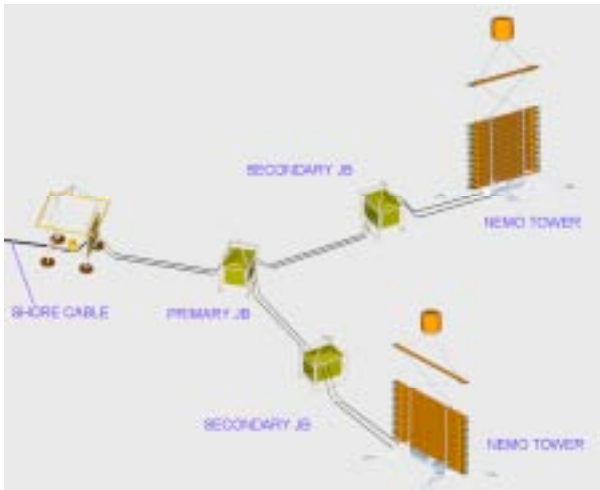


Figure 2: Artist view (not to scale) of the NEMO Phase 1 project.

4 JUNCTION BOXES

An alternative design to the standard Titanium pressure vessels used for junction boxes operating in seawater for a long lifetime has been developed. The approach is to decouple the pressure and the corrosion problems. Therefore, the proposed JB will be made by a pressure resistant steel vessel hosted in a fibreglass container to avoid direct contact between steel and sea water. The fibreglass container will be filled with oil to compensate the external pressure. This solution should improve the reliability and also reduce costs by avoiding the use of expensive alloys.

5 MECHANICAL STRUCTURES

Optical modules and instrumentation will be mounted on a structure that we have call *tower*. This is a three dimensional structure composed by a sequence of storeys (that host the instrumentation) interlinked by a system of cables and anchored on the seabed. The structure is kept vertical by an appropriate buoyancy on the top.

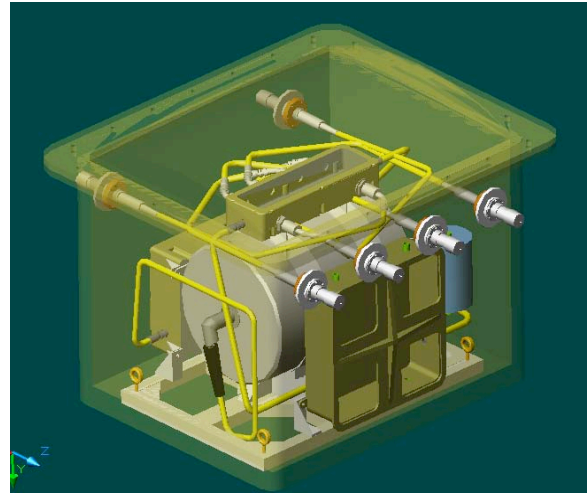


Figure 3: The Junction Box. The external fibreglass container dimensions are approximately 1.2 x 1.2 x 1.2 m.

The final features of the tower (number of storeys, number of optical modules per storey, distance between the storeys) can be optimized following the results of numerical simulations. However, the modular structure of the tower will permit to adjust these parameters to the experimental needs.

The Phase 1 project foresees the realization of two of these towers. The first one will be a prototype with only four storeys, while the second one will be a complete 16 storey tower. Each storey will be realized with a 20 m long structure (fig. 4), hosting two optical modules at each end (4 OM per storey), realized in titanium or marine Al. The vertical separation between storey will be fixed at 40 m. An additional spacing of 150 m is added at the base of the tower, between the anchor and the lowermost storey to allow for a sufficient water volume below the detector. In its working position each storey will be rotated by 90°, with respect to the up and down adjacent ones, around the vertical axis of the tower.

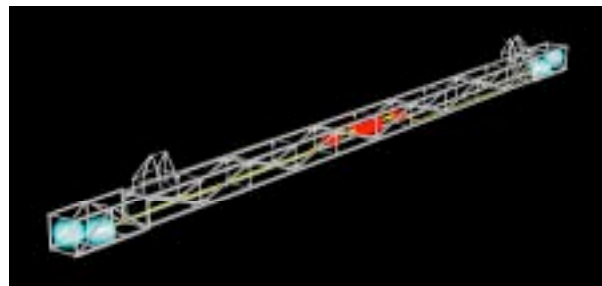


Figure 4: A "NEMO tower" storey.

One of the advantages of this structure is represented by the fact that it can be compacted, by piling each storey upon the other, to simplify transport and deployment. The structure is unfurled, reaching its operating configuration, only after its deployment on the seabed.

The feasibility of such operation has been successfully tested in april 2004 using a 1:5 scale model of the tower deployed at a depth of 70 m.

5 DATA TRANSMISSION SYSTEM

Considering NEMO Phase 1 as a feasibility test toward the km³ detector, its data transport system has been designed based on technical choices that allow scalability to a much bigger apparatus.

The basic idea consists of making the smallest, though most significant, fraction of the km³ apparatus, i.e. a junction box plus a complete tower. Moreover, connection reliability has been taken into account as a key issue in the design.

At the centre of each floor of the tower an electronics circuit, called Floor Control Module (FCM), is placed. The FCM collects data from the floor photo-multipliers (PMTs) and the floor control and auxiliary signals, creates an STM-1/SDH data stream at about 155 Mbps, and send data toward the land side laboratory. From the opposite direction, the FCM receives slow control data, commands and auxiliary information, and the clock and synchronizations signals needed for apparatus timing.

Bidirectional data transport is realized by means of a single optical fibre connecting the FCM with the Tower Junction Box (T-JB) located at the base of the tower. Inside the T-JB a WDM device is placed, which packs all the bidirectional bit streams coming from all the floors onto a single fibre directly linked to the on shore side. Actually, in order to provide redundancy, data streams are doubled and re-directed onto two fibres using a "power splitter". The one fibre of the two used to carry the meaningful information is chosen on the on-shore station.

The underwater structure has a complementary on-shore counter part, where all optical signals are converted back to electrical signals. In the on-shore laboratory the Primary Reference Clock (PRC), which is used to give the same timing to all the towers of the apparatus, is also located. Assuming that the two fibres per tower maintain their integrity, the designed system

provides other experiments with a further bidirectional channel.

6 ELECTRICAL POWER SYSTEM

Since the Phase 1 project is intended as a test of the km³ technologies, for the electrical power system the same design choices proposed for km³, with the appropriate changes due to the constraints imposed by the already existing electro-optical cable, were taken. A preliminary design of the power control system was made. This should be able to acquire currents and voltages plus some environmental parameters, such as temperature, humidity, etc., inside the boxes, switch the power on and off to each feeding line, both under ordinary and fault conditions, detect failures and remotely control the breakers in order to continue feeding the JB interested by the fault.

7 PROJECT STATUS

The project is presently in ad advanced phase of realization. The submarine cable is already installed and it will be completed with the installation of the cable terminations in September 2004. The shore station is now fully operational.

All the components of the junction boxes have been ordered and the integration is foreseen in the first half of 2005, while their deployment and connection will be performed at the end of 2005. This will accomplish a major milestone of the project offering the complete availability of a fully operational deep sea laboratory also to external users.

A first prototype of tower, composed by only 4 storeys, will be realized and integrated in 2005. It will be deployed and connected, together with junction boxes, at the end of 2005. A second complete tower of 16 storeys will follow in 2006.

REFERENCES

1. E. Migneco et al., in this report.

A SUPERCONDUCTING CYCLOTRON AS A PRIMARY ACCELERATOR FOR EXOTIC BEAM FACILITIES

L. Calabretta, L. Celona, G. Cuttone, S. Gammino, M. Maggiore, G. Raia, M. Re, D. Rifuggiato, S. Farion*, P. Fabbriatore*, R. Musenich*

I.N.F.N.- Laboratori Nazionali del Sud, Via S. Sofia 44, 95123 Catania, Italy

* I.N.F.N.- Sez. Genova, Via dodecaneso 33, 16146 Genova Italy

Abstract

The design of a compact superconducting cyclotron able to deliver light ions with $q/A=0.5$ at 250 A MeV is presented. This cyclotron is optimised to accelerate H_2^+ molecules to be extracted by stripping. The extraction by stripping allows to extract high beam power to drive a facility of radioactive ion beams. Simultaneously a low intensity beam could be extracted to perform radiotherapy treatment and interdisciplinary research. The main characteristics of the accelerator are presented.

1 INTRODUCTION

The scenario of the world's nuclear facilities over the last years is characterized by a reduction in number due to serious difficulties to find the necessary funds. At the same time in many countries there is an exploding interest to build facilities for radiotherapy based on proton accelerators with energy of around 250 MeV.

The accelerator here presented would allow medium size Laboratories to realize a facility for radioactive ions and for therapy treatment at the same time, therefore the cost of the facility could be shared among the national scientific agencies and the National Health service. Laboratories interested in building this kind of cyclotron could have as expert partners existing private companies which have already build cyclotrons for therapy. This kind of co-operation among nuclear physicists, and physicians could be promoted by the governments and have a large social approval.

The existence of more radioactive facilities should offer to the nuclear communities the opportunities to perform ever experiments which need a lot of time and moreover would allow to develop new activities related to the radioactive ion beams.

Indeed, our proposal is for a compact superconducting cyclotron able to accelerate H_2^+ at 250 A MeV. The acceleration of H_2^+ molecules allows to perform the extraction of the beam by stripping, ref.[1]. The extraction by stripping is very easy to be performed and its efficiency is 100%, then very appropriate to extract high beam power. Moreover two beams with different power can be extracted from cyclotron at the same time ref.2. The higher power beam (up to 50 kW) could be used to drive a radioactive ion beam facility while at the same time the low power (<500 nA) beam could be

dedicated to drive a medical proton radiotherapy facility.

2 DESCRIPTION OF THE CYCLOTRON

The cyclotron model has been designed to accelerate particles having a charge to mass ratio $q/A=0.5$. So H_2^+ molecules and light ions can be accelerated up to 250 A MeV. The reference cyclotron which has inspired the present study was the K1200 cyclotron operating in the Michigan State University, USA. Of course a lot of parameters have been modified and in some aspects it has been greatly simplified. The characteristics of our design are summarised in table 1. The main differences with the K1200 are :

- i) The operation frequency and the magnetic field are fixed, with a narrow tuning range ($\pm 0.4\%$), to allow for acceleration of different light ions with $q/A \approx 0.5$;
- ii) The cyclotron does not have any trim coils to simplify the routine operations. The trimming of the field will be done during the commissioning by trim rods.
- iii) The number of sectors is increased from 3 to 4, and the pole radius is 1.325m.

As compared to the K1200 cyclotron, the larger radius together to the smaller gap of the pole produces a higher value of flutter, so we have achieved a focusing power $K_{FOC} > 500$ maintaining the spiral angle of the sectors at a value similar to the K1200.

The use of this cyclotron to deliver also high beam power suggested a quite large radius of pole to have enough room for cooling, maintenance, diagnostic and extraction devices.

Due to the radius of pole, only a 3.8 Tesla mean field at extraction radius is required. In spite of its large radius, the cyclotron pole can be opened by lift in similar way for the existing superconducting cyclotrons. This solution guarantees a quite fast opening procedure for the unscheduled maintenance operation.

Table 1: Cyclotron parameters

Sectors number	4	Hill width	33°-47°
Pole radius	1330 mm	<Spiral Angle>	107 [Deg./m]
Yoke diameter	5 m	Coil width	150 mm
B at centre	3.1 T	Coil height	210 mm
Maximum 	3.7 T	Current density	<45 A/mm ²
Max. Field	4.5 T	LHe Losses	10 W
K _{bending}	1200	RF frequency	91 MHz
K _{focusing}	500	RF harmonic	4 th
Valley height	900 mm	Number of cavities	4
Hill gap	50 mm	Total weight	300 tons

To guarantee enough room for the design and positioning of the extraction channels and more generally for an easy access to the median plane of the cyclotron the distance among the superconducting coil is 170 mm, quite high as compared with the 120 mm of our cyclotron.

The cryostat design is not yet completed but enough room has been allocated to guarantee safe operation and minimum consumption of liquid helium. Using the present insulation technology, fibre glass tie rods and high temperature superconducting current leads, the expected thermal losses are estimated below 8 W. This moderate value of refrigeration power could be delivered by 4 commercial reliquefier. Also a 50 Kelvin shield will be cooled by 2 commercial cryogenerators. The available commercial reliquefiers and criogenerators need a scheduled maintenance with a frequency of more than one year and mainly they allow to avoid the construction and the operation of a Helium liquefier plant.

The optimisation of the magnetic field has been made using the 3D electromagnetic code OPERA. A parametric model of the cyclotron has been built, and an iterative process has been realised in order to optimise automatically several parameters of the machine like sectors width, hill and valley gaps, spirral angle, to fulfil the beam requirements, like the isochronous field and radial and vertical focusing.

The beam dynamics properties have been studied by the code GENSPE1, which calculates the equilibrium orbits using the magnetic field maps produced by OPERA.

The four spiral accelerating electrodes will be part of four Radio-Frequencies cavities driven at ≈ 91 MHz, fourth harmonic of the particle revolution frequency. The 4th harmonic allows to drive the 4 cavities at the same phase and maximize the energy gain per turn for a

given voltage. The cavities will be galvanically connected each other and driven by a single RF Amplifier, which simplifies significantly the technical plant and reduces the cost.

The mean voltage needed to accelerate the beam has been chosen to be 100 kV. This value allows to have an acceptable energy gain per turn and consequently an acceptable total number of turns. Due to the large capacitance of the accelerating electrodes the design of the RF cavities with voltage higher than 100 kV and thermal power losses lower than 50 kW is a challenge. The design of the cavities is in progress. To study and simulate these cavities both the HFSS and M.W.S. computer codes are used.

3 EXTRACTION BY STRIPPING

The stripping process has largely been used to extract H⁻ ions at energies as high as 520 MeV (200 kW) and in many commercial cyclotrons to extract H⁻ or D⁻ beams with power up to 40 kW. Indeed due to the ion speed and to the magnetic field of the cyclotron, in the reference frame of the beam there is an electric field: $\epsilon = 0.3\gamma\beta B$ [MV/cm]

The binding energy of the H₂⁺ molecule is about 16.3 eV and allows to use a magnetic field as high as 10 T even at energies as high as 1 GeV per nucleon without beam losses due to electromagnetic dissociation.

In figure 1 the trajectories of the stripped protons and of fully stripped light ions, extracted by electrostatic deflectors, are shown. The two trajectories can be guided to the same extraction line. The stripper angular straggling is negligible due to the high energy of the beam and the small thickness of the stripper. There is a strong focusing effect when the fringing of the magnetic pole is crossed. At this location a magnetic channel will be installed to control the beam focusing. The radial positions where it is necessary to place the magnetic channels are quite far from the last accelerated orbit and the gap between the superconducting coils allows to design and install proper magnetic channels quite easily.

4 BEAM CURRENT, LOSSES AND VACUUM REQUIREMENTS

According to our experience, commercial ion sources are today able to deliver beam currents larger than 1 mA of H₂⁺. If a current of 400 μ A is injected inside the cyclotron and a single frequency buncher is used to increase the injection efficiency, the expected accelerated current is about 25% of the injected current, ≈ 100 μ A. Considering the 100% extraction efficiency of the stripping method, a proton beam current of ≈ 200 μ A, corresponding to 50 kW, will be extracted. The space charge effects are negligible. As reported by Baartman ref[3] for a proton cyclotron with stripping extraction, the space charge effects become significant at current values higher than 1 mA. For H₂⁺ this limit is a factor 2 higher.

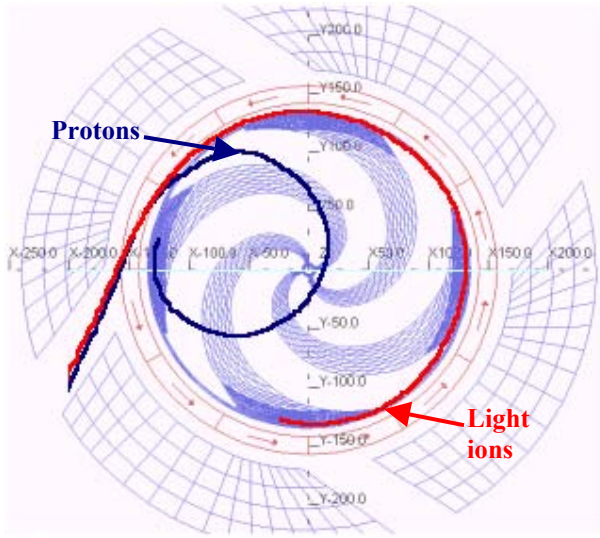


Figure 1: Cyclotron layout and extraction path by stripping (protons) and by electrostatic deflectors (light ions)

The limit of 50 kW is not a physical limit due to cyclotron parameters but it is related mainly with the RF amplifier size and also to the problem of the so called beam loading effect on the RF plants (200 kW of power to drive the 4 cavities vs. 50 kW for the beam).

A possible source of beam losses are the interactions with the residual gases, which may produce stripping of the electron of H_2^+ . The fraction of particles which survives at these interactions has been evaluated according the Betz-Bohr model, that takes into account the beam cross section for electron loss in function of the beam energy and summarised by the following formula [4]:

$$T = N / N_0 = e^{-\frac{P}{KT} \int \sigma(E) d\ell}$$

where P is the pressure (Torr), L is the path length (m), $\sigma(E)$ is the cross section of electron loss. This formula is in quite good agreement with experimental data. Using this formula, assuming an accelerating voltage per turn of 800 kV and a pressure value of $1 \cdot 10^{-7}$ Torr, the fraction of particles lost during the acceleration is less than 1%. The previous formula allows to evaluate the fraction of particles lost at each turn (or at each energy), so the amount of beam lost all along the machine should be ≈ 170 W over 50 kW, see fig.2.

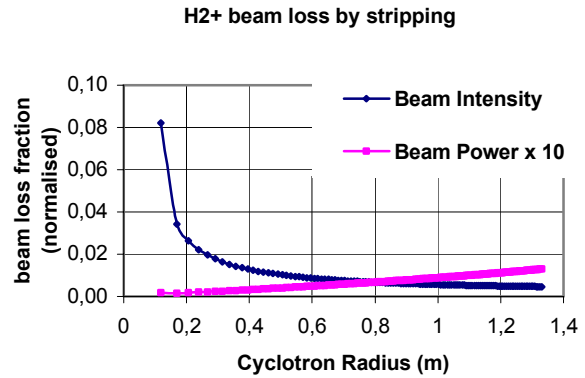


Fig. 2: Beam loss due to interaction with residual gas

These power losses are acceptable for the accelerator. Our experience with the K800 superconducting cyclotron shows that also with beam power higher than 100 W lost at the extraction radius (very close to the cryostat) there are no detectable effects on the cryogenic parameters of the cryostat or other devices of the machine. However a power of 100 W lost inside the accelerator for long time could activate very much the machine with problems for the maintenance operations. These losses can be strongly reduced if a better vacuum inside the acceleration chamber is achieved.

5 CONCLUSION

Although a lot of work is necessary to achieve a final design of the cyclotron, the study here presented shows clearly that a compact superconducting cyclotron equipped with extraction by stripping is a good solution to drive both a radioactive ion beam and a proton therapy facility.

6 REFERENCES

- [1] L. Calabretta et Al., proc. of Part. Acc. Conf.(1999) pag.3288.
- [2] L. Calabretta et Al., proc. of Eur. Part. Acc. Conf. (2002) pag. 614
- [3] Baartman, proc.of XIV Int. Conf.Cyc. and App., Cape Town (1995) pag. 440
- [4] Betz, Rev. of Mod. Phys. Vol.44,N° 3(1972) 465

THE ECLISSE METHOD: COMMENTS AND PERSPECTIVES

S. Gammino^{a*}, L. Torrisi^a, G. Ciavola^a, L. Andò^a, L. Celona^a, S. Manciangli^a,
L. Laska^b, J. Krasa^b, M. Pfeifer^b, G. Shirkov^c, J. Wolowski^d

a) INFN Laboratori Nazionali del Sud, Catania, Italy

b) IP-ASCR, Prague, Czech Republic

c) JINR, Dubna, Russia

d) IIPM, Warsaw, Poland

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

Abstract

The ECLISSE experiment (ECR ion source Coupled to a Laser Ion Source for charge State Enhancement) has been carried out in 2002 by coupling a Laser Ion Source (LIS) to an electron cyclotron resonance (ECR) ion source with the goal to obtain intense beams of highly charged ions (cw and pulsed mode) from metal samples. The coupling efficiency of the ion beam produced by the LIS to the ECR plasma was good, and the maximum charge states obtained from the ECRIS were 38⁺ for Ta and 41⁺ for Au. The peak current was obtained for 25⁺ and 29⁺ respectively and it was in the order of tens of μ A. The data analysis was performed in 2003, showing an interesting behavior in pulsed mode. A new experiment is under preparation for the end of 2004 with some changes that will improve the ionisation fraction.

1 INTRODUCTION

Laser generated plasmas have been used either to produce ions from refractory elements to be further ionized in an ECRIS and to produce intense pulsed beams for other applications. In particular, the ECLISSE method (ECR ion source Coupled to a Laser Ion Source for charge State Enhancement) based on the coupling between LIS and ECRIS, have shown to be a viable solution for beam production either in dc mode and in pulsed mode. The theory suggests that this concept may be effective provided that the ion energy from the LIS is of the order of a few hundreds eV, i.e. sufficiently low to permit the trapping and the further step-by-step ionization in the plasma region of ECR ion source [1]. The description of the ECLISSE experiment is reported in [2]

In ref. [3] a detailed study of the neutrals behavior and of the ionization fraction is also reported. These parameters were relevant to determine the effectiveness of the hybrid source.

The plasma energy content fixes the amount of LIS-produced beam power that can be deposited in the plasma, then the higher are the electron temperature and the electron density that can be reached in the plasma, the better is the coupling of LIS-generated ions. The plasma density is related to the microwaves frequency by the relation $n_e \text{ (cm}^{-3}\text{)} \leq 1.24 \cdot 10^{10} f^2$ where f is microwave frequency in GHz (18 GHz in our case). Therefore a high rf frequency is requested and the SERSE source represents at this date the ideal testbench for such a method because of its high plasma energy content.

2 THE EXPERIMENTAL SETUP

Because of the cryostat geometry, there is no radial accessibility to the plasma chamber of SERSE and even

the axial accessibility is poor due to the extraction system on one side and to the biased electrode, to the microwave and gas inputs on the other side. Therefore the easier solution is to inject the laser beam from the extraction hole, as the laser optics cannot be used inside the ECR plasma chamber.

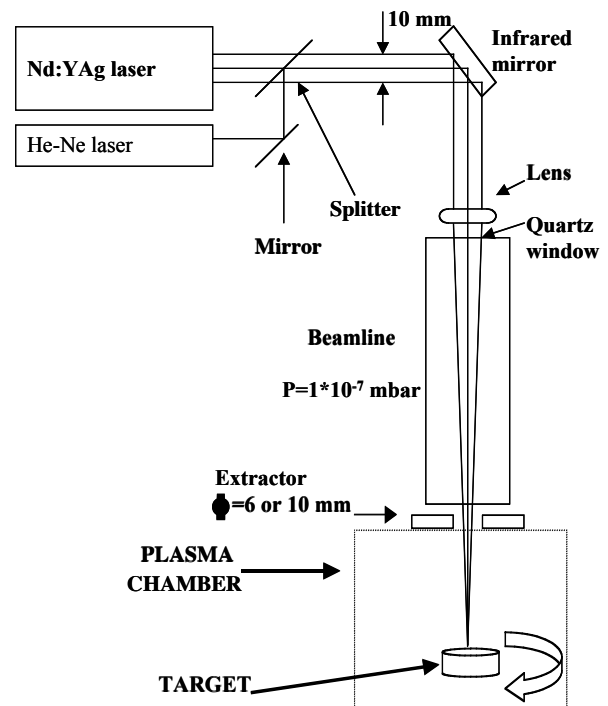


Fig. 1 – The optical scheme of the ECLISSE experiment.

The laser beam was injected into the beamline from the 0° port of the 90° analysis magnet, on-axis with the extracted beam (the interaction between the laser beam and the beam of highly charged ions extracted from the source is negligible). The optical scheme is sketched in fig. 1.

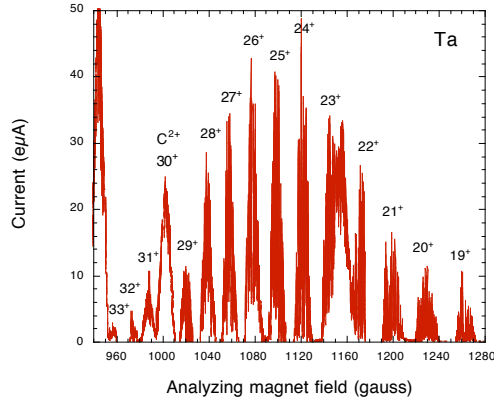


Fig. 2 – High charge state Tantalum beams produced with low laser energy (current is in $e\mu A$)

3 EXPERIMENTAL RESULTS AND COMMENTS

Tests with the ECLISSE facility have been carried out in October 2002 with tantalum and gold target and they have confirmed that cw beams can be created.

Preliminary measurements with Argon plasma, not optimised for high charge states have given a current of $40 \mu A$ of Ta^{25+} and Ta^{26+} , $11 \mu A$ of Ta^{31+} , $1 \mu A$ of Ta^{33+} , with a bias voltage of 240 V and a chamber pressure in the order of 3×10^{-7} mbar. The rf power was about 1500 watt and the laser repetition rate was 30 Hz. Laser power was 450 mJ only, because at higher rate there was an excessive target outgassing, and high voltage sparks occurred at the extraction. With a higher laser energy, more than $50 \mu A$ of Ta^{24+} and Ta^{25+} could be obtained for a short time, in order of minutes, afterwards the target outgassing deteriorated the vacuum and the high charge states buildup.

Fig. 2 shows a typical charge state distribution for Tantalum.

Operations in afterglow mode [4] were also studied in 2003 by analyzing the data collected in the previous experiment. A typical plot of the beam current in the Faraday cup vs. time is given in fig. 3.

The reproducibility was quite good and the dependance on the phase of the waveguide confirmed the theoretical analysis, i.e. that the ions generated by the laser source should arrive some milliseconds after the start of the radiofrequency, so that the plasma is stable and its temperature is high.

The optimum results for Ta^{28+} were obtained for a quite high laser power and a rf power above 1.5 kW with a duty factor between 30% and 90% (the influence of the duty factor was not relevant indeed). For sake of simplicity neither gas mixing nor biased disk were used, so that a pure afterglow behavior was observed. The

laser repetition rate was 30 Hz, but different pulse repetition rates could be used.

In general, the time width of the laser generated ion beams last a few tens of microseconds, which adapts very well to the characteristics of afterglow mode pulse generation.

In terms of absolute currents, it can be observed that about a factor three to seven current increase was obtained; e.g. in the case shown in fig. 3, the average current was below $4 e\mu A$, while in afterglow mode it exceeded $14 e\mu A$.

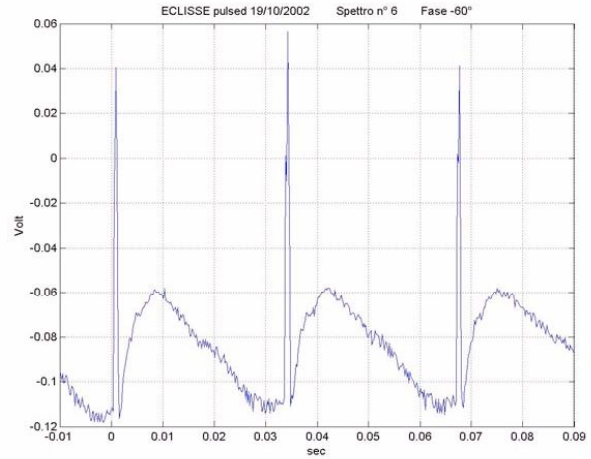


Fig. 3 – Typical afterglow peak for high charge state Tantalum beams.

4 FUTURE EXPERIMENTS

In conclusion, our tests have shown that not only a pulsed beam but also a cw beam can be obtained for the highest charge states [2] which is relevant for cyclotron – based facilities, as LNS, Catania or RIKEN, Tokyo (where a similar experiment is under way).

The scientific motivation of the next experiment approved by the LNS Advisory Committee is linked to the possibility to improve the experimental conditions by means of an adequate technology of vacuum, of materials, of laser synchronization with RF pulse, as well as with the use of 2nd harmonic of the laser frequency.

The success of the ECLISSE experiment, which is still continuing with a daughter project named PLAIA, is confirmed by the interest of different international laboratories to participate to future experiments and some of them are repeating the experiment.

The mid-term perspectives consist of the repetition of the tests with the goal to obtain more intense beam of highly charged ions (not only in cw mode, but also in pulsed mode) from metal samples. As the possibility to enhance the available charge state was limited by charge exchange processes following the outgassing of the target, a different positioning and a different optics will be used to improve either the maximum charge states and the peak current.

The steps to be followed will be:

- Careful adjustment and alignment of the optical system.
- Measurements by changing the target bias in order to investigate about the electron injection action and on the ion stopping power inside the ECR plasma.
- Measurements with electrons injection in the ECR plasma from a different source will be also considered
- Measurements with increasing laser repetition rate, from 1 Hz to 30 Hz.
- Measurements with pulsed ECR plasma, at the same frequency and in synchronism with the laser pulse rate (afterglow mode).
- Measurements with light targets (copper or aluminium) and comparison of results with heavy targets (Ta and W).
- Investigation about the role of neutrals injection in ECR.
- Change of the target geometrical position with respect to the injector hole and to the chamber walls.
- Measurements with watercooled target.
- Measurements of the ion energy and charge state distribution by using the fundamental laser wavelength (1064 nm) and the second harmonics (532 nm), as in fig. 4.
- Comparative tests with other similar facilities.

The 3rd generation of ECR ion sources now under development will have a frequency of RF plasma heating in the range of 28-30 GHz and a much higher plasma density (a factor of 3 or 4) and electron energy. The higher plasma energy content will give a further boost to the availability of metallic ion beams according to the ECLISSE method.

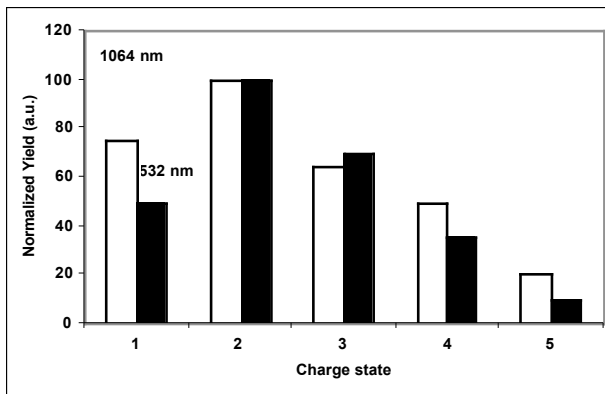


Fig. 4 – Ion output of the LIS at first and second harmonic of LNS Nd:Yag laser (about 100 mJ).

A series of numerical simulations was carried out in order to estimate the possible performance of the future ECR sources under the laser loading of neutral atoms. Uranium was chosen as an examples of species of the laser loading. The following parameters of a hypothetical 30 GHz ECR source were used:

- electron temperature of 20 keV;

- magnetic field mirror ratio of 4.0;
- plasma length of 25 cm and diameter of 8 cm.

It was assumed that a plasma is created and stored during 5 ms up to a stable electron density of 10^{13} cm^{-3} before the laser pulse. Results of numerical simulation of laser pulse injection of Uranium are presented in Figs. 5.

The afterglow affect was modeled starting at 1.0 ms after the neutral loading. The output current of U^{35+} could be more than 2 mA with duration of about 0.5 ms according to this numerical experiment.

Finally it was observed that adequate repetition rates of the rf pulse and of the laser pulse with delay lines for synchronization, may permit to handle high amount of ions and to obtain any any time structure from short pulses to cw regime.

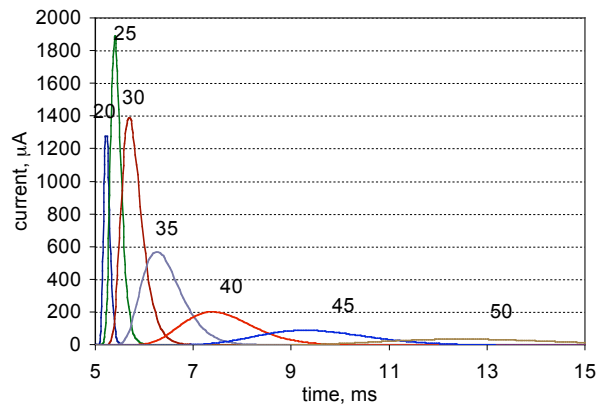


Fig. 5. Pulsed laser injection of U neutrals into O plasma of GyroSERSE.

ACKNOWLEDGEMENTS

The support of the Fifth National Committee of INFN (ECLISSE and PLAIA experiment) is gratefully acknowledged.

We thanks Mr. C. Percolla for his continuous and effective support to the experiment.

REFERENCES

- [1] S. Gammino et al., INFN/TC-02-06 (2002)
- [2] S. Gammino et al., Journal of Appl. Phys. 95 (15), (2004)
- [3] L. Torrisi et al., Journal of Applied Phys. 91 (7), (2002) 4685
- [4] R. Geller, Electron Cyclotron Resonance Ion Sources and ECR plasmas, Institute of Physics Publishing, Bristol, 1996

THE EXPERIMENT E435 AT GANIL

M. Menna^a, F. Chines^a, G. Cuttone^a, D. Garuff^a, E. Messina^a, M. Re^a, M.-G. Saint-Laurent^b,
A. C. C. Villari^b, R. Alves-Condé^b, M. Dubois^b, G. Gaubert^b, C. Huet-Equibec^b,
P. Jardin^b, N. Lecesne^b, R. Leroy^b, J. Y. Pacquet^b

a) INFN - Laboratori Nazionali del Sud, via S. Sofia 62, 95123 Catania, Italy

b) GANIL, Caen, France

Abstract

The EXCYT facility (EXotics with CYclotron and Tandem) at the INFN-LNS is under completion and its commissioning with ^8Li as the first radioactive beam is foreseen by the end of 2004. Since the previous Target-Ion Source assembly (TIS) had been radically modified in its shape, dimensions and geometry, it became necessary to verify off and on-line the TIS behaviour with respect to the mechanical and thermal stresses at 2300 K as well as to obtain information about the production and the release processes. In order to save time, this was successfully achieved at the SIRa test-bench of SPIRAL, GANIL, by shooting a ^{13}C primary beam (60 MeV/amu) on a ^{12}C target under the same operational conditions that will be initially used at EXCYT. The measured yields and production efficiencies for $^8,^9\text{Li}$ were compatible with the ones obtained at SIRa. In the following, we report the work done with an emphasis on the details of the preparation, running and target post-mortem of the experiment conducted at GANIL under the heading E435

1 INTRODUCTION

At the EXCYT facility the primary beam coming from the SERSE ECR ion source goes into a $K = 800$ cyclotron (up to 80 MeV/amu, 1 μA) and then to the target-ion source assembly. Here the species of interest are produced mainly by projectile fragmentation in a target thicker than the projectile range. The products diffuse through the heated target, are desorbed from its surface and via a transfer line go to the ion source where they are ionised. Then, when positive, they pass through the vapours of a charge exchange cell to become negative. They are mass-separated in two stages, the first with a resolving power of about 2000 and the second up to 20000. It is worth noting that besides the post acceleration there is also an option to supply 300 keV beams for low energy experiments. The facility is described and shown in a number of publications and reports [1].

For the development of prospective radioactive ion beams or to check their feasibility, it is of paramount importance to carry on tests for determining the efficiencies of the production, diffusion, desorption, effusion and ionisation. Besides, one gets reasonable estimates of the final ion-beam intensity deliverable to the users. The following paragraphs contain in some details the work done to obtain radioactive ion beams of $^8,^9\text{Li}$.

2 TARGET MATERIAL AND GEOMETRY

The main characteristics of an ideal target are:

- 1) High production rates;
- 2) Large diffusion coefficient of the products;

- 3) Low product hold-up time on surfaces;
- 4) Large values of dissipated power;
- 5) High melting point;
- 6) Low vapour pressure to preserve ion-source efficiency ($< 10^{-8}$ mol/s);
- 7) Low Z to reduce activation;
- 8) No sintering;
- 9) No reaction with the container;
- 10) No damage due to the radiations.

By taking into account some of these characteristics (points 4-10), graphite has been chosen as a suitable material. To comply also with favourable production and release properties (points 1-3), it has been necessary to select among the many kinds of commercially available graphite the ones with higher open porosity, lower closed porosity, smaller grain size, higher thermal conductivity, higher density. After an extensive market research, we chose the graphite type UTR146 manufactured by XYCARB with a few parts per million of impurities. Experiments with radiotracers in collaboration with CERN-ISOLDE clearly showed a better release from this kind of graphite compared to other materials [2]. As for the production rates, we were less restricted on the choice since at EXCYT the radioactive nuclides are obtained mainly by projectile fragmentation. Nevertheless, we obtained good yields of ^{18}F , ^7Be and $^{22,24}\text{Na}$ by shooting ^{19}F (48 MeV/amu) on a XYCARB UTR146 graphite target [3].

To get an efficient heat dissipation for simple heat radiation loss, the target is tilted by a certain angle with respect to the incoming beam while keeping constant its

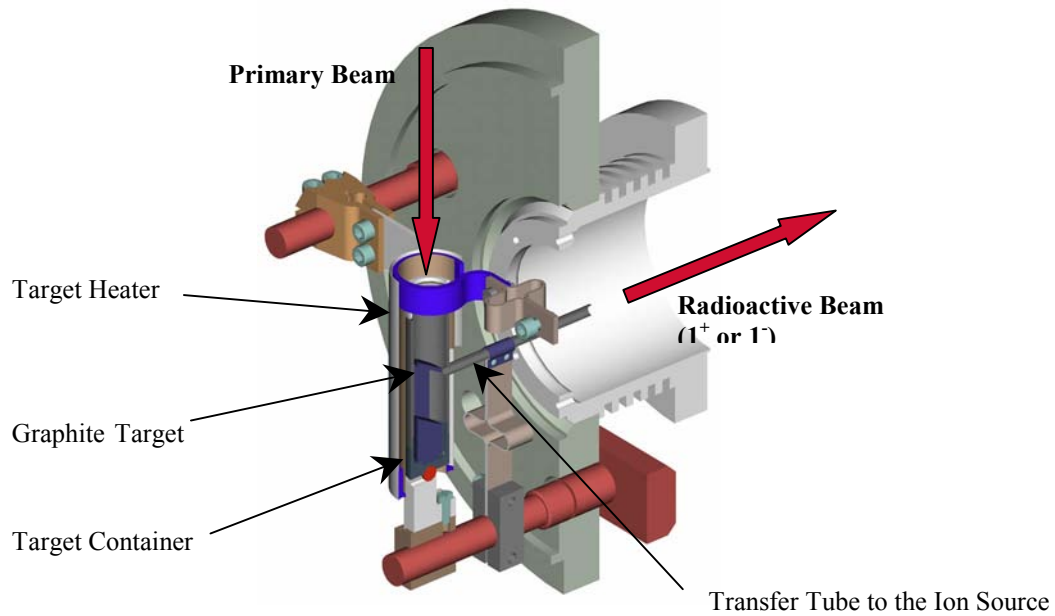


Figure 1: The new TIS. The real target area is mainly constituted by its upper part and is tilted to enhance both power dissipation and desorption

volume, thus reducing the effective target thickness and increasing the area of two of the heat-dissipating surfaces [4].

The previous TIS assembly [4] proved to be unreliable and was therefore radically modified in its shape, dimensions and geometry as shown in fig. 1. In the new TIS the graphite target is standing in a tantalum container, which in turn is inside a tantalum heater. In this configuration, the heater doesn't touch the container and the primary beam impinge on the target from the top. Heating is achieved by means of direct current while several tantalum layers on the outside of the heater shield the aluminium external container (not shown) from high temperature. The target container is heated by irradiation; the target is heated by: irradiation, contact at its bottom, primary beam power. The effective target volume is mainly its upper part, the rest constituting a simple mechanical support. In fact, the thickness of the upper part is chosen according to the range of the primary beam and of the produced radioactive nuclides. By a judicious choice, in principle it is possible to obtain that most of the products are located into the upper part of the target close to the transfer tube. Besides increasing the power dissipation, tilting of the target allows for a better desorption from its surface towards the transfer tube (cosine law).

3 POSITIVE SURFACE ION SOURCE (PIS)

Given its physical and chemical properties, the ionisation efficiency of lithium can be conveniently studied by implanting stable ${}^6\text{Li}$ into the graphite substrate. The substrate is then positioned nearby the ion source and heated to allow for the escape of the implanted atoms to be ionised.

Then the heating temperature is varied in order to keep the extracted beam in the range 1-10 nA (operational values for radioactive beams), the total extracted charge for the selected mass is recorded and converted into the number of extracted ions. The ratio of the latter to the implanted atoms gives the lower limit for the ionisation efficiency. By using an ISOLDE-type Positive Ion Source with a hollow W cathode, we obtained an efficiency of 75% for ${}^6\text{Li}^+$, very close both to its theoretical value and to on-line extrapolations [5].

4 THE EXPERIMENT

Since the TIS had been radically modified, it became necessary to verify off-line its behaviour with respect to the mechanical and thermal stresses at 2300 K as well as to obtain information about the on-line production and the release processes. In order to save time, it was decided to run an experiment at the SIRa test-bench of SPIRAL, GANIL, by shooting a ${}^{13}\text{C}$ primary beam (60 MeV/amu) on a ${}^{12}\text{C}$ target under the same operational conditions that will be initially used at EXCYT.

4.1 Interface and off-line tests

Since the primary beam at SIRa is horizontal, we needed to:

- 1) Rotate by 90° the target, its container and its heater;
- 2) Design and test an interface between EXCYT assembly and SIRa.

This implies that in the GANIL configuration the heater touches the container, unless one puts something in between. In order to make the minimum electrical contact we put a thin tantalum zigzag structure between

the target heater and the target container, thus keeping their temperatures almost independent.

The same configuration problem, to a minor extent, exists between target and container: at high temperatures the graphite target reacts with the tantalum container and the transfer tube can be obstructed by misplacement of the target. Therefore spacing between the target and its container was obtained by inserting a few tiny porous graphite lumps. Off-line tests at LNS showed that the assembly was mechanically and thermally stable up to 2300 K.

4.2 ANSYS simulations

The second task consisted in simulating by means of the ANSYS code the target behaviour in terms of mechanical and thermal stresses under the simultaneous influence of the heating power and of a 400 W primary beam. For radioprotection purposes this was done long before conducting the real experiment. The results allowed to determine the target and the heater temperatures as functions of input heater current and primary beam power. In addition, we could extrapolate the best operational parameters and ascertain that under those conditions the target was not going to break. Details of the simulations can be found in [6]

4.3 Radioprotection issues

Prior to the experiment it was necessary to:

- 1) Present it to the GANIL Advisory Committee to obtain 18 shifts of ^{13}C at 75 MeV/amu, then

reduced to 60 MeV/amu for a better distribution of the products inside the target;

- 2) Make qualitative and quantitative estimations of all the radionuclides produced during the experiment;
- 3) Collaborate with GANIL Radioprotection Service in order to assure traceability of every single TIS component used during the experiment;
- 4) Plan a post-mortem inspection of the TIS as well as arranging radioactive transport back to LNS

4.4 The production of $^{8,9}\text{Li}$

After all the preliminary work reported above, in May 2003 the TIS was mounted and outgassed at SIRa. During the off-line outgassing the TIS withstood three abrupt thermal cycles from about 1700 K to room temperature due to failures of the power supplies.

We started the on-line experiment and on May 14th at 2:20 am we detected the first radioactive beams of $^{8,9}\text{Li}$. The run lasted three days and the system proved to be robust and reliable (fig. 2): because of radioprotection constraints the maximum primary beam power was limited to 370 W but there was no sign of leaks or breakdown, despite five additional on-line failures of the primary beam (i.e. unwanted thermal cycles).

The graphs in fig. 3 show the production efficiencies for $^{8,9}\text{Li}$: these are defined as the ratios of the extracted radioactive ions to the atoms produced by nuclear reactions in the target core, as estimated via the EPAX code. It is clear from the plots that the efficiencies increase by passing time.

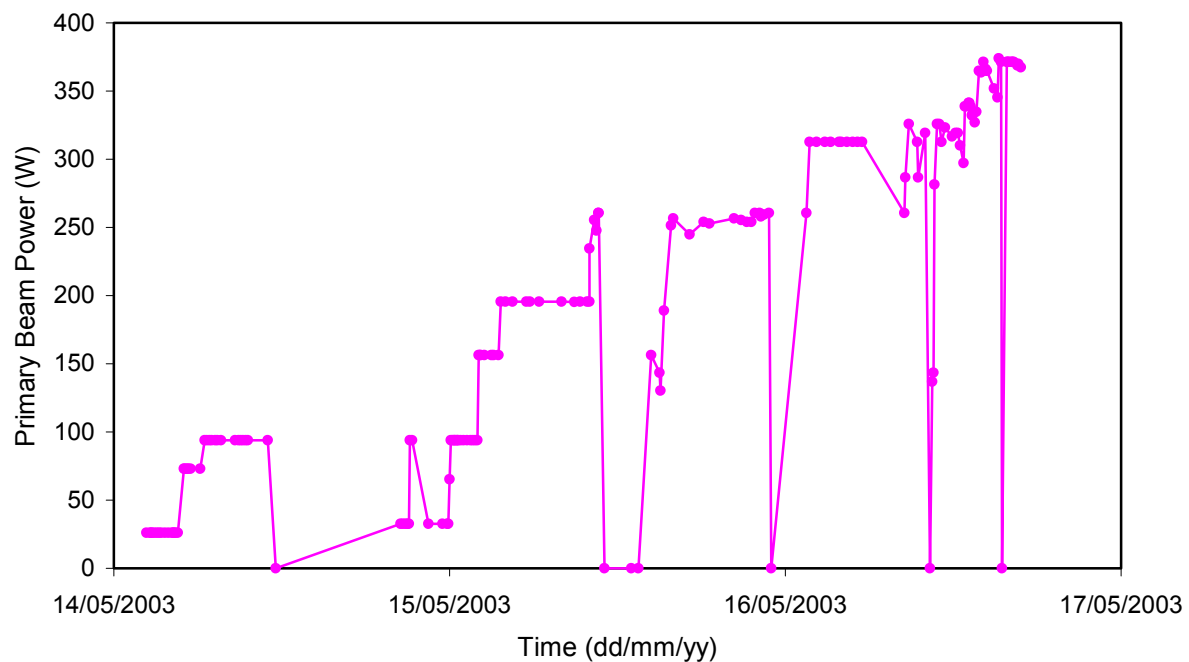


Figure 2: Primary beam power versus time. The target withstood five on-line plus three off-line abrupt thermal cycles due respectively to power and primary beam failures

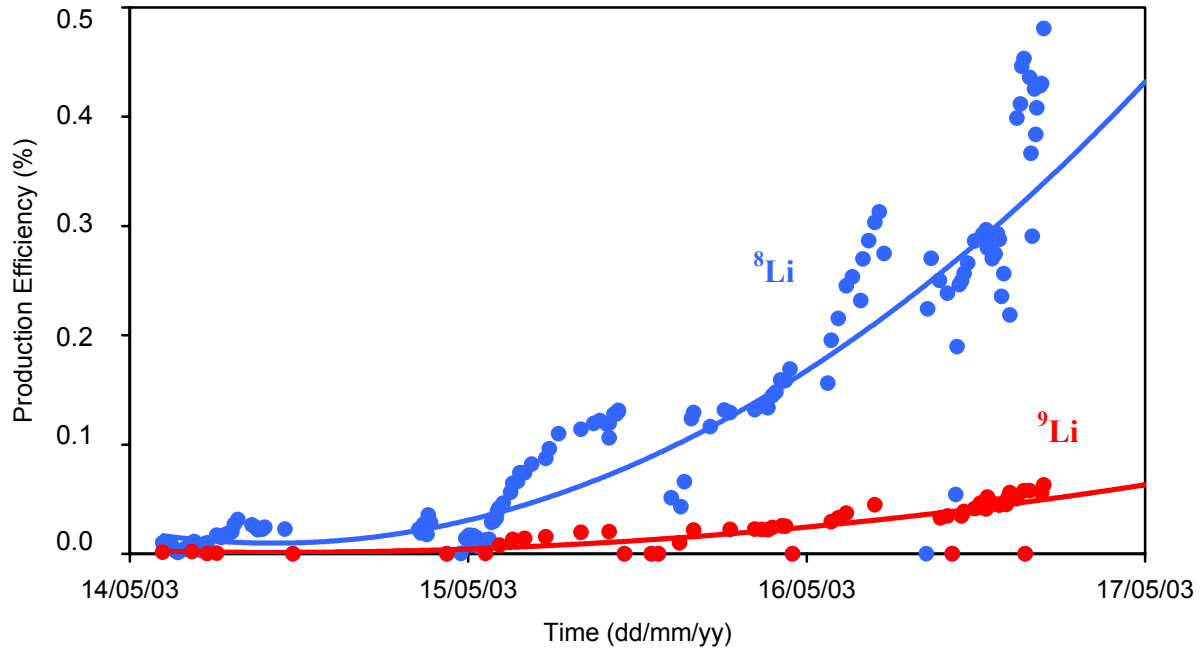


Figure 3: Production efficiencies for $^8,^9\text{Li}$ versus time. The production efficiency is the ratio of the extracted radioactive ions to ones theoretically produced into the target (estimation by the EPAX code)

This is mainly due to three factors: loss of impurities from the target, increase of target temperature by the primary beam power and increase of the heater temperature by ohmic heating. Currently we are estimating the influence of the second factor on the third one as well as trying to unfold the three stages of the production process: diffusion, effusion and ionisation, thus getting the efficiencies for each stage.

The yields for $^8,^9\text{Li}$ were compatible with the estimation made at the beginning of the project (table 1). However, they can be improved by adding a Re liner inside the ioniser and by increasing the target and ion source operational temperatures.

A comparison with SPIRAL graphite target in table 2 shows that its efficiency [7] is about twice compared to

EXCYT. Some tentative explanations for this difference are:

- 1) A better performance of GANIL assembly with respect to EXCYT's one;
- 2) We could not push the TIS to its real limits in terms of duration (schedule), target temperature (power supplies limitations) and primary beam intensity (radioprotection constraints);
- 3) The figures for the production efficiencies are affected by a large error ($\pm 100\%$) coming from the uncertainties in the EPAX code. We remind that the figures for SPIRAL are based on another nuclear reaction, namely 95 MeV/amu ^{36}Ar on graphite.

Beam	Projectile	Energy (MeV/amu)	Target	Intensity		
				Pre-accelerated (pps/pμA)	Post-accelerated (pps/pμA)	Post-accelerated, 500W primary beam (pps)
^8Li	^{15}N	50	C	$6.7 \cdot 10^7$	$2.4 \cdot 10^6$	$1.6 \cdot 10^6$
^8Li	^{13}C	60	C	$1.4 \cdot 10^7$	$5.0 \cdot 10^5$	$3.3 \cdot 10^5$
^9Li	^{13}C	60	C	$3.2 \cdot 10^5$	$1.2 \cdot 10^4$	$7.4 \cdot 10^3$

Table 1: Beam intensities for $^8,^9\text{Li}$ pre and post-accelerated by the Tandem. Values in the first row were estimated at the beginning of the project while in the second and third row are reported the expected experimental rates deduced from the experiment at GANIL

EXCYT		SIRa	
Efficiency (%) ^8Li	Efficiency (%) ^9Li	Efficiency (%) ^8Li	Efficiency (%) ^9Li
0.480	0.063	1.200	0.1400

Table 2: Maximum production efficiencies achieved respectively with EXCYT and GANIL graphite targets

By taking into account the third point, the values are consistent and their overlap seems to indicate an order of magnitude for the efficiency of lithium produced from graphite matrices: around 1% and 0.1% respectively for ^8Li and ^9Li .

4.5 The TIS post-mortem at GANIL

The post-mortem inspection showed that the target unit was intact (fig. 4) and reusable after a suitable radioactive cooling period. The TIS was partly dismantled inside a glove box and put in a special stainless steel container designed and built at LNS. Low-activity items were put in the bottom of the container, adequately shielded by layers of 1 cm lead. High-activity items (e.g. target) were put in a small stainless steel cylinder; the cylinder was sealed by screwing its cap on a metallic gasket, put on a dedicated shelf inside the container and additionally shielded by lead bricks. The container was sealed by screwing its cap on a plastic gasket and put into a wooden box for radioactive transportation back to LNS.

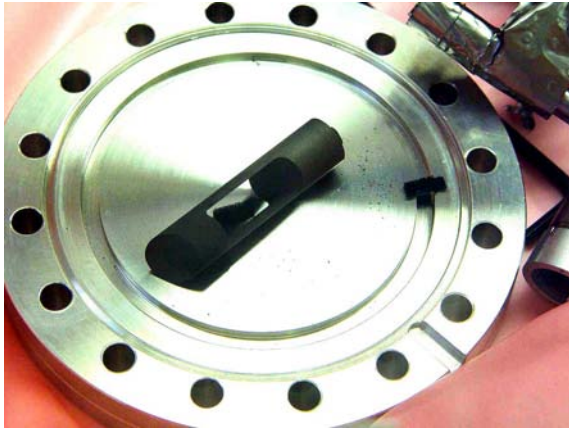


Figure 4: The target still intact after irradiation

5 CONCLUSIONS

This year signed two milestones for the EXCYT activity: the radioactive beams $^8,^9\text{Li}$ were successfully obtained at GANIL with the EXCYT TIS and a 100 W ^{12}C primary beam was extracted at LNS [8]. In 2004, EXCYT will be completed and authorised to work with a primary beam power of 500 W. The commissioning of the facility with stable beams is planned for September 2004, while the start of the nuclear experiments with ^8Li is foreseen by the end of 2004.

The experimental programme takes into account the availability of the MAGNEX detector [9, 10], the requests and the first results obtained by the “Big Bang” collaboration [11] and the RSM experiment [12].

6 REFERENCES

- [1] G. Cuttone et al., Status of the EXCYT facility at INFN-LNS, Proc. of the 2004 International Conference on the Labyrinth in Nuclear Structure, Crete, Greece (in publication on American Institute of Physics)
- [2] M. Menna et al., Release of implanted fluorine from C and SiC matrices, (in preparation)
- [3] M. Menna, NIM B184 (2001) 466
- [4] G. Ciavola et al., LNS Report 1996-99, 225
- [5] Ravn et al., NIM B88 (1994) 441
- [6] M. Re et al., Thermal simulations for the EXCYT target assembly, LNS Report 2003
- [7] S. Gibouin, Ph.D. Thesis N° T 03 02, 2003, University of Caen, France
- [8] G. Cuttone et al., The EXCYT facility towards its commissioning, LNS Report 2003
- [9] A. Cunsolo et al., NIMA 481 (2002) 48
- [10] A. Cunsolo et al., NIMA 484 (2002) 56
- [11] S. Cherubini et. Al., Eur. Phys. Journ. A20 (2004) 355
- [12] A. Di Pietro et al., Using the resonance scattering method to study Li-He cluster states in boron exotic isotopes, LNS Report 2003

CATHODE FIELD ELECTRON EMISSION INHIBITION BY GAS TREATMENT

M. Re^a, G. Sarta^a, E. Zappalà^a and G. Cuttone^a

a) INFN Laboratori Nazionali del Sud, Catania, Italy

Abstract

Studying the effects of gas treatments on cathodes working in high electrical field conditions has led to a better understanding of the role played by different gases on the field electron emission inhibition whose mechanism is still not completely clarified. This study was conducted introducing a small gas leak (He, Ar, N₂ or O₂) into the electrostatic deflectors cathodes of the K800 Superconducting Cyclotron. The Fowler-Nordheim analysis of the cathode voltage and dark current has put in evidence that the electron emission suppression is mainly due to gas adsorption effects on the cathode surface rather than gas surface sputtering as reported in literature. It was found out that the most effective gas was oxygen for which the strongest memory effect was noticed after the treatments.

1 INTRODUCTION

The Field Electron Emission (FEE) by different operational conditions has been widely studied [1], but the phenomenon involved in the FEE inhibition by gas treatments is still not fully understood [2]. The gas normally used for this process is He, and the phenomenon has been traditionally interpreted in terms of the blunting of the metallic emitters by the sputter action of high-energy gas ions [1,3]. In this experiment we report our data analysis and compare the effects of several gases, proposing a different interpretation of the results in terms of gas chemical and physical absorption at surface.

2 EXPERIMENTAL

The electrostatic deflectors [4,5] of the K800 Superconducting Cyclotron were treated with different gases in order to study the electron emission behaviour of titanium cathodes under several conditions. The gap between cathodes and the ground was set at 6 mm, the magnetic field was 2.8 T, the base pressure was $7 \cdot 10^{-7}$ mbar and the electric field spanned from 7 to 10 MV/m. By means of a leak valve different gases were introduced into the electrodes: He, Ar, N₂ and O₂ up to a pressure of about 10^{-3} mbar. The applied high voltage and the related dark current were recorded to be analysed using the Fowler-Nordheim (F-N) model [6,7]. In agreement with this model the field electron emission (FEE) is responsible for the electrons dark current emitted from the metallic cathode to the vacuum, this is mainly due by the presence of metallic tips on the cathode surface where the electric field is geometrically enhanced by a 'field-enhancement factor' called β -factor. By these conditions the current-voltage plot is not linear but follows a shape depending, by the first order terms [8], on the following relation:

$$\text{Log} \frac{I}{V^2} = K_1 \cdot \frac{1}{V} + K_2$$

In a F-N plot [$\text{Log}(I/V^2)$ versus $1/V$], if the main mechanism generating the dark current is due to FEE, the plotted data will result in a straight line where the slope is determined by K_1 and the intercept is determined by K_2 . The K_1 value is related to the cathode work function, the gap distance and the β -factor, while the K_2 value mainly depends on the total effective emitting surface. From the K_1 and K_2 values it is possible to estimate the β -factor and the emitting surface area. The voltage and current data were recorded by increasing and decreasing the applied voltage by step of 1 kV, starting from 50 kV and spanning from 42 kV up to 60 kV. The current intensity is obtained as an average of the measured current for each voltage setting and it spanned from 1 μ A to 60 μ A. In order to avoid cathode conditioning by the applied voltage, during the measure, the whole voltage scan had to be applied in a relatively short time (~ 3 min). All data have been then fitted both by a F-N fit and by a linear fit to check the correlation factors and whether the measured dark current was due to FEE or to resistive surface conduction.

3 RESULTS AND DISCUSSION

The starting conditions before every gas treatment were almost similar to each other, as it is shown in the F-N plot reported in figure 1. By fitting the data reported in figure 1, we obtain good F-N correlation and the mean values for slope and intercept are respectively $-1.9 \pm 0.1 \cdot 10^5$ and -10.2 ± 0.3 . These data are referred as "starting conditions" of the cathodes. These data show a far correlation with the resistive fit, thus we can conclude that the measured dark current was mainly due to FEE.

The He gas treatment was performed to a pressure up to 10^{-3} mbar. In figure 2 is reported the F-N plot of the data fit before, during and after the treatment. By this

test we experienced that the effect of the He gas is negligible since the lines slope of all the fitted values lies in between $1.8 \cdot 10^5$ and $1.9 \cdot 10^5$ and the intercepts in between -10.6 and -10.3 , these values are not far from the starting conditions.

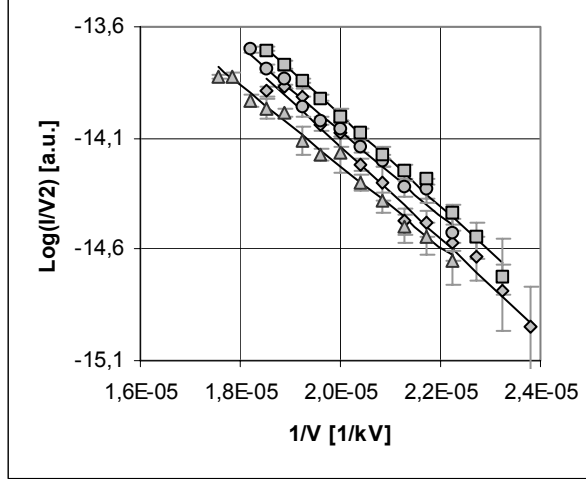


Figure 1: F-N plot before the gas treatments on Ti cathodes. Triangles diamonds, circles and squares indicate respectively the initial conditions ($7 \cdot 10^{-7}$ mbar) before He, O_2 , N_2 and Ar treatments. The error bars are wider at low current values. Lines indicate the F-N fit for each data set.

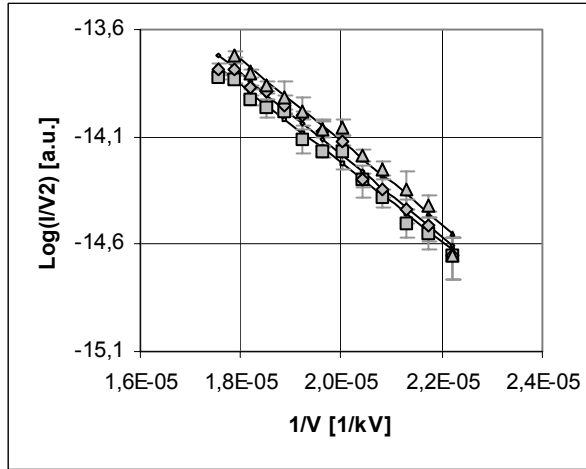


Figure 2 : F-N plot referred to He gas treatments on Ti cathodes. Squares, diamonds and triangles indicate respectively the data before, during (10^{-3} mbar) and after the He treatment, related error bars are also reported. The lines indicate the F-N fit.

The slight increasing in the current during the He treatment, in figure 2, is rather related to the measurement uncertainty and current instabilities than to a real current increasing. These data and the related analysis do not give evidence of gas conditioning nor evidence of any sputtering effects.

In order to increase the sputtering effect, if any, we performed also an Ar treatment to a pressure up to $5 \cdot 10^{-4}$ mbar. The Ar data reported in figure 3 show that, by this case, the treatment is effective. By comparing the fit

slopes before and after the gas treatment we noticed that the values change from $-2.0 \cdot 10^5$ to $-2.4 \cdot 10^5$ and the intercepts change from -9.9 to -9.5 . This changing can be related to a 15% decreasing of the β -factor (blunting of the emitter tips) in addition to an increasing of the emitting area. Since Ar is a non-reactive gas, it is unable to form compounds with the cathode, therefore its effect can be exclusively referred to cathode surface sputtering causing the blunting of the sharpest tip structures.

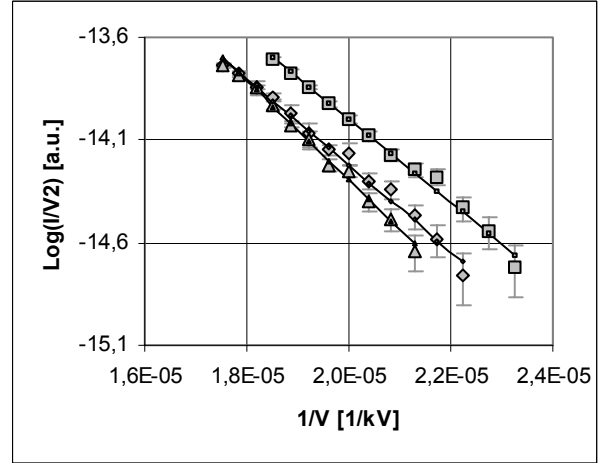


Figure 3 : F-N plot referred to Ar gas treatments on Ti cathodes. Squares, diamonds and triangles indicate respectively the data before, during ($5 \cdot 10^{-4}$ mbar) and after the Ar treatment, related error bars are also reported. The lines indicate the F-N fit.

These considerations are supported by the fact that the FEE inhibition is maintained after the Ar treatment, as it is shown in figure 3. We experienced also a threshold in the FEE inhibition that lies at about $5 \cdot 10^{-5}$ mbar of pressure.

The treatment results, using the N_2 gas, are shown in figure 4. Its effects is weaker compared to the Ar treatment. Moreover the memory effect at high voltage can be neglected, whereas at low voltage the error bars hardly let discriminate the different current values. The treatment pressure was about 10^{-3} mbar. The F-N fittings of these data do not show a high correlation, but suggest that the changing in the slope and intercept (from $-1.9 \cdot 10^5$ to $-2.4 \cdot 10^5$, and from -10.3 to -9.8 , respectively) is related to a temporary FEE inhibition of the emitting tips during the treatment, that are quite all reactivated after it. By this interpretation the sputtering effect is quite negligible. In normal conditions N_2 is a non-reactive gas, but if ionized it will show a strong chemical reactivity especially if associated with Ti; but in this experiment the loss of the FEE inhibition after the gas treatment suggest that even if the N_2 is able to modify the cathode surface characteristic, this modification is achieved by a weak bonding like as surface physical N_2 absorption, and not by means of a strong chemical bonding which could assure a stable effect.

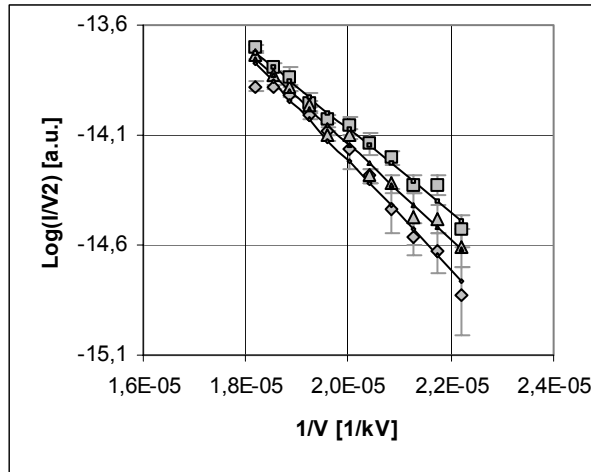


Figure 4 : F-N plot referred to N_2 gas treatments on Ti cathodes. Squares, diamonds and triangles indicate respectively the data before, during (10^{-3} mbar) and after the N_2 treatment, related error bars are also reported. The lines indicate the F-N fit.

The treatment using the O_2 gas, exhibit the strongest FEE inhibition effects, as shown in figure 5. During the gas treatment the highest current was $10 \mu A$ at 60 kV, while before the treatment the same current was measured at 48 kV. Also the memory effect is stronger compared to the other gases. The fit slope values change from $-2.1 \cdot 10^5$ to $-2.7 \cdot 10^5$ since the intercepts remain at about -10.0 . This strong changing in the slope is related to a large reducing in the FEE emission. This is understandable if we assume that the whole cathode surface is covered by several layers of molecular oxygen. At the operating pressure this will likely appends in less than a tenths of second, since the coverage rate is about $3 \cdot 10^{17}$ molecules $s^{-1} cm^{-2}$. This coverage is able to increase the cathode work function from the metallic Ti value of 4.1 eV to the oxidized surface value of 5.2 eV [9], indeed F-N fit indicate a value of about 5.0 eV consistent with the expected one. By this interpretation the FEE inhibition is mainly due to an increasing of the cathode work function due to the physical and chemical absorption of the O_2 gas. After the O_2 treatment the fit show that the slope does not change by a considerable amount since the intercept moves from -9.99 to -9.2 , this is associated with a strong increasing of the emitting area and a slight decrease of the work function. This means that the oxygen adsorbed by the sharper tips is strongly bonded forming a chemical bond which increases the work function value, while the oxygen weakly adsorbed in other sides is again released reactivating a large number of emitting tips. We experienced also a threshold in the FEE inhibition that lies at about $2 \cdot 10^{-6}$ mbar of pressure, considerable low compared with the other gases.

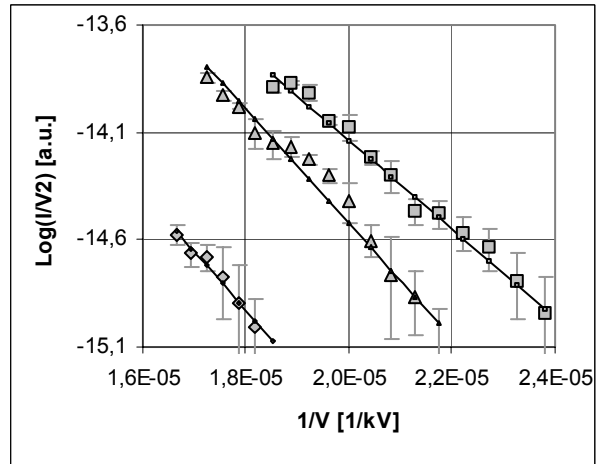


Figure 5 : F-N plot referred to O_2 gas treatments on Ti cathodes, squares, diamonds and triangles indicate respectively the data before, during ($5 \cdot 10^{-4}$ mbar) and after the O_2 treatment, related error bars are also reported. The lines indicate the F-N fit.

4 CONCLUSIONS

By this experiment we can conclude that the hypothesis of the O_2 reactive sputtering effect, as it was previously thought [5], is not fully compatible with the observations. Moreover simulating the deflector geometry and the magnetic and electric field distribution it is possible to calculate the electrons path from the cathode to the anode, which is about 14 mm long. At the operating pressure the electrons mean free path for gas ionization is about 140 mm, but then the ionization efficiency depends on the electrons energy and on the treatment gas [10]. Taking into account all these parameters it is possible to estimate the highest number of produced O_2 ions, which is less than 10^{13} atoms s^{-1} , the ion production for Ar is slightly higher and for He is about one tenth.

The F-N fit of the experimental data lead to a better understanding of the role played by different gases on the field electron emission inhibition. Except for the Ar case, there is no evidence of sputtering effect. Nitrogen and Oxygen gases show a surface effect due to gas adsorption and desorption. The strongest effect was seen by the O_2 treatment for which we experienced the strongest memory effect. The effect of He gas treatments is negligible.

In our experimental set up the surface sputtering is probably inhibited because of the short electron path compared to the electron mean free path. The results here presented suggest that high voltage electrostatic devices under vacuum could exhibit a better behaviour if the residual gas pressure is not too low or if a small leak is allowed into the system.

5 REFERENCES

- [1] R. Latham, High Voltage Vacuum Insulation, R. Latham Ed., Academic Press, (1995)
- [2] GP. Beukema, Physic C , **61**, (1973), p. 259
- [3] S. Bajic, AM. Abbot, RV. Latham. IEEE Trans. Elec. Insul., **24**, (1989), p. 89
- [4] M. Re, G. Cuttone, E. Zappalà, S. Passarello. Cyclotron and their Applications 2001, AIP Conference Proceedings, **600**, p.151, (2001)
- [5] G. Cuttone, A. Grmek, S. Passarello, M. Re, E. Zappalà, LNS Activity Report 2001, p.137 (2002)
- [6] R.H. Fowler, L. Nordheim. Proc. Roy. Soc. **A119**, 178 (1928)
- [7] M. Re, G. Cuttone, E. Zappalà. LNS Activity Report 2000, p.144 (2001)
- [8] D. Nicolaescu. J.Vac. Sci. Technol. (B), **11**(2), p. 392 (1993)
- [9] M. Brause, S. Skordas, V. Kempter, Surface Science **445** (2000) p. 224
- [10] B. Ferrario, Introduzione alla tecnologia del vuoto. Patron Editore Bologna (1999) p.61-63.

THERMAL SIMULATION FOR THE EXCYT TARGET ASSEMBLY

M. Re^a, D. Garuffi^a, M. Menna^a, G. Raia^a, and G. Cuttone^a

a) INFN Laboratori Nazionali del Sud, Catania, Italy

Abstract

In this work we present the results of the simulated thermal and mechanical stresses induced by the simultaneous influence of primary beam irradiation and heating power in the EXCYT target-ion source assembly. Relevant parameters such as target mean temperature, container mean temperature and target mechanical stresses have been calculated and are in agreement with the experimental observations. These parameters will be used in the calculation of the diffusion, effusion and ionisation efficiencies. In addition, the simulations were used to check for radioprotection issues whether the TIS could withstand the primary beam power at 2300 K.

1 INTRODUCTION

During May 2003 the EXCYT Target-Ion Source assembly (TIS) was tested at GANIL under the same operational conditions that will be initially used at LNS. In the experiment, the radioactive beams ^8Li , ^9Li were successfully obtained at the SIRa test bench [1, 2].

Before the target irradiation at GANIL, for radioprotection issues it was of paramount importance to check whether the TIS could withstand the primary beam power at the operational temperature of 2300 K or not. Therefore we performed a steady-state thermal analysis by means of ANSYS and SRIM 2003 simulations to determine the mechanical and thermal stresses under the simultaneous influence of primary beam irradiation and heating power. The obtained temperatures will be also used as parameters to calculate the efficiencies of the Lithium diffusion, effusion and ionisation which will be compared to GANIL graphite target [3].

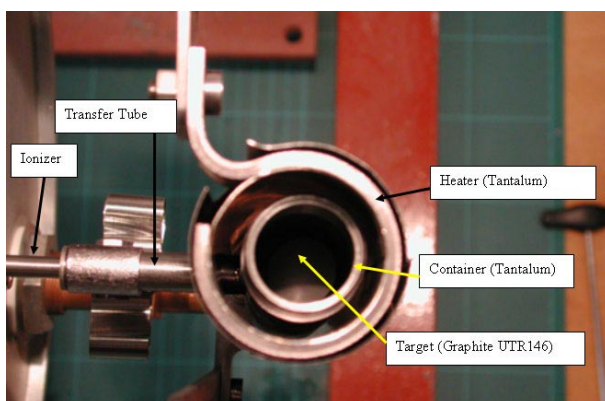


Figure 1: View of the TIS from the top. The Rhenium window and the Tantalum thermal screens were removed.

2 TARGET-ION SOURCE ASSEMBLY

Figure 1 shows a picture taken from the top of the TIS after removing its Rhenium window. The external aluminium vacuum vessel (not shown here) is shielded from the heater temperature by several foils of stainless steel placed on the inside of the vessel. Additional shielding is obtained by means of Tantalum foils on the outside of the heater.

The target is made by a single piece of graphite (XYCARB UTR 146) mounted in a Tantalum container, which in turn stands inside a Ta heater. Direct current flowing through the heater allows the TIS to reach the required operational temperature for an efficient release of Li. A sketch of the TIS assembly (figure 2) shows the direction of the beam impinging on the target and an example of the temperature distribution.

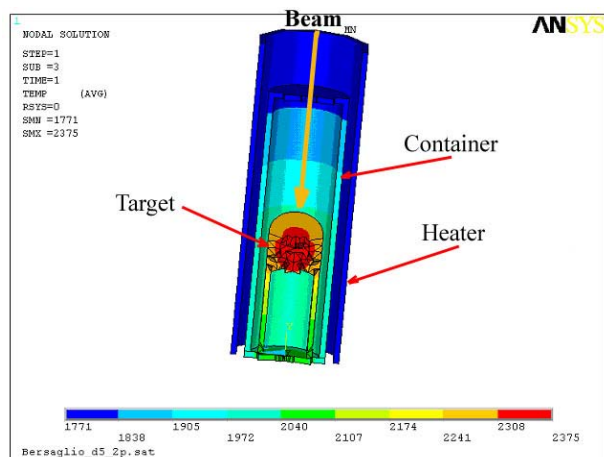


Figure 2: Cross-section of the TIS model used for the ANSYS simulations. In this example the beam power is 360 W, beam size 5 mm and heater temperature 1773 K. The coloured temperature scale is in Kelvin.

3 MODELING AND SIMULATIONS

We built a model of the TIS in order to define its radiating surfaces, and then we performed simulations with the ANSYS finite-element method to investigate the combined thermal effects of conduction and radiation within the TIS model. We used the auxiliary program AUX12 to calculate the form factors between the radiative elements and the resulting radiation matrix was subsequently incorporated into the model to generate a solution. An iterative solution is required to solve the fourth-power radiation equation using ANSYS linear equation solver. Only when the results converge a solution is considered to be valid and is loaded into a structural model, which solves for stresses and displacements.

The input characteristics of the target model are shown in table 1. Graphite data are the reported in the table below.

Table 1: Target characteristic
(Graphite XYCARB UTR 146)

Density	1880 Kg m ⁻³
Conductivity	122 W m ⁻¹ K ⁻¹
Bulk Modulus	11 GPa
Poisson Ratio	0.35
Thermal expansion coefficient	7.7 * 10 ⁻⁶ K ⁻¹
Tensile Strength	69 MPa
Emissivity	0.9

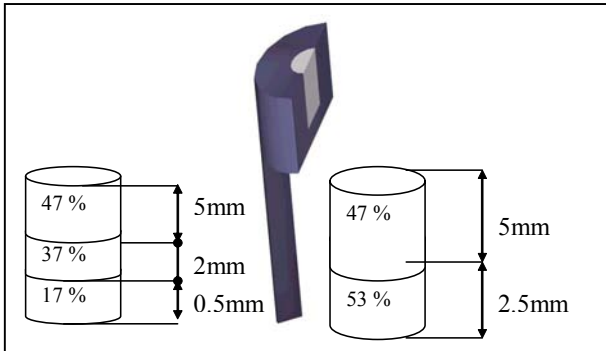


Figure 3: The picture at the centre is a cross section of the target. The volume where the beam energy (¹³C, 60 MeV/u) is released is in light grey. The cylinders at the two sides, respectively split into three and two zones, approximate the released beam energy ratio. This figure is not to scale

The deposition profile of the beam energy on the target is calculated by the program SRIM 2003 for a ¹³C beam with energy 60 MeV/u. This energy distribution was approximated to a discrete cylinder whose diameter is 4 sigmas of the beam gaussian profile, i.e. 5 mm (fig. 3). The simulation was performed with a cylinder split

in either two or three zones acting as sources of thermal power.

The transfer tube and the ioniser (fig. 1) are not considered in the ANSYS numerical simulation because they are heated independently. Since their temperatures are comparable to the one of the container, theoretical considerations suggested that thermal conduction between the container and the tubes is negligible. Experimental tests validated this assumption.

Thermal simulations were conducted by setting the heater temperature at three different values (1773, 1973, 2173 K) and the beam power at four different values: 1 W, 90 W, 180 W, 360 W. These two independent variables generated a 12-element matrix useful for an analytic fitting of the results.

From the ANSYS simulations we calculated the following main parameters:

- 1) Target maximum temperature;
- 2) Target mean temperature at its lower surface, where most of the produced Li is distributed (parameter for the diffusion calculations);
- 3) Container mean temperature (parameter for the effusion calculations);
- 4) Top-of-container mean temperature (to compare with the experimental measurements);
- 5) Target mechanical stresses according to the Von Mises model;

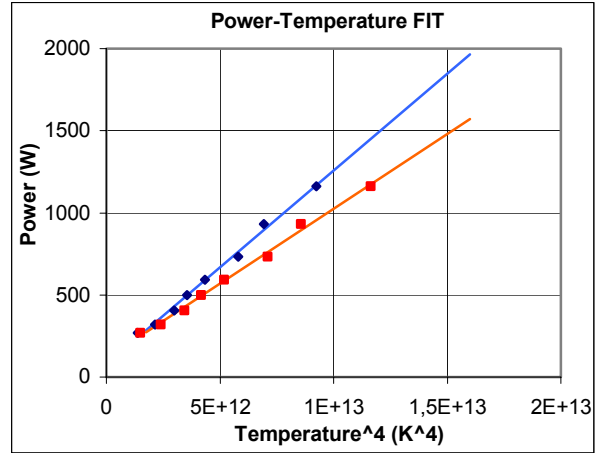


Figure 4 : Heater Power Vs Temperature Fits. The blue and the red data are respectively related to the Top-of-container Temperature and to the heater temperature. Dots and lines are respectively experimental and fit data. The data fit correlation is good and shows a linear dependence on the 4th power of the temperature

The choice of heater temperature as a free variable takes into account considerations on the thermal balance of the TIS. This temperature depends with negligible deviations on the total power introduced in the system, i.e. on the sum of the electrical heater power and beam power. In addition, the heater temperature can be correlated with experimental measurements. In fact, the Top-of-container Temperature and the heater temperature measured before the beam irradiation by means of an optical pyrometer were consistent with the

ANSYS simulations. By fitting these data it was possible to correlate the total power with the heater temperature as reported in figure 4. This graph represents the TIS calibration for Power–Temperature dependence.

The data fits in fig. 4 show the linear dependence of the total power on the temperature to the 4th, confirming that the thermal dissipation is mainly due to blackbody radiation. Thermal conduction is thus negligible within the errors.

4 DATA ANALYSIS

The temperatures in the experimental conditions were estimated with a good approximation (standard deviation = ± 50 K). Fig. 5 and 6 show two results of the ANSYS temperature simulations.

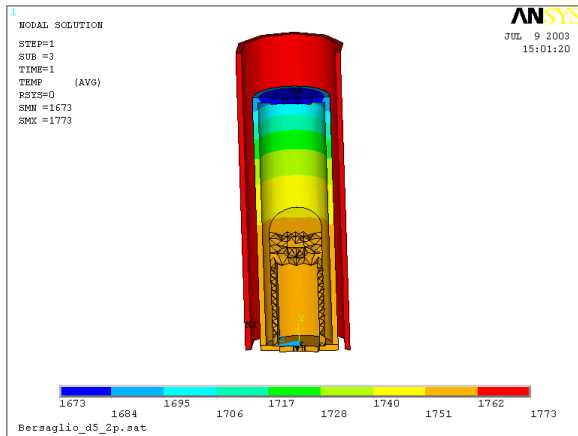


Figure 5: Temperature distribution in the TIS with heater temperature 1773 K and beam power 1 W. The Top-of-container temperature is about 100 K lower than the heater temperature

As for the mechanical stresses, it turned out that the target was always well below (~ 10 MPa) its tensile strength (69 MPa) as shown in fig. 7. Therefore even under a beam power larger than 360 W the target would not break but rather sublimate due to the high temperature.

Structural simulations evidenced that the mechanical stresses are higher when the beam size is smaller and the heater temperature is lower. This effect is related to the larger temperature gradient.

Under a beam power of 200 to 400 W the graphite vapour pressure will be higher than 10^{-5} mbar, thus leading to a graphite deposition in the container. The post-mortem analysis of the TIS evidenced the presence of a thin graphite layer deposited on the internal surface of the container, thus demonstrating the target sublimation.

The resulting target mean temperature is reduced of about 40-60 K as shown in figure 8. In fact, an increase of the container surface emissivity causes an increase of its thermal absorption: therefore the heat exchange is enhanced and the target temperature is reduced.

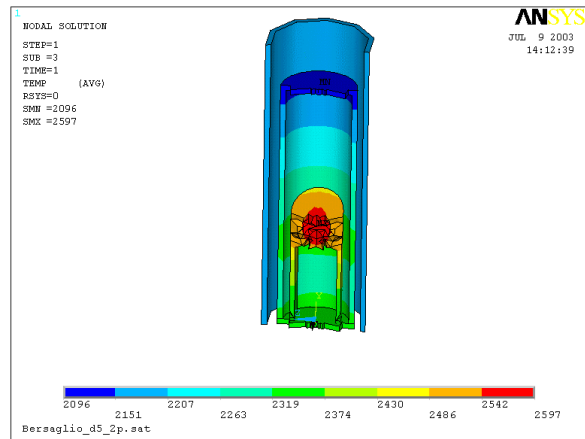


Figure 6: Temperature distribution in the TIS with heater temperature 2173 K and beam power 360 W. The Top-of-container temperature is about 80 K lower than the heater temperature

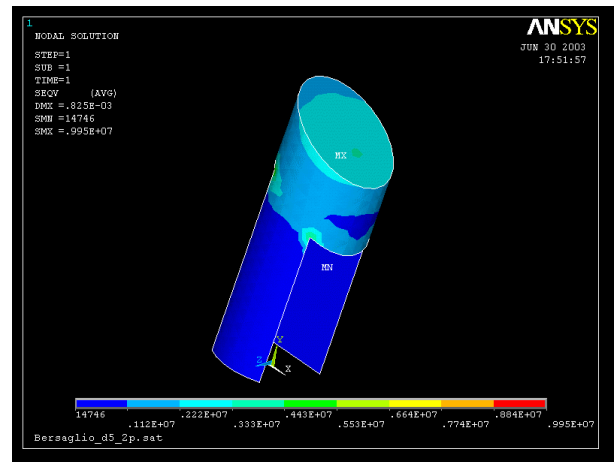


Figure 7: Analysis of the target mechanical stresses. The average stress is about 2 MPa since the maximum in correspondence of the edges is less than 10 MPa. Simulation conditions are the same as in figure 2

The target surface is inclined by 30° with respect to the direction of the incoming beam. Changing this angle in the simulation to 0° did not significantly affect any of the mean temperatures up to a beam power of 800 W. Also changing the beam release model from a cylinder with two zones to one with three zones had almost no effect on the results. Finally we also checked the stability of the simulation when increasing the mesh of the finite-elements model.

Figure 9 shows the results and the fits for the mean target temperature versus the heater temperature at different beam powers while figure 10 shows the results and the fits for the target mean temperature versus the beam power at different heater temperatures. Plots were obtained by a full quadratic fit of the two free variables: heater temperature and beam power. The fit correlation is higher than 0.9993.

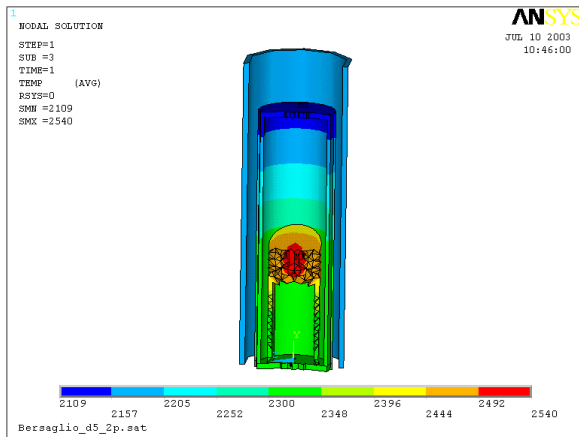


Figure 8: Temperature distribution in the TIS with the same operational conditions as in figure 6. Here a thin layer of carbon covers the container internal surface, i.e. the surface emissivity in the simulation is higher

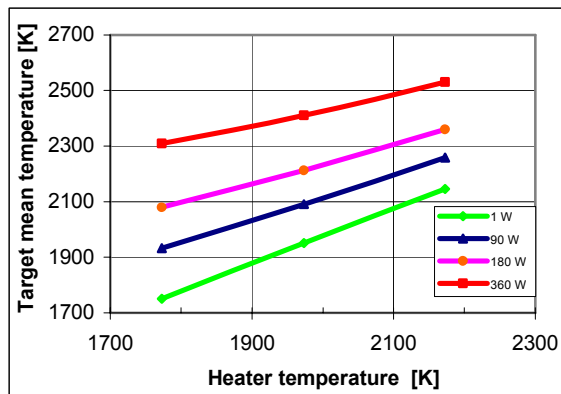


Figure 9: Fit of the target mean temperature versus the heater temperature at different beam powers

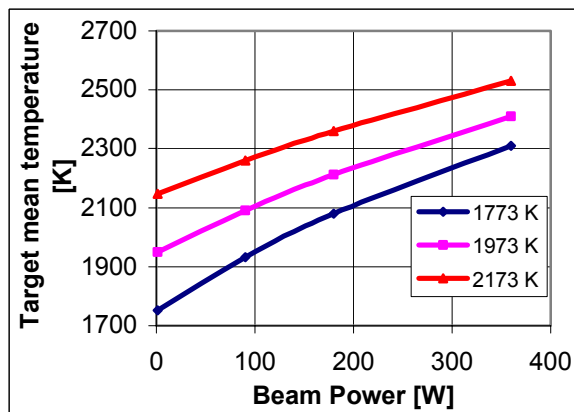


Figure 10: Fit of the target mean temperature versus the beam power at different heater temperatures

Figure 11 and 12 show analogous plots for the container mean temperature. Once again, plots were obtained by a full quadratic fit of the two free variables. The fit correlation is higher than 0.99992 .

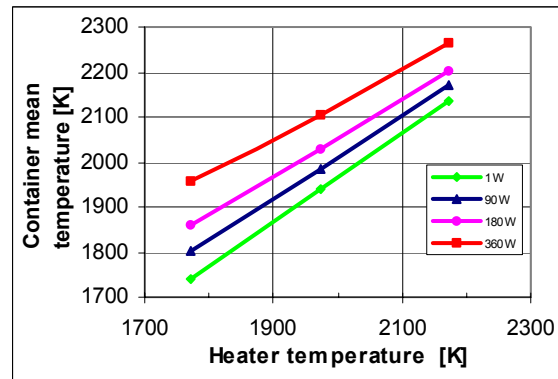


Figure 11: Fit of the container mean temperature versus the heater temperature at different beam powers

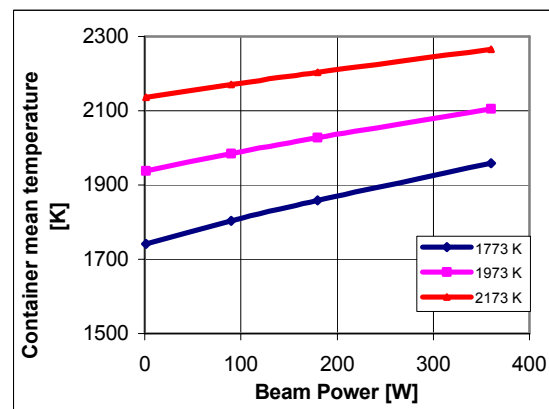


Figure 12: Fit of the container mean temperature versus the beam power at different heater temperatures

By using the calibration data for the beam and heater power in figure 4 it is possible to deduce the heater temperature, which in turn is used to determine the target and the container mean temperatures in the experimental conditions.

5 CONCLUSIONS

Simulations and experimental observations confirmed that the TIS can withstand the beam power even at 2600 K. Mechanical and thermal simulations are in agreement with the experimental observations. These simulation approaches will be useful in future studies when re-designing the TIS as well as for changing and optimising the geometric parameters and the temperature profiles.

6 REFERENCES

- [1] M. Menna et al., "The experiment E435 at GANIL", LNS Report 2003
- [2] G. Cuttone et al., "The EXCYT facility towards its commissioning", LNS Report 2003
- [3] S. Gibouin, Ph.D. Thesis N° T 03 02, 2003, University of Caen, France

TANDEM AND SUPERCONDUCTING CYCLOTRON ACTIVITY

D. Rifuggiato on behalf of the LNS Accelerator staff

INFN Laboratori Nazionali del Sud, Catania, Italy

Abstract

LNS accelerator activity in 2003 is described with details on the Cyclotron and Tandem beam time distribution. A status report on the Cyclotron upgrading is also given.

1 BEAM OPERATION

In the year 2003, beams accelerated with the Tandem and the Superconducting Cyclotron were delivered to users in the period January-July and in December. The period September-November was in fact devoted to the development of the Excyt project, as well as to ordinary and extraordinary maintenance. Like in the previous year, in spite of the long machine stop, it was possible to perform a big number of experiments, thanks to the high reliability level and to the capability of quick recovering in case of failures. About 2800 Cyclotron beam hours and 2300 Tandem beam hours were delivered, approximately 10% more than in 2002, for the same time interval of working.

In 2003, experiments were performed with the detector Chimera assembled for the first time in its full configuration inside the Ciclope scattering chamber. Several beam types were delivered for calibration of Chimera, both Tandem and Cyclotron, and for experiments with Chimera. In particular experiments demanded Cyclotron beams of different mass and energy (40Ca, 58Ni, 62Ni, 112Sn, 124Sn, 197Au) from

15 to 35 AMeV. They were delivered, as requested, with very good timing quality (FWHM lower than 1 nsec) and inter-burst separation longer than 100 nsec. All over the year 2003, 8 experiments were performed with Chimera, for a total of 1200 Cyclotron hours.

In 2003, 6 sessions of proton therapy of ocular tumours (Catana) were accomplished, using the 62 MeV proton beam from the Superconducting Cyclotron, for a total amount of 630 Cyclotron hours.

The Tandem was mainly used for experiments in the field of nuclear astrophysics, for a total of 1100 hours of the 2300 delivered. The remaining beam time was distributed among several experiments in the interdisciplinary field (biological studies on cellular samples, radiation hardness and detection techniques).

A few tests on the ECR sources were accomplished aiming to improve their performance.

All the experiments approved by the Program Advisory Committee for the year 2003 were executed.

In figure 1, the beam statistics for the year 2003 are shown.

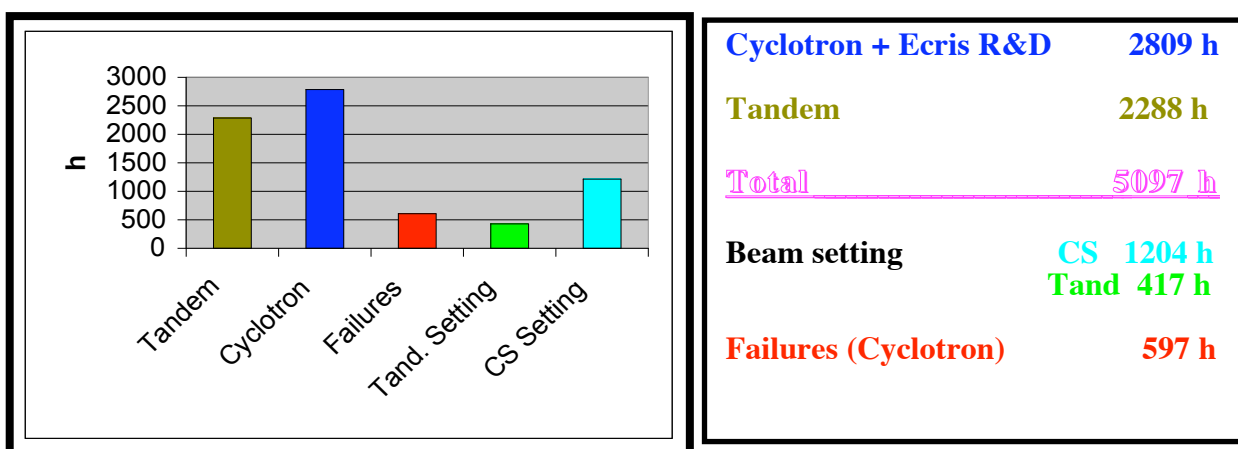


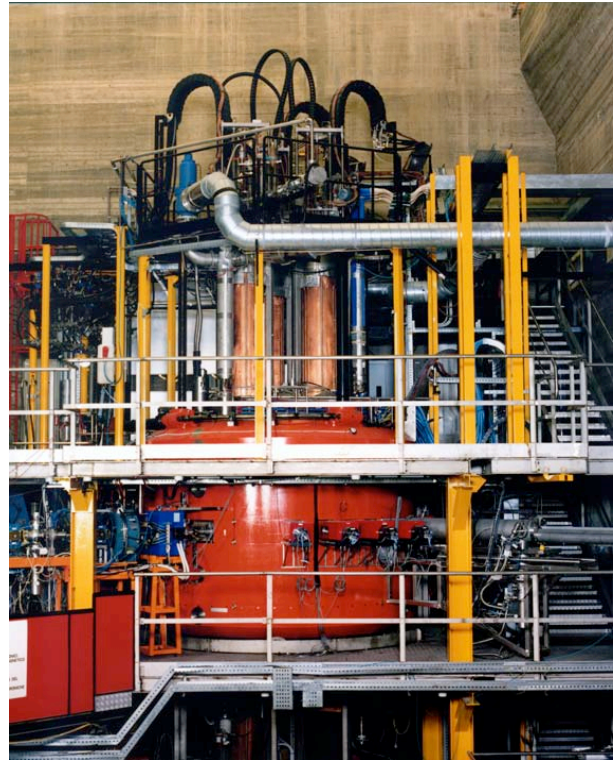
Figure 1: 2003 beam statistics

2 SUPERCONDUCTING CYCLOTRON

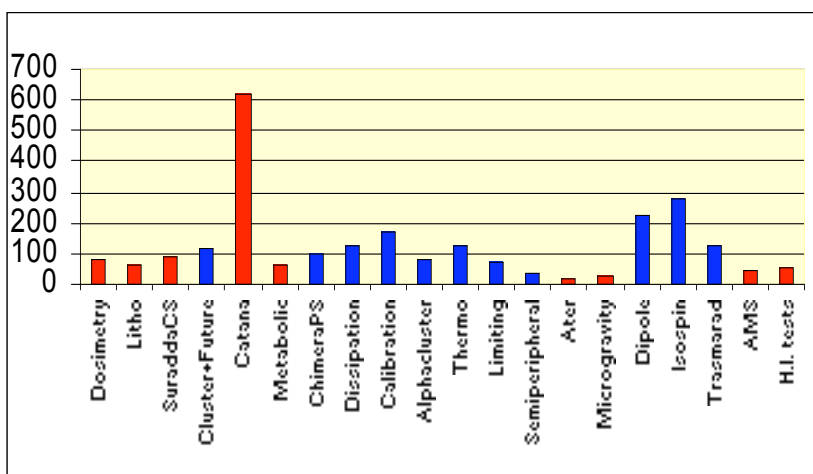
The reliability of the Superconducting Cyclotron has significantly improved as compared to the machine performance of 3 years ago. This has been possible thanks to the improved performance of the electrostatic deflector and to the replacement of old and obsolete components of the RF system, of the ECR sources and of several power supplies.

In 2003 the following Cyclotron beam types were delivered.

Beam	Time
Protons 62 MeV	805 h
Deuterons 62 MeV	32 h
^4He 25 AMeV	24 h
^{12}C 62 AMeV	112 h
^{16}O 25 AMeV	37 h
^{20}Ne 45 AMeV	51 h
^{36}Ar 16 AMeV	86 h
^{40}Ar 15 AMeV	144 h
^{40}Ca 10 AMeV	132 h
^{40}Ca 25 AMeV	152 h
^{58}Ni 25 AMeV	80 h
^{62}Ni 25 AMeV	80 h
^{86}Kr 15 AMeV	40 h
^{86}Kr 25 AMeV	80 h
^{112}Sn 35 AMeV	72 h
^{124}Sn 25 AMeV	172 h
^{124}Sn 35 AMeV	208 h
^{197}Au 15 AMeV	124 h
^{197}Au 21 AMeV	90 h
ECR experiment	288 h
Total	2809 h



In fig. 2 a plot of the experiments performed in 2003 with Cyclotron beams is presented, showing the beam time distribution among different experiments. All the experiments approved in the Program Advisory Committee meeting were performed.



Cyclotron beam time: 2809 h

Nuclear physics 1458 h

Applications 1063 h

ECR experiment 288 h

Fig. 2: Cyclotron beam time distribution

During the machine stop, high intensity beam tests were performed, in order to test the cooled deflector and especially ascertain the possibility of extracting a light ion beam so intense to be used as a primary beam in the Excyt facility for production of radioactive beams. The first tests were made with a ^{20}Ne beam accelerated to 45 AMeV. A limitation was found out at a power of 40 watt when trying to increase the extracted beam current. A mechanical damage was caused by the beam in the electrostatic deflector: the septum showed a hole along the median plane and a deformed area at the beam entrance (figure 3).

Few months later, the test was made again. In this case, a beam of ^{13}C was chosen instead of ^{20}Ne , because it was selected as the most convenient one to produce a secondary beam of ^8Li , which will be the first radioactive beam in Excyt. The test was made using a small chopper installed in the injection beam line, allowing to decrease the beam current in the longitudinal way, i.e. suppressing several bursts. In this test, an internal current probe, provided with a cooling circuit, was available for the first time. It proved to be a fundamental tool in the high intensity operation, especially when trying to increase the extraction efficiency, because it allowed to find the best conditions of minimum beam dissipation in the septum. Phase slits were used to increase the extraction efficiency, which reached a maximum value of 60%. As a result of this test, a 100 watt beam power was obtained at the Cyclotron exit, corresponding to 680 enA (figure 4). This current is estimated to be sufficient for an adequate production of ^8Li (10^4 - 10^6 pps on target). Further increasing of the beam current was not tried, waiting for the final authorization and also because we think that the cooling efficiency must be improved.

Instabilities were due to the effect of the beam on the

electrostatic behavior of the deflector, and are supposed to be reduced after a conditioning period of few hours.



Figure 3: Septum of the electrostatic deflector with damages due to the high beam power

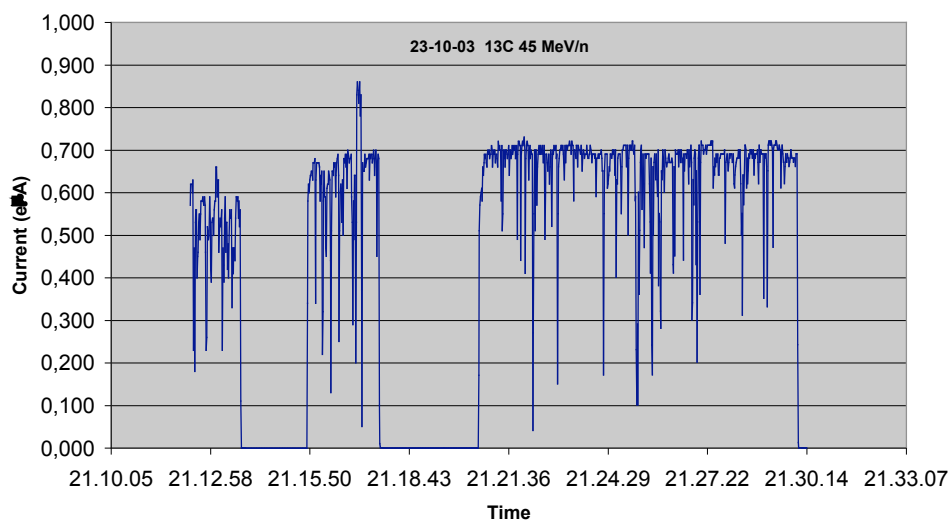


Figure 4: First extraction of a 100 watt beam. Plot of the intensity measured on a Faraday cup in the beam line

3 TANDEM

Tandem beams have been delivered mainly to the 60° and 80° beam lines, the so-called by-pass area allowing the complete decoupling of the two accelerators, with two beams contemporarily sent to two different experimental areas.

In 2003 the following Tandem beam types were delivered.

Beam		Time
Protons	26 MeV	72 h
⁶ Li	20 MeV	564 h
⁷ Li	20 MeV	392 h
⁹ Be	50 MeV	368 h
¹² C	91 MeV	236 h
¹⁴ N	90 MeV	68 h
¹⁶ O	117 MeV	88 h
¹⁹ F	130 MeV	96 h
³² S	117 MeV	16 h
³⁷ Cl	180 MeV	80 h
⁵⁸ Ni	150 MeV	224 h
¹⁹⁷ Au	237 MeV	84 h
Total		2288 h



In figure 5 a plot of the 2003 experiments performed with Tandem beams is presented, showing the beam time distribution among different experiments.

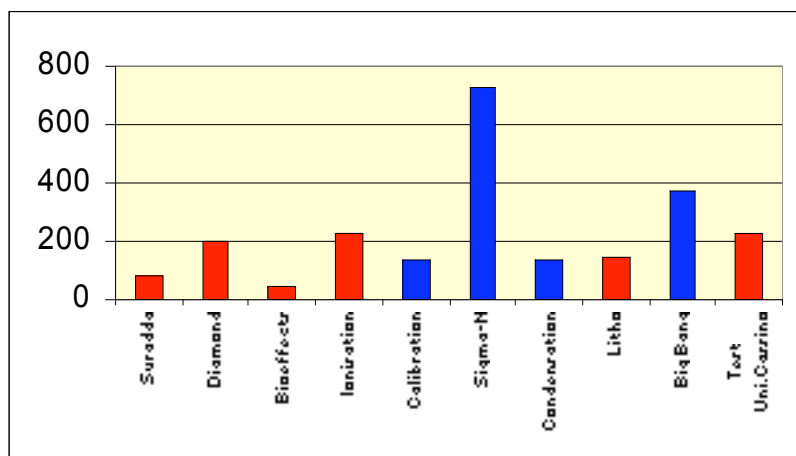


Figure 5: Tandem beam time distribution

**Tandem beam time:
2288 h**

**Nuclear physics
1368 h**

**Applications
920 h**

4 CONCLUSION

In 2003, a considerable amount of beam time has been delivered to users, although a long accelerator stop has been scheduled in order to have time and resources for the Excyt project. Proton-therapy, which started in 2002, has successfully gone on with 6 sessions, during which 34 patients were treated. Throughout the year 2003, a lot of research activity has been performed in the field of nuclear physics, but also a significant amount of interdisciplinary applications have been carried out.

STUDY OF PHOTONS EMISSION FROM PLASMA GENERATED BY FAST PULSED LASER

L. Torrisi^{1,2}, E. Amato², S. Gammino¹, D. Margarone¹, G. Bonanno³ and S. Scuderi³

¹INFN-Laboratori Nazionali del Sud di Catania, Italy

²Dipartimento di Fisica, Università di Messina, Italy

³INAF, Osservatorio Astrofisica di Catania, Italy

Abstract

A Nd:Yag laser operating at the fundamental wavelength of 1064 nm with 9 ns pulse width and 900 mJ maximum pulse energy, at 10^{10} W/cm² power density is employed to generate plasma in vacuum by irradiating metallic targets. The ablation produces a high photon emission of infrared, visible, ultraviolet and soft X-rays together emission of neutral, electrons and ionised particles. CCD cameras are employed to measure the photon yield. A Si(Li) detector is used to detect the soft X-rays emission.

1 INTRODUCTION

The production of pulsed plasma generated by energetic fast laser pulses is an attractive phenomenon which physical interpretation is not entirely clear. By using laser pulses with duration of the order of nanoseconds and power density of the order of 10^{10} W/cm², the produced plasma is in non equilibrium conditions and the parameters such as the temperature, the density and the charge distributions are strongly function of the time and of the space. Generally the plasma is generated in vacuum and it expands adiabatically at supersonic velocity along the normal to the target surface. Moreover, inside the plasma an high electrical field produces ion acceleration at high kinetic energy of the order of keV, as detected from time-of-flight (TOF) measurements.

The plasma emits ions at high charge state and high velocity, and also energetic neutrals and electrons, which find interesting application in the injection into ion sources in order to increase the extracted currents and the maximum ion charge states [1, 2].

The laser-matter interaction and the consequent plasma generation at the target surface produce photons emission in a large range of wavelengths, from the infrared to the soft X-ray regions, the intensity of which is strongly dependent on the energy of the laser fluence [3]. It is not known the amount of the laser energy transferred to the photons production, the relative amount of photons yield in the different wavelength regions, the angular distribution of the emitted photons and the maximum photon energy obtainable from the plasma emission. These information permit to know better the mechanism of plasma formation and the measure of its temperature, density and charge state distribution. In this direction this work reports about preliminary results obtained at LNS within the INFN Commission V Research project so called PLAIA (Plasma Laser Emission for Ion Acceleration).

2 MATERIALS AND METHODS

A Nd:Yag Q-switched laser, emitting a fundamental wavelength of 1064 nm, with 9 ns pulse width, 900 mJ maximum pulse energy, operating in single pulse or at 30 Hz repetition rate, is focused on a metallic target placed in a scattering chamber at a vacuum of 10^{-7} mbar. Generally the laser spot size is 0.5 mm² and the maximum pulse power density is 10^{10} W/cm².

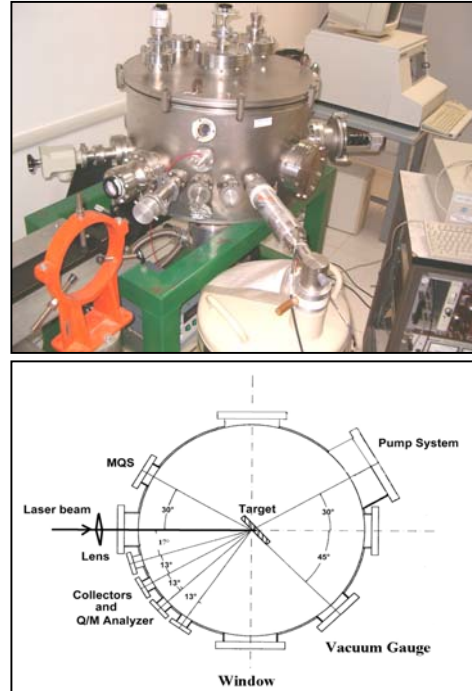


Fig.1: Photo (upper) and scheme (bottom) of the experimental set-up at LNS.

Gold, copper and tantalum were employed as target. The incidence angle (ϕ) of the laser beam was changed from 5° up to 60°. Three different CCD detectors were employed in this experiment. The first one, CCD-1, is a DTA D401-E camera equipped with a Kodak KAF-

0401E chip (768x512 pixel, 9x9 $\mu\text{m}/\text{pxl}$), 14-bit ADC and single stage Peltier cooler. It operates in binning 1x1, with gain of 12.2 e^-/ADU , at a temperature $T = -5.0^\circ\text{C}$. This chamber was mounted at 30° angle with respect to the laser incidence. The second one, CCD-2, is a camera developed by the COLD Group of INAF, equipped with an EEV-3011 chip (1024x256 pixel, 26x26 $\mu\text{m}/\text{pxl}$), 16-bit ADC and liquid nitrogen cryostat. It operates in binning 1x1, with gain of 2 e^-/ADU , at a temperature $T = -130^\circ\text{C}$. This chamber was mounted at 90° angle with respect to the laser incidence. The third one, CCD-3, is a Pixelfly VGA camera (640x480 pixel, 9.9x9.9 $\mu\text{m}/\text{pxl}$) with a fast frame exposition of 5 μs . It was triggered with the laser pulse. This chamber was mounted at 120° angle with respect to the laser incidence. Furthermore, a Si(Li) X-ray detector Ortec SLP-10180 was employed in order to measure the soft X-ray spectroscopy emitted from the plasma generated by laser pulses.

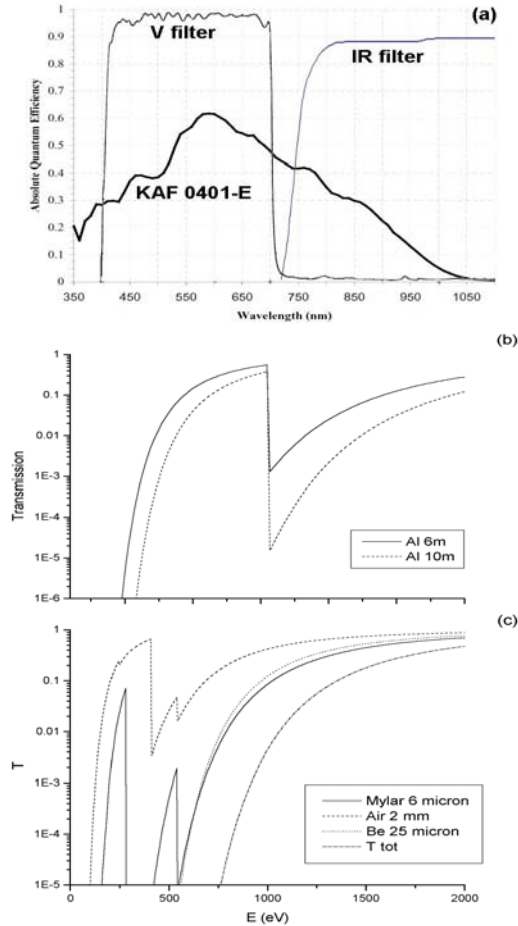


Fig.2: CCD, IR and Visible filter efficiency as a function of the wavelength (a), Al filter transmission (b) and the Si(Li) detector windows transmission (c) as a function of the photon energy.

The photon emission was detected by using various filters tailored for the infrared, visible, ultraviolet and X-ray regions.

Fig. 2 (a) shows the comparison between KAF 0401-E detection efficiency and IR (Kodak Wratten 88A) and Visible (Baader) filters as a function of the wavelength. In panel (b) we present the transmission of 6 and 10 μm Al filters employed together with CCD-2, and in (c) the transmission of Si(Li) windows.

3 RESULTS

The measurements in the visible region performed with the CCD-3 fast camera have given interesting information about the plasma dimension, directivity, expansion velocity and density. Fig. 3 shows an example of plasma at two different exposition times: 5 (upper) and 10 μs (bottom) from the laser pulse irradiating a gold target.

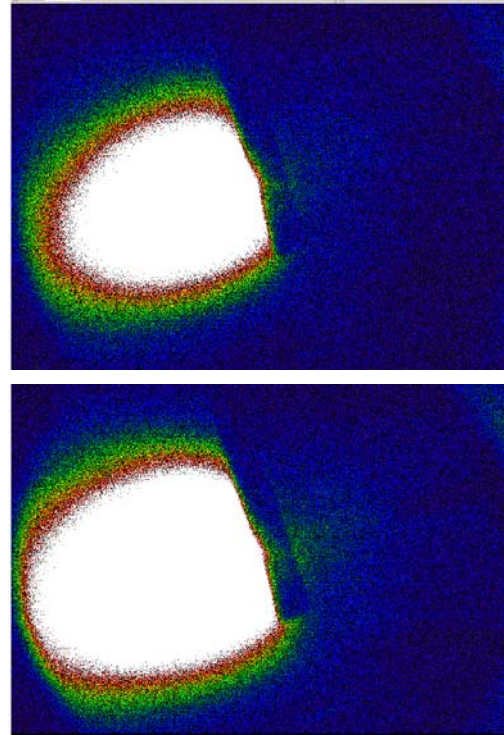


Fig. 3: Plasma photos with CCD-3 camera at 5 (upper) and 10 μs (bottom) from the laser pulse.

The plasma expansion occurs toward the normal to the target surface with a directivity of about $\pm 30^\circ$. Along this direction the plasma plume, in 5 μs exposure time, has a length of about 8 cm. Thus the plasma expansion velocity in vacuum is about 1.6×10^4 m/s and the plume dimension is about 100 cm^3 . Because in these conditions the ablation yield in gold is about 8 $\mu\text{g}/\text{pulse}$ [4], the plasma density at this time corresponds to $2.4 \times 10^{14}/\text{cm}^3$. From the measurement of the adiabatic

expansion velocity, v , of the plasma in vacuum it is possible to calculate the plasma temperature T according to the following equation:

$$T = mv^2/\gamma K, \quad (1)$$

where m is the atomic mass, γ the adiabatic coefficient and K the Boltzmann constant. The calculated value for Au is 3.6×10^6 K, in good agreement with previous measurements which have determined a plasma temperature of about 10^7 K [5].

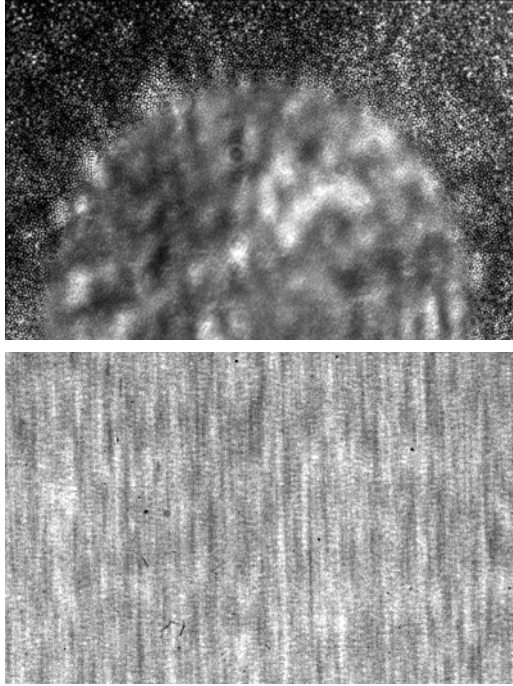


Fig. 4: Photo due to visible and infrared radiation obtained with the CCD-1 camera (upper) and photo due to ultraviolet and X-ray radiation obtained with the CCD-2 camera (bottom).

The images of the plasma due to infrared, visible, ultraviolet and soft X-rays were obtained singularly or together, by using the other CCD cameras and the different filters. As an example, Fig. 4 shows an image due to visible and infrared radiation obtained in 10 s exposure time with the CCD-1 camera without filter (upper) and an image due to 10 s ultraviolet and X-ray radiation obtained with the CCD-2 camera and 10 μ m aluminum filter (bottom). Both images are due to single pulse laser hitting the Au target and subtracting the background signal.

The angular distribution of the emitted photons demonstrates that the emission is isotropic, except for the infrared radiation which follows the Snell reflection law. Fig. 5 shows examples of angular dependence for the infrared (a), visible (b), ultraviolet (c) and X-ray (d) radiation, respectively. Moreover, by changing the laser

fluence the visible intensity increases proportionally, as reported in the plot of Fig. 6 for Cu and Au targets.

The X-ray emission was investigated with a Si(Li) detector during the laser irradiation of the target at 30 Hz repetition rate. Two typical spectra obtained with this technique, during 100 s acquisition time, are reported in Fig. 7. The first spectrum (a) shows the background signal while the second spectrum (b) the X-rays produced by a gold plasma. The difference between the two spectra indicates that soft X-rays are produced by the plasma and that the maximum photon energy is of the order of 1 keV, in good agreement with the literature and with the TOF measurements of ion and electron energies produced by the plasma laser [5, 6].

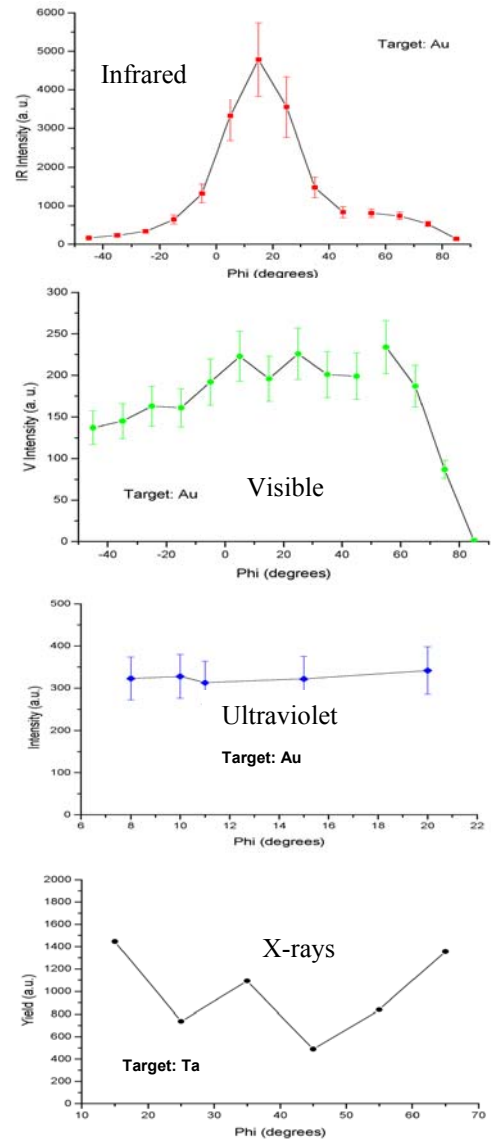


Fig. 5: Angular dependence for the infrared (a), visible (b), ultraviolet (c) and X-ray (d) radiation emitted from the plasma.

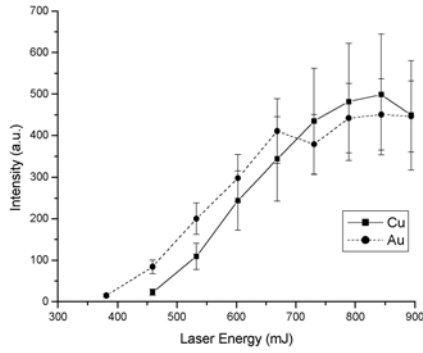


Fig. 6: Intensity of Visible emission vs. laser energy.

The spectrum of Fig. 7b represents the collection of the X-rays acquired through a solid angle of 0.3 mstr due to 3000 laser pulses. By subtracting the background, considering the detection efficiency and extending to the isotropic emission, the total measured X-ray yield from Cu, with energy higher than 700 eV, is of about 10^8 X-ray/pulse. A similar analysis relative to the visible and UV data, indicates that the total emission in these regions is about 4 orders of magnitude higher than that of X-rays.

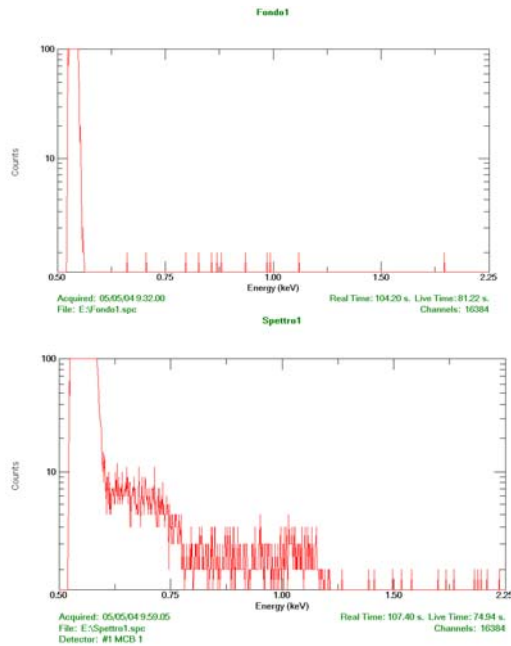


Fig. 7: X-ray spectra relative to 100 s acquisition time, 30 Hz repetition laser pulse, for the background (a) and for the Au target irradiation (b).

4 DISCUSSION AND CONCLUSIONS

The measurements about the photon emission from the plasma generated by laser ablation of metallic targets are innovative and they have the aim to give a better understanding of the mechanisms involved in the fast

plasma production by laser and in the plasma time and space evolution in vacuum. For example the results concerning the formation of photons up to about 1 keV energy, at the used laser fluence, is in agreement with the evaluation of the average ion and electron energy of the plasma and with the plasma temperature of the order of 1 keV corresponding to about 10^7 K, as obtained analyzing the ion energy distribution spectra by our previous works [6, 7]. Moreover, the obtained frame images of the plasma indicate interesting aspects about the plasma density evolution with the time and the space. The plasma temperature and density decrease strongly with the distance from the target surface and with the time from the laser pulse. The plasma expansion exhausts in times of the order of tens of microseconds during which the density decreases from values near to the solid materials to about zero.

Further measurements of this kind, together to those about the fluorescence emission from the ablated atoms, are in progress at LNS. A special interest is devoted to the development of intense and energetic photon sources such as X-ray. By using laser power densities of the order of 10^{15} W/cm² it is already possible to produce very intense X-ray sources, as reported in recent papers [8]. While at the used laser fluence only very high visible and ultraviolet photon yields can be produced.

ACKNOWLEDGEMENTS

Authors thank the INFN-Commission V for the financial support given to the PLAIA project in which theme this work is realized.

REFERENCES

- [1] L. Torrisi, S. Gammino, L. Andò, V. Nassisi, D. Doria and A. Pedone; Appl. Surf. Sci. 210, 262, 2003
- [2] L. Laska, K. Jungwirth, B. Kralilova, J. Krasa, M. Pfeifer, K. Rohlena, J. Skala, J. Ullschmied, J. Badziak, P. Parys, J. Wolowski, E. Woryna, S. Gammino, L. Torrisi, F.P. Boody and H. Hora Plasma Phys. Control. Fusion 45, 585-599, 2003
- [3] L.A. Gizzi, Rapp. Int. CNR-Pisa, IFAM01-072000, 2000
- [4] L. Torrisi et Al., Rev. Sci. Instr. 71(11), 4330-4334, 2000
- [5] L. Torrisi, S. Gammino and L. Andò Rad. Eff. And Def. In Solids 157, 333-346, 2002
- [6] L. Torrisi, L. Andò, S. Gammino and L. Laska J. Appl. Phys. 91(5), 18, 2002
- [7] L. Torrisi Nucl. Instr. and Methods in Phys. Res. B, 183, 271-278, 2001
- [8] D. Giulietti et Al., Phys. Rev. Lett. 79, 4266, 1997

DL SPECTRAL ANALYSIS OF EPITHELIAL CELLS.

Lee Ann Applegate^b, Francesco Musumeci^{a,c}, Hugo J. Niggli^d, Giuseppe Privitera^{a,c}, Agata Scordino^{a,c} * and Salvatore Tudisco^{a,c}

a) INFN Laboratori Nazionali del Sud, Catania, Italy

b) Department of Obstetrics, Laboratory of Oxidative Stress and Ageing, University Hospital, CHUV, CH-1011 Lausanne, Switzerland

c) Dipartimento di Metodologie Fisiche e Chimiche per l'Ingegneria, University of Catania, I-95125 Catania, Italy

d) BioFoton AG, Treyvaux, Switzerland

** Corresponding author, e-mail: ascordin@dmfci.unict.it*

Abstract

Some preliminary results are shown that demonstrate that, by using Delayed Luminescence (DL), it is possible to discriminate between normal fibroblast and human melanoma cells. These cultures exhibit in fact differences both in the time trend and in the emission spectrum of DL.

1 INTRODUCTION

In the last years has been recognized the importance, in order to have successful therapies, to individuate the pathologies in their early stages.

This identification is difficult because the traditional diagnostic techniques are not very efficacious in the stage in which pathologies don't give rise to clear symptoms. On the other hand the application of the traditional techniques to a larger number of potentially sick persons will present very high costs. A possible solution to this problem could be constituted from the development of optical biopsy techniques characterized by low costs both from the point of view of the materials and from that of the man time required. These techniques are based on the use, to diagnostic scope, of the information obtained from the light re-emitted, elastically or not elastically from the human tissues and cells illuminated [1-5].

An important candidate, from this point of view, is the Delayed Luminescence (DL).

In the last decade several papers have demonstrated that the DL is closely connected to the state of the biological systems and, therefore, that is possible to use it as an indicator of such a state. [6-8].

Having this in mind, we have carried out preliminary measurements on normal and tumor human cells [9] which demonstrated that there is a remarkable difference between the total number of photons emitted from cultures of normal and tumor human cells of the same density. However, since the number total of counts is an extensive parameter, not always under control, we decided to improve the measurement set up making it able to execute both time and frequency resolved analysis of the DL emitted from the cells. In this paper the results of such analysis are exposed.

2 MATERIAL AND METHODS

2.1. Cell and Cell Culturing

Skin fibroblasts and melanoma cells were obtained from the H.G.M.C. Repository (Camden, NJ, USA). Normal cells were plated 1:2 and melanoma cells 1:10. For the determination of ultraweak photon emission, cells were cultured in tissue culture plastic flasks (surface, 75cm², Gibco Basel, Switzerland) in 15 ml Dulbecco's modified Eagle's medium (DMEM; Gibco, Basel Switzerland) supplemented with 10% fetal calf serum and 100 units (U) ml⁻¹ penicillin-streptomycin. Cells were frozen gently in liquid nitrogen in DMEM with 10% DMSO and then transported in liquid nitrogen to Catania. Before measurement the cells were thawed and diluted in phosphate buffered saline (PBS) up to a density of 4×10⁶ cells/ml and 180 ml of cell suspension was placed directly in the measurement chamber.

2.2. DL Measurements

In order to measure the DL of cell cultures an improved version of ARETUSA set-up [9] was used. This equipment is able to detect single photons and has a very low background signal; moreover it presents a high efficiency in collecting the luminescence emitted by cell cultures, and a low delay time between the end of the illumination pulse and the beginning of signal acquisition. The improvements concern mainly the possibility to perform a spectral analysis of the examined samples. The samples, with a volume of about 180 ml, confined by surface strength in a

hemispherical shape, were placed on the upper side of a horizontal quartz window.

The background signal, of the order of ten percent of the total one, was measured apart and was subtracted from the signal coming out from the samples.

As a light source a Nitrogen Laser (Laser Photonics LN 230C), characterized by a wavelength $\lambda=337$ nm, a 5 ns pulse width, an energy of 100 ± 5 μ J/pulse, was chosen. We performed the spectral analysis by a set of seven broad band (80 nm) Lot-Oriel interferential filters.

A multi-alkali photomultiplier tube (PMT) selected for single photons counting (Hamamatsu R-7602-1/Q), cooled down up to -30°C , was chosen as a detector.

During the laser pulses, the photomultiplier has been protected by an electronic gate. The acquisition started 100 ms after the illumination pulse. The detected signals were acquired by a MCS (Ortec MCS PCI).

3. RESULTS AND DISCUSSION

Many measures on various samples, coming from various donors, have been executed. During the measurements the temperature of the cell culture has been maintained constant at 10 ± 1 $^\circ\text{C}$ or at 32 ± 1 $^\circ\text{C}$. It is, indeed, well known from the literature, that, in the human cells, at this two temperatures the cytoskeleton exhibits different states.

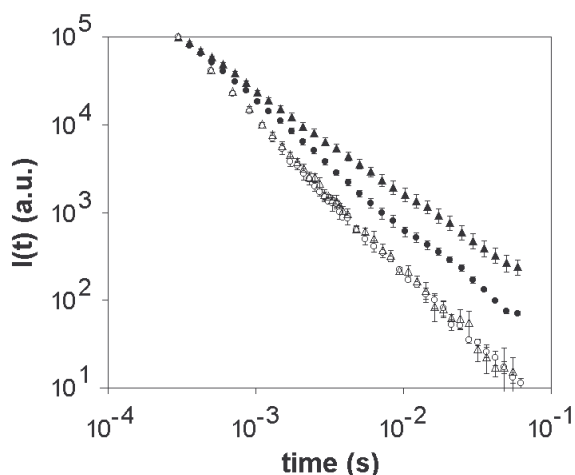


Figure 1. DL time trend of human cells samples at several temperatures: (●) human fibroblasts at 32 $^\circ\text{C}$, (▲) human melanoma at 32 $^\circ\text{C}$, (○) human fibroblasts at 10 $^\circ\text{C}$ (△) human melanoma at 10 $^\circ\text{C}$.

Actually, on increasing the temperature, a sort of phase transition happens, in connection to the processes of polymerization of the monomers constituting the cytoskeleton structures [10]. In particular at 10 degrees the chains nearly disappear while at 32 $^\circ\text{C}$ they include most of the present monomers.

We expected that there was a remarkable difference between these two situations since DL dynamics appears to be connected with the state of cells.

Figure 1 shows that DL of tumor cells is different from that of normal ones and that both depend from temperature.

This dependence is probably connected to the variation of the length of the polymer chains because, although the change of temperature is rather moderate, there is a considerable change of the slope and, therefore, of the probability of decay of the excited states [11].

Moreover is confirmed the fact that, at lower temperature, when the chains of the cytoskeleton are about fully depolymerized, the DL coming from the tumor cells is completely indistinguishable from that coming from the normal ones. It is only at higher temperature, when the structure of the cytoskeleton is consolidated, that a difference appears.

Figure 2 shows the result of the spectral measurements executed on the total number of count re-emitted by normal fibroblast cell cultures. Black bars histogram shows the measured intensities normalized to their total sum. This histogram does not represent the effective spectrum of the sample, because it does not take in account the sensitivity factor i.e. the product between the optical transmittance of the filtering system and the quantum efficiency of the photomultiplier. Taking in account this correction we obtain the white bars histogram, which represents the effective spectrum of the sample in the investigated spectral region.

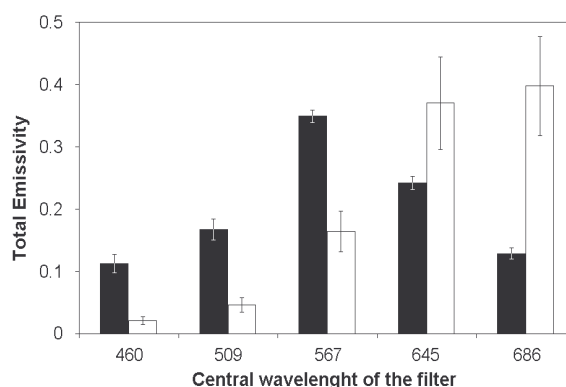


Figure 2. Back bars: intensities, normalized to the value of their sum, obtained with the various filters from the total DL of human fibroblasts

White bars: emission spectrum of total DL of human fibroblasts obtained by the previous one multiplying each value by the respective sensitivity factor.

This emission spectrum shows that most of the emission seems to take place in the near infrared region. Unfortunately such spectrum, as shown in figure 3, is affected by remarkable systematical errors.

However, since this measurement does not aim to establish an absolute spectrum of the various cells but to characterize the differences between the various spectra, the raw spectral measure, not corrected by the

sensitivity factor, is sufficient. Under this point of view figure 3 shows the spectral trends of normal fibroblasts and human melanomas at 32 °C and 10 °C.

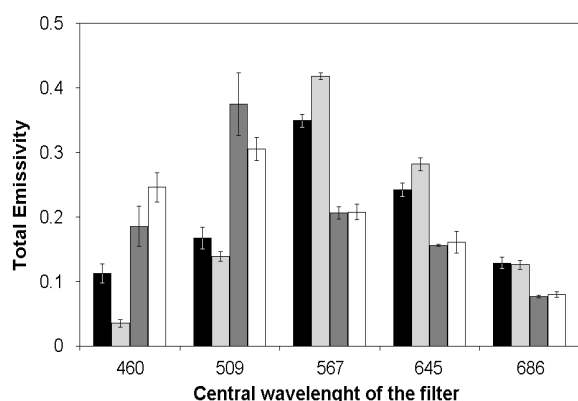


Figure 3. Intensities, normalized to the value of their sum, obtained with the various filters from the total DL of human cells at different temperatures:

Black bars: human fibroblasts at 32 °C. Clear gray bars: human melanoma at 32 °C. Dark gray bars: human fibroblasts at 10 °C. White bars: human melanoma at 10 °C

It is possible to see that, as supposed, the temperature influences remarkably the spectra. In particular, rising the temperature both the spectrum of the fibroblasts and that of the melanomas move towards the infrared. However, while at 10 °C the two spectra are, inside the experimental errors, nearly indistinguishable on growing the temperature they show measurable diversities.

This difference could constitute the base of a future strategy of diagnostic discrimination.

5 REFERENCES

- [1] Meurens M, Wallon J, Tong JS, Noel H, Haot J. (1996) Breast cancer detection by Fourier transform infrared spectrometry *Vibrational Spectroscopy* 10 (2): 341-346
- [2] Chwirot BW, Chwirot S, Jedrzejczyk W, Jackowski M, Raczynska AM, Winczakiewicz J, Dobber J (1997) Ultraviolet laser-induced fluorescence of human stomach tissues: Detection of cancer tissues by imaging techniques *Lasers in Surgery and Medicine* 21 (2): 149-158
- [3] Kobayashi M, Tajiri H, Seike E, Shitaya M, Tounou S, Mine M, Oba K (2001) Detection of early gastric cancer by a real-time autofluorescence imaging system *Cancer Letters* 165 (2): 155-159
- [4] Rolando A. et al. (2001) An Objective Morphologic Parameter to Aid in the Diagnosis of Flat Urothelial Carcinoma In Situ *Human Pathology* 32, No.9 997-1002
- [5] Mayinger B, Jordan M, Horner P, Gerlach C, Muehldorfer S, Bittorf BR, Matzel KE, Hohenberger W, Hahn EG, Guenther K (2003) Endoscopic light-induced autofluorescence spectroscopy for the diagnosis of colorectal cancer and adenoma *J Photochem Photobiol B* 70 (1): 13-20
- [6] Scordino A, Triglia A, Musumeci F, Grasso F, Rajfur Z (1996) Influence of the presence of atrazine in water by on the in-vivo delayed luminescence of *Acetabularia acetabulum*. *J Photochem Photobiol B* 32: 11-17
- [7] Triglia A, La Malfa G, Musumeci F, Leonardi C, Scordino A (1998) Delayed luminescence as an indicator of tomato fruit quality. *J Food Sci* 63: 512-515
- [8] Yan Y, Popp FA, Rothe GM (2003) Correlation between germination capacity and biophoton emission of barley seeds (*Hordeum vulgare* L.). *Seed Sci Technol* 31: 249-258
- [9] Tudisco S, Musumeci F, Scordino A, Privitera G (2003) Advanced research equipment for fast ultraweak luminescence analysis. *Rev Sci Inst* 74: 4485-4490
- [10] Scordino A, Triglia A, Musumeci F (2000) Analogous features of delayed luminescence from *Acetabularia acetabulum* and some solid state systems. *J Photochem Photobiol B* 56: 181-186
- [11] Ho M.W., Musumeci F., Scordino A., Triglia A. (1998) Influence of cations in extracellular liquid on delayed luminescence of *Acetabularia acetabulum* *J Photochem Photobiol B* 45, 60-66

Relation between Delayed Luminescence and cytoskeleton state in yeast cells.

Irina Baran^{a,b}, Virgil Baran^{a,c}, F.Musumeci^{a,d}, G. Privitera^{a,d}, A. Scordino^{a,d} and S.Tudisco^{a,d*}

- a) INFN Laboratori Nazionali del Sud, Catania, Italy
- b) University of Medicine and Pharmaceuticals 'Carol Davila', Biophysics Dept., bd. Eroilor Sanitari 8, Bucharest, Romania
- c) University of Bucharest, Physics Faculty, Theoretical Phys. And Mathematics Dept. and NIPNE-HH, Bucharest, Romania
- d) Dip. di Metodologie Fisiche e Chimiche per l'Ingegneria, Università di Catania, Italy

* Corresponding author, e-mail: tudisco@dmfci.unict.it

Abstract

We describe the influence of some antimitotic chemicals, that specifically acts on cytoskeleton, on the Delayed Luminescence (DL) of Yeast cells *Saccharomyces cerevisiae* Hansen. A standard microscope connected to a CCD camera detected the morphology of yeast cells, as a result of the action of chemicals. Independently of the start phase of the cell cultures, a strong effect of colchicine on some spectral components of the DL was revealed while the effect of taxol was less pronounced. This results supports the model that explains the DL as due to collective excited states present in the low dimensional structures of cytoskeleton.

1 INTRODUCTION

The cytoskeleton is an interconnected network of actin, microtubule and intermediate filaments which spans the entire cytoplasm [1]. The microtubule array is mainly restricted to the cell body, although it enters the actin-rich peripheral cytoplasm to some extent. A critical property of microtubules is their dynamicity, on which many cell functions depend. The interphase microtubule array develops as cells progress through the cell division cycle and undergoes dramatic changes as cells enter mitosis, when a bipolar spindle is formed. Colchicine binds to a high affinity site of tubulin. Binding of colchicine inhibits tubulin polymerization into microtubules [2], and stabilizes microtubule dynamics [3]. At concentrations of 1 mM and higher, colchicine depolymerizes >95% of the microtubules in the cells [4]. Taxol binds reversibly and with high affinity to tubulin subunits in microtubules; it has no effect on actin filaments or on cellular mechanical properties [5] but high concentrations of taxol (100 nM – 10 mM) inhibit microtubule disassembly [6] and enhance microtubule polymerization, thus increasing microtubule mass in cells. Low levels of taxol which have no measurable effect on microtubule polymerization however are able to suppress microtubule dynamic instability by inhibiting growth and shortening rates [7].

We have used high concentrations of colchicine and taxol respectively to induce disruption or to enhance polymerization of microtubules in the *Saccharomyces cerevisiae* yeast cells. This to check their influence on the DL of these biological systems and to try, in such

way, to better understand the origin and the characteristics of this phenomenon and to check its recent theoretical explanation.

2 MATERIAL AND METHODS

2.1 Cell growth and synchronization

Wild-type *Saccharomyces cerevisiae* yeast cells were grown overnight in rich glucose medium YPD (composed of 2% glucose, 1% yeast extract and 2% bactopectone) at 27-29°C. Cells were brought to logarithmic phase by transfer to fresh YPD at a starting density of $2 \cdot 10^6$ cells/ml. For stationary phase G1 synchronization, log-phase cells were grown for either 60-65 h in normal YPD until saturation (>90% unbudded cells) or 17 h in YPD medium with 0.01% glucose. Release from G1 arrest was achieved by transferring the culture to $5 \cdot 10^6$ cells/ml in fresh medium.

Mitotic blockage was induced by treatment either with 1 mg/ml colchicine or 5 mM paclitaxel (taxol) in fresh medium, at a starting density of $5 \cdot 10^6$ cells/ml. Dead cells were detected by the methylene-blue method (Iida et al., 1990). The selection criteria for budding profiles and cell cycle phase distributions were: unbudded cells for G1, small-budded cells for S, medium-budded cells for early-to-middle-G2 and large-budded cells for late-G2-M phase [8]. Prior to DL measurements, cells were collected by centrifugation (1500 g, 2 min.) of a 5-10 ml culture aliquot and transferred at a final concentration $\sim 70 \cdot 10^6$ cells/ml cells into a minimal medium (Sigma-Aldrich Y0626) with 10 g/liter dextrose. 0.2 ml of the resulting culture were prepared

for microscopic examination and 150 ml drops were used for DL measurements under aerobic conditions, at a temperature of 23 ± 0.5 °C.

2.2 Delayed Luminescence Spectroscopy

In order to measure the DL of cell cultures an improved version of ARETUSA [9] set-up was used.

This equipment is able to detect single photons and has a very low background signal; moreover it presents a high efficiency in collecting the luminescence emitted by cell cultures, and a low delay time between the end of the illumination pulse and the beginning of signal acquisition. The improvements concern mainly the possibility to perform a spectral analysis of the examined samples [10].

The samples, confined by surface strength in a hemispherical shape, were placed on the upper side of a horizontal quartz window. The spectral analysis has been performed by a set of seven broad band (Lot-Oriel, about 80 nm FWHM) interferential filters putted, in a wheel, between the sample and the photomultiplier

As a light source a Nitrogen Laser (Laser Photonics LN 230C), characterized by a wavelength $\lambda=337$ nm, a 5 ns pulse width, an energy of 100 ± 5 μ J/pulse, was chosen. The laser power was reduced, in some cases, to prevent the dimpling of photomultiplier.

The detected signals have been acquired by a Multi-channel Scaler (MCS) (Ortec MCS PCI), able to collect analogical or logical signals as a function of time, with a minimum dwell time 200 ns.

3 RESULTS AND DISCUSSION

The analysis of the DL emission spectrum of yeast cells, in both synchronized and non-synchronized cultures, shows that the various spectral components differ considerably in intensity and dynamics.

Figure 3 shows the DL emission spectrum of non synchronised samples and synchronised samples after addition of taxol or colchicine as above specified. The total emissivity values shown in fig. 1 have been

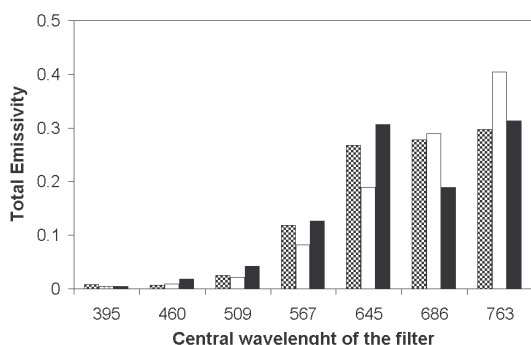


Figure 1 – Emission spectrum of DL of a native culture of yeast cells. (gray) non synchronised sample, (white) sample with colchicine, (black) sample with taxol.

normalized taking into account the different transmittivity of the filters. It is evident, from figure 1,

that the main part of DL in these systems is emitted in the range of red and near infra-red.

As it regards the dynamics, Fig. 2 reports the time trend of the spectral components for a non-synchronized sample. More precisely each trend is the average of five different samples measured in the same conditions.

It is evident that the decays of the various spectral components have different time trends. In order to underline the differences in the spectral components dynamics, the curves of fig. 2 are normalized so to have the same (arbitrary) initial value.

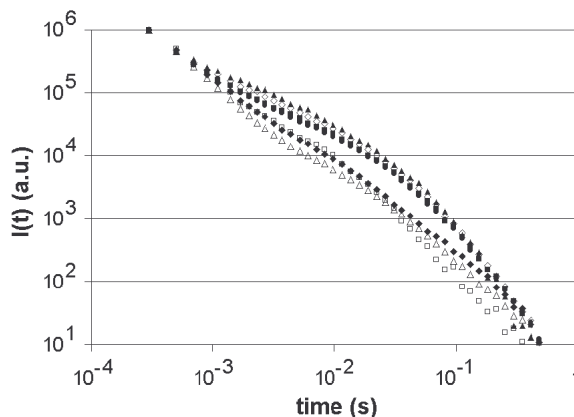


Figure 2 – Time trend of the DL emission spectral component of non-synchronised culture renormalized in order to have the same initial (arbitrary) value: (□) F1, (◆) F2, (△) F3, (●) F5, (■) F6, (◇) F7, (▲) F8

Figure 2 shows that two different dynamic behaviours are present. The first trend concerns the spectral components with wavelength less than 550 nm. They are characterized by an about linear trend in a log-log plot and their dynamics are quite different. The second trend concerns the spectral components with wavelength greater than 550 nm. This group of spectral components is characterized by a non linear trend in a log-log plot and the dynamics of the single component are quite close one to another.

The two groups of spectral components, i.e. spectral components with wavelengths greater and smaller than 550 nm respectively, react in a remarkably different way to the presence of colchicine or taxol. More precisely the spectral components with $\lambda_{emis} < 550$ nm seems to feel rather weakly the presence of the two agents capable of changing the cytoskeleton functionality while the spectral components with wavelength greater than 550 nm show a noticeable sensitivity to the presence of colchicines.

In order to illustrate this point in Figure 3 is shown the DL time trend of one of the spectral components of the group having longer wavelengths, representative of the behaviour of the other components of the same group. It is possible to see that colchicine strongly affects the DL time trend, especially in the shorter time interval, while the influence of taxol seems to be much weaker. The large increase in the probability of decay,

in relation to the colchicine-induced reduction of the average length of the microtubules, is consistent with the predictions of the theoretical model which explains the DL as due to excitation and successive decay of collective states [11].

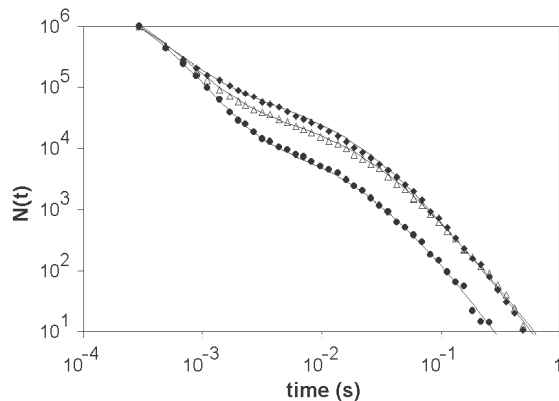


Figure 3 – Time trend of a spectral component ($\lambda_{\text{emis}} = 645 \text{ nm}$) of non-synchronised samples ($\blacklozenge$) and samples with taxol ($\triangle$) and colchicine ($\bullet$).

With the aim to make a qualitative comparison between the experimental data and a theoretical predictions, Figure 4 shows the trends that we obtain in the frame of the above cited model for two different values of probability of decay, keeping constant all the other parameters of the model for both the curves. It appears evident the strict similarity between these curves and the short time interval trends of non-synchronised and colchicine-synchronised samples reported in Fig. 3.

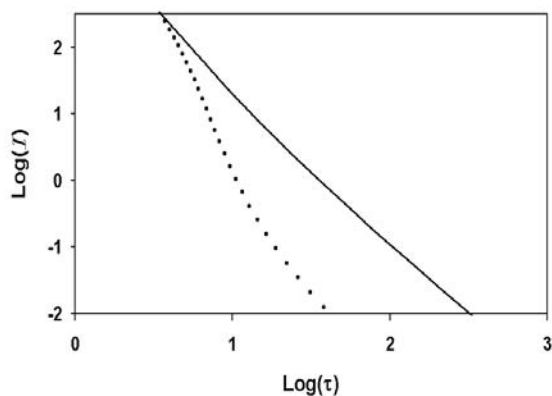


Figure 4 – Dimensionless intensity I as a function of dimensionless time τ , in the frame of the correlated many-solitons states model.

4 CONCLUSIONS

This paper reports several characteristics of the DL of biological systems never studied before. On one hand it demonstrates that what is normally measured as integral DL consists of two parts with distinct time trends. The low-wavelengths range and the long-time intervals seem

to be almost insensitive to the influence of colchicine and taxol. The long-wavelength range, likely extended up to the NIR range, exhibits, in the short-time interval (up to ms), a time trend strongly affected by the cytoskeleton state.

5 REFERENCES

- [1] Pollard TD (2003) The cytoskeleton, cellular motility and the reductionist agenda. *Nature* 422:741-745
- [2] Mareel MM and De Mets M (1984) Effect of microtubule inhibitors on invasion and on related activities of tumor cells. *Int Rev Cytol* 90:125-168
- [3] Panda D, Daijo JE, Jordan MA and Wilson L (1995) Kinetic stabilization of microtubule dynamics at steady-state in-vitro by substoichiometric concentrations of tubulin-colchicine complex. *Biochemistry* 34:9921-9929
- [4] Anderson DC, Wible LJ, Hughes BJ, Smith CW and Brinkley BR (1982) Cytoplasmic microtubules in polymorphonuclear leukocytes: effects of chemotactic stimulation and colchicine. *Cell* 31:719-729
- [5] Tsai MA, Waugh RE and Keng PC (1998) Passive mechanical behavior of human neutrophils: effects of colchicine and paclitaxel. *Biophys J* 74:3282-3291
- [6] Caplow M, Shanks J and Rublen R (1994) How taxol modulates microtubule disassembly. *J Biol Chem* 269:23399-23402
- [7] Yvon AMC, Wadsworth P and Jordan MA (1999) Taxol suppresses dynamics of individual microtubules in living human tumor cells. *Mol Biol Cell* 10:947-959
- [8] Hanna DE, Rethinaswamy A and Glover CVC (1995) Casein kinase II is required for cell cycle progression during G_1 and G_2/M in *Saccharomyces cerevisiae*. *J Biol Chem* 270:25905-25914
- [9] Tudisco S, Musumeci F, Scordino A, Privitera G (2003) Advanced research equipment for fast ultraweak luminescence analysis. *Rev Sci Instr* 74: 4485-4490
- [10] F.Musumeci, G. Privitera, A. Scordino S.Tudisco (2004) Developments of ARETUSA LNS-INFN report
- [11] Brizhik L, Scordino A, Triglia A, Musumeci F (2001) Delayed luminescence of biological systems arising from correlated many-soliton states. *Phys Rev E* 64: 031902

PROPOSAL FOR THE CONSTRUCTION OF AN HADRONTHERAPY CENTER IN CATANIA

L. Calabretta, G. Cuttone, G.A.P. Cirrone, M. Maggiore, L. Raffaele, G. Schillaci
S. Lo Nigro*
L. Biagioni⁺, M. G. Sabini⁺

I.N.F.N.- Laboratori Nazionali del Sud, Via S. Sofia 44, 95123 Catania, Italy

*Dipartimento di Fisica ed Astronomia dell'Università di Catania, Viale A. Doria 55,
95123 Catania, Italy

⁺Azienda Ospedaliera Cannizzaro, Via Messina 829, 95126 Catania, Italy

Abstract

A preliminary layout for an hadrontherapy center for the A.S. Cannizzaro in Catania has been studied. It is based on a new superconducting cyclotron able to deliver protons and light ions.

1 INTRODUCTION

Since the sixty years in several laboratories started the experimentation of the tumors radiotherapy by proton and other charge particles. Today, around the world about 27 centers are using proton or ions to threat tumors. More than 40.000 patients are been treated with successfully results.

In the last years a lot of new centers are been founded mainly in Japan and USA, but also in Australia, Korea, China and Europe. In Italy in particular the CNAO

center has been founded and also the Trento country has decided to found an agency to promote the construction of a proton therapy center.

Moreover in Catania since beginning of 2002 the proton-therapy of the eye melanoma is in operation at LNS. The experience gained with this facility and the interest of the A.S. Cannizzaro Hospital in Catania joint to the positive support of the Sicilian regional Government, has triggered the study for a new Hadrontherapy center in Catania.

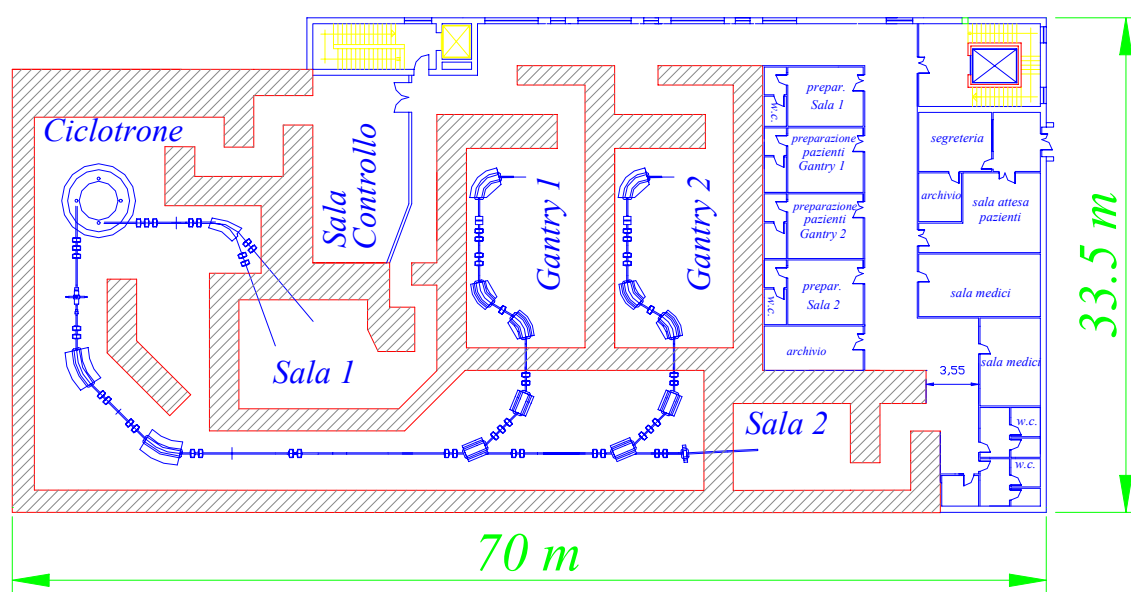


Fig. 1) Layout of the new center for hadrontherapy for the Hospital A.S. Cannizzaro, Catania

2 LAYOUT OF THE CATANIA HADRONTHERAPY CENTER

The figure here under shows the layout of the new center. It is based on a new superconducting cyclotron studied by the LNS group [1]. This cyclotron is able to deliver proton beam by stripping extraction but also light ions like carbon at energy of 250 MeV/amu, more information about the cyclotron characteristics are presented elsewhere in this annual report.

The size of the center is quite compact and fit in the area where it will be located inside the area of the A.S. Cannizzaro. The treatment building will consists of three floor. The underground floor dedicated to the technical plant for the cyclotron and the other technical devices. The ground floor is dedicated to the preparation of the patients, to the treatments and to the control of the accelerator. The upper floor is dedicated to host the room for the medical and technical staff and for additional technical plants.

3 ENERGY SELECTOR AND BEAM LINES

The beam accelerated and extracted from the cyclotron has a fixed energy. To allow a treatment of the tumors with the so called multi-painting technique and to avoid the beam energy degradation in front of the patients, we decided to use an energy degrader and a selector magnet system similar to the devices already under construction for the RPTC centre in Munich and at IUCF. The variation of the beam is achieved by a continuously variable double wedge beryllium energy degrader, which permit an energy variation of beam from 250 MeV down to 70 MeV in less than 10 sec. The purpose of the Energy Selection Beam Line is to select and transport particles with desired energy from the energy degrader target to the entrance of either a gantry or a fixed horizontal treatment beam line. The design of the energy selection beam line will be similar to the IUCF devices but the magnetic rigidity would be doubled to allow the selection of the carbon ions too. For this reason we select magnets with bending angle of 45° instead of the original 63° of the IUCF project. The reduction in the resolving power due to the reduction of the bending angle is compensated by the larger bending radius of the magnets.

Momentum resolution lower than 2×10^{-3} , corresponding at energy resolution of 250 KeV for the minimum energy of 65 MeV for proton, is expected.

The room 1 is dedicated to the treatment of eye melanoma and more generally to un-deep tumors. The cyclotron beam, thanks to the stripper extraction, is feed to this room independently from the "Energy Selector line". The beam delivered to this room is energy degraded down to 150/70 MeV by fixed energy absorbers. These absorbers will be placed before the last bending magnet. The final range shifter and range modulator will be placed inside the treatment room, but a local concrete shield will protect the patient.

4 GANTRIES

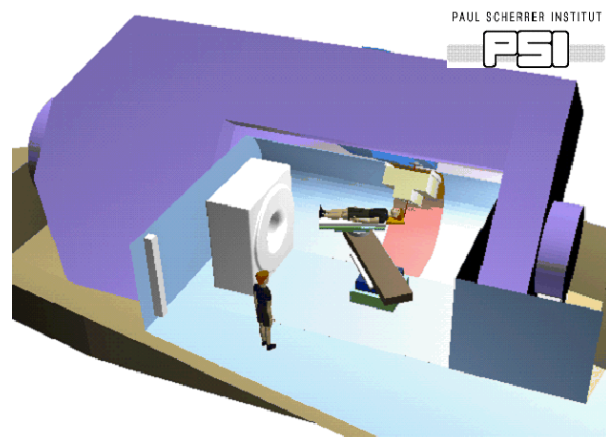
The gantries for the centre are the same of the so called PSI Gantry II. This novel concept Gantry rotates over an angle range of 180°. The treatment from every prescribed beam direction is feasible by rotating the patient position of 180°.

The scanning magnets are installed upstream of the last bending magnet, allowing for scanning with quasi parallel proton beams. The maximum irradiation field-size being of about 10 cm by 20 cm.

Others advantage of this new kind of gantry are:

- Maximum gantries radius is reduced;
- There is enough space in the treatment area for installing a CT-scanner for position verification.

To allow the preparation of a certain number of medical team and also for economic reasons one of the two gantries will be installed in a second phase.



5 TREATMENT WITH LIGHT IONS

The main advantage of the new cyclotron proposed for the centre is the availability of light ions for therapy and also for research. According to the statistics of the HIMAC about 45% of the patients with head & neck tumors can treated with carbon ion beam with energy of 250 A MeV. So despite the centre is mainly a protontherapy centre it could take advantage of the carbon ion availability to dedicate a 10-20% of the beam time to treat patient with carbon ion or other lighter ions like Litium. Moreover the room 1 was designed large enough to allow the installation of an extra beam line for research experiment to be performed during the night or weekend.

6 REFERENCES

- [1] L. Calabretta et Al., proc. of Eur. Part. Acc. Conf. (2002) pag. 614
- [2] L. Calabretta et Al., this report
- [3] Anferov V. et Al., proc. Of Part. Acc. Conf. (2003) pag 699
- [4] Pedroni E., private communication

THE CATANA PROTON THERAPY FACILITY: TWO YEARS OF CLINICAL AND DOSIMETRIC EXPERIENCE

G.A.P. Cirrone^{a*}, G. Cuttone^a, P.A. Lojacono^b, E. Mongelli^a, S. Lo Nigro^c, J. Ott^d, V.I. Patti^a, G. Privitera^b, L. Raffaele^b, M.L. Rallo^d, A. Reibaldi^d, G. Russo^a, V. Salamone^b, M.G. Sabini^a, C. Spatola^b, L. Valastro^a

a) INFN Laboratori Nazionali del Sud, Catania, Italy

b) Istituto di Radiologia, Azienda Policlinico, Catania, Italy

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

d) Istituto di Oftalmologia, Università di Catania, Catania, Italy

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

Abstract

After three years of activity 60 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 radiotherapeutic 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 30 patients demonstrated the efficacy of high energy protons in the radiotherapeutic field and encouraged us in our activity in the battle against cancer.

1 INTRODUCTION

The use of proton beams offers 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 recent years. 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 hemangioma, 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

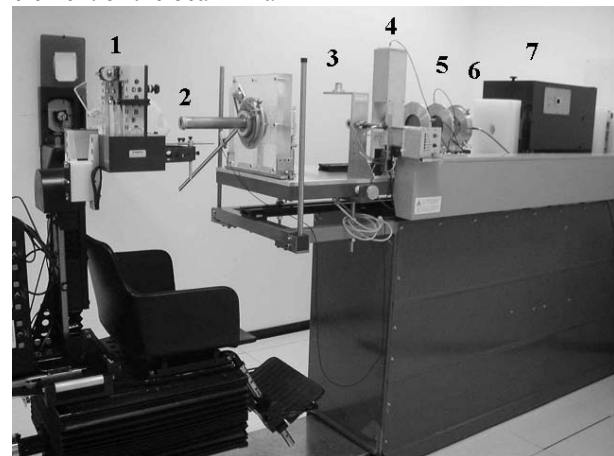


Figure 1: View of the CATANA beam line: 1. Treatment chair for patient immobilization; 2. Final collimator; 3. Positioning laser; 4. Light field simulator; 5. Monitor chambers; 6. Intermediate collimator; 7. Box for the location of modulator wheel and range shifter.

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 optimized 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).

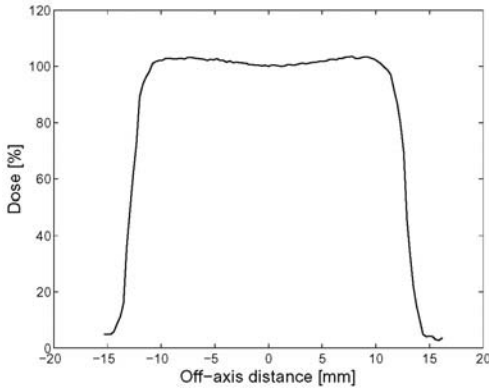


Figure 2: Lateral dose distribution for 62 MeV proton beam.

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 THE PROTON BEAM LINE

The CATANA collaboration is planning to devote particular care to the development of dosimetric techniques and 2D and 3D dose distribution reconstruction. A plane-parallel *advanced* PTW 34045 Markus Ionization Chamber has been adopted for reference dosimetry (beam calibration). 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%.

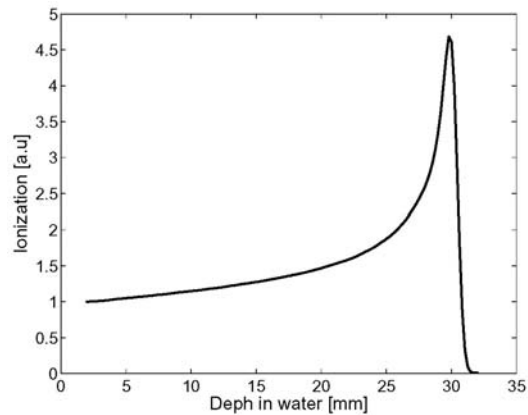


Figure 3: Bragg peak of 62 MeV proton beam acquired in a water-tank with the Markus ionization chamber at CATANA facility.

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. We have developed, in collaboration with the Clatterbridge Center for Oncology (UK), wheel modulators to obtain therapeutic SOBPs. Proton beam energies lower than 62 MeV are obtained inserting PolyMethylMethAcrylate (PMMA) range shifters of different thickness along the beam path. Finally 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. 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].

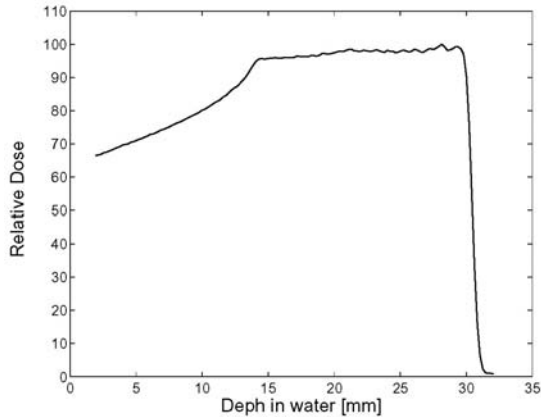


Figure 4: Spread Out Bragg Peak obtained with a modulator wheel.

4 TREATMENT PROCEDURES

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, 66 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 which

of them suffered from uveal melanoma (61 pts, 92%), is the most common tumor of the ocular region in the adult. We have also treated other pathologies with proton beams, like conjunctival melanoma (2 patients), conjunctival rhabdomyosarcoma (1), eyelid carcinoma (1) and conjunctival Mucosa-Associated Lymphoid Tissue-Non Hodgkin Lymphoma (MALT-NHL) (1). Twenty-six patients came from Sicily, 40 from the other Italian regions (Figure 6).

Among the 66 patients, 34 were women (51 %) and 32 men (49 %). Patient age ranged from 14-81 years (mean 55.6).



Figure 6: Patient's place of origin.

5.2 Results

During the follow-up, the first data regarding local tumor control are available only after 6-8 months from the end of the treatment. Actually, we have the preliminary results of the follow-up for 52 patients at 6-8 months, and for 32 patients at 1 year. The local control is defined as a tumor shrinkage or cessation of growth at B-Mode ultrasonography, or as an increase of ultrasound reflectivity at A-Mode ultrasonography (a surrogate for tumor control). A size reduction, especially regarding the thickness of the tumor, was seen in 39 patients (75%), while 13 patients maintain a stable dimensional lesion (25%). An increased A-Mode ultrasound reflectivity was detected in almost all patients. These data clearly show a tumor control, particularly for those patients with 1 year follow-up. No major side effects requiring eye enucleation have been detected: an 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 CONCLUSIONS

The preliminary results show an high percentage of local tumor control, despite the limited follow-up period (1 year for 32 patients, 6-8 months for 52 patients), with a limited acute and subacute toxicity and visual outcome according to the previsions. The results are in agreement with those reported in the literature, regarding the treatment of uveal melanoma by means of hadrons.

Even if CATANA should not be the clinical answer for all the Italian patients affected by this kind of disease, it represents the first successfully Italian example of the collaboration between Nuclear and Medical Physicists together with Medical Doctors in fighting tumors with hadrons. CATANA is the first milestone in Italy through the extensive use of hadrontherapy in cancer treatment.

7 REFERENCES

- [1] D.W Miller et al., Med. Phys., Vol. XXII, N.11, 1995, pp. 1943-1954.
- [2] M. Fuss, L.N. Loredi, et al., Int. J. Radiat. Oncol. Biol. Phys., N.49, 2001, pp. 1053-1059.
- [3] G. Cuttone, G.A.P. Cirrone, et al., Particle, Journal of the Proton Therapy Co-Operative Group, N.28, July 2002, pp. 8-10.
- [4] International Atomic Energy Agency (IAEA). Technical Report Series N.398, 2000, pp. 135-150.
- [5] G.A.P. Cirrone, G. Cuttone et al., Proceedings of the IEEE NSS MIC 2003, pp. 26.
- [6] M.A. Sheen. Abstracts of XX PTCOG meeting at Chester, UK, May 16-18, 1994

BEAM MONITORING ENHANCES DEEP PROTON LITHOGRAPHY: TOWARDS HIGH-QUALITY MICRO-OPTICAL COMPONENTS

L.Cosentino^b, P.Finocchiaro^b, A.Hermanne^a, H.Ottevaere^a, A.Pappalardo^b,
H.Thienpont^a, P.Tuteleers^a, M.Vervaeke^a, B.Volckaerts^a, P.Vynck^a

a) Department of Applied Physics and Photonics (TW-TONA), Vrije Universiteit Brussel, Belgium

b) Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali del Sud, Catania, Italy

Abstract

In this paper we will explain the importance of a well controlled and accurately positioned ion beam profile in Deep Lithography with Protons (DLP) to prototype high-quality micro-optical components. We will illustrate how to that aim, we implemented two types of Beam Profile Monitors (BPM) in our in-house beam line. A first BPM device is based on two four-segment apertures that allow to monitor the beam position, while a second one uses a Scintillating Fiber Optic Plate (SFOP) and a CCD camera to visualize the beam profile.

1 INTRODUCTION

The use of refractive micro-optical and mechanical structures are playing more and more important roles in many optical systems. 2D arrays of spherical micro-lenses together with micro-prisms and cylindrical micro-lenses or mechanical positioning structures like 2D fibre array holders are likely to be combined with opto-electronic emitters, receivers and optical fibres to play a key-role in optical sensor arrays, in high definition display and projection systems, in biomedical and invasive medical technology and in optical interconnection and telecommunication technologies [1].

The concept of this technology is based on the fact that the proton irradiation of a sample, made of linear high molecular weight poly(methylmetacrylate) (PMMA), will result in an important reduction of the molecular weight of the material located in the irradiated zones [2,3]. As a consequence, these irradiated zones feature a higher solubility than the bulk material and they can be selectively etched using a special solvent (Figure 1) [4]. This procedure allows e.g. the fabrication of 2D arrays of micro-holes, rows of smoothly curved cylindrical micro-lenses and optically flat micro-mirrors and micro-prisms. Also alignment features and mechanical support structures can be fabricated with this procedure [5].

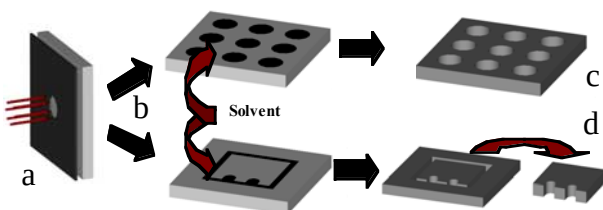


Figure 1: The basic processing steps for the fabrication of micro-hole arrays (c) and more complex 2 1/2 dimensional structures with high optical surface quality (d), by irradiating the PMMA-layer through an accurate pinhole (a) and etching the irradiated zones in a selective solvent (b).

On the other hand, we can swell the irradiated domains using a monomer vapor, which for circular footprints will result in hemispherical surfaces (Figure 2) [6]. This process permits the fabrication of stable spherical micro-lenses with well-defined heights.

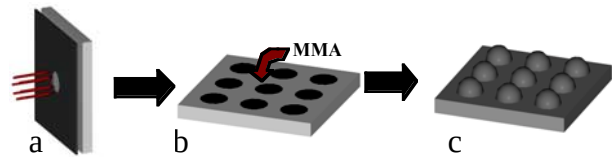


Figure 2: The basic processing steps for the fabrication of 2D arrays of stable and uniform spherical micro-lenses (c) by irradiating the PMMA-layer through an accurate pinhole (a) and applying an MMA-vapour on the surfaces of the irradiated sample (b).

2 SHORTCOMINGS OF THE PRESENT IRRADIATION SET-UP

The absorbed dose in the irradiated domains of the PMMA sample is a crucial parameter that affects both the etching and the swelling behavior of these zones.

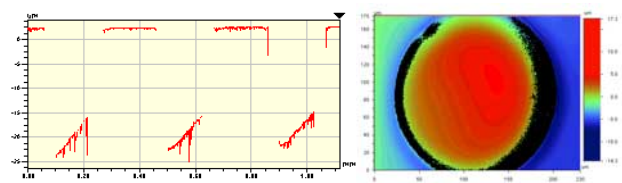


Figure 3: Tilted etching surfaces (left) and shifted lens tops (right) as a direct effect of inhomogeneous ion densities.

Indeed, even small local changes in the particle density of the proton beam and therefore in the absorbed dose distribution in the irradiated zones will result in inhomogeneously etched surfaces, in a tilt of these surfaces (Figure 3.a), or in case of applying the swelling

process in a distortion of the symmetrical shape of the spherical micro-lenses (Figure 3.b). If we want to eliminate these shortcomings we have to be able to control the homogeneity of the accelerated ion beams in a fast and efficient way.

3 BEAM MONITORING

It is evident that controlling the size, the shape and the profile of the proton beam is quite important. A better control of this micro-beam, by means of a set of enhanced diagnostic tools, can remarkably improve the quality of the components made with Deep Lithography with Protons.

In a first approach we adapted the first of three collimators in the ion beam line at the Vrije Universiteit Brussel [7]. This water-cooled aperture stops the outer part of the beam, allowing only the central part to pass. Measuring and analyzing this part of the beam by means of metallic segments we are able to roughly position and shape the beam. The second aperture acts as a pre-mask and reduces the beam diameter further down to 1mm. The final mask is a 300 μ m Nickel plate sufficiently thick to fully absorb the incoming 8.3 MeV protons. To fine-tune the tip-tilt of this mask we placed a Scintillating Fiber Optic Plate (SFOP) just behind the mask. By visualizing the illuminated spot via a CCD and a frame grabber it is possible to position the mask perpendicular to the proton beam and this in real-time. This experiment was performed at the INFN LNS Tandem facility.

3.1 Eight segment beam monitor

This beam monitor consists of eight electrically isolated Aluminium segments fixed on a water-cooled disc by means of a thermally conductive sheet. The four segments facing the proton beam have an inner diameter of 2cm while the other four collimate the beam to a diameter of 1cm (Figure 4.a). Each segment covers a given area (Top, Left, Bottom and Right) and two planes, vertical (Top and Bottom segment) and horizontal (Left and Right segment) are defined. When the proton beam hits a segment, a current is induced in a sensitive picoammeter, built around four dual current input 20bit AD converters (DDC112 from Burr-Brown).

The measurements with the 8 segments beam monitor are represented graphically in figure 4.b. The proton beam can be manipulated by a set of magnetic quadrupole lenses. When for example the beam is moved upwards, the current on the Top and Bottom segments change in an opposite way. Because the incident beam is not necessarily circular, the current on other segments will also vary.

3.2 μ -SFOP beam monitor

This device is mainly meant to get live images of the beam intensity distribution in the transverse plane. For this purpose we used a Scintillating Fiber Optic Plate (SFOP), made from a bundle of Terbiumglass scintillating fibres, observed by a compact CCD camera. Each fibre in the bundle has a 10 μ m diameter, while the

overall plate size is 25x25x1.6 mm³. From a practical point of view, we decided to perform these first experiments in air, using a 10 MeV proton beam accelerated at the LNS Tandem facility. In figure 5 we image two pictures of proton beams with diameters of respectively 800 μ m ($I_{tot}=40$ pA) and 50 μ m ($I_{tot}=2.5$ pA). These images can be rapidly processed to determine the detailed profile of the ion beam and consecutively allow the fine-tuning of the acceleration parameters [8, 9].

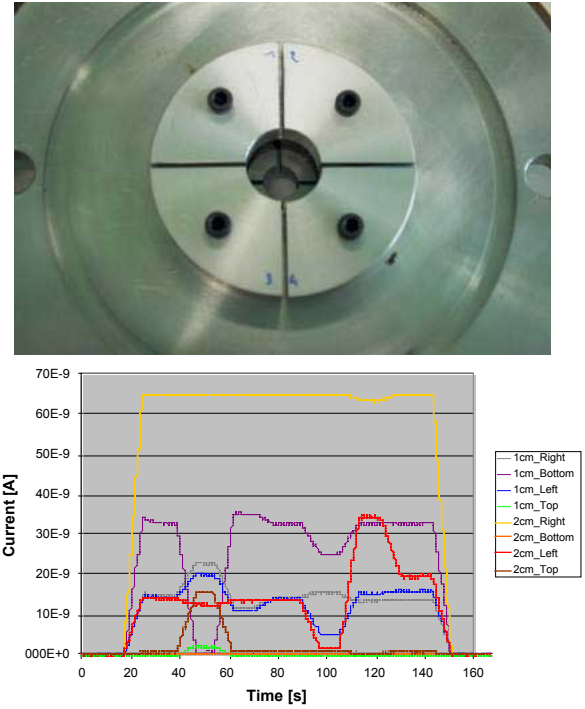


Figure 4: Construction of an 8 segment beam monitor (top) and resp. current measurements with individual picoammeters (bottom).

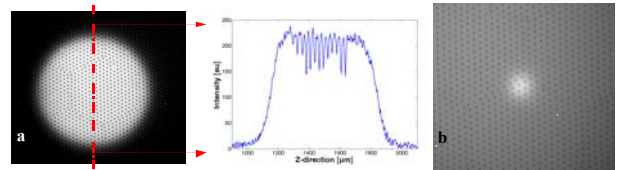


Figure 5: Images of an 800 μ m (a) and a 50 μ m (b) 10 MeV proton beams, delivered by the LNS Tandem, with a SFOP that allows real-time beam analysis.

4 CONCLUSIONS

In this paper we have described the benefit and added value of beam monitoring to improve the quality of micro-optical components made with Deep Lithography with Protons. The first Beam Profile Monitor (BPM), based on two sets of four-segment apertures allows the monitoring of the beam position while a second one uses a Scintillating Fiber Optic Plate (SFOP) and a CCD camera to visualize the beam profile. The results of the SFOP are promising in that this device will definitely allow a better beam position and beam quality control. In its turn this will greatly improve the

accuracy and quality with which micro-optical components can be fabricated using DLP.

REFERENCES

- [1] H.Thienpont, et al, "Plastic Micro-Optical Interconnection Modules for Parallel Free-Space intra MCM Data Communication", Proceedings of the IEEE, Special Issue on 'Short distance Optical Interconnects for Digital Systems, Vol. 88, No. 2, June 2000.
- [2] M.Dole, "The radiation chemistry of macromolecules, II", Academic press, pp. 97-117, 1973
- [3] H.Kudoh, et al, Polymer, 37, 21, pp. 4663-4665, 1996
- [4] F.J.Pantenburg, et al, "Characterization of defects in very high deep-etch X-ray lithography microstructures", Microsystem technologies, Vol. 4, pp. 89-93, 1998
- [5] B.Volckaerts, et al, "Deep lithography with protons: A generic technology for the fabrication of refractive micro-optical modules", Proceedings of IEEE/LEOS International conference on optical MEMS, Kauai, Hawaii, pp. 103-104, August 2000.
- [6] H.Ottevaere, et al, "Refractive Microlens Arrays made by Deep Lithography with Protons: Technology and characterisation", Proceedings Fifth Annual Symposium of the IEEE/LEOS Benelux Chapter, Delft (N), pp. 87-90, 2000.
- [7] P.Vynck, et al, "Deep proton lithography as rapid prototyping technology: towards improved micro-optical components", Proc. Symposium IEEE/LEOS Benelux Chapter, Mons (B), pp. 207-210, 1999
- [8] L.Cosentino, et al, "Ion micro-beam diagnostics with photodetectors for Deep Lithography applications", Nuclear Instruments and Methods in Physics Research, Section B (NIMB).
- [9] B.Volckaerts, et al, "The fabrication of micro opto-mechanical components with high energetic heavy ion beams", Experiment proposal submitted to the INFN-LNS PAC, Catania, Italy, Sept. 2002.

ACKNOWLEDGEMENTS

The work reported here is funded by DWTC IUAP13, FWO, GOA, IWT, GBOU and the OZR of the VUB; by INFN Gruppo V (SIMPLE experiment) and LNS (LITHO experiment). Bart Volckaerts is indebted to the IWT for his research fellowship and for financial support. We want to express our gratitude to the staff of the accelerator and chemical departments of LNS.

INNOVATIVE ION SOURCES AT LNS

S. Gammino^a, G. Ciavola^{*,a}, L. Celona^a, L. Andò^a, M. Presti^a, A. Galatà^a, F. Consoli^a, S. Passarello^a, XZh Zhang^{a,f},
L. Schachter^b, S. Dobrescu^b, K. Stiebing^c, M. Winkler^d, P. Spadtke^d, R. Gobin^e

a) INFN Laboratori Nazionali del Sud, Catania, Italy

b) IFIN-HH, Bucharest, Rumania

c) University of Frankfurt, Germany

d) GSI, Darmstadt, Germany

e) CEA, Saclay, France

f) IMP, Lanzhou, China

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

Abstract

The activity of the Ion Source R&D Team at LNS was mainly focused in 2003 over the following themes:

1. the preparation of the design of the GyroSERSE beam extraction system and transfer line;
2. the study of electron donors injection in SERSE;
3. the use of TWT generators in place of klystrons for SERSE and the effect on highly charged ion beam
4. the reliability and emittance measurements of the TRIPS source;
5. the design of a permanent magnets version of the TRIPS source called PM-TRIPS.

A brief review of each of these issues follows.

1 HIGH CURRENT BEAM EXTRACTION AND TRANSPORT FOR THE GYROSERSE SOURCE

The GyroSERSE project [1,2] was completed in 2002 but its funding was not made available so that in 2003 the same project was proposed for the Joint Research Project named ISIBHI inside the 6th Framework Programme proposal named EURONS that will be funded in the second half of 2004. During 2003, the R&D effort was anyway continued, by studying in details the extraction and transport under different constraints, so that now all the informations are available for the construction. It is well established that the upcoming 3rd generation of ECRIS (operating at 28 GHz or higher frequency) will produce a total extracted current in the range of several tens of mA and multi-mA beams may be provided for some ion species, either in dc mode and in pulsed mode. The development of a model describing the phenomena taking place in the extraction system was undertaken at GSI in order to define the key parameters for the beam optics of 3rd generation ECRIS [3] and the importance of the spatial distribution of the ions in the radial dimension (related to the influence of the hexapole) was demonstrated in the frame of a common research with our group at INFN-LNS [4]. The Kobra3-INP code has been used to calculate the extraction geometry for the GyroSERSE source. An accel decel system has been chosen, to ensure space charge compensation. A flat plasma boundary is a desirable operating condition in order to decrease the coupling of the radial electric field with the longitudinal magnetic field. A homogeneous particle distribution in front of the plasma electrode is necessary

in order to decrease the coupling of an azimuthal electric field component with the B-field. Then a quiet and uniform plasma must be created inside the ECRIS plasma chamber and homogeneity in the plane of the plasma electrode is mandatory, otherwise (in spite of a current increase) the beam brightness will be poor. A good magnetic confinement of the plasma will ensure the limitation of the ion temperature to which the emittance is linked [4] but the uniformity of the plasma boundary and the homogeneity of the particle distribution on the meniscus is achieved only through a plasma cross section much larger than the extraction aperture and through an adequate uniformity of the magnetic trap which is anyway consistent with the standard technology of the superconducting coils to be used for the 3rd generation ECRIS.

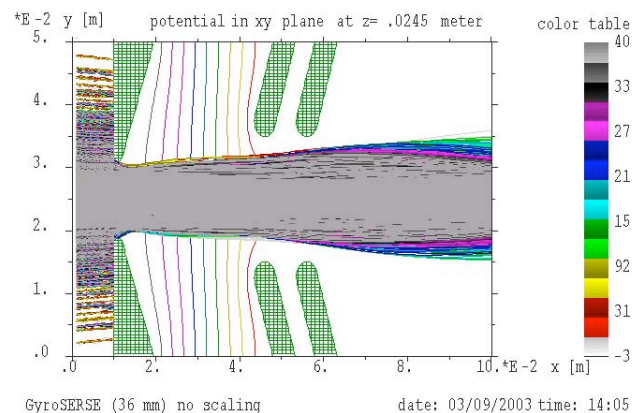


Figure 1: the geometry of the Gyroserse extraction [4].

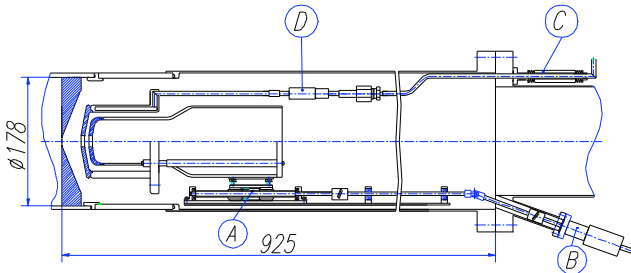


Fig. 2 – The GyroSERSE extractor (A- ball screw, B - rotary drive, C - bellow, D - insulated water tube).

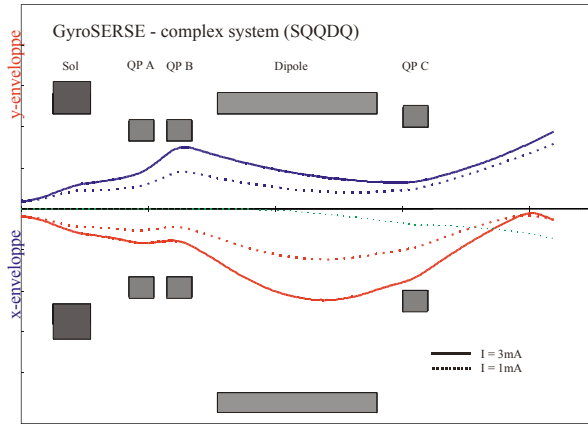


Fig. 3 – Beam envelopes for a SQQDQ system (total length is 4.2m).

Fig. 1 shows the extraction geometry; the ray tracing of the trajectories has been performed only up to 10 cm far from the extraction aperture as this point was the interface between the extraction simulations and the beam line simulations. The charge state distribution (CSD) used in this preliminary calculation is equal to the one obtained with SERSE at 28 GHz. An optimum distance between the plasma and the puller electrodes was calculated (for a puller inclined at 80° with respect to the axis). The beam emittance was calculated for different values of ion temperature, acceleration gap, beam current (up to 50 mA) and it was always in the range $110\text{--}220 \pi \text{ mm mrad}$. More details about the calculations are given in [4]. The mechanical design of the extraction system has been adapted to the different constraints. In fact, the length of the cryostat (2150 mm) have obliged to design a complicate system to move the extractor. The need of a water-cooled puller electrode made more complex the design (fig. 2). Calculations for the beam transport were performed using the computer code GICO and then GIOS, to handle the space charge effects. For some cases TRANSPORT was also used. Ion-optical calculations were performed assuming an initial phase space of $x_0 = y_0 = \pm 6 \text{ mm}$ and $a_0 = b_0 = \pm 25 \text{ mrad}$, which was consistent with the results of the KOBRA simulations. Calculations were done for $^{208}\text{Pb}^{27+}$ and $^{129}\text{Xe}^{20+}$ beam. A source extraction voltage of 40kV was considered.

We have investigated 5 different types of analysing systems for GyroSERSE, as described in [4], but we describe here only the option that we consider as the ideal one. Other solutions obey to different site constraints, including a possible compact system consisting of a compact 90° dipole magnet and a quadrupole doublet that can be adapted to injectors placed on high voltage platform. The ideal injector combines the use of a SC solenoid and a quadrupole multiplet. The solenoid is integrated in the cryostat and it is followed by a quadrupole doublet which prepares the beam for the dipole magnet. After the dipole, a third quadrupole is placed, which enables to get small spot size at the image plane with a high resolving power. Fig.3 shows the beam envelopes in x- and y-direction for a beam current of 1mA and 3mA respectively. The beam is kept rather narrow in the dipole magnet (the drawn gap in y-direction is $\pm 70 \text{ mm}$). The gap of the first and second quadrupole is assumed to be $\pm 50 \text{ mm}$, while the gap of the last one is $\pm 60 \text{ mm}$. The system achieves a 1st order image (for $I = 3 \text{ mA}$) of approximately $\pm 3.5 \text{ mm}$ (x-direction) and $\pm 48 \text{ mm}$ (y-direction), which leads to a 1st order mass resolving power of ≈ 140 . Space charge forces are important but some compensation occurs through the beamline. Anyway the design of the beamline must be carried out with the aim to maintain the beam as parallel as possible, with a large cross section to limit the space charge forces.

2 AN MD-LINER FOR SERSE

The metal-dielectric (MD) structure method represents a new approach to the production of high charge states ion beam production in the ECR ion sources. The effect of a MD structure introduced in the plasma chamber on the source output for different charge states is illustrated in [5]. The previous measurements were performed at 800 W for the IKF source and at 300 W for the KVI source. It is interesting to remark that the enhancement factor was rising with the ion charge state. For Ar^{16+} ions it was 50 at IKF and 100 at KVI. The MD liner for the highest charge states gave a clear advantage of the MD method over other methods like gas mixing, electron gun or biased disk. This advantage was completed by a much better magnetohydrodynamic stability of the ECR plasma which permitted to identify the Ar^{17+} ion beam at KVI.

The results obtained at IKF and KVI suggested to test this method with the source with the best magnetohydrodynamical stability and the highest performance, i.e. SERSE, which in addition uses a much higher rf power. A MD cylindrical structure was produced out of a 1 mm thick sheet of pure aluminum rolled in the form of a tube with length and diameter corresponding to the SERSE plasma chamber and hexapole dimensions (130 mm diameter and 400 mm long). The primary goal of the experiments was to measure and compare the high charge state ion production without and with the MD structure in the plasma chamber of the source.

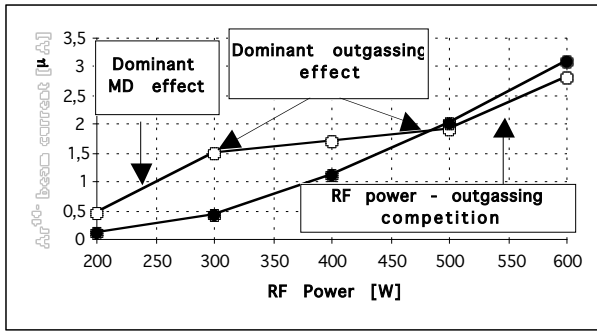


Fig. 4 – Highly charged Argon beam production for increasing rf power with and without the MD liner.

Table 1 – Characteristics of different generators available at LNS.

Generator	Emission frequency	Maximum power	Bandwidth
Klystron	14 or 18 GHz	2 KW	< 100 MHz
TWT1	8 to 18 GHz	< 300 W	~ 2 GHz
TWT2	13,75 to 14,5 GHz	< 600 W	~ 750 MHz

It can be observed in figure 4 that up to 400 W the SERSE Ar¹⁴⁺ ion production with the MD structure is much higher than the production without the MD structure, though in the reference measurements gas mixing that increases several times the high charge state ion production was used. The role of the outgassing for a high charge state ion production is clearly put in evidence by fig. 4; the increase of the microwave power increases dramatically the charge exchange rate and the formation of HCS ions deteriorated. At higher levels of the RF power (>600 W in our experiment) the strong increase of the charge exchange rate becomes dominant over the HCS ion production. Due to this fact the rate of HCS ion production decreases with the increase of the RF power, which is the contrary of usual behavior. The increase of contaminants' current with the power is also evident. In conclusion, for RF power up to 400 W the Ar¹⁴⁺ ion production is several times higher with the MD structure than in its absence but for higher power the increase was covered by the charge exchange rate. There was a similitude between the behaviour of the MD structure in SERSE and the KVI ECRIS. At KVI the MD structure had a poor thermal contact with the plasma chamber walls. Practically the best results with the MD (100 times more Ar¹⁶⁺) were obtained at 300 W RF power. For SERSE the situation was similar: in the case of the very thin aluminum foil (0.5 mm) the MD cylindrical structure was deformed and did not assure a good thermal contact to the plasma chamber walls. Finally, the 1 mm thickness permitted to operate but the contact was still not satisfactory; the ability of MD liner to work as electron donor was confirmed, but

technological limits to its availability for highly charged ion beam production exist.

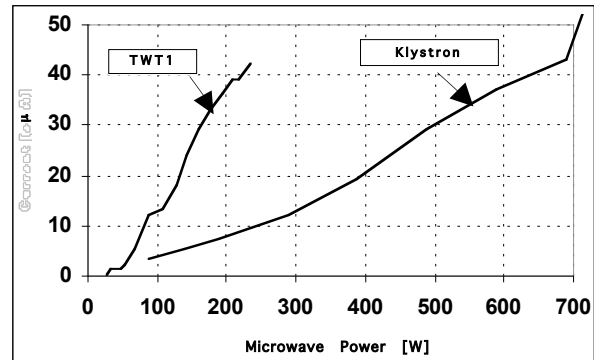


Fig. 5 – Comparison between the of O⁷⁺ current at 14 GHz for Klystron and TWT1, for increasing rf power.

3 STUDY OF THE EFFECT OF MICROWAVE INJECTION BY MEANS OF TWT

A complete set of measurements has been carried out in order to confirm the enhancement of the performances of the SERSE source, previously observed [6], when microwaves are fed by means of a TWT generator instead of the Klystron generator, which is commonly used. We observed that higher extracted currents are produced for higher charge states by using TWT at 14 GHz, while higher extracted currents for every charge state were obtained when microwaves at 18 GHz are fed into the source. A systematic series of measurements was carried out in October 2003 in such a way to have a precise comparison between the performance obtained in the two cases. The comparison regarded both the working frequencies commonly used, 14 and 18 GHz. At LNS the microwaves needed to heat the plasma electrons can be produced by five different generators (tab.1): three Klystrons, a Travelling Wave Tube, called TWT1 in the following, able to work from 8 to 18 GHz and a Travelling Wave Tube, called TWT2, with variable frequency from 13,75 to 14,5 GHz. It can be observed (fig. 5) that the current are much higher for TWT1. A complete descriptions of the tests and a preliminary analysis of the results is presented in [7], but it must be considered that further tests should be carried out in future to have a full comprehension of the phenomenon; in particular the test with TWT2 at higher power need to be repeated, because signal amplification was not excellent.

4 TRIPS EMITTANCE AND RELIABILITY

The TRasco Intense Proton Source (TRIPS) is a high intensity microwave source whose goal is the injection of a proton current of 35 mA in the following RFQ, with a rms normalized emittance lower than 0.2π mm mrad; the operating voltage is 80 kV. Its design and status are described in [8]. In 2003 the R&D was mainly focused on the emittance and reliability measurements which are described in details in [8]. Fig. 6 shows the beamline during the emittance measurements. The EMU

allows the beam species analysis and emittance measurements for the desired particle beam. It consists of a modified Wien filter placed just after a beam sampler. It accepts the whole beam at the same time and the electric and magnetic field are fixed to certain values to discriminate a species. Finally a wire measures the beamlet intensity. A polarized plate located in front of the wire minimizes the secondary electron effects. Typical emittance values were measured to be within the value of 0.2π mm mrad set by the design of the following RFQ, but even a minimum value of 0.07π was obtained. During 2003 a relevant study for the improvement of the reliability was carried out and some tests were carried out, as the one reported in fig. 7, where an excellent reliability figure of 99.8% is obtained. Finally it should be mentioned that in 2003 a bending magnet was installed to permit the correct measurements of proton fraction.

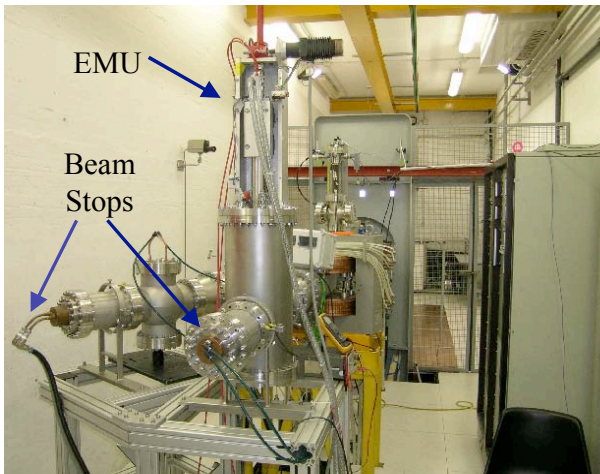


Fig. 6 - The Low Energy Beam Transfer Line with the Emittance Measurement Unit on the 0° line.

5 THE PM-TRIPS DESIGN

A full set of magnetic field measurements has been carried out to define a different design, based on permanent magnets, in order to increase the reliability of the TRIPS source. The two coils of the source generate a maximum field of 0.15 T and the optimum field was determined around 95 mT. The OPERA-3D package was used to simulate the magnetic field and a new magnetic system was designed as a combination of three rings of NdFeB magnets and soft iron.

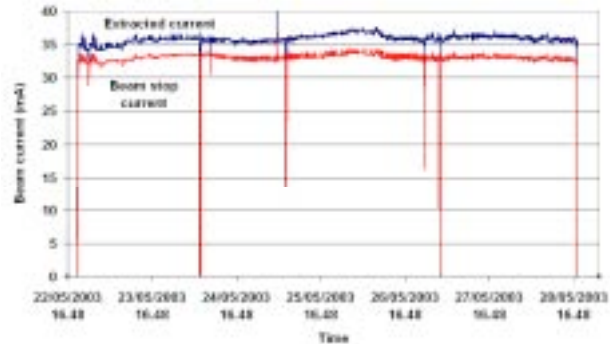


Fig. 7 - The test over 142 hours (reliability=99.8%).

With PM-TRIPS the high voltage platform and the insulating transformer will be not necessary, as the permanent magnets, the gas pipe and the waveguide line will be insulated. In this case all the devices for the remote control will be at ground potential, thus leaving at high voltage only the plasma chamber. A simpler extraction column with four electrodes instead of five was also designed to reduce the dimensions and to get a better and easier maintenance.

The OPERA code calculations of the new magnetic system made with permanent magnets featured a good agreement with the measured optimum profile (better than 3 %). The final design is shown in fig. 8 as compared with the TRIPS source.

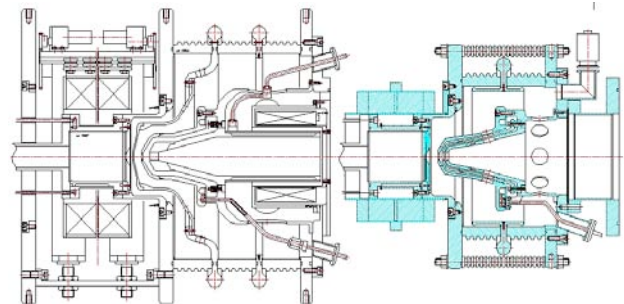


Fig. 8 - Comparison of TRIPS and PM-TRIPS.

REFERENCES

- [1] S. Gammino et al., Proc. Part. Acc. Conference, Portland (2003) 81
- [2] S. Gammino, Nukleonika 48 (2003) 73
- [3] P. Spadtke, Rev. Sci. Instr. 75 (5), (2004) 1643
- [4] S. Gammino et al., Rev. Sci. Instr. 75 (5), (2004) 1637
- [5] L. Schachter et al., Rev. Sci. Instr. 73 (2) 570 (2002)
- [6] S. Gammino, G. Ciavola, L. Celona, Nucl. Instr. & Meth. A491 (2002) 342
- [7] A. Galatà, L. Celona, G. Ciavola, F. Consoli, S. Gammino, S. Marletta, Report INFN/TC - 04/04, 19 Marzo 2004.

EFFECTS OF PROTON BEAMS ON INTACT TUMOUR CELLS EXAMINED BY MRS

S. Grande^a, P.A. Lojano^b, A.M. Luciani^a, A. Palma^a
V.I. Patti^b, L. Raffaele^b, A. Rosi^a, L.M. Valastro^b, V. Viti^{a*}, L. Guidoni^a.

a) Laboratorio di Fisica and INFN, Istituto Superiore di Sanità, Roma, Italy.

b) INFN Laboratori nazionali del Sud, Catania, Italy

**Corresponding author, e-mail: viti@iss.it*

Abstract

The effects of proton irradiation on intact MCF-7 cells have been examined by means of high resolution MRS. The increase in intensity of mobile lipid signals is observed in irradiated samples. The radiation quality affects the entity of the effects in a very sensitive way.

1 INTRODUCTION

Proton beams are believed to be more efficient than gamma rays in inducing cell death and many studies are in progress to exploit proton efficiency to provide new therapeutic modalities for some class of tumors. In the present study, the effects of proton irradiation on lipid and metabolite signals from MCF-7 cells (breast carcinoma) have been examined by means of high resolution ¹H MRS.

Cells were irradiated with proton beams of different energy. The experimental setup included measures at different Linear Energy Transfer (LET).

Spectral modifications induced by proton beams are compared with those previously observed in gamma irradiated cells. Intensities of relevant peaks were quantified after spectral deconvolution, both in intact cells and in lipid cell extracts.

2 MATERIALS AND METHODS

2.1 Sample preparation

MCF-7 cells were purchased from ATCC (Manassas, VA, USA) and kindly donated by Dr. Stefania Meschini, Istituto Superiore di Sanità, Roma (Italy). Cells were grown, as adherent cells, in RPMI 1640 medium (Hyclone, Logan, Utah) supplemented with 10% fetal calf serum (Hyclone, Logan, Utah) and 50 µg/ml gentamicin. Cells were routinely seeded in 175 cm² flasks in 50 ml medium. The medium was replaced every 72 hours.

To prepare cell samples for MRS measurements, cells were detached with a solution of 0.05% EDTA in phosphate-buffered saline (PBS), and cell suspensions centrifuged at 1200 rpm for 4 min. The pellet, suspended in phosphate-buffered saline (PBS) (approximately 20 x 10⁶ cells) was inserted in a coaxial tube system.

Sodium 3-(trimethyl-silyl) propionate 2,2,3,3-d (TMSP) 1mM in D₂O in the external compartment was used to provide a lock signal and a frequency standard.

To prepare extracts, cells were first treated with perchloric acid to obtain perchloric acid extracts. The cellular material was dissolved in deuterated water. The residual cellular material was washed, frozen and lyophilized. The samples so obtained were then treated with chloroform/methanol 2:1 to extract total lipids. The final material was suspended in deuterated 2:1 chloroform: methanol solution shortly before the MR measurements.

2.2 Irradiation

Cell systems were irradiated with the proton beam available at LNS at different depths along the 62 MeV proton beam.

A new collimator built for the housing and irradiation of the samples allows automatic movement of the flasks. Figure 1 shows the new system and Figure 2 shows the housing of the flasks with the hole for the irradiation. The irradiation, due to the automatic movement, is more precise than with the previous collimator [1] and irradiation of a larger number of flasks is now possible.

GafChromic films were applied on the surface of the flasks to control that all the cells growing adherent to the flask surface had been irradiated. With this method, we are planning to obtain in the future also dose and dose distributions.

2.3 MRS measurements

¹H MR spectra were run at 400 and 700 MHz on WB spectrometers (Bruker, AG, Darmstadt, Germany) by gated irradiating water signal. 1D and 2D COSY spectra were acquired.

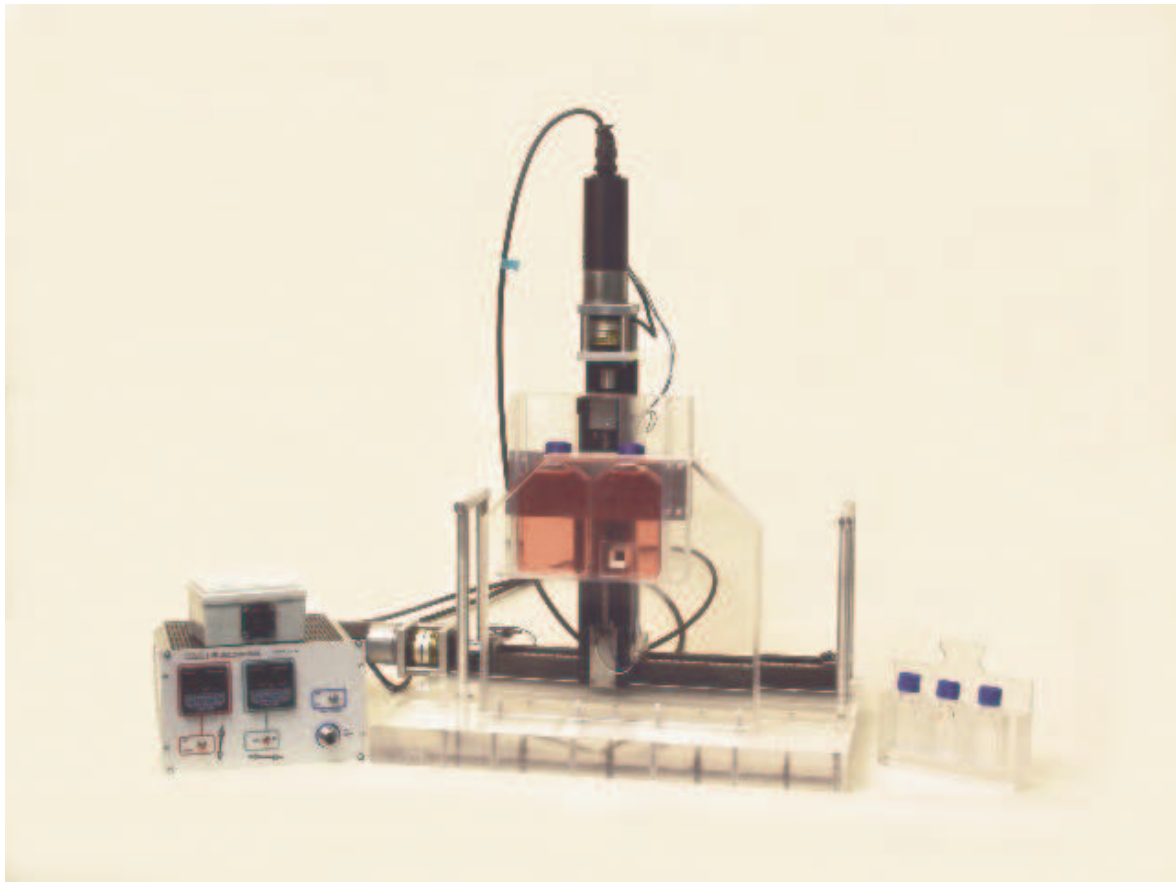


Figure 1. Collimator and flask holder.

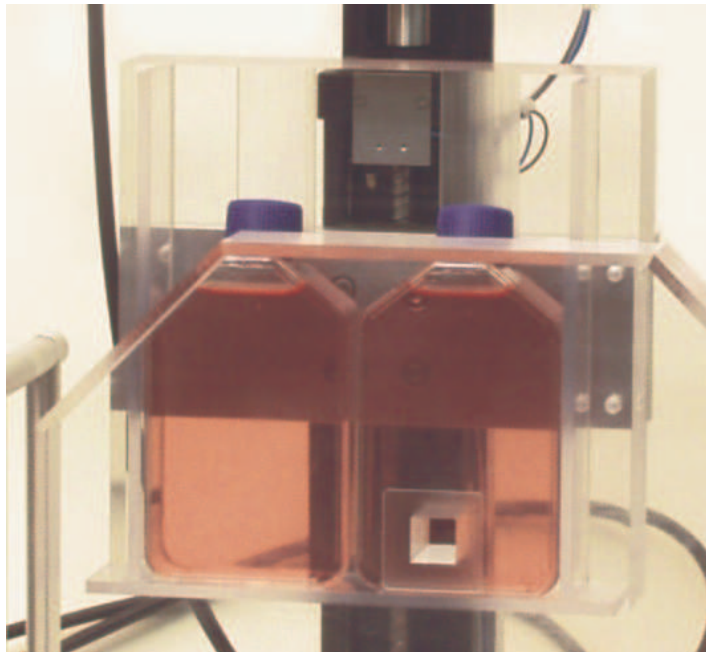


Figure 2. Flask housing and hole for irradiation.

3 RESULTS AND DISCUSSION

Figure 3 shows the ^1H 1D MR spectra of MCF-7 cell samples, run 48 hours after proton beam irradiation. Spectra are dominated by mobile lipid (ML) signals, in particular the signal from $(-\text{CH}_2)_n$ of fatty acids at 1.28 ppm in 1D and the cross peak A from the $\text{CH}_2\text{-CH}_3$ coupling of fatty acids in 2D COSY spectra (not shown).

The choline signal is also detectable in the 1D spectra, labeled as Cho in Figure 3.

The signal is resolved in the 2D COSY spectra, showing next to the intense signal from phosphocholine (PC), the glycerophosphocholine (GPC) signal. Phosphorylethanolamine (PE) and glycerophosphorylethanolamine (GPE) are also detectable (not shown).

An increase of the ML signals 48 hours after proton beam irradiation was observed (Figure 3). The macromolecule signal (M) at 0.92 ppm was taken as a chemical shift and intensity reference.

This effect was evident also in the 2D spectra where the signal A increases in intensity as reported in Table 1. Lys and Ala signals were taken as a reference for 2D.

Lipid metabolism and catabolism is strongly affected by proton irradiation, as observable from the 1D and 2D spectra. In fact, the Cho signal decreases in intensity in the irradiated with respect to the control sample (Figure 3).

On the contrary, phosphorylethanolamine and the lipid catabolite GPC and GPE signals increase with respect to the PC (Table 1). In lipid cell extracts, we observed an increase in triglycerides (TG) concentration (not shown). This observation confirms previous results [1].

Table 1: Intensity of MR signals in 1D and 2D COSY spectra

	Control	Irradiated
ML/M	7.3	9.2
A/(Lys+Ala)	3.5	5.1
Cho/M	3.1	1.9
GPC/PC	0.6	0.8
PE/PC	0.6	0.7
GPE/PC	0.5	0.8

The concomitant increase of ML signals in cells and of TG in lipid extracts reinforces the attribution of the ML signals to TG as reported in the literature. Furthermore, it is also possible to infer that the observed effects are due to changes in concentration and not in mobility of the corresponding molecules.

In a previous work [2], we observed that very intense ML and A signals when associated to low intensity PC, are characteristic of cultured cells at late confluence. The increase of ML and A and the concomitant decrease of PC signals after irradiation can be related to the presence of quiescent cells, similar to cells at late confluence. This point will be further investigated.

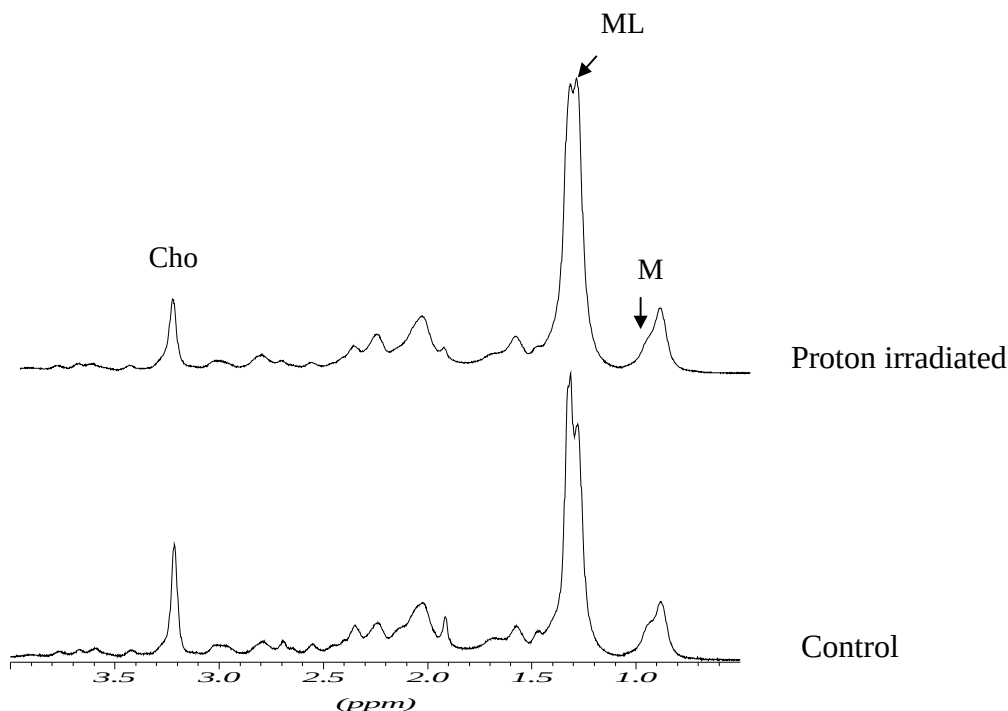


Figure 3. ^1H MR spectra of MCF-7 cells

A similar ML and TG increase was observed after gamma irradiation of MCF-7 cells. The entity of the effect observed in gamma irradiated samples seems comparable when using a considerably lower dose of protons in the region of high LET of the Bragg peak. This observation must be confirmed with experiments carried out at different energy.

As the lipid metabolites and catabolites are concerned, the effects reported in Table 1 confirms previous observation obtained in other cell systems [3] of a strong increase of catabolism in proton irradiated samples.

6 ACKNOWLEDGEMENTS

The support of drs. G. Cuttone, M.G. Sabini and P. Cirrone for the irradiation of cells with proton beams is greatly acknowledged.

7 REFERENCES

- [1] S. Grande et al. LNS-INFN Activity Report 2002, 178
- [2] A. Rosi et al. NMR Biomed 17 (2004) 76.
- [3] S. Grande et al. Int J Cancer (Radiat Oncol Invest) 96 (2001) 27.

PROVENANCE OF OBSIDIAN ARTEFACTS FROM DIFFERENT ARCHAEOLOGICAL LAYERS OF PHAISTOS AND HAGHIA TRIADA

Karydas A.¹, La Rosa V.², Militello P.², Pappalardo G.^{3,4,2,*}, Pappalardo L.^{3,5}, Rizzo F.^{3,4}, Romano F.P.^{3,5}

1. Institute of Nuclear Physics, NSCR Demokritos, Athens, Greece

2. Centro di Archeologia Cretese, University of Catania, Italy

3. Laboratori Nazionali del Sud, INFN, Catania, Italy

4. Dipartimento di Fisica e Astronomia, University of Catania, Italy

5. Sezione di Catania dell'Istituto per i Beni Archeologici e Monumentali, CNR, Italy

* Corresponding author: pappalardo@lns.infn.it

Abstract

26 obsidian artefacts from different archaeological layers (dated back from Neolithic to Middle Minoan period) of Phaistos and Haghia Triada excavation sites have been analysed by using non-destructive methods and portable instruments.

The results indicate that all the samples can be clustered into two groups.

A comparison of our data with existing ones, indicates that the two groups correspond to the Sta. Nychia and the Dhemenegaki quarries of Melos.

The obsidian artefacts corresponding to Neolithic layers were found to belong only to the Dhemenegaki quarry, those corresponding to Early Minoan (EMI, EMII, EMIIIB, EMIII) layers to the Sta. Nychia quarry (with the exception of the sample labelled Fes09) and those of Middle Minoan (MM1A/B) layers to both quarries.

1 INTRODUCTION

Twenty six obsidian artefacts from Phaistos and Haghia Triada excavations belonging to different archaeological layers (from Neolithic to Middle Minoan I) have been analysed by using non destructive methods and portable instruments.

The results indicate that all the samples can be clustered into two groups.

A comparison of our data with existing Aegean ones indicates that the two groups correspond to the Sta Nychia and the Dhemenegaki quarries of Melos.

The obsidians artefacts corresponding to Neolithic layers were found to belong only to Dhemenegaki quarry, those corresponding to Early Minoan (EMI, EMII, EMIIIB, EMIII) layers to Sta Nychia quarry (with the exception of the sample labelled fes09) and those of Middle Minoan (MM IA/B) layers to both quarries.

The measurements have been performed in Crete at the Italian Archaeological Mission of Phaistos of the Italian School of Athens directed by Prof. Emanuele Greco

2 EXPERIMENTAL METHODS

The XRF technique was used. The artefacts were placed in contact to the spectrometer head and were exposed to the X-rays emitted by a Cd-109 radioactive source. A typical energy spectrum, acquired by means of a Si (Li) detector, taken in 30 min acquisition time, is shown in fig.1.

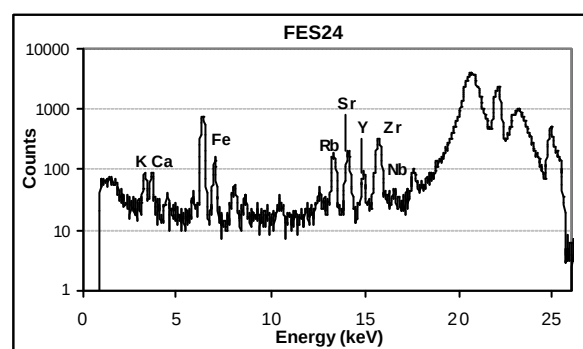


Figure 1 - Typical X-ray energy spectrum obtained by approaching an obsidian sample to the XRF spectrometer head. Trace-elements useful for the present work are well evidenced. Also Fe, Ca and K are evident.

The characteristic X-ray peaks of the trace-elements Rb, Sr, Y, Zr and Nb are clearly distinguished, whereas K, Ca and Fe are also present in the spectrum.

The well defined geometry and the stability of the X-ray beam due to the use of radioactive sources ensured a very high reproducibility of the data.

3 DATA ANALYSIS

The set of data useful for the analysis has been obtained by dividing the net counts of each trace-element peak (xi) to the sum of the counts relative to all the other peaks ($\sum xi$): this procedure minimizes the geometrical effects due to the different shape of the artefacts.

The obtained relative values were used to perform a multivariate cluster analysis by using the Ward algorithm and the square Euclidean distance. Fig.2 shows the results.

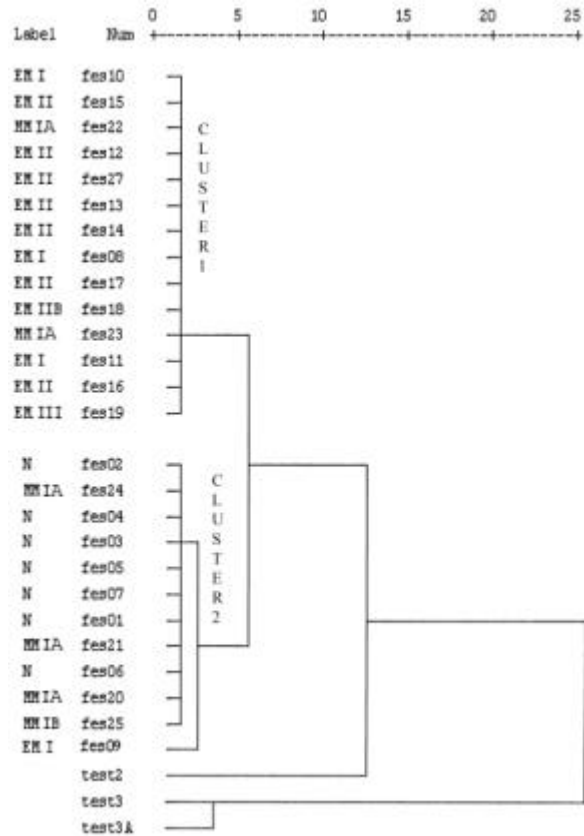


Figure 2 - The cluster analysis of the Phaistos and Haghia Triada obsidian data. The relative values of the trace-element net counts - straightforwardly extracted from the X-ray energy spectra - are used as input. Two groups are well evidenced. N, EM/I, EM/II, EM/IIB, EM/III, MM,

indicate the different stratigraphic layers (N = Neolithic, EM/I = Early Minoan I, EM/II = Early Minoan II, EM/IIB = Early Minoan IIB, EM/III= Early Minoan III, MM = Medium Minoan). The elements labelled fes10, fes08, fes11 and fes09 refer to samples from Haghia Triada excavations

All the data are scattered into two well separated groups. It is also shown as the various obsidian artefacts coming from different stratigraphic layers are distributed into the two groups.

To establish a correspondence between the two observed groups and the Aegean obsidian quarries, the absolute values of the trace elements concentrations have been determined by means of a standardization method which uses a least square fitting biparametric procedure [1][2][3][4].

The ratio Rb/Sr has been evaluated and compared to the existing data of Gale N.H. [5].

As it can be seen from fig. 3 the data of cluster 1 correspond to the STA NYCHIA Melos quarry and those of cluster 2 to the DHEMENEGAKI Melos quarry.

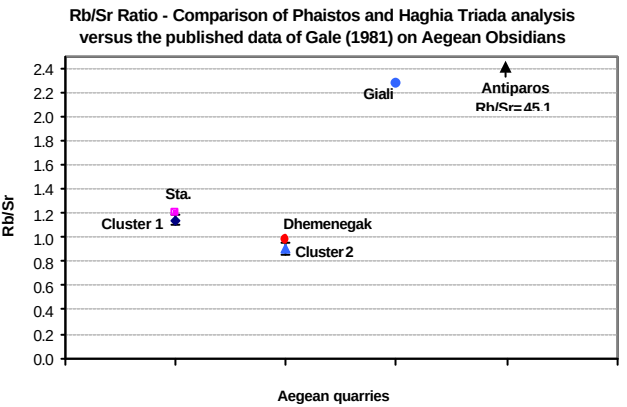


Figure 3 - Comparison of the Phaistos and Haghia Triada obsidians data with the existing Aegean quarries published data. The ratio of Rb and Sr absolute concentration determinations is reported and compared to the data from Gale 1981. Cluster1 corresponds to group I, Cluster 2 to Group II.

4 REFERENCES

[1] PAPPALARDO G., DI PIETRO A., MUSUMARRA A., PAPPALARDO L. (1994) - *Un sistema di spettrometria XRF portatile: Applicazioni nel*

settore dei beni monumentali. Boll. Acc. Gioenia Sci. Nat., Vol 27, n. 346, pp 329-340.

- [2] PAPPALARDO G., DI PIETRO A., MUSUMARRA A., PAPPALARDO L. (1995) - *Un sistema di spettrometria XRF portatile: applicazioni nella analisi di ossidiane*. Atti della V conferenza scientifica triennale del CRRNSM. Messina, 27-28 ottobre, 1994. Accademia Peloritana dei Pericolanti, Vol. LXX2, supplemento n. 1.
- [3] BARONE G., BRANDAGLIA M., PAPPALARDO L., TRISCARI M. (1996) - *Caratterizzazione di ossidiane mediante spettrometria XRF con sorgenti radioattive*. Plinius n. 16, Dicembre 96, pp. 25-27.
- [4] GIGLI R., PAPPALARDO L., PAUTASSO A., ROMANO F.P., CARASTRO A. (2002) - *Identification of a class of pottery within the votive deposit of Demetra Sanctuary in Catania by using a non destructive XRF method*, in Proceeding of 33th International Symposium on Archeometry, 22-26 April, Amsterdam, in press.
- [5] GALE N.H., 1981. *Mediterranean obsidian source characterisation by strontium isotope analysis*. Archaeometry 23, 1, 41-51.

MEASUREMENTS OF TRANSMISSIBLE CHROMOSOME ABERRATIONS IN HUMAN LYMPHOCYTES EXPOSED TO HIGH-ENERGY PROTONS AND ^{12}C IONS

L. Manti^{a,b,*}, G.A.P. Cirrone^c, G. Grossi^{a,b}, M. Durante^{a,b}, P. Lojacono^c, M. Pugliese^{a,b},
M. G. Sabini^c, P. Scamporrino^{a,b}, L. Valastro^c and G. Gialanella^{a,b}

^a Dipartimento di Scienze Fisiche, Università Federico II, Napoli, Italy

^b Istituto Nazionale di Fisica Nucleare, Sezione di Napoli, Italy

^c Laboratori Nazionali del Sud-Istituto Nazionale di Fisica Nucleare, Sezione di Catania, Italy

* Corresponding author, e-mail: manti@na.infn.it

Abstract

The transmission of radiation-induced chromosome aberrations (CAs) is relevant for cancer risk estimates since inheritable DNA damage may initiate carcinogenic alterations. CA stability depends most certainly on the aberration structure, with symmetrical exchanges being favoured over asymmetrical rearrangements, but it may be affected by other factors such as radiation quality. We therefore measured CAs induced by various LET radiations in 1st, 2nd and 3rd-generation peripheral blood lymphocytes by FISH/harlequin staining of both metaphase and prematurely condensed interphase chromosomes. The level of transmissible aberrations did not vary significantly through successive cell divisions, while the fraction of non-transmissible aberrations, which appears to be responsible for radiation-induced cell-cycle delays, decreased with time. Asymmetrical, complex type exchanges were found following both low and high LET-irradiation but were more likely to be transmitted after protons rather than ^{12}C ions.

1. INTRODUCTION

It has long been maintained that cytogenetic damage can be a biomarker for cancer induction since it is related to radiation-induced stochastic effects. There is evidence that the frequency of chromosomal aberrations (CAs) in human peripheral blood lymphocytes may reflect equivalent yields of damage in precursor cells of the carcinogenic processes in target tissues [1]. However, not all CAs can be responsible of late stochastic effects, and cancer in particular. In fact, dicentric, rings and other asymmetrical-type exchanges are non-transmissible, i.e. cells carrying these aberrations are unlikely to divide more than 1 or 2 times. On the other hand, symmetrical interchanges, such as reciprocal translocations, and possibly some classes of complex-type exchanges, are generally assumed to be transmissible, since they do not interact with the anaphase bridge and can therefore be transmitted for an unlimited number of cell cycles.

It is well known that radiation quality influences the spectrum of aberrations. It has been shown that α -particles produce a higher fraction of insertions than γ -rays, and these insertions can be transmitted through the cell cycle [2]. Time course analysis of aberrations induced by α -particles [3] or heavy ions [4, 5] demonstrate that the aberration yield increases with time, while no significant changes are observed for low-LET radiation, suggesting that heavy ion-induced

aberrant cells may be arrested by a G₂/M block [6]. However, these studies did not look at post-irradiation mitosis and, so far, the yield of specific chromosome aberrations at different cell-cycle replication rounds after exposure to high LET radiation has not been measured. Aberrations that are transmitted through the cell cycle are relevant for cancer risk estimates, as cells carrying these aberrations are genetically altered but able to propagate. Therefore, measurements of transmissible chromosomal rearrangements are necessary to provide sound risk estimates from biological dosimetry.

The goal of the present research project is to determine the transmission to 1st, 2nd and 3rd division cells, of stable chromosome aberrations in peripheral blood lymphocytes after *in vitro* exposure to ionising radiation (protons or ^{12}C ions).

2. EXPERIMENTAL PROCEDURE

Pools of healthy donors' lymphocytes from buffy coats were irradiated using the hadrontherapy-dedicated CATANA beam line at the LNS-INFN superconducting cyclotron with 0, 1, 3 and 5 Gy of 60 MeV protons, and 60 MeV/u ^{12}C ions (0, 0.5, 1 and 3 Gy), the radiation LET being 1 and 40 keV/ μm , respectively. Being routinely used for patient treatment, proton dosimetry is very accurate. ^{12}C ion beam uniformity was checked by radiochromic GAF detectors and its dosimetry was performed using a Markus ionisation chamber as well

as nuclear track-etch CR-39 detectors. Cells were stored frozen and carried to our laboratories in Naples where they were stimulated by the mitogen phytoemagglutinin to proliferate in bromodeoxyuridine (BrdU)-supplemented cell culture medium and sampled at 48, 72 and 96 hours. Chemically-condensed chromosomes were harvested as elsewhere described [7, 8]. Chromosome spreads were obtained by treating cultures separately with either colcemid (0.2 $\mu\text{g/ml}$) or calyculin A (50 ng/ml). The former arrests cells that are in mitosis while calyculin A condenses chromosomes irrespective of the cycle phase cells are in, so that aberration analysis could be performed on both metaphase (MET) and interphase (PCC) cells by specific FISH whole-chromosome probes. All symmetrical chromosome rearrangements were considered as transmissible aberrations. Non-transmissible aberrations included dicentrics, incomplete translocations and fragments. By means of an automated system for chromosome spread recognition spreads were re-visited after differential replication staining by UV quenching of BrdU-incorporating chromatids. Hence, cells previously scored for aberrations were classified as being in 1st, 2nd and 3rd mitosis or 1st, 2nd and 3rd cycle post-irradiation.

3. RESULTS AND DISCUSSION

The differential, cycle-dependent BrdU incorporation pattern in proliferating lymphocytes allowed to monitor cells' progression through the first three post-irradiation mitoses. At 72 h and 96 h the majority of cells were in 2nd and 3rd mitoses or cycles. However, the fraction of slower cells, i. e. those that were in 1st mitosis at these times, was higher in irradiated samples compared to sham-irradiated cells (data not shown). Accordingly, in irradiated samples the fraction of 1st cycle cells was greater than that of 1st mitosis cells, the magnitude of such a difference being clearly dose-dependent. Since those cells that are lagging behind in the cell cycle cannot be seen at mitosis but are detected by interphase analysis, these data agree with a dose-dependent radiation-induced delay of the cells' transit through the first post-irradiation G₂/M. We also found that 0.5 Gy of ¹²C ions were as efficient as 5 Gy of protons in slowing cells down, since these doses yielded a similar proportion of cells held in the 1st cycle. At 96 h, however, there were more 1st cycle/mitosis cells after 5 Gy of protons than after ¹²C ions, suggesting that ¹²C-irradiated cells were not only delayed but also swiftly removed from the culture.

Analysis of the fraction of aberrant cells measured at the different cycles or mitoses after proton- (Fig. 1) or ¹²C ion- (Fig. 2) irradiation showed that among the descendants of irradiated cells there were fewer aberrant cells compared to their progenitors in 1st cycle. This can be ascribed to the ablation of lethally damaged cells and the replenishment of the culture by proliferating ones. Also, the fraction of aberrant cells found at 1st mitosis was much lower than that found in 1st cycle interphase

cells and this difference was seen to persist at subsequent mitoses/cycles for protons (Fig. 1) while becoming less pronounced for ¹²C and actually disappearing at high dose (Fig. 2).

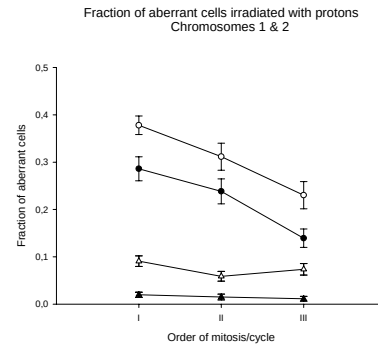


Fig. 1: Fraction of aberrant cells following proton irradiation obtained summing all cells scored as aberrant at the sampling times and grouping them according to the mitosis/cycle they were in. Circles refer to 5 Gy and triangles to 1 Gy.

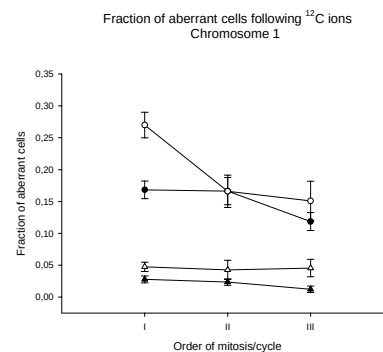


Fig. 2: Fraction of aberrant cells as a function of mitosis/cycle following ¹²C ion-irradiation. Data were calculated as described above. Circles are for 3 Gy and triangles for 0.5 Gy.

After 3 Gy of ¹²C ions many aberrant cells are not revealed by mitotic analysis if they are arrested in the 1st cycle G₂ phase. They eventually reach 1st post-irradiation mitosis but fail to progress since no significant difference was found between MET and PCC cells at later cycles. In support of the idea that such a block affects mainly cells carrying aberrations is the fact that 1st mitosis late-reaching cells showed a higher fraction of aberrant cells than those being in 1st mitosis already at 48 h (Fig. 4a). Conversely, such a fraction was constant in 1st cycle PCCs (Fig. 4b) which can be explained by considering that interphase analysis includes delayed cells.

Proton irradiation also causes cells to accumulate in the first-cycle G₂ because Fig. 1a clearly shows that the fraction of aberrant interphase cells is higher than that

of mitotic cells in 1st cycle. However, the idea that further blockades may occur prior to subsequent mitoses is consistent with the observation of more aberrant cells seen in interphase than at mitosis at all cycles (Fig. 1a). Furthermore, such delays were dose-dependent.

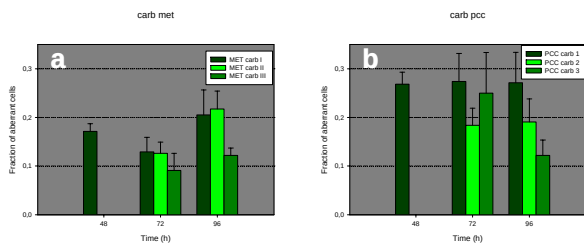


Fig. 4: Time-course of the fraction of aberrant cells found in mitosis (a) or in interphase (b) after 3 Gy of ¹²C irradiation. Data were grouped by order of mitosis/cycle: the number of aberrant cells in a given mitosis/cycle was divided by the total number of cells in the same mitosis/cycle.

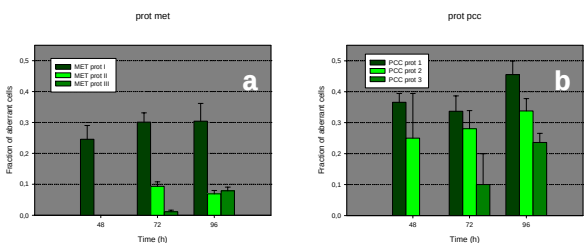


Fig. 5: Time-course for fraction of aberrant cells found in mitosis (5a) or in interphase (5b) after 5 Gy of protons. Fractions were calculated as explained above.

The fact that aberrant cells in 2nd and 3rd were more numerous at 96 h than at 72 h supports the occurrence of a similar delay also in the daughter cells (Fig. 4a). At low dose of both radiations, many aberrant cells are able to progress through cell divisions as indicated by the absence of a clear decrease in the fraction of aberrant cells in PCCs and METs (Figs. 1, 2). After 3 Gy of ¹²C ions, however, a higher proportion of 1G₂-arrested cells may have not reached 1st mitosis, as opposed to those that, by overcoming the first block, experience further delays along the 2nd cycle but eventually reach 3rd cycle.

In the case of protons, the fraction of aberrant 2nd mitosis cells decreased while that of 3rd mitosis increased (Fig. 5a), as did also 2nd and 3rd cycle cells (Fig. 5b) which agrees with the notion that many aberrant cells were cycling. After 3 Gy of ¹²C ions, fewer aberrant cells make it to the 3rd cycle than after 5 Gy of protons as suggested by comparison of data in Fig. 4b with those in Fig. 5b. Radiation-induced aberrations were divided in two categories,

transmissible and non-transmissible ones, based on the criteria mentioned earlier, and their frequency per cell was studied as a function of the order of mitosis or cycle (Fig. 6). As expected by the definition itself of transmissible aberrations, their frequency was basically constant. In mitotic and interphase cells, the frequency of non-transmissible aberrations was higher than that found for transmissible ones and readily decreased in the mitotic descendants of irradiated cells for both radiations (Fig. 6a, 6c). It appears that even low-LET radiation-induced non-transmissible aberrations are partly transmitted through cell division since their frequency does not drop to zero in 3rd cycle (Fig. 6d) but actually their decline was less sharp than that observed for ¹²C ions (Fig. 6b) as the difference between the frequency of non-transmissible aberrations and that of the transmissible-type in 3rd cycle cells was higher after protons than after ¹²C ions. The higher fraction of aberrant cells in the 1st cycle

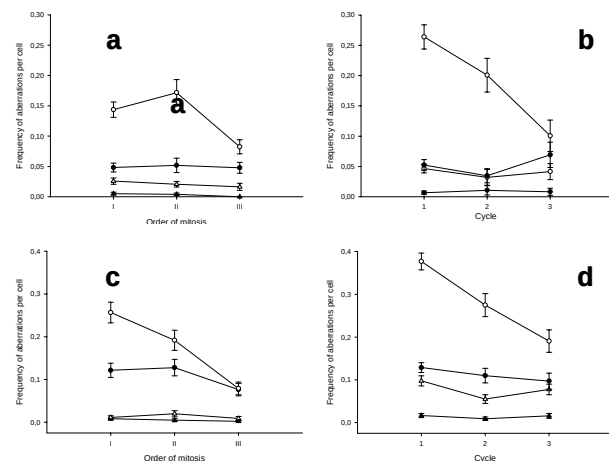


Fig. 6. Frequency of transmissible (open symbols) and non-transmissible (closed symbols) aberrations after ¹²C ions (a, b) and protons (c, d) and shown for METs (a, c) or PCCs (b, d). Circles and triangles are for high and low dose, respectively.

compared to those in 1st mitosis after 3 Gy of ¹²C ions, which reflects slower, aberrant cells (Fig. 2), is clearly accounted for by the higher frequency of non-transmissible versus transmissible aberrations (Fig. 6b). As for protons, non-transmissible aberrations did cause aberrant cells to slow down during the 1st cycle (Fig. 1) but affected their ability to proceed and further divide to a lesser extent.

Fig. 7 show the frequency of the two aberration types in metaphase and interphase cells at 72 h and 96 h. An increase with time occurred in the frequency of proton-induced non-transmissible aberrations in 2nd and 3rd cycle, while a decrease was seen in 3rd cycle following ¹²C ions. These data suggest that, at high doses, proton-

irradiated cells incur severe 1st cycle delay but cycling resumes and chromosome aberrations, even those of a complex interchange type, eventually are carried over, while ¹²C ions preferentially remove those cells that have been arrested in 1st cycle.

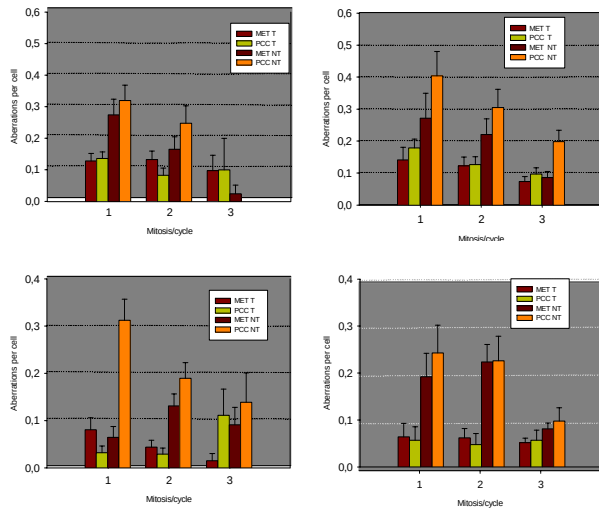


Fig. 7 Frequency of transmissible and non-transmissible aberrations induced by 5 Gy protons (top) and 3 Gy ¹²C ions (bottom) grouped by mitosis/cycle and shown at 72 h (left panel) and 96 h (right panel) post-irradiation.

Overall, our results concur with the hypothesis [9] that non-transmissible aberrations (particularly acentrics) are involved in the first post-irradiation cycle delay/arrest. Furthermore, despite slowing cells down also at later cycles, they are more likely to be transmitted through cell division after low-LET irradiation than after high-LET irradiation. Analysis of break down aberration data (not shown) indicates this be especially the case for non reciprocal, complex-type exchanges.

4. ACKNOWLEDGEMENTS

Thanks to Ms. O. Ortenzia for her contribution to chromosome aberration scoring.

5. REFERENCES

- [1] S. Bonassi, *et al.*, Cancer Res. 60 (2000), 1619.
- [2] R.M. Anderson *et al.*, Int. J. Radiat. Biol. 76 (2000) 31.
- [3] M.Durante *et al.*, Radiat. Environm. Biophys. 34 (1995) 195.
- [4] K. George *et al.*, Int. J. Radiat. Biol. 77 (2001) 175.
- [5] S. Ritter *et al.*, Int. J. Radiat. Biol. 78 (2002) 191.
- [6] M. Durante *et al.*, Radiat. Environm. Biophys. 34 (1995) 195.

[7] L. Manti *et al.*, Microgravity and Space Station Utilization, 3 (2002) 23.

[8] M.Durante *et al.*, Int. J. Radiat. Biol., 74 (1992) 457.

[9] Durante *et al.*, Radiat. Res., 151 (1999) 670-676.

A NEW FACILITY FOR HEAVY ION MICRO-LITHOGRAPHY

E. Mezzetti^{a,*}, D. Botta^a, A. Chiodoni^a, R. Gerbaldo^a, G. Ghigo^a,
L. Gozzelino^a, F. Laviano^a, B. Minetti^a, A. Rovelli^b, A. Amato^b

a) INFN Sez. Torino and Dept. of Physics, Politecnico di Torino, Torino, Italy

b) INFN Laboratori Nazionali del Sud, Catania, Italy

** Corresponding author, e-mail: enrica.mezzetti@polito.it*

Abstract

In this paper we report on an X-Y writing facility, developed and constructed at LNS, aimed at heavy ion beam micro-lithography. Micrometric patterns with different geometries are obtained by a high-precision bi-directional movement of the target system with respect to the 4.2 GeV Au ion beam, which is confined over few tens of microns. Patterns were visualized by means of polyester sheets. In order to exploit both nanostructuring effects of heavy ions across superconducting films and electrodynamics effects due to geometrical constraints on a superconducting condensate, not simply connected patterns were also drawn on YBCO films. Magneto-optical imaging was used both to further visualize the micro-patterns and to read the “writing” from the electrodynamics point of view.

1 INTRODUCTION

The high rate of development of beam particle accelerators aimed at modifying, up to nanoscale, material and tissue properties, claims extending the beam writing technology to high energy ions. Namely, they are able to act at a deeper level (i.e. on 3-dimensional targets) with respect to keV accelerators.

The central point at the present status of art consists into confining, with step by step increasing accuracy, the ion-modified regions, by means of tailored irradiation protocols.

In this paper we report on the main steps successfully performed at LNS towards an high energy microprobe (heavy ion micro-lithography), aimed at challenging

submicrometer ion writing. It will be also shown how high energy ions have the intrinsic capability to modify, at nanometric scale, the properties of functional materials. Confining lithography coupled in superconductors with nanostructuring allows to put at reaching level a not limited number of micro-devices, where, in fact, functional nanostructuring can be exploited. Thus, the microprobe writing has been checked on superconducting films and the beam confining was visualised by the induced magnetic signal of magnetic materials whose high speed micro-domains are ordered by the field distribution in the patterned superconducting films [1].

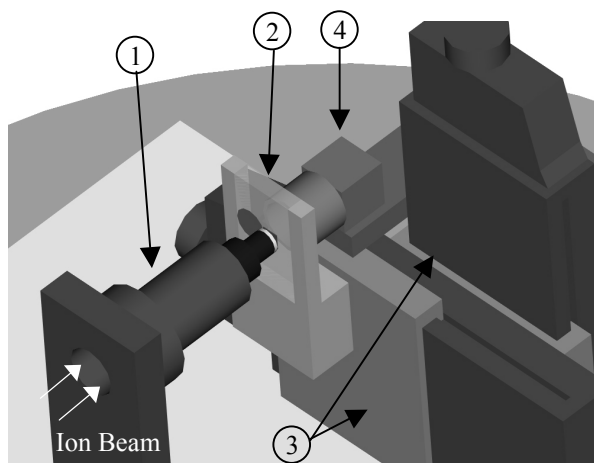


Figure 1 – Schematic drawing of the experimental apparatus of the irradiation set-up for high-energy heavy-ion lithography: (1) Faraday cup and collimator with a pinhole micrometric aperture, (2) sample holder with scintillating screen and sample, (3) linear stages, (4) CCD camera.

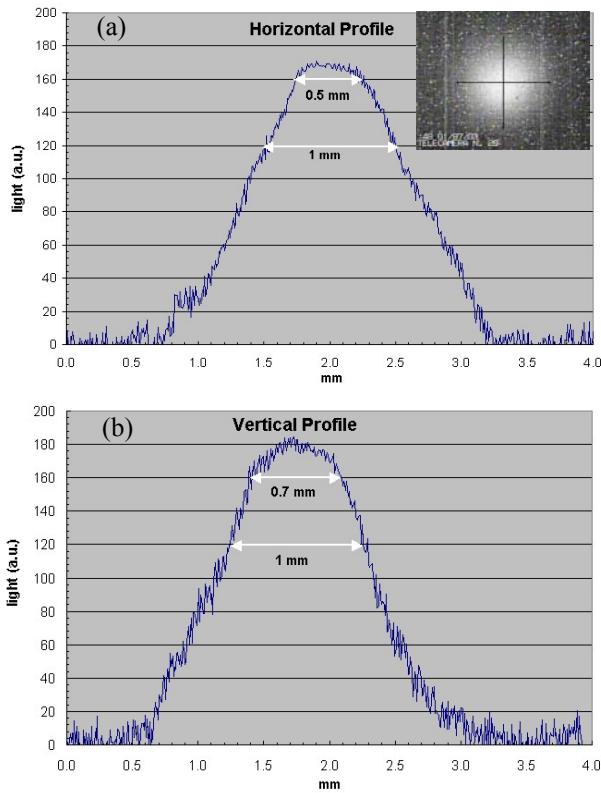


Fig. 2 - Beam spot profiles evaluated along the horizontal (a) and vertical (b) directions of movement.

2 EXPERIMENTAL SET-UP

The new irradiation apparatus has been developed and constructed at INFN Laboratori Nazionali del Sud (Catania, Italy). A schematic view of the apparatus is reported in Fig. 1.

The apparatus consists into a bi-directional target moving system, automatically driven in order to obtain local in-vacuum irradiation of micro-sized regions of samples.

The ion beam spot is confined in few tens of microns ($70\ \mu\text{m}$ at the present state of art). The ion writing is obtained by a high precision movement of the target system with respect to the ion spot. Any kind of pattern can be reproduced. These patterns include also non-simply connected geometries, not obtainable with conventional irradiation through laser-cut masks. This apparatus allows performing uniform irradiations at a given tailored dose. Moreover irradiations exhibiting smooth or sharp dose profiles are also allowed [4].

In particular, once defined the irradiation typology (constant or variable dose), the single step of movement and the origin of the coordinate system, the chosen pattern can be written by loading in the control software an ASCII file containing the (X,Y) coordinates of the points defining the desired geometry. The bi-directional

movement in the plane perpendicular to the ion beam direction is allowed by two cross-mounted MICOS Linear Stage LS-110. Each stage has an optical encoder that, once connected to the motor controller electronics MICOS SMC Taurus, allows a movement with a resolution of $15\ \text{nm}$ over a total length of $28\ \text{mm}$. The sample (to be patterned) together with a scintillating screen, used in the beam calibration procedure, are positioned on a suited transparent holder (lead-glass $8\ \text{mm}$ thick) fixed to the moving system. It can be viewed through a CCD camera from the opposite side of the glass. The ion beam is tuned in order to obtain a centred circular spot of small dimensions and a good homogeneity in the central region. Fig. 2 shows the result of this calibration: we obtained a circular beam spot of about $2\ \text{mm}$ with a good central homogeneity (better than 5% over $0.5\ \text{mm}$). The ion beam is then guided through a special Faraday cup that ends with a changeable stainless steel disk with pinhole aperture. The pinhole diameter defines the beam spot size and it is chosen accordingly to the irradiation requirements.

A dedicated electronic acquisition system was developed in order to measure the integrated ion beam current (dose). This system, originally developed in the framework of the INFN-LASCAR project [2,3], has been upgraded for the heavy ion micro-lithography. It is connected to the Faraday cup and consists of a current to frequency converter that allows the beam charge integration with a resolution of $1\ \text{pC/pulse}$. The target stands in a given (X,Y) position until a preset charge value is reached; then, the control program reads the following couple of (X,Y) coordinates and the linear stages move in the new position.

3 PATTERN VISUALISATION

Patterns with different geometries were created by means of $4.2\ \text{GeV}$ gold ions over heavy-ion beam-sensitive polyester sheets. The patterns corresponding to the map of the ion dose distributions on these irradiated sheets was evaluated by the local value of the darkening level (Fig. 3 (a)-(d)). A representative irradiation-dose profile across a side of a square perimeter drawn on these sensitive sheets is reported in Fig. 3(e). Due to the collimator shape (pinhole), the irradiation dose profile shows a bell-shape with a small plateau in the central part where the dose is maximum.

4 TEST ON SUPERCONDUCTING FILMS

The ion beam lithography facility has been checked on high-temperature superconducting materials. YBCO films with thickness ranging from 200 to $500\ \text{nm}$ and grown by means of thermal co-evaporation technique on yttria stabilized zirconia (YSZ) substrate, with a CeO_2 buffer layer, were patterned by means of $4.2\ \text{GeV}$

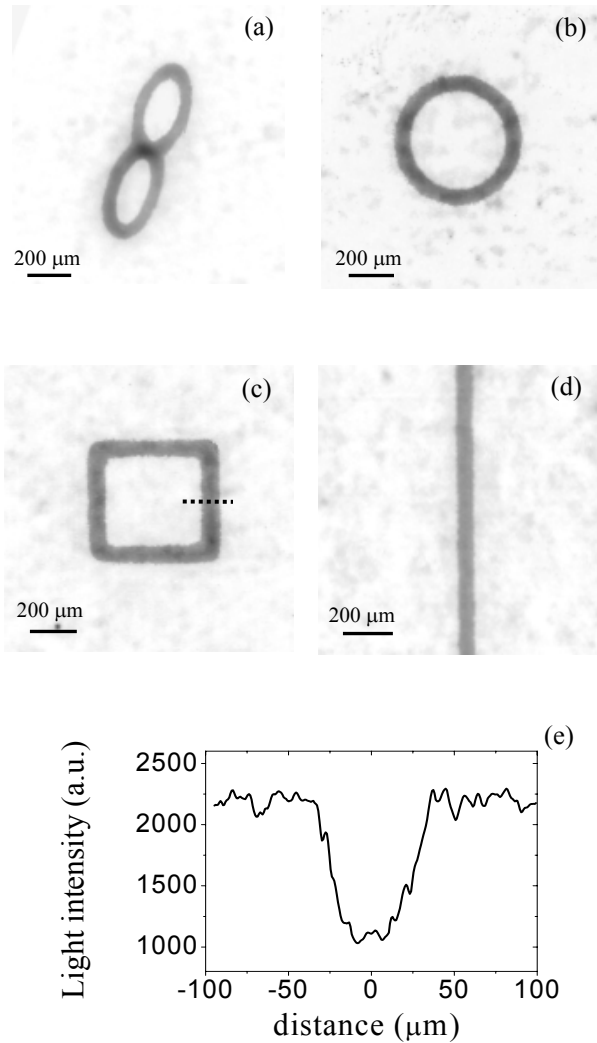


Figure 3 – (a)-(d) Optical image of polyester sheets micro-patterned following different geometries; (e) beam profile distribution along the dotted line of fig. (c). The spikes in the curves are due to the granularity of the polyester sheet surface.

gold ions beam that, as estimated by means of a TRIM code simulation, produce nanosized columnar defects in these superconducting films and implant in the substrate at about 110 μm of depth. The ion fluences was 10^{11} Au-ions/ cm^2 .

TEM (Transmission Electron Microscopy) analysis was performed on a twin sample, irradiated in the same conditions. The planar view of the sample surface in Fig. 4 displays the damage produced by heavy ions crossing the film. We note that extrinsic defects are insulating columns with a diameter of a few nanometers and that they are surrounded by an amorphous zone caused by the heavy ion collision too.

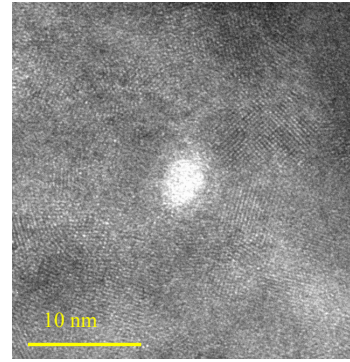


Figure 4 – High-resolution TEM image of a [001] planar view of the YBCO surface with a columnar defect (white area) produced by the Au ion irradiation. The column is surrounded by an amorphous region, which results in enlarged and inhomogeneous defected zone.

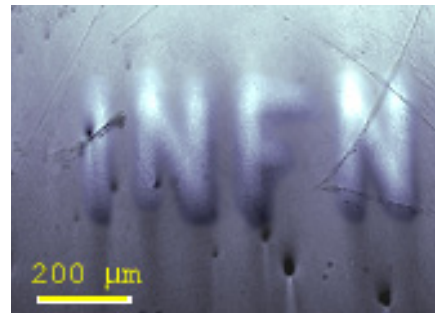


Figure 5 – Magneto-optical image of a patterned YBCO sample. The image was taken at T 35 K after a field cooling in a field of 80 mT. *Brighter regions: higher magnetic flux density zones, darker regions: lower magnetic flux density zones.*

To visualize the patterned regions into superconducting films, whose signature is the induced modulation of the magnetic field, magneto-optical analysis was performed on the irradiated samples. The magneto-optical signal is obtained by coupling the superconductor with a ferromagnetic film whose domain orientation is decorated by the superconducting electro dynamical signal. The change of the domain orientation is read as a rotation of a monochromatic light polarization plane [1].

A first example of patterning is reported in Fig. 5. In Figs. 6 and 7 other different geometries (“infinity”, rings, spiral and rectangular strip with transverse channel), observed by magneto-optical analysis, are reported. Particularly suited for short-term device application is the configuration reported in Fig. 7. In this configuration the transport of the Meissner current along the superconducting strip can be modulated in space and time across the irradiated transversal channel.

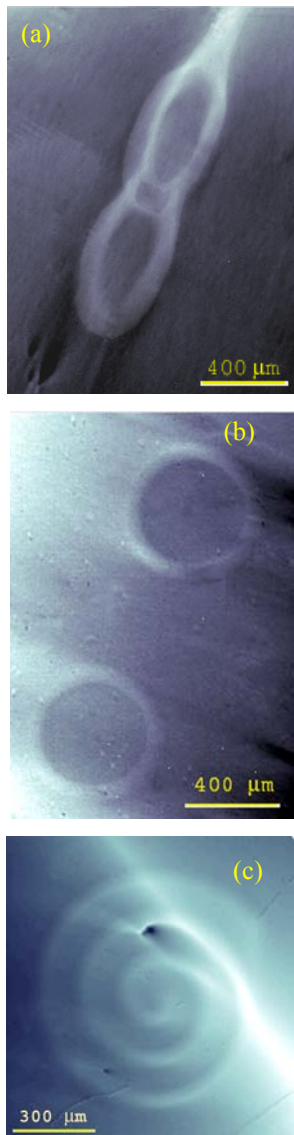


Figure 6 - Magneto-optical images of patterned YBCO samples with different geometries (a) “infinity”, (b) rings, (c) spiral. The images were taken at $T = 50$ K after a field cooling in a field of 80 mT. Brighter colours: higher magnetic flux density regions, darker colours: lower magnetic flux density regions.

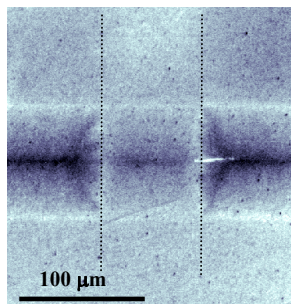


Figure 7 - Magneto-optical images of a rectangular strip patterned YBCO samples with a transversal channel in to the central region. The image was taken at $T = 70$ K and in a applied field of 5 mT. The critical temperature is 88 K. Brighter colours correspond to higher magnetic flux density regions, the black zones inside the sample correspond to regions where the shielding Meissner currents flow.

5 CONCLUSIONS

An X-Y writing facility aimed at heavy ion beam micro-lithography development has been projected and checked on polyester sheets as well as on high temperature superconducting YBCO films. For the first time at our best knowledge, the possibility to control at micrometric and sub-micrometric scale the two-dimensional movement of a confined heavy-ion beam was successfully exploited. The (X,Y) writing input coordinates, known with a resolution of 15 nm, are transferred to an integrated-charge counter that, once a pre-selected charge (dose) value is reached, drives step by step a bi-directional moving frame (a 10 microns single step was chosen). The programmed ion dose is guided through a stainless steel collimator with a pinhole aperture (70 microns in diameter at the present status of art) towards the in-vacuum moving target. A magneto-optical check has been performed by coupling a “written” superconducting film with magnetic iron garnets nicely decorated by the superconducting magnetic flux lines. Different micrometric patterns profiles have been analyzed. The tool opens new possibilities for creating micro-patterns inside super/semi conducting heterostructures. Thus micro-sized high-speed device layouts, based on the electrodynamics behavior of such confined, not simply connected, nanostructured architectures, are under study.

6 ACKNOWLEDGEMENTS

This work was accomplished under INFN-NASTRI project.

We gratefully acknowledge substantial technical assistance in irradiation from the INFN-LNS staff.

7 REFERENCES

- [1] F. Laviano, D. Botta, A. Chiodoni, R. Gerbaldo, G. Ghigo, L. Gozzelino, E. Mezzetti, and S. Zannella - *Supercond. Sci. Technol.* **16** (2003), pp. 71-79.
- [2] A. Rovelli, A. Amato, D. Botta, A. Chiodoni, R. Gerbaldo, G. Ghigo, L. Gozzelino, F. Laviano, B. Minetti, E. Mezzetti, L. Martini, F. Curcio - *International Journal of Modern Physics B* **17**, (2003) pp 727-733.
- [3] R. Gerbaldo, D. Botta, A. Chiodoni, G. Ghigo, L. Gozzelino, F. Laviano, B. Minetti, E. Mezzetti, A. Rovelli, A. Amato, L. Martini, F. Curcio - *IEEE Transactions on Applied Superconductivity* **13** (2003), pp. 3000-3003.
- [4] G. Ghigo, D. Botta, A. Chiodoni, R. Gerbaldo, L. Gozzelino, F. Laviano, B. Minetti, and E. Mezzetti, D. Andreone - *Supercond. Sci. Technol.*, in press

ACTIVITY REPORT OF DEVICES DESIGN GROUP

S. Passarello, F. Caruso, G. De Luca, G. Gallo, A. Grmek, G. Manno, F. Musarra, E. Zappalà, M. Maggiore.

INFN Laboratori Nazionali del Sud, Catania, Italy

Abstract

The devices design group's activity is presented; its aim is to design and develop sophisticated devices both of accelerator machines and experimental devices for physics with accelerators, servomechanism, remote handling, working in radioactive or high-risk contaminated areas, and to design and develop ion sources

1. NEW SHORT CIRCUITS FOR THE RF CAVITIES OF THE SUPERCONDUCTING CYCLOTRON

The cyclotron has 6 rf cavities, 3 above and 3 below the median plane, which must be regulated in frequency through sliding short circuits. They have linear movements based on trapezoidal standard screws; the frequent use due to changes of cyclotron frequency for different experiments damaged heavily the system which often blocks. We have redesigned the system with new special ball screws that will permit to get rid of the existing problem.

A complete analysis of the problems linked to the ball screws has been carried out and we are confident that this solution does not present any inconvenient, as an accurate study of materials was carried out with the 3D code OPERA and an adequate pre-charge of the spring was calculated.

1.1 Materials' study

The material of the special screws cannot be diamagnetic and then the influence on the cyclotron magnetic field must be considered. The force and torque acting on a twin group of nine bars iron made, symmetrically positioned respect to the median plane, at the top and the bottom of the machine, embedding into the fringing magnetic field of the Superconducting Cyclotron operating in Catania, have been calculated by 3D code OPERA [1]. Three dimensional finite elements method provides an accurate approach to this kind of calculation by the Maxwell stress tensor method [2]. The Maxwell stress tensor method calculates the torque or force directly from the magnetic field distribution by adding up the torque or force density over a surface related to the part of interest, in our case the iron bar surfaces. Since the magnetic flux is stronger near the cyclotron, the maximum value of the forces should be done when the position of the bars is closer to the accelerator (see fig. 1). Due the configuration of the magnetic field, the predominant components of the forces will be axial or radial, depending on the bars positioning (see fig. 2). From the simulations, we found that the radial component varies from 1.5 N/m near the cyclotron, up to 0.2 N/m along the bar's length. The total maximum strength of radial component is 56 N. The action point of the torque

calculated is localized on the bar at c.ca 435-440 cm respect to the median plane of the cyclotron.

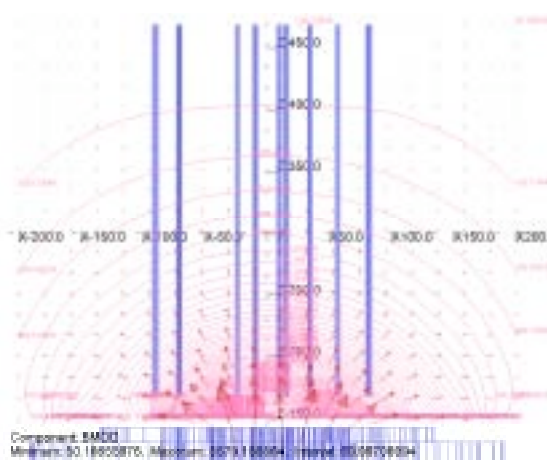


Fig.1-Magnetic field iso-lines embedding screws on the top of the cyclotron

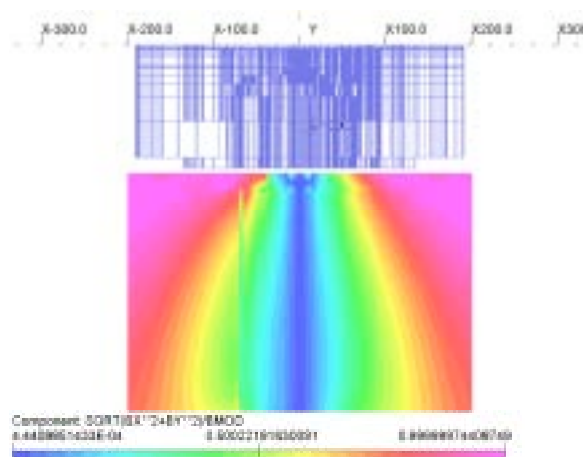


Fig.2- Distribution of the radial component (red) of magnetic field respect to the axial one (blu) outside the cyclotron

1.2 Precharge of the ball screws

The high quality factor (95%) of these systems is expected to create problems with unwanted movements as the weight of the cavities may generate risks if the chains would be broken. Because of that, we inserted a

regulated pre-charge system that increase the friction so that the risks are minimized.

If we consider a total weight of 3000 N for the movable parts, a screw quality factor of 0.9 and a screw pitch of 5 mm, the requested torque is:

$$T = \frac{F \cdot ph}{2000 \cdot \pi \cdot \mu_p} = \frac{3000 \cdot 5}{2000 \cdot \pi \cdot 0,9} \approx 2,65 N \cdot m$$

2. NEW ELECTROSTATIC DEFLECTORS FOR HIGH POWER BEAMS FOR SUPERCONDUCTING CYCLOTRON

The extraction of high intensity beams have required to completely redesign the electrostatic deflectors.

2.1 Housing

The new deflector housing is composed by three parts (see fig.3), as the liners are separated and are screwed to the body ; we have changed material of housing from AISI 304 to OFHC copper. E1 deflector is designed with slots to contain water-cooling circuits while for E2 deflector it was impossible to cool because accelerator has no location for water feedthrough. New design allow to increase thermal exchange, so that it permits now to dissipate power up to 500 W and its assembling and replacing are easier than before.



Fig. 3- E2 deflector housing

2.2 Electrodes

We have changed old titanium electrodes with new hard-anodized aluminum electrodes (see fig.4); this treatment was used on K 1200 Michigan deflectors and we achieved very good results by following the same procedure.



Fig.4- New aluminum electrode hard-anodized

2.3 Electrode insulators

We replaced Macor insulator for electrodes with new alumina 99.8% insulator with stainless steel brazed cups, in order to have longer duration and to minimize conditioning time.

2.4 100 kV feedthrough

Old plastic high voltage feedthrough couldn't dissipate high power and a new feedthrough had to be realized. It is composed by copper cup brazed on ceramic insulator tube (see fig.5). Ceramic tube contains high voltage cable and a N₂ gas tube for cooling. Copper cup is pushed on the electrode by the force originated by different pressure on bellows and a good electrical contact is then insured. This feedthrough is movable following all the deflector movements and a welded bellows allows such a movement. We perceived that forces for different pressure could even get to about 200 N and this large value may cause several kind of accidents, thus an automatic device was developed to keep always the force on the electrode below 50 N.

This pneumatic device is controlled by the console and electronic hardware and software to control pressure regulator and diagnostics sensors were developed and built on our own.

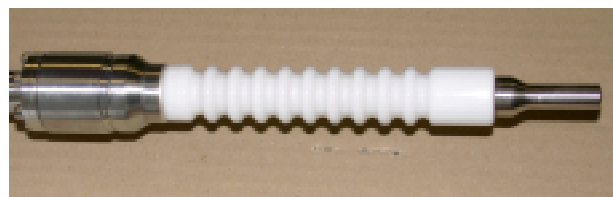


Fig. 5-Ceramic feedthrough

2.5 Water feedthrough

The new E1 deflector is water cooled to be able to extract beam power up to 500 W. The old design of deflector was completely modified in order to place water cooling tube. The development of a dedicated water feedthrough was requested and we realized 12 mm coaxial tube (see fig.6) with a double seal connection (see fig.7) movable by automatic remotized device (similar to high voltage feedthrough). This system permits to the deflector to move according to the different extraction beam trajectories. The main procedure consists of the connection of feedthrough and

housing, which should be made carefully to avoid O-Ring damage. Is impossible to control this operation and only the value of vacuum into the acceleration chamber give us information about the achieved connection.



Fig. 6-water feedthrough



Fig. 7-water feedthrough

2.6 Dismounting and replacing

When the high intensity beams will be routinely provided by the cyclotron the radioactivity levels of the accelerator won't allow us to replace the deflectors and a dismounting dedicated device is requested for such a job. We had to modify the deflector movement systems (see fig.8); it permits now that all movement connections could be automatically disconnected. Rotary drive feedthroughs permits to dismount the connection from deflector housing coming from the outer part of the cyclotron; so the deflector is based over the median plane of the accelerator and an automatic device can collect it.

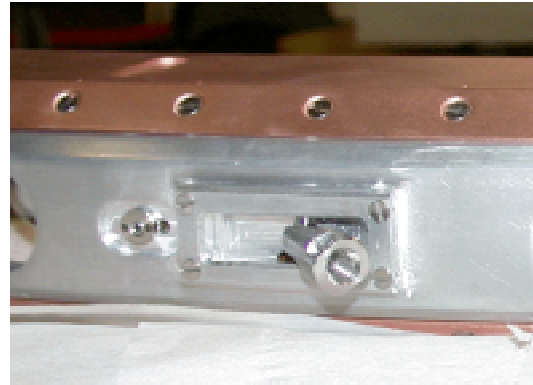


Fig. 8-A view of the 'hook' connection

2.7 Septum

The new septum is not screwed, but it moves into a groove, to help us in maintenance and control operations. A V-notch (see fig.9) was realized, situated in the entrance of the beam, to improve the power dissipation.



Fig. 9- New V-notch septum

2.8 Conclusion and future plan

In October 2003 the new deflectors were tested inside the cyclotron with fully operational conditions and a 100 W power beam was successfully extracted (fig.10). A new E1 deflector with an improved cooling circuit is under study in order to increase the amount of power that can be safely managed.

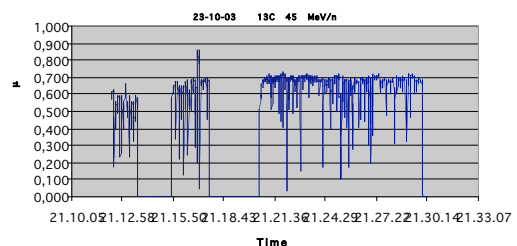


Fig.10-13C (45MeV/n) extracted beam

3 NEW CURRENT PROBES FOR THE HIGH INTENSITY BEAMS FOR THE SUPERCONDUCTING CYCLOTRON

The high intensity beam extraction requires the readout of the beam current at the entrance of the E1 deflector. There is only an aperture that permits the probe installation in that point, the old current probe tube located at 12° in the median plane; as the movement system already placed is not adequate for the easy dismantling, we had to replace it with a linear table with ball screw and linear ball bearings (see fig. 11), so that a total drift of 1200 mm is allowed by means of eight soldered bellows, guided by the linear table as well. All the movement system is not anymore under vacuum, which makes easier the dismantling and higher the reliability.

The probe is made of OFHC copper and insulated through a aluminum nitride plate, in order to improve the thermal exchange. The watercooled probe is requested to withstand a beam power up to 500 W. The probe head is thicker than before as it should adapt to high energy light ions range, as required by the EXCYT project, and must also permit an effective thermal exchange.



Fig. 11- Movement system probe 12°

The readout of the beam current at the exit of the deflectors is essential to know the extraction efficiency and to estimate the power released on the deflectors. A watercooled probe (see fig.12) was installed in the cyclotron aperture named M2 so that the current can be read inside the Cyclotron extraction channel.



Fig. 12-Water-cooled probe M2

The probe structure is quite similar to the previous one but the movement system is much simpler as the drift is just 150 mm.

4 COOLING SYSTEM FOR DIAGNOSTIC

The cyclotron upgrading for high power beams requires to design watercooled diagnostics, so that we plan to review the magnetic channels; the water used to cool the diagnostics devices is coming from one dedicated rack (see fig.13) with six reservoirs (one per each device), so that we can avoid that the vacuum chamber of the cyclotron could be filled of water in case of accidents. Each reservoir uses three level gauges, one for normal behavior, one for shortage, the other for water excess due to the accident. An additional temperature probe is used. A digital flowmeter gives an alarm if the flow is lower than a set point, that could create dangerous overheating for the accelerator. Each circuit has a pressure valve that allows a fine tuning of the hydraulic circuitry in terms of speed and flow of the cooling water, as different diagnostics devices have different request. A PT100 gauge is used for any device, to know the water temperature at the exit of the cyclotron, so that we can estimate where the beam hits the device itself. A pressurized air circuit allows also to fill out the water circuits, in order to dismount the diagnostics, and to avoid water falling on the cyclotron chamber. All the controls and interlocks are managed by a modular PLC by a RS232-optics fiber converter, that is linked to the cyclotron console (see fig.14), from which all parameters are monitored and the alarms are put in evidence.



Fig. 13-Cooling rack for diagnostic devices

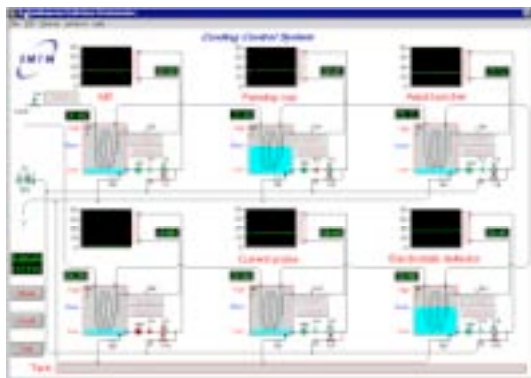


Fig. 14-Cooling control panel on console

5 NEW PERMANENT MAGNET ECR ION SOURCE FOR ADS PROJECT

The ADS (Accelerator Driven System) project requires a high power proton beam (1 GeV-30 mA) with high stability and reliability. A new source has been designed on the basis of the experience gained with the 2.45 GHz TRIPS source [3], in order to increase the long-term reliability from 99.8% to 100%. The permanent magnet source PM-TRIPS [4] (see fig.16) was designed with a few important changes with respect to TRIPS:

- a new magnetic system with NeFeB of VACODYM 745HR type.
- Compact acceleration column.
- Four electrodes extraction system to simplify the mounting/dismounting and maintenance operations..
- Redesign of the high voltage platform (see fig.15), with compact high voltage shielding and source-beamline alignment systems, in order to have a simple and reliable setup.

The construction, assembly and tests will be carried out at LNS in 2004, then the source will be transferred and installed at LNL during 2005.

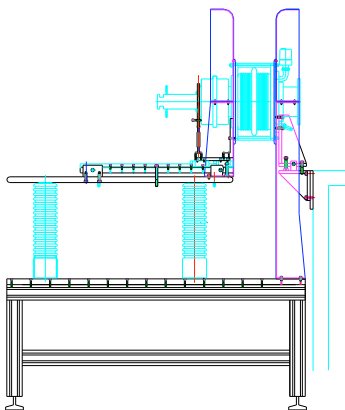


Fig. 15- Schematic view of PM-TRIPS platform



Fig. 16- 3D view of PM-TRIPS source

6 ACTIVITY FOR THE EXCYT PROJECT

The devices' design group has designed a lot of special systems for the EXCYT project in the previous years; in particular in 2003 some of them were installed on the preseparator and in the 1st stage of the mass separator. The support of the group during the assembly was mandatory, as many of the devices require particular care in the positioning and alignment. The most relevant and delicate devices that were installed in 2003 were the electrostatic quadrupoles quadruplet (see fig.17), the electrostatic multipoles and the electrostatic steerers. Their design was done by using adequate materials and by taking into account the presence of radiation. A full description is given in [4].



Fig. 17- Electrostatic quadrupole

In 2003 we also designed and built the horizontal and vertical slits (see fig.18), new Faraday cups (see fig.19) and fully automatized beam viewers (see fig.20) that allows to measure the shape and size of the beam.



Fig 18-Horizontal and vertical slit



Fig. 19- Faraday cup



Fig. 20- Beam viewers

REFERENCES

- [1] Opera 3D Vector Fields Limited, oxford (UK)
- [2] Opera 3D Reference Manual p.4-70, Vector Fields, Oxford (UK)
- [3] L. Celona et. al, Rev. Sci. Instrum. 75(5), 2004, 1423
- [4] G. Ciavola et. al, Rev. Sci. Instrum. 75(5), 2004, 1453

CELL CYCLE PHASE REDISTRIBUTION AND APOPTOSIS OF HTB140 MELANOMA CELLS EXPOSED TO 62 MeV PROTONS

A. Ristić-Fira^{a*}, I Petrović^a, D. Todorović^a, L. Valastro^b, P. Cirrone^b, G. Cuttone^b

a) Vinca Institute of Nuclear Sciences, P.O.Box 522, 11001 Belgrade, Serbia and Montenegro

b) Istituto Nazionale di Fisica Nucleare, LNS, 95100 Catania, Italy

** Corresponding author, e-mail: aristic@vin.bg.ac.yu*

Abstract

The objective of this study was to determine whether apoptosis and cell cycle redistribution were influenced by high-LET irradiation. Exponentially growing HTB140 cells were exposed to an unmodulated 62 MeV proton beam, within the Bragg peak, delivered over the single dose range from 8 Gy to 24 Gy. At 6 h postirradiation, there was a low level of early apoptosis. At 48 h irradiated cells were more damaged, showing the increase in number of apoptotic nuclei. The dose dependent cell cycle phase distribution was detected at 48 h postirradiation. The cell population exhibited phase redistribution toward G2/M phase.

1 Introduction

Ionizing radiation is a very effective mean of killing tumour cells. A great deal of attention is focused on understanding the key molecular pathways that modulate the survival of tumour cells exposed to radiotherapy. Over the last decades, efforts have been dedicated on studies of the molecular mechanisms involved in the cell cycle regulation and cell death.

The basic task of the cell cycle is to provide a faithful DNA replication during S phase and equal distribution to two daughter cells during M phase. The recent expansion of molecular biology provided us with new informations about cell cycle checkpoints, moments when cells temporarily arrest after exposure to DNA damaging agents such as ionizing radiation. The process of malignant transformation includes deregulation of normal cell cycle controls. Due to specific gene mutations, cancer cells fail to respond to normal homeostatic signals. Mutational losses of cell cycle control genes (such as p53) are common in transformed cell lines and also found in primary human cancers. The response of malignant cells to DNA damage induced by ionizing radiation or drugs may be unlike to that observed in normal cells. When normal tissues are exposed to DNA damaging agents, p53 is activated and cells subsequently arrest in G1. After exposure to ionizing radiation, DNA repair and apoptosis are also induced in normal (wt p53) cells. However, most tumour cells lack functional p53. These cells, containing mutant or no p53, should be more radioresistant than their p53 wild-type (wt) counterparts. The most commonly seen cell cycle perturbation observed when such tumour cells are treated with radiation is a delay in the transition from G2 to M phase [1].

The ability of radiation to induce apoptosis is detected in many cell types. However, there are cells which are resistant to radiation induced apoptosis, and they die by radiation induced necrosis or enter a terminal cell cycle

arrest [2]. Literature data have shown that malignant melanomas have been increasingly analyzed in recent years. Although this is a very malignant and highly metastatic tumour, with poor prognosis, some forms of melanoma specially localized, such as uveal melanoma and other eye tumours are treated with good results [3, 4].

Knowing that some forms of melanoma are successfully cured using proton irradiation, there is a great interest to investigate the effects of protons on different human melanoma cell lines. The effects of irradiation within the Bragg peak of an unmodulated 62 MeV proton beam on HTB140 cells regarding the induction of apoptosis and cell cycle phase redistribution are given in this study.

2 Materials and methods

2.1 Cell culture and irradiation conditions

Human HTB140 melanoma cells were maintained and irradiated under the same conditions already described elsewhere [5]. Exponentially growing cells were irradiated within the Bragg peak of an unmodulated 62 MeV proton beam, delivering to the cells doses from 8 to 24 Gy, at the dose rate of 15 Gy/min.

2.2 DNA isolation and agarose gel electrophoresis

DNA was extracted from irradiated cells after 6 or 48 hours of post-irradiation incubation under standard conditions, according to Armstrong and co-workers [6]. Briefly, approximately 10^7 cells, collected from 6 tissue culture dishes (Nunc, 35x10 mm) were harvested, washed in TBS buffer (150 mM NaCl, 10 mM TRIS-HCl, pH 8.0) and centrifuged at $15300 \times g$ (Eppendorf centrifuge) for 5 min. Cells were lysed by adding the digestion buffer (100 mM NaCl, 25 mM EDTA, 10 mM TRIS-HCl, 0.5 % SDS and 0.5 mg/ml RNase A). After incubation at 55 °C for 2 hours, the homogenate was treated with proteinase K (0.6 mg/mL) and incubated over night at 55 °C. DNA was extracted with phenol-chloroform-isoamyl alcohol (25:24:1) three times, and

precipitated by the addition of 1/10 volume 7.5 M of ammonium acetate and 1 volume of isopropanol. The precipitate was additionally incubated for 4 hours at 4 °C and then centrifuged at 15300 x g for 15 minutes. DNA was resuspended in 50 µl TE buffer (10 mM TRIS, 1 mM EDTA, pH 8.0). Concentration of DNA was determined by measuring UV absorbance at the wavelength of 260 nm. DNA samples (20 µg/line) were electrophoretically separated on 2 % agarose gel (Gibco BRL) containing ethidium bromide (1 µg/ml) in 1xTBE running buffer. Samples were mixed with a sample buffer (30 % glycerol in 1x TBE). Molecular weight marker, a 100 bp DNA Ladder (Gibco BRL) was used. The gel was run for 5 minutes at 150 V and 55 minutes at 100 V. DNA profiles were analyzed using Multi – Analyst/PC Software Image Analysis System (Gel Doc 1000, BioRad).

2.3 Flow cytometric analysis

Approximately 1×10^6 cultured cells were used to analyse the cell cycle and apoptosis. Assays were performed using Annexin-V-Fluos kit (Boehringer, Mannheim, Germany), according to the manufacturer's protocol. Cells were harvested from tissue culture plates, centrifuged at 660 x g for 5 minutes at room temperature and after removing the medium cells were washed once in PBS. Cells were then resuspended in 0.1 ml of Annexin-V-Fluos labelling solution. Samples were incubated at room temperature for 10-15 minutes, in tubes covered with aluminum foil. Finally, 0.4 ml of incubation buffer (5 mM CaCl₂, 140 mM NaCl, 10 mM HEPES/NaOH pH 7.4) was added. Propidium iodide (PI) was added 5 minutes prior to flow cytometric analysis (final concentration 1 µg/ml). Samples were filtered through nylon mesh and analyzed by flow cytometry (Becton Dickenson, Heidelberg, Germany). Apoptotic population was calculated using CellQuest computer program (Becton Dickenson, Heidelberg, Germany).

2.4 Agarose gel processing

DNA profiles obtained on agarose gel electrophoresis were analyzed using Multi – Analyst / PC Software Imaging System (Bio Rad).

2.5 Statistical analysis

The independent Student's *t*-test was performed to assess the significance of differences among the experimental groups (irradiation vs. control and effects of 6 hours postirradiation incubation vs. the effects at 48 hours postirradiation). The level of significance was set at $P < 0.05$. Results are presented as the Mean $\pm$ S.D. Triplicate measurements were made during each experiment, and each experiment has been repeated three times.

3 Results and Discussion

3.1 Radiation induced apoptosis

The ability of proton radiation with respect to the induction of apoptosis in the HTB140 cells was examined. The gel electrophoretic analyses of DNA samples, isolated from control and irradiated HTB140 cells, 6 and 48 hours postirradiation, have shown ladder pattern, a typical DNA fragmentation characteristic for apoptotic cells (Fig. 1, panels A and B, lanes 3 - 7).

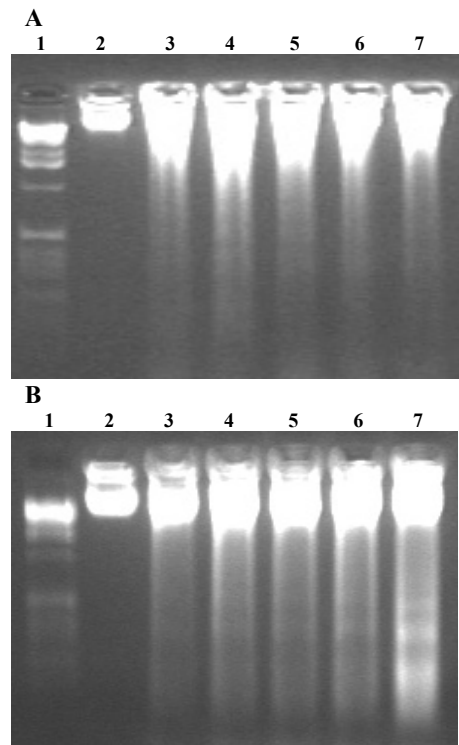


Fig. 1 Proton-induced DNA fragmentation in HTB140 cells at 6h postirradiation (**A**) and 48 h postirradiation (**B**). Lanes: 1 - marker, 2 - control, 3 - 7 cells irradiated with protons of 8, 12, 16, 20 and 24 Gy respectively.

Table I contains data obtained by flow cytometric analyses for the proportion of cells in apoptosis as a function of dose and time. At 6 hours postirradiation there was a moderate level of apoptosis, not more than 10 % of apoptotic cells for irradiation with 16 Gy protons. At 48 hours postirradiation, the highest number of detected apoptosis was 17.71 % for the irradiation with 8 Gy protons, while the number of apoptosis after irradiation with 16 Gy did not exceed 12.11 %. Corresponding apoptotic indexes for 6 hours postirradiation incubation ranged from 2.91 to 3.96 and for 48 hours postirradiation from 1.76 to 3.15, as shown in Table I.

TABLE I
Radiation-Induced Apoptosis in HTB140 Cells

Time after irradiation	Dose of protons (Gy)	Apoptosis (%) [†]	Apoptotic index [†]
6 hours	0	2.66 ± 0.85	1
	8	9.77 ± 0.47	3.84 ± 1.04
	12	8.96 ± 1.49	3.37 ± 0.05
	16	10.3 ± 1.98	3.96 ± 0.52
	20	7.47 ± 0.81	2.91 ± 0.62
	24	8.64 ± 3.05	3.23 ± 0.11
48 hours	0	5.98 ± 2.71	1
	8	17.71 ± 3.52	3.15 ± 0.83
	12	15.39 ± 4.09	2.69 ± 0.54
	16	12.11 ± 2.81	2.13 ± 0.49
	20	11.52 ± 2.57	2.04 ± 0.48
	24	10.24 ± 3.45	1.76 ± 0.21

[†]Mean ± S.D.

The detected apoptosis, induced in HTB140 cells by proton-beam radiation was almost immediate, appearing at about 6 hours after irradiation. It appears that these cells enter directly into programmed cell death, without a lag typical of those described for intact cell cycle checkpoint processes, which allow cells to repair damage prior to undergoing division [7].

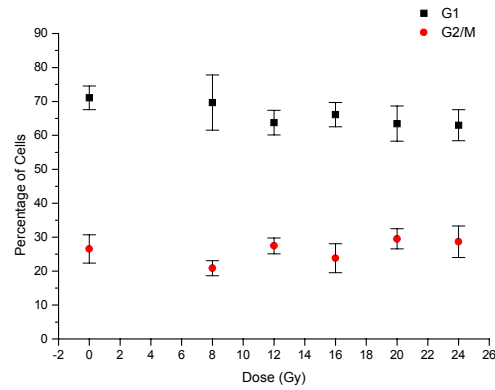
3.2 Changes in cell cycle phase redistribution

The analysis of the cell cycle redistribution determined by flow cytometry (FACS), has shown that unirradiated, exponentially growing, HTB140 human melanoma cells contain approximately 71.09 % in G1 phase, 8.17 % in S phase and 26.56 % in G2/M phase. After the exposure to ionizing radiation, cell samples were further incubated for 6 and 48 hours and then submitted to FACS analysis. When irradiated with 62 MeV protons, the increase of the dose delivered to the cell monolayer, at 48 hours postirradiation, exhibited phase redistribution toward G2/M phase. After single exposure to 12 and 16 Gy, the number of cells in G2/M phase ranged from 30.67 to 35.44 % respectively. This was followed by the reduction on cells arrested in G1 phase, with the low level of cells in S phase, in all analyzed samples. Data from two duplicate experiments are represented in Fig. 2. The redistribution of cells irradiated with protons at 6 h (A) or 48 h (B), in the phases of cell cycle (±S.D.) was not significantly different. The small decrease of G2/M cells after single application of 20 and 24 Gy protons is connected with an increased percentage of apoptotic cells [8].

It is known that γ -rays and protons produce a similar dose-dependent redistribution of cells from a predominantly G1 phase population to the population with predominantly G2 phase cells when they were assayed at the time equivalent to one cell division. This is also consistent with what has been seen for continuously passaged cell lines [7]. It seems that the transit times for irradiated G2 phase cells to progress into mitosis will be different for different radiation sources applied, i.e. γ -rays and protons. We are in the

process of determining the effects of different types of ionizing radiation on successive HTB140 melanoma cell divisions.

A



B

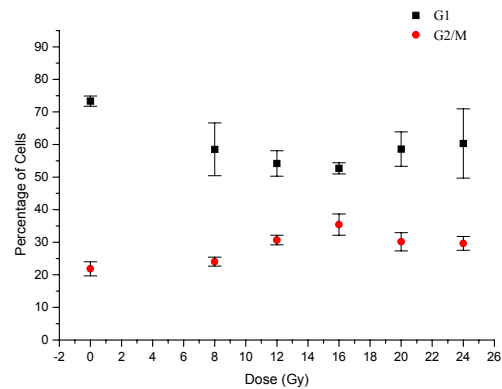


Fig. 2 The effects of proton irradiation on cell cycle phase redistribution in HTB140 cells. Panel A - 6h postirradiation and panel B - 48h postirradiation.

4 Conclusions

Damage to the DNA of proliferating cells by ionizing radiation causes an arrest of mammalian cells in the G1 and G2 phases of the cell cycle. Absence of such cell cycle arrests has been associated with hypersensitivity of eukaryotic cells to ionizing radiation. This leads to the hypothesis that radiosensitive tumours may have genetic defects in cell cycle regulation. Although the presence of p53 in some melanoma cells was already reported [8], the obtained data on the response of HTB140 cell to proton irradiation regarding the cell cycle phase redistribution confirm that melanoma cells are mostly radioresistant

In conclusion, we have assessed damage introduced by proton irradiation using few biological endpoints. Responses produced by proton beams shared features observed for high-LET particles in other experimental systems[7]. Reported results have shown the ability of protons to induce early apoptosis in irradiated HTB140 cells using doses and dose rates applied in proton therapy of ocular melanoma.

The results obtained indicate that cell cycle phase redistribution in HTB140 cells was dependent on dose but not on the duration of postirradiation incubation. The position of cells in cell cycle at the time of irradiation did not influence the results obtained.

5 References:

- [1] G. Iliakis, *Sem. Oncol.*, 1997, **24**, 602-615.
- [2] K.R. Blank *et al.*, *Int. J. Radiat. Biol.*, 1997, **71**, 455-466.
- [3] A. Courdi *et al.*, *Int. J. Radiat. Oncol. Biol. Phys.*, 1999, **45** (1), 5-11.
- [4] D. Bettega *et al.*, *Int. J. Radiat. Biol.*, 2000, **76** (10), 1297-1303.
- [5] A. Ristic-Fira *et al.*, same issue.
- [6] D.K. Armstrong *et al.*, *Cancer. Res.*, 1992, **52**, 3418-3424.
- [7] L.M. Green *et al.*, *Radiat. Res.* 2001, **155**, 32-42
- [8] A. Ristić-Fira, *et al.*, *J. Exp. Clin. Canc. Res.*, 2001, **20** (1), 525-533.

SURVIVAL OF HTB140 MELANOMA CELLS AFTER EXPOSURE TO 62 MeV PROTONS

A. Ristić-Fira^{a*}, I Petrović^a, D. Todorović^a, L. Valastro^b, P. Cirrone^b, G. Cuttone^b

a) Vinca Institute of Nuclear Sciences, P.O.Box 522, 11001 Belgrade, Serbia and Montenegro

b) Istituto Nazionale di Fisica Nucleare, LNS, 95100 Catania, Italy

** Corresponding author, e-mail: aristic@vin.bg.ac.yu*

Abstract

The main purpose of this work was to determine the initial inactivation of cells induced by high-energy proton beam designed for the treatment of eye melanoma. Exponentially growing HTB140 cells were exposed to an unmodulated 62 MeV proton beam delivered over the single dose range from 8 Gy to 24 Gy. Position of samples was in the zone of the Bragg peak, having high LET values. Surviving fractions were evaluated at 6, 24 and 48 hours postirradiation. The survival curves exhibited a well known shoulder, decreasing for doses higher than 8 Gy. Therefore, a significant dose dependent early cell inactivation after single delivery of 16 Gy to 24 Gy to the cell monolayer was observed. With the increase of the postirradiation incubation time, a better killing effect, as the consequence of clonogenic survival, was detected.

1 Introduction

One of most important aims in cancer research is to identify and explain the mechanisms, which regulate cell proliferation. The role of the cell death in cancerogenesis, monitoring the tumour growth, the speed of metastasis and the ability of transformed cells to respond to the usual clinical treatment are today in the focus of fundamental and applied researches. Malignant melanomas are widely analyzed in the past few years. Although this is a very malignant and highly metastatic tumour, with poor prognosis, some forms of melanoma specially localized, such as uveal melanoma and other eye tumours (conjunctive melanoma, iris melanoma, choroidal melanoma or retinoblastoma) are nowadays treated with good results [1].

In the past decades, therapeutic proton beams were successfully used in treating several tumour types [2]. The physical properties of protons, especially its Bragg peak, are used to target large radiation dose precisely in the tumour. When charged particles enter the patient, their specific energy per unit of length deposited along the track (LET, linear energy transfer) increases with decreasing particle velocity. This gives rise to a sharp maximum in ionization near the end of the range at the position of Bragg peak [3, 4]. In radiotherapy, to cover a target volume at the given depth, the Bragg peak is spread out by modulating the energy of the particles. It is known that the relative biological effectiveness (RBE) of protons strongly depends on LET, therefore reaching its maximum value at about 100 keV/ μ m which corresponds to the proton energy of about 65 keV. The 62 MeV protons, that are used here, have a low initial LET of about 1 keV/ μ m at the entrance point which is comparable with LET values of ^{60}Co and high energy X-rays used in conventional therapy.

The main point in most radiobiological studies is how different malignant cells respond to the irradiation.

Radiosensitivity of analyzed cells, together with their clonogenic capacity is of interest for predicting results of radiotherapy. In the studies of cell survival, the reported RBE values are between 1.1 and 1.2 before the distal part of the Bragg peak [5]. Studies on cell inactivation have been performed on different mammalian cells, irradiated with low energy, monoenergetic beams, showing a significant RBE increased with LET [4 - 9]. Several studies have been reported on the effects of proton beams with energy less than 100 MeV that are used for the treatment of eye melanoma [1, 10, 11].

This paper gives data on early cell inactivation in human melanoma cells irradiated within the Bragg peak of an unmodulated 62 MeV proton beam.

2 Materials and methods

2.1 Cell culture and irradiation conditions

Human melanoma HTB140 cells were used in this study. Cells ($5 \times 10^4/\text{ml}$) were maintained in a monolayer culture using RPMI 1640 tissue culture medium, supplemented with 10 % foetal calf serum, in tissue culture dishes (Nuncclon, 35 x 10 mm) and were grown under standard conditions (37 °C humidified incubator, 5 % CO_2). The plating efficiency (PE) for HTB140 cells was approximately 70% and the doubling time (Td), evaluated from the growth curve, was $24 \pm 2,7$ h. It was considered that the thickness of the cell monolayer was between 3 - 6 μm .

We have examined early effects of high-energy proton irradiation on human melanoma cells *in vitro*. Exponentially growing cell monolayers were irradiated within the Bragg peak of the 62 MeV protons obtained by a compact superconducting cyclotron. Figure 1 shows the 62 MeV proton depth-dose distribution measured in Perspex. The arrow indicates the depth at which the irradiation position of the cells was chosen.

To obtain the irradiation position within the Bragg peak, 25 mm thick Perspex plates were inserted just before the Petri dish. This gave the corresponding relative dose of $90.4\% \pm 4\%$.

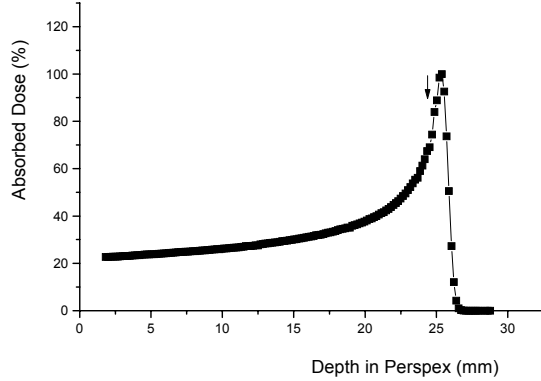


Fig. 1 Measured dose in Perspex vs. depth for the 62 MeV proton beam produced at the INFN, LNS, Catania. Arrow indicates cell irradiation position.

Cells were irradiated in air at room temperature. Just before irradiation, the medium was discarded and the Petri dish was fixed vertically in a special device, facing the horizontal beam. Single doses delivered to the cells were 8, 12, 16, 20 and 24 Gy, with the dose rate of 15 Gy/min. Immediately after irradiation, fresh RPMI1640 culture medium supplemented with foetal calf serum was added. For morphological study, cells were observed and photographed under inverted microscope with phase contrast (Olympus CK30, magnification $\times 100$) at 6 and 48 hours of postirradiation incubation.

2.2 Cell survival assay

The viability of cells was measured at different time points by MTT assay (Roche) based on the ability of viable cells to reduce 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide into blue-purple formazan crystals. The absorbance was measured using a microplate reader (Wallac, VICTOR2 1420 Multilabel counter, LKB) at a test wavelength of 550 nm and a reference wavelength of 690 nm.

For cell survival assay, irradiated, exponentially growing cells were harvested by trypsinization, seeded at suitable number (7×10^3) for inactivation assay and incubated at 37°C for 6, 24 and 48 hours, when cells were fixed with methanol and stained with 10% Giemsa solution for evaluation of survival. Colonies with more than 50 cells were scored as survivors. The surviving fractions were evaluated by fitting the linear-quadratic model to the data [4]. The Student t-Test was used for standard analysis. The level of significance was set at $P < 0.05$. Results are presented as the Mean $\pm$ S.D.

3 Results and Discussion

A standard curve for HTB140 cells revealed that there was a linear relationship between MTT conversion and the number of cells plated, for the data after 6 and 48 hours postirradiation. The obtained results are presented in Figure 2, estimated as a percentage of the control value. The level of early cell growth inactivation, estimated at 48 hours postirradiation, has shown a dose dependent increase. The obtained growth inhibition ranged from 55.16% to 58.97% for irradiation with 16 Gy and 20 Gy respectively, reaching even 91.35% of inhibition after single delivery of 24 Gy protons.

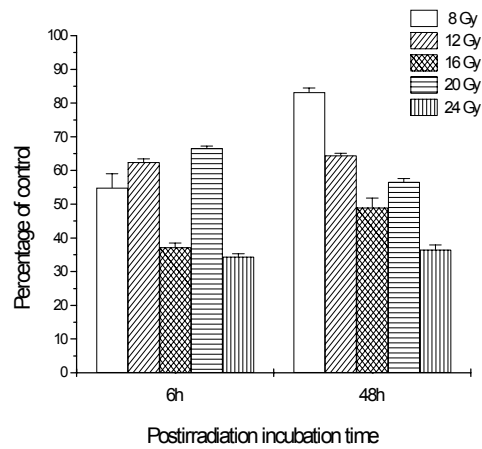


Fig. 2 Effect of 62 MeV proton irradiation on HTB140 cells. Cell viability after 6 and 48 hours postirradiation estimated by MTT assay at 6 and 48 hours postirradiation. Each data represents Mean $\pm$ S.D. ($n = 4$).

To quantify the dose response in exponentially growing cultures, the surviving fraction of HTB140 cells from an average of three duplicate experiments were fitted to a linear-quadratic equation [4]. For the generation of cell survival curves, possible differences in response were further investigated after giving high single doses similar to those delivered in the radiotherapy of ocular melanoma.

The survival curves of HTB140 cells exhibited a shoulder at lower doses and an exponential decrease for doses higher than 8 Gy (Fig. 3). The width of the shoulder and the initial slope of the survival curves generated at 24 and 48 hours of postirradiation time, were not significantly different. At 6 hours of postirradiation incubation cell surviving fraction for all doses applied (8 - 24 Gy) ranged from 41 - 65% ($50.01\% \pm 0.11$, Mean $\pm$ S. D.) with no significant difference regarding the increase of the delivered dose. At 24 hours postirradiation, the shape of the fitted curve showed the decrease of the survival fraction with the increase of the dose, having the high S.D. values for the

irradiation with 24 Gy. This can be explained by the fact that unsynchronized, heterogeneous cell cultures, having melanoma cells in different stages of differentiation, were irradiated in our experiments.

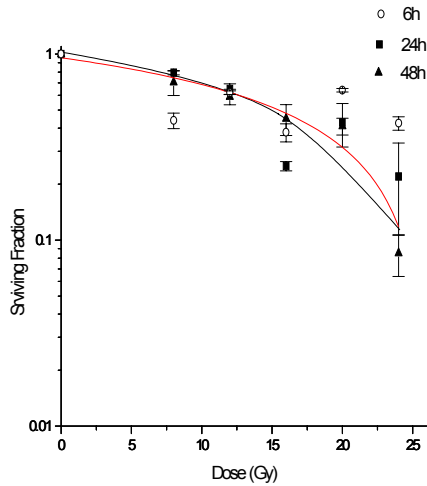


Fig. 3 Survival fraction of HTB140 cells exposed to 62 MeV protons at 25 mm in Perspex. At 6, 24 and 48 h postirradiation, the number of surviving cells was determined by colorimetric dye conversion and fitted by L - Q equation.

The survival curve generated after the additional postirradiation incubation, up to 48 hours, has shown almost the same shape compared to survival obtained at 24 hours postirradiation, with significantly lower S.D. values. The present shape of the dose-response curve is consistent with the results obtained in studies carried out by other authors [4, 6].

Photomicrographs presented in Figure 4 illustrate morphological changes of irradiated cells, and their non-irradiated counterparts, up to 48 hours postirradiation. Melanoma cells grew in predominantly fusiform morphology, with round to oval nuclei, multiple small irregular nucleoli, and pale - staining chromatin. Day 1 and Day 2 postirradiation appear to have cells similar in terms of overall morphology, nuclear structure and pigmentation after irradiation with doses ranging from 8 Gy to 20 Gy. Single irradiation of HTB140 cells with 24 Gy protons produced severe damage to the cells with the significant reduction of cell number. The recovery of the cell monolayer, from 24 to 48 hours postirradiation, decreased with the increase of the dose applied, showing a strong inhibitory effect after single application of 24 Gy protons (Fig. 4).

The data on the effects of conventional radiation, i.e., X or γ - rays, have shown that the sensitivity of normal human cells is higher than the sensitivity of rodent cell lines, while the sensitivity of tumour cell lines varies over a wide range of values. Less information is available on human cells irradiation with protons.

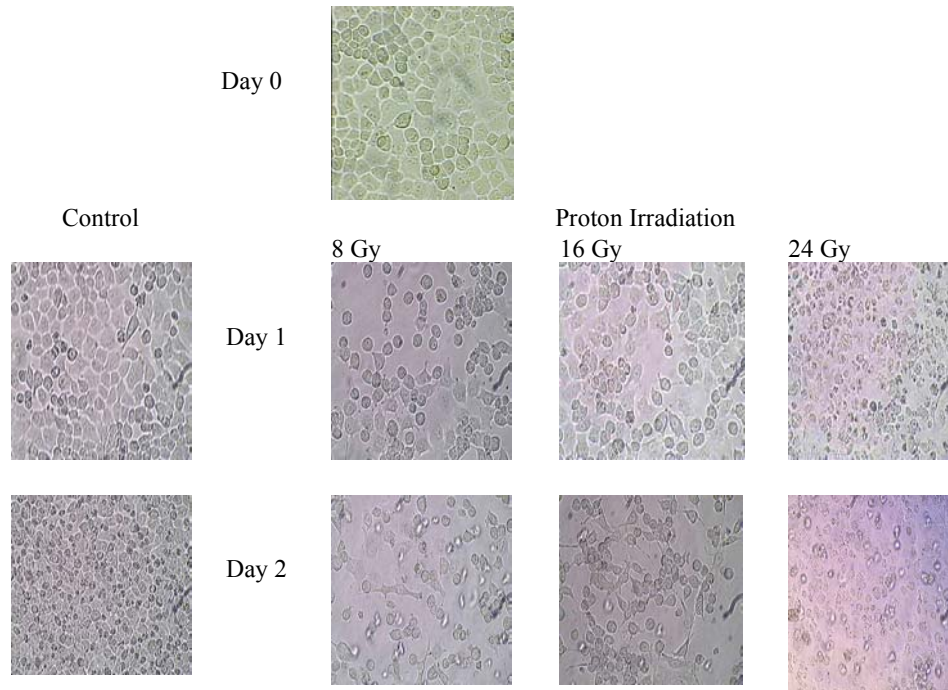


Fig. 4 Phase-contrast photomicrographs of HTB140 cells. Exponentially growing cells (Day 0) were irradiated with protons using single doses in the range from 8 to 24 Gy and followed for 48 h postirradiation (Day 1 and 2). Left panel: control. Right panel: cells irradiated with different doses of 62 MeV protons. The photomicrographs presented are representative of three independent experiments with similar results (original magnification, $\times 100$).

Some differences in the detected cell sensitivity might be a consequence of the nature of cell damage induced by high-LET radiation, cell-repair capacity and other cell parameters involved in the different metabolic processes. Considering that HTB140 melanomas are among cell lines with higher radioresistance, the evaluated parameters (higher RBE at 10% survival) were in agreement with literature data [4, 6, 7, 8].

4 Conclusion

The data obtained on human melanoma cells irradiated within the Bragg peak of an unmodulated 62 MeV proton beam pointed out a significant dose dependent early cell inactivation. With the increase of the postirradiation incubation time, a better killing effect, as the consequence of clonogenic survival, was detected.

This study is part of an overall effort to understand the mechanisms involved in cell survival after irradiation with high-LET charged particles of human cells with different radiosensitivity. All the knowledge gained through these investigations is aimed to improve the efficiency of the therapeutic approach to cure different malignant diseases.

5 References

- [1] A. Courdi, *et al.*, Int. J. Radiat. Biol. Phys., 1999, **45** (1), 5-11.
- [2] U. Amaldi, Tumori, 1998, **84**, 188-199.
- [3] W.T. Chu, *et al.*, Rev. Sci. Instr., 1993, **64**, 2055-2122.
- [4] M. Belli, *et al.*, Int. J. Radiat. Biol., 2000, **76** (6), 831-839.
- [5] J. Gueulette, *et al.*, Radiat. Res., 1996, **145**, 70-74.
- [6] D. Bettega, *et al.*, Int. J. Radiat. Res., 2000, **76** (10), 1297- 1303.
- [7] A. Ristić-Fira, *et al.*, J. Exp. Clin. Canc. Res., 2001, **20** (1), 525-533.
- [8] A. Ristić-Fira, *et al.*, Phys. Med., 2001, **17** (3), 71-76.
- [9] A. Ristić-Fira, *et al.*, Turk. J. Biochem, 2003, **28** (3), 85-86.
- [10] S.Kroll *et al.*, Ophthalmol., 1998, **105**, 2035-2045.
- [11] C. Chiquet *et al.*, Br. J. Ophthalmol., 2000, **84**, 98-102.

THE DEEP PROTON ACTIVATION ANALYSIS: A NEW NON-DESTRUCTIVE METHOD FOR THE DETERMINATION OF CHEMICAL ELEMENTS IN THE BODY OF ANCIENT COINS.

*F.Rizzo^{a,b)}, G.A..Cirrone^{a,b)}, G.Cuttone^{b)}, A.Esposito^{a,b,c)}, S.Garaffo^{d)}, G.Pappalardo^{a,b)}, L.Pappalardo^{b,e)},
F.P. Romano^{b,e)}, S.Russo^{b)}

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

b) INFN Laboratori Nazionali del Sud, Catania, Italy

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

d) CNR, Istituto per le Tecnologie Applicate ai Beni Culturali, Montelibretti-Roma, Italy

e) CNR, Sez. di Catania dell'Istituto per i Beni Archeologici e Monumentali, Catania, Italy

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

Abstract

The new Deep Proton Activation Analysis (DPPAA) method to perform non-destructive determination of the chemical composition of ancient coins of archeological interest will be illustrated. The first experimental results obtained by irradiating a “dummy coin” will be presented.

The knowledge of the chemical composition of ancient coins is of particular interest for the archaeologists. In fact, for example, the alloy composition can give information on the manufacturing technology and the variation of the noble metals content can be related to the economic evolution. Moreover the minor and trace-elements content allows to define groups and to establish the location of provenance mines.

To solve the several numismatic troubles in the past the chemical analytical methods have been largely used. Unfortunately they are destructive methods, as they require the analysis of the solution obtained through a powdered fraction of the coins.

Since the partial or total destruction of ancient coins is not permissible, different non-destructive methods have been developed:

- a) XRF (X-Ray Fluorescence) method [1]. It consists in bombarding the sample with X-rays ($E_x = 20\div60$ keV) to stimulate X-rays fluorescence emission characteristic of the various chemical elements. This analysis involves only the near surface layers, typically up to 100 μ . However the surface composition is generally not identical to the composition of the bulk of coin due to effects such as corrosion and/or diffusion.
- b) The Activation Analysis. It consists in irradiating the sample with Neutrons (Neutron Activation Analysis -NAA-) [2] or Protons (Proton Activation Analysis -PAA-) [3] to produce radioactive

isotopes by projectile absorption. After the irradiation the measurement of γ -rays emitted by such radioisotopes allows to determine the amount of different element present in the sample by means of the relation:

$$m_x = \frac{N_g P_A I}{s \Phi N_0 q P_g h IDC} \quad (1)$$

being η = Efficiency, P_g = Branching Ratio, P_A = Mass Number, λ = decay constant, N_0 = Avogadro number,

Φ = p/n flux [cm^2s^{-1}], σ = Proton/Neutron absorption cross section, θ = Isotopic abundance, $I = 1 - e^{-I t_{irr}}$, $D = e^{-I t_w}$, $C = 1 - e^{-I \Delta t_c}$.

Note that the absolute determination of m_x requires the knowledge of all the nuclear and experimental above listed parameters.

The Activation Analysis has the disadvantage to involve the bulk composition without distinguish between surface and interior contribution.

To overcome the previously described limits we developed a new method, called Deep Proton Activation Analysis (DPAA), which allows the confining of the analysis only in the interior of the coins.

It is well known, in fact, that the cross-section for the production of a given residue in reaction induced by protons displays a bell-shaped behavior as a function of

the incident energy (see for example [4]). Consequently, by choosing the suitable incident energy and taking advantage of the natural energy loss of protons inside the coin (thickness $\approx 2000 \mu$) we can limit the radioisotopes production just on its interior.

To verify this idea we used the protons beam delivered by Tandem of LNS and accelerated at 22.5 MeV on 80° beam line along which the beam can emerge in air through an aluminum window (thickness $\approx 75 \mu$). The sample was positioned 950 mm far from Al-window (see FIG.1.). Due to the energy loss in the Al-window and in air, the incident energy on the sample is 19.2 MeV.

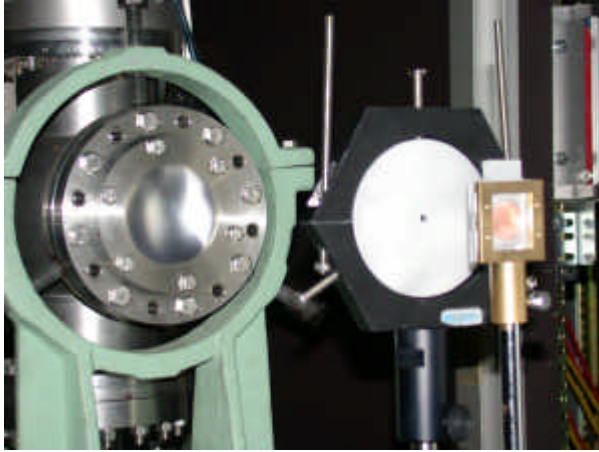


FIG.1. - Experimental set-up along LNS 80° beam line for the DPAA method. It is visible the collimator which defines the beam spot on the dummy coin.

After the irradiation, the γ -rays emitted by the different produced radioisotopes were measured by using an HPGe semiconductor detector (diameter 52 mm, thickness 64.6 mm).

As initial experimental step we irradiated different “dummy” coins made up by alternating foils of different material and different thickness to better simulate a “real” coin. For example the first dummy coin (DUM1) was built alternating Cu foils (thickness $\delta = 100 \mu$) with Sn foils ($\delta = 100 \mu$) up to a total thickness $\Delta = 2000 \mu$.

The second dummy (DUM2) was obtained repeating 10 times a stack constituted by Cu ($\delta = 100 \mu$), Sn ($\delta = 14 \mu$), Ag ($\delta = 10 \mu$), Pb ($\delta = 10 \mu$), Zn ($\delta = 10 \mu$), Ni ($\delta = 1.5 \mu$), Fe ($\delta = 1.5 \mu$) up to a total thickness $\Delta = 1470 \mu$, corresponding to a mass percentage of 68% Cu, 8% Sn, 8% Ag, 9% Pb, 5% Zn and about 1% of Ni and Fe. Other dummy coins were used constituted by 20 foils, 100 μ each, of “pure” elements: Lead, Zinc, Silver and Tin.

The purpose to irradiate these dummy coins is twofold:

- to verify that the radioisotope production cross section displays a bell-shaped trend inside the dummy coins.
- to use the dummy coins as standard to evaluate the unknown mass m_x present in the genuine coins.

The a) item was fulfilled by measuring the γ -rays emitted by the single foil (or stack of foils) and calculating the Activity A_0 for the radioisotopes produced at the different coin depths by:

$$A_0 = A_C e^{t/t} \text{ were } A_C = \frac{N_g}{P_g \Delta t_C h}$$

A_0 is the Activity at the end of the irradiation. A_0 is directly connected with the radioisotopes production cross section.

The b) item is because the measure of the unknown mass m_x by eq. (1) requires, as said before, the exact knowledge of several nuclear and experimental parameters. It is more practical to irradiate one standard sample and the unknown coin under the same condition and to find m_x by comparing the Activities [5,6].

$$m_x = m_{st} \frac{A_x}{A_{st}} \frac{Q_{st}}{Q_x} \frac{R_{st}}{R_x} \quad (2)$$

Q_i and R_i represent the total beam charge and the range respectively in the standard and in the coin irradiations.

Up to now only dummy coins have been irradiated. We report, as example, the results obtained with DUM2 coin irradiated for 1 hour with protons of incident energy 19.2 MeV and intensity $i=10\text{nA}$.

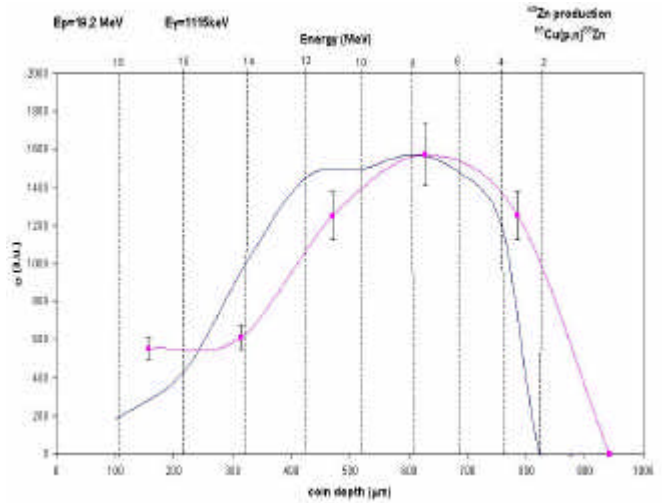


Fig. 2 - ^{65}Zn production cross section vs. proton energy and depth inside the sample. The thick line represents the theoretical prevision calculated by means CASCADE statistical code.

In Fig.2 the ^{65}Zn production cross section obtained via (p,n) reaction on the Copper isotope ^{65}Cu is shown as a

function of the coin depth. The cross section (in arbitrary units) is obtained through the Activity measured by the γ -line at $E_\gamma = 1115$ keV following the ^{65}Zn decay (half time $t_{1/2} = 244\text{d}$). As expected, the cross section displays a bell-shaped behavior centered at about $600\ \mu\text{m}$, which means that the “information” comes essentially from the inner part of the dummy coin.

In the same figure the ^{65}Zn evaporation residue cross section calculated by the statistical code CASCADE is reported for comparison.

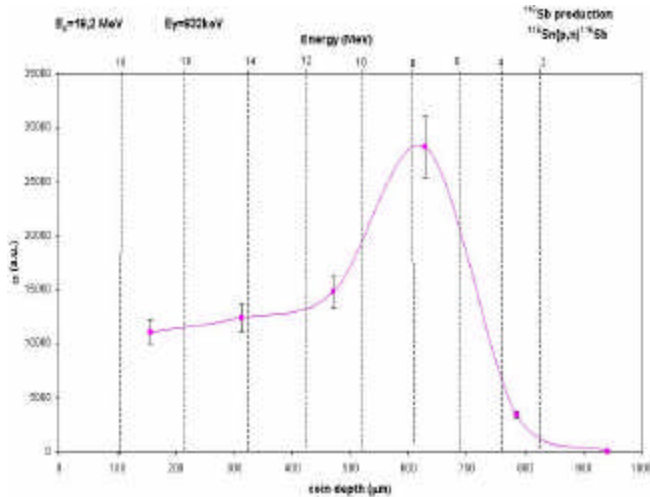


Fig.3 - ^{116}Sb production cross section vs. proton energy and depth inside the sample

In Figs.3-5 similar trends are shown for the ^{116}Sb , ^{107}Cd and ^{66}Ga production via (p,n) reaction on ^{116}Sn , ^{107}Ag and ^{66}Zn respectively. Also in these cases the main contribution comes from the interior of the dummy coin.

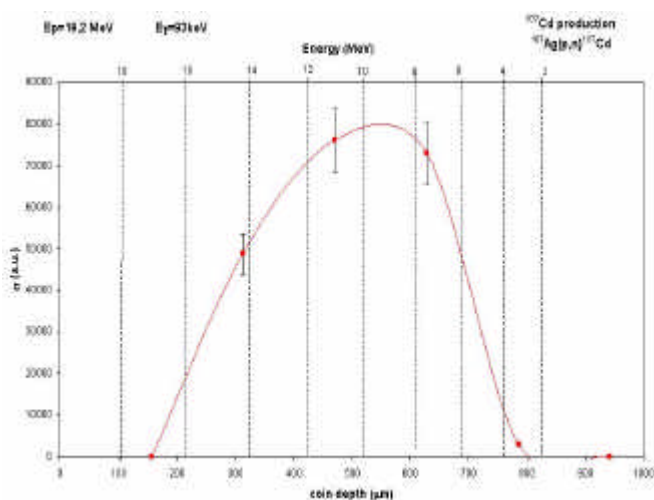


Fig.4 - ^{107}Cd production cross section vs. proton energy and depth inside the sample

The obtained experimental results confirm that, with a suitable choice of incident energy and reaction mechanism, we can limit the radioisotopes production used in the Deep Proton Activation Analysis at the inner part of the coin, so avoiding the uncertainties coming from the surface layers.

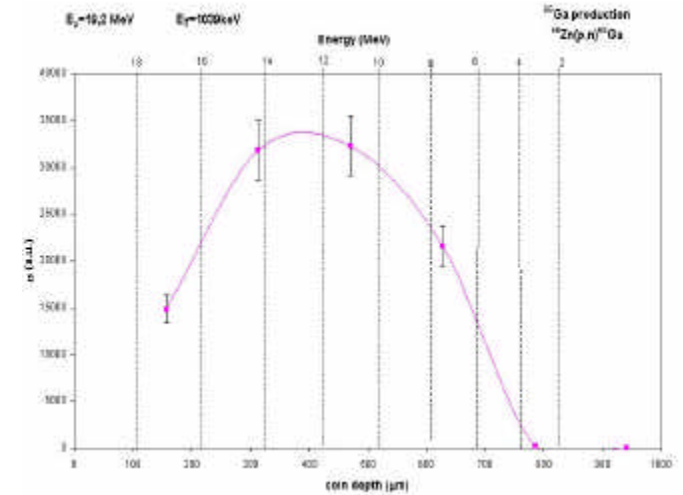


Fig.5 - ^{66}Ga production cross section vs. proton energy and depth inside the sample

As the measurements on the standards can be considered concluded, we plan next year to start the measurements on authentic silver and bronze coins.

REFERENCES

- [1] J.Lutz and E.Pernicka. Archeometry 38, 2 (1996)313.
- [2] M.D.Glascock and H.Neff. Meas.Sci.Technol. 14 (2003)1516.
- [3] P.Meyers. Archeometry 11 (1969)67.
- [4] P.J.Daly et all. Nucl.Phys.56(1964)322.
- [5] E.Ricci and R.L.Hahn. Anal.Chem.39,1(1967)794.
- [6] J.L.Debrun et all. Anal.Chem. 48, 1 (1976) 167.

INVESTIGATION OF DEFECT DENSITY AS A FUNCTION OF GROWTH TEMPERATURE AND THICKNESS IN CVD DIAMONDS

Cristina Tuvè^{a,*}, R. Potenza^a, C. Sutura^a
V. Bellini^b, A. Bonanno^b, F. Mammoliti^b

G. Pucella^c, M. Marinelli^c, E. Milani^c, A. Paoletti^c, A. Tucciarone^c, G. Verona-Rinati^c

a) Università di Catania, Via Santa Sofia 64, I-95123 Catania, Italy

INFN – Sezione di Catania, Via Santa Sofia 64, I-95123 Catania, Italy

b) Università di Catania, Via Santa Sofia 64, I-95123 Catania, Italy

INFN – LNS, Via Santa Sofia 62, I-95123 Catania, Italy

c) Università di Roma "Tor Vergata", Via di Tor Vergata 110, I-00133 Roma, Italy

INFN – Sezione di Roma2, Via di Tor Vergata 110, I-00133 Roma, Italy

Abstract

We studied the spatial defect distribution in CVD diamonds grown in Roma Tor Vergata Laboratory through bombardment with ⁷Li, ¹²C and ¹⁴N ions of various energies (and so various penetrations) produced in the 15 MV Tandem accelerator of LNS. Use was made of a model recently developed by this group as described in more detail in the previous LNS 2002 Report [1]. In few words a modified “two fluid” Hecht model was accomplished in which the different behaviors of both carriers with Bragg’s non-uniform ionization density along particle path and the inhomogeneous distribution of defects along the same path could be taken into account, obtaining good agreement with the data concerning the mean charge collection efficiency of the diamond specimen as a function of the penetration of the ionizing particle. The unidimensional defect distribution along the particle path was so obtained for specimens grown at different temperatures and various thickness, indicating the optimum values for these growth parameters

1 INTRODUCTION

Diamond was shown to be a suitable material for applications in high energy particle detection [2] due to its striking electrical and thermal properties and its radiation hardness, which allows the diamond to be a very good detector of accelerator beam profiles. High quality diamond films can be obtained by microwave plasma enhanced chemical vapour deposition (CVD), but their polycrystalline nature and the presence of high concentrations of various defects in form of vacancies, interstitials and their combinations still constitutes a severe limitation to most of the applications as nuclear detectors [3].

The main parameters which relate to the quality of a diamond as nuclear detector are:

i) the average charge collection distance $\delta = \lambda_e + \lambda_h = (\mu_e \tau_e + \mu_h \tau_h)E$, sensor thickness and so cause of too low pulse heights (μ_e , μ_h , τ_e and τ_h are mobilities and lifetimes of electrons and holes respectively and E the electric field);

ii) the detector efficiency $\eta = Q_c / Q_0$, that is the ratio between the collected charge and the total charge generated by a single incident ionizing particle; Q_c is proportional to the pulse height and can vary much from one particle to another of the same monoenergetic beam due to the different paths inside the specimen, giving rise to bad energy resolution.

In the two fluid model proposed by our group [4] the mean efficiency of a diamond sensor of thickness L , in which a particle penetrates up to a deepness G , is given, through a simple extension of the Hecht formula [5], as:

$$\eta = \frac{\lambda_e + \lambda_h}{L} - \frac{\lambda_e^2 \left(1 - e^{-\frac{G}{\lambda_e}} \right) + \lambda_h^2 \left(e^{-\frac{L-G}{\lambda_h}} - e^{-\frac{L}{\lambda_h}} \right)}{LG} \quad (1)$$

where $\lambda_{e,h}$ are the different mean free paths for electrons and holes. Constant electric field, ionization density and defect concentration are assumed inside the specimen. The different behavior of electrons and holes [4] had been previously shown through measurements with α -particles from ²⁴¹Am in the pumped state (that is after sufficiently long bombardment with β -particles in order to saturate part of charge carrier traps).

2 EXPERIMENT

Detector grade CVD diamond films were grown on single crystal (100) p-type silicon substrates using a CH₄-H₂ gas mixture in a tubular reactor of Roma Tor Vergata Laboratories [6,7]. The usual scratching procedure was adopted to promote nucleation. The CH₄ content in the gas feed and the substrate temperature during the deposition process were fixed to 1%. Growth temperatures were varied from a specimen to the other from 670 °C to 700 °C to 750 °C and, for each temperature, three specimens of different thickness from

50 μm to 100 μm in intervals of 25 μm were grown. The detectors were obtained by depositing Au contacts 7 mm² wide and 100 nm thick on diamond samples. A 60 hours irradiation with β -particles from a ⁹⁰Sr source was made as the standard procedure to drive the detectors in the fully pumped state.

Each diamond detector was allowed to detect ⁷Li, ¹²C and ¹⁴N ions scattered by a target ¹⁹⁷Au at 20 degrees with respect to the incident beam. The particles impinged on the growth side of the diamond. This side was in turn placed at identical positive or negative value of the tension, which generated an electric field $E = \pm 1 \text{ V}/\mu\text{m} = \pm 10 \text{ kV/cm}$. The use of different beams was suggested by a need of comparison of radiation damage, if any, between the carbon beam (homologous with diamond) and others beams.

The energy of ¹²C ions was varied in steps between 22.0 MeV and 91.2 MeV, that of ⁷Li ions was 50.6 MeV and that of ¹⁴N ions from 31.5 MeV to 84.5 MeV. The intensity of the beam varied between 2 and 10 pA (that is between $1.25 \cdot 10^{10}$ and $6.25 \cdot 10^{10}$ particles/s), was measured and integrated with a picoamperometer and monitored through a silicon detector placed also at 20 degrees from the beam on the other side with respect to diamonds. The target thickness was 280 $\mu\text{g/cm}^2$. During all the measurements the pulses produced in the diamonds were amplified by conventional electronics, digitalized through ADC's and stored.

The smallest penetration depth G were obtained rotating the specimen around an axis orthogonal to the beam, so that the particles hit the detectors obliquely.

3 RESULTS

The main observable feature in the samples, that is the asymmetric behavior when they are driven in the two different bias polarities, due to the different mean free paths of electrons and holes [4], was well observed for all the specimens and beams. So we report here only the results obtained for the carbon: all the other result have the same features and no radiation damage was noted for the used beams. The efficiency grows with thickness. We report here the results for a thickness of 75 μm .

Fig.1 shows the mean efficiency η as a function of ¹²C penetration depth and growth temperature of the samples. We see at first sight that the efficiency is maximum for $T = 700^\circ\text{C}$ and decreases rapidly on both sides of this value: so this temperature can be chosen as optimal. The other two interesting features are: i) the fact that the efficiency begins again to grow while the energy increases and the (apparent) penetration depth overcomes sample thickness; ii) the slope at low penetration depths is rather high. The two fluid model cited above cannot give account of these features, at least in the form used up to now. We report for comparison in fig. 2 the data obtained in the previous measurements with carbon, compared with the model. As we see, the model (full curve) foresees a horizontal mean trend at penetration depths larger than sample

thickness and a smooth trend at low penetrations. We can perhaps explain the growth at high energies as the influence of the silicon backing, since when particles overcome sample thickness begin to penetrate into the backing. The large slope at low energies could be produced by space charge produced by the high ionization density of low energy particles. Both unsuspected features are still under study to give the right refinement to the model.

4 CONCLUSIONS

⁷Li, ¹²C and ¹⁴N ions of various energies produced by Tandem of LNS, Catania (Italy) have been used as probes to scan the defect density in samples of diamond grown with CVD technique in Roma Tor Vergata laboratories. The results obtained through the application of the new model of charge conduction in diamond [4] clearly show (fig. 2) the high sensitivity of the diamond to the temperature of the $\text{H}_2 - \text{CH}_4$ growth mixture. So, as we foresaw, the conduction model is adequate to allow for the optimization of the growth parameters (at least for mixture temperature, there is still need for investigation when the mixture composition is changed).

Moreover, the model is open to further refinements which can include other phenomena (like, e.g. spatial charge effects) that we hope to include in order to explain the residual discrepancies like the disagreements with the slopes of η vs G (penetration depth along the electric field) for small G and for $G = L$ (see eq. (1)). So nuclear particle detection is confirmed to be a very sensitive probe for diamond defect investigation and in particular it results a powerful instrument to suggest improvements in the engineering of the first stages of diamond growth in order to obtain diamonds of better and more uniform quality.

5 REFERENCES

- [1] C. Tuvè, V. Bellini, R. Potenza, C. Rancieri, C. Sutura, G. Pulcella, M. Marinelli, A. Paoletti, A. Tucciarone, G. Verona-Rinati, LNS Activity Report 2002, (2003) 133;
- [2] W. Adam et al., Electrochem. Soc. 5th Symposium on Diamond Materials Proc. (1998) 491
- [3] D. R. Kania in "The Physics of Diamond", A. Paoletti and A. Tucciarone Editors, IOS Press, Amsterdam, 1997
- [4] Marco Marinelli, E. Milani, A. Paoletti, A. Tucciarone, G. Verona Rinati, M. Angelone, M. Pillon, Phys. Rev. B **64** (2001), 195205
- [5] K. Hecht, Z. Phys **77**, 235 (1932)
- [6] M. Marinelli, et al., Proc. Of Applied Diamond Conference/Frontier Carbon Technology Joint Conference, Tsukuba, Japan, August 31-September 3, (1999) 154

[7] Marco Marinelli, E. Milani, A. Paoletti,
A. Tucciarone, G. Verona Rinati, M. Angelone,
M. Pillon, Appl.Phys.Lett. **75** (1999) 3216.

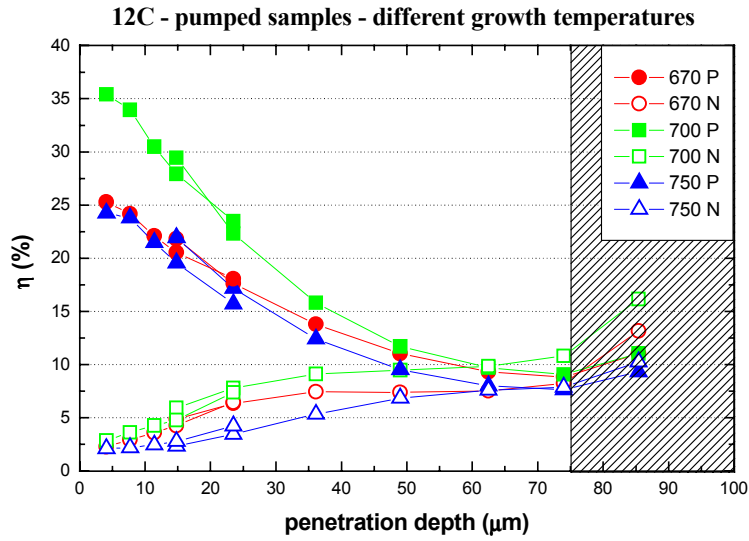


Fig. 1: Mean efficiency of a diamond detector hit by ^{12}C as function of the carbon energy: preliminary result, no fitting curve has been computed. Note that the least value of penetration depth is around 3 μm .

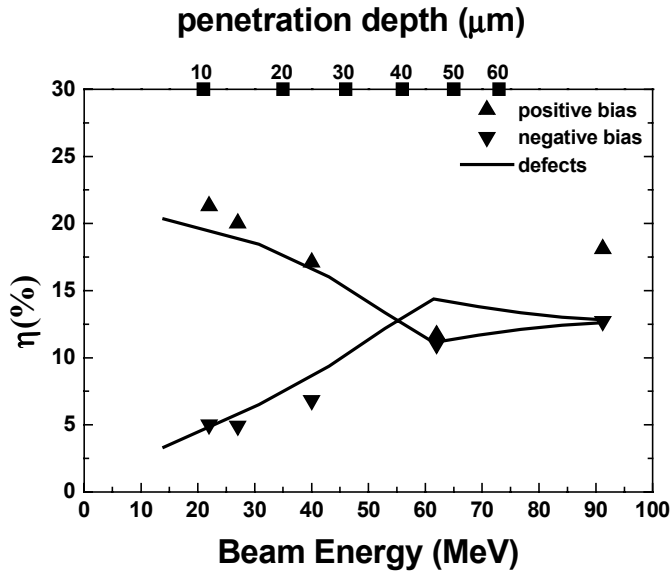


Fig. 2: Mean efficiency of a diamond detector hit by ^{12}C as function of the carbon energy from previous measurements. The curves report the efficiency computed with the two fluid model for non-uniform distributions of ionizations density (Bragg curve) and of defects (exponentially decreasing from substrate to free surface of the diamond). Note that the least value of penetration depth is around 11 μm .

AN ORIGINAL APPROACH TO STUDY THE CHARGE GENERATION MECHANISMS IN POWER MOSFETS DURING HEAVY IONS EXPOSURE

F. Velardi^a, F. Iannuzzo^a, G. Busatto^a, A. Porzio^a, A. Sanseverino^b,
G. Currò^c, A. Cascio^c, F. Frisina^c, A. Candelori^d

^aD.A.E.I.M.I., Università degli Studi di Cassino, Via Di Biasio, 43 – 03043 CASSINO (FR) - ITALY

^bD.I.E.T., Università degli Studi di Napoli, Via Claudio, 21 – 80125 NAPOLI – ITALY

^cST-Microelectronics, Stradale Primrose, 50 – 95100 CATANIA – ITALY

^dI.N.F.N. - Sez. di Padova - Dipartimento di Fisica Galileo Galilei, Via Marzolo - 35131 PADOVA - ITALY

Abstract

The usage of a power MOSFET in an harsh radiation environment, such as outer space, is subordinated to its ability to tolerate the mechanisms initiated by the passage of energetic ions through the active volumes of the device. In this paper, we briefly describe the approach employed to study the reliability, to sustain heavy ion impacts, in low and medium voltage power MOSFETs

1 INTRODUCTION

Power MOSFETs are very important devices for aerospace applications, unfortunately their reliability in this environment is drastically reduced by several phenomenon related to the presence in the space of high doses of energetic particles that impact the device during his lifetime. So that their reliability is defined as the ability to properly operate while accumulating the levels of total ionisation dose (TID), and to be insensitive to single event effects caused by the passage of single ionising particles through the active volumes of the device. Single event effects (SEE) include single event upsets (SEU), burnout (SEB), and the rupture of the gate oxide layer in MOS devices (SEGR).

When an heavy ion impacts on a power MOSFET, it produces an amount of ionization space charge along its trajectory through the device depending on the energy loss in the several layers of the device.

If the N-drain/P+-body junction is reverse biased, an intense electric field is present in the depletion region of this junction. The interaction between the ionisation charge and the high electric field generates a current spike, due to a charge amplification mechanism, which can cause a device malfunction or permanent damage. In the worst case a failure event is ascribed to the activation of the parasitic transistor of the structure (Single Event Burnout) [1, 2, 3] or to the gate oxide dielectric breakdown (Single Event Gate Rupture) [4, 5, 6]. In addition to the well known mechanisms reported in literature, in new generation power MOSFETs, having a lower gate oxide thickness, we noted that before a typical burnout event, a premature increase of the gate leakage current reveals a damage of the gate structure [7, 8].

The damage is related to the activation of the parasitic BJT and to the development of a large electric field. Although the gate leakage current seems to recover its original value, the damage is irreversible and leads the

gate oxide to the breakdown when the device is subsequently biased. The common characterization of these failure mechanisms is based on the concept of SEE cross-section (σ_{SEB} or σ_{SEGR}) defined as the ratio of the number of SEE to the ion fluence (ions/cm²-sec).

The experimental estimate of the SEE cross section expresses the relationship between the possible occurrence of the SEB, the LET of the impacting ion and the voltage between drain and source (V_{DS}), as well as the relationship between the drain-source voltage (V_{DS}), the gate-source voltage (V_{GS}) and the fluence necessary to cause gate rupture.

Our approach to evaluating the SEE reliability of power MOSFETs is based on a statistical characterization of the charge generation mechanisms that can lead to failure.

First, we perform a classification of the drain and gate pulse shapes that a power MOSFET may generate; subsequently, for each type of current pulse, we employ a maximum-likelihood technique to determine the gamma-like probability density functions (Γpdf 's) that best describe the correlated charge distributions. In this way we can perform a detailed study of the relation between the total charge generated, the ion energy and species, and the bias voltages.

In this paper, we briefly describe the approach employed to study the reliability to SEE in low and medium voltage power MOSFETs.

2 EXPERIMENTAL SET-UP

The experimental study of the reliability of power MOSFETs to be used in 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

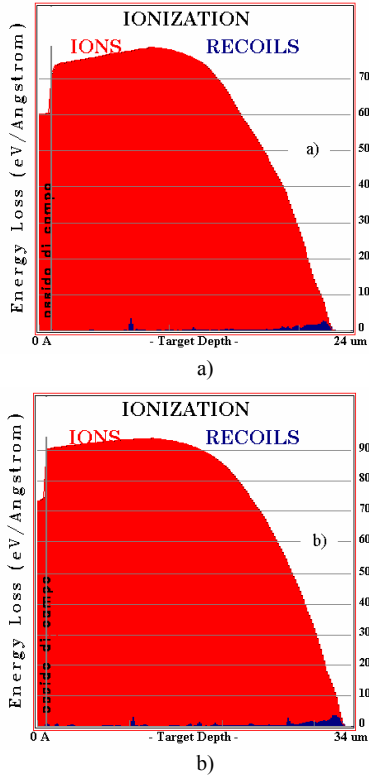


Fig.1: Bragg curves ,
a) $^{58}\text{Ni}_{28}$, 140 MeV; b) $^{79}\text{Br}_{35}$, 236 MeV.

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) [9]. The SRIM simulations had been conducted on two different structures in order to describe a typical device able to blocking 30V and a typical device able to blocking 400V.

Starting from the above criterium, the ion species and energies chosen for the experiments were ^{58}Ni (140 MeV), ^{79}Br (223-236 MeV). With this choice the simulations had shown that the ionisation energy loss (LET) is high in the active layer of both structures.

Fig.1 shows the Bragg diagrams of the ^{58}Ni ions at 140 MeV and of the ^{79}Br ions at 236 MeV.

During the experiments the device was turned off and a positive V_{ds} voltage was applied so as to reverse biasing the N/epi-P⁺/body junction. The drain leakage current and the gate leakage current of the DUTs were continuously monitored, in order to detect failure events.

In Fig.2 the experimental set-up we employed for the SEE characterisation in power MOSFETs is reported.

The set-up proposed is in agreement with the Test Method 1080 imposed by the military standard MIL-STD 750. This test method establishes the basic requirements for the performance of the SEB/SEGR test on power MOSFETs.

Two 1M Ω resistors limit the current in short circuit

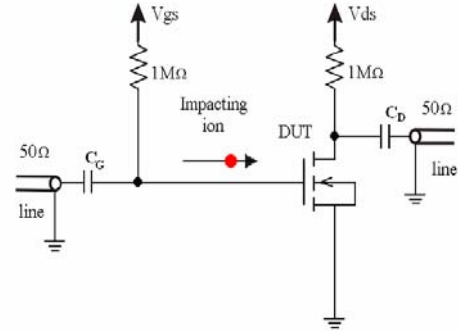


Fig.2: The experimental set-up

circumstance in order to protect the instrumentation, furthermore, they allow us to measure the gate and drain leakage currents during the experiment.

The role of the decoupling capacitors C_D and C_G is threefold: 1) eliminating the DC bias voltage from the oscilloscope input, 2) supplying the energy to the device during the impact while keeping practically stable the voltage across it and 3) reducing the effect of the stray inductances of the connections.

The charge generated during an ion impact produces a current transient that is detected by a fast sampling oscilloscope (Tektronix TDS784, a four trace scope with 4 Gsamples/sec and a 1GHz band width). No amplification electronics was used. With this system a large number of current pulses can be acquired in a short time allowing the statistical analysis of the raw wave forms with no loss of information.

3 CLASSIFICATION OF THE CURRENT PULSES

Experimentally it was found that the drain current waveforms recorded by the oscilloscope can be classified into two types (classes) that strongly differ with respect to pulse shape and associated charge (Fig. 3-4). The maximum current attained by the wave forms of one class (2nd class) is orders of magnitude higher than that achieved by those of the other class (1st class) and, correspondingly, the integrated charge is larger too. The gate current pulses registered with the second circuit set-up show a similar bimodal behaviour.

To achieve a complete characterisation of the tested devices, we classify each current waveform in accordance to three parameters: the current peak, the total charge (obtained by integrating the waveform) and the decay time.

A scatter plot was employed to represent each waveform by a point in a two- or three-dimensional space, with the aim of identifying the possible mechanisms involved in the experiment starting from the plot shape. In Fig. 5, a typical 2D scatter plot (mean charge versus current peak) is reported.

4 STATYSTICAL ANALYSIS

Starting from a classification of the acquired gate and drain wave forms, we use a statistical procedure to extract the relation between the total charge generated,

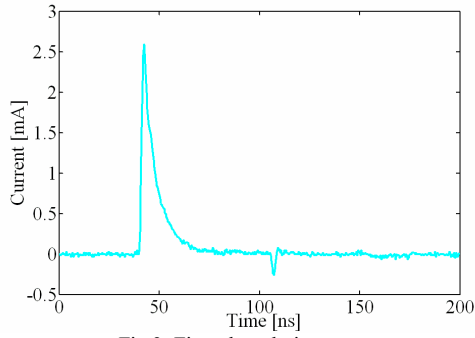


Fig.3: First class drain current.
200V VDMOSFET, $V_{ds}=52V$,
 $V_{gs}=0V$

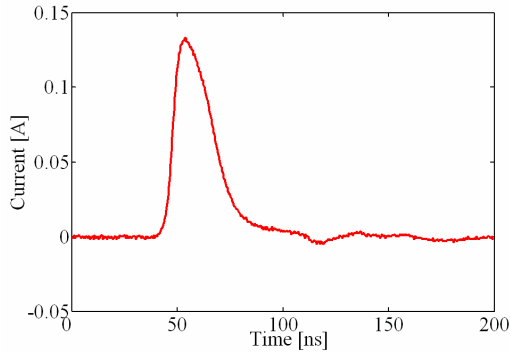


Fig.4: Second class drain current.
200V VDMOSFET, $V_{ds}=52V$, $V_{gs}=0V$

the ion energy and species, and the bias voltage V_{GS} and V_{DS} . The charge generated has been obtained, for each impact, by integrating the generated current pulse.

The characteristics of the charge generation mechanisms were studied by a parametric statistical analysis of the reduced information of the wave forms.

The first step was to describe the distribution of the integrated charge of the wave forms with a parametric shape: the gamma function well describes the experimental charge distributions [10].

The gamma-like probability distribution function (Γ pdf) is a two parameters function defined by:

$$f(x|(a,b)) = \begin{cases} \frac{x^{a-1} e^{-x/b}}{b^a \Gamma(a)}, & x > 0 \\ 0, & x \leq 0 \end{cases} \quad (1)$$

where $\Gamma(\cdot)$ is the gamma function,

$$\Gamma(a) = \int_0^{+\infty} t^{a-1} e^{-t} dt, \quad a \in]0, +\infty[. \quad (2)$$

The mean and the variance of the statistical distribution are easily expressed in terms of the parameters a and b :

$$\begin{aligned} \text{mean}_f &= a \cdot b; \\ \text{variance}_f &= a \cdot b^2. \end{aligned} \quad (3)$$

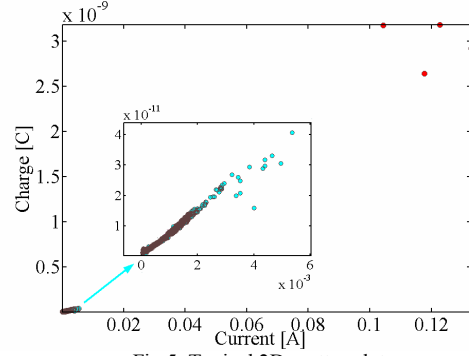


Fig.5: Typical 2D scatter plot
200V VDMOSFET, $V_{ds}=52V$, $V_{gs}=0V$

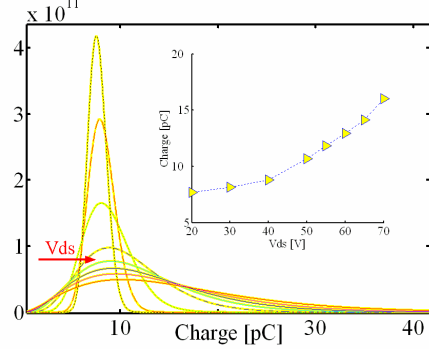


Fig.6: Typical Γ pdf of the drain charge. The inset reports the first moment of the probability distribution functions.

For each value of V_{DS} , a maximum-likelihood estimation (MLE) was used to determine the gamma-like probability distribution functions that best describe the bi-modal experimental distributions (Fig. 6).

Every parameter estimation process adopts a criterion of goodness to determine the parameters of the distribution that best describes the data. The MLE technique maximizes the likelihood function: the likelihood function is constructed using the set of experimentally observed values $\mathbf{x} = (x_1, x_2, \dots, x_n)$, where n is the number of experimental values obtained from the sample set X , and then assuming the parametric probability distribution function $f(x|(a,b))$, where however the parameters a and b are unknown and to be determined:

$$L((a,b)|\mathbf{x}) = \prod_{i=1, \dots, n} f(x_i|(a,b)) \quad \mathbf{x} \in X. \quad (4)$$

The values of a and b that best describe the experimental data are determined by maximizing the likelihood function $L((a,b)|\mathbf{x})$. By varying the bias voltages we can perform a detailed study of the relation between the total charge generated, the ion energy and species, and the bias voltages

5 EXPERIMENTAL RESULTS

The experimental set-up and the analysis proposed allow us to obtain useful information about the damage voltage, the mean charge generated during the exposure and the related mechanism involved. In particular, we have successfully employed this methodology to study the dependence of the first class charge on the parasitic

BJT turn-on and the dependence of the second class charge on an avalanche mechanism [10, 11]. Further, the impact of the technology changes on the SEE reliability is then considered [12]. Specifically, the effect of the epitaxial layer parameters (resistivity and thickness) on the BJT activation have been detected. Currently our efforts are spent to explain the role played by the parasitic transistor and by the surface electric field on a premature increase of the gate leakage current that reveals a damage of the gate structure [7, 8]. Although the gate leakage current seems to recover its original value, the damage is irreversible and leads the gate oxide to the breakdown when the device is subsequently biased.

6 ACKNOWLEDGMENT

The authors wish to acknowledge Prof. Migneco, Prof. Lattuada and Dr. Rifuggiato of the INFN – Laboratori del Sud for having permitted the experiment at that facility, and all the technicians for the assistance during the experiments.

7 REFERENCES

- [1] J.H. Hohl et al. "Features of the Triggering Mechanism for Single Event Burnout of Power MOSFETs", *IEEE Trans. Nuc. Sci.*, Vol.36, No.6, December 1989, pp.2260-2266.
- [2] E.G. Stassinopoulos et al. " Charge Generation by Heavy Ions in Power MOSFETs, Burnout Space Predictions, and Dynamic SEB Sensitivity", *IEEE Trans. Nuc. Sci.*, Vol.36, No.6, December 1992, pp.1704-1711.
- [3] S. Kuboyama et al. " Numerical Analysis of Single Event Burnout of Power MOSFETs", *IEEE Trans. Nuc. Sci.*, Vol.40, No.6, December 1993, pp.1872-1879.
- [4] J.L. Titus et al. "Experimental Studies of Single-Event Gate Rupture and Burnout In Vertical Power MOSFET's", *IEEE Trans. Nuc. Sci.*, Vol.46, No.2, April 1996, pp.533-545.
- [5] I. Mouret, P. Calvel, M. allespach, J.L. Titus, C.F. Wheatley, K.A. LaBel, M.C. Calvet, R.D. Schrimpf, K.F. Galloway, "Measurement of a Cross-Section for Single-Event Gate Rupture in Power MOSFET's", *IEEE Trans. Nuc. Sci.*, Vol.17, No.4, April 1996, pp.163-165.
- [6] M. Allenspach et al. " SEGR and SEB in N-Channel Power MOSFETs", *IEEE Trans. Nuc. Sci.*, Vol.43, No.6, December 1996, pp.2927-2931.
- [7] Submitted to ESREF 2004
- [8] Submitted to ISPS 2004
- [9] SRIM (The Stopping and Range of Ions in Matter), Ziegler J.F., IBM Research, 28-0, Yorktown, NY, 10598, USA.
- [10] F. Velardi et al. "The Reliability of New Generation Power MOSFETs in Radiation Environment," *Microelectronics Reliability*, Vol. 42, pp.1629-1634, Sept.-Oct. 2002.
- [11] F. Velardi et al. "Experimental Study of Charge Generation Mechanisms in Power MOSFETs due to Energetic Particle Impact," *Microelectronics Reliability*, Vol. 43/4, pp.549-555, April 2003.
- [12] F. Velardi et al. "Effect of the Epitaxial Layer Features on the Reliability of Medium Blocking Voltage Power VDMOSFET during Heavy Ion Exposure" *Proc. RADECS 2003 - 8th Radiation and its effects on components and Systems*, Sept. 2003.

FABRICATION OF MICRO OPTO-MECHANICAL COMPONENTS WITH HIGHLY ENERGETIC HEAVY ION BEAMS

Bart Volckaerts^a, Luigi Cosentino^b, Alfio Pappalardo^b, Pedro Vynck^a, Michael Vervaeke^a
and Paolo Finocchiaro^b, Alex Hermanne^a, Hugo Thienpont^a

a) Vrije Universiteit Brussel, Dept. of Applied Physics and Photonics (TW-TONA), Brussels, Belgium
b) Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali del Sud, Catania, Italy

Abstract

The fabrication of deep micro-structures with high aspect ratios is a challenge that pushes today's established lithographic technologies more and more to their physical limits. In this project we propose to continue the investigation of high energetic heavy ion beams as a suitable source for the creation of this type of micro-features. We hereby aim to further explore the fundamental physical differences between heavy ions and proton interactions with respect to the fabrication of deep micro-structures with optically flat surfaces. Moreover, we will spend an important part of our beam time on the fabrication of some dedicated micro-optical components with possible applications in the optical communication business. More in particular our goal is to realize with the aid of a 5.2AmeV Carbon Tandem beam planar micro-structures like 1D fiber-alignment grooves with integrated micro-lenses and diffractive gratings. We propose in a second session to use a 62AmeV Carbon Cyclotron beam for the fabrication of true 3D deep micro-structures like prisms with integrated micro-lenses which form the basic components to realize huge parallel data streams in optical pathway blocks. The experiments proposed in this document will be part of an international study to test the compatibility between the irradiation facility in Catania, the SNAKE Tandem beam line at the E12 department of the TUM in Germany and the cyclotron facility situating at the VUB in Brussels for the fabrication of high-quality plastic micro-structures using heavy ion beams, focused micro-beams and intense proton beams, respectively.

1 INTRODUCTION

One of the major research topics at the Department of Applied Physics and Photonics of the Vrije Universiteit Brussel (VUB), Belgium is the development of precision micro-opto-mechanical components that can be used in parallel optical interconnection modules. To that aim, we opted in 1996 to start developing an alternative technology, based on lithography with high energetic protons. Hereby we take advantage of the lithographic spatial precision of the proton mask as well of the particle's large penetration depth for the fabrication of deep, accurate micro-structures. After an optimisation period of six years, Deep Lithography with Protons is nowadays considered by the "Optical Interconnect" community to be a unique and powerful rapid-

prototyping tool for the fabrication of monolithic refractive micro-optical elements and micro-mechanical structures [1].

The fabrication process consists of three basic procedures: a proton irradiation of a Poly(MethylMethacrylate) (PMMA) substrate, followed by either a development of the irradiated regions in a selective solvent or by a volume expansion of the bombarded zones caused by a diffusion of an organic monomer vapour. If needed, both processes can be applied to different regions of the same sample. This procedure allows for the fabrication of large 2D arrays of mechanical micro-holes, rows of smoothly shaped cylindrical micro-lenses with high numerical apertures, micro-prisms with high optical qualities and uniform 2D spherical micro-lens arrays (Figure 1) [2].

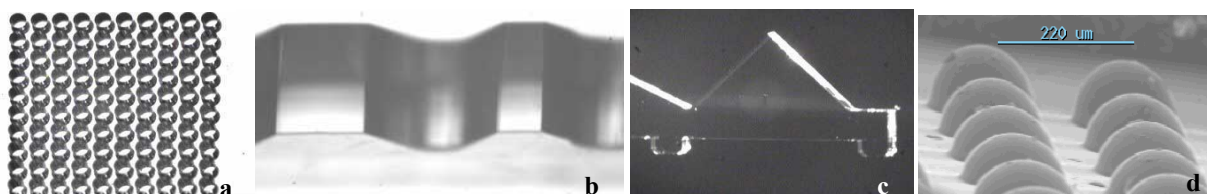


Figure 1: Different micro-optical components fabricated with DLP: Large 2D hole arrays (a), cylindrical micro-lenses (b), micro-prisms with mechanical alignment pins (c) and spherical micro-lenses (d).

2 FABRICATION OF PLANAR FIBERHOLDING STRUCTURES WITH INTEGRATED MICRO-LENSES AND DIFFRACTIVE GRATINGS

Mechanical alignment errors inside optical systems are nowadays an important source for internal coupling losses that tremendously reduce the global performances of the system. Therefore, one has to aspire at an integration of the internal subparts in a monolithic system block, preferable during one single process step. Its possibility to fabricate high-quality stable micro-mechanical and micro-optical structures in high-grade plastic materials, makes DLP a suitable generic fabrication technology to fulfil this ambitious task.

Therefore, we were recently able to realize at the VUB proton beam-line 1D fiber-alignment structures with integrated cylindrical micro-lenses to enhance the coupling efficiency in a parallel fiber link. The fabrication method relied mainly on the fine-tuning of the etching parameters to stop the development process when U-grooves with a correct depth were formed. One of the main goals of our last irradiation session at LNS, was to construct a similar component using a collimated 5.2AMeV Carbon ion beam with a diameter of 125mm instead of the 8.3MeV proton beams we use at the VUB. Since this particular type of heavy ion particles have stopping depths of circa 125mm, which corresponds to the diameter of an optical fiber, we were able to completely etch the entire exposed rectangular-shaped zones to obtain U-grooves with a cross section of 125mm by 125mm and a length depend on the length of the accommodating fiber (figure 2).

In a first step we characterized the crucial process parameters of our technology for Carbon ion beams, which are the local absorbed doses during the irradiation step and the etching time and temperature during the development step. As reported in the literature, we found that in the low dose region degradation effects play an important role with respect to crosslinking and we therefore may expect higher etching rates when higher fluences are deposited in the PMMA-plates. However,

contrary to proton interactions, crosslinking effects become important for the fabrication of high-quality micro-optical surfaces once a threshold fluence of 6.105ions/mm² is exceeded. Crosslinking namely results in a reduction of the solvent selectivity, hence in developed sidewalls with a higher roughness and larger crack density. During our last irradiation session we found that an optimized fluence region for the fabrication of high-quality optical surfaces situates between 105ions/mm² and 6.105ions/mm². In figure 3 we show the surface profile of a micro-mirror fabricated with a collimated 5.2AMeV Carbon beam at LNS.

During this first experimental run we proved that DLP is a candidate technology for the fabrication of micro-structures with steep sidewalls with a lateral deviation of 0.8mm over a depth of 60mm. However, we found that a further optimization of the fluence range is required in order to improve the optical roughness quality.

This is the first task we propose to execute during a next beam-time at LNS in 2004. As an extension to these basic experiments, we additionally propose to explore Carbon ion beams with energies which slightly differ from 5.2AMeV. This allows us to shape the top surface of the plastic material to different heights. We will work out this concept for the fabrication of parallel fiber holding structures where the individual fibres can be easily aligned at a well-defined longitudinal position. Beside this fiber coupling structure, our goal is to investigate the integration of this type of U-shaped alignment grooves with a diffractive grating which tends to spatially separate the wavelength components of an optical signal. This opens some perspectives to realize dedicated micro-spectrometers for the analysis of the fluorescence spectrum of biologic specimen. The steep, sub-micrometer sized grating will be irradiated with a new type of rectangular metal mask that will be constructed in our workshop. Before the beam time starts, we will perform a tolerance study of both optical designs at the VUB in order to know the exact, tolerant dimensions of the individual micro-features of the global systems. We will finally characterize the developed structures in our optical testing lab at the VUB.

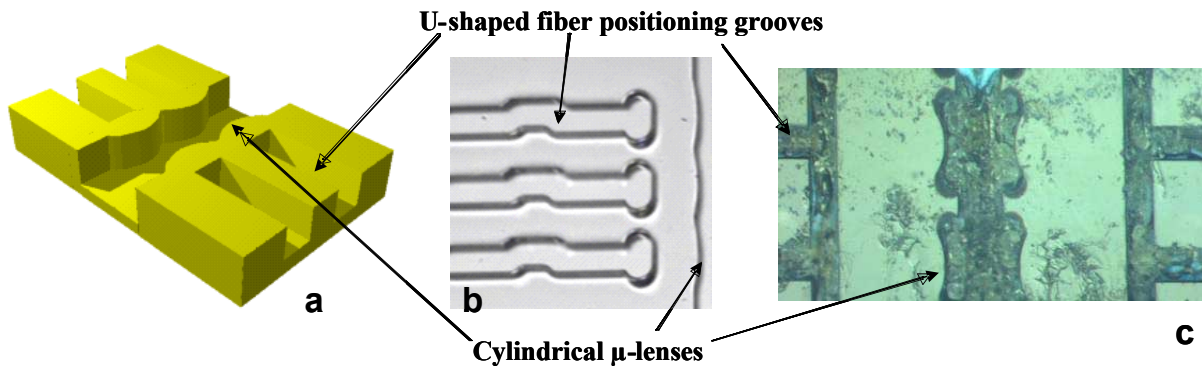


Figure 2: Concept of the proposed 1D fiber connector (a) and pictures of related micro-structures realized after a 8.3MeV proton (b) and a 5.2AMeV Carbon ion (c) irradiation at the VUB and LNS.

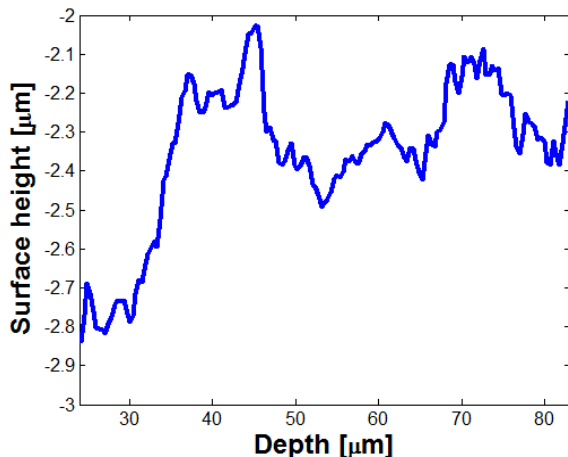


Figure 3: Surface profile of a developed sidewall over a depth of 60mm

3 FABRICATION OF HIGH ASPECT RATIO MICRO-STRUCTURES FOR MASSIVE PARALLEL OPTICAL DATA COMMUNICATION

One of the most crucial characteristic parameters of micro-structures is their aspect ratio which is defined by the ratio between the maximum depth and the minimum lateral dimension of the structure. For Deep Lithography with swift Particles the latter parameters are physically determined by the ion range and the ion scattering behaviour, respectively. In the second part of our last irradiation session, we aimed to explore the possibilities of 62AMeV Carbon ions for the creation of deep micro-structures in PMMA with ultra-flat sidewalls. Due to serious instabilities of the LNS-cyclotron accelerator, we had to finish our experiments in the middle of the assigned irradiation time. Notwithstanding, we were able to expose point arrays with different fluences and average diameters of 850nm on targets consisting of several stacked 500mm thick PMMA-plates. This allowed us to define the characteristic threshold fluence of the selective etching process and to evaluate the scattering behaviour of the particle beams after each 500mm of penetration through the entire target. We compared the obtained data with the results of equivalent experiments we performed at the cyclotron of the VUB with 32MeV proton beams. As expected, we may conclude from figure 4 that, due to their higher mass, Carbon ion beams experience less scattering during their propagation through the PMMA-plates. Therefore, Carbon beams are a more suitable ion source for the construction of high aspect ratio components, whereas proton beams are candidate to fabricate some particular mechanical alignment structures with enhanced conical insertion profiles.

In a next irradiation session we propose to fabricate with the aid of a 62AMeV Carbon beam dedicated thick micro-prisms featuring additional alignment elements for a user-friendly integration in more sophisticated optical systems. Because this plastic prism is compatible with the DLP micro-lens swelling technique, it will offer us a unique possibility to realize high-efficient free-space optical pathway blocks which might be used to realize ultra-high bit streams over short distances on next

generation opto-electronic chips. The working principle of this type of micro-structures is shown in figure 5.

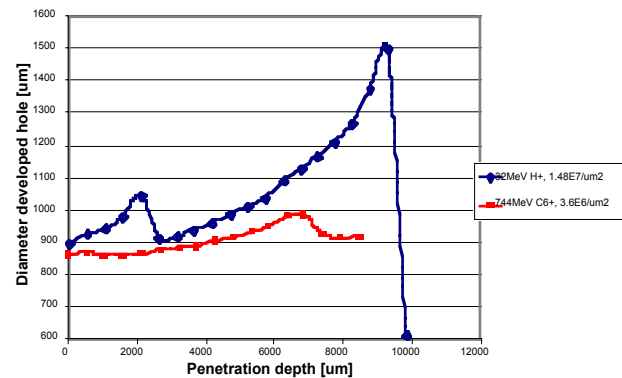


Figure 4: Surface profiles of micro-holes after 60AMeV Carbon and 32MeV proton irradiations

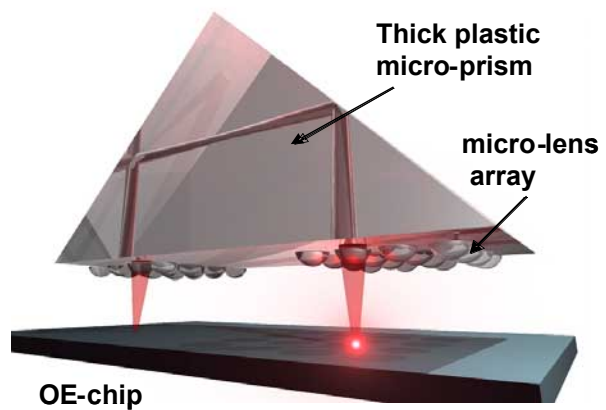


Figure 5: The integration of thick plastic prisms above an opto-electronic chip for short-distance massive parallel data communication

5 REFERENCES

- [1] H. Thienpont et al, Proc. of the IEEE, 2000, Vol. 88, No. 6, pp. 769-779.
- [2] B. Volckaerts et al, Asian Journal of Physics, 2001, Vol. 10, No. 2, pp. 195-214.
- [3] L.Cosentino, P.Finocchiario, A.Pappalardo, A.Hermanne, H.Thienpont, M.Vervaeke, B.Volckaerts, P.Vynck, Ion micro-beam diagnostics with photodetectors, Nuclear Instruments & Methods in Physics Research sect.B, in print
- [4] L.Cosentino, P.Finocchiario, A.Pappalardo, A.Hermanne, H.Thienpont, M.Vervaeke, B.Volckaerts, P.Vynck, Ion micro-beam diagnostics with photodetectors for Deep Lithography applications, Proceedings of the 5th SHIM, Taormina, May 22-25, 2002
- [5] L.Cosentino, P.Finocchiario, A.Pappalardo, A.Hermanne, H.Thienpont, M.Vervaeke, B.Volckaerts, P.Vynck, Ion micro-beam diagnostics with photodetectors, Proceedings of the 3th

International Conference on New Developments on photodetection, Beaune, France, June 17-21, 2002

- [6] L.Cosentino, P.Finocchiario, A.Pappalardo, A.Hermanne, H.Thienpont, M.Vervaeke, B.Volckaerts, P.Vynck, Ion micro-beam diagnostics with photodetectors, Proceedings of the IEEE Nuclear Science Symp. Norfolk, Virginia (USA), November 12-14, 2002
- [7] L.Cosentino, P.Finocchiario, A.Pappalardo, A.Hermanne, H.Thienpont, M.Vervaeke, B.Volckaerts, P.Vynck, Diagnostic Tools For Low Intensity Ion Micro-Beams, 17th International Conference on the Application of Accelerators in Research and Industry CAARI 2002 November 12-16, 2002 University of North Texas Department of Physics Denton, Texas, USA
- [8] P.Vynck, B.Volckaerts, M.Vervaeke, H.Ottevaere, P.Tuteleers, L.Cosentino, P.Finocchiario, A.Pappalardo, A.Hermanne, H.Thienpont, Beam monitoring enhances Deep Proton Lithography: towards high-quality micro-optical components, Proceedings of the Annual Symposium of the IEEE/LEOS Benelux Chapter. Amsterdam (N), November 2002

LNS Journal publications

Amram P, Anghinolfi M, Anvar C, et al.

Sedimentation and fouling of optical surfaces at the ANTARES site
ASTROPART PHYS 19 (2): 253-267 MAY 2003

Angulo C, Azzouz M, Descouvemont P, et al.

Experimental determination of the Be-7+p scattering lengths
NUCL PHYS A 716: 211-229 MAR 24 2003

Angulo C, Descouvemont P, Cogneau M, et al.

The elastic scattering Be-7 + p at low energies: implications on the Be-7(p, γ)Be-8 S-factor
NUCL PHYS A 719: 300C-303C MAY 19 2003

Assafiri Y, Bartalini O, Bellini V, et al.

Double $\pi(0)$ photoproduction on the proton at GRAAL
PHYS REV LETT 90 (22): JUN 6 2003

Baldo M, Farine M, Lombardo U, et al.

Surface behaviour of the pairing gap in a slab of nuclear matter
EUR PHYS J A 18 (1): 17-23 SEP 2003

Baldo M, Lombardo U, Saperstein EE, et al.

Energy dependence of effective nucleon-nucleon interaction and position of the nucleon drip line
PHYS ATOM NUCL 66 (2): 233-246 FEB 2003

Balkanov V, Belolaptikov I, Bezrukov L, et al.

Simultaneous measurements of water optical properties by AC9 transmissometer and ASP-15 inherent optical properties meter in Lake Baikal
NUCL INSTRUM METH A 498 (1-3): 231-239 FEB 11 2003

Baran V, Colonna A, Di Toro M, et al.

Isospin effects in nuclear fragmentation
PHYS ATOM NUCL+ 66 (8): 1460-1470 AUG 2003

Boscolo I, Cialdi S, Gammino S, et al.

Operation of an electron-cyclotron-resonance ion source with supplemental electron injection
PHYS REV SPEC TOP-AC 6 (7): JUL 2003

Caruso A, Calabretta L, Sparta A, et al.

DDS-based multiple frequencies generator for the RF systems at INFN-LNS
NUKLEONIKA 48: S69-S72 Suppl. 2 2003

Ciavola G, Gammino S, Celona L, et al.

Beamline design for the transport of high intensity beams
NUCL INSTRUM METH B 204: 410-415 MAY 2003

Cirrone GAP, Cuttone G, Raffaele L, et al.

Natural and CVD type diamond detectors as dosimeters in hadrontherapy applications
NUCL PHYS B-PROC SUP 125: 179-183 SEP 2003

Cosentino L, Finocchiaro P

Ion beam imaging at very low energy and intensity
NUCL INSTRUM METH B 211 (3): 443-446 NOV 2003

Cosentino L, Finocchiaro P, Pappalardo A, et al.

Ion micro-beam diagnostics with photodetectors
NUCL INSTRUM METH B 209: 340-344 AUG 2003

Cosentino L, Finocchiaro P, Pappalardo A, et al.

Ion microbeam diagnostics with scintillators for application of deep lithography with particles
IEEE T NUCL SCI 50 (4): 774-777 Part 1 AUG 2003

De Filippo E, Lanzaò G, Rothard H, et al.

Absolute cross sections for binary-encounter electron ejection by 95-MeV/u Ar-36(18+) penetrating carbon foils
PHYS REV A 68 (2): AUG 2003

de Sereville N, Coc A, Angulo C, et al.

H-2(F-18,p alpha)N-15 reaction applied to nova gamma-ray emission
PHYS REV C 67 (5): MAY 2003

de Sereville N, Coc A, Angulo C, et al.

Study of the F-18(p,alpha)O-15 reaction for application to nova gamma-ray emission
NUCL PHYS A 718: 259C-262C MAY 5 2003

Di Pietro A, Figuera P, Amorini F, Angulo C, Cardella G, Cherubini S, Davinson T, Leanza D, Lu J, Mahmud H, Milin M, Musumarra A, Ninane A, Papa M, Pellegriti MG, Raabe R, Rizzo F, Ruiz C, Shotter AC, Soic N, Tudisco S

Light-particle emission in the reaction He-6+Zn-64 around the Coulomb barrier
EUROPHYS LETT 64 (3): 309-315 NOV 2003

Di Toro M, Baran V, Colonna M, et al.

Dynamics of phase transitions in asymmetric nuclear matter
NUCL PHYS A 722: 129C-135C JUL 14 2003

Gammino S

R&D of ECR ion sources: news and perspectives
NUKLEONIKA 48: S73-S79 Suppl. 2 2003

Gammino S, Ciavola G, Celona L, et al.

Third generation ECR ion sources: News and perspectives
NUCL INSTRUM METH B 205: 162-167 MAY 2003

Gammino S, Torrisi L, Ciavola G, et al.

Highly charged heavy ion generation by pulsed laser irradiation
NUCL INSTRUM METH B 209: 345-350 AUG 2003

Gerbaldo R, Botta D, Chiodoni A, et al.

Pseudo-periodic nanostructuring of Ag-clad BSCCO-2223 multifilamentary tapes as a tool to tune in-field superconducting performance
IEEE T APPL SUPERCON 13 (2): 3000-3003 Part 3 JUN 2003

Ghetti R, Helgesson J, Avdeichikov V, et al.

Chronology of particle emission from the $E/A=61$ MeV Ar-36+Al-27 reaction

PHYS REV LETT 91 (9): AUG 29 2003

Girard A, Hitz D, Melin G, et al.

Utilization of gyrotrons in the field of ECRIS for accelerators, first results and perspectives

NUCL FUSION 43 (11): 1520-1525 NOV 2003

Goldberg VZ, Trzaska WH, Rogachev G, et al.

Recent results in the studies of nuclear structure by resonance scattering with radioactive beams

REV MEX FIS 49: 124-129 Suppl. 4 NOV 2003

Goldberg VZ, Trzaska WH, Rogachev GV, et al.

New perspectives in the studies of resonance scattering

ACTA PHYS HUNG NS-H 18 (2-4): 215-222 2003

Gramegna F, Mastinu PF, Vannucci L, et al.

New perspectives for studies of reaction mechanisms at low-medium energies

ACTA PHYS POL B 34 (4): 2353-2362 APR 2003

Greco V, Baran V, Colonna M, et al.

Relativistic effects in the search for high density symmetry energy

PHYS LETT B 562 (3-4): 215-220 JUN 12 2003

Greco V, Colonna M, Di Toro M, et al.

Collective modes of asymmetric nuclear matter in quantum hydrodynamics

PHYS REV C 67 (1): JAN 2003

Lanzanò G, Anzalone A, Arena N, et al.

Recent results on fast electron production induced by energetic heavy ions on thin solid targets

NUCL INSTRUM METH B 209: 212-218 AUG 2003

Lanzanò G, De Filippo E, Anzalone A, et al.

Recent results on fast intermediate velocity electron production induced by $19(+)$ 45 A MeV Ni-58 highly charged ions on thin solid targets

NUCL INSTRUM METH B 205: 841-846 MAY 2003

Laska L, Jungwirth K, Kralikova B, et al.

Generation of multiply charged ions at low and high laser-power densities

PLASMA PHYS CONTR F 45 (5): 585-599 MAY 2003

Lepine-Szily A, Oliveira JM, Galante D, et al.

Spectroscopy of light proton-rich unbound nuclei: F-15, N-10, N-11

NUCL PHYS A 722: 512C-517C JUL 14 2003

Lombardo U, Shen CW, Van Giai N, et al.

Neutrino mean free path in neutron stars

NUCL PHYS A 722: 532C-537C JUL 14 2003

Maggiore M, Rifuggiato D, Calabretta L

A superconducting cyclotron as a primary accelerator for exotic beam facilities
NUKLEONIKA 48: S165-S167 Suppl. 2 2003

Mikhailov IN, Briancon C, Mikhailova TI, et al.

Memory effects in nuclear friction
PHYS ATOM NUCL+ 66 (9): 1599-1606 SEP 2003

Nociforo C, Cappuzzello F, Cunsolo A, et al.

Investigation of light neutron-rich nuclei via the (Li-7, Be-7) reaction
ACTA PHYS POL B 34 (4): 2387-2390 APR 2003

Papa M, Bonanno A, Amorini F, et al.

Coherent and incoherent giant dipole resonance gamma-ray emission induced by heavy ion collisions: Study of the Ca-40+Ca-48 system by means of the constrained molecular dynamics model
PHYS REV C 68 (3): SEP 2003

Peng GX, Chiang HC, Ning PZ, et al.

Chiral condensates in quark and nuclear matter
INT J MOD PHYS A 18 (18): 3151-3174 JUL 20 2003

Pierroutsakou D, Di Toro M, Amorini F, Baran V, Boiano A, De Rosa A, D'Onofrio A, Inglis G, La Commara M, Ordine A, Pellegriti N, Rizzo F, Roca V, Romoli M, Sandoli M, Trotta M, Tudisco S

Pre-equilibrium dipole strength in charge asymmetric peripheral heavy-ion reactions
EUR PHYS J A 16 (3): 423-435 MAR 2003

Pierroutsakou D, Boiano A, De Rosa A, Di Pietro M, Inglis G, La Commara M, Ming Ruhan, Martin B, Mordente R, Ordine A, Rizzo F, Roca V, Romoli M, Sandoli M, Soramel F, Stroe L, Trotta M, Vardaci E.

Prompt dipole γ -ray emission in fusionlike heavy-ion reactions
EUR PHYS J A 17 (1): 71-76 MAY 2003

Pizzone RG, Spitaleri C, Lattuada M, et al.

Bare astrophysical $S(E)$ -factor for the Li-6(d, α)He-4 and Li-7(p, α)He-4 reactions at astrophysical energies
NUCL PHYS A 718: 496C-498C MAY 5 2003

Pizzone RG, Spitaleri C, Lattuada M, et al.

Proton-induced lithium destruction cross-section and its astrophysical implications
ASTRON ASTROPHYS 398 (2): 423-427 FEB 2003

Pizzone RG, Spitaleri C, Lattuada M, et al.

The Li-7(p, α)He-4 fusion reaction studied via the Trojan Horse Method and its astrophysical implications
NUCL PHYS B-PROC SUP 118: 455-455 APR 2003

Rifuggiato D, Calabretta L, Cuttone G

Status report of the LNS superconducting cyclotron
NUKLEONIKA 48: S131-S134 Suppl. 2 2003

Rovelli A, Amato A, Botta D, Chiodoni A, Gerbaldo R, Ghigo G, Gozzelino L, Laviano F, Negro M, Mezzetti E, Martini L, Curcio F

An irradiation facility for in-vacuum heavy-ion irradiation of large area superconductors
International Journal of Modern Physics B 17 (2003) 727

Shchepunov VA, Cunsolo A, Cappuzzello F, et al.

Numerical computation of arbitrary order transfer maps and reconstructive correction of aberrations in the large acceptance spectrometer MAGNEX

NUCL INSTRUM METH B 204: 447-453 MAY 2003

Shen CW, Lombardo U, Schuck P, et al.

Screening effects on $S=1(0)$ pairing in neutron matter

PHYS REV C 67 (6): JUN 2003

Shen CW, Lombardo U, Van Giai N, et al.

Neutrino mean free path in neutron stars

PHYS REV C 68 (5): NOV 2003

Soic N, Cherubini S, Lattuada M, et al.

Li-8 + alpha decay of B-12 and its possible astrophysical implications

EUROPHYS LETT 63 (4): 524-530 AUG 2003

Song HQ, Baldo M, Fiasconaro A, et al.

Three nucleon correlations in nuclear medium

MOD PHYS LETT A 18 (2-6): 317-321 FEB 28 2003

Spatola C, Privitera G, Raffaele L, et al.

Clinical application of proton beams in the treatment of uveal melanoma: The first therapies carried out in Italy and preliminary results (Catana project)

TUMORI 89 (5): 502-509 SEP-OCT 2003

Spitaleri C, Cherubini S, Del Zoppo A, et al.

The Trojan Horse Method in nuclear astrophysics

NUCL PHYS A 719: 99C-106C MAY 19 2003

Szydlowski A, Badziak J, Parys P, et al.

Measurements of energetic ions emitted from laser produced plasma by means of solid state nuclear track detectors of the PM-355 type

PLASMA PHYS CONTR F 45 (8): 1417-1422 AUG 2003

Szydlowski A, Badziak J, Parys P, et al.

Measurements of energetic ions produced by high-energy laser pulses by means of solid-state nuclear track detectors

HIGH TEMP MATER P-US 7 (3): 327-332 2003

Torrisi L

Radiation effects and pulsed laser deposition of titanium by Nd : Yag laser

RADIAT EFF DEFECT S 158 (11-12): 811-818 NOV-DEC 2003

Torrisi L

Tungsten ions produced by infrared pulsed laser irradiation

RADIAT EFF DEFECT S 158 (10): 689-703 OCT 2003

Torrisi L, Gammino S, et al

Non-equilibrium plasma production by pulsed laser ablation of gold

RADIAT EFF DEFECT S 158 (11-12): 757-769 NOV-DEC 2003

Torrise L, Gammone S, L, et al.

Comparison of nanosecond laser ablation at 1064 and 308 nm wavelength
APPL SURF SCI 210 (3-4): 262-273 APR 15 2003

Torrise L, Gammone S, Mezzasalma AM, et al.

Implantation of ions produced by the use of high power iodine laser
APPL SURF SCI 217 (1-4): 319-331 JUL 15 2003

Torrise L, Gammone S, Mezzasalma AM, et al.

Tantalum irradiation by high power pulsed laser at 1315 and 438 nm wavelengths
APPL SURF SCI 220 (1-4): 193-202 DEC 30 2003

Torrise L, Gentile C, Visco AM, et al.

Wetting modifications of UHMWPE surfaces induced by ion implantation
RADIAT EFF DEFECT S 158 (10): 731-741 OCT 2003

Torrise L, Visco AM, Valenza A

Ion implantation on ultra high molecular weight polyethylene (UHMWPE) for medical prosthesis
RADIAT EFF DEFECT S 158 (9): 621-633 SEP 2003

Tudisco S, Musumeci F, Scordino A, Privitera G.

Advanced research equipment for fast ultraweak luminescence analysis
REV SCI INSTRUM 74 (10): 4485-4490 OCT 2003

Tumino A, Spitaleri C, Cherubini S, et al.

Indirect study of the $Li-6(p,\alpha)He-3$ reaction at astrophysical energies
NUCL PHYS A 718: 499C-501C MAY 5 2003

Tumino A, Spitaleri C, Di Pietro A, et al.

Validity test of the "Trojan horse" method applied to the $Li-6(p,\alpha)He-3$ reaction
PHYS REV C 67 (6): JUN 2003

Wolowski J, Badziak J, Boody FP, et al.

Characteristics of ion emission from plasma produced by high-energy short-wavelength (438 nm) laser radiation
PLASMA PHYS CONTR F 45 (7): 1087-1093 JUL 2003

Zuo W, Lejeune A, Lombardo U, et al.

Three-body force effects on EOS of asymmetric nuclear matter and proton fraction in neutron star matter
COMMUN THEOR PHYS 39 (4): 439-446 APR 15 2003

Zuo W, Lombardo U, Li ZH, et al.

Properties of isospin asymmetric nuclear matter and extended BHF approach (III) HVH theorem and Fermi energy
HIGH ENERG PHYS NUC 27 (1): 31-35 JAN 2003

Zuo W, Lombardo U, Liu JL, et al.

Properties of isospin asymmetric nuclear matter and extended BHF approach proton and neutron mean free paths and their isospin dependence
HIGH ENERG PHYS NUC 27 (10): 888-891 OCT 2003

Zuo W, Lombardo U, Liu JY, et al.

Properties of isospin asymmetric nuclear matter and extended BHF approach (IV) - Single-particle potential and effective mass

HIGH ENERG PHYS NUC 27 (5): 416-420 MAY 2003

Zuo W, Lombardo U, Liu JY, et al.

Properties of isospin asymmetric nuclear matter and Extended BHF approach (V) - Three-body force effect on single-particle potential

HIGH ENERG PHYS NUC 27 (7): 585-589 JUL 2003

Zuo W, Lombardo U, Shen CW

Spin-polarized states of nuclear matter

COMMUN THEOR PHYS 39 (2): 219-222 FEB 15 2003

Zuo W, Lombardo U, Shen CW, et al.

Equation of state of spin-polarized neutron matter

HIGH ENERG PHYS NUC 27 (11): 999-1004 NOV 2003

Zuo W, Shen CW, Lombardo U

Landau parameters of nuclear matter in the spin and spin-isospin channels

PHYS REV C 67 (3): MAR 2003

SEMINARS

9-01-2003

Danilo Giulietti

Dipartimento di Fisica "E. Fermi", Università di Pisa

Fasci di elettroni e protoni energetici prodotti nei plasmi con impulsi laser ultra-corti ed intensi

27/01/2003

A.G. Karydas

Laboratory for Material Analysis, Institute of Nuclear Physics, NCSR "Demokritos", Athens

Importance of the in-situ X-Ray Fluorescence (XRF) analyses in the preservation and conservation of material culture

28/01/2003

A.G. Karydas

Laboratory for Material Analysis, Institute of Nuclear Physics, NCSR "Demokritos", Athens

A critical review of the Greece experience and future perspectives

29/01/2003

V. Costa

INAF Osservatorio Astrofisico di Catania

Utilizzo dei modelli in astrofisica nucleare

20/02/2003

Ugo Amaldi - G. Tosi

Università Bicocca e Fondazione TERA- Istituto Europeo di Oncologia e Fondazione TERA

L'adroterapia profonda e il Centro Nazionale per protoni e ioni carbonio

4-03-2003

P. Spaedtke

GSI, Darmstadt

Design of extractors for intense beams of highly charged heavy ions

5-03-2003

P. Spaedtke

GSI, Darmstadt

Design of extractors for intense beams of highly charged heavy ions (Part II)

6-03-2003

P. Spaedtke

GSI, Darmstadt

The role of ion source in the future of GSI Accelerator Division

10/03/2003

Na-Ngo-Leung

Lawrence Berkely National Laboratory, USA

Development of Compact Neutron Generator and Its Applications : BNCT Brachytherapy and Radioactive Ion Beam Systems

30/04/2003

M. Di Giacomo

GANIL

Cavità a radiofrequenza per SPIRAL II

20/05/2003

Art Olin

TRIUMF Laboratory, Vancouver, Canada

Nuclear Astrophysics with DRAGON at ISAC: the $^{21}\text{Na}(p,g)^{22}\text{Mg}$ Reaction

13/06/2003

M. Menna

LNS

Produzione on-line di ^8Li : primi risultati e prospettive future

1/07/2003

V. Kuznetov

Institute for Nuclear Research, Moscow

Neutron detection in fundamental physics

25-09-2003

A. Larionov

Giessen University

Pion production in heavy ion collisions around 1 A GeV

22-12-2003

M. Peez

CPPM Marsiglia

Research of signature of deviation to SM at HERA collider

EXPERIMENTS PERFORMED AT THE LNS ACCELERATORS IN 2003

Superconducting Cyclotron Experiments				
Proposal	Spokesperson Affiliation	Title	Beam	hours
DOSIMETRY	S.Onori (ISS- Roma)	Solid state dosimetry of proton beams	P	80
LITHO	B.Volckaerts (Vrije Univ. Brussel)	The Fabrication of Micro Opto-Mechanical Components with High Energetic Heavy Ion Beams	^{12}C	64
SURADDACS	E.Mezzetti (Politecnico Torino)	High energy ion irradiation	^{197}Au	90
CLUSTER-FUTURE	A.Pagano (INFN-Sez.Catania)	Cluster production in multifragmentation	$^{124}\text{Sn}, ^{112}\text{Sn}$	120
CATANA	G.Cuttone (INFN-LNS)	CATANA	P	620
METABOLIC	V.Viti (ISS-INFN- Roma)	Metabolic effects induced by proton irradiation of human tumor cells as evidenced by Magnetic Resonance Spectroscopy	P	60
CHIMERAPS	A.Pagano-G.Politi (INFN-Sez. Catania)	Pulse shape with the CHIMERA Detector	$^{86}\text{Kr}, ^{58}\text{Ni}$	100
DISSIPATION	J.Wilczynski-A.Pagano (Univ. Warsaw)	Signatures of the onset of two-body dissipation in nucleus-nucleus collisions	^{197}Au	124
CALIBRATION-CS	A.Pagano (INFN-Sez. Catania)	Calibration of CHIMERA II campaign with CS beam	$^{16}\text{O}, ^4\text{He}, \text{P}, ^{12}\text{C}, \text{d}$	173
ALPHA CLUSTER	B.Borderie (IPN-Orsay)	Search for alpha cluster condensation with CHIMERA	^{40}Ca	80
THERMO	M.Bruno (Univ. Bologna)	Thermodynamical coordinates of excited nuclear systems	$^{58}\text{Ni}, ^{62}\text{Ni}$	126
LIMITING	G.Cardella (INFN-Sez. Catania)	Limiting excitation energy of nuclear matter	^{40}Ca	71
SEMIPERIPHERAL	G.Poggi (Univ. Firenze)	Test measurements with the CHIMERA array for studies of non equilibrium emission in semiperipheral reactions	^{124}Sn	40
ATER	P.Colautti (INFN-LNL)	To measure the microdosimetric features of the therapeutic proton beam	P	16
MICROGRAVITY	M.Durante-P.Scampoli (Univ. Napoli)	Radiation induced transmissible chromosomal aberrations and their modification in simulated microgravity	^{12}C	30
DIPOLE	D.Pierroutsakou (INFN-Sez. Napoli)	Study of the pre-equilibrium dipole γ -ray emission as a function of the incident energy in fusion like heavy ion reactions	^{40}Ar	220
ISOSPIN	A.Pagano (INFN-Sez.Catania)	Isospin dependence of the nuclear reaction mechanism in semi-peripheral collisions at the fermi energies	$^{124}\text{Sn}, ^{112}\text{Sn}$	280
TRASMARAD	M.Papa (INFN-Sez. Catania)	Dipolar γ decay in selected fusion reactions and binary dissipative reactions	^{40}Ca	126
AMS	B.Alpat (INFN-Sez. Perugia)		^{86}Kr	48
H.I. Test	D. Rifuggiato (INFN-LNS)	High intensity test	^{20}Ne	53
ION-SOURCES	S.Gammino (INFN-LNS)	Laser ion source coupled to ECR ion source for heavy ion production		288
				2809

Tandem Experiments				
Proposal	Spokesperson Affiliation	Title	Beam	hours
SURADDA	E.Mezzetti (Politecnico Torino)	High energy ion irradiation	^{197}Au	78
DIAMOND	R.Potenza, C.Tuvé (Univ. Catania)	Quality standardization of diamond detectors	^{12}C , ^{14}N , ^7Li	196
BIO-EFFECTS	M.Purrello (Univ. Catania)	Biological effects of proton beams	P	49
IONISATION	M.Menna (INFN-LNS)	Ionisation studies for improving the performance of the EXCYT facility	^6Li	224
CALIBRATION	A.Pagano (INFN-Sez.Catania)	Calibration of CHIMERA II campaign with Tandem beam	^{16}O , ^{12}C , ^{32}S , P, ^{19}F , ^{58}Ni	136
SIGMA-N	S.Cherubini (Ruhr-Univ. Bochum)	The Trojan Horse Method as a tool for studying the influence of electron screening on measurements of astrophysical cross sections	^6Li , ^9Be , ^7Li	729
CONDENSATION	M.Brenner (Abo Akademi-Finland)	Search for condensates of alpha particles in ^{32}S by α particle transfer	^6Li	132
LITHO	B.Volckaerts (Vrije Univ. Brussel)	The fabrication of micro opto-mechanical components with highly energetic heavy ion beams	^{12}C	148
BIG BANG	C.Rolfs (Ruhr-Univ. Bochum)	Astrophysical S(E) factor of $^8\text{Li}(\alpha, n)^{11}\text{B}$: Big Bang nucleosynthesis	^7Li	371
PIRAMIDE	G.Busatto (Univ. Cassino)	Particle Irradiation tests for Aerospace Missions of power DEvices	^{58}Ni	225
				2288

ORGANIZATION AND PERSONNEL

Director: E. Migneco

Research Coordinators

Experimental Nuclear Physics : R. Alba

Interdisciplinary Physics and Technological Developments: L. Calabretta

Theoretical Physics: U. Lombardo

Division Head

Research : M. Lattuada

Accelerators: D. Rifuggiato

Technical and General Service: G. Schillaci

Scientific Committee

Chairman: Bernard Tamain (Laboratoire de Physique Corpusculaire, Caen Cedex)

Members: Marcel Arnould (Université Libre de Bruxelles), Giacomo De Angelis (INFN-LNL) Alessandro Olmi (Firenze University), Willibrord Reisdorf (GSI), Marie France Rivet (IPN), Rolf Siemssen (Argonne National Laboratory)

Administration Service Unit

C. Vittorio

Users Committee

Director's Delegate: A. Pagano

Accelerator Coordinators

TANDEM: V. Scuderi

LABORATORY PERSONNEL

Research Division

- | | |
|---------------------------|-----------------------------------|
| 1. AGODI Clementina | 14. DI PIETRO Alessia Francesca |
| 2. ALBA Rosa | 15. FIGUERA Pierpaolo |
| 3. ANDO' Lucio | 16. FINOCCHIARO Paolo |
| 4. ANZALONE Antonino | 17. GAMMINO Santo |
| 5. BARAN Virgil (art. 23) | 18. MAIOLINO Concettina |
| 6. BONASERA Aldo | 19. MENNA Mariano |
| 7. CALABRETTA Luciano | 20. PIATTELLI Paolo |
| 8. CELONA Luigi Giuseppe | 21. RAIA Guido |
| 9. CIAVOLA Giovanni | 22. RIFUGGIATO Danilo |
| 10. COLONNA Maria | 23. RE Maurizio |
| 11. CONIGLIONE Rosa | 24. ROVELLI Alberto |
| 12. CUTTONE Giacomo | 25. SAPIENZA Piera |
| 13. DEL ZOPPO Antonio | 26. WINFIELD John Stuart (art 23) |

Administrative Technical Staff

- | | |
|---------------------|--|
| 1. AGNELLO Gaetano | 5. AVOLIO Renato |
| 2. ALLEGRA Antonino | 6. BANDIERAMONTE Davide (art. 15) |
| 3. AMATO Antonino | 7. BARBAGALLO Giovanni |
| 4. ATTINA' Giuseppe | 8. BILLA Maria Anna |
| | 9. BRANCATO Sebastiana Liliana (art. 15) |

10. CACOPARDO Giorgio
11. CAFICI Maurizio
12. CALI' Claudio
13. CALZONA Vincenzo (art. 15)
14. CAMPAGNA Vincenzo
15. CANTONE Alessandro (art. 6)
16. CARBONARO Antonio
17. CARDILLO Salvatore
18. CARUSO Antonino
19. CARUSO Carmelo (art. 15)
20. CARUSO Fausta
21. CASTRO Maurizio
22. CAVALLARO Salvo Rita
23. CHINES Francesco
24. COSTA Eugenio
25. COSTANZO Orazio
26. D'AGATA Antonino
27. D'AMATO Carmelo
28. D'AMATO Vito
29. D'AMBRA Agata (art. 6)
30. DE LUCA Giovanni
31. DEL TEVERE Francesco (art.15)
32. DI BIASI Romeo
33. DI MODICA Salvatore
34. DI NUNZIO Dorotea
35. DI PRIMA Maria Lucia (art 6)
36. DISTEFANO Antonio
37. FERLITO Santa art. 6
38. FERRERA Francesco
39. FURIA Enrico
40. GALLO Giuseppe
41. GARRAFFO Rosa (art. 6)
42. GRECO Giovanna
43. GRMEK Antonio
44. LITRICO Francesco
45. LITRICO Pietro
46. LO VECCHIO Vincenzo
47. MANCUSO Margherita (art.6)
48. MANISCALCO Paolino
49. MANNO Giovanni
50. MARCHESI Letizia
51. MARCHETTA Carmelo
52. MARINO Salvatore
53. MARLETTA Rosario
54. MARLETTA Salvatore
55. MAUGERI Antonio
56. MESSINA Esteban
57. MIRABELLA Alfio
58. MUSARRA Fortunato
59. PACE Luigi
60. PAGANO Antonio
61. PANASCI' Giuseppe
62. PASSARO Giuseppe (art. 15)
63. PASSARELLO Santi
64. PERCOLLA Carmelo (art. 15)
65. PISCOPO Massimo
66. PLATANIA Grazia (art. 6)
67. POTENZA Virginia Rita (art. 15)
68. PRIVITERA Patrizia
69. PUGLISI Patrizia (art. 6)
70. PULVIRENTI Salvatore
71. REINA Paolo
72. ROBERT Emmanuel (art. 15)
73. RUGGIERI Giovanna
74. RUSSO Salvatore
75. RUSSO Simona (art.6)
76. SALAMONE Sebastiano
77. SANTONOCITO Antonino
78. SAPIO Paola Maria (art. 6)
79. SARTA Giuseppe
80. SCHILIRO' Nunzia
81. SCHILLACI Gaetano
82. SCUDERI Dario (art. 6)
83. SEDITA Mario
84. SEMINARA Angelo
85. SPARTA' Antonino
86. SPARTI Annalisa (art. 6)
87. SPEZIALE Fabrizio
88. TODARO Venera
89. TOSCANO Carmelo (art. 6)
90. TOSCANO Lucio
91. TRINGALE Matteo
92. TRINGALE Salvatore
93. TROVATO Biagio
94. TUDISCO Debora (art. 6)
95. TUDISCO Francesco
96. TUDISCO Roberta (art. 15)
97. VARISANO Antonio
98. VASTA Giovanni
99. VITTORIO Carmelo
100. ZAMMATARO Rachela
101. ZAPPALA' Emilio

Scientific & Technological Associates

1. BELLIA Giorgio
2. BELLINI Vincenzo
3. CAVALLARO Salvatore
4. CUNSOLO Angelo
5. DI TORO Massimo
6. GIUSTOLISI Francesco
7. LATTUADA Marcello
8. LOMBARDO Umberto
9. MIGNECO Emilio
10. PAPPALARDO Giuseppe
11. PORTO Francesco
12. RACITI Giovanni
13. RIZZO Francesca
14. SCUDERI Vincenzo
15. SPERDUTO Maria Leda
16. SPITALERI Claudio
17. TORRISI Lorenzo
- 18. VINCIGUERRA Domenico**

INFN Fellows

1. ALLIA Maria Concetta
2. BATTAGLIA Daniele
3. BONOMO Carmen
4. CAPPUZZELLO Francesco
5. CARACE Fausto
6. COSENTINO Luigi
7. COCIMANO Rosanna
8. COSTA Michele
9. COSTA Rosa
10. D'AMICO Antonio
11. GAITANOS Theodoros
12. GARUFI Donatella
13. KIMURA Sakie
14. LA COGNATA Marco
15. LAMIA Livio
16. MELE Stefania
17. MUSUMECI Mario Salvatore
18. OCCHIPINTI AMATO Rosario
19. PAPPALARDO Luciano
20. PELLEGRITI Maria Grazia
21. PELLEGRITI Nicola
22. PIZZONE Rosario
23. PRESTI Mario
24. PRIVITERA Simona
25. RICCOBENE Giorgio
26. RIZZO Joseph
27. SANTONOCITO Domenico
28. SHEN Caiwan
29. TIAN Wendong

INFN/CIAE Fellows

1. FAN Hongmei
2. FAN Hongshen
3. GUO Xiaohong
4. Li Chen Bo
5. LI Xia
6. ZHANG Xuezheng
7. ZHANG Xin

Other Fellows

1. AMORINI Francesca
2. BONANNO Antonino
3. CABIBBO Maurizio
4. CHERUBINI Silvio
5. GULINO Marisa
6. LANZALONE Gaetano
7. KUZNETSOV Viacheslav
8. LOJACONO Pietro Augusto
9. MAMMOLITI Francesco
10. MIDILI Federica
11. NICOLETTI Luisa
12. PATTI Iolanda Valeria
13. PEDALINO Alberto
14. SFIENTI Concettina
15. SIRAGUSA Carmelo
16. TUDISCO Salvatore
17. TUMINO Aurora
18. VALASTRO Lucia Mari

PHD Students

1. CIRRONE Giuseppe
2. CONSOLI Fabrizio
3. DE NAPOLI Marzio
4. DI STEFANO Carla
5. FERINI Graziella
6. GIUSA Antonio
7. LA GUIDARA Elena
8. LAZZARO Alberto
9. MAGGIORE Mario
10. ORRIGO Sonja
11. PRIVITERA Giuseppe
12. RAPISARDA Elisa
13. RINOLLO Angelo
14. SPATARO Stefano
15. SPEZZI Loredana
16. TERRANOVA Salvatrice

Under Graduated

1. AMORE Isabella
2. BUFALINO Stefania
3. CALANNA Alessandra
4. LEANZA Deborah Maria
5. LIONTI Riccardo
6. LONGO Giovanni
7. LO PRESTI Carmelo
8. MANZITTO Patrizia
9. MESSINA Rosaria
10. MORABITO Vittoria
11. PIEMONTE Alessandra
12. PITTERA Salvatore
13. RUSSO Giorgio
14. STRAZZERI Elisabetta
15. TOSCANO Simona

Scientific Guest

1. ALVES-CONDE' Robert
2. BARAN Virgil
3. BASRAK Zoran
4. BLICHARSKA Joanna
5. BRENNER Marten
6. CHATTERJEE Mihir Baran
7. DOBRESCU Serban
8. FAN Hongmei
9. FAN Hongsheng
10. GAITANOS Theodoros
11. GAUBERT Gabriel
12. GORYUNOV Oleg
13. GRZESZCZUK Andrzej
14. GUINET Daniel
15. GUO Xiaohong
16. KARIDAS Andreas-Germanos
17. KHLEBNIKOV Sergev
18. KIMURA Sachie
19. KOWALSKI Seweryn Cezary
20. KRASA Josef
21. KUZNETSOV Viacheslav
22. LAPIK Alexander
23. LARIONOV Alexei
24. LASKA Leos
25. LE NEINDRE Nicolas
26. LEJEUNE Andr 
27. LEUNG Ka-Ngo
28. LI Chen Bo
29. LI Xia
30. LIU Bo
31. LOPEZ Olivier
32. MA ZhongyuMAIDIKOV Vasyl
33. MAJKA Zbigniew
34. MIKHAYLOVA Tatiana
35. MILE Zadro
36. MILJANIC Djuro
37. NIGGLI Hugo
38. NIKOLAOS Nicolis
39. OSTASHKO Volodymir
40. OTTEVAERE Heidi
41. PECELI Davorin
42. PETRASCU Horia
43. PFEIFER Miroslav
44. Piasecki Ernest
45. PIASECKI Ernest
46. PLANETA Roman
47. POP Amalia
48. RODRIGUEZ Gonzalo Sebastian
49. SCHACHER Leon
50. SCHUCK Peter
51. SHEN Caiwan
52. SIEMSEN Rudolf Hendrik
53. SPADTKE peter
54. STIEBING Berthard
55. SWIDERSKI Eukasz
56. THIENPONT Hugo
57. TIAN Wendong
58. TRZASKA Wladislaw
59. TUREA Aurelia
60. VAN GIAI Nguyen
61. WIELECZKO Joan Pior
62. WILCZYNSKI Sanusz
63. WILCZYNSKA Siwek
64. WOLTER Hermann
65. YILDIRIM Gerbulent
66. ZHANG Xin
67. ZHANG Xuezheng
68. ZHOU Daimei
69. ZIELINSKAPFABE Malgorzata
70. ZIPPER Wiktor

Events at LNS

February 7

Nuove metodologie per l'imaging mammografico. Problematiche mediche e fisiche

February 14

Olimpiadi della Fisica

February 27-28

FINUPHY(Frontier In Nuclear PHYsics) Round Table Meeting

March 14

Giornata di studio in ricordo del Prof.Antonino Rubbino

March 20-22

Workshop on forthcoming facilities at LNS: EXCYT and MAGNEX

April 7-11

I.N. F. N. Helium Refrigeration School

April 28-May 3

13 Settimana Cultura Scientifica e Tecnologica

June 24-28

III Mediterranean Medical Physics Meeting

September 18-19

Plasma production by Laser Ablation (Messina and Catania)

September 28 - October 5

Second European Summer School on Experimental Nuclear Astrophysics

October 22

visita del Dott.Alberto Di Pace Prefetto della Provincia di Catania

October 24

comitato internazionale per il coordinamento delle attività di fisica nucleare nei laboratori dell'INFN presieduto dal Prof. F. Iachello

November 10

Visit of the Japan Ambassador

November 24

LNS Users Committee

November 25-26

LNS Scientific Committee

December 3-6

XIII HADES Collaboration Meeting