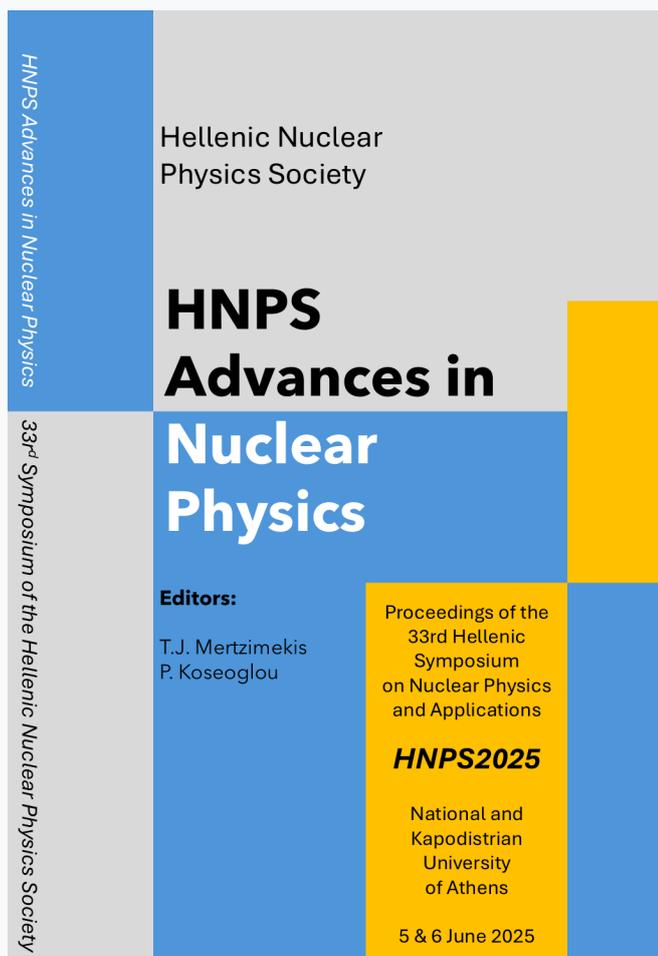


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The cover image features a blue and yellow color scheme. On the left, vertical text reads "HNPS Advances in Nuclear Physics" and "33rd Symposium of the Hellenic Nuclear Physics Society". The main title "HNPS Advances in Nuclear Physics" is prominently displayed in the center. Below the title, the editors' names "T.J. Mertzimekis" and "P. Koseoglou" are listed. To the right, it states "Proceedings of the 33rd Hellenic Symposium on Nuclear Physics and Applications", "HNPS2025", "National and Kapodistrian University of Athens", and the dates "5 & 6 June 2025".

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ARTICLE

Multinucleon Transfer Channels in $^{86}\text{Kr} + ^{124}\text{Sn}$ Peripheral Collisions at 15 and 25 MeV/nucleon.

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Abstract

Reaching the region of exotic neutron rich nuclei is one of the main interests of the nuclear physics community. Apart from projectile fragmentation and reactions near the Coulomb barrier, another route to this region is through multinucleon transfer (MNT) reactions near the Fermi energy (15–35 MeV/nucleon). In this work, we present part of our detailed study of MNT reaction mechanisms on peripheral collisions by using a ^{86}Kr projectile at 15 and 25 MeV/nucleon impinging on a ^{124}Sn target focusing specifically on the momentum per nucleon distributions. Experimental data were obtained by using the Momentum Achromat Recoil Separator (MARS) at Texas A&M University in a previous experimental campaign performed by our group. The interaction between the projectile and the target was simulated by the phenomenological Deep Inelastic Transfer model (DIT) and the microscopic Constrained Molecular Dynamics model (CoMD). The subsequent deexcitation of the initial excited projectile-like fragments was performed by the GEMINI model. Both models appear to describe the overall features of the data fairly well especially at 25 MeV/nucleon. The comparison of the model calculations with the experimental data at two different energies aims to elucidate the evolution of the reaction mechanisms in this energy regime. We concluded that apart from independent nucleon exchange, target inelastic excitation and direct reaction processes involving neutron and proton pair transfer, cluster transfer and meson-mediated charge exchange may be present.

Keywords: Heavy Ion Reactions; Multinucleon Transfer; Neutron Rich Nuclei; Deep Inelastic Collisions; Constrained Molecular Dynamics

1. Introduction

Moving to nuclei far from the limits of stability towards the neutron dripline and the r-process path has been a crucial topic in the development of modern nuclear physics [1]. Apart from the traditional routes of fragmentation reactions, multinucleon transfer reactions from the Coulomb barrier to the Fermi energy (15-35 MeV/nucleon) have been proven to be an effective path to reach these neutron rich nuclei [2-4].

Our work has been focused on the systematic study of multinucleon transfer reactions in the Fermi energy domain [5-11]. This contribution describes our study of momentum per nucleon distributions of projectile-like fragments from reactions involving a ^{86}Kr projectile at 15 and 25 MeV/nucleon with the neutron rich target ^{124}Sn .

Our intention is to expand our understanding of the reaction mechanisms in this energy range. We believe that we have at hand a rather reliable model framework that, on the one hand, will be able to fairly describe the experimental data obtained so far and, on the other hand, will allow for dependable predictions of rates of neutron rich isotopes in various production and separation schemes employing such reactions.

2. Experimental Data

The experimental data of the reactions reported in this work were obtained at the Cyclotron Institute of Texas A&M University employing the Momentum Achromat Recoil Separator (MARS) in previous works of our research group. In the first experiment [5], a ^{86}Kr beam ($\approx 3\text{pA}$) at 15 MeV/nucleon interacted with a ^{124}Sn target (2.2 mg/cm^2 thickness) at $\theta_{exp}=7.4^\circ$ relative to the optical axis of the spectrometer resulting in the collection of ejectiles in the angular range of $5.6^\circ - 9.2^\circ$. In the second experiment [6], a ^{86}Kr beam ($\approx 1\text{pA}$) at 25 MeV/nucleon interacted with a ^{124}Sn target (2.0 mg/cm^2 thickness) at $\theta_{exp}=4.0^\circ$ relative to the optical axis of the spectrometer resulting in the collection of ejectiles in the angular range of $2.7^\circ - 5.4^\circ$. In both experiments, the angular settings lie within the grazing angles for these reactions (9.0° and 6.5° for the 15 and 25 MeV/nucleon reactions, respectively).

3. Calculation Models

The theoretical models used in this work are based on a two-stage Monte-Carlo approach. The interaction between the projectile and the target is simulated with the DIT and CoMD models. For the deexcitation of the hot projectile-like fragments the GEMINI model was used.

The DIT (Deep-Inelastic Transfer) model [12] is a phenomenological model designed for peripheral collisions in the Fermi energy domain. The projectile and the target follow Coulomb trajectories until they enter the range of nuclear interaction. Then a "window" opens between the nuclear surfaces and the stochastic exchange of nucleons takes place. The result is the production of very neutron rich projectile-like fragments.

The CoMD (Constrained Molecular Dynamics) model [13, 14] is a microscopic semi-classical model based on Quantum Molecular Dynamics (QMD) [15]. Here, the nucleons are considered to be gaussian wave-packets interacting through a phenomenological effective potential. A restriction in the phase-space is used to impose the Pauli principle, essentially restoring the fermionic nature of the system.

The GEMINI model [16, 17] is a statistical deexcitation code employing the Hauser-Feshbach formalism to calculate the probabilities for fragment emission. Generally, the final products come from suc-

cessive binary decays. For the rest of this work we refer to the DIT/GEMINI and the CoMD/GEMINI calculations simply as DIT and CoMD calculations, respectively.

4. Comparisons

In this section, we present comparisons between the experimental data and the described models, focusing on the momentum per nucleon (p/A) distributions. We focus on channels of neutron pickup, proton removal and multiple charge exchange that produce neutron rich isotopes.

In all the distributions discussed below, the experimental data are shown in full black points and these distributions refer to the data just inside the grazing angle for each system, namely, 9.0° and 6.5° for the 15 and 25 MeV/nucleon reactions, respectively. CoMD calculations are represented by full red squares and DIT calculations by full blue circles. Green vertical dashed lines indicate the p/A of the projectile as it exits the target. Numbers on top of some regions represent the total excitation energy (in MeV) of the binary quasi-projectile and quasi-target system obtained by binary kinematics. Q_{gg} is the ground-to-ground state Q -value in MeV as well. Also evident in all the distributions is a characteristic shape with a quasi-elastic peak near the p/A of the projectile and a more dissipative region as the p/A decreases.

4.1 Neutron Pickup Channels

Fig. 1 reports the neutron pickup channels for the reaction $^{86}\text{Kr} + ^{124}\text{Sn}$ at 15 MeV/nucleon (left) and 25 MeV/nucleon (right). For the 15 MeV/nucleon reaction, we present channels where the projectile has received up to 4 neutrons from the target, and for the 25 MeV/nucleon reaction, up to 2 neutrons from the target.

For the 15 MeV/nucleon reaction, the CoMD calculation seems to describe the quasi-elastic (QE) peak and the dissipative region on the +2n and +3n channels, while it underestimates them on the +1n channel. The DIT calculation on the other hand, while it follows the overall trend of the experimental distributions, underestimates them.

On the other hand, when the energy of the projectile is increased to 25 MeV/nucleon, the CoMD and DIT calculations describe equally well the QE regions for the both the +1n and +2n channels.

4.2 Proton Removal Channels

Next, we present in Fig. 2 the proton removal channels (-1p to -4p) for the reactions $^{86}\text{Kr} + ^{124}\text{Sn}$ at 15 MeV/nucleon (left) and 25 MeV/nucleon (right).

At 15 MeV/nucleon, we observe that the CoMD calculations tend to overestimate the QE regions of the -1p, -2p, -3p channels but are closer to the data on the dissipative regions (from $p/A = 155$ MeV/c and lower). The DIT calculations still seem to underestimate the experimental data with an overall better agreement on the middle part of the dissipative region of the -1p channel.

The fair description of the data by the models at 25 MeV/nucleon is more evident on the proton removal channels. On the -1p and -2p channels, the CoMD calculation describes the QE and the middle part of the dissipative region of the data quite accurately, as well as the middle part of the distribution on the -3p channel. As for the DIT calculation, it follows the experimental data closely for the -1p channel, the QE region of the -2p channel and the middle part of the -3p channel.

4.3 Multiple Charge Exchange Channels

Finally, in Fig. 3 we present multiple charge exchange channels (removal of protons and addition of neutrons) for the reactions $^{86}\text{Kr} + ^{124}\text{Sn}$ at 15 MeV/nucleon (left) and 25 MeV/nucleon (right).

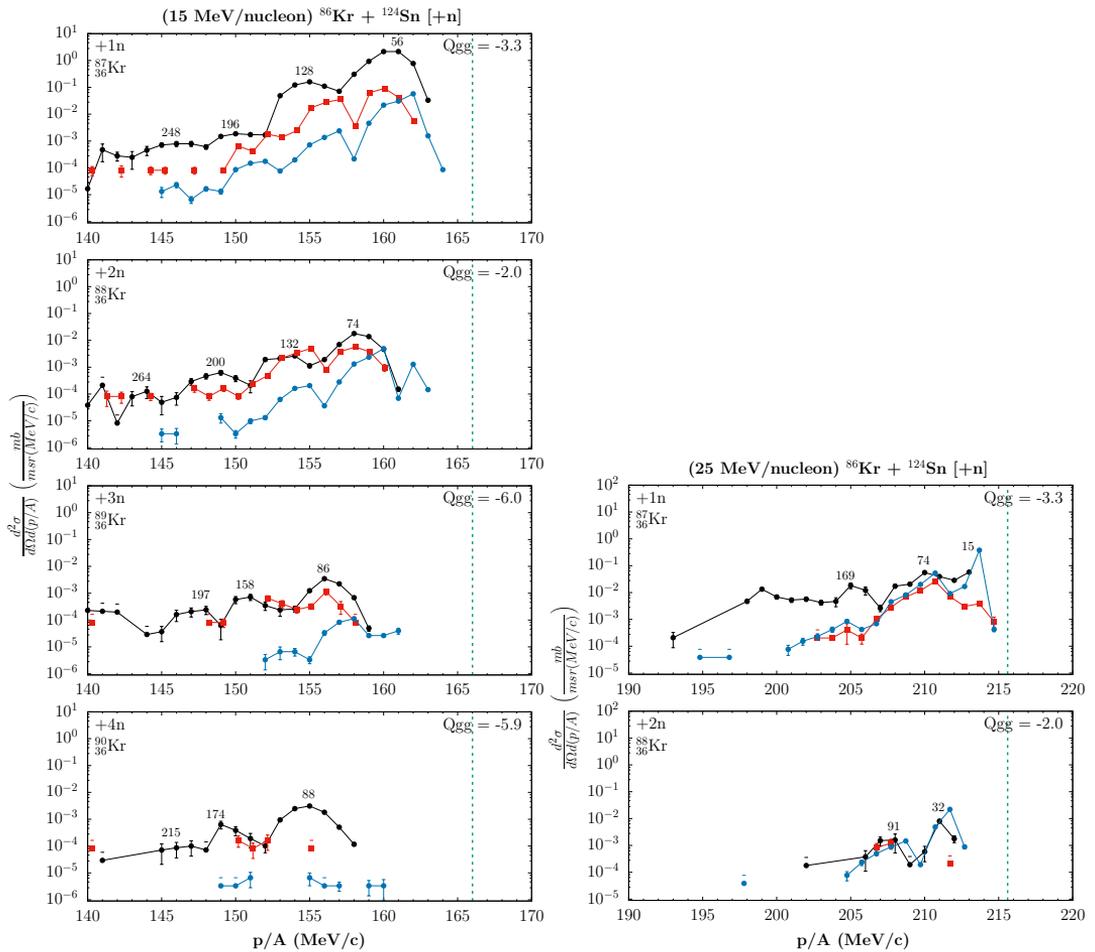


Figure 1. Momentum per nucleon distributions of ejectiles from neutron pickup channels of $^{86}\text{Kr} + ^{124}\text{Sn}$ at 15 MeV/nucleon (left) and 25 MeV/nucleon (right). Experimental data: closed (black) circles. Vertical dashed (green) line: p/A of the beam. Numbers above peaks: total excitation energy of QP-QT system in MeV. Q_{gg} : Ground-to-ground state Q-value in MeV. CoMD calculations: closed (red) squares. DIT calculations: closed (blue) circles.

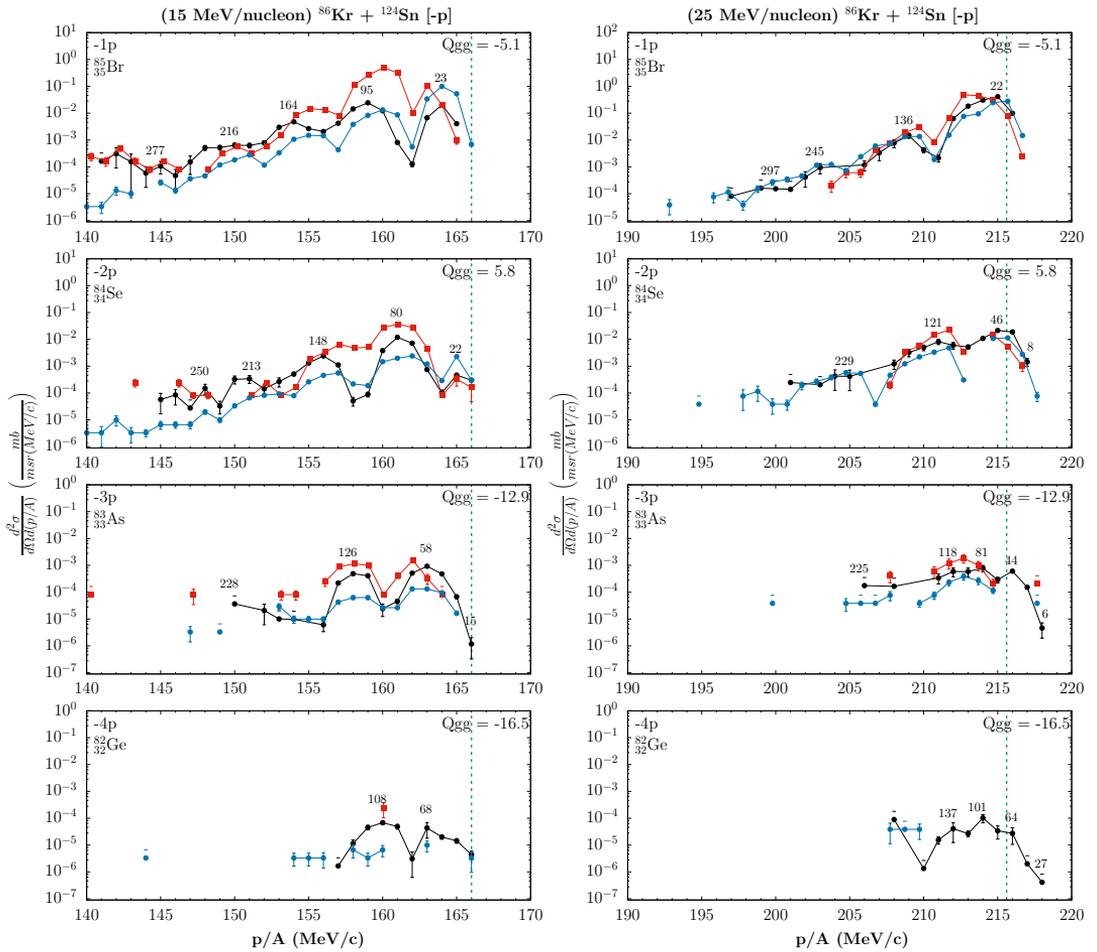


Figure 2. Momentum per nucleon distributions of ejectiles from proton removal channels of $^{86}\text{Kr} + ^{124}\text{Sn}$ at 15 MeV/nucleon (left) and 25 MeV/nucleon (right). Experimental data: closed (black) circles. Vertical dashed (green) line: p/A of the beam. Numbers above peaks: total excitation energy of QP-QT system in MeV. Q_{gg} : Ground-to-ground state Q-value in MeV. CoMD calculations: closed (red) squares. DIT calculations: closed (blue) circles.

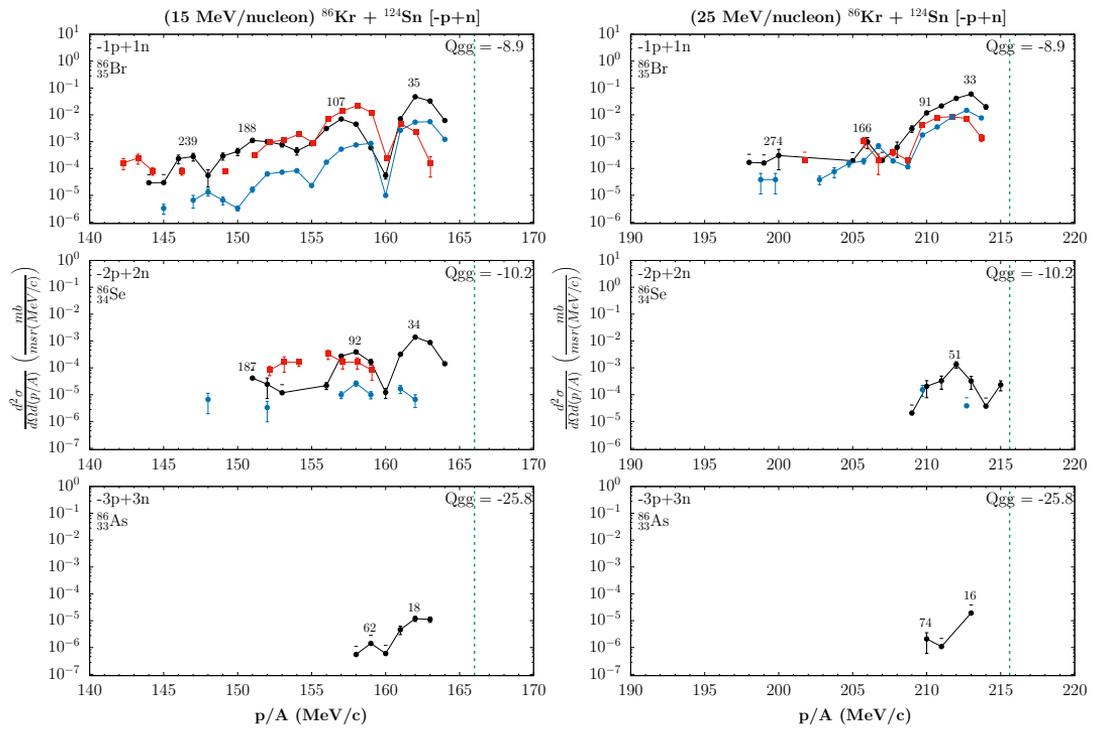


Figure 3. Momentum per nucleon distributions of ejectiles from multiple charge channels of $^{86}\text{Kr} + ^{64}\text{Ni}$ at 15 MeV/nucleon (left) and 25 MeV/nucleon (right). Experimental data: closed (black) circles. Vertical dashed (green) line: p/A of the beam. Numbers above peaks: total excitation energy of QP–QT system in MeV. Q_{gg} : Ground-to-ground state Q-value in MeV. CoMD calculations: closed (red) squares. DIT calculations: closed (blue) circles.

These channels are expected to be more complicated because they involve removal of protons and addition of neutrons. We present single charge exchange (SCE), double charge exchange (DCE) and triple charge exchange (TCE) channels.

Comparing the data with the DIT and CoMD calculations we can make observations analogous to those of the neutron pickup and proton removal channels. Specifically, at 15 MeV/nucleon, the QE region is underestimated by both calculations, with CoMD being closer to the experimental data on the more dissipative region. At 25 MeV/nucleon, both calculations show improvement on the description of the SCE channel.

As for the TCE channels at both energies neither calculation has reached these very low cross section distributions. We assume that larger statistics in these Monte Carlo Calculations and/or the inclusion of a meson-mediated charge exchange mechanism may improve the results, but this is beyond the scope of this paper.

5. Results and Discussion

In this paper we presented part of our systematic study of the momentum distributions of neutron rich projectile-like fragments from the reaction $^{86}\text{Kr} + ^{124}\text{Sn}$ at 15 and 25 MeV/nucleon. In our comparisons, we observed an overall good agreement between both DIT and CoMD calculations and the experimental data at 25 MeV/nucleon with more discrepancies at 15 MeV/nucleon. Specifically, going from 15 MeV/nucleon to 25 MeV/nucleon, DIT and CoMD calculations tend to become similar and rather close to the experimental data for most of the channels that produce neutron rich nuclides. This may suggest that the mechanism of independent nucleon exchange implemented phenomenologically in the DIT model and microscopically in the CoMD model appears to be the major contributor in these reactions producing neutron rich nuclides near the projectile. At 15 MeV/nucleon, apart from independent nucleon exchange other processes such as the direct transfer of neutron pairs or proton pairs and meson-mediated single, double, and triple charge exchange may be present. These effects tend to diminish as the projectile energy increases to 25 MeV/nucleon. Examining each one of these processes is a whole new research field in itself, leading to new possibilities for future research inspired by the present work.

Some of our future plans include the use of direct reactions models, such as FRESCO [18] and/or PTOLEMY [19] along with DIT and CoMD, to attain a well rounded understanding of the quasi-elastic processes in this energy regime. Furthermore, we plan to develop a procedure for the reconstruction of the excitation energy distributions in order to elucidate the reaction mechanisms and conditions necessary for the production of neutron rich nuclei. Finally, we plan to include more statistics in our calculations that may benefit the low cross section reaction paths. We envision that the study of the momentum distributions of these reactions along with recent work on reactions with a ^{64}Ni target in a similar energy range, will contribute to the elucidation of the reaction mechanisms that are responsible for the production of exotic neutron rich nuclei near and below the Fermi energy regime.

References

- [1] M. Thoennessen. "2023 update of the discoveries of nuclides". In: *International Journal of Modern Physics E* 33.03n04 (2024), p. 2430001. doi: 10.1142/S0218301324300017.
- [2] Jun-Jun Cai, Li-Lin Zhou, Gen Zhang, Lu-Qi Li, and Feng-Shou Zhang. "Production of neutron-rich nuclei with $Z=95-100$ in multinucleon transfer reactions considering the effect of deformation relaxation". In: *Phys. Rev. C* 110 (2024), p. 044602. doi: 10.1103/PhysRevC.110.044602.
- [3] R. Perez-Vidal, F. Galtarossa, T. Mijatović, S. Szilner, I. Zanon, and D. Brugnara. "Nuclear structure advancements with multinucleon transfer reactions". In: *Eur. Phys. J. A* 59 (2023), p. 114. doi: 10.1140/epja/s10050-023-01027-2.
- [4] L. Corradi, S. Szilner, G. Pollarolo, D. Montanari, E. Fioretto, A. M. Stefanini, et al. "Multinucleon transfer reactions: Present status and perspectives". In: *Nucl. Instrum. Meth. B* 317 (2013), p. 743. doi: 10.1016/j.nimb.2013.04.093.

- [5] G. A. Souliotis, M. Veselsky, S. Galanopoulos, M. Jandel, Z. Kohley, L. W. May, D. V. Shetty, B. C. Stein, and S. J. Yennello. "Approaching neutron-rich nuclei toward the r -process path in peripheral heavy-ion collisions at 15 MeV/nucleon". In: *Phys. Rev. C* 84 (6 2011), p. 064607. doi: 10.1103/PhysRevC.84.064607.
- [6] G. A. Souliotis, M. Veselsky, G. Chubarian, L. Trache, A. Keksis, E. Martin, D. V. Shetty, and S. J. Yennello. "Enhanced Production of Neutron-Rich Rare Isotopes in Peripheral Collisions at Fermi Energies". In: *Phys. Rev. Lett.* 91 (2003), p. 022701. doi: 10.1103/PhysRevLett.91.022701.
- [7] O. Fasoula, G. A. Souliotis, S. Koulouris, A. Pakou, M. Veselsky, S. J. Yennello, and A. Bonasera. "Peripheral Heavy-Ion Collisions below the Fermi Energy: the case of $^{86}\text{Kr} + ^{64}\text{Ni}$ and $^{86}\text{Kr} + ^{124}\text{Sn}$ at 15 MeV/nucleon". In: *Phys. Rev. C* (submitted 2025).
- [8] O. Fasoula, G. A. Souliotis, S. Koulouris, A. Pakou, M. Veselsky, S. J. Yennello, and A. Bonasera. "Multinucleon Transfer in 25 MeV/nucleon $^{86}\text{Kr} + ^{64}\text{Ni}$, ^{124}Sn Peripheral Collisions". In: *EPJ Web Conf.* 304 (2024), p. 01011. doi: 10.1051/epjconf/202430401011.
- [9] O. Fasoula. "Systematic Studies of Heavy-Ion Reactions in the Fermi Energy Domain for the Production of Rare Isotopes". PhD thesis. Laboratory of Physical Chemistry, Department of Chemistry, National and Kapodistrian University of Athens, 2025.
- [10] S. Koulouris. "Studies of Peripheral Heavy-ion Reactions with the MAGNEX Spectrometer for the Production of Neutron-rich Isotopes". PhD thesis. Laboratory of Physical Chemistry, Department of Chemistry, National and Kapodistrian University of Athens, 2025.
- [11] S. Koulouris, G. A. Souliotis, F. Cappuzzello, D. Carbone, A. Pakou, C. Agodi, et al. "Multinucleon transfer channels from ^{70}Zn (15 MeV/nucleon) + ^{64}Ni collisions". In: *Phys. Rev. C* 108 (2023), p. 044612. doi: 10.1103/PhysRevC.108.044612.
- [12] L. Tassan-Got and C. Stéphan. "Deep inelastic transfers: A way to dissipate energy and angular momentum for reactions in the Fermi energy domain". In: *Nuclear Physics A* 524 (1991), p. 121. doi: 10.1016/0375-9474(91)90019-3.
- [13] M. Papa, T. Maruyama, and A. Bonasera. "Constrained molecular dynamics approach to fermionic systems". In: *Phys. Rev. C* 64 (2001), p. 024612. doi: 10.1103/PhysRevC.64.024612.
- [14] M. Papa, G. Giuliani, and A. Bonasera. "Constrained molecular dynamics II: An N-body approach to nuclear systems". In: *Journal of Computational Physics* 208 (2005), p. 403. doi: 10.1016/j.jcp.2005.02.032.
- [15] J. Aichelin. "Quantum" molecular dynamics—a dynamical microscopic n-body approach to investigate fragment formation and the nuclear equation of state in heavy ion collisions". In: *Physics Reports* 202.5 (1991), p. 233. doi: 10.1016/0370-1573(91)90094-3.
- [16] R. J. Charity, M. A. McMahan, G. J. Wozniak, R. J. McDonald, L. G. Moretto, D. G. Sarantites, et al. "Systematics of complex fragment emission in niobium-induced reactions". In: *Nuclear Physics A* 483 (1988), p. 371. doi: 10.1016/0375-9474(88)90542-8.
- [17] R. J. Charity. "N-Z distributions of secondary fragments and the evaporation attractor line". In: *Phys. Rev. C* 58 (2 1998), p. 1073. doi: 10.1103/PhysRevC.58.1073.
- [18] I. J. Thompson. "Coupled reaction channels calculations in nuclear physics". In: *Comput. Phys. Rep.* 7.4 (1988), pp. 167–212. doi: 10.1016/0167-7977(88)90005-6.
- [19] M. H. Macfarlane and S. C. Pieper. "Ptolemy: a program for heavy-ion direct-reaction calculations. [Cross sections, DWBA]". In: *Argonne National Laboratory report* (1978). doi: 10.2172/6750864.