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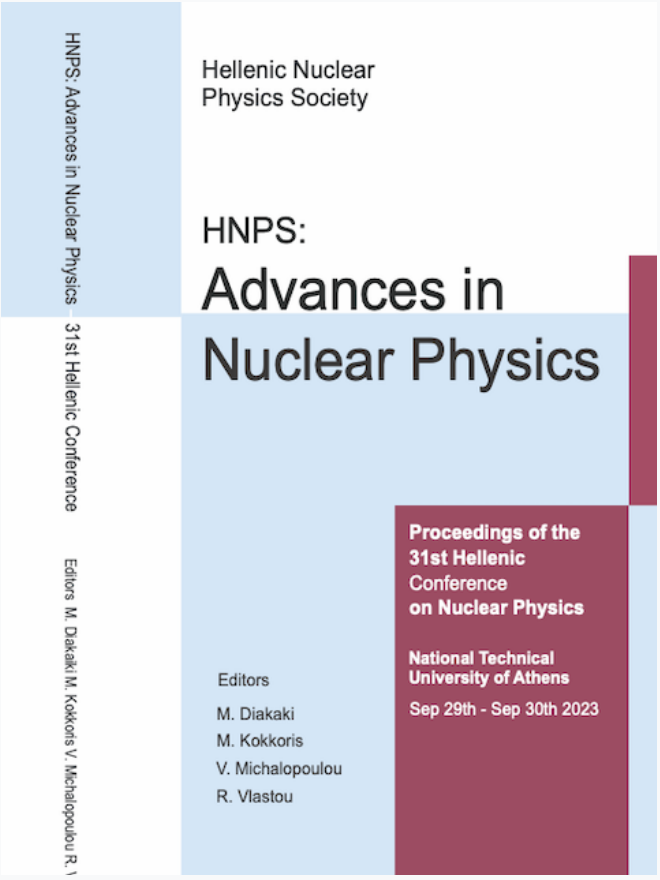

Signatures of Clustering and Cluster Transfer in Peripheral Collisions of 40Ar on 64Ni at 15 MeV/nucleon

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Signatures of Clustering and Cluster Transfer in Peripheral Collisions of ^{40}Ar on ^{64}Ni at 15 MeV/nucleon

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Abstract We study the momentum distributions of several projectile-like fragments resulting from the reaction of an ^{40}Ar beam with a ^{64}Ni target at 15 MeV/nucleon. The data, obtained at the Cyclotron Institute of Texas A&M University, refer to products corresponding to light cluster pick-up or removal. We thoroughly study the momentum distributions and the production cross sections for various cluster transfer channels. Comparisons with the Deep-Inelastic Transfer (DIT) and Constrained Molecular Dynamics (CoMD) models reveal partial agreement and an inability to fully describe the quasi–elastic part. We tentatively attribute this discrepancy as an indication of direct cluster transfer or breakup. By comparing our experimental data with appropriate models, we anticipate gaining valuable insight into the mechanisms governing clustering and cluster transfer in peripheral collisions within the Fermi energy regime.

Keywords Cluster Transfer, Momentum Distributions, Peripheral Collisions, Fermi Energy

INTRODUCTION

Currently, there is renewed interest in cluster effects, both experimentally and theoretically [1]. Cluster structures can be observed when the excitation energy is close to the corresponding decay threshold [2,3]. Considering these observations, we expect that peripheral heavy ion collisions may provide optimal conditions for cluster formation and may favor the possibility of cluster transfer. Accordingly, our research attempts to examine possible direct cluster transfer in the reaction ^{40}Ar (15 MeV/nucleon) + ^{64}Ni and to explore similar reactions considered by our research group in previous studies [4,5,9,10]. In the present work, the reaction dynamics/mechanisms in the ^{40}Ar+^{64}Ni collision are sought through the study of momentum distributions for a variety of reaction products. The corresponding isotopic distributions were obtained employing the MARS recoil separator at the Cyclotron Institute at Texas A&M University [4,5]. Mass and momentum distribution spectra were analyzed adopting two dynamical models namely, the Deep Inelastic Transfer (DIT) [6] and the Constrained Molecular Dynamics (CoMD) [7], each one coupled to the statistical de-excitation code GEMINI [8]. Using this hybrid model the experimental mass distributions are described adequately-well, whereas for the momentum distribution in the ^{36}S production a rather fair description is inferred, signaling the presence of new reaction mechanisms that may contribute to the ^{36}S production.

EXPERIMENTAL DETAILS

The experimental data were obtained with the MARS recoil separator of the Cyclotron Institute at Texas A&M University. With this experimental setup, the projectile-like products of the ^{40}Ar + ^{64}Ni reaction at 15 MeV/nucleon were collected and identified. An ^{40}Ar (15 MeV/nucleon) beam, accelerated by the K500 Cyclotron, interacted with a ^{64}Ni target with thickness of 2 mg/cm^2. The MARS separator

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was then used to analyze and identify the projectile fragments [4]. The fragments, after the interaction with the target, passed through a parallel-plate avalanche counter (PPAC) located at the dispersive image of MARS, which provided the position and the magnetic rigidity of the products as well as their START time, and were subsequently focused at the end of the separator passing through a second PPAC (for STOP-time information) and were collected in a ΔE−E Si detector telescope. The particle identification procedure of the fragments was based on standard techniques of magnetic rigidity, energy-loss, residual energy and time-of-flight on an event-by-event basis, as described in detail in [5].

BRIEF OVERVIEW OF THEORETICAL FRAMEWORK

The simulations performed are based on a two-step Monte Carlo approach. The dynamical phase of the interaction was simulated using two theoretical frameworks: the phenomenological DIT model and the microscopic CoMD model. The Deep-Inelastic Transfer (DIT) model [6] is a phenomenological model, used in peripheral collisions in the Fermi energy region. Assuming initially that both the projectile and the target are spherical entities, they approach each other along Coulomb trajectories. When the dinuclear system falls within the field of nuclear interaction, it is depicted as two Fermi gases in contact, allowing a stochastic nucleon exchange through a "window" that opens between the contacting nuclear surfaces. The Constrained Molecular Dynamics (CoMD) model [7], a microscopic code based on the broader framework of quantum molecular dynamics (QMD), characterizes nucleons as localized Gaussian wavepackets interacting through an effective nucleon-nucleon interaction. The Pauli exclusion principle is enforced through a constraint on phase space. After the dynamical phase of the reaction, the de-excitation of the primary fragments was described using the GEMINI statistical de-excitation code [8].

From the recent work of our group [9,10] we have gained confidence that the above two models can reasonably well describe the mechanism of nucleon exchange, as a sequential transfer of nucleons. We intend to explore the possibility of direct transfer of a cluster from a projectile to a target or vice versa, or cluster breakup from the projectile. These possibilities are schematically depicted in Fig. 1.

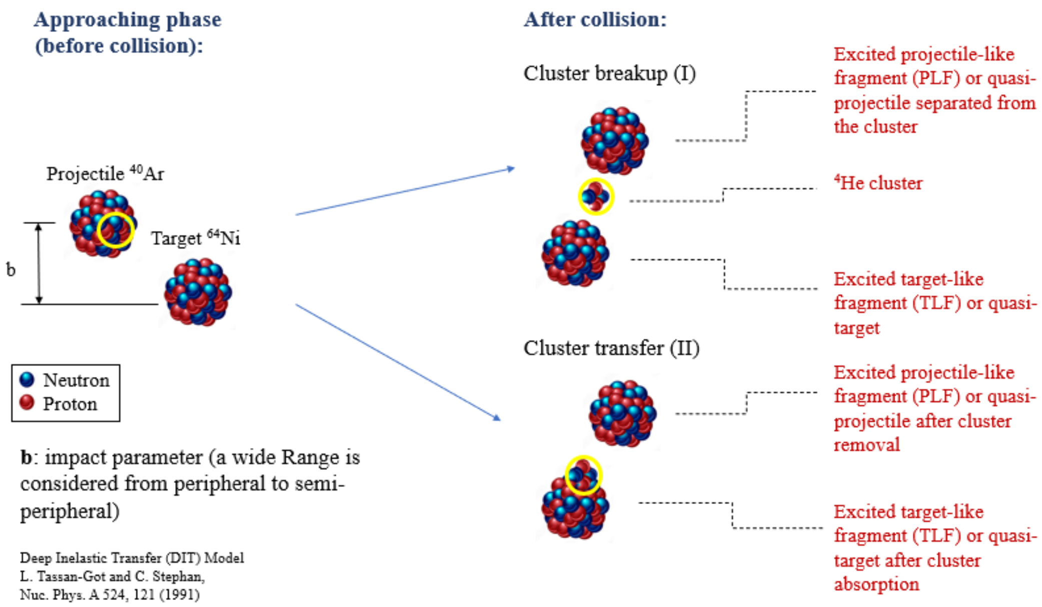

Figure 1. *Cluster breakup (I) or cluster transfer (II) after cluster absorption in peripheral collisions*

RESULTS AND DISCUSSION

In this section, we present experimental results of ejectile distributions from the reaction of ^{40}Ar (15 MeV/nucleon) with ^{64}Ni, along with a comparison of the experimental data with theoretical calculations employing the aforementioned models.

In Fig. 2, we show mass distributions of projectile fragments with Z=18–15 from the reaction ^{40}Ar (15 MeV/nucleon) + ^{64}Ni. We observe that the theoretical calculations lead to cross sections that are in reasonable agreement with the experimental data. The neutron-rich sides of the distributions are rather well described by both DIT and CoMD models. On the neutron-deficient side, we see that the models tend to overestimate the experimental data. The orange arrow in the panel (c) indicates the isotope $^{36}_{16}S$, produced with large cross section. We believe that it may have been produced in part by the $^{4}_{2}He$ cluster emission from the $^{40}_{18}Ar$ projectile.

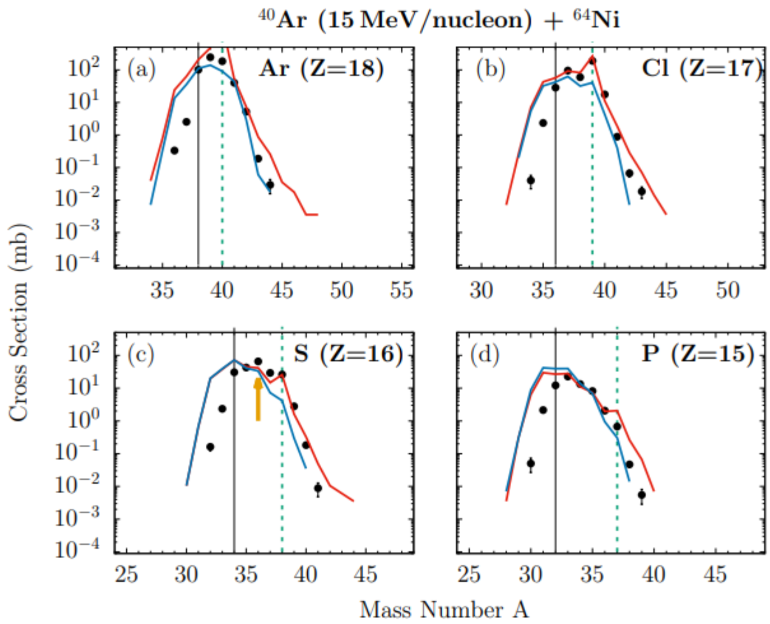

Figure 2. *Projectile fragment mass distributions for the ^{40}Ar (15 MeV/nucleon) reaction with ^{64}Ni target for elements with Z=15–18. Black circles show the experimental data. The blue solid line shows the DIT calculation and the red solid line the CoMD calculation. The vertical black line indicates the limit of completeness of the experimental data and the green line the starting point of neutron uptake. The orange arrow in the panel (c) indicates $^{36}_{16}S$, assumed to have been produced in part by a cluster breakup of the ^{40}Ar projectile.*

Fig. 3 shows the experimental data for the momentum distribution of the ^{36}S fragment, on which we have focused our interest, because its formation shows a large cross section and has an increased probability to have been formed by ^{4}He cluster breakup from the ^{40}Ar projectile. The DIT/GEMINI calculations are slightly lower than those with CoMD/GEMINI which is probably due to lower excitation energies in the CoMD model. It is obvious that in the right part of the momentum distribution there is a large discrepancy between the experimental data and the calculations. This may indicate the presence of a ^{4}He cluster breakup and/or transfer from the ^{40}Ar projectile that cannot be described by either the DIT or the CoMD models.

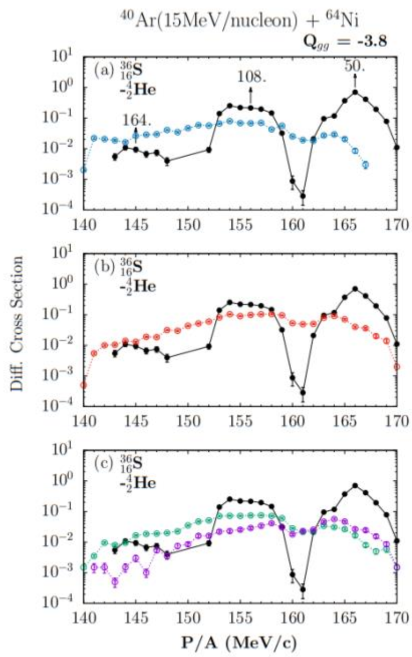

Figure 3: *Momentum distributions of the projectile fragment ^{36}S for the ^{40}Ar (15 MeV/nucleon) reaction with a ^{64}Ni target. Black points show the experimental data. In panel (a), the blue line shows the standard DIT calculation, while, in panel (b), the red line shows the CoMD calculation. In panel (c), the green line shows the CoMD calculation involving nucleon transfer and the purple line shows the CoMD calculation involving nucleon breakup. The numbers above some peaks give the total excitation energy (in MeV) obtained from binary kinematics using the corresponding p/A values.*

SUMMARY AND CONCLUSIONS

We studied the yields and momentum distributions of projectile fragments for the reaction between a ^{40}Ar projectile and a ^{64}Ni target at 15 MeV/nucleon. Calculations with the theoretical models DIT and CoMD were compared with the experimental data. Both theoretical models provide a satisfactory description of the experimental distributions, with the CoMD model being of particular importance due to its microscopic nature. From the mass distributions, we observe that the production of isotopes like ^{36}S could be an indication of a possible presence of clustering mechanisms. From the momentum distribution we see that the data are only partially described by both calculations, which is taken as indication of direct cluster transfer or breakup. However, further improvements of the CoMD model as well as systematic study of more reactions in the Fermi energy range are in line to further understand the mechanisms leading cluster transfer or breakup. Through a rigorous comparative analysis of our experimental momentum distributions with reaction models, we may obtain insight into the underlying mechanism of cluster breakup and cluster transfer in peripheral collisions in the Fermi energy regime.

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