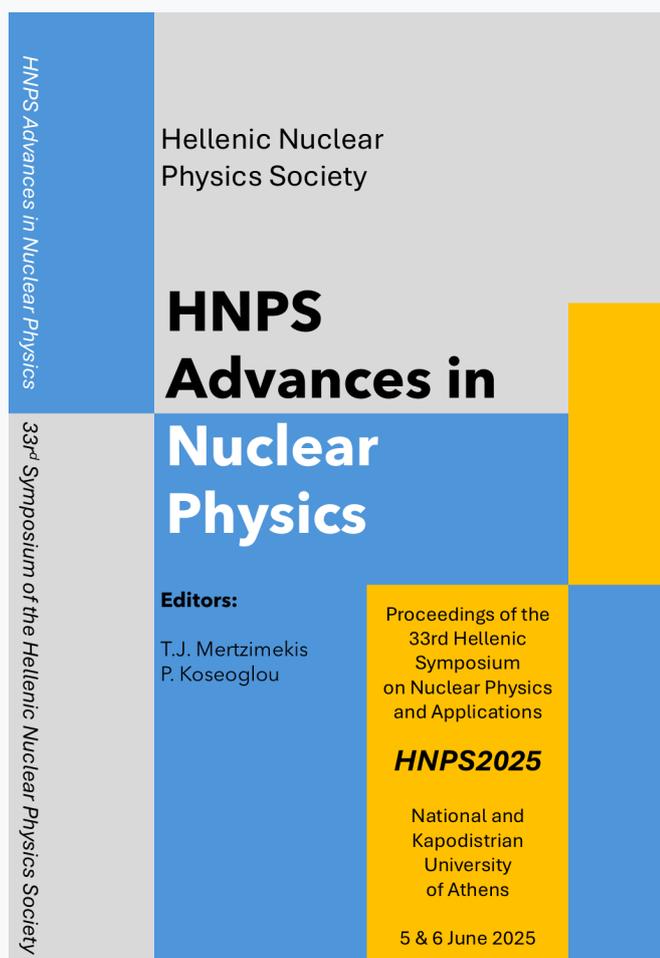


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*Eleftheria Travlou, Giannitsa Chryssi, Souliotis Georgios, Gkatzogias Konstantinos, Kontogianni Eirini, Fasoula Olga, Emannouil Theocharis, Martin Veselsky, Sherry Yennello, Aldo Bonasera*

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ARTICLE

# Multinucleon transfer in peripheral collisions of $^{86}\text{Kr}$ on $^{208}\text{Pb}$ at 25 MeV/nucleon

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## Abstract

In this work, we study projectile-like fragments resulting from multinucleon transfer during the reaction of a  $^{86}\text{Kr}$  beam with a  $^{208}\text{Pb}$  target at 25 MeV/nucleon using experimental data obtained with the MARS spectrometer at the Cyclotron Institute of Texas A&M University in previous works of our group [1]. The data are systematically compared to theoretical model calculations. Our analysis involved two models: the Deep Inelastic Transfer model (DIT) [2] and the Constrained Molecular Dynamics model (CoMD) [3]. Additionally, the GEMINI code [4] was used to simulate the de-excitation of primary fragments. We performed mass and angular distribution analyses to gain insight into the reaction mechanism of peripheral collisions involving extensive multinucleon transfer. Both models appear to describe the behavior of the data in an overall satisfactory way.

**Keywords:** Neutron Rich Isotopes, Multinucleon Transfer, Angular Distributions, Mass Distributions

## 1. Introduction

Heavy ion reactions occurring in the Fermi energy regime (15–25 MeV/nucleon) are of particular importance. In this energy range, the production of neutron-rich nuclides from peripheral heavy-ion collisions has attracted significant attention, as such studies can shed light on fundamental aspects of nuclear structure and provide insights into the astrophysical rapid neutron-capture process (r-process), responsible for the synthesis of heavy elements above iron during neutron-star mergers and supernova explosions [5].

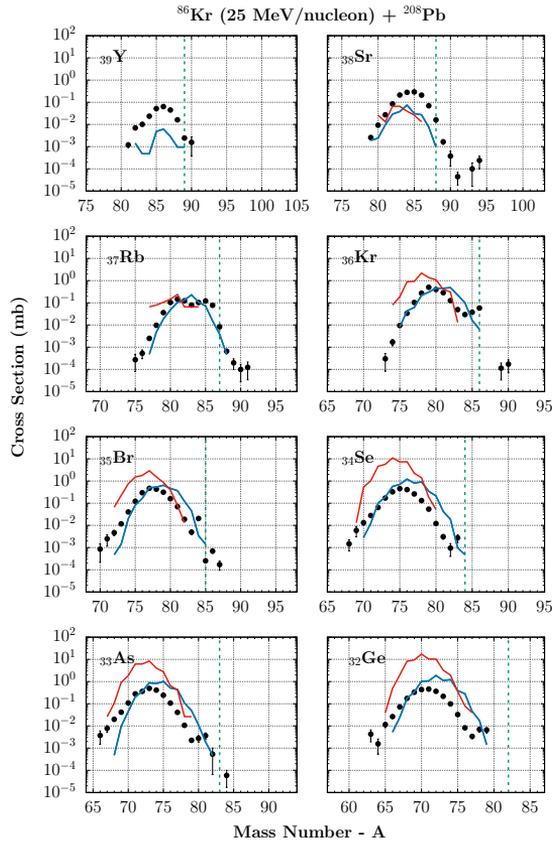
In this work, we employ two dynamical models—the Deep-Inelastic Transfer (DIT) model [2] and the Constrained Molecular Dynamics (CoMD) model [3]. The DIT model is a phenomenological approach that describes peripheral collisions by treating the projectile and target as spherical nuclei

modeled as Fermi gases that stochastically exchange nucleons. In contrast, the CoMD model is a fully microscopic approach in which nucleons are represented as Gaussian wave packets, and the Pauli exclusion principle is explicitly enforced through constraints on the dynamical evolution of the system.

Our research group systematically compares the predictions of these models with experimental data [6–9] in order to elucidate the underlying mechanisms and reaction dynamics governing nuclear reactions in the Fermi energy domain.

## 2. Experimental Details

The experimental investigation was carried out at the Cyclotron Institute of Texas A&M University. A  $^{86}\text{Kr}$  beam with an energy of 25 MeV per nucleon was accelerated using the K500 cyclotron and directed onto a  $^{208}\text{Pb}$  target. The reaction products were analyzed employing the MARS (Momentum Achromat Recoil Spectrometer) recoil separator. The beam impinged on the target at an angle of  $0^\circ$  with respect to the optical axis of the MARS, whereas fragments were accepted in an angular window of  $1.0^\circ - 2.7^\circ$  corresponding to a solid angle of 6.0 msr.

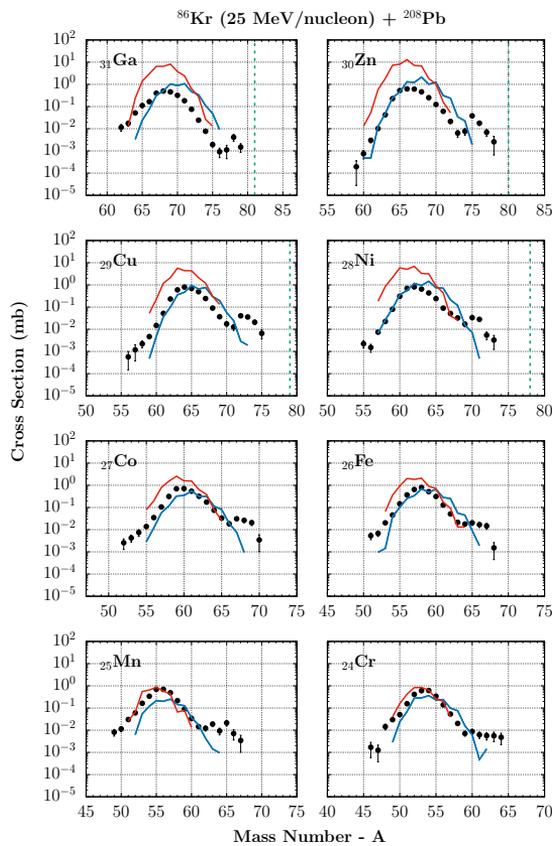


**Figure 1.** Production cross sections (mass distributions) of elements with  $Z=32-39$  from the reaction  $^{86}\text{Kr}$  (25 MeV/nucleon) +  $^{208}\text{Pb}$ . Black points: experimental data. Full (blue) lines: DIT calculations for the final fragments, filtered for angular acceptance and magnetic rigidity. Full (red) lines: CoMD calculations for the final fragments, filtered for angular acceptance and magnetic rigidity. The vertical dashed (green) lines indicate the initiation of neutron pickup.

Following the interaction with the target and guided by two quadrupoles and one dipole, projectile fragments traversed a parallel-plate avalanche counter (PPAC) that provided event-by-event mea-

measurements of position, magnetic rigidity, and the START time for the time-of-flight determination. The fragments were subsequently focused at the focal plane of the separator, where a second PPAC supplied the STOP-time signal. Energy-loss and residual energy measurements were obtained using a  $\Delta E - E$  silicon detector telescope positioned at the focal plane.

Fragment identification, including the determination of atomic number ( $Z$ ), mass number ( $A$ ), velocity, and charge, was accomplished on an event-by-event basis using standard reconstruction techniques based on correlations among magnetic rigidity, energy loss, residual energy, and time of flight [1, 9]. Data were collected over a series of magnetic rigidity settings of the spectrometer to ensure complete coverage of the relevant fragment distributions.



**Figure 2.** Production cross sections (mass distributions) of elements with  $Z=24-31$  from the reaction  $^{86}\text{Kr}$  (25 MeV/nucleon) +  $^{208}\text{Pb}$ . Black points: experimental data. Full (blue) lines: DIT calculations for the final fragments, filtered for angular acceptance and magnetic rigidity. Full (red) lines: CoMD calculations for the final fragments, filtered for angular acceptance and magnetic rigidity. The vertical dashed (green) lines indicate the initiation of neutron pickup.

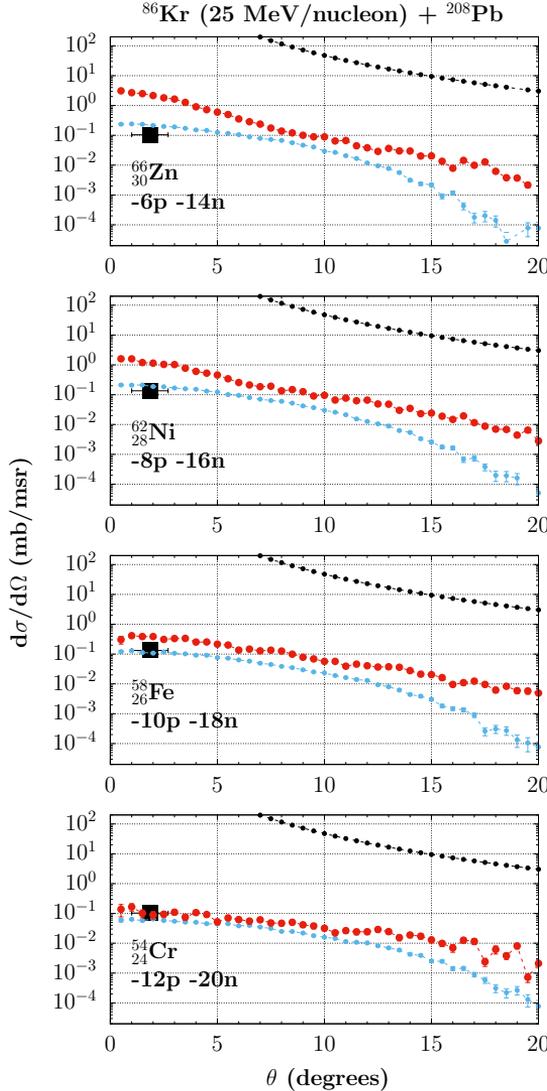
### 3. Results and Discussions

The experimental results obtained from the setup described above were employed for comparison with theoretical predictions from the Deep-Inelastic Transfer (DIT) and Constrained Molecular Dynamics (CoMD) models, followed by statistical de-excitation using the GEMINI code.

Figures 1 and 2 present the measured mass distributions of projectile-like fragments produced in the  $^{86}\text{Kr} + ^{208}\text{Pb}$  reaction at 25 MeV/nucleon. Figure 1 displays the isotopic production cross sections for

elements with atomic numbers  $Z=32-39$ , whereas Figure 2 shows the corresponding distributions for  $Z=24-31$ .

The comparison of the model calculations with the data indicates that both models reproduce the general features of the experimental data, with the DIT model showing somewhat better agreement. It is also observed that both models provide a more accurate description for the less neutron-rich isotopes compared to the more neutron-rich ones.



**Figure 3.** Angular distributions (in the lab system) of projectile-like fragments for peak isotope channels. Black circles: Rutherford scattering. Black square: Experimental data. Blue full circles: DIT calculations filtered for magnetic rigidity acceptance. Red full circles: CoMD calculations filtered for magnetic rigidity acceptance.

The simulations were performed with a large event sample to minimize statistical fluctuations. In addition, we notice that primary fragments always have higher cross sections compared to the final products, because they lose nucleons and other particles during the de-excitation. The final cold fragments were obtained after de-excitation using the GEMINI code. Similarly, the CoMD calcula-

tions were carried out using standard parameters, with a nuclear matter compressibility of  $K=254$  MeV and an impact parameter range of  $b=0-14$  fm. The system evolution was followed up to  $t=600$  fm/c to capture the full dynamical process before de-excitation.

In Figure 3, we present examples of angular distributions of projectile-like fragments for isotopes corresponding to the peaks of the yield distributions of isotopes of figure 2. The full dots represent the calculations filtered for angular acceptance and magnetic rigidity. The black dots represent the Rutherford scattering, while the black square is our experimental data point. We only have one data point because the experiment was done only in one angle interval. It is evident that, DIT calculations are in accordance with the experimental result. From our results we understand that this angle is not preferable for the study of neutron rich nuclides, and thus for their production, angles near the grazing angle of  $8^\circ$  for this system would be necessary [8, 9].

#### 4. Conclusions

In summary, in this work we investigated the reaction of  $^{86}\text{Kr}$  with  $^{208}\text{Pb}$  at 25 MeV per nucleon using the MARS recoil separator at the Cyclotron Institute of Texas A&M University. The experimental mass and angular distributions of projectile-like fragments were compared with theoretical predictions obtained from the Deep-Inelastic Transfer (DIT) and Constrained Molecular Dynamics (CoMD) models, coupled with the statistical decay code GEMINI.

Both theoretical approaches reproduce the main features of the experimental data, with the DIT model demonstrating a slightly better overall agreement, particularly for isotopes closer to the line of stability. Nevertheless, discrepancies remain for the more neutron-rich isotopes, suggesting that refinements in the microscopic treatment of nucleon exchange and de-excitation mechanisms may be necessary. Furthermore, the angular distribution analysis indicates that measurements at forward angles (near  $0^\circ$ ) are not optimal for investigating the production of neutron-rich nuclei, as such products are more favorably emitted at angles near the grazing angle of the system.

Future work will focus on further systematic theoretical studies using the CoMD and DIT codes to refine the modeling of deep-inelastic transfer processes and to enhance the predictive capability for neutron-rich fragment production. In parallel, new experiments employing a spectrometer capable of covering larger angles, such as the MAGNEX facility at LNS Catania, may be employed. This future effort aims to extend the current investigation to a broader angular domain, thereby enabling a more comprehensive understanding of the reaction dynamics and improving access to regions of the nuclear chart far from stability.

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