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Investigation of the nuclear matter distribution of ^{56}Ni by elastic proton scattering in inverse kinematics

M von Schmid¹, S Bagchi², S Bönig¹, M Csatlós³, I Dillmann⁴,
C Dimopoulou⁴, P Egelhof⁴, V Eremin⁵, T Furuno⁶, H Geissel⁴,
R Gernhäuser⁷, M N Harakeh², A-L Hartig¹, S Ilieva¹,
N Kalantar-Nayestanaki², O Kiselev⁴, H Kollmus⁴, C Kozhuharov⁴,
A Krasznahorkay³, T Kröll¹, M Kuilman², S Litvinov⁴, Yu A Litvinov⁴,
M Mahjour-Shafiei^{2,8}, M Mutterer⁴, D Nagae⁹, M A Najafi², C Nociforo⁴,
F Nolden⁴, U Popp⁴, C Rigollet², S Roy², C Scheidenberger⁴, M Steck⁴,
B Streicher^{2,4}, L Stuhl³, M Thürauf¹, T Uesaka¹⁰, H Weick⁴, J S Winfield⁴,
D Winters⁴, P J Woods¹¹, T Yamaguchi¹², K Yue^{1,4,13}, J C Zamora¹,
J Zenihiro¹⁰ for the EXL collaboration¹⁴

¹ Institut für Kernphysik, Technische Universität Darmstadt, Germany

² KVI-CART, University of Groningen, The Netherlands

³ Institute for Nuclear Research, MTA-Atomki, Debrecen, Hungary

⁴ GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany

⁵ Ioffe Physical-Technical Institute, St. Petersburg, Russia

⁶ Division of Physics and Astronomy, Kyoto University, Japan

⁷ Physik-Department E12, Technische Universität München, Germany

⁸ Department of Physics, University of Tehran, Iran

⁹ Department of Physics, University of Tsukuba, Japan

¹⁰ RIKEN Nishina Center, Wako, Saitama, Japan

¹¹ Institute for Particle and Nuclear Physics, University of Edinburgh, UK

¹² Department of Physics, Saitama University, Sakura-ku, Saitama, Japan

¹³ Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou, People's Republic of China

E-mail: schmid@ikp.tu-darmstadt.de

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Abstract

We have measured the nuclear-matter distribution of the doubly-magic $N = Z$ nucleus ^{56}Ni by investigating elastic proton scattering in inverse kinematics. The radioactive beam of ^{56}Ni was injected and stored in the experimental storage ring (ESR, GSI) and interacted with an internal hydrogen gas-jet target. The high revolution frequency of the ions in the ring enabled a high luminosity, despite the low density of the target being used. This way, measurements at very low momentum transfers became possible. By measuring the energy and the scattering angle of the recoiling protons, we were able to separate the elastic reaction channel from inelastic scattering to the first excited 2^+ state of ^{56}Ni and deduced the differential cross section of $^{56}\text{Ni}(p, p)^{56}\text{Ni}$. The data were analyzed within the framework of the Glauber multiple-scattering theory in order to extract the nuclear-matter radius and radial matter distribution of ^{56}Ni . Parameterizing the matter distribution with the phenomenological Symmetrized Fermi distribution, a preliminary value of 3.5 fm for the rms matter radius was deduced. This experiment was part of an EXL (EXotic nuclei studied in Light-ion induced reactions at storage rings) campaign at GSI in 2012

¹⁴ <http://rug.nl/kvi/Research/hnp/Research/EXL/index>

and was the first successful investigation of nuclear reactions with a stored radioactive beam ever.

Keywords: direct reactions, in-ring experiments, radioactive beams, elastic proton scattering, nuclear-matter distribution, ^{56}Ni

(Some figures may appear in colour only in the online journal)

1. Introduction

EXL (EXotic nuclei studied in Light-ion induced reactions at storage rings) is a project within NUSTAR at FAIR [1, 2]. Its aim is the study of the nuclear structure of exotic nuclei with direct reactions in inverse kinematics. One of the key interests of EXL is the investigation of reactions at very low momentum transfers where, for example, the nuclear-matter distribution, giant resonances or Gamow–Teller transitions can be studied [3, 4]. Performing this kind of experiment in storage rings leads to several advantages over conventional spectrometer experiments with thick targets. When aiming at more and more exotic nuclei, usually their lifetimes get shorter and the production rate of a radioactive beam drops. Both will limit the feasibility of experiments and the study of those nuclei. If the lifetimes allow to store the beam in a ring, the low rates can be compensated by the high revolution frequency of the stored ions in the ring, which is in the order of few MHz. This, in turn, allows for the use of thin targets enabling the detection of low energetic recoils and thus the investigation of reactions at lower momentum transfers than before. Additionally, by utilizing the possibilities of beam cooling in storage rings ion beams with low emittance and momentum spread can be achieved [5]. Altogether, this enables measurements almost free of background and contaminants.

The existing storage ring ESR (Experimental Storage Ring) at GSI [6], together with its internal gas-jet target, provides a unique opportunity to perform such experiments at the present. After the first feasibility measurements with the stable nuclei ^{132}Xe (2005) [7, 8] and ^{40}Ar (2011) [9], we successfully performed an experiment (E105, 2012) with stable ^{58}Ni , as well as, radioactive ^{56}Ni beams interacting with H_2 and ^4He targets. Besides the commissioning of our detection system we performed a physics programme with the goal of measuring the nuclear-matter distribution of the doubly-magic ^{56}Ni by employing elastic proton scattering [10]. The measured differential cross section is being analyzed within the frame of the Glauber multiple-scattering theory. By using phenomenological density distributions and by varying their free parameters, the calculated cross section will be fitted to the experimental data. In this way, the nuclear-matter radius and radial matter distribution can be extracted (see for example [11, 12] and references therein).

2. Experimental setup

In the last few years, we have developed a UHV compatible detector setup based on double-sided silicon-strip detectors

(DSSDs) and Si(Li)s for the target recoils [13, 14]. To cope with the demanding vacuum requirements inside a storage ring, the DSSDs act as active windows separating the UHV from an auxiliary vacuum where non-bakeable components can be placed. In this way, additional dead layers are avoided and a low energy-threshold is maintained. With this vacuum setup, we have reached a pressure of 2×10^{-10} mbar in the target region of the ESR and 7×10^{-8} mbar in the auxiliary vacuum [13, 14]. Figure 1 shows a schematic drawing of the prototype-detector setup around the gas-jet target of the ESR. The first detection system at a position close to 90° is used for the investigation of elastic and inelastic scattering processes. Here, in inverse kinematics, a large dynamical range of energies needs to be covered, i.e. starting from zero energy at 90° laboratory scattering angle up to energies of the order of several tens of MeV. For example, one has reached 65 MeV at 75° laboratory scattering angle for $^{56}\text{Ni}(p,p)^{56}\text{Ni}$ at 400 MeV u^{-1} . To cope with this dynamic range, the system is set up as a telescope consisting of one $285 \mu\text{m}$ thick DSSD, which has an active area of $(6.4 \times 6.4) \text{ cm}^2$ divided into 128 vertical strips at the front side and 64 horizontal strips at the rear side, and two 6.5 mm thick Si(Li) detectors, which are segmented into 2×4 pads of $(2 \times 2) \text{ cm}^2$ each. They were placed in the auxiliary vacuum behind the DSSD, and were actively cooled during both the bake-out of the ESR and the experiment [14].

Since the gas-jet target has a radial extension of approximately 5 mm (FWHM), it would not be possible to separate the kinematical bands for elastic and inelastic scattering (see figure 2). To reach the necessary angular resolution, a remotely moveable aperture with two piezoelectric drives operated inside the UHV was placed in between the target and the first detector telescope [14].

A second, single DSSD placed at forward angles is foreseen to study different reaction channels [15]. Not shown in figure 1 is a detection system for the projectile-like heavy ions further downstream of the target. It features an array of six silicon PIN-diodes directly placed in the UHV. Furthermore, a SSD was used in a vacuum pocket for the same purpose. To investigate the conditions for the detection of neutrons and gammas, we utilized the European low energy neutron spectrometer (ELENs) [16] and a CsI detector placed outside the vacuum chamber.

3. Preliminary results

As already outlined, the main physics goal of the experiment was the measurement of the nuclear matter distribution in ^{56}Ni by investigating $^{56}\text{Ni}(p, p)^{56}\text{Ni}$ at an energy of

Figure 1. Schematic drawing of the EXL prototype setup at the ESR.

Figure 2. Reconstructed energy of recoiling protons versus laboratory scattering angle for $^{56}\text{Ni}(p, p)^{56}\text{Ni}$ and $^{56}\text{Ni}(p, p')^{56}\text{Ni}^*$ at 400 MeV u^{-1} with 1 mm slit aperture in front of the 90° telescope.

400 MeV u^{-1} . By stacking the secondary beam coming from the fragment separator (FRS) [17]), it was possible to accumulate 3×10^6 ions stored in the ring [18]. A good beam quality was maintained by utilizing both stochastic and electron cooling [5, 19]. Together with the target density of approximately $2 \times 10^{13}\text{ cm}^{-2}\text{ H}_2$ and the revolution frequency in the ESR of about 2 MHz this yields a luminosity of about $10^{26}\text{ particles s}^{-1}\text{ cm}^{-2}$ which was monitored during the experiment by constantly measuring both the beam current and the target density. This represents a tremendous increase of three orders of magnitude in luminosity compared to a previous unsuccessful attempt to measure the same reaction at the ESR in 1997 [21].

Figure 2 shows a two-dimensional plot of the reconstructed energy of the recoiling protons measured by the detector telescope close to 90° as a function of the laboratory scattering angle. By using the 1 mm slit aperture at a distance of 3 cm from the target, the angular resolution becomes sufficient to separate the kinematical bands of elastic scattering and inelastic scattering to the first 2^+ -state at 2.7 MeV. It should be noted here that the irregularity, which is emerging

Figure 3. Experimental cross section of $^{56}\text{Ni}(p, p)^{56}\text{Ni}$ at 400 MeV u^{-1} and a fit to the data using Glauber multiple-scattering theory (dashed line). Only a subset of the obtained data is shown.

from the band of elastic scattering at around 6 MeV, arises from imperfect energy reconstruction in the detector telescope.

With such an improved angular resolution, it is possible to gate on the elastically-scattered events and to deduce their angular distribution. In a next step, corrections for the loss in acceptance caused by the slit aperture, have to be applied. These corrections have been determined with the help of GEANT4 simulations taking into account the realistic geometry of the setup. In figure 3 the preliminary result for the experimental cross section is plotted versus t , i.e. the invariant momentum transfer squared. To extract the nuclear-matter radius as well as the matter density distribution, cross sections, calculated using the Glauber multiple-scattering theory, are fitted to the data. For this purpose, it is necessary to select a suitable parameterization for modelling the nuclear density distribution. In the present case, a symmetrized Fermi distribution was used (dashed line in figure 3) and a preliminary rms point matter radius, i.e. the matter radius assuming point like nucleons, of $r_{\text{rms}} = 3.5\text{ fm}$ was extracted.

The choice of the parameterization for the nuclear density distribution generates a model dependence which cannot be quantified easily. Therefore, a final analysis of the cross section will be done using a model-independent sum-of-Gaussians method where the density parameterization is represented by a sum of independent Gaussians [20, 22]. In this way, realistic error bars on the density can be deduced.

4. Conclusion and outlook

The experiment described here was the first of its kind and represents an essential milestone towards the realization of the EXL project for in-ring reaction studies at FAIR. It is worth to mention that the implementation of a EXL-like setup is considered also at other future storage rings [23–25].

By using the DSSDs as active windows, we were able to operate our detectors directly in the UHV without

compromising a low-energy threshold. A good angular resolution for the detector telescope located close to 90° was maintained by using a slit aperture in front of the target. In the future, this will become obsolete thanks to reductions in the spatial extent of a new droplet target replacing the present gas-jet target, enabling an interaction zone with sizes smaller than 1 mm [26–28].

The key goal of this latest EXL campaign was the determination of the nuclear-matter distribution of ^{56}Ni from the measured cross section of $^{56}\text{Ni}(p, p)^{56}\text{Ni}$. A preliminary rms point matter radius of $r_{\text{rms}} = 3.5$ fm for ^{56}Ni was extracted in a model-dependent way. The analysis is ongoing.

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