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Feasibility Studies for the EXL Project at FAIR[*]

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For the EXL Collaboration

This contribution presents the results of feasibility measurements performed for the EXL project. In order to investigate the performance of a Si detector under realistic storage ring conditions, a measurement was carried out at the Experimental Storage Ring (ESR) at GSI, Darmstadt. The stored 400 MeV/u ^{40}Ar beam was interacting with an internal hydrogen gas-jet target. An UHV (Ultra High Vacuum) compatible single-sided Si strip detector was mounted inside the vacuum chamber around the internal gas-jet target to detect recoil protons. The proton elastic-scattering cross section obtained using the recoil detector is compared with theoretical predictions. Preliminary results of the target and beam size as well as the background conditions of the recoil detector will also be presented. In order to investigate the response of DSSD (Double-Sided Silicon Strip Detector) prototype detectors to very low-energy protons, a detector test was performed at the Van-de-Graaff accelerator at Tübingen University. Protons with energies from 74 keV to 1.5 MeV were used in the test. An energy resolution of 20 keV (FWHM) has been obtained for the slowest protons.

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1. Introduction

The future facility FAIR [1, 2] will provide unique opportunities in experimental studies on nuclei far off stability and will also allow to explore new regions in the chart of nuclides of high interest for nuclear structure and astrophysics. As a part of the NUSTAR (NUclear STructure, Astrophysics and Reactions) [3] program at FAIR, the objective of the EXL [4] (EXotic nuclei studied in Light-ion induced reactions at the NESR storage ring) project is to capitalize on light-ion induced reactions in inverse kinematics by using storage-ring techniques and a universal detector system providing high resolution and large solid angle coverage in kinematically complete measurements. In inverse kinematics, small momentum transfer corresponds to target-like recoil ions moving at large scattering angles with very small energies. The essential nuclear structure information can be deduced from high-resolution measurements at low-momentum transfer.

The key physics issues being covered within the EXL project are described in Ref. [4]. With high efficiency and resolution, EXL is a universal detection system, applicable to a wide class of reactions. The set-up foreseen to be installed at the internal target of the storage ring NESR (The New Experimental Storage Ring) includes a Si-detector array for recoiling target-like reaction products, completed by gamma-ray and slow-neutron detectors, as well as forward detectors for fast ejectiles and an in-ring spectrometer for the detection of beam-like reaction products.

In order to investigate the response of the EXL prototype DSSD to very low-energy protons, a detector test was performed at the 3 MeV Van-de-Graaff accelerator at Tübingen University. In addition, another feasibility study of the EXL experiment was performed at the existing storage ring ESR (Experimental Storage Ring [5]) at GSI Darmstadt, Germany. An aim of this test was to prove the possibility of deducing an elastic-scattering cross section by using silicon detectors in the storage ring. The background conditions of the silicon detector installed directly in UHV environment was also investigated.

2. The feasibility study at the ESR

2.1 Experimental setup

For the feasibility experiment, an ^{40}Ar beam with an energy of 400 MeV/u was injected into the ESR from the heavy-ion synchrotron SIS, periodically exposed to electron cooling. On average more than 10^8 ions were circulating with a revolution frequency of 2×10^6 s^{-1}, and interacting with an internal hydrogen gas-jet target (with a thickness of 10^{13} atoms/cm^2) which was installed inside the vacuum chamber of the ESR.

The schematic drawing of the detector setup is shown in Fig. 1. An UHV compatible single-sided silicon detector was mounted in the vacuum chamber to detect the target-like reaction products (Fig. 2). As compared to the test performed at the ESR in 2005 [6], there was no any metal foil in front of the recoil detector. Without any shield, the detector may be exposed to the ultraviolet (UV) light coming from beam-target interactions. A corresponding

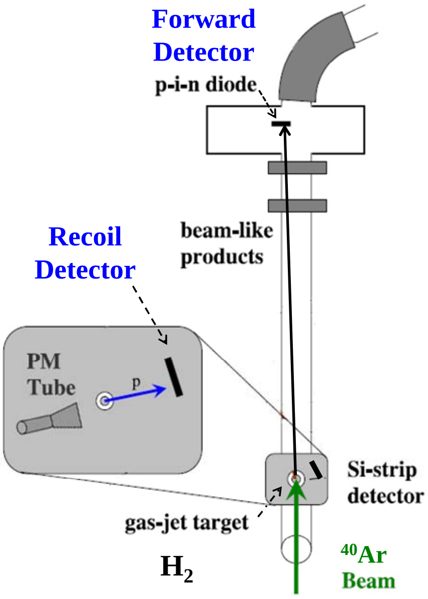

Fig. 1. Experimental setup for the feasibility experiment performed at the ESR at GSI.

background produced by UV photons has been investigated. The silicon strip detector of 1 mm thickness and an area of 40×40 mm^2 was mounted on a vacuum compatible ceramic support. It has 40 strips in total, read out in five groups of 8 strips each. For each group of the strips, the energy deposition and position of the particles were reconstructed using a charge division method. The polar angle coverage of the recoil detector is shown in Fig. 3.

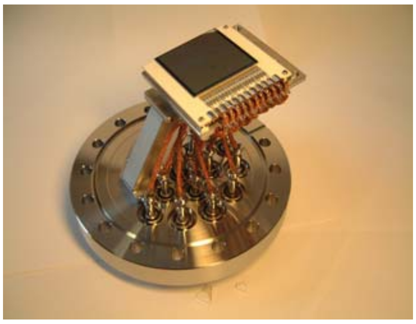

Fig. 2. Photo of the UHV compatible Si-strip detector used in the EXL experiment.

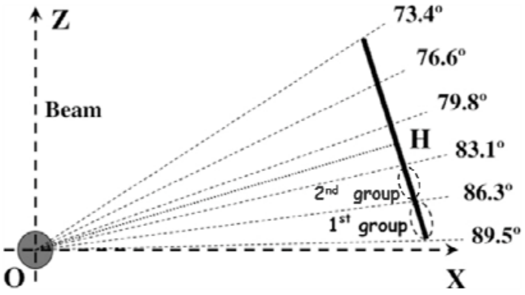

Fig.3. Polar angle coverage of the recoil detector.

For the detection of the ^{40}Ar ions in coincidence with protons in the recoil detector, six silicon PIN diodes with a thickness of 500 μm were installed downstream the target before the dipole magnet, about 7 m away from the target. They formed a forward tagging detector which has been mounted on a moving mechanism directly in a UHV chamber at the ESR. Unfortunately, the moving mechanism did not work properly during the beam time. So this detector could not be used in the test. Furthermore, a photomultiplier tube (PMT) for the detection of the UV light produced from the beam-target interaction was mounted outside the reaction chamber surrounding the internal target. This device was used to monitor the beam intensity and measure the beam-target interaction profile by scanning the beam over the target.

2.2 Results

At the beginning of the experiment, the beam moving across the target region was adjusted and the interaction profile was measured using the photomultiplier tube, detecting UV light produced by the interaction of the heavy ions with the hydrogen atoms. The interaction profile obtained with different beam intensities is shown in Fig. 4. At very low beam intensity (~0.2 mA), an interaction profile of 5.1 mm (FWHM) width was obtained. It could be considered to be identical to the target size because of the very narrow beam profile expected at such low beam intensity. At high intensity (~6.6 mA), the deduced interaction profile was 6.1 mm (FWHM). The beam size at high intensity was determined after unfolding from the target size to be 3.3 mm (FWHM). The beam and target profiles were used as the input parameters in the simulation for the scattering experiment (see below). The target size is reduced from 7.4 mm (FWHM) to 5.1 mm (FWHM) as compared to the test performed with ^{136}Xe beam in 2005 [6].

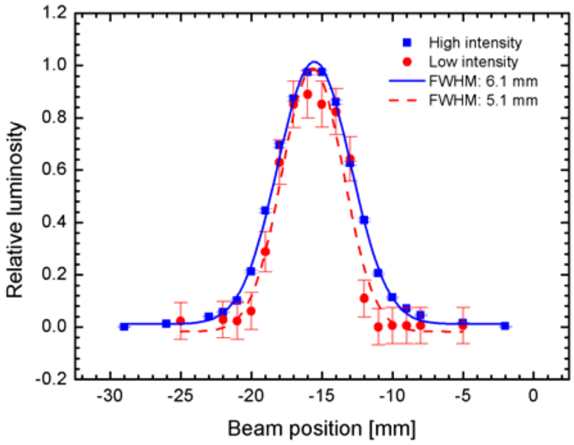

Fig. 4. The target profile as measured by the photomultiplier tube.

Fig. 5 (left side) shows the energy deposition of recoil protons from the p-^{40}Ar interaction on the recoil detector. Beside the recoil protons which follow the E-θ_{lab} correlation expected from simulations (taking into account the punching-through events for energies larger than ~7 MeV), see the Fig. 5 (right side), low-energy events ($E \leq 0.5$ MeV) were observed over the whole angular range. According to the observation during the experiment, some of them are due to electronic noise, and some are low-energy events correlated with the beam-target interaction, most probably due to UV light. A pulse-shape analysis technique for events from the silicon detector is currently under development for identifying low-energy protons from the background [7].

For the p-^{40}Ar interaction, the differential elastic-scattering cross section has been deduced using data from the first two groups of the Si-strip detector only corresponding to c.m. angles close to 0°. According to the calculations assuming a point-like vertex, in the first two groups of strips, the amount of inelastic-scattering events should be small. Due to the limited angular resolution caused by the extended beam-target interaction zone the four momentum transfer squared

$$-t = 2m_pE_p \ , \qquad (1)$$

was determined from the energy of recoils. In Eq. (1), m_p is rest mass of the proton and E_p the kinetic energy of the recoil proton in the laboratory frame. An energy-scattering angle correction was not possible.

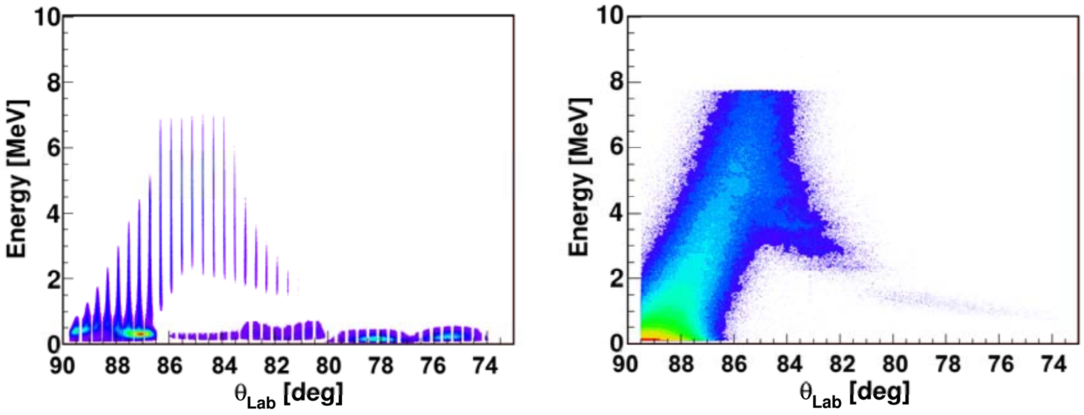

Fig. 5. Energy deposition on the detector obtained by the experiment data (left plot) and the simulated data (right plot).

It is obvious from Fig. 5 that starting from the second group of strips in the recoil detector, the punching-through events for which only an energy loss ΔE could be determined with the recoil detector have to be taken into account in the cross section determination. For the correction of these punching-through events, Monte Carlo simulations were performed by implementing the detector, target and beam geometry in the Geant4 code. At this stage, only elastic proton scattering was considered in the simulations. On the basis of these simulations, a correction factor for deducing the final cross section has been extracted. Fig. 6 shows the experimental differential cross section as a function of $-t$ obtained using Eq. (1) without (solid

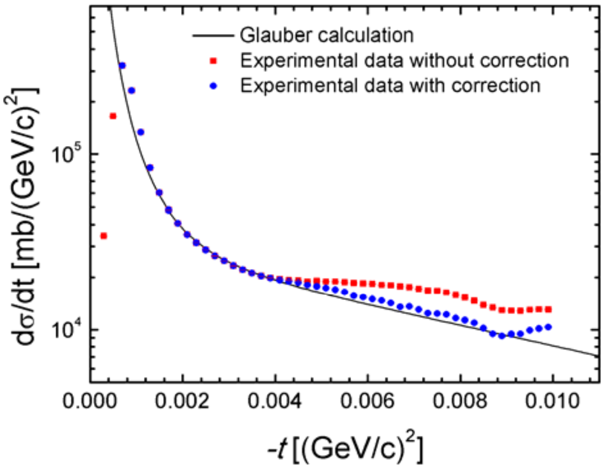

Fig. 6. The experimental cross section for p-^{40}Ar scattering at 400 MeV/u as a function of the four momentum transfer squared $-t$, without (solid squares) and with (solid circles) the correction of punching-through events by comparing to Geant4 simulated data. The solid line represents the result of a Glauber calculation.

squares) and with (solid circles) the correction for the punching-through events. The solid line represents the elastic-scattering cross section obtained from theoretical Glauber calculations using the single-Gaussian parameterisation of matter distribution for a point-like vertex. At the moment, only the relative experimental cross section is extracted; for comparison it is normalized to the theoretical calculations at $-t = 0.0021$ (GeV/c)^2. A good agreement between the theoretical prediction and the corrected data is obtained.

3. The test of the EXL prototype DSSD at low proton energy

3.1 Experimental Setup

The detection of very low-energy protons is very important for the EXL experiment which is dedicated to investigate reactions at low momentum transfer. To study the response of the recoil detector to low-energy protons, a test at the Van-de-Graaff at the Tübingen University was performed. A 16×16 strips DSSD was tested, which is similar in the strip structure to the detectors to be used in the future EXL recoil detector. A detailed description of this DSSD can be found in Ref. [7].

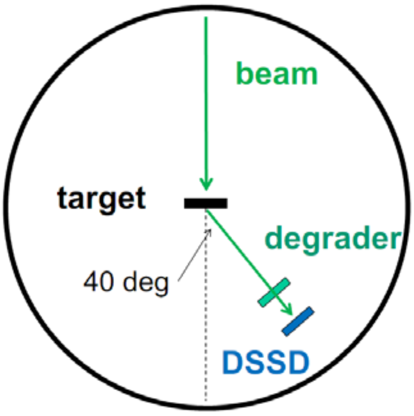

Fig. 7. Experimental setup of the DSSD test in Tübingen.

The experimental setup is shown in Fig. 7. As the lowest energy obtained from the accelerator was about 800 keV, a beam of H_2 hydrogen molecules was used to produce a proton beam of about 400 keV. In order to further reduce the beam energy, protons were scattered off carbon and gold targets, and in addition the energy of the scattered protons was reduced by aluminium or Mylar degrader foils. Finally, protons in the energy range from 74 keV to 1.5 MeV were used in the test.

3.2 Results

Fig. 8 shows the test results for the highest and lowest energy protons. The energy resolution for 1.44 MeV protons was 17.7 keV FWHM; when the energy of the protons was reduced down to 74.7 keV, the resolution became 25.0 keV. In order to investigate the contribution of the energy resolution caused by the beam profile, scattering angle and degraders, a Geant4 simulation was performed. If we subtract the contribution of energy straggling, a detector resolution of about 20 keV (FWHM) is deduced for 74.7 keV protons.

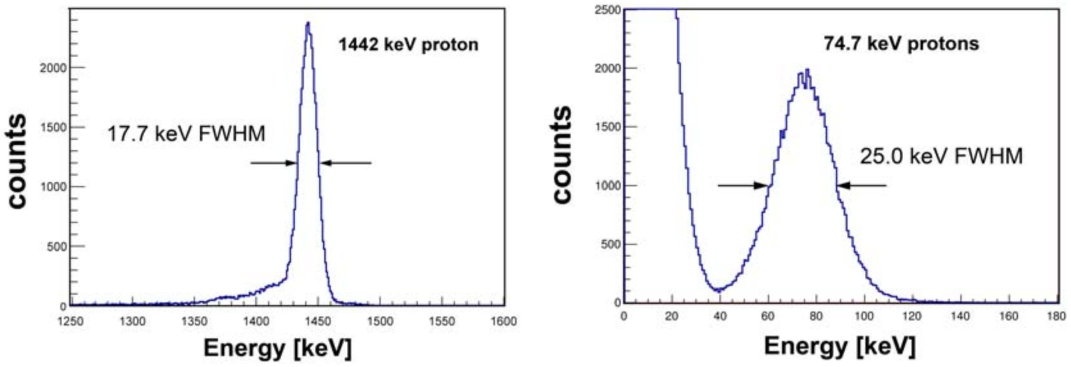

Fig. 8. Energy resolution of DSSD for the highest (left plot) and the lowest (right plot) energy of protons.

4. Conclusions

Two in-beam tests for the EXL project were performed. From these tests and a very first test performed in 2005, we obtained important information about the operation and performance of the silicon detectors under UHV conditions, and about the background conditions in the interaction region of a stored beam with an internal target. The deduced elastic p-^{40}Ar scattering cross section was obtained, in good agreement with theoretical predictions. The prototype EXL DSSD has good response to very low-energy protons.

As a more extended feasibility study for the EXL project, an experiment with stable and radioactive beams which aims to investigate elastic and inelastic proton-^{58,56}Ni scattering at the ESR has been proposed. In a new vacuum chamber, the recoil detector composed of large-size DSSDs and Si(Li) detectors and a new forward tagging detector will be used.

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