Vol. 41 (2010) *ACTA PHYSICA POLONICA B* No 2

EXL, R^{3}B AND ELISe PROJECTS AT FAIR*

N. Kalantar-Nayestanaki

for the EXL, R^{3}B and ELISe Collaborations

KVI/University of Groningen
Zernikelaan 25, 9747 AA Groningen, The Netherlands

(Received January 14, 2010)

In this contribution, the physics program for three of the experiments at FAIR-NuSTAR, namely EXL, R^{3}B and ELISe will be briefly outlined. All these experiments aim to study the structure and the dynamics of radioactive ions which collide with either light ions in an inverse kinematics, or electrons in a collider mode. Although the physics issues addressed in all three are rather similiar, the experimental equipment used for them are quite different. The experimental plans will, then, also be briefly discussed.

PACS numbers: 24.30.Cz, 25.60.2t, 25.70.De, 27.60.+j

1. Introduction

With the advent of new facilities producing high-intensity radioactive ion beams around the world, the field of nuclear structure has received a tremendous boost. Many activities have been initiated to capitalize on various aspects of the new facilities. The Facility for Anti-proton and Ion Research (FAIR) in Darmstadt, Germany is one of these facilities which is capable of producing beams of nuclei far from the valley of stability. These beams will be distributed among various experimental setups which are used in different subfields ranging from high-precision spectroscopy to reactions in nuclei under extreme conditions such as very large neutron–proton asymmetry [1].

In the reaction studies, since the nucleus under investigation is the one which is produced in the process of in-flight fragmentation, one has to deal with inverse kinematics in which the hadronic probe, generally a light nucleus, is the target being bombarded by the heavy (radioactive) nucleus. The inverse kinematics will impose particular conditions on the design of

* Presented at the XXXI Mazurian Lakes Conference on Physics, Piaski, Poland, August 30–September 6, 2009.

detection systems. In order to take full advantage of the new FAIR facility, the plan is to have an external target hall (R^{3}B, Reactions with Relativistic Radioactive Beams [2]), an internal target hall (EXL, EXotic nuclei studied in Light-ion induced reactions [3]), and an electron–ion collider (ELISe, ELectron–Ion Scattering experiment in a storage ring [4]). All these setups deal with the bulk properties (such as matter and charge radii) of nuclei, giant resonances, spectroscopic information on valence nucleons, and reaction mechanisms governing the nuclei. EXL will specialize in low-momentum-transfer aspects of nuclear structure, R^{3}B will focus on the high-momentum-transfer and ELISe will investigate nuclear properties with an electromagnetic probe. The beam energy used in these studies generally ranges from 200 MeV/nucleon to 1 GeV/nucleon. For the case of the electron collider, electron beam energies from 125 MeV to 500 MeV will be used, yielding energies of up to 1.5 GeV in the center of mass. Figure 1 shows part of the proposed FAIR facility primarily used for nuclear-structure studies. EXL and ELISe are located in NESR while R^{3}B is placed in the high-energy branch of the facility immediately after the Fragment Recoil Separator (Super-FRS). In this contribution, an overview will be given on the physics case for these setups and the detection systems developed for them will be separately discussed.

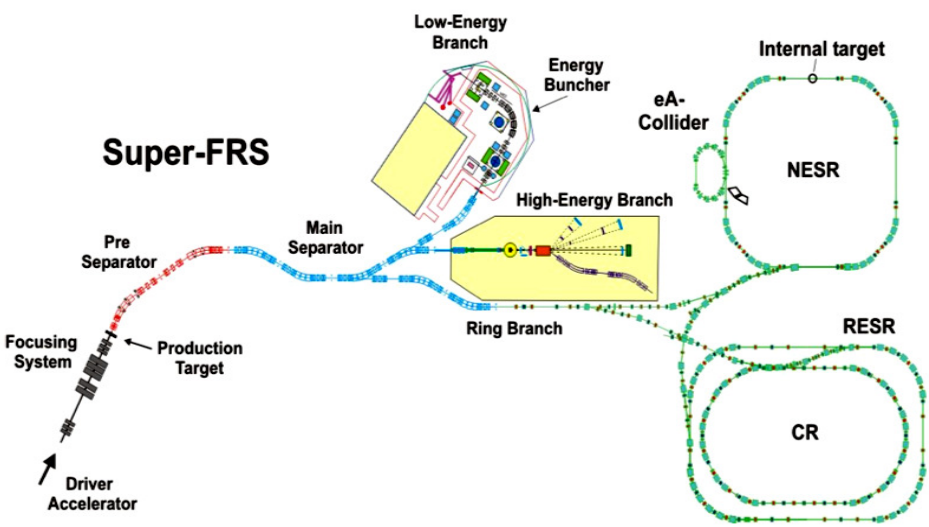

Fig. 1. The overview of the beam lines after the main part of the Super-FRS leading to NuSTAR experiments. EXL and ELISe are placed in the NESR ring while R^{3}B is located at the high-energy branch of the facility immediately after the Super-FRS.

2. Physics and experimental setups of EXL and $\mathbf{R^3B}$

In the study of the structure of nuclei, one has to perform measurements in a large range of momentum transfers in order to fully understand the details. However, the experimental conditions for low-momentum and high-momentum-transfer measurements are quite different. Since all studies of interest will be carried out in inverse kinematics, a low-momentum-transfer measurement necessitates the utilization of storage rings due to very small recoil energies. These low-energy particles would simply be stopped in any external target. One should then perform these measurements in internal-target facilities in which the target thickness must be very small to allow a reasonable life-time for the beam. The very small target thicknesses used in the rings are compensated for by circulating the beam in the ring a couple of million times a second increasing, thereby, the effective luminosity, making the in-ring experiments comparable to external-target measurements as far as the luminosity is concerned. In addition, the large momentum spread and the large emittance of the beam coming from the Super-FRS should be reduced in order to achieve the goals of the low-momentum-transfer measurements. This is done by cooling the beam in the storage ring. One clear advantage of performing the experiments in the storage ring is the lack of background from the target windows which are present in the external-target experiments. The high-momentum-transfer measurements, on the other hand, do not suffer from the above-mentioned energy limitations and as such are better carried out in external-target facilities. The intensity of the beams delivered from Super-FRS could in fact be low, since the required luminosity can be obtained by making the target thicker. To this end, the compromise between the energies of the outgoing particles, their required resolutions and the cross-sections of a given reaction determines what target thickness one can use. In short, one would need a storage ring to perform the low-momentum-transfer measurements and an external target for the high-momentum-transfer measurements. The EXL and R^3B experiments are designed to address these two aspects and are, in that sense, completely complementary to each other.

The key physics issues being covered with the EXL and R^3B programs are:

- nuclear matter distributions near the drip lines. The halo structures as well as the nuclear skins will be thoroughly studied;
- the isospin-dependence of the single-particle shell structures (new magic numbers, new shell gaps and spectroscopic factors);
- nucleon–nucleon correlations and cluster formation;
- new collective modes (different deformations for protons and neutrons), giant and pygmy resonances with different multipolarities;
- in-medium interactions in asymmetric and low-density nuclear matter;

- parameters of nuclear equation of state;
- the astrophysical r- and rp-processes in the form of Gamow–Teller transitions, neutron capture, *etc.*

All these can be done in the light-ion induced direct reactions, such as elastic (p, p), (α, α) scattering, inelastic scattering in (p, p'), (α, α'), charge-exchange reactions of the type (p, n) or $(^3\mathrm{He}, t)$, and $(d,^2\mathrm{He})$, quasi-free scattering like $(p, 2p)$, (p, pn), and $(p, p + \mathrm{cluster})$ and finally the transfer reactions of the type (p, t), $(p,^3\mathrm{He})$, (p, d), and (d, p). The relevant information should be extracted from an energy and momentum measurement of the outgoing particles. In these experiments, it should be possible to detect many of the outgoing particles, making most of the channels kinematically (over)complete. This is particularly necessary in reducing the backgrounds in measurements when the cross-sections are very low. An example of the type of measurements which could be performed with EXL is shown in Fig. 2 [5]. With elastic proton scattering on radioactive isotope and, in particular, at low momentum transfers, one can deduce the matter-density distribution. This, combined with electron scattering on the same object (a la ELISe) will result in neutron density distributions.

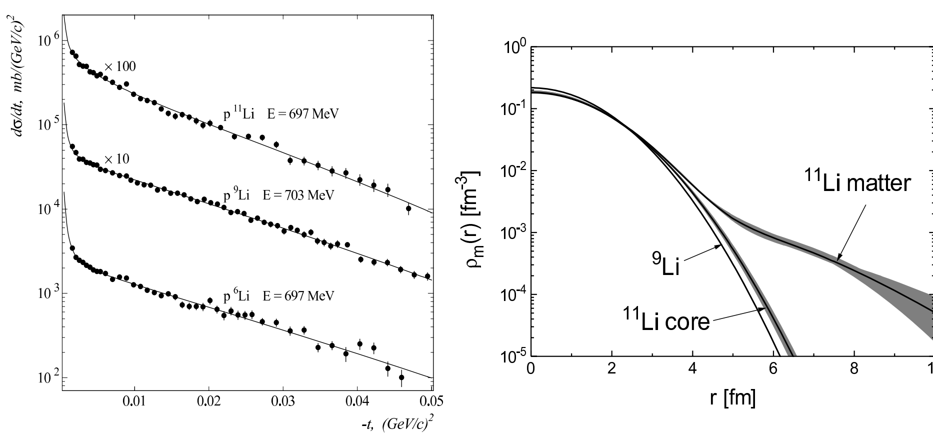

Fig. 2. Elastic proton scattering from Li ions. Cross-sections are shown on the left, while the resulting densities are depicted on the right. Here, the halo structure of ^{11}Li is quite nicely observed.

Figure 3 shows the dipole strength distributions in various Sn isotopes [6]. One can perform these measurements using the Coulomb field of a heavy nucleus. As can be seen in the figure, for neutron-rich isotopes, ^{130}Sn and ^{132}Sn, a new resonance is observed at lower energies. This resonance is interpreted as a soft oscillation of the neutron skin around the core against the core. This new mode of oscillation is called the pygmy resonance due to its smaller size compared to the giant dipole resonance at higher energies. With the help of R^{3}B, one can perform a systematic study of such effects.

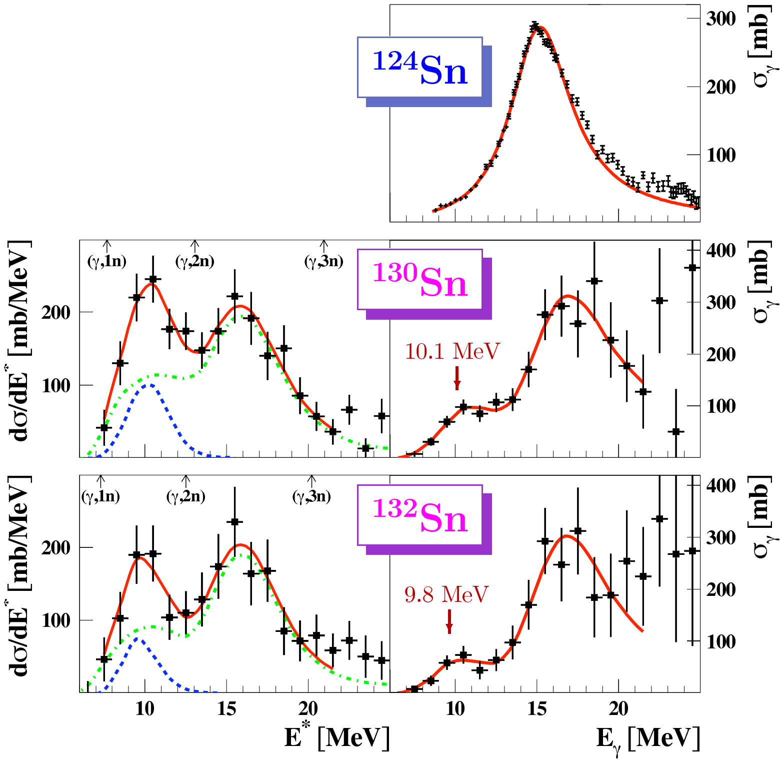

Fig. 3. Dipole strength distributions in Sn isotopes. In the study of the excitation of ^{130}Sn and ^{132}Sn, the Coulomb field of a heavy nucleus was used. The results are depicted in the left panels. Arrows indicate the neutron-separation thresholds. From these cross-sections, the equivalent photo-neutron cross-sections are deduced, using the procedure outlined in [7], and shown in the right panel of the figure. Comparing to the results obtained from a real-photon absorption experiment [8], (top-right panel), one can clearly see the presence of a new resonance at lower energies in the heavier isotopes. These are called pygmy dipole resonance.

2.1. EXL setup

Within the EXL Technical Proposal, the design of a complex detection system was investigated with the aim to provide a high-efficiency, high-resolution, and a universal setup, applicable to a wide class of reactions (see Fig. 4). The apparatus is foreseen to be installed at the internal target of the NESR storage cooler ring. The detection system includes:

- a Si-strip and Si(Li) detector array for recoiling target-like reaction products, completed by slow-neutron detectors (not shown in the figure), and a calorimeter with a high granularity for γ-rays and for the total-energy measurement of more energetic target recoils;
- detectors in forward direction (schematically shown in the figure as forward scintillator arrays) for fast ejectiles from the excited projectiles, *i.e.* neutrons and light charged particles;
- heavy-ion detectors for the detection of beam-like reaction products.

All detector components will practically cover the full relevant solid angle and have detection efficiencies close to unity. With this setup, kinematically-complete measurements will become possible.

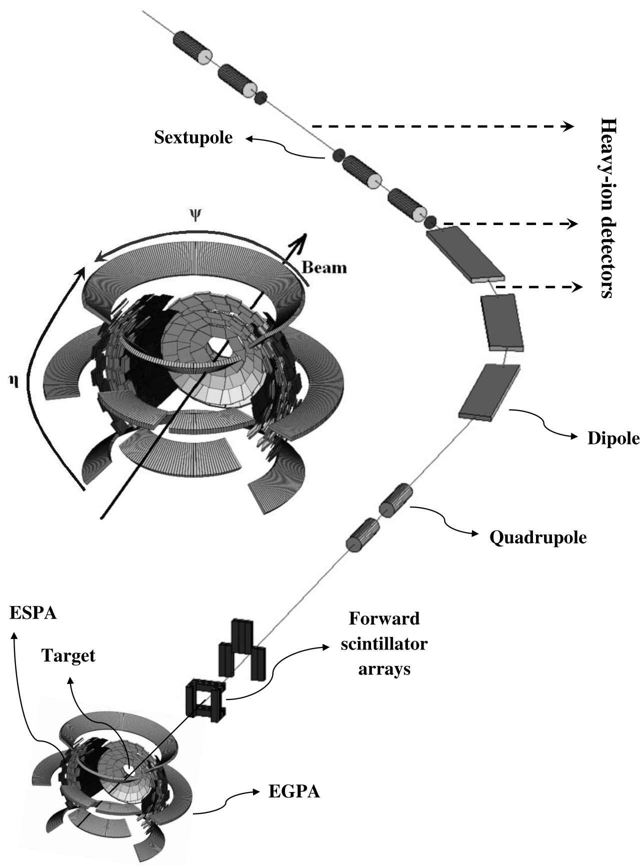

Fig. 4. The overview of the EXL setup with various components shown. The recoil detector is enlarged and shown in the middle. Note that only a few rings of the calorimeter are drawn here for the sake of clarity.

Major research and development work is required for the design and the technical implementation of the target-recoil detector which will be the most challenging part of the project. In particular, the detector components need to fulfil strong demands concerning angular and energy resolutions, detection thresholds, dynamic range, granularity, vacuum compatibility, *etc.*, partly not available or derivable from the existing detection technologies. A second major task is to achieve high densities in the internal gas-jet target, of the order of 10^{14}–10^{15} atoms/cm^2 or above with a well localized interaction zone [9]. On both fronts, there are major developments going on with very promising results. In 2005, a feasibility measurement in the present ESR ring at GSI was performed with a small number of detectors representing various components of the EXL detection system [10–14]. These include a Si-strip detector placed in vacuum, plastic scintillators to detect the fast forward recoil particles, and a combination of a p-i-n diode and a scintillator placed after the first bending magnet to detect the projectile-like heavy ions. The results of elastic-scattering cross-sections for ^{136}Xe(p,p), obtained on an absolute scale from this feasibility measurement, are shown in Fig. 5. The results of this first measurements are very promising, paving the way for the installation of the full setup in the future.

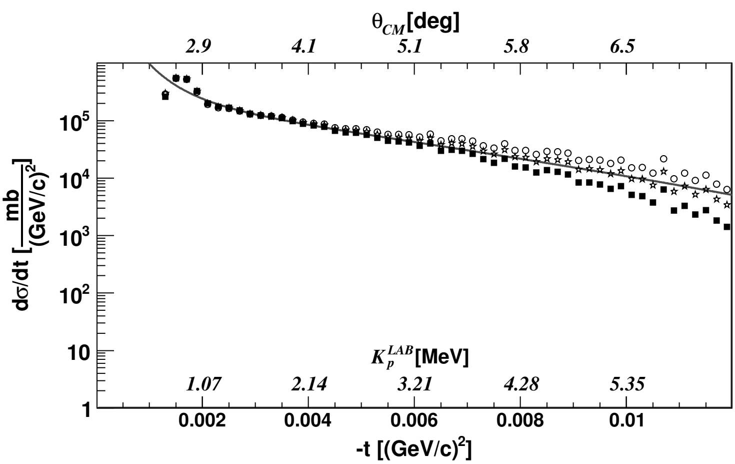

Fig. 5. The elastic-scattering cross-section for ^{136}Xe(p,p) at $E_{\mathrm{inc.}} = 350$ AMeV, obtained in the feasibility measurement at ESR as a function of various kinematical variables (θ_{CM}, scattering angle, K_p^{lab}, outgoing proton kinetic energy and $-t$, the invariant four-momentum-transfer squared). Solid squares are the experimental data. Circles and hollow stars show the experimental data corrected for a finite size of an extended target of 7.4 and 10.5 mm, respectively. The solid curve is the result of a Glauber calculation using a matter radius of 4.9 fm.

2.2. R^3B setup

The experimental setup of R^3B is placed at the high-energy branch (see Fig. 1). The detection system consists of several parts as shown in Fig. 6. The incoming radioactive beam is tagged with the help of a number of tracking detectors. Around the target region, there is a calorimeter for the detection of γ-rays, slow neutrons, and protons. The particles which go forward, will go through a large-acceptance magnet which separates various particles with different rigidities. A fraction of the reaction products are analyzed with the high-resolution spectrometer. For the detection of fast neutrons, there is a large-acceptance neutron detection system placed at a large distance from the target. This large distance, coupled to the very high time resolution of the detector (sub 100 ps), makes it possible to have a reasonable energy resolution for the outgoing neutrons.

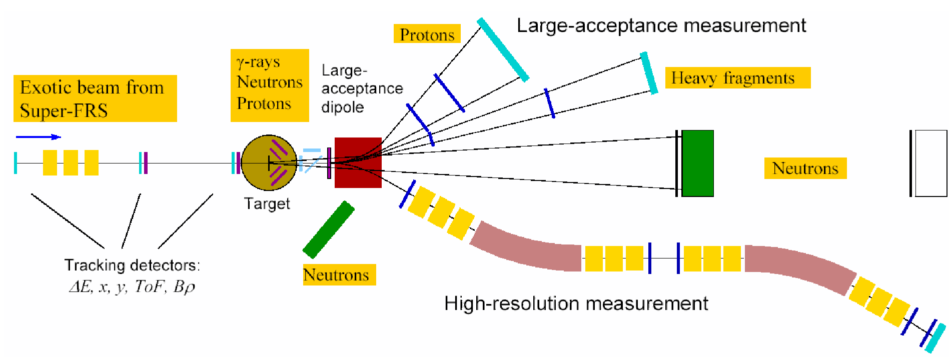

Fig. 6. The R^3B setup with its various components.

3. Physics and experimental setup of ELISe

The advantage of using electrons instead of hadronic probes is two-fold. Electrons are point-like objects and the interaction of electrons with matter is very well understood in the framework of QED. In addition, the interaction is weak, making it possible to have a very good description of the collision process already in the first order of the perturbation theory. The second advantage of electron scattering is that, with the exchange of photon, the process is space-like allowing one to fix the excitation energy of any state and study the interaction for that particular state as a function of momentum transfer. These advantages have been used in the past to study, for example, the charge distribution of nuclei [15]. These studies can now be extended to exotic nuclear matter. The (new) collective states and giant resonances which were described in the EXL and R^3B subsection can also be well studied with electron scattering with its high selectivity to different multipolarities. Furthermore, electro-fission can be employed with this facility due to the fact that the outgoing fissioning particles will be primarily going in the direction of the primary beam, however, with different rigidities allowing them to be easily detected. Depending on the luminosity of the beam, one can go further and study quasi-free scattering, such as $(e, e'N)$ or even cluster knock-out, to provide information on the internal structure of the nucleus and to study nucleon–nucleon correlations in nuclear medium [16].

Here, I will give one example of the power of electron scattering as studied with ELISe. In this example, an experiment is simulated the results of which are shown in Fig. 7. For simplicity, two known cases have been taken for this study, namely ^{12}C and ^{208}Pb. A center of mass energy of 400 MeV, a heavy-ion beam energy of 740 AMeV, a luminosity of 10^{28}, and a detec-

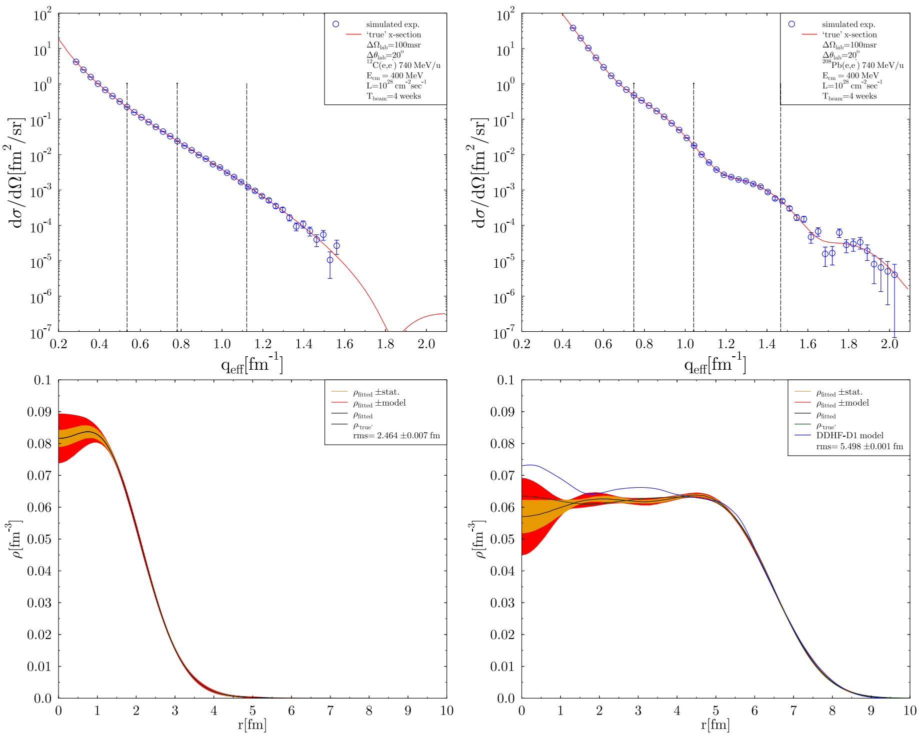

Fig. 7. Results of the simulations for elastic electron scattering from ^{12}C (left) and ^{208}Pb (right). The bands in the lower panels represent the results for charge-density distributions with their errors, obtained from the simulated experiments. The curve shown in the lower-right panel is the result of a mean-field calculation for the charge-density distribution of ^{208}Pb.

tion solid angle of 100 msr are assumed for this simulation. In addition, we have assumed that the spectrometer has an opening angle of 20° which results in a simultaneous measurement of the points within the vertical bars. These "data points" would then be obtained in a run of four weeks. One can see that the Fourier transformation of these "measured" points results in rather precise charge-density distributions which, in turn, can be compared with theoretical predictions shown for ^{208}Pb in the picture. The error bands, observed in the picture, are the results of the limited q-range of the measurements and the statistical accuracy of the points measured. To obtain these results, we started from the known charge-density distributions, Fourier transformed them to calculate the expected cross-sections and made a Monte-Carlo randomization around these expected values.

The spectrometer which has to perform the task of detecting the outgoing electrons has to be a very special one. First, one has to guide the scattered electrons out of the beam environment without disturbing the circulating beams of electrons and heavy ions. Subsequently, these electrons should be momentum analyzed in a second magnet with special detectors at its focal plane. A sketch of such a setup, being designed at the moment, is depicted in Fig. 8.

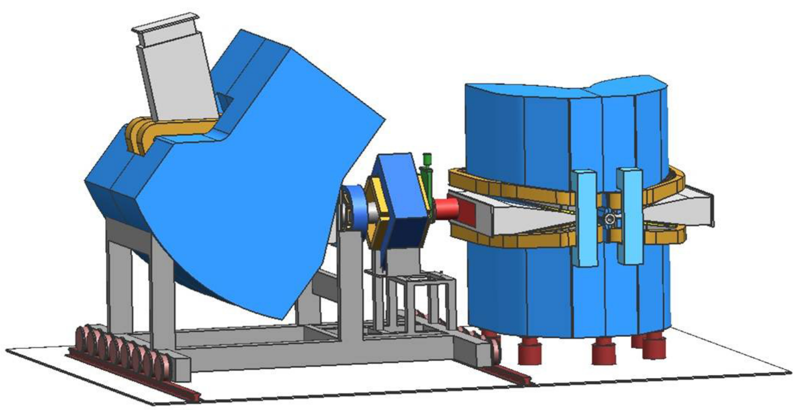

Fig. 8. Present design of the magnetic system to be employed at the ELISe setup. Shown are the butterfly magnet (on the right) which acts as a pre-deflector of the scattered beam and the main magnet (on the left) which further momentum analyzes the scattered electrons. The radioactive ions and the electron beams go through the beam pipe shown in the middle of the butterfly magnet.

4. Conclusions

In this contribution, the physics case for three of the NuSTAR experiments, namely EXL, R^3B and ELISe was briefly discussed and the experimental setups were also introduced. Presently, all three collaborations are performing intense R&D to finalize their designs. The Technical Design Reports for all three are expected within the next two years. On the way to the final experiments, several measurements have been done or are planned to be performed with the present facility at GSI albeit with down-graded specifications as compared with the final design. The first measurements with beams from the Super-FRS are expected in 2016 in the high-energy beam-line.

I would like to thank all my colleagues and collaborators from the EXL, R^3B and ELISe collaborations.

REFERENCES

[1] `http://www.gsi.de/fair/experiments/NUSTAR/projects_e.html`

[2] `http://www.gsi.de/forschung/kp/kr/R3B_e.html`

[3] `http://www.rug.nl/kvi/Research/hnp/Research/EXL/index?lang=en`

[4] `http://www.gsi.de/fair/experiments/elise/index_e.html`

[5] P. Egelhof *et al.*, *Eur. Phys. J.* **A15**, 27 (2002).

[6] P. Adrich *et al.*, *Phys. Rev. Lett.* **95**, 132501 (2005).

[7] M.N. Harakeh, A. van der Woude, *Giant Resonances*, Oxford Studies in Nuclear Physics Vol. 24, Oxford University, New York 2001.

[8] S.C. Fultz *et al.*, *Phys. Rev.* **186**, 1255 (1969).

[9] R. Grisenti, University of Frankfurt, private communication.

[10] S. Ilieva, Ph.D. Thesis, University of Mainz, 2009.

[11] H. Moeini, Ph.D. Thesis, University of Groningen, 2010.

[12] S. Ilieva *et al.*, *Eur. Phys. J.* **ST150**, 357 (2007).

[13] N. Kalantar-Nayestanaki *et al.*, *Int. J. Mod. Phys.* **E18**, 524 (2009).

[14] H. Moeini *et al.*, submitted to *Nucl. Instrum. Methods Phys. Res.*

[15] H. de Vries, C.W. de Jager, C. de Vries, *At. Data Nucl. Data Tables* **36**, 495 (1987).

[16] A.N. Antonov *et al.*, submitted to *Nucl. Instrum. Methods Phys. Res.*