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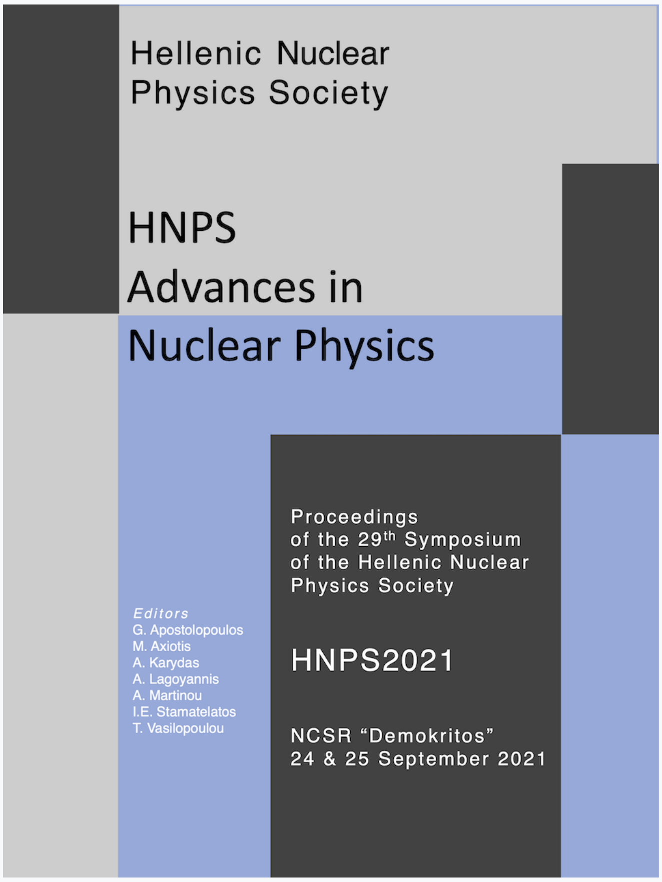

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Measurements of projectile fragments from ^{70}Zn + ^{64}Ni collisions with the MAGNEX spectrometer at INFN-LNS

S. Koulouris[1], G. A. Souliotis[1,*], F. Cappuzzello[2,3], D. Carbone[3], A. Pakou[4], C. Agodi[3], G. Brischetto[2,3], S. Calabrese[3], M. Cavallaro[3], I. Ciraldo[2,3], O. Fasoula[1], J. Klimo[5], K. Palli[1], O. Sgouros[3], V. Soukeras[3], A. Spatafora[2,3], D. Torresi[3], M. Veselsky[6]

[1] *Laboratory of Physical Chemistry, Department of Chemistry, National & Kapodistrian University of Athens, Athens, Greece*
[2] *Dipartimento di Fisica e Astronomia "Ettore Majorana", Universita di Catania, Italy*
[3] *Laboratori Nazionali del Sud, INFN, Catania, Italy*
[4] *Department of Physics and HINP, The University of Ioannina, Ioannina, Greece*
[5] *Institute of Physics, Slovak Academy of Sciences, Bratislava, Slovakia*
[6] *Institute of Experimental and Applied Physics, Czech Technical University, Prague, Czech Republic*

Abstract The present work is focused on our efforts to produce and identify neutron-rich rare isotopes from peripheral reactions below the Fermi energy. High-quality experimental data were obtained from a recent experiment with the MAGNEX spectrometer at INFN-LNS in Catania, Italy. The main goal of this effort is to describe the adopted identification techniques used to analyze the data from the reaction ^{70}Zn (15 MeV/nucleon) + ^{64}Ni. The particle identification procedure is based on a novel approach that involves the reconstruction of both the atomic number Z and the ionic charge q of the ions, followed by the identification of the mass. Our method was successfully applied to identify neutron-rich ejectiles from multinucleon transfer in the above reaction ^{70}Zn + ^{64}Ni at 15 MeV/nucleon. The analysis of the data is ongoing. We expect to obtain the angular and momentum distributions of the fragments, along with their production cross sections. These data, along with comparisons with theoretical models are expected to contribute to a better understanding of the complex reaction mechanisms of multinucleon transfer that dominate this energy regime.

Keywords Particle Identification, Neutron-rich Nuclei

INTRODUCTION

Up to the present time, approximately one half of the theoretically estimated 7000 bound nuclei have been investigated. Nuclei located far away from the valley of beta stability, toward the neutron dripline, are not present in nature and need to be prepared in the laboratory with proper nuclear reactions and separation techniques [1,2]. The main interest of our research group is the study of heavy-ion reactions below the Fermi Energy (~15-20 MeV/nucleon), in order to access nuclides with high neutron excess [3-6]. In order to access those nuclides however, apart from traditional routes like projectile fragmentation or spallation, it is necessary to pick up nucleons from the target nucleus. Such multinucleon transfer and deep-inelastic reactions dominate this energy regime, leading to a substantial production of neutron-rich projectile-like fragments. For the efficient collection of these fragments, the use of a large acceptance spectrometer is essential. For this reason, we initiated a project to produce and identify projectile-like fragments with the MAGNEX large-acceptance spectrometer at the INFN-LNS from the reaction $^{70}Zn^{15+}$ (15 MeV/nucleon) + ^{64}Ni.

* Corresponding author: soulioti@chem.uoa.gr

EXPERIMENTAL SETUP AND MEASUREMENTS

The measurements took place at the MAGNEX facility of the Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali del Sud (INFN-LNS) in Catania, Italy. MAGNEX is a large-acceptance magnetic spectrometer installed at the INFN-LNS laboratory in Catania, Italy. It is a high-acceptance device which utilizes both the advantages of the traditional magnetic spectrometry and those of a large momentum and angular acceptance detector [7,8]. A beam of $^{70}Zn^{+15}$ at 15 MeV/nucleon which was delivered by the S800 superconducting cyclotron, bombarded a 1.18 mg/cm^2 ^{64}Ni-target foil. The ejectiles passed through a 6 μm stripper foil, in order to reset their charge state to the equilibrium charge state value (+29) and then were detected by the spectrometer's Focal Plane Detector (FPD).

The focal plane detector (FPD) is a gas-filled (isobutane gas of 40 mbar pressure) hybrid detector with a wall of 60 silicon detectors at the end. The detector mainly consists of a Mylar foil (6μm) at the entrance window and a proportional drift chamber spanning at six sequential planes, responsible for the extraction of the horizontal and vertical coordinates of each incident particle. Thus, leading to a simultaneous determination of the angles theta (θ) and phi (φ) of the ion's trajectory. Moreover, the FPD provides the energy loss of the reaction products in the gas and also the residual energy of these fragments in the silicon detectors. Finally, the time-of-flight (TOF) of the ions was measured via a start signal from the silicon detectors of FPD and a stop signal from the radiofrequency of the cyclotron. In the experiment, only one-half of the active area of FPD was used and the vertical acceptance was limited, resulting in the use of only seven Si detectors of FPD.

PARTICLE IDENTIFICATION PROCEDURE

In general, the identification procedure is based on a novel approach that we developed in Ref. [9], in combination with the technique of Ref. [7]. According to the latter, the determination of the atomic number of the ejectiles involves a correlation between the residual energy measured by the silicon detectors (E_{resid}) and the total energy loss (ΔE_{cor}) in the gas section of the FPD corrected for path length differences depending on the angle of incidence. In Fig. 1, we present two plots depicting the total energy loss at the gas section of the FPD vs the residual energy measured by a single silicon detector. On the left-hand side, we present the results of our data from the reaction of ^{70}Zn + ^{64}Ni with the MAGNEX spectrometer. While on the right-hand side, we can see the results from the analysis that was carried out in Ref. [10]. It is evident that this correlation is actually quite useful for the determination of the atomic number Z in light ions. However, in our case of heavier medium-mass ions, we could not obtain an effective Z separation.

Based on this observation we moved on to a systematic approach to reconstruct the atomic number Z, by making use of the measured and calibrated quantities ΔE_{cor}, E_{resid} and TOF. Guided by Bethe's stopping power formula Z~u√ΔE, Z is reconstructed according to the following expression:

$$Z = a_0(\upsilon) + a_1(\upsilon)\sqrt{\Delta E_{cor} E_{tot}} + a_2(\upsilon)(\sqrt{\Delta E_{cor} E_{tot}})^2$$

where E_{tot} is the total kinetic energy of the ions reaching the FPD and determined from the expression:

$$E_{tot} = \Delta E_{tot} + \Delta E_w + E_{resid}$$

where ΔE_{tot} is the sum of the measured energy loss in the gas section of the FPD, E_{resid} the residual energy, as already mentioned, and ΔE_w a calculated correction for the energy loss in the entrance window of the FPD. In order to determine the velocity-dependent coefficients $a_0(\upsilon)$, $a_1(\upsilon)$ and $a_2(\upsilon)$ in the velocity range of interest, we followed the scheme of Ref. [11,12] for Z range 6-36 and in the energy range of 8–18 MeV/nucleon via a least-squares fitting procedure at each energy in steps of 0.5 MeV/nucleon. The values of each coefficient at the various energies were afterwards fitted with polynomial functions of velocity.

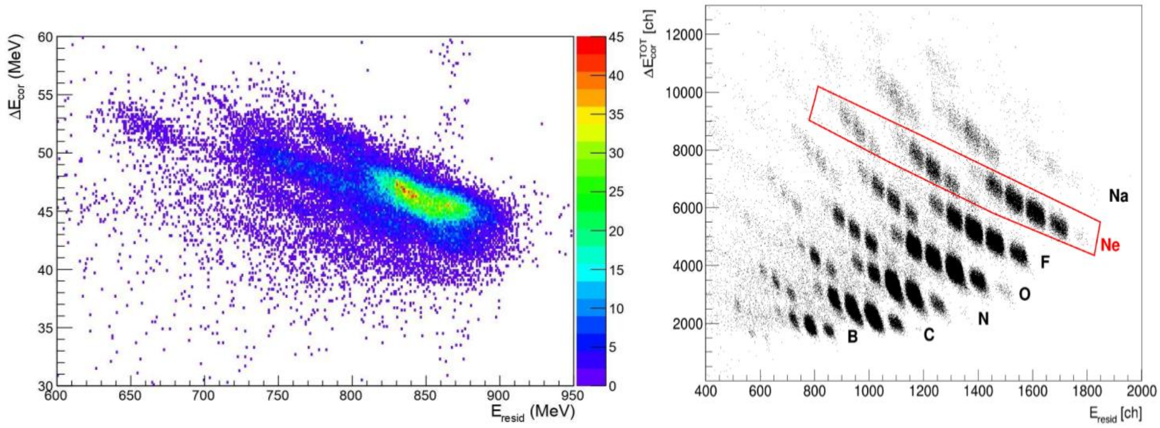

Fig. 1. *ΔE_{cor} vs E_{resid} correlation for the identification of Z. On the left, our data from the reaction of ^{70}Zn + ^{64}Ni with the MAGNEX spectrometer are presented. On the right, data from [10] are presented.*

The TOF measurement, along with the trajectory length of each particle, enabled us to calculate the charge state from the equation:

$$q = \frac{2\,E_{tot}}{B\rho}\,\frac{TOF}{L}$$

where L is the trajectory length obtained from the trajectory reconstruction, E_{tot} is the total energy of each particle and Bρ the magnetic rigidity. Bρ is extracted from the following equation:

$$B\rho = B\rho_0\,(1 + \delta)$$

where $B\rho_0$ is the magnetic rigidity of the central trajectory and δ is the fractional deviation from the central trajectory, which is calculated from the standard procedure of optical reconstruction as proposed in Ref. [7].

Our new effort for particle identification involves a correlation of the reconstructed atomic number Z with the reconstructed ionic charge state q of the products in a two-dimensional plot. After various efforts of reconstruction which are still ongoing, we present in Fig. 2 a preliminary plot. The presence of different areas is evident, corresponding to elements with also specific charge states. We were in position to select events of a specific Z and q, after proper gating as can be seen with the graphical contours on Fig. 2. An alternative approach could involve the construction of a reconstructed atomic number 1D spectrum as well as a reconstructed ionic charge state 1D spectrum. We can estimate the achieved resolutions (FWHM) of Z and q to be ∼0.8 and ∼0.7 units, respectively, for ejectiles near the projectile.

After proper gating, we implement the standard approach of particle identification for large acceptance spectrometers. This approach depends mainly on the relationship between the total kinetic energy of the ejectiles and the magnetic rigidity, according to the equation:

$$B\rho = \frac{\sqrt{m}}{q}\,\sqrt{2E_{tot}}$$

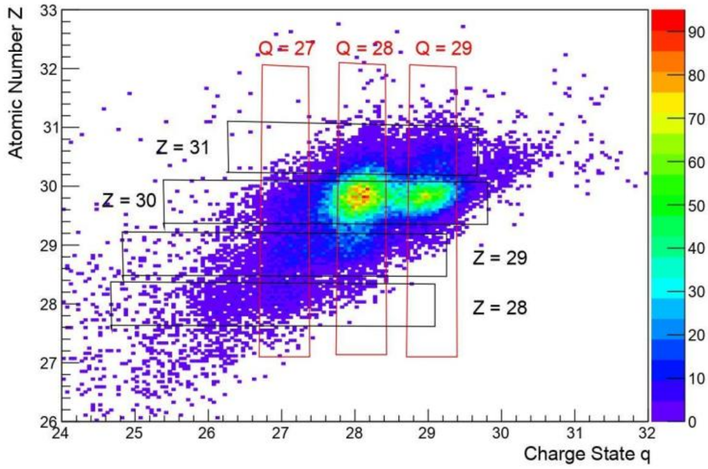

Fig. 2. *Reconstructed atomic number Z vs charge state q correlation of ejectiles from the ^{70}Zn + ^{64}Ni reaction. Graphical contours are shown on each band depicting the atomic numbers Z (horizontal bands) and the ionic charge states q (vertical bands) of the ejectiles.*

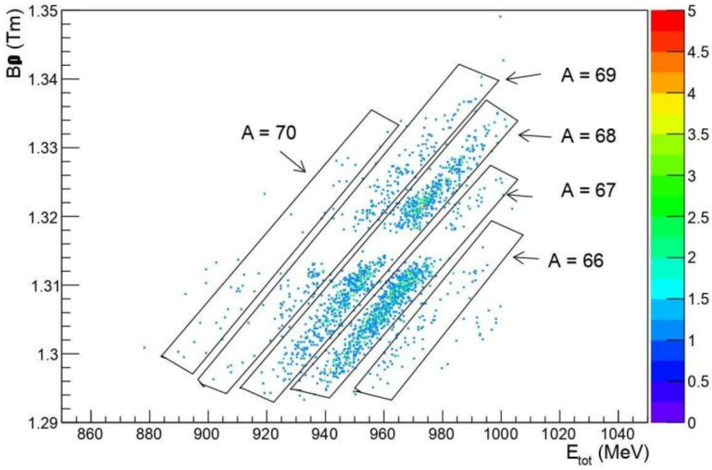

Fig. 3. *$B\rho$ vs E_{tot} correlation of ejectiles with Z = 29 and q = 28+. The gap in $B\rho$ is due to a gate set to exclude elastically scattered $^{70}Zn^{29+}$ ejectiles. Graphical contours indicate Cu^{28+} isotopes with A = 66–70.*

CONCLUSIONS

In the present work, the MAGNEX spectrometer was used to identify medium-mass ejectiles from peripheral reactions of a^{70}Zn beam at 15 MeV/nucleon energy with ^{64}Ni target. While analyzing the data, we found that the energy loss vs residual energy correlation was not adequate for the identification of the atomic number Z of the medium-mass ejectiles. For this reason, we developed a systematic approach, by employing the TOF and reconstructing both the atomic number Z and the ionic charge state q. We then moved on to a correlation of the reconstructed atomic number and the charge state to identify particles of specific Z and q. Finally a correlation of the magnetic rigidity vs the total energy yielded a mass separation of isotopes.

After the proper identification of the products, we plan to obtain their angular and momentum distributions and then their production cross sections. The experimental data will be compared with our model calculations. Recent efforts of our research group on calculations can be found in Ref. [13]. The analysis of the data, along with comparisons with theoretical models will play a key role in better understanding the complex reaction mechanisms that dominate this energy regime.

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