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Technische Universität München

Precise Measurement of Nuclear Interaction Cross Sections
with R3B

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Vollständiger Abdruck der von der TUM School of Natural Sciences der Technischen
Universität München zur Erlangung des akademischen Grades eines

Doktors der Naturwissenschaften (Dr. rer. nat.)

genehmigten Dissertation.

Vorsitz:

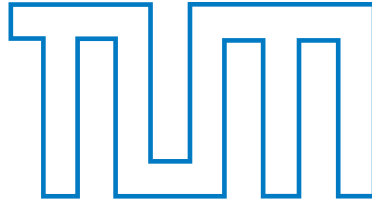
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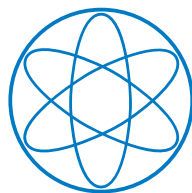
Die Dissertation wurde am DATUM-HIER bei der Technischen Universität München
eingereicht und durch die TUM School of Natural Sciences am DATUM-HIER
angenommen.



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Technische Universität München

Fachbereich: Dense and Strange Hadronic Matter (E62)

2023

Abstract

Astrophysical observations of neutron stars (NS) provide rather precise data about the global properties of such unique and fascinating objects, e.g., the mass and radius. For the interpretation of this data and to gain a profound understanding of the inner structure of NS, it is essential to investigate nuclear matter under extreme conditions. A key instrument to describe nuclear matter over a wide density range is the equation of state (EOS). The radius and stability of NS are governed by the pressure of the highly asymmetric matter in the inside, which is defined by the so-called symmetry energy in the EOS. This quantity and especially its slope parameter L around nuclear saturation density are experimentally only weakly constraint so far.

A experimental attempt to constrain the L parameter is to measure the neutron-skin thickness of highly asymmetric nuclei since both quantities are directly correlated. One of the most established experimental methods to probe the nuclear density distribution is the measurement of total interaction cross section at radioactive beam facilities. A common method to describe integrated cross sections is the Glauber reaction model. In such a model, which includes realistic in-medium modification for composite nuclei, the only inputs are the experimental nucleon-nucleon cross sections and the density distribution of the projectile and target nucleus.

For a precise determination of the neutron-skin thickness of exotic nuclei, and thus to constrain the symmetry energy slope parameter, it is essential to quantify the uncertainty of the reaction model under ideal conditions.

This work provides a detailed summary of the precise measurement of total interaction cross sections of $^{12}\text{C}+^{12}\text{C}$ collisions in the energy regime between 400 and 1000 MeV/nucleon. The underlying experiment was carried out as part of the commissioning of the R^3B setup during the FAIR Phase-0 campaign at GSI. The present analysis of total interaction cross sections is based on a transmission measurement, where the numbers of incoming and non-reacted projectiles before and after the reaction target have been identified. The identification of the non-reacted ^{12}C poses a challenge to the experimental setup since the time- and rate-dependent detector efficiency, as well as the geometrical acceptance of the whole setup, have to be considered.

The presented cross sections was determined with a total experimental uncertainty down to 0.4 % and represent the most precise data currently available in this energy regime. The validity of the measurement and analysis method was confirmed by data from previous experiments. It was shown that predictions based on a realistic Glauber reaction model are in good agreement with the presented experimental results for low energy but overestimate them by around 2.5 % at higher energies.

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1 Introduction

1.1 Astrophysical interest

1.2 EOS

1.3 Glauber Theory?

1.4 QFS Theory in inverse kinematics

2 Experiment

The present commissioning experiment was performed in 2020 at the FAIR Facility at GSI (Gesellschaft für Schwerionenforschung) in Darmstadt (Germany). The GSI Helmholtzzentrum für Schwerionenforschung operates a unique accelerator facility for heavy ions and focuses on several cutting-edge research fields. These include:

1. **Nuclear Physics:** Studying the properties of atomic nuclei, exploring the forces that bind protons and neutrons, and investigating exotic nuclei far from stability.
2. **Hadron and Quark Matter:** Investigating the behavior of hadrons (particles made of quarks) and the state of matter under extreme conditions, such as those found in neutron stars or during the early universe.
3. **Atomic Physics:** Examining the structure and dynamics of atoms, including highly charged ions, to understand fundamental atomic interactions and refine quantum electrodynamics.
4. **Plasma Physics:** Creating and analyzing high-energy-density plasmas to simulate conditions found in stellar interiors and other astrophysical phenomena.
5. **Biophysics and Medical Research:** Exploring the effects of ion beams on biological systems for applications in cancer therapy, particularly using heavy ion therapy, and studying radiation protection for space missions.
6. **Materials Research:** Investigating the response of materials to high radiation doses to develop more resilient materials for use in various technologies, including nuclear reactors and space exploration.

2.1 GSI facility

The GSI Helmholtzzentrum für Schwerionenforschung located at Darmstadt has a long history of research.... tell something about the beginnnings, first really heavy elements found there.

The GSI Helmholtzzentrum für Schwerionenforschung GmbH was founded in 1969 (as "Gesellschaft für Schwerionenforschung mbH) looks back on a successful research history. In the time between 1981 and 2010 six new superheavy elements were discovered. In the medical research field GSI has developed advanced cancer therapy techniques using heavy ion beams which target tumors with high precision, minimizing damage to surrounding healthy tissues.

Along with those groundbreaking discoveries in research the facility at GSI has always been an inspiring source of drive for new technologies.

The key devices/apparatus which enable to carry out experiments with heavy ions at GSI are: important to mention: GSI is the only facility with heavy ions in the world The starting point for the production of relativistic heavy ions at GSI is the ion source where ions are generated by stripping electrons off the shell of the atoms. Depending on the experimental needs the ion sources at GSI are able to produce ions of many different kinds of elements (up to Uranium).

On the first acceleration stage the stable primary ions are injected from the ion source into the UNiversal Linear Accelerator (UNILAC). On a length of 120 meters ions are accelerated up to maximum energy of 11.4 AMeV. The low energy beam is now injected into the ring accelerator SIS18 (Schwerionensynchotron 18). Here the ion beam is further accelerated up to 4.7 GeV/u (for protons) / 1 GeV/u (for Uranium). The magnets and the ultra-high vacuum (10^{-9} Pa) keep the ions well on their circular path (SIS18 has a circumference of 216 meters). For the production of rare heavy isotopes the primary ion beam from SIS18 can be impinged on a light nuclear target, e.g beryllium, the so called production target. These secondary beams of radioactive isotopes can be either stored in the experimental storage ring (ESR) for later use or transferred to the FRagment Separator (FRS). The FRS as a high-resolution magnetic spectrometer is capable to precisely select specific isotopes and to forward the desired beam of exotic relativistic nuclei to the various experiments or direct it to the ESR for later use.

2.1.1 FAIR Project

The FAIR (Facility for Antiproton and Ion Research) situated next to the GSI will be one of the most complex and largest accelerator facilities in the world. The construction of the superconducting ring accelerator SIS100 with a circumference of 1.1 km, storage rings and experiment sites begun in the summer of 2017. Commissioning is planned in 2025 (?). Early Science.

2.2 R3B Setup

2.2.1 Detector Setup in S444 Commmissioning Experiment 2020

2.2.2 Calibration of the Detector Systems

3 Analysis

3.1 qfs analyis

3.2 reaction cross section Analysis

4 Results and Discussion