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Study of the reaction ^{70}Zn (15 MeV/nucleon) + ^{64}Ni with the MAGNEX spectrometer for the production of neutron-rich isotopes

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Abstract. We describe our efforts to study the production of neutron-rich isotopes from peripheral reactions of medium-mass heavy ions with the MAGNEX spectrometer at the INFN-LNS in Catania, Italy. Experimental data were obtained for the ^{70}Zn+^{64}Ni reaction at 15 MeV/nucleon. For the analysis of the data, we developed a new procedure for the reconstruction of both the atomic number Z and the ionic charge q of the ions, which is then followed by the identification of the mass. Preliminary results and the analysis plan will be discussed.

1 Introduction

To date, approximately one half of the theoretically estimated 7000 bound nuclei have been produced and investigated. Exotic nuclei located far away from the line of beta stability are not present in nature and need to be prepared in laboratory using proper nuclear reactions and separation techniques [1, 2]. One of the main concurrent challenges of the nuclear community in rare isotope beam facilities around the world is the production of neutron-rich nuclides to the limit of the neutron dripline. The investigation of neutron-rich nuclei could lead to a better understanding of important astrophysical nucleosynthesis processes, such as the rapid neutron capture process (r-process), which is responsible for half of the abundance of the nuclides heavier than iron. To have access to nuclides with high neutron-excess, besides the traditional routes of spallation, fission and projectile fragmentation, it is necessary to pick up neutrons from the target. Such nucleon transfer mechanisms mainly take place in peripheral nucleon-exchange reactions at beam energies from the Coulomb barrier [3] to the Fermi energy (20–40 MeV/nucleon) [4, 5].

Our interest was initially focused on the study of heavy-ion reactions at 25 MeV/nucleon, which led to a substantial production of neutron-rich nuclides [4]. Encouraged by these results, we moved on to studies at 15 MeV/nucleon [6, 7] that were mainly based on the use of the medium-acceptance MARS spectrometer [8]. Our studies at this energy, in particular with heavier targets such as Sn and Pb, underlined the importance of a large acceptance spectrometer for the access of nuclides with high neutron excess, which are concentrated at angles near the grazing angle. For this reason, we started a project to identify projectile-like fragments with the MAGNEX large acceptance spectrometer at the INFN-LNS from the reaction ^{70}Zn (15 MeV/nucleon) + ^{64}Ni.

The structure of the paper is as follows. In section 2, theoretical calculations are briefly presented. In section 3, the experimental setup and measurements are described. In section 4, the analysis of the data is presented with emphasis on the identification of heavy projectile-like fragments. Finally, a discussion and conclusions are given in section 5.

2 Calculations

Theoretical calculations carried out with the models CoMD [9] and DIT [10], followed by the statistical deexcitation code GEMINI [11], indicated substantial production of neutron-rich projectile fragments. In Fig. 1, we show the calculated mass distributions of projectile fragments with Z = 27–32 from the reaction of ^{70}Zn (15 MeV/nucleon) with ^{64}Ni obtained by DIT/GEMINI (solid red line), and by CoMD/GEMINI (dashed blue line). The results are encouraging concerning the production of neutron-rich isotopes especially near the projectile (e.g. Ni, Cu, Zn).

Furthermore, in Fig. 2 we present the elemental angular distributions of the same projectile fragments with

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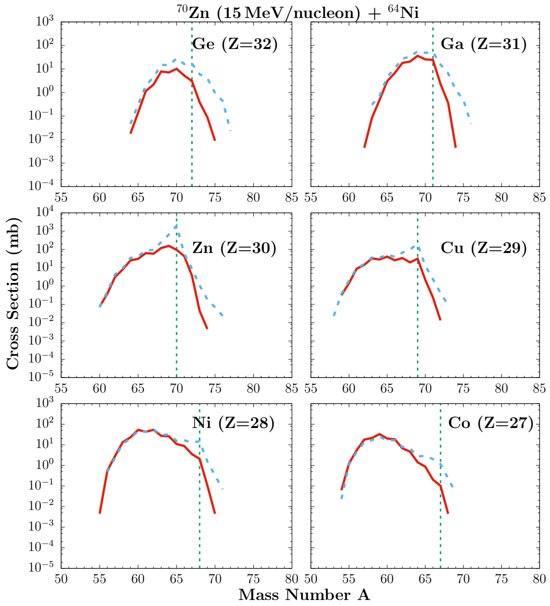

Figure 1. (Color online) Calculated mass distributions (lines) of projectile fragments with Z = 27–32 from the reaction of ^{70}Zn (15 MeV/nucleon) with ^{64}Ni. The calculations shown are: DIT/GEMINI (solid red line), CoMD/GEMINI (dashed blue line). The green vertical line indicates the starting point of neutron pickup.

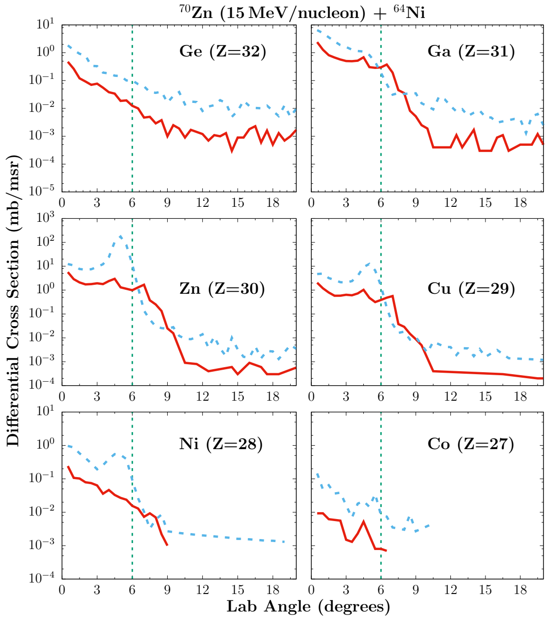

Figure 2. (Color online) Calculated elemental angular distributions of projectile fragments with Z = 27–32 from the reaction of ^{70}Zn (15 MeV/nucleon) with ^{64}Ni. The calculations shown are: DIT/GEMINI (solid red line), CoMD/GEMINI (dashed blue line). The green vertical line indicates the grazing angle for this reaction (θ_{gr} = 6.0°).

Z=27–32 from the above ^{70}Zn+^{64}Ni reaction. We note that for this system, the grazing angle is θ_{gr} = 6.0°. (A vertical dashed green line indicates this angle in Fig. 2.) The general feature of the calculated angular distributions with both the DIT and the CoMD models is that they peak near the grazing angle for elements close to the projectile (Cu, Zn, Ga). However, elements further away from the projectile are characterized by a rather monotonically decreasing angular distribution. As we see in Fig. 1 and Fig. 2, the CoMD model appears to give higher yields compared to DIT, especially for the neutron-rich products. We are currently trying to understand these differences. Of course, the plan is to compare these calculations with the experimental data from our MAGNEX experiment after the analysis will be completed in the near future.

3 Experimental Setup and Measurements

The experimental measurements were performed at the MAGNEX facility of the Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali del Sud (INFN-LNS) in Catania, Italy. MAGNEX is a high-acceptance device which makes use of both the advantages of the traditional magnetic spectrometry and those of a large angular and momentum acceptance detector [12, 13]. A beam of ^{70}Zn^{+15} at 15 MeV/nucleon, delivered by the S800 superconducting cyclotron, bombarded a 1.18 mg/cm^2 ^{64}Ni target foil. The ejectiles coming out from the target passed through a 6 μm stripper foil and then were detected by the spectrometer's Focal Plane Detector (FPD). In this pilot experiment, only one-half of the active area of FPD was used and the vertical angular acceptance was restricted in the range $-0.8°$ to $0.8°$, resulting in the use of only seven Si detectors of FPD. 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.

4 Particle Identification Procedure and Data Analysis

The particle identification is based on a new technique that we developed in ref. [14] in combination with the approach of [12]. Herein, we give an overview of the main points. According to [12], the atomic number of the ejectiles is determined by the ΔE$_{cor}$–E$_{resid}$ correlation involving the residual energy measured by the silicon detectors (E$_{resid}$) and the total energy loss (ΔE$_{cor}$) in the gas section of FPD corrected for path length differences depending on the angle of incidence. Although this correlation is adequate for the determination of Z of light ions (see, e.g., [15]), in the present case of medium-mass heavy ions, we could not obtain a clear Z separation. We thus developed an approach to reconstruct the atomic number Z based on the measured and properly calibrated quantities ΔE$_{cor}$, E$_{resid}$ and TOF. Using these calibrated quantities, and guided by the relation $Z \propto \upsilon\ \sqrt{\Delta E}$ from Bethe-Bloch equation, we developed an approach for the Z reconstruction, following [16], that is based on the velocity, ΔE$_{cor}$ and E$_{tot}$, where E$_{tot}$ is the total kinetic energy of the ions reaching FPD and determined from the expression:

$$E_{tot} = \Delta E_w + \Delta E_{tot} + E_{resid} \tag{1}$$

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 FPD. In our procedure, Z is reconstructed according to the following expression:

$$Z = c_0(\upsilon) + c_1(\upsilon)\sqrt{\Delta E_{cor} E_{tot}} + c_2(\upsilon)(\sqrt{\Delta E_{cor} E_{tot}})^2 \tag{2}$$

To determine the functions $c_0(\upsilon)$, $c_1(\upsilon)$ and $c_2(\upsilon)$ in the velocity range of interest, we used the energy loss data of Hubert et al. [17] to determine the coefficients of eq. (2) for the 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 subsequently fitted with polynomial functions of velocity.

After the Z reconstruction, we proceeded to reconstruct the ionic charge state of the ejectiles from the equation:

$$q = \frac{2E_{tot}}{B\rho}\frac{TOF}{L} \tag{3}$$

employing the total energy E$_{tot}$, the TOF measurement, as well as the trajectory length L of each particle, obtained from the trajectory reconstruction [9]. The magnetic rigidity Bρ was obtained from the equation:

$$B\rho = B\rho_0(1+\delta) \tag{4}$$

where δ is the fractional deviation from the magnetic rigidity Bρ_0 of the central trajectory obtained from the trajectory reconstruction procedure.

Our approach for particle identification involves a correlation of the reconstructed atomic number Z with the reconstructed ionic charge state q of the ejectiles in a two dimensional plot [14]. Adequate separation of the Z and q groups was achieved. The resolutions (FWHM) of Z and q are ~0.8 and ~0.7 units, respectively.

For the mass determination, we first set proper gates on the atomic number Z and the charge state q plot. Furthermore, we implement the standard approach of particle identification for large acceptance spectrometers [13]. This approach is based on the relationship between the total kinetic energy of the ions and the magnetic rigidity, according to the equation:

$$B\rho = \frac{\sqrt{m}}{q}\sqrt{2E_{tot}} \tag{5}$$

In a Bρ vs E$_{tot}$ correlation, the ejectiles are distributed on bands according to their $\frac{\sqrt{m}}{q}$. We note that in the Z vs q plot, we have identified and separated products with specific Z and q. Since q is given, the dependence is only on $\sqrt{m}$. Consequently, these bands represent various masses for a specific Z and q. In Fig. 3, we present a Bρ versus E$_{tot}$ plots of Cu^{28+} (Z=29, q=28) events. These events were selected by proper graphical contours of Z=29 and q=28 in the Z–q correlation [14]. The gap in the Bρ range is due to a software gate applied to exclude the elastically scattered ^{70}Zn^{29+} ejectiles. Adequate separation between the different mass bands of Cu^{28+} products is achieved. In this plot, the selection of the various masses can be performed by setting the respective graphical cuts, as shown in Fig. 3. Thus, we conclude that our goal to produce and identify medium-mass neutron-rich nuclides is achieved with a large acceptance spectrometer as MAGNEX.

5 Discussion and Conclusions

In this work, we presented our effort to produce and identify medium-mass ejectiles from a heavy-ion reaction with the use of the large acceptance magnetic spectrometer MAGNEX at INFN-LNS. We investigated the reaction of a ^{70}Zn beam at 15 MeV/nucleon with a ^{64}Ni target. In the data analysis, we found that the ΔE$_{cor}$ vs E$_{resid}$ correlation was not adequate for the Z identification of the medium-mass ejectiles. For this reason, we developed a new identification approach employing a measurement of TOF and

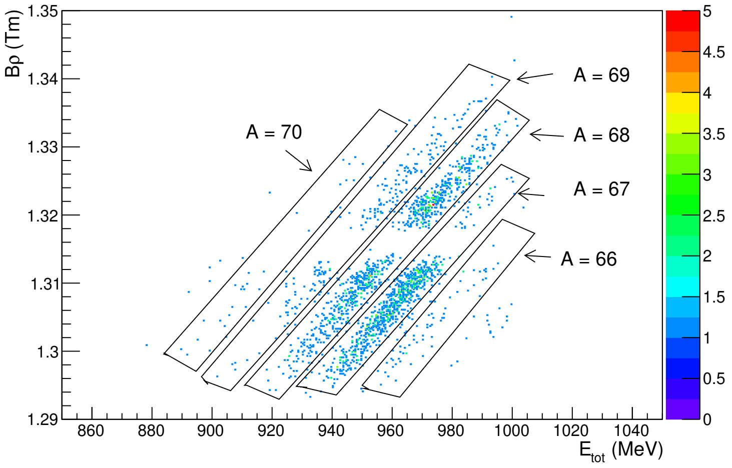

Figure 3. (Color online) Magnetic rigidity vs E_{tot} correlation of ejectiles from the ^{70}Zn (15 MeV/nucleon) + ^{64}Ni reaction corresponding to the gate of Z=29, q=28. The gap in Bρ is due to a gate set to exclude elastically scattered ^{70}Zn^{29+} ejectiles. Graphical contours are drawn to separate the masses A = 66–70 of Cu^{28+}.

the reconstruction of both the atomic number Z and the ionic charge state q of the ejectiles. Our Z reconstruction approach is based on the energy loss, the residual energy and the TOF measurements after appropriate absolute calibration. Moreover, a reconstruction of q was performed using the magnetic rigidity and the trajectory length of the ions, obtained from the ion optical trajectory reconstruction. Finally, the mass identification was performed with specific gates on Z and q via a magnetic rigidity vs. total energy correlation. The present analysis of medium-mass projectile-like fragments indicates the necessity for our new procedure that has to be applied in relation to the use of a large acceptance spectrometer like MAGNEX.

We expect that with our newly developed PID procedure, a good identification of the neutron-rich ejectiles will be achieved. After identification, 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, as those shown in Figs. 1 and 2. We hope that the extracted experimental distributions, along with comparisons with the theoretical models will shed light to the complex reaction mechanisms leading to the production of neutron-rich nuclides at this energy regime.

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