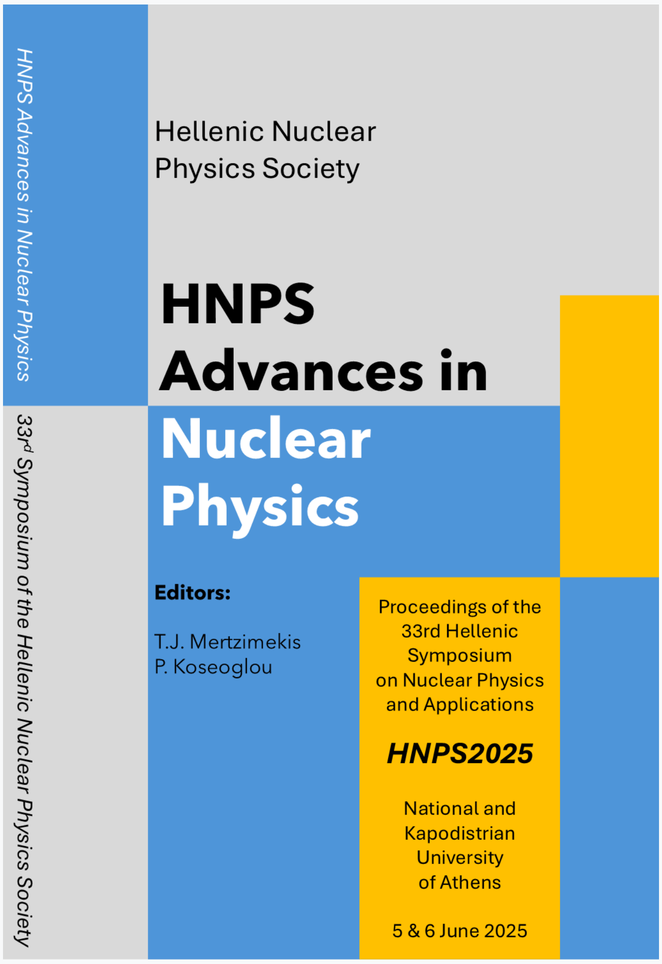
HNPS Advances in Nuclear Physics

Vol 32 (2026)

HNPS2025



Elastic Scattering of Medium-Mass Heavy-Ions and the Compressibility of the Nuclear Equation of State

Stergios Koulouris, Georgios A. Souliotis, Athina Pakou, Francesco Cappuzzello, Diana Carbone, Manuela Cavallaro, Olga Fasoula, Onoufrios Sgouros, Vasileios Soukeras, Martin Veselsky

doi: [10.12681/hnpsanp.8863](https://doi.org/10.12681/hnpsanp.8863)

Copyright © 2025, Stergios Koulouris, Georgios A. Souliotis, Athina Pakou, Francesco Cappuzzello, Diana Carbone, Manuela Cavallaro, Olga Fasoula, Onoufrios Sgouros, Vasileios Soukeras, Martin Veselsky

This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0.

To cite this article:

Koulouris, S., Souliotis, G. A., Pakou, A., Cappuzzello, F., Carbone, D., Cavallaro, M., Fasoula, O., Sgouros, O., Soukeras, V., & Veselsky, M. (2026). Elastic Scattering of Medium-Mass Heavy-Ions and the Compressibility of the Nuclear Equation of State. *HNPS Advances in Nuclear Physics*, *32*, 20–24. https://doi.org/10.12681/hnpsanp.8863

https://epublishing.ekt.gr | **e-Publisher:** EKT | **Downloaded at:** 03/03/2026 18:11:52

HNPS Advances in Nuclear Physics Vol. **32**, 20–24 (2025)
doi: 10.12681/hnpsanp.8863

Hellenic Nuclear Physics Society
Advances in Nuclear Physics
since 1990

ARTICLE

Elastic Scattering of Medium-Mass Heavy-Ions and the Compressibility of the Nuclear Equation of State

S. Koulouris,[*,1] G.A. Souliotis,[1] A. Pakou,[2] F. Cappuzzello,[3,4] D. Carbone,[4] M. Cavallaro,[4] O. Fasoula,[1] O. Sgouros,[3,4] V. Soukeras,[3,4] and M. Veselsky[5]

[1]Laboratory of Physical Chemistry, Department of Chemistry, National and Kapodistrian University of Athens, Athens, Greece
[2]Department of Physics, The University of Ioannina, Ioannina, Greece
[3]Dipartimento di Fisica e Astronomia "Ettore Majorana", Universita di Catania, Catania, Italy
[4]Laboratori Nazionali del Sud, INFN, Catania, Italy
[5]Institute of Experimental and Applied Physics, Czech Technical University, Prague, Czech Republic
*Corresponding author: stekoul@chem.uoa.gr

(Received: 9 Nov 2025; Accepted: 16 Nov 2025; Published: 17 Nov 2025)

Abstract

Preliminary results on the elastic scattering channel of the ^{70}Zn (15 MeV/nucleon) + ^{64}Ni reaction, studied with the MAGNEX large-acceptance spectrometer at INFN-LNS, are presented. This work is part of an extended effort to investigate reaction mechanisms in the Fermi energy regime, following previous analyses of momentum-per-nucleon distributions, angular distributions, and production cross sections of multinucleon transfer channels. Attention is here focused on elastic scattering of medium mass heavy ions and its sensitivity to the parameters of the nuclear equation of state (EOS).

Experimental angular distributions were compared with Constrained Molecular Dynamics (CoMD) model calculations performed under different assumptions of nuclear matter compressibility (K = 200, 254, 308 MeV). The results indicate sensitivity of the elastic scattering differential cross sections to the compressibility of the nuclear EOS. Optical model calculations are also planned to complement the microscopic approach and provide complementary insight in the EOS.

Keywords: Large Acceptance Spectrometer; Neutron-Rich Isotopes; Multinucleon Transfer; Elastic Scattering

1. Introduction

The study of nuclei away from the valley of β-stability remains a central focus of nuclear physics, as it provides key insights into the effective nuclear interaction and astrophysical processes such as the rapid neutron-capture (r-) process [1–4]. Multinucleon transfer and deep-inelastic reactions near and above the Coulomb barrier, constitute an important tool for producing exotic neutron-rich projectile-like fragments (PLF) [5, 6]. These reactions, typically governed by sequential nucleon exchange,

© 2025 by the Author(s). Published by the Hellenic Nuclear Physics Society (HNPS) and the National Documentation Centre (EKT.gr). This is an open access article under the CC BY-NC license. ISBN 2654-007X (print), 2654-0088 (online).

represent an important framework for investigating nuclear structure and reaction dynamics.

This work extends earlier analyses performed in the 15-25 MeV/nucleon region [7, 8], where a systematic approach to identifying and characterizing projectile-like fragments (PLF) using the MAGNEX large-acceptance spectrometer at INFN–LNS was established. Previous analyses focused on momentum per nucleon (p/A) distributions, angular distributions and production cross sections of various multinucleon transfer channels [9–13].

The present study focuses on elastic scattering, which offers a complementary probe of the nuclear potential and the nuclear matter equation of state (EOS). At intermediate energies, elastic scattering angular distributions at forward angles are dominated by the Coulomb interaction and follow the Rutherford prediction. At larger angles, however, nuclear effects emerge and interfere with the Coulomb potential, leading to deviations from the Rutherford form. These deviations can reveal properties of the nuclear potential such as range, surface diffuseness, and are sensitive to bulk nuclear matter properties such as the compressibility parameter. Similar approaches have been followed by other groups to explore the sensitivity of elastic scattering observables to the nuclear EOS and potential characteristics [14–18].

To investigate this sensitivity, experimental elastic-scattering angular distributions for the ^{70}Zn (15 MeV/nucleon) + ^{64}Ni reaction were measured using the MAGNEX spectrometer and compared with Constrained Molecular Dynamics (CoMD) [19] calculations performed with different assumptions of the nuclear matter compressibility.

2. Overview of Data Reduction

The experimental data employed in this work were obtained with the MAGNEX spectrometer [20] at Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali del Sud (INFN-LNS) in Catania, Italy. The spectrometer's magnetic structure consists of a vertically focusing quadrupole followed by a horizontally dispersing and focusing dipole magnet, as well as a focal plane detector (FPD). The observation window was defined by a horizontal angular acceptance of $\Delta\theta = 11^\circ$ (from 4° to 15°) and vertical angular acceptance of $\Delta\phi = 1.6^\circ$ resulting in a solid angle coverage of $\Delta\Omega = 5.4$ *msr* [21].

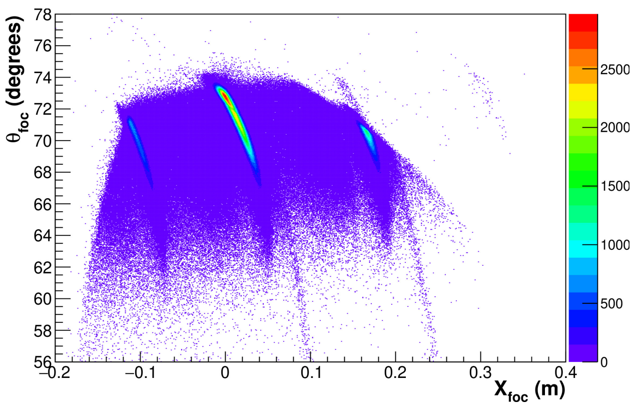


Figure 1. Plot of the horizontal angle versus the horizontal position measured at the MAGNEX FPD for ejectiles from the interaction of a ^{70}Zn beam (15 MeV/nucleon) with a ^{64}Ni target. This plot shows the totality of experimental data of ejectiles distributed on all the FPD silicon detectors used for this experiment. Distinct concentrated regions ("stripes") correspond to elastically scattered ejectiles in the charge states 30+, 29+, 28+, from left to right respectively. These events were isolated through dedicated data analysis to extract angular and p/A distributions.

In Fig. 1, a plot of the horizontal angle versus the horizontal position measured at the MAGNEX FPD for ejectiles from the interaction of a ^{70}Zn beam (15 MeV/nucleon) with a ^{64}Ni target is presented. This plot shows the totality of experimental data of ejectiles distributed on all the FPD silicon detectors used for this experiment. Distinct concentrated regions ("stripes") correspond to elastically scattered ejectiles in the charge states 30+, 29+, 28+, from left to right, respectively. These events were isolated and then identified through dedicated data analysis as established and outlined in [11, 12] in order to extract angular and momentum per nucleon distributions (p/A) [12, 13, 21].

These distributions, obtained through the systematic analysis of produced PLF, formed the basis for a broader investigation into reaction mechanisms at the Fermi energy regime. This study marked a step toward detailed exploration of peripheral reactions using high-resolution magnetic spectrometry. In the following section, we focus on the elastic scattering channel of the same reaction system, to assess the sensitivity to the nuclear matter EOS through angular distribution analysis.

3. Results and Discussion

The elastic scattering angular distributions for the reaction ^{70}Zn (15 MeV/nucleon) + ^{64}Ni are shown in Fig. 2, where the ratio of the experimental data to the Rutherford scattering cross section is presented as a function of the lab angle θ_{lab}. The experimentally reconstructed θ_{lab} had a resolution of 0.4 degrees (FWHM). This plot emphasizes the deviation from pure Coulomb behavior and provides direct sensitivity to nuclear effects.

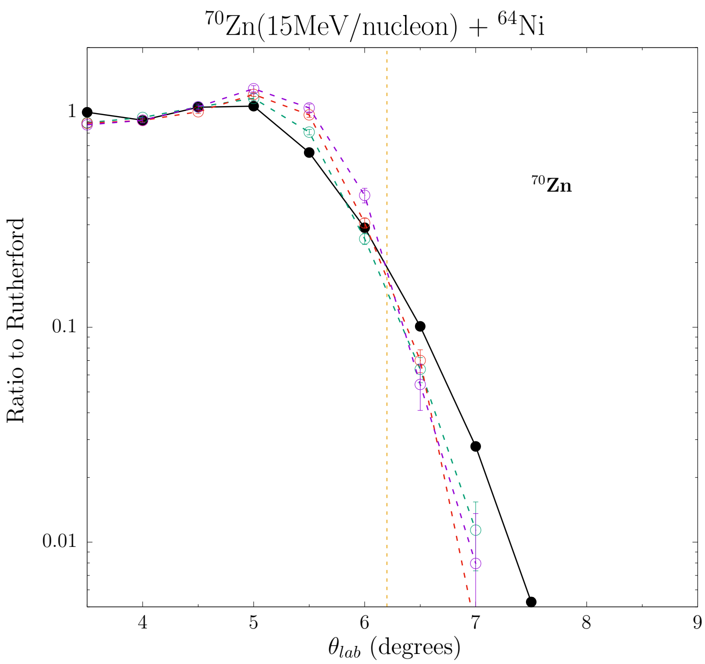


Figure 2. Elastic Scattering Angular Distributions of ^{70}Zn (15 MeV/nucleon) + ^{64}Ni. Ratio of experimental data to Rutherford cross section [closed (black circles) with solid lines], compared with CoMD calculations using three nuclear matter compressibility (K) options: K200 (soft) [open (green circles) with dashed lines], K254 (standard) [open (red circles) with dashed lines], and K308 (hard) [open (purple circles) with dashed lines]. The (yellow) dashed line indicates the grazing angle (θ_{gr} = 6.5°).

At very forward angles (θ_{lab} < 5°), the cross section follows the Rutherford prediction. This region is dominated by the Coulomb interaction and of course, shows negligible sensitivity to the EOS. In the transition region (5° ≤ θ_{lab} ≤ 6°), suppression of the ratio indicates destructive interference between the Coulomb and nuclear amplitudes. This is the region where differences among the CoMD calculations become visible. The soft (K=200 MeV) and the standard (K=254 MeV) compressibility options reproduce the experimental trend more closely, whereas the hard EOS (K=308 MeV) underestimates the ratio. At larger angles ($\theta_{lab} > 6°$), the cross section exhibits a strong fall-off due to nuclear absorption and flux loss to non-elastic channels. In this regime, the models begin to diverge: softer EOS assumptions overshoot the data just before the drop, while the stiffer EOS appears less absorptive. These differences reflect the nuclear density profiles and interaction ranges and their connection to the EOS compressibility parameter.

Table 1. Angular Region Summary

Angular Range	Dominant Effect	Observations
$\theta_{lab} < 5°$	Coulomb Dominated	Cross section close to Rutherford; minimal nuclear interference
$5° \leq \theta_{lab} \leq 6°$	Nuclear-Coulomb Interference	Onset of nuclear effects; best described by soft EOS (K = 200 MeV)
$\theta_{lab} > 6°$	Nuclear Dominated	Rapid fall-off in cross section; sensitive to EOS

The present comparison (Fig. 2), as summarized also in Table 1, indicates that elastic scattering in the energy regime below the Fermi energies (10-30 MeV/nucleon) provides a sensitive probe of nuclear matter compressibility, particularly in the transition region around the grazing angle. Incorporating optical model analyses alongside the microscopic CoMD framework will allow for complementary constraints on the EOS and nuclear potential parameters.

4. Conclusions

The elastic scattering angular distributions offer a sensitive probe of the nuclear EOS through the interplay of Coulomb and nuclear interactions. The overestimation of the cross section in the quasi-elastic region and the underestimation in the absorptive region by CoMD calculations suggest that further refinement of the model is necessary, particularly in the treatment of surface diffuseness. Future comparisons with optical model calculations may provide complementary constraints and help isolate the key physical ingredients governing elastic scattering in medium-mass heavy-ion collisions.

References

[1] T. Mijatovic. “Multinucleon transfer reactions: a mini-review of recent advances”. In: *Front. Phys.* 10:965198 (2022). DOI: 10.3389/fphy.2022.965198.

[2] G.G. Adamian, N.V. Antonenko, A. Diaz-Torres, and S. Heinz. “How to extend the chart of nuclides?” In: *Eur. Phys. J. A* 56.47 (2020). DOI: 10.1140/epja/s10050-020-00046-7.

[3] F. Nowacki, A. Obertelli, and A. Poves. “The neutron-rich edge of the nuclear landscape: Experiment and theory”. In: *Prog. Part. Nucl. Phys.* 120.103866 (2021). DOI: 10.1016/j.ppnp.2021.103866.

[4] L. Corradi, G. Pollarolo, and S. Szilner. “Multinucleon transfer processes in heavy-ion reactions”. In: *J. Phys. G: Nucl. Part. Phys.* 36.113101 (2009). DOI: 10.1088/0954-3899/36/11/113101.

[5] J.J. Cowan, C. Sneden, J.E. Lawler, A. Aprahamian, M. Wiescher, K. Langanke, G. Martinez-Pinedo, and F.K. Thielemann. “Origin of the heaviest elements: The rapid neutron-capture process”. In: *Rev. Mod. Phys.* 36.015002 (2021). DOI: 10.1103/RevModPhys.93.015002.

[6] T. Mijatovic, S. Szilner, L. Corradi, D. Montanari, G. Pollarolo, E. Fioretto, and et al. “Multinucleon transfer reactions in the ^{40}Ar + ^{208}Pb system”. In: *Phys. Rev. C* 94.064616 (2016). DOI: 10.1103/PhysRevC.94.064616.

[7] 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* 84.064607 (2011). DOI: 10.1103/PhysRevC.84.064607.

[8] A. Papageorgiou, G.A. Souliotis, T. Tshoo, S.C. Jeong, B.H. Kang, Y.K. Kwon, M. Veselsky, S.J. Yennello, and A. Bonasera. “Neutron-rich rare isotope production with stable and radioactive beams in the mass range A ∼ 40–60 at beam energy around 15 MeV/nucleon”. In: *J. Phys. G* 45.095105 (2018). DOI: 10.1088/1361-6471/aad7df.

[9] O. Fasoula, G.A. Souliotis, S. Koulouris, K. Palli, M. Veselsky, S. Yennello, and A. Bonasera. “Study of multinucleon transfer mechanisms in ^{86}Kr-induced peripheral reactions at 15 and 25 MeV/nucleon”. In: *HNPS Adv. Nucl. Phys.* 28.47 (2022). DOI: 10.12681/hnps.3572.

[10] K. Palli, G.A. Souliotis, I. Dimitropoulos, T. Depastas, O. Fasoula, S. Koulouris, M. Veselsky, S.J. Yennello, and A. Bonasera. “Microscopic description of multinucleon transfer in ^{40}Ar + ^{64}Ni collisions at 15 MeV/nucleon”. In: *EPJ Web Conf.* 252.07002 (2021). DOI: 10.1051/epjconf.

[11] G.A. Souliotis, S. Koulouris, F. Cappuzzello, D. Carbone, A. Pakou, C. Agodi, and et al. "Identification of medium mass (A=60-80) ejectiles from 15 MeV/nucleon peripheral heavy-ion collisions with the MAGNEX large-acceptance spectrometer". In: *Nucl. Instrum. Methods A* 1031.166588 (2022). DOI: 10.1016/j.nima.2022.166588.

[12] S. Koulouris, G.A. Souliotis, F. Cappuzzello, D. Carbone, A. Pakou, C. Agodi, and et al. "Measurements of projectile fragments from ^{70}Zn + ^{64}Ni collisions with the MAGNEX spectrometer at INFN-LNS". In: *HNPS Adv. Nucl. Phys.* 28.42 (2022). DOI: 10.12681/hnps.3571.

[13] G.A. Souliotis, S. Koulouris, F. Cappuzzello, D. Carbone, A. Pakou, C. Agodi, and et al. "Multinucleon transfer channels from ^{70}Zn (15 MeV/nucleon) + ^{64}Ni collisions". In: *Phys. Rev. C* 108.044612 (2023). DOI: 10.1103/PhysRevC.108.044612.

[14] K. Palli, A. Pakou, P.D. O'Malley, L. Acosta, A.M. Sánchez-Benítez, G.A. Souliotis, and et al. "Elastic scattering of ^{8}B + ^{nat}Zr at the sub-barrier energy of 26.5 MeV". In: *Phys. Rev. C* 109.064614 (2024). DOI: 10.1103/PhysRevC.109.064614.

[15] A. Pakou, O. Sgouros, V. Soukeras, J. Casal, and K. Rusek. "Reaction mechanisms of the weakly bound nuclei ^{6,7}Li and ^{7,9}Be on light targets at near barrier energies". In: *Eur. Phys. J. A* 58.8 (2022). DOI: 10.1140/epja/s10050-021-00655-w.

[16] K. Washiyama, K. Hagino, and M. Dasgupta. "Probing surface diffuseness of nucleus-nucleus potential with quasielastic scattering at deep sub-barrier energies". In: *Phys. Rev. C* 73.034607 (2006). DOI: 10.1103/PhysRevC.73.034607.

[17] M. Mazzocco, N. Keeley, A. Boiano, C. Boiano, M. La Comara, C. Manea, and et al. "Elastic scattering for the ^{8}B and ^{7}Be + ^{208}Pb systems at near-Coulomb barrier energies". In: *Phys. Rev. C* 100.024602 (2019). DOI: 10.1103/PhysRevC.100.024602.

[18] L.M. Fonseca, R. Linares, V.A.B. Zagatto, F. Cappuzzello, D. Carbone, M. Cavallaro, D. Carbone, M. Cavallaro, and et al. "Elastic and inelastic scattering of ^{16}O on ^{27}Al and ^{28}Si at 240 MeV". In: *Phys. Rev. C* 100.014604 (2019). DOI: 10.1103/PhysRevC.100.014604.

[19] M. Papa, T. Maruyama, and A. Bonasera. "Constraint molecular dynamics approach to fermionic systems". In: *Phys. Rev. C* 64.024612 (2001). DOI: 10.1103/PhysRevC.64.024612.

[20] F. Cappuzzello, C. Agodi, D. Carbone, and M. Cavallaro. "The MAGNEX spectrometer: Results and perspectives". In: *Eur. Phys. J. A* 52.167 (2016). DOI: 10.1140/epja/i2016-16167-1.

[21] S. Koulouris. "Studies of Peripheral Heavy-ion Reactions with the MAGNEX Spectrometer for the Production of Neutron-rich Isotopes". Ph.D. Thesis. National and Kapodistrian University of Athens, 2025.