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A B S T R A C T

The R^{3}B (Reactions with Relativistic Radioactive Beams) experiment as a major instrument of the NUSTAR collaboration for the research facility FAIR in Darmstadt is designed for kinematically complete studies of reactions with high-energy radioactive beams. Part of the broad physics program of R^{3}B is to constrain the asymmetry term in the nuclear equation-of-state and hence improve the description of highly asymmetric nuclear matter (e.g., in neutron stars). For a precise determination of the neutron-skin thickness – an observable which is directly correlated with the symmetry energy in theoretical calculations – by measuring absolute fragmentation cross sections, it is essential to quantify the uncertainty and challenge the reaction model under stable conditions. During the successful FAIR Phase-0 campaign of R^{3}B, we precisely measured the energy dependence of total interaction cross sections in ^{12}C+^{12}C collisions, for a direct comparison with calculations based on the eikonal reaction theory.

1. Introduction

Neutron stars (NS) serve as unique astrophysical laboratories for studying nuclear matter under extreme conditions. With densities several times greater than nuclear saturation density, they form the most compact objects in the visible universe [1]. The equation-of-state (EoS) is fundamental to describe the properties of nuclear matter over a wide range of densities and isospin asymmetry, such as those expected in the interior of NS. The so called symmetry energy $S(\rho)$ characterizes the EoS of asymmetric nuclear matter. Its value and especially its density dependence around the nuclear saturation density $\mathrm{L} = 3\rho_0 \partial\epsilon_{\mathrm{sym}}(\rho)/\partial\rho|_{\rho_0}$, are so far experimentally poorly constrained and vary over a wide range for various relativistic and non-relativistic model calculations [2].

Despite these varying predicted values for the symmetry energy, it has been shown that both relativistic and non-relativistic calculations exhibit a direct correlation between the equation of state (EoS) for neutron matter and the neutron skin thickness [3]. A promising experimental method for determining the spatial neutron distribution, even in the most exotic and short-lived nuclei, is the measurement of absolute cross sections, with particular emphasis on the total neutron-removal cross section [4]. The high sensitivity of the later on the neutron skin could potentially constrain the symmetry energy slope parameter by ± 10 MeV, given an experimental and model-dependent uncertainty of 1%. A widely established framework for calculating cross sections of proton removal (total charge-changing $\sigma_{\Delta\mathrm{Z}}$), neutron removal ($\sigma_{\Delta\mathrm{N}}$) or the sum of both – the total interaction cross section $\sigma_{\Delta\mathrm{I}}$ – is the Glauber reaction model [5]. In parameter-free calculations, the only inputs are the total cross sections of free nucleon-nucleon collisions (σ_{pp} and σ_{np}) and the projectile and target density distributions. While the former are available over a wide energy range from experimental data, the latter can be directly taken from energy density functionals (EDF) and compared with the experimental measured cross sections. In a realistic Glauber calculation, several in-medium modifications – such as Coulomb repulsion, Fermi motion, and Pauli blocking – must also be taken into account [6].

As part of the FAIR Phase-0 campaign at R^{3}B (Reactions with Relativistic Radioactive Beams), several experiments were conducted to determine the neutron-skin thickness. These include the measurement of the Coulomb excitation [7] of neutron-rich tin isotopes ($^{124\text{–}132}$Sn), using a Pb Target, as well as total interaction and neutron-removal cross section measurements [8] with light carbon and proton targets in the 2021 experiment S515. In a precursor experiment in 2019 (S444/S473) absolute cross sections were measured using both, a stable ^{120}Sn beam and in ^{12}C+^{12}C collisions. Especially with the later measurement, were the nucleon density distribution of ^{12}C is well known, it is possible to investigate the predictive power of Glauber model and thus the model-dependent uncertainty of the underlying analysis over a wide energy range. The analysis and measured cross sections of the ^{12}C data were published in Ref. [9] and will be presented in this conference report.

2. Experiment

The combined experimental campaign S444/S473 was carried out in 2019 at the GSI Helmholtz Centre for Heavy Ion Research in Darmstadt as first experiment of the FAIR Phase-0 campaign. Stable ^{12}C and ^{120}Sn beams were accelerated in the SIS18 synchrotron and transported to Cave-C were the R^{3}B experimental setup, which is illustrated in Fig. 1, was installed.

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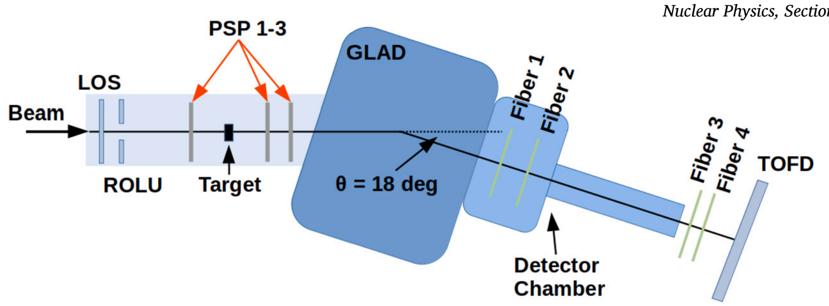

Fig. 1. A schematic view of R^3B experimental setup used in the S444/S473 campaign. Sizes are not to scale.

The position and charge of the incoming fully-striped isotopes, with energies of 400, 550, 650, 800 and 1000 MeV/nucleon, are identified with the scintillating start detector LOS [10] at the cave entrance. The measurement of the time difference between incoming particles, combined with the veto detector ROLU [10] and an additional particle identification, provided by the first silicon strip detector PSP1 just before the target, ensures a single-particle-per-event situation. This assembly helps prevent deadtime issues and overflows in the remaining system and ensures a strict event selection for incoming particles. Two additional PSP silicon strip detectors are used to identify the charge, position, and angle of both the unreacted beam and the reaction fragments immediately after the target. The magnetic field of the superconducting dipole magnet GLAD bends the unreacted beam by an angle of 18 degrees, enabling mass identification of the different reaction fragments. This is achieved by reconstructing the particle trajectories after the magnetic field using four fiber detectors. At the end of the setup, perpendicular to the 18-degree line, a time-of-flight wall – TOFD [11] – was installed to measure both charge and flight time of the reacted and unreacted particles.

3. Analysis and results

The analysis of the total interaction cross sections, used in both the $^{12}C+^{12}C$ and $^{120}Sn+^{12}C$ case, is based on a standard transmission measurement. In this approach, the probability of a nuclear fragmentation reaction (such as proton or neutron removal) is determined by measuring the unreacted beam after it passes through the target. The total interaction cross section is then expressed as:

$$\sigma_I = -\frac{1}{N_t} \ln\left(\frac{N_2^i/N_1^i}{N_2^o/N_1^o}\right),$$

where N_t is the number of scattering centers per unit area, $N_1^{i/o}$ denotes the number of incoming isotopes identified before the reaction target, and $N_2^{i/o}$ refers to the number of unreacted nuclei for the target-in (i) and target-out (o) runs, respectively. The systematic uncertainty for N_t was minimized by using three different target thicknesses (1.01 $g\,cm^{-2}$, 1.99 $g\,cm^{-2}$ and 4.06 $g\,cm^{-2}$) and performing precise density measurements of the natural carbon targets. The previously described event selection using detectors positioned before the reaction target allows for an accurate determination of the number of incoming isotopes. The main challenge in an absolute cross-section measurement lies in identifying the unreacted particles, as this requires accounting for the absolute efficiency of the used detectors and the geometric acceptance of the entire setup. In the present analysis, a strategy was employed to minimize systematic uncertainty by reducing the number of detectors used. In the first step, the number of isotopes with the same charge as the incoming beam was determined at the end of the setup using the TOFD detector. This detector, in the configuration used, consisted of four overlapping planes, each with 44 scintillator bars. This design ensures 100% geometric acceptance within the active detector area. By analyzing plane 1–2 and 3–4 separately, the detection efficiency can also be determined with high precision. In the next step, two correction factors were determined. The first factor represents the ratio of isotopes with the same charge and mass as the incoming beam to the isotopes with Q_{Beam} identified with TOFD. In this process, the spatial separation of isotopes in the magnetic field of GLAD was utilized based on their different A/Q ratios. Since the TOFD detector was placed approximately 15 m after the deflection point of GLAD, most isotopes with masses different from that of the beam were deflected to larger angles. As a result, the contamination is less than 1%. The second correction factor accounts for the limited geometric acceptance outside the active area of the TOFD detector. By comparing the position distribution of the targeted isotopes with and without TOFD identification, it is possible to determine the loss due to limited acceptance independently of detector efficiencies. Using this information, the cross sections were accurately determined, as shown in Fig. 2 by the green symbols for all beam energy and target combinations [9]. The cross sections are compared with predictions from a Glauber calculation – both with (red symbols) and without in-medium modifications (black symbols) [6] – as well as with results from previous experiments (blue symbols) [12–14].

4. Summary and conclusions

The presented cross sections, with an uncertainty of approximately ±0.4%, represent the most precise data available in this energy range and agree within 2σ with the results of previous experiments. However, the increase in reaction probability at higher energies could not be fully reproduced by the model calculations so far, which overestimate the experimental values by up to 3%.

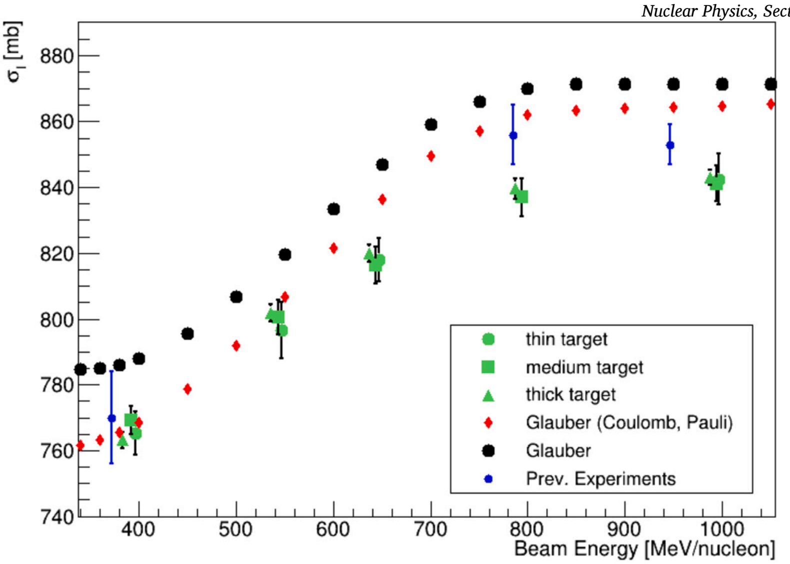

Fig. 2. Total interaction cross sections of ^{12}C+^{12}C versus beam energy. Experimental data for all target beam combinations (green symbols) [9] are compared with calculations based on a reaction model [6] – with (red symbols) and without in-medium corrections (black symbols) – and data from previous experiments (blue symbols) by Takechi et al. [12], Tanihata et al. [13], and Ozawa et al. [14]. (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

This reinforces the assumption that not all in-medium effects have been fully accounted for in the parameter-free reaction model. It remains an open challenge for both experimental and theoretical efforts to investigate and identify the origin of this unknown energy dependent effect. The reported analysis confirms the potential of precise absolute cross-section measurements with R^{3}B. The ongoing analysis of the ^{120}Sn data presents additional challenges, such as the more difficult mass separation and collective excitations, which are not accounted for in the reaction model. However, the presented data are encouraging, suggesting that the required precision for constraining the L parameter can also be achieved in the analysis of heavier nuclei.

CRediT authorship contribution statement

L. Ponnath: Formal analysis, Writing – original draft, Data curation, Investigation, Software. **T. Aumann:** Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision. **C.A. Bertulani:** Conceptualization, Methodology, Software, Supervision, Writing – review & editing. **R. Gernhäuser:** Conceptualization, Funding acquisition, Investigation, Project administration, Resources, Supervision, Writing – review & editing. **T. Almusidi:** Investigation. **H. Alvarez-Pol:** Investigation, Resources, Software. **L. Atar:** Investigation. **L. Atkins:** Investigation. **Y. Ayyad:** Investigation. **J. Benlliure:** Funding acquisition, Investigation, Resources. **K. Boretzky:** Investigation, Resources. **M.J.G. Borge:** Funding acquisition, Investigation. **L.T. Bott:** Investigation. **G. Bruni:** Investigation. **B. Brückner:** Investigation. **P. Cabanelas:** Investigation. **C. Caesar:** Investigation, Resources. **E. Casarejos:** Funding acquisition, Investigation, Resources. **J. Cederkall:** Funding acquisition, Investigation, Resources. **A. Corsi:** Investigation. **D. Cortina-Gil:** Funding acquisition, Investigation, Project administration, Resources. **J.A. Dueñas:** Investigation. **M. Duer:** Investigation. **Z. Elekes:** Investigation. **S. Escribano Rodriguez:** Investigation. **A. Falduto:** Investigation. **M. Feijoo:** Investigation. **M. Feijoo Fontan:** Investigation. **L.M. Fonseca:** Investigation, Writing – review & editing. **A. Frotscher:** Investigation. **D. Galaviz:** Funding acquisition, Investigation. **E. Galiana:** Investigation. **G. García-Jiménez:** Investigation, Software. **I. Gašparić:** Funding acquisition, Investigation, Resources. **E.I. Geraci:** Investigation. **A. Gillibert:** Investigation. **B. Gnoffo:** Investigation. **D. González Caamaño:** Investigation. **A. Graña González:** Investigation. **K. Göbel:** Investigation. **A.-L. Hartig:** Investigation. **M. Heil:** Investigation, Resources, Software. **A. Heinz:** Investigation, Writing – review & editing. **T. Hensel:** Investigation. **M. Holl:** Investigation. **A. Horvat:** Investigation. **A. Jedele:** Investigation. **D. Jelavić Malenica:** Investigation. **T. Jenegger:** Investigation. **H.T. Johansson:** Investigation, Software. **B. Jonson:** Investigation, Writing – review & editing. **N. Kalantar-Nayestanaki:** Investigation. **A. Kelic-Heil:** Investigation, Resources, Software. **O.A. Kiselev:** Investigation. **P. Klenze:** Investigation. **D. Kresan:** Software. **T. Kröll:** Funding acquisition, Investigation. **E. Kudaibergenova:** Investigation. **D. Kurtulgil:** Investigation. **D. Körper:** Investigation, Resources. **M. Labiche:** Investigation. **C. Langer:** Investigation. **I. Lihtar:** Investigation. **Yu.A. Litvinov:** Investigation. **B. Löher:** Investigation, Software. **J. Mayer:** Investigation. **N. Mozumdar:** Investigation. **S. Murillo Morales:** Investigation. **E. Nacher:** Investigation. **T. Nilsson:** Funding acquisition, Investigation. **A. Obertelli:** Investigation. **V. Panin:** Investigation, Software, Writing – review & editing. **J. Park:** Investigation. **S. Paschalis:** Investigation, Writing – review & editing. **A. Perea:** Investigation, Software. **M. Petri:** Funding acquisition, Investigation. **S. Pirrone:** Investigation. **T. Pohl:** Investigation. **R. Reifarth:** Investigation. **H.-B. Rhee:** Investigation. **J.L. Rodriguez-Sanchez:** Investigation, Software, Writing – review & editing. **L. Rose:** Investigation. **D.M. Rossi:** Investigation. **P. Russotto:** Investigation. **D. Savran:** Investigation, Resources. **H. Scheit:** Investigation, Project administration, Supervision. **H. Simon:** Investigation, Project administration, Resources. **S. Storck-Dutine:** Investigation. **A.M. Stott:** Investigation.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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