Nuclear reactions in the storage ring ESR with EXL

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Abstract.
The EXL project aims to study nuclear structure by direct reactions in inverse kinematics at the storage rings of the future FAIR facility. In this contribution, we present the status of the project: the technical implementation at the ESR at GSI and preliminary results of the EXL campaign in 2012, the first using also a radioactive beam.

1. Introduction

EXL (EXotic nuclei studied in Light-ion induced reactions at storage rings) is part of NUSTAR (NUclear STructure, Astrophysics and Reactions) at FAIR, the future Facility for Antiproton and Ion Research, which is currently under construction at the site of the GSI Helmholtzzentrum für Schwerionenforschung in Darmstadt [1]. EXL aims for the investigation of nuclear structure with direct reactions in inverse kinematics on an internal target at storage rings [2]. The programme is mainly focussed on reactions with very low momentum transfers and therefore largely complementary to R^3B [3].

[14] http://www.rug.nl/kvi/Research/hnp/Research/EXL/index

The physics menu of EXL comprises:

- elastic and inelastic scattering
- capture, transfer and charge-exchange reactions
- knockout and quasi-free scattering

EXL aims for kinematically complete measurements which requires a large dynamic range and angular coverage. In the final implementation, this will be achieved by an onion-like design with different layers of Si detectors (ESPA: EXL Silicon Particle Array) to measure target-like recoils. This will be surrounded by a CsI(Tl) calorimeter and spectrometer (EGPA: EXL Gamma and Particle Array) to measure photons and high-energy charged particles punching through ESPA. In addition, detectors for beam-like ejectiles and neutrons will be placed downstream of the ESPA/EGPA setup centred around the target.

The experiments presented in this contribution have been performed with two prototype detectors, which have been built to demonstrate the feasibility of the EXL programme. They will be described later in detail.

2. Technical implementation at ESR

The existing storage ring ESR at GSI provides a unique opportunity to perform part of the programme already. The ESR has a circumference of 108.4 m and a maximal magnetic rigidity of 10 Tm. After electron cooling, the momentum spread is in the order of $\delta p/p \approx 10^{-5}$ [4]. The operation of a storage ring requires an ultra-high vacuum (UHV) better than 10^{-10} mbar which imposes a major challenge on experiments performed in the ring.

In our experiments, the stored beam impinged on an internal gas-jet target of H_2 or He [5]. Although the energy of the stored beams is high in the order of a few 100 MeV/u, scattering in inverse kinematics at low momentum transfer implies that the recoiling target-like particles have very low energy in the laboratory system. Figure 2 shows as example the elastic scattering of ^{56}Ni on protons in inverse kinematics at 400 MeV/u.

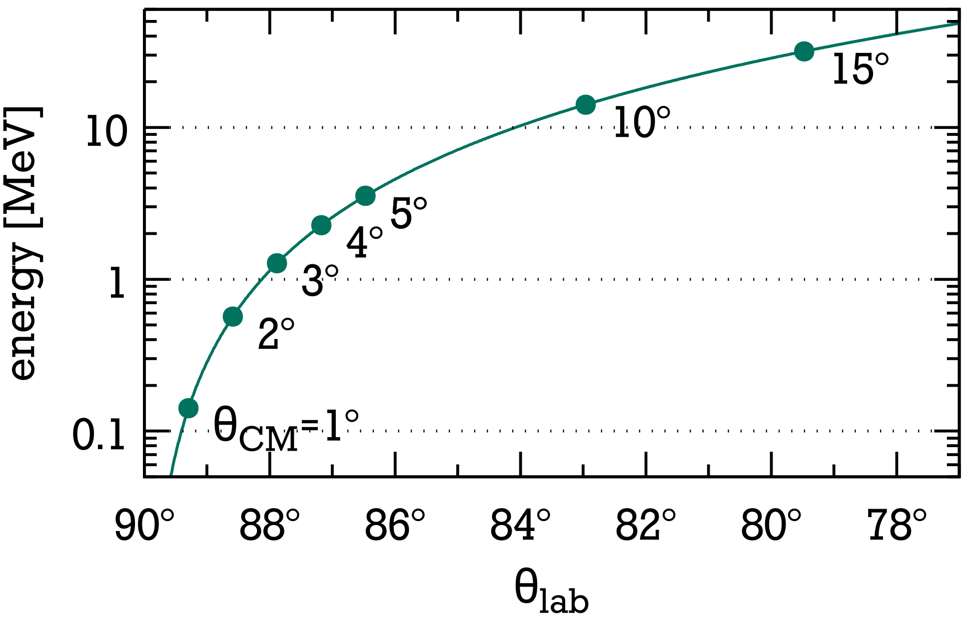

Figure 1. Kinetic energy of the recoiling protons in the laboratory system following the ^{56}Ni(p,p) reaction at 400 MeV/u (adapted from [6])

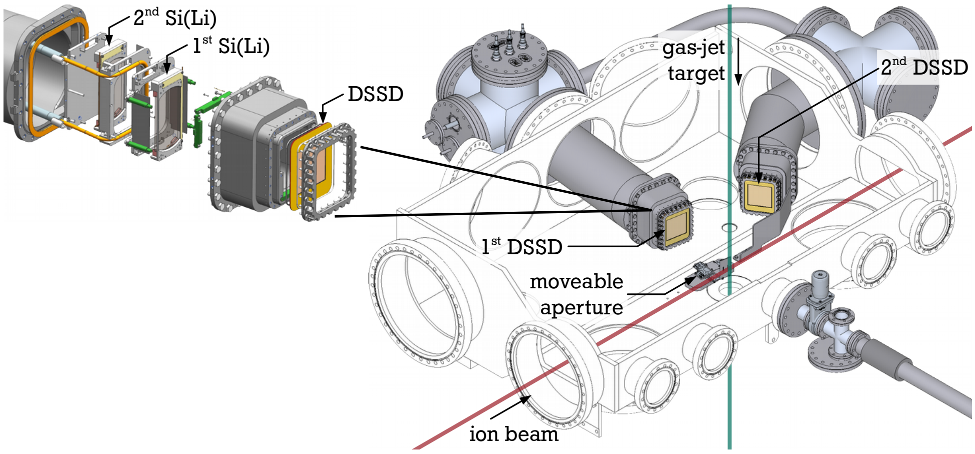

Figure 2. The two detectors, the movable aperture (see text) and indications of the beam direction and the gas-jet target (drawings by M. Lindemulder, adapted from [6])

Therefore, the main challenge was the development of window-less highly-segmented Si strip detectors which can be operated under UHV conditions [7, 8]. In our concept, these detectors serve as active windows separating the UHV of the storage ring and an auxilliary vacuum in a so-called pocket which accommodates the non-bakeable parts of the system. In order to achieve the UHV conditions, the DSSDs were mounted on ceramic AlN boards, a material which is non-outgassing and bakeable. This concept was implemented, tested in the laboratory and, finally, two detectors were built.

Figure 2 shows the experimental setup used in our experiments with the two detectors mounted in the scattering chamber which was placed in the ESR. The first detector, labelled "1^{st} DSSD" in Figure 2, consisted of a 6×6 cm^2 DSSD (Double-sided Si Strip Detector) of 285 μm thickness with 128×64 segments followed by two 8×4 cm^2 Si(Li) detectors of 6.5 mm thickness with 4×2 segments. The Si(Li)s were equipped with a cooling system to keep their temperature low even during the baking of the pocket. This detector was centred at 80.5° in the laboratory system. The second detector, labelled "2^{nd} DSSD" in Figure 2, consisted only of a DSSD of the same type and was centred at 32.5°.

3. First physics experiments

In 2012, we successfully performed an experiment (E105) with stable ^{58}Ni as well as radioactive ^{56}Ni beams [9]. Before our experiment, we had the opportunity to take data with a stable ^{20}Ne beam from another experiment (E087) as well. The beams hit the internal gas-jet target (H_2 or He) and the respective target recoils were measured by our newly developed UHV compatible Si detector setup described above.

The first physics goal was to deduce the nuclear matter distribution of ^{56}Ni from elastic proton scattering at 400 MeV/u [6, 10]. The radioactive ^{56}Ni was produced by projectile fragmentation of a primary ^{58}Ni beam in the FRagment Separator (FRS) of GSI. Approximately $3 \cdot 10^6$ particles were stored in the ESR. As every spill from the FRS contained only about $4 \cdot 10^4$ ^{56}Ni ions, several injections were needed, the so-called beam stacking [11]. The average lifetime of the stored beam, limited by collisions with the residual gas, was about 1.5 h, before the ring had to be refilled.

The small target density of the H_2 gas-jet target of $3 \cdot 10^{13}$ cm^{-2} and the available beam intensity of the stored beam were compensated by the revolution frequency of about 2 MHz to obtain a luminosity of about $2 \cdot 10^{26}$ cm^{-2}s^{-1} which allowed us to perform the experiment.

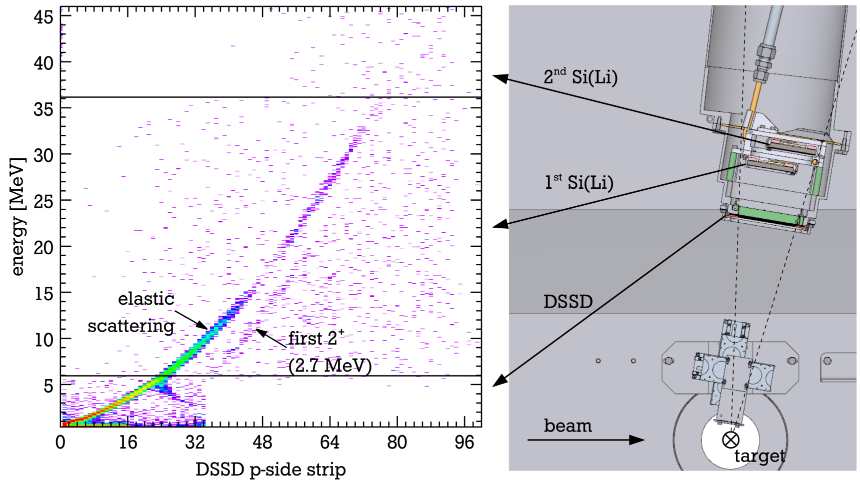

Figure 3. Reconstructed laboratory energies of the recoiling protons from the reaction ^{56}Ni(p,p) at 400 MeV/u using a 1 mm slit aperture (adapted from [6])

The achievable angular distribution is limited by the size of the beam ($\sigma \approx 0.6$ mm) and, in our case the most severe limitation, by the size of the target (radius about 3.2 mm). In order to separate the inelastic scattering to the first 2^+ state in ^{56}Ni at 2.7 MeV from the elastic scattering a movable aperture with a 1 mm slit between the target and the detector was introduced. Figure 3 shows the energy spectrum obtained with this setup. The energy of the protons was reconstructed by summing up the energy deposits in the DSSD and the subsequent Si(Li)s. Protons with energies above 6 MeV punch through the DSSD and above 36 MeV also through the first Si(Li).

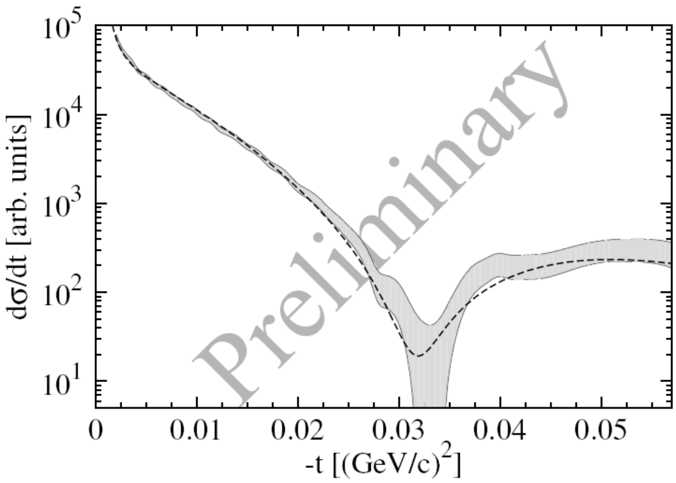

Figure 4. Experimental cross section of ^{56}Ni(p,p) at 400 MeV/u (the grey area between the solid lines represents the $\pm 1\sigma$ accuracy of the experimental cross section in bins corresponding to the vertical detector strips of the first DSSD converted into momentum transfer) and a fit to the data using Glauber multiple-scattering theory (dashed line) (adapted from [6])

The extracted differential cross section was fitted assuming a symmetrised Fermi function to describe the matter distribution and applying a Glauber multiple-scattering theory (Figure 4).

In order to estimate the effect originating from the a-priori assumption of this particular shape of the matter distribution, also a Sum-of-Gaussians (SOG) analysis has been performed. For consistency, all steps of the analysis have been analogously performed with data obtained under the same experimental conditions with a stable ^{58}Ni beam for which the matter radius is well known [12].

A preliminary RMS matter radius of 3.7-3.8 fm could be extracted which is well within the range of predictions by most of theory calculations [13, 14] whereas older predictions with smaller values are already excluded [15]. This experiment was the *first successfully observed nuclear reaction with a stored radioactive beam.*

The second part of the experimental campaign was the first study of isoscalar giant resonances populated in inelastic α scattering on stored nuclei [16, 17]. Of particular interest was the isoscalar giant monopole resonance, the excitation energy of which is related to the nuclear incompressibility, an important quantity in the equation of state for nuclear matter. This quantity is also of high interest in nuclear astrophysics to describe neutron stars [18].

As isoscalar giant resonance can be selectively excited using isoscalar probes, for this experiment we used a He gas-jet target (mainly the isoscalar isotope ^{4}He). The density is an order of magnitude lower compared to hydrogen, therefore this experiment has been performed using a stable ^{58}Ni beam. The giant monopole resonance is the dominant channel at very forward angles in the centre-of-mass system. In the laboratory system, the corresponding inelastically scattered α particles are detected at forward laboratory angles. For this experiment, the second detector centred at 32.5° was important (see Figure 2). The cross section increases with beam energy, however, the kinetic energy of the inelastically scattered α particles decreases. As compromise, an energy of 100 MeV/u was chosen resulting in recoil energies of a few 100 keV. Again, the use of a window-less detector was mandatory.

Figure 5 shows the measured energy spectra for two different scattering angles in the laboratory system. In the analysis, the δ-electrons seen in the low-energy part of the spectra turned out to be a challenge as their energies in forward direction are only slightly lower than those of the recoiling α particles. This interpretation of the spectra has been confirmed by extensive GEANT4 simulations.

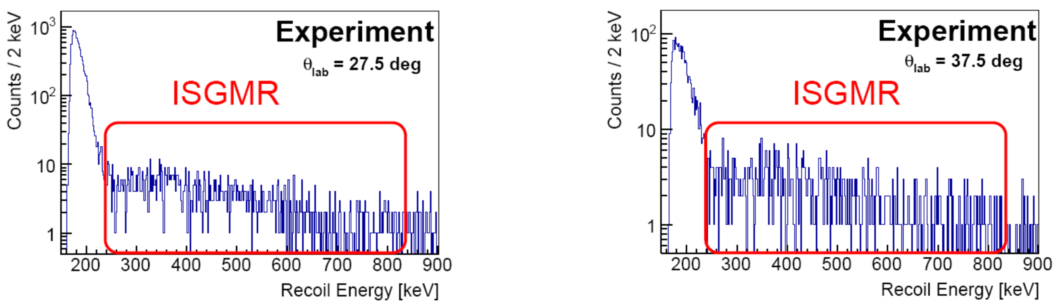

Figure 5. Experimental α spectra measured at two scattering angles in the laboratory system. The region corresponding to the excitation of the isoscalar giant monopole resonance is indicated, the peak at low energies is due to δ-electrons (adapted from [17])

For the double-differential cross section a multipole-decomposition analysis has been performed. The dominant contribution to the double-differential cross section for the inelastic α scattering at angles in the centre-of-mass system $\vartheta_{CM} < 1.5°$ was identified to be the excitation of the isoscalar giant monopole resonance. Figure 6 shows the double-differential cross section in the centre-of-mass system at an average scattering angle of $\bar{\Theta}_{CM} = 1°$. The most important contributions, the isoscalar monopole (ISGMR) and quadrupole (ISGQR) giant resonances, are indicated. The preliminary results for the position, width and strength of the ISGMR in ^{58}Ni are in very good agreement with previous experiments performed in normal kinematics.

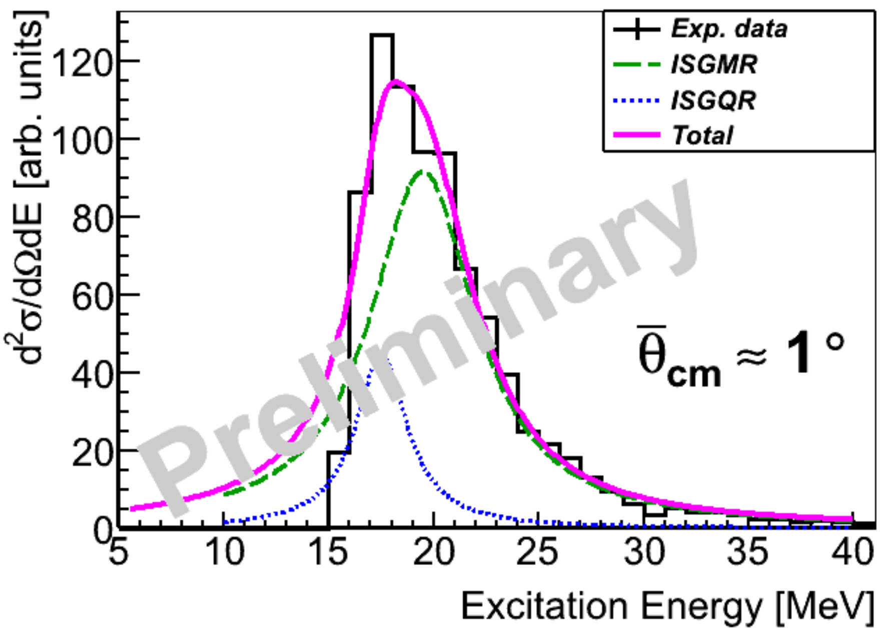

Figure 6. Double-differential cross section for ^{58}Ni(α,α') at 100 MeV/u transformed to the centre-of-mass system. From the results of the multipole decomposition the monopole and quadrupole terms are indicated (adapted from [17])

During the preparations of the experiment with the detectors already mounted at the ESR, it was possible to use a stable ^{20}Ne beam at 50 MeV/u with the hydrogen target. Besides the elastic scattering, also the ^{20}Ne(p,d)^{19}Ne one-neutron transfer reaction was observed [17]. Although the kinetic energies of the deuterons were too high to be stopped in the DSSD, the measured energy losses clearly showed the kinematic curve with a maximum angle $\vartheta < 35°$ in the laboratory system which is characteristic for this reaction. The obtained energy resolution was not sufficient to resolve the transfer to the ground state and the low-lying excited states in ^{19}Ne, however, a multipole decomposition of the differential cross section identified the $L = 0$ and $L = 2$ as the dominant contributions. The extracted spectroscopic factors using the Adiabatic Distorted Wave Approximation (ADWA) approach are well described by shell model calculations

4. Summary and outlook towards FAIR

The first experimental campaign has successfully demonstrated the feasibility of the EXL concept. As major breakthrough, the use of highly-segmented Si detectors as active vacuum windows separating the UHV of the storage ring from an auxilliary vacuum has been proven to work for the detection of low-energy recoils.

For three of the major reaction types comprised in the physics programme of EXL - elastic and inelastic scattering as well as nucleon transfer reactions - first physics results were obtained. The measurement of the matter radius of ^{56}Ni with elastic proton scattering was *the first nuclear reaction performed with a stored radioactive ion beam and an internal target.*

An upgraded detector setup covering a larger solid angle is under design which will be used for further reaction experiments at the ESR. EXL is a very versatile setup and its use at FAIR is considered for experiments with low-energy (at the CRYRING), medium-energy (at the ESR) and high-energy beams up to 5 GeV/u (at the HESR).

Acknowledgments

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