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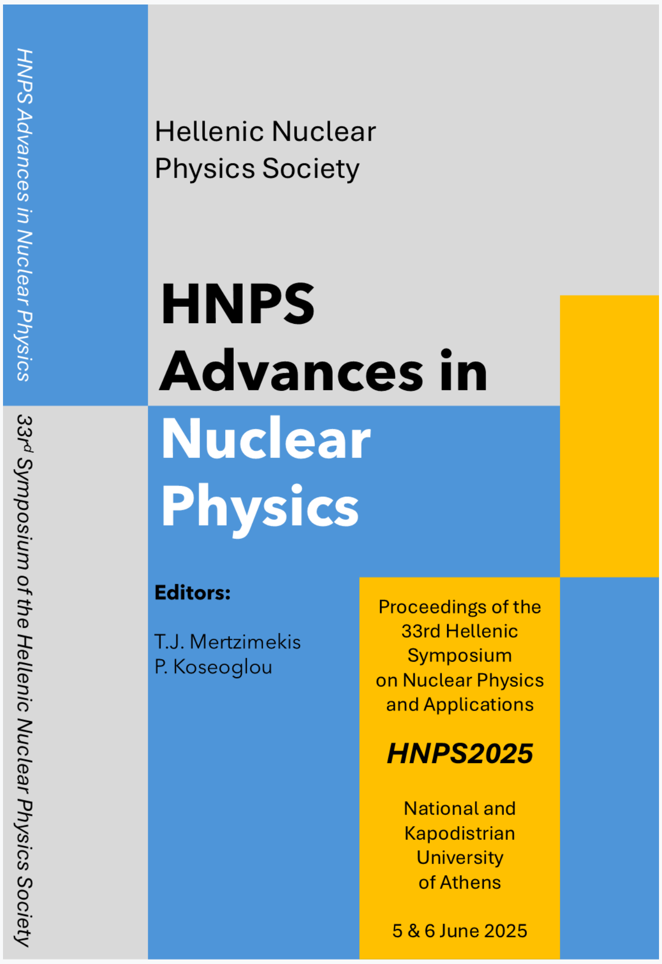

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ARTICLE

Investigation of α-cluster Transfer in Peripheral Collisions of ^{40}Ca (12.3 MeV/nucleon) + ^{27}Al using the MARS Spectrometer

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Abstract
Peripheral heavy-ion collisions at energies from the Coulomb barrier to the Fermi regime offer a unique environment for studying α-cluster transfer and nucleon-exchange processes. We present a preliminary study of α-cluster transfer from the reaction ^{40}Ca (12.3 MeV/nucleon) + ^{27}Al, that was performed at the Cyclotron Institute of Texas A&M University using the MARS recoil separator. Projectile-like fragments resulting from α-cluster transfer were identified with a Si detector telescope located at the focal plane of MARS. Production cross sections are extracted and compared with calculations with the Deep Inelastic Transfer (DIT) model. This procedure aims to provide a foundation for systematic comparison with appropriate theoretical models, leading to further insights into direct transfer mechanisms and clustering phenomena.

Keywords: Cluster Transfer; Peripheral Collisions; Fragment Identification

1. Introduction

The study of clustering phenomena in nuclei has been a central theme in nuclear structure and reaction dynamics. In particular, α clustering is known to play a crucial role in light and medium-mass nuclei, influencing both their excitation spectra and their reaction pathways [1, 2]. Peripheral collisions provide an optimal environment for the study of cluster transfer mechanisms, as they occur at relatively low excitation energies and are sensitive to the substructure of the interacting nuclei [3].

The nucleus ^{40}Ca is an ideal projectile for the present study, due to its doubly magic character and cluster substructure. Previous experimental and theoretical works have highlighted its role as a reference system for exploring cluster transfer [2, 3].

In this work, we present a preliminary analysis of the reaction ^{40}Ca (12.3 MeV/nucleon) + ^{27}Al, performed at Texas A&M Cyclotron Institute using the MARS recoil separator [4]. The primary objective is the identification and characterization of projectile-like fragments (PLFs) resulting from the transfer of α-clusters and the construction of their yield distributions.

2. Experimental Setup and Data Reduction

The experiment was carried out at the Cyclotron Institute of Texas A&M University, following the methodology of previous studies [5]. A (12.3 MeV/nucleon) $^{40}Ca^{14+}$ beam, accelerated by the K500 Cyclotron, interacted with an ^{27}Al target of 1.7 mg/cm^2 thickness. The MARS recoil separator [4], operated in its standard mode as a radioactive-beam separator, was used to collect the projectile fragments. The ^{40}Ca beam was sent to the primary target of MARS along its optical axis and projectile fragments were collected in a square window corresponding to horizontal and vertical angles of 2.7°, thus, defining a solid angle $\Delta\Omega = 2.2$ msr. The fragments traversed the first dispersive section of MARS and passed through slits defining a 1% magnetic rigidity acceptance. Then, they continued via the second dispersive section of MARS and passed through the velocity filter defining a 10% velocity window. Finally, they traversed the third dispersive section of MARS that provides a vertical dispersion, offering an A/q separation of the fragments. The fragments were collected in a (5 cm × 5 cm) $\Delta E - E$ Si detector telescope consisting of a 68 μm resistive 16-strip detector and followed by a 1000 μm detector, providing the energy-loss and residual energy information necessary for fragment identification.

Fragment identification and data reduction followed the procedure described in [5]. The Si telescope calibration was performed using elastically scattered ^{40}Ca beam particles. The fragment velocity was determined empirically from the energy loss and total energy according to the relation: [5]

$$\upsilon \propto \left(\frac{E_{tot}}{\sqrt{\Delta\ E}} \right)^{\frac{1}{3}} \tag{1}$$

where ΔE is the energy loss in the first Si detector and $E_{\text{tot}} = \Delta E + E$ is the total energy, given by the sum of the energy loss ΔE and the residual energy E in the second Si detector.

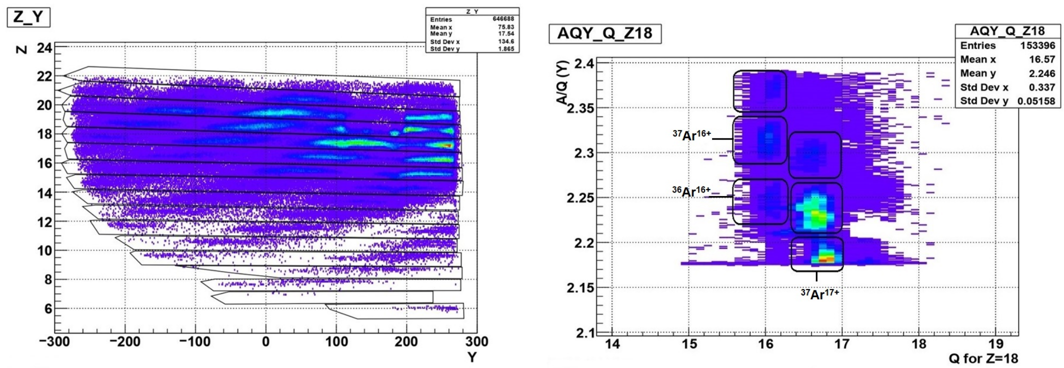
The atomic number Z of the ejectiles was reconstructed from the correlation between ΔE and the extracted velocity, assuming a linear dependence with respect to $\upsilon\sqrt{\Delta E}$ [5]. Figure 1a shows the resulting correlation of Z with respect to the vertical position Y, where appropriate gates were defined to select events corresponding to specific atomic numbers. The ionic charge state of the ejectiles was obtained from the magnetic rigidity relation:

$$B\rho = \frac{p}{A}\frac{A}{q} \tag{2}$$

The magnetic rigidity is given by the setting of the spectrometer with width of 1% defined by the opening of the slits at the intermediate image, while the momentum per nucleon p/A is essentially the velocity obtained as above, see Eq. (1). Subsequently, the mass number is obtained from the total energy and velocity, in order to extract the ionic charge state q. A correlation of the mass-to-charge ratio A/q of the ions with respect to the Y position was obtained, assuming a linear relation of the form:

$$\frac{A}{q} = B\rho_0 \left(\alpha_0 + \alpha_1 Y\right) \tag{3}$$

where $B\rho_0$ is the magnetic rigidity of a given setting of the separator, and the coefficients α_0 and α_1 were determined from the position of elastically scattered projectiles at various charge states and $B\rho_0$ settings. Using Eq. (2) and the correlation of Eq. (3), the mass number A of each projectile-like fragment was obtained.



(a) Identification of projectile-like fragments based on atomic number (Z) and vertical focal-plane position (Y).

(b) Isotopic identification for Z=18 (Ar) in the A/q-q spectrum.

Figure 1. Representative results of the particle identification procedure. Left panel (a): Software gating was performed on the atomic number Z versus Y position spectrum. Right panel (b): Software gating was performed on the A/q versus q spectrum to obtain the mass of the isotopes.

Figure 1b illustrates the correlation of A/q with respect to q for Z=18. This channel is of particular interest, since the isotope ^{36}Ar may have been produced in part by the stripping of an α-cluster from ^{20}Ca. For each atomic number Z, gated regions were defined in the (A/q)−q spectrum to extract the corresponding yields for the identified masses. This procedure enabled the separation of distinct cluster-transfer channels.

3. Results and Comparison with Theoretical Calculations

In this section, the experimental results of ejectile distributions from the reaction of ^{40}Ca (12.3 MeV/nucleon) + ^{27}Al will be presented and compared with theoretical calculations. The calculations are performed using a standard two-stage Monte Carlo approach. In the first, dynamical stage, the interaction between the projectile and the target was described by the phenomenological Deep-Inelastic Transfer (DIT) model [6]. After the dynamical stage, the primary fragments undergo de-excitation, which is modeled by the statistical de-excitation code GEMINI [7]. The combined results from these calculations will be referred to as DIT calculations.

Figure 2 shows the isobaric cross sections of the ejectiles. The experimental data are given by the closed symbols. The dashed (blue) line indicates the calculated total cross sections by the DIT model. The solid (blue) line shows the cross sections that result after filtering for the angular acceptance and the magnetic rigidity range covered in the experiment, while the solid (yellow) line shows the cross sections that result after filtering for the angular acceptance only. It is interesting to note that the total calculations show the same behaviour as the corresponding filtered ones. Furthermore, comparing the DIT total cross sections with the DIT calculations filtered for the experimental acceptances, we observe that the angular and magnetic rigidity acceptance of this experiment were such as to accept only 1/80 of the cross section in this forward angle of the experimental setup. Breaking this down, the limited angular acceptance alone reduces the yields by a factor of $\sim$ 10, while the incomplete coverage of the magnetic-rigidity ($B\rho$) region further reduces them by a factor of $\sim$ 8. The remaining factor corresponds to the limited angular acceptance of the MARS separator. The filtered DIT calculations are in good agreement with the experimental data, especially for the data with the largest cross sections (A = 39-42), despite the slight underestimation of the remaining data. This confirms that the implemented angular and magnetic-rigidity acceptances adequately represent the transmission characteristics of the spectrometer.

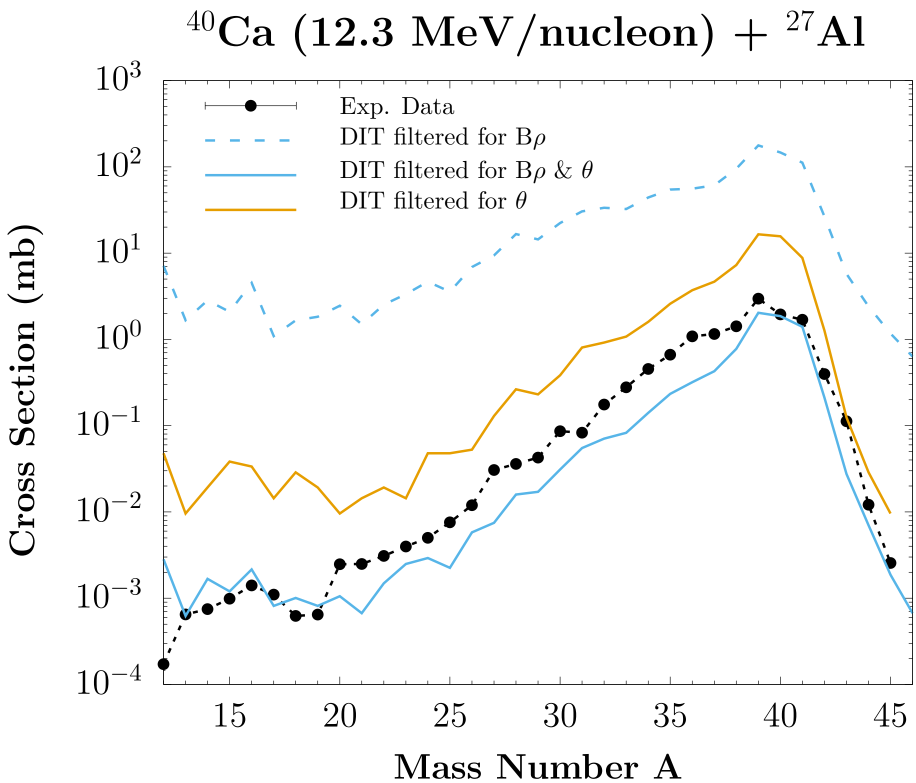


Figure 2. Isobaric mass distributions from ^{40}Ca (12.3 MeV/nucleon) + ^{27}Al. Closed (black) circles: Experimental Data. Dashed (blue) line: DIT calculation for total nuclide cross sections. Solid (yellow) line: DIT calculation for nuclide cross sections filtered for the angular acceptance. Solid (blue) line: DIT calculation for nuclide cross sections filtered for the angular and magnetic rigidity acceptance.

In Fig. 3, we present mass distributions for the observed isotopes of the elements with Z = 16, 18, 20 and 22, some isotopes of which may have been produced in part by a direct α-cluster transfer. The experimental data are given by the closed symbols. The dashed (blue) lines indicate the calculated total cross sections by the DIT model. The solid (blue) lines are the cross sections that result after filtering for the angular acceptance and the magnetic rigidity range covered in the experiment, while the solid (yellow) lines are the cross sections that result after filtering for the angular acceptance only. The vertical dashed (green) line indicates the initiation of neutron pickup. We observe that DIT calculations filtered for the angular and the magnetic rigidity acceptance lead to cross-sections that overall underestimate the experimental data, with the exception of the Z=20 channel of the ^{40}Ca (12.3 MeV/nucleon) + ^{27}Al reaction, where DIT calculations lead to cross sections that are in overall reasonable agreement with the experimental data. Further detailed calculations with DIT are in line along with options to vary the phenomenological potentials of the model.

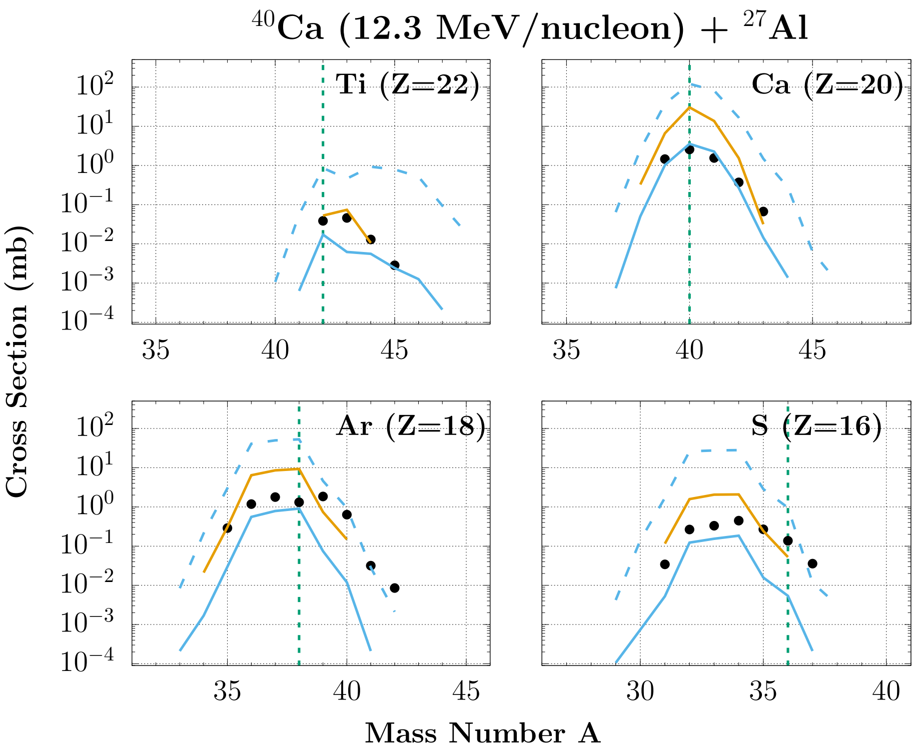


Figure 3. Production cross sections (mass distributions) of elements with Z=16,18,20,22 from ^{40}Ca (12.3 MeV/nucleon) + ^{27}Al. Closed (black) circles: Experimental Data. Dashed (blue) lines: DIT calculation for total nuclide cross sections. Solid (yellow) lines: DIT calculation for nuclide cross sections filtered for the angular acceptance. Solid (blue) lines: DIT calculation for nuclide cross sections filtered for the angular and magnetic rigidity acceptance. The vertical dashed (green) line indicates the initiation of neutron pickup.

4. Conclusions

In this work, we have presented preliminary results of the analysis procedure from the study of the ^{40}Ca + ^{27}Al reaction at 12.3 MeV/nucleon, performed at the Cyclotron Institute of Texas A&M University using the MARS recoil separator. The experiment focused on projectile-like fragments (PLFs) produced through α-cluster transfer processes, taking advantage of the pronounced α-cluster structure of the ^{40}Ca projectile. Event-by-event identification of the reaction products was achieved through the combination of $\Delta E - E$ measurements with magnetic rigidity and position information at the MARS focal plane, allowing the separation of different cluster transfer channels.

The production cross sections were compared with theoretical calculations using the DIT model, followed by the de-excitation code GEMINI. Furthermore, the calculations were filtered for the angular and magnetic rigidity acceptance of the separator. The theoretical DIT calculations mainly show the same behaviour as the experimental data, even though a slight underestimation of the experimental data is obtained.

As a next step, the momentum distributions (p/A) of the produced fragments will be obtained and analyzed in detail for the the ^{40}Ca (12.3 MeV/nucleon)+ ^{27}Al reaction. This will enable systematic comparisons with theoretical models such as DIT, CoMD and HαC [8], in order to clarify the coexistence of direct cluster transfer and stochastic nucleon exchange processes, offering deeper insight into the dynamics in this energy domain.

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