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Multinucleon Transfer in ^{40}Ar + ^{64}Ni collisions at 15 MeV/nucleon explored via Studies of Momentum Distributions

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Abstract. We present a detailed analysis of the mass and the momentum per nucleon distributions of ejectiles from the reaction of a ^{40}Ar beam at 15 MeV/nucleon with a ^{64}Ni target. The experimental data were obtained in a previous work with the MARS separator at the Cyclotron Institute of Texas A&M University. The experimental distributions are compared with two dynamical models, the Deep-Inelastic Transfer (DIT) model and the Constrained Molecular Dynamics (CoMD) model, followed by the de-excitation code GEMINI. Both models describe the experimental data to some extent and further optimization is underway in efforts to deepen our understanding of the mechanisms taking place in the production of exotic neutron-rich nuclides in the Fermi energy regime.

1 Introduction

The production of neutron-rich nuclides in peripheral collisions of heavy ions within the Fermi energy range (15-25 MeV/nucleon) is of significant interest to the nuclear physics community [1, 2].

In this study we further advance our group's previous work in the ^{40}Ar + ^{64}Ni reaction at a beam energy of 15 MeV/nucleon [3, 4]. The experimental data that we use were obtained in a previous work with the MARS separator at the Cyclotron Institute at Texas A&M University. In this work, calculations with two dynamical models are employed to describe the data: the Deep-Inelastic Transfer (DIT) model [5] and the Constrained Molecular Dynamics (CoMD) model [6]. De-excitation in both models is achieved by the GEMINI code [7]. By comparing these models with experimental data, particularly through the study of momentum distributions, as consistently explored by our group, we gain insight into the reaction mechanisms in the Fermi energy regime [8–11].

2 Experimental Setup

The experimental data for the ^{40}Ar + ^{64}Ni reaction were obtained with the Momentum Achromat Recoil Spectrometer (MARS) at the Cyclotron Institute at Texas A&M University [12]. A $^{40}Ar^{9+}$ beam from the K500 Superconducting Cyclotron at 15 MeV/nucleon interacted with a ^{64}Ni target with a thickness of 2 mg/cm^2 at 4.0° relative to the optical axis of MARS leading to the collection of ejectiles in the polar angular range 2.2° – 5.8° covering a solid angle window of $\Delta\Omega$ = 4 msr. The projectile fragments 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. Subsequently, the ions were 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 range of the experimental magnetic rigidity was 1.1-1.5 Tm, not sufficient to cover the full range of the products, as it can be seen in Figure 1. The projectile-like products were collected and identified with standard techniques of magnetic rigidity, energy-loss, residual energy and time-of-flight on an event-by-event basis, as described in detail in [2].

3 Theoretical Models

The calculations are based on a two-step Monte Carlo approach. The dynamical phase of the interaction is simulated by two theoretical models, the principles of which are described below. The Deep-Inelastic Transfer (DIT) model [5] is a phenomenological model, used to describe peripheral collisions in the Fermi energy domain. Both the projectile and the target are assumed to be spherical and approach each other along Coulomb trajectories, until they are within the range of nuclear interaction, at which point a stochastic exchange of nucleons takes place through a "window" created in the touching nuclear surfaces.

The Constrained Molecular Dynamics (CoMD) model [6] is a microscopic model for heavy-ion nuclear reactions. The framework is based on the approach of quantum molecular dynamics (QMD), describing the nucleons as

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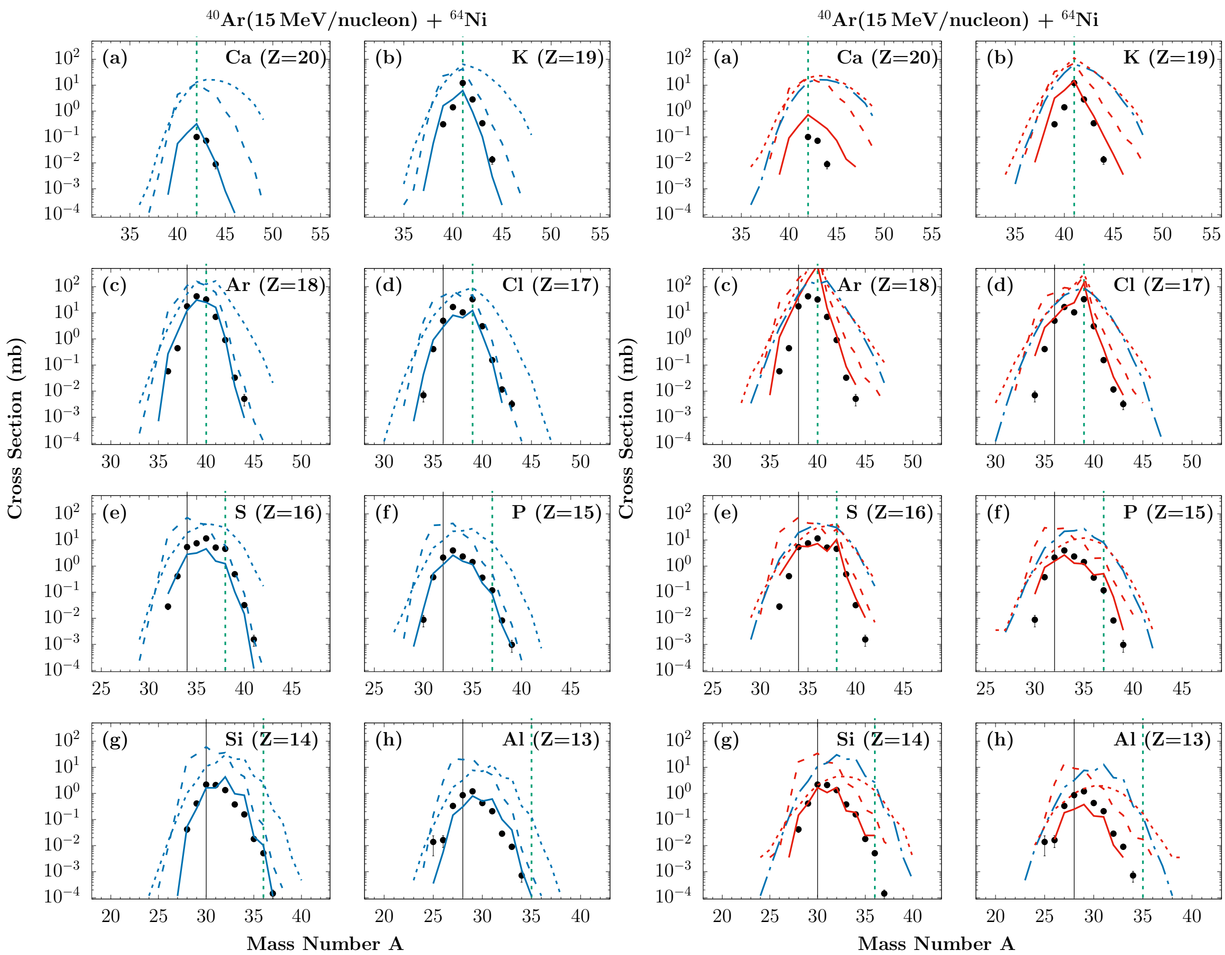

Figure 1. Production cross sections (mass distributions) of elements with Z=13-20 from the reaction ^{40}Ar (15 MeV/nucleon) + ^{64}Ni. Black points: experimental data. Left Panels (a)-(h): DIT calculations: Dotted (blue) lines: primary fragments, Dashed (blue) lines: final (cold) fragments, Full (blue) lines: final fragments filtered for angular acceptance and magnetic rigidity. Right Panels (a)-(h): CoMD calculations: Dotted (red) lines: primary fragments, Dashed (red) lines: final (cold) fragments, Full (red) lines: final fragments filtered for angular acceptance and magnetic rigidity. The dashed-dotted (blue) lines show again the primary fragments from the DIT calculations for comparison. The vertical dashed (green) lines indicate the initiation of neutron pickup. On the left of the vertical black lines the data are obtained with incomplete magnetic rigidity coverage.

localized Gaussian wavepackets in phase space that interact in a Skyrme-type potential. In our calculations we use a standard value of nuclear matter compressibility, namely K=254 MeV [4]. We have also tested two additional values K=200 MeV and K=308 MeV [13]. Recent work of our group [4, 11] shows that these two models are able to describe the mechanism of nucleon exchange to reasonable extend as a sequential transfer of nucleons.

4 Results and Discussion

In this section we present a comparison of our calculations with the experimental data. We also compare the calculations of CoMD with different parameters. Specifically, we compare the standard calculations of K=254 MeV with lower and higher compressibilities of nuclear matter, K=200 MeV and K=308 MeV, respectively. All the data are referred to the ejectiles of the reaction under study, as only these were measured by the aforementioned experimental setup.

In Figure 1 we present the yields for the observed isotopes of the elements with Z=13-20. The experimental data are shown by the black points. The vertical dashed (green) lines indicate the beginning of neutron pickup. The vertical full (black) lines indicate the limit of completeness of the experimental data, due to incomplete magnetic rigidity coverage. As it is demonstrated, several neutron-rich isotopes have been produced.

On the left panels of Fig. 1 the experimental data, denoted with the black points are compared with the DIT calculations. The dotted (blue) lines represent the calculations for the primary fragments, dashed (blue) lines represent the total calculations for the cold fragments and full (blue) lines represent the calculations filtered for the angular acceptance ($\Delta\theta = 2.2° - 5.8°$) and magnetic rigidity coverage of the experiment. The DIT calculations lead

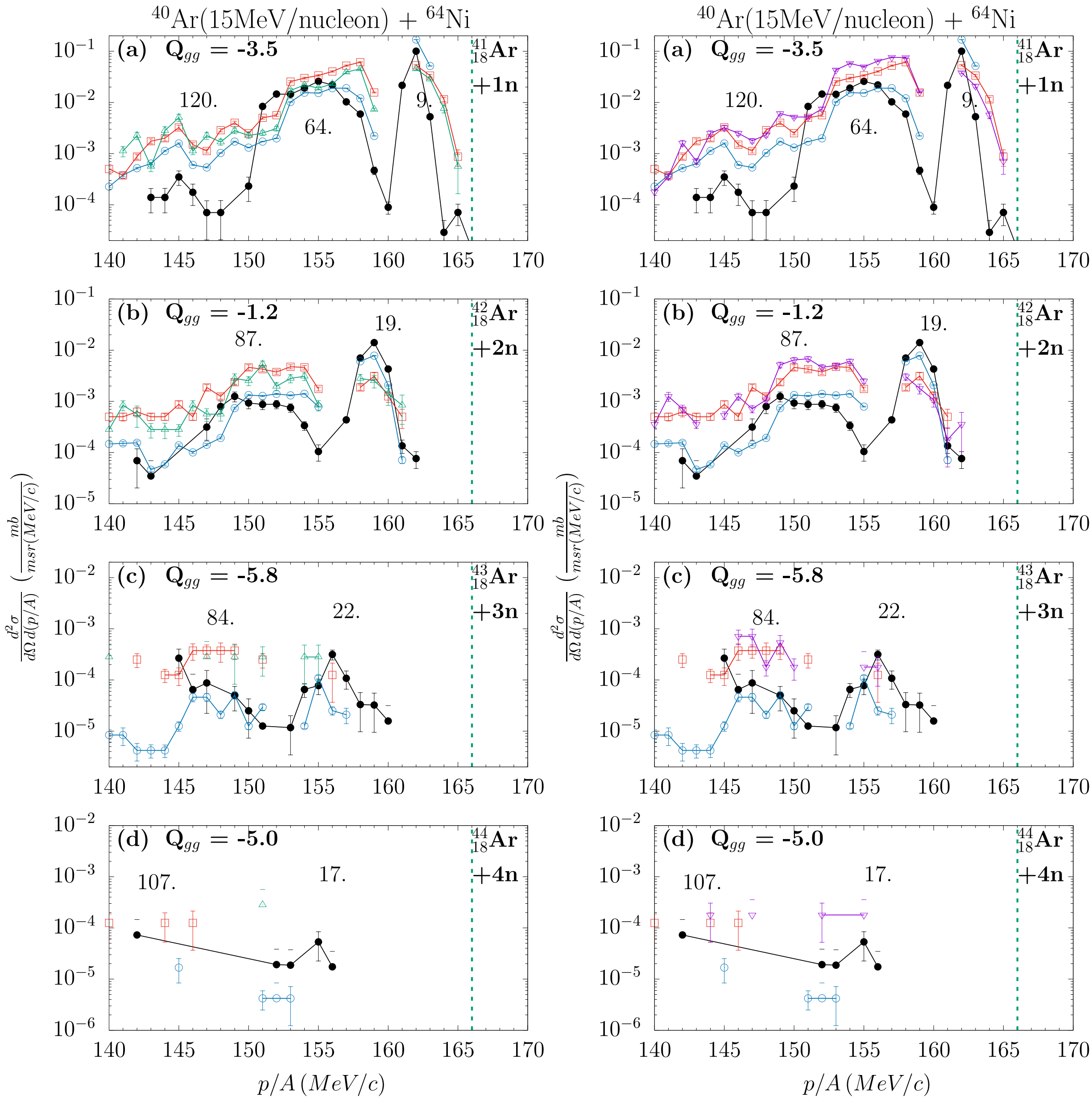

Figure 2. Momentum per nucleon distributions of projectile-like fragments for neutron pick-up channels. Black points: experimental data. Blue circles: DIT calculation. Red squares: CoMD calculation, with K=254 MeV. The vertical dashed (green) lines indicate the velocity of the beam. Left Panels: Green triangles: CoMD calculations, with K=200 MeV. Right Panels (a)-(d): Purple inverse triangles: CoMD calculation, with K=308 MeV.

to cross sections that are overall in reasonable agreement with the experimental data.

On the right panels of Fig. 1 the experimental data, denoted with black points are compared with the CoMD calculations. The dotted (red) lines represent the calculations for the primary fragments, dashed (red) lines represent the total calculations for the cold fragments and full (red) lines represent the calculations filtered for the angular acceptance and magnetic rigidity coverage of the experiment. Finally, the dashed-dotted (blue) lines are again the DIT calculations for the primary fragments and seem to be nearly similar to those of the CoMD calculation. Comparison of the DIT and CoMD filtered calculations with the data shows that the DIT calculations perform somehow better than the CoMD calculations.

In Figures 2 - 4, we present momentum per nucleon distributions for various channels of the reaction under study. The p/A distributions can provide important information on the mechanisms of the production of the fragments of interest. Momentum per nucleon, which is essentially velocity, is a measure of the energy dissipation caused by the interaction of the projectile-target binary system.

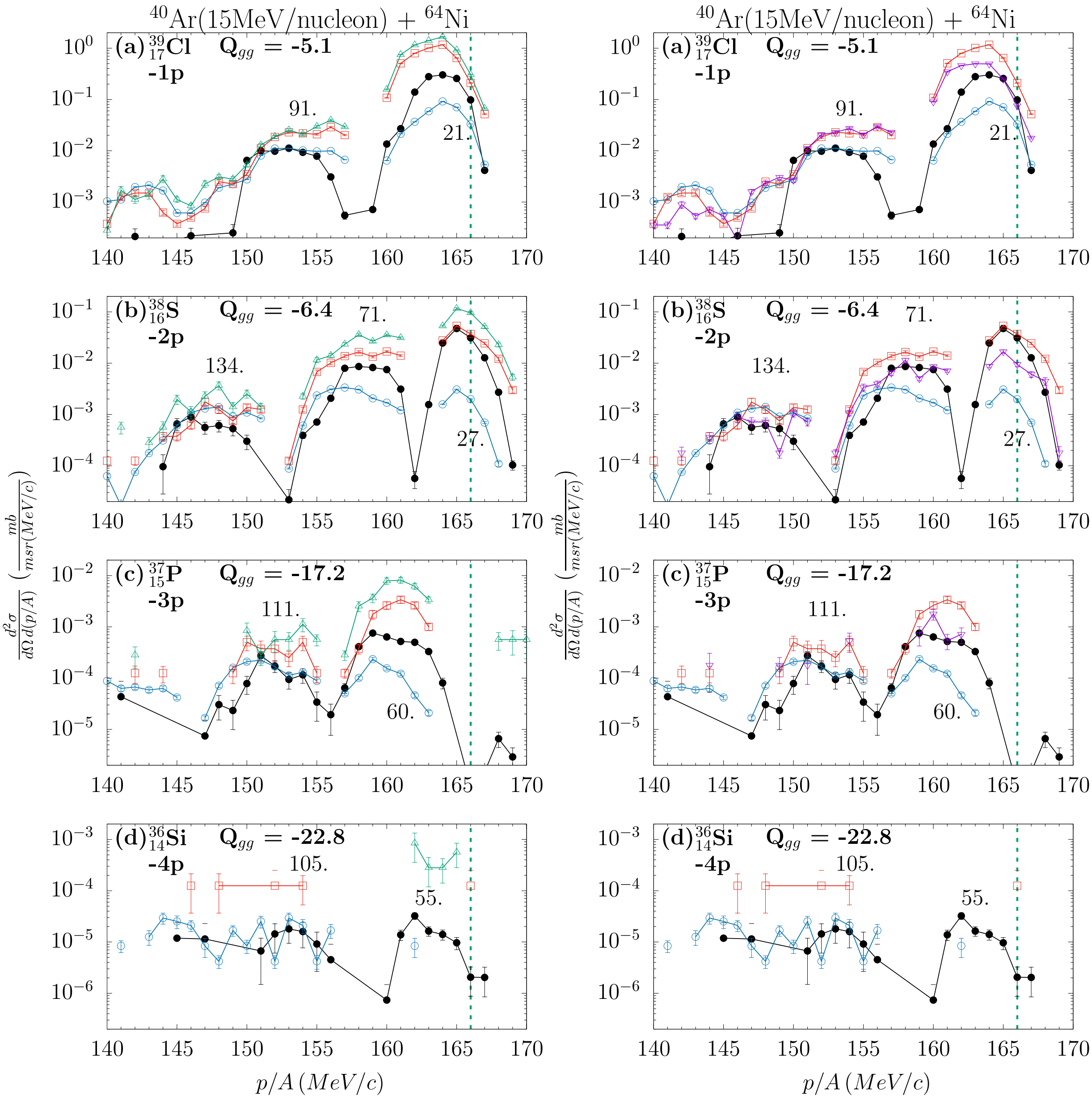

Figure 3. Momentum per nucleon distributions of projectile-like fragments for proton removal channels. Black points: experimental data. Blue circles: DIT calculation. Red squares: CoMD calculation, with K=254 MeV. The vertical dashed (green) lines indicate the velocity of the beam. Left Panels: Green triangles: CoMD calculations, with K=200 MeV. Right Panels (a)-(d): Purple inverse triangles: CoMD calculation, with K=308 MeV.

We may consider two regions on the diagrams, a quasi-elastic region on higher p/A values that corresponds to direct processes, and a broad region on lower p/A values that corresponds to deep inelastic processes and extensive multinucleon transfers. Each row of panels shows the distribution for different reaction channels. On the left panels we have the comparison of the experimental data with our standard DIT and CoMD calculations and CoMD calculations for compressibility K=200 MeV, and on the right panels we have the same comparison for compressibility K=308 MeV. Black points represent the experimental data, (blue) circles represent the DIT calculation, (red) squares represent the CoMD calcualtion for compressibility K=254 MeV, (green) triangles represent the CoMD calculation for compressibility K=200 MeV and (purple) inverse triangles represent the CoMD calculation for compressibility K=308 MeV. The vertical dashed (green) lines indicate the velocity of the beam. The numbers above or below some points give the total excitation energy of the quasiprojectile-quasitarget system obtained using binary kinematics and the corresponding p/A values. Q$_{gg}$ is the ground-state to ground-state Q-value of the reaction channel.

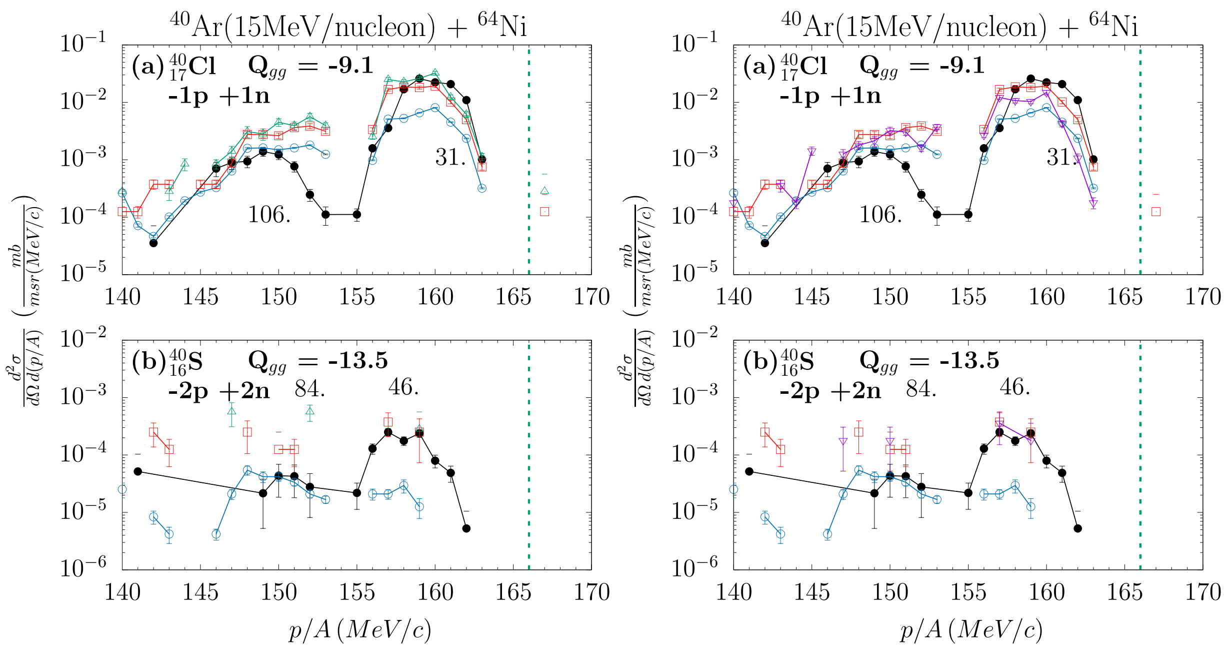

Figure 4. Momentum per nucleon distributions of projectile-like fragments for charge exchange channels. Black points: experimental data. Blue circles: DIT calculation. Red squares: CoMD calculation, with K=254 MeV. The vertical dashed (green) lines indicate the velocity of the beam. Left Panels: Green triangles: CoMD calculations, with K=200 MeV. Right Panels (a)-(d): Purple inverse triangles: CoMD calculation, with K=308 MeV.

The dips observed in the experimental distributions are mainly due to incomplete magnetic rigidity coverage. In Figure 2, we observe neutron pick-up channels, from 1 to 4 neutron pick-ups. In Figure 3, we observe proton removal channels, from 1 to 4 protons removed, and, in figure 4, we show the single and double charge exchange channels. All these channels lead to neutron-rich products. We can observe that the calculations with DIT and CoMD are more or less in overall agreement with the data, except the quasielastic part that may indicate the presence of direct nucleon transfer or other processes. The CoMD calculation with lower nuclear matter compressibility are generally above our standard calculations and the ones with higher compressibility are generally slightly lower.

5 Conclusions and Future Plans

In this article we presented a detailed analysis of the mass and the momentum per nucleon distributions of ejectiles from the reaction of a ^{40}Ar beam at 15 MeV/nucleon with a ^{64}Ni target. We used experimental data obtained in previous work with the MARS separator at the Cyclotron Institute of Texas A&M University. The experimental distributions were compared with calculations that we performed with two dynamical models, the Deep-Inelastic Transfer (DIT) model and the Constrained Molecular Dynamics (CoMD) model, followed by the de-excitation code GEMINI.

The emphasis of this work is on channels leading to neutron rich products, up to 4 neutrons added, up to 4 protons removed and charge exchange channels. We filtered the total calculations with respect to the angular acceptance of the spectrometer and the magnetic rigidity coverage in the experiment. The calculations appear to describe the data to a good extent. In the CoMD model, we tested the compressibility values for a lower and a higher value with reasonable results. We are in the process of understanding the comparison of different nuclear matter compressibility values within the CoMD model by appropriately varying its parameters. An increase of the statistics of the CoMD calculations could improve our insight on the channels of interest with very low cross sections.

Further experiments with other combinations of projectile and target may contribute to our systematics and to our understanding of nuclear reactions in the Fermi energy regime.

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