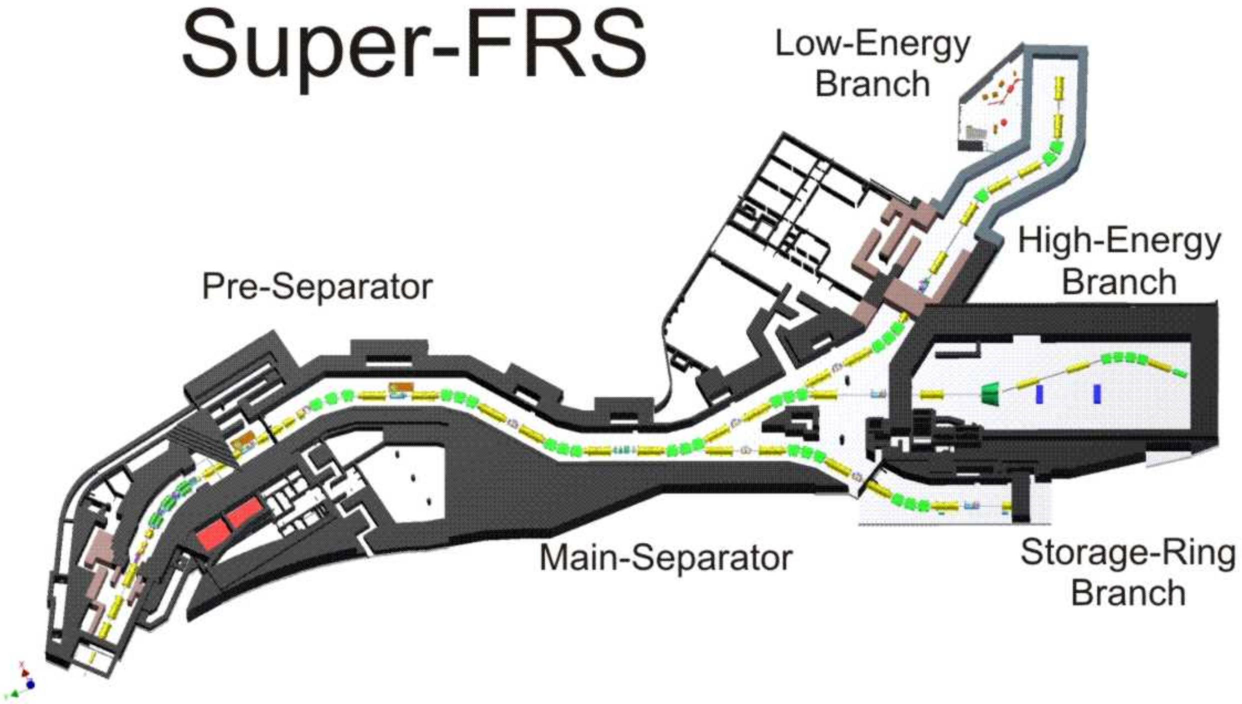
Conceptual Design Report for the Scientific Program of the Super-FRS Experiment Collaboration



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Abstract:

This Conceptual Design Report (CDR) presents the plans of the Super-FRS Experiment Collaboration for a variety of experiments, which build on the versatile high-resolution separator and spectrometer performance of the Super-FRS. The characteristic feature of these experiments is the fact that they use the separator as an integral part of the measurement. These experiments build on the experience of the collaboration and their scientific program pursued at the FRS in the last 25 years, but also includes recently developed novel topics.

Under these premises, the Super-FRS Experiment Collaboration has identified ten major topics of current interest and with far-reaching scientific potential. In this CDR, the scientific case is briefly recapitulated and the conceptual design of the experiments, the setups and their implementation are described. Much of the needed equipment is already available or, if not, will be realized with new, additional resources and efforts outside the FAIR Cost Books. The related R&D works and some pilot experiments can be carried out at the existing FRS of GSI in FAIR Phase-0. On the midterm, the science program of this collaboration can start at the commissioning phase of the Super-FRS and will continue on the long term with the established full performance. Accordingly, the prototype equipment and other already existing devices can be tested and used at the FRS and can later, when completed or upgraded, be moved to the Super-FRS, see Appendix I. The related developments and organization of the Super-FRS Experiment Collaboration are described in Appendices II and III, respectively; the collaboration partners and institutes are listed in Appendix IV.

The Super-FRS Experiment Collaboration is formally and firmly established and is a comprising part of the NUSTAR Collaboration. A large variety of modern nuclear physics experiments with new scientific possibilities and outstanding scientific potential were presented in the scientific program (GSI-Report 2014-4), which was very positively evaluated and approved by the FAIR-ECE in its 4th meeting in June 2014. In its report, the ECE encouraged the collaboration to develop TDRs. The present CDR is the next step on the way to TDRs for the ancillary equipment, that shall be integrated in the Super-FRS.

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1. Introduction and overview

Super-FRS experiments form one of the science pillars of the NUSTAR Collaboration. The high-resolution spectrometer-separator experiments with relativistic beams open up unique scientific research opportunities. The scientific program of the Super-FRS Experiment Collaboration was outlined in a report to the FAIR management (GSI-Report 2014-4), which was positively reviewed by the Expert Committee Experiments (ECE); the preparation and submission of TDRs was recommended by the ECE in November 2014. The contents of the present document gives the conceptual design of the planned experiments and the related ancillary detectors in some more detail and thus forms another step to the realization of the experiments.

The program of the Super-FRS Experiment Collaboration builds on the specific features of this world-unique facility:

1. At Super-FRS, high-energy and high-intensity primary and secondary nuclear beams can be used with energies up to 1,500 *A* MeV for uranium ions ($B\rho_{max}$=20 Tm).
2. The Super-FRS is an unparalleled high-energy, high-resolution multiple-stage spectrometer with a large acceptance and with flexible ion-optical settings.
3. It provides high primary-beam suppression and high separation power of nuclides up to Z=92, and can also provide fully stripped ions of all elements.
4. It provides versatile spectrometer modes by different combinations of separator sections, in particular with dispersion-matching capabilities.

The connecting element of the experiments presented here is the common feature that the Super-FRS will not only serve for separation or/and identification of exotic nuclei, but that the precise momentum measurement and the high momentum-resolution capabilities will be an integral part of the measurement. Along these lines, the experiments are largely unique and complementary to the other experiments of the NUSTAR collaboration. It is not intended to duplicate equipment within the NUSTAR collaboration. Also on the worldwide scale, the planned experiments are unique when compared with the goals of other next-generation exotic nuclear beam facilities. The scientific program of the Super-FRS Collaboration is in line with the scientific goals of FAIR and with the scope of the Modularized Start Version. The collaboration is open to new members, and exploits synergies with the scientific and technical programs of the other FAIR collaborations.

It was convincingly demonstrated in several reviews, including the FAIR review in 2014, that the targeted experimental results will be at the forefront of basic nuclear science even in many years from now. Therefore, the collaboration presents the present Conceptual Design Report.

2. Experiment concept and goals of the Super-FRS Experiment Collaboration

The Super-FRS Experiment Collaboration is guided by its physics goals: Research with relativistic exotic nuclei using the high-resolution spectrometer performance of the FRS and later the Super-FRS. In contrast the other NUSTAR sub-collaborations, which use the exotic nuclei produced, separated and identified at (Super-)FRS for measurements at the various end stations that are located behind the final focal planes of the three branches, the present collaboration uses the (Super-)FRS as a comprising part of the experiment together with ancillary detectors that are integrated at the (Super-)FRS intermediate and final focal planes. The Super-FRS Experiment Collaboration will use different operation modes, namely for instance high-resolution spectrometer and dispersion-matched modes for studies with exotic nuclei. The key to all proposed activities is the high-resolution high-suppression separator-spectrometer capabilities of the (Super-)FRS. In the planned activities, the FRS serves as a platform for R&D, for tests, training and pilot experiments in the FAIR Phase-0. Later, in FAIR Phase-1, the collaboration will perform experiments at the Super-FRS, mostly building on its standard instrumentation (for separation and identification), but some of them will be carried out with the addition of ancillary detectors at the major focal planes in order to reach the specific experimental goals.

Following this approach, the collaboration has identified a number of experiments, which address excellent science, and, related to these, there is a number of dedicated equipment like cryogenic targets and specialized detectors. The planned experiments are unique on the worldwide scale, beneficial for the whole NUSTAR collaboration, and can be implemented in an early phase of FAIR. It is important to be highly complementary to the experimental program of the other NUSTAR experiments. From the organizational point of view, the role of the Super-FRS Experiment Collaboration is similar to the other sub-collaborations in NUSTAR. The organization and governance of the Super-FRS Experiment Collaboration does not duplicate nor modify the role and mandate of existing committees and structures.

The Super-FRS is the central device of the NUSTAR collaboration. It will provide high quality radioactive ion beams for the whole NUSTAR collaboration, ranging from hydrogen up to uranium over a large energy range equivalent to a maximum magnetic rigidity of up to 20 Tm. As a beam delivery system, the exotic nuclides are produced via projectile fragmentation, fission and two-step reactions; the nuclides of interest will be separated in flight within several hundred nanoseconds and delivered to the large-scale detector systems (“end stations”) which are planned within the Modularized Start Version of FAIR. These detector systems will be placed at the exits of the three separator branches: HISPEC/DESPEC and MATS/LaSPEC at the Low-Energy Branch (LEB), R3B at the High-Energy Branch (HEB) and ILIMA at the Storage-Ring Branch (RB). The high separation power is achieved under the phase-space condition of 40 π mm mr at a specific kinetic energy up to 1,500 A MeV uranium beams and a longitudinal momentum acceptance of $\Delta p/p=\pm2.5\%$. Properties of the Super-FRS are summarized in figure 1. These challenging performance parameters are achieved with a multi-stage magnetic system, comprising intermediate degrader stations. Specialized detector systems for full particle identification event-by-event and at high rates verify the separation performance. This Super-FRS standard detector system (for separation and identification of exotic nuclei), combined with additional, so-called “ancillary detectors”, secondary and tertiary target stations and specially shaped degraders, that will be placed at the different focal planes of the Super-FRS, can also be used advantageously for high-resolution momentum measurements. For instance, the energy-buncher spectrometer at the LEB can ion-optically be coupled to the main separator in a dispersion-matched mode, which yields a high momentum resolving power of up to 20,000 for a 1 mm object size. Such an arrangement can be used for spectroscopy of nuclear states after secondary reactions. It is these features which make the Super-FRS unique also for stand-alone experiments.

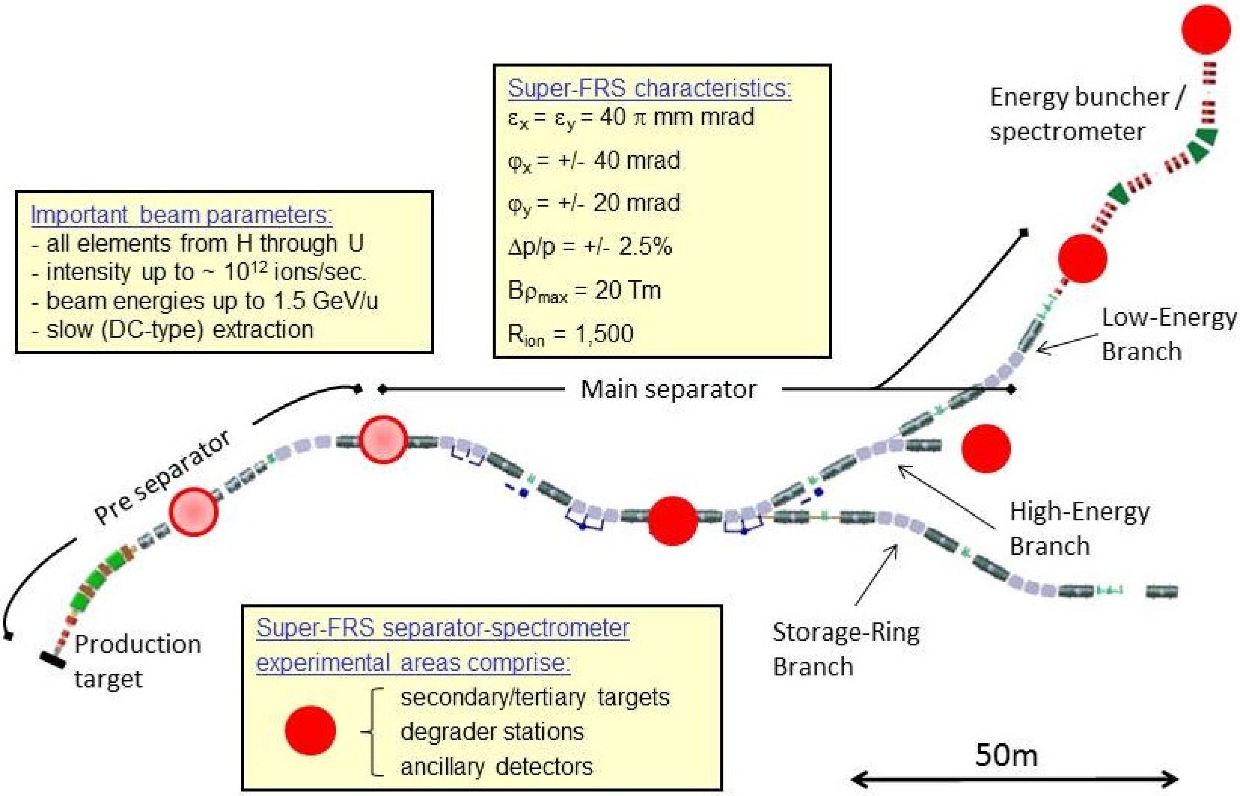

Fig. 1: Characteristics of the Super-FRS with its three branches and the LEB spectrometer-energy-buncher system. The focal planes, where the ancillary equipment of the Super-FRS Experiment Collaboration will be located, are indicated.

3. Experiments at Super-FRS

In this chapter, the scientific case is briefly recapitulated and the conceptual design of the experiments, the setups and their implementation are described.

3.1 Physics goals

The Super-FRS Experiment Collaboration is one of the NUSTAR sub-collaborations. Many of the present scientific cases are unique in the world and also within NUSTAR. The cases presented here naturally comprise experiments that have common goals with other NUSTAR experiments, as they aim at studying nuclear structure, nuclear astrophysics and reactions. However, these experiments are largely complementary and use the unique characteristics of the Super-FRS that were described above.

Basically, three different modes can be distinguished, which provide the measurement conditions for the various planned experiments and which are depicted in figure 2.

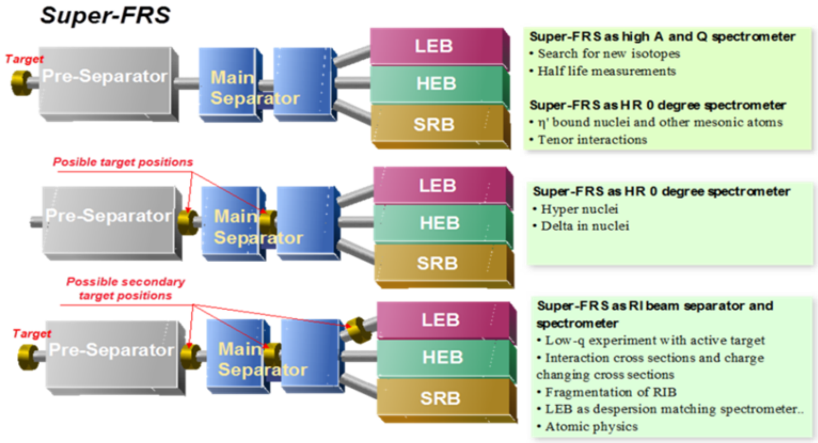

Fig. 2: This figure shows main operation modes of the Super-FRS and the corresponding experimental opportunities, which are described in the following. The major functional units are indicated schematically: pre- and main separator, target positions, and the three branches of the Super-FRS (LEB: low-energy branch, HEB: high-energy branch, SRB: storage-ring branch). In the present context, the LEB will be used as high-resolution spectrometer, e.g., for secondary reaction studies with exotic beams, such as single-nucleon knockout, multi-nucleon transfer or others.

The experimental program includes new physics opportunities such as exotic atoms, exotic hypernuclei, delta resonances in exotic nuclei, new exotic radioactivity modes, the importance of tensor forces and high-momentum nucleons in nuclei, and equation-of-state of cold asymmetric nuclear matter. It also includes highly unique and important frontiers of physics such as the search for new isotopes, determination of nuclear (matter and charge) radii, and the atomic interaction of highly-charged atoms of heavy elements. These studies are continuously discussed in the Super-FRS Experiment Collaboration meetings, and more ideas are still to be expected.

The key of all proposed activities is that they exploit the separator-spectrometer capabilities of the Super-FRS. The various stages of the Super-FRS and their ion-optical performance are integral parts of the measurements. With this objective the collaboration has proposed experiments, which a) are intrinsically connected with the separator, such as production and separation of new isotopes, b) are highly unique and c) emerge as new physics opportunities characteristic for this instrument within the FAIR facility.

All these key functions of the Super-FRS, depicted in figure 2, can be tailored for the specific goals of each measurement. This opens up a large variety of modes and experimental opportunities, including new measurement concepts. For most of the experiments, the standard detector equipment of the Super-FRS, as specified in the Super-FRS TDR (Technical Design Report, Dec. 2008), will be used; only some experiments will need new, additional dedicated detector setups, which are described in the following.

3.2 Experiments using the Super-FRS for mass and charge resolution

The experiments that use outstanding separation power and ion-optical resolution combined with high-energy beams from SIS-100 are listed here. These experiments can be started in an early stage of the FAIR facility. They not only provide new information in the nuclear chart, but also show the perspective for many other NUSTAR experiments at the Super-FRS.

Topic 1: Search for new isotopes and production mechanism studies

Scientific goals: Searching for the limits of existence of nuclei is one of the most essential studies in nuclear physics. Combined with high-intensity primary beams up to uranium accelerated by SIS-100, the Super-FRS is the world's most powerful spectrometer to search for new isotopes far from the beta-stability line by projectile fragmentation, fission and combined production reactions.

The Super-FRS beams, characterized by kinetic energies which are up to 500 *A* MeV higher than those at the FRS at SIS-18, will have the advantage that even the heaviest fragments will be fully ionized. The search for new isotopes will be beneficial for all NUSTAR experiments. Firstly, the separation performance with respect to ion-optical resolution and possible contamination will be tuned and elaborated. Furthermore, measuring the production cross sections and kinematics, reliable rates of the most interesting isotopes at the limit of the new facility will be obtained, which is essential for all NUSTAR experiments. Possible regions of interest are shown in figure 3.

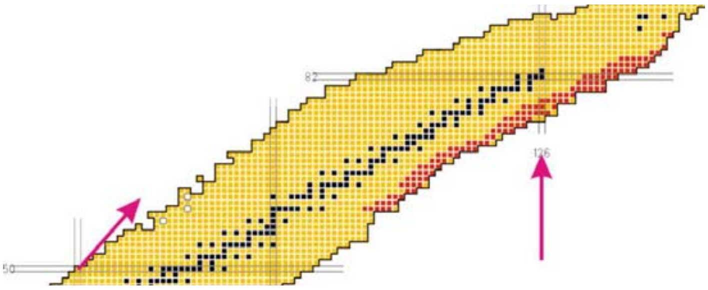

Fig. 3: Region of recently discovered neutron-rich isotopes with the FRS illustrated in the chart of nuclides (the new nuclides are marked in red color). Arrows indicate future directions of the proposed isotope search experiments.

To complement the kinematics and production cross section measurement described above the other goal is to perform experiments on nuclear reaction mechanisms above the Fermi energies and related spin distribution studies. This is planned to be done by measuring isomeric ratios of high-spin states after in-flight separation, which can be linked to the pre-fragment formation and the related distributions in the excitation/spin plane of the fragments at the end of the evaporation phase. In such experiments, some other observables (e.g., longitudinal momentum distributions, number of transferred nucleons etc.) will help to test and constrain the underlying models.

Experiments: Such measurements can be accomplished with the standard Super-FRS detectors for separation, identification and momentum measurements of nuclei plus additional equipment of other NUSTAR collaborators, in combination with for instance DESPEC detectors (for measurement of isomeric ratios of short-lived isomers, $T_{1/2}$~μs) or the Super-FRS Ion Catcher (for longer-lived states; see also topic 10 below). The implantation in solid detectors will verify and complement the properties measured in flight. Otherwise, the planned experiments build on the Super-FRS as a unique instrument to achieve simultaneously high resolution for isotope separation, background suppression for the detection of the rarest nuclei, and relativistic energies up to 1,500 *A* MeV so that even the heaviest projectile fragments are fully ionized and allow for unambiguous identification. The standard detector suite of the Super-FRS can be used for the new isotope searches and the additional ancillary detectors will be located at FLF3 and FLF6. Both ancillary setups are already listed in the cost-books of the Super-FRS project and the NUSTAR experiments; major parts are already available at GSI and can be used in FAIR Phase-0.

Topic 2: Atomic collisions

Science Case and Motivation: Accurate knowledge of the atomic interaction of heavy ions penetrating through matter is essential for the successful operation of the in-flight separator Super-FRS [Geissel-02]. An uncertainty of one percent in the momentum prediction would already cause difficulties for the identification of rare isotopes at the outskirts of the chart of nuclides where no guidance of reference isotopes is available in the spectrum. The operating domain with the Super-FRS extends more than 500 *A* MeV higher than the present FRS for uranium ions. In this new energy range no data for stopping powers, energy and angular straggling and charge-state distributions of heavy ions exist. The Fermi density effect starts to play a significant role at these energies.

At lower energies the ionization and electron capture processes of the projectile lead to different charge-state distributions and further to the uncertainties in the theoretical predictions. Stopping power calculations at these energies are presently larger than a few percent. For efficient isotope separation, basic atomic collision processes have to be measured in an early stage of the Super-FRS commissioning. A detailed study of atomic collisions at the new regimes of Super-FRS is particularly important for experiments in the Low-Energy Branch (LEB).

Different contributions to the range straggling have to be correctly predicted to perform efficient experiments with very exotic nuclei such as the complete slowing down of beams in a gas-filled stopping cell. In this case, adequate stopping efficiencies can be achieved only after reduction of the energy spread in a dispersive magnetic stage combined with a mono-energetic degrader System. In such experiments the atomic interaction of heavy ions has to be known with high accuracy over the full energy range down to thermalization.

Besides amorphous solids, crystals will be used which will enable for the first time to observe the nuclear Okorokov effect of resonant coherent excitation (RCE) [Okorokov-07]. The feasibility of channeling experiments has been demonstrated with pilot experiments at the FRS many years ago. At Super-FRS, RCE experiments will be performed with exotic nuclei. Already the first measurements of the Cherenkov radiation from relativistic heavy ions with the present FRS have revealed that the well-known Tamm-Frank theory cannot describe the observed results [Ruzicka-01]. It was already investigated in new models that slowing-down in the radiator leads to additional broadening and appearing of the complex diffraction-like structures of both spectral and angular distributions. Experiments with the Super-FRS will contribute to the detailed understanding of Cherenkov radiation of heavy ions and will lay the grounds for improved and novel detector developments.

Experimental Setup: The planned location for the experimental setups to study the stopping powers, energy and angular straggling as well as charge-state distributions at Super-FRS energies is at FMF2 of Super-FRS, see figure 4. A modification of the focal plane diagnostic chambers is not required for the installation of measurement devices. Super-FRS and its standard detectors (mainly TPCs for position measurements and ionization chambers) and data acquisition system serve as the experimental setup for the stopping powers, energy and angular straggling and charge-state distributions studies for these studies and no additional infrastructure is necessary.

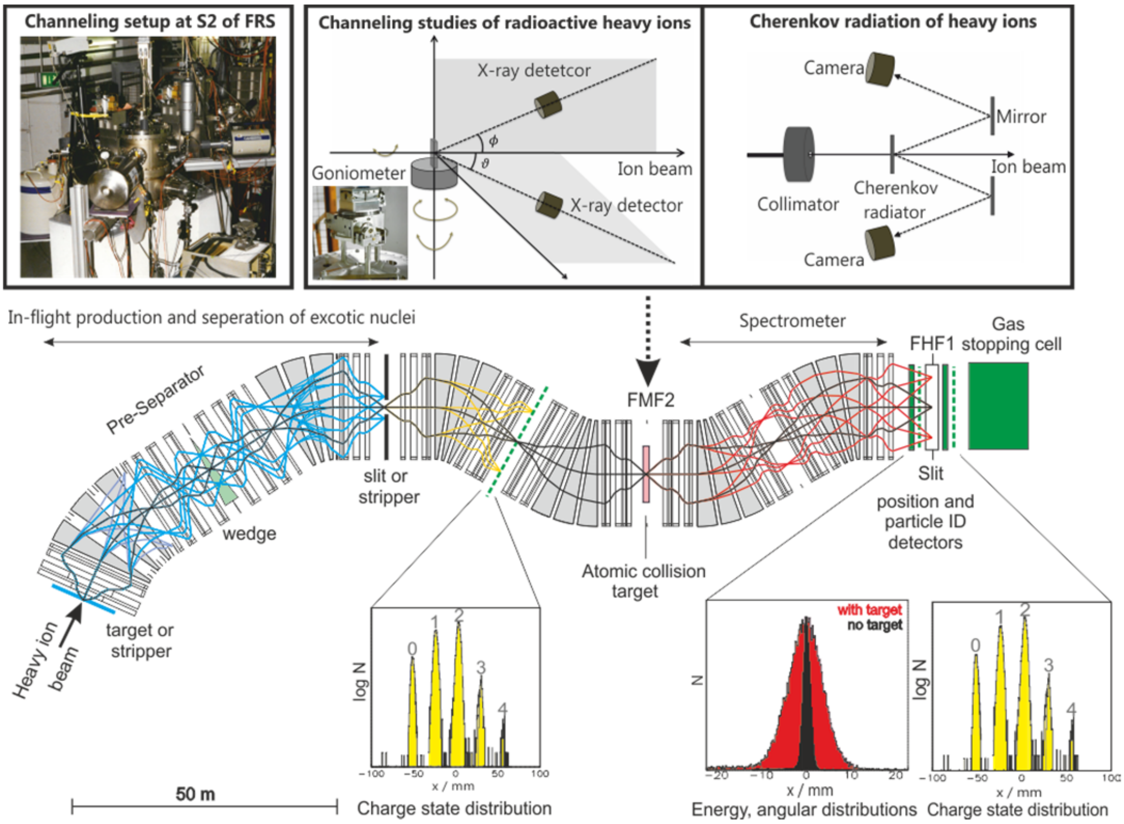

Fig. 4: Layout for atomic collision studies with the Super-FRS. The pre-separator can be used for production and separation including nuclear fragments. The main separator is used as a spectromter to analyze the projectiles after the atomic collision target.

For the systematic investigations of low energy atomic collision experiments the intended location is at UNILAC, other accelerator facilities for lower energy and later at LEB of the Super-FRS. An offline experiment setup to study the target properties is already setup at the FRS research division at GSI. A cryogenic micro calorimeter for precise energy measurement of low energy heavy ions already exists [Echler-14].

The target laboratory at GSI is well experienced at producing high quality targets required for these experiments. Target ladders for holding many different targets necessary for these experiments exist including drives. Positions for the ladders are included in the common research infrastructure for the Super-FRS (dedicated slots in beam diagnostic chambers). The FRS research division is already active in channeling experiments [Dauvergne-99] and atomic collision studies for decades and all the necessary equipment like gas target system already exists and can be used to continue the research program at Super-FRS. The atomic physics group at GSI has an active research group studying channeling phenomena with relativistic stable ions. Experimental efforts, equipment and expertise can be combined with the atomic physics group and the Super-FRS Experiment Collaboration. Components like a high precision multi axis goniometer (resolution ~1 μrad), control system and data acquisition (partly common NUSTAR-DAQ, partly extra electronics), Beryllium windows, X-ray detectors, collimators and mechanical infrastructure (support frame etc.) are either available within the FRS research group of GSI or will be provided by the present collaboration.

Investigations on Cherenkov radiation from relativistic heavy ions will be performed in close collaboration with the detector laboratory at GSI. It is already active in the investigation of using Cherenkov radiation in liquid radiator as a diagnostic tool for relativistic heavy ion. Detectors, data acquisition, collimators and mechanical infrastructure (support frames etc.) required for this science case either exist already at the FRS research group at GSI or will be provided by the collaborators. Tomsk Polytechnic University, Russian Federation, is already an important collaborator in this science topic and negotiations on possible collaborations with other universities and research institutes like University of Aarhus, Denmark and RIKEN, Japan are ongoing.

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[Ruzicka-01]Ruzicka, J., et al. "Vavilov–Cherenkov radiation emitted by heavy ions near the thresh-old." Vacuum 63.4 (2001): 591-595.

[Echler-14] Echler, A., et al. "Application of Calorimetric Low Temperature Detectors (CLTD's) for Precise Stopping Power Measurements of Heavy Ions in Matter." Journal of low temperature physics 176.5-6 (2014): 1033-1039.

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3.3 Unique experiments at Super-FRS as high-energy high-resolution spectrometer

Topic 3: Spectroscopy of meson-nucleus bound system ("mesonic atoms")

The discovery of deeply-bound pionic states in heavy atoms at FRS has opened up a new field of fundamental studies of the meson-nucleus interactions, which contribute to the understanding of the non-trivial structure of the vacuum of quantum chromodynamics (QCD) [Suzuki-04]. The experiments on the meson-nucleus bound system will first concentrate on the existence of the states and secondly will reveal possible modification of meson properties inside nuclear matter. The results will help to answer the key question of partial restoration of chiral symmetry breaking, which is related to the unknown process of mass evolution. The experiments employ transfer reactions with light incident nuclei like protons and deuterons and then look for bound states in missing mass spectra. The high-momentum resolving power and the independent multiple-stage operation of the Super-FRS ion-optical system are the essential key features for these experiments.

The first planned experiment is on η′ bound nuclei. The (p,d) reaction at 2,500 MeV is suitable for producing and observing η′-bound nuclei. A large mass of η′ compared with other mesons in the same pseudo-scalar nonet has been stimulating theoretical and experimental interests. Recent theories interpret the origin to be an interplay between dynamical breakdown of chiral symmetry and axial U(1) quantum anomaly. Studying the mechanism of the large η′-mass leads to understanding of the low-lying fundamental symmetries and to investigations of the non-trivial structure of the QCD vacuum. One can study this quantum anomaly effect via spectroscopy experiments of η′ meson bound systems. The second candidates will be the η′-bound nuclei. η-bound nuclei can be produced either by the (d,^{3}He) reaction or by the (p,^{3}He) reaction.

In order to enhance the versatility of the Super-FRS we consider a large acceptance detector apparatus near the central focal plane FMF2 of Super-FRS as depicted in figure 5. A WASA-type 4π detector [Bargholtz-08] is ideal for detection of charged particles by the solenoidal magnetic field, tracking detectors and trigger detectors and γ's by the CsI(Na) crystal detectors. This combination of a forward high-resolution spectrometer and target-surrounding 4π detector system will open very broad physical studies and serve unique opportunities to various novel experiments. Besides the search for η′-mesic nuclei, rather simple considerations may lead to the measurements of elementary η, η′ and ω production cross sections, spectroscopy of η/ω-mesic nuclei and Λ hypernuclei, and possibly other exotic systems at the boarder line of nuclear and hadron physics.

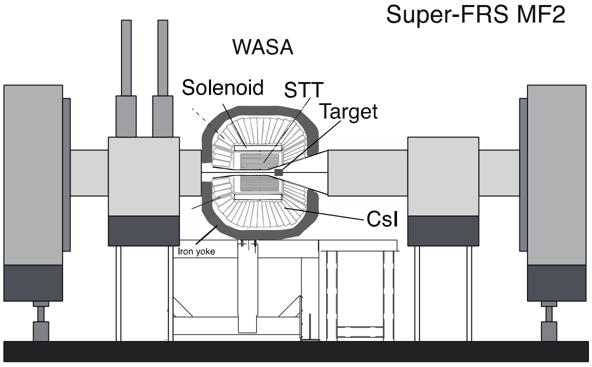

Fig. 5: Schematic view of a WASA-like detector installed at FMF2, the central focal plane of the main separator of the Super-FRS. The beam comes from the left.

The search for η‘-nucleus bound systems using Super-FRS as a spectrometer is conducted along the lines of a three-step approach. The first experiment step utilizes an inclusive measurement of the ^{12}C(p,d)-reaction with protons at an energy of 2.5 GeV; this is suitable for production and observation of η′-mesic nuclei. This pilot experiment was performed in year 2014 and the missing mass of the reaction was measured precisely by the FRS. The experiment achieved the designed statistical and systematic precision with a good spectral resolution, and the result is being published [Tanaka-16]. The second step will employ semi-exclusive measurement of the ^{12}C(p,dp)-reaction by selecting events of η‘-mesic nuclei formation by its decay in a dominant channel of $\eta'NN \rightarrow NN$ (where N stands for a nucleon, proton or neutron). Such an exclusive measurement is realized uniquely by a combination of a WASA-type 4π-detector surrounding the reaction target. We plan to construct such a 4π-detector and install it at FMF2 of Super-FRS after having elaborated pilot runs in a realistic environment, i.e. in the existing facility FRS. As the third step, we plan to upgrade the detector for the detection of γ's. A detailed numerical simulation shows that the discovery of η′-mesic nuclei will be possible, even in case that the attractive interaction between the η′ and a nucleus is weak.

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[Bargholtz-08] C. Bargholtz et al., Nucl. Instr. Meth. Phys. Res. A 594, 339 (2008).

[Tanaka-16] Y.K. Tanaka et al., Phys. Rev. Lett. in print

Topic 4: Exotic hypernuclei and their properties

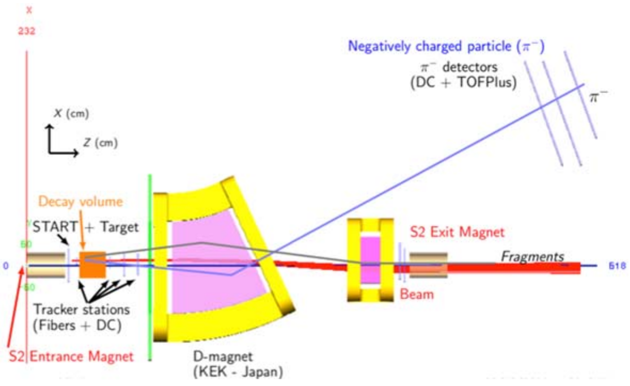

Fig. 6: Schematic layout of the proposed setup at the mid-focal plane of FRS at FAIR Phase-0.

Science case: The study of nuclear bound systems with hyperons (a nucleon containing a strange quark), so called hypernuclei, provides information on the interaction between an ordinary nucleon (proton, neutron) and a hyperon. This information is essential to understand the baryon-baryon interaction under the flavored-SU(3) symmetry. It contributes to the detailed understanding of the short-range repulsive part of the nuclear force as well as the effect of a three-body force to the nuclear force. Hypernuclei with the lightest hyperon, the Λ, have been experimentally studied for more than six decades by using cosmic rays, secondary meson beams and electron beams. In these experiments, the isospin of the produced hypernuclei is very similar to the target nucleus since target nuclei are converted to hypernuclei, thus they were observed in the direct vicinity of the β-stability line of their core nucleus. Despite a variety of studies over many years, the available data are scarce, often not precise and sometimes conflicting. Therefore, more precise data are needed, and in contrast to these stable-target techniques, hypernuclei can be produced in fragmentation reactions of heavy ion beams at energies of approximately 1.7 A GeV and larger. In the heavy-ion fragmentation reactions, hypernuclei emerge when the projectile fragments capture a hyperon produced in the hot participant zone. This is a universal process, which applies to stable and radioactive nuclear beams. Because of the wide distribution of isospins of the projectile fragments, the isospins of the produced hypernuclei are also widely distributed. Thus, hypernuclei with large neutron- or proton-excess can be studied. With this novel approach neutron- and proton-rich hypernuclei will be extensively studied with RI-beams at energies in excess of 1.7 A GeV, which are only available at GSI and FAIR. By studying a variety of Λ-hypernuclei at different isospin, the isospin dependent Λ-nucleon interaction and the three body force induced by the ΛN-ΣN coupling will be studied.

Experimental Setup: The planned experiments at the Super-FRS aim at semi-exclusive measurements of hypernuclei production (such as cross sections, kinematics, etc.) and their properties (such as lifetimes and binding energies). The spectrometer properties allow for invariant mass measurements with high precision. At the multi-stage separator Super-FRS, these studies can be extended even to secondary beams (isotopically clean or cocktail beams) that have been separated with the pre-separator. Pilot studies are planned to be performed at the FRS of GSI.

With both, stable heavy ion and RI-beams, hypernuclei will be studied by means of the invariant mass method, i.e. by measuring the momenta and energies of a negative charged pion, π^-, and the other decay residues. The HypHI collaboration has already demonstrated the feasibility with the ^{6}Li+^{12}C reaction at 2 A GeV at GSI and found exciting results. They observed short lifetimes of $^{3}_{\Lambda}$H and $^{4}_{\Lambda}$H (C. Rappold et al., Nucl. Phys. A913 (2013) 170) as well as, surprisingly, an indication of a strange neutral nucleus with two neutrons and one Λ-hyperon, the so-called nnΛ bound state (C. Rappold et al., Phys. Rev. C88 (2013) 041001R). The first hypernuclear experiment of the Super-FRS Experiment Collaboration at FAIR Phase-0 aims at verifying the short lifetime of $^{3}_{\Lambda}$H and $^{4}_{\Lambda}$H with much better precision as well as recheck the existence of the nnΛ state. In the proposed hypernuclear experiment at FAIR Phase-0, a pion spectrometer will be installed in the mid-focal plane of FRS, and decay residues will be measured by the second half of FRS by using its standard detectors. Figure 6 shows the proposed setup at the central focal plane of the FRS, where additional dipole magnets will be installed to measure the π^-. The dipole magnets are already available and will be provided by Japanese collaboration partners. Ion-optical calculations and experiment simulation have been performed. The magnetic settings of the FRS (and the same applies for Super-FRS) can be adjusted such that they account for the influence of the additional magnetic fields while the general properties (separation, identification, momentum resolution) are maintained. Indeed, also one additional dipole magnet can be effectively used if the four main dipole magnets of the FRS are carefully tuned to compensate the off-axis deflection of the pion dipole magnet. Detailed simulations yield that with this setup the invariant mass resolution will be 800 keV. This is a very competitive figure and will allow one to extract precise binding energies of many hypernuclei. Similar performance figures will be obtained with the Super-FRS at FAIR. As the next step after pilot experiments at GSI, a pion spectrometer will be installed at the middle focal plane of the main separator of the Super-FRS. As another option, alternative to the dipole-magnet based pion spectrometer, a detector based on a solenoid magnet is investigated and simulations are ongoing. With the solenoid magnet, the acceptance for the pions will be increased by almost a factor three, and the acceptance of the decay residues will be also increased. One possible choice for the solenoid magnet is to use the WASA system for the FAIR Phase-0, that is currently installed at COSY, and a new solenoid-type pion spectrometer can be developed for later stages.

Topic 5: Importance of tensor forces in nuclear structure

Science Case: Recent ab-initio calculations of light nuclei demonstrate the importance of the pion for binding nuclei. It was found that about 80% of attraction is due to pions. The pion interaction is written as

$$\vec{\sigma}_1 \cdot \vec{q}\,\vec{\sigma}_2 \cdot \vec{q} = \frac{1}{3} q^2 S_{12}(\hat{q}) + \frac{1}{3} \vec{\sigma}_1 \cdot \vec{\sigma}_2 q^2$$

$$S_{12}(\hat{q}) = \sqrt{24\pi}\left[Y_2(\hat{q})\left[\sigma_1\sigma_2\right]_2\right]_0$$

where S_{12} is the tensor operator and provides the contribution of the tensor forces in the first term of the right hand side of the first equation. The second term is the spin-spin term of the central forces. As seen in the equation, the tensor force is as important as the central forces in the pion exchange interactions. However, the tensor forces have not been explicitly treated in nuclear models except for the lightest nuclei such as the deuteron and ^{4}He. Moreover, recent studies of nuclei far from the stability line show the importance of the tensor forces through changes of magic numbers and a peculiar mixing of s- and p-waves in the neutron-halo nucleus ^{11}Li. An important property of the tensor force is that it produces a strong correlation between a proton and neutron pair (pn pairing) in a nucleus and introduces high-momentum nucleons in nuclei. In fact, it is these tensor-correlated nucleons that provide the main part of the binding energy of the deuteron and ^{4}He. Most nuclear models, however, are based on the mean-field picture and do not include the correlations induced by the tensor forces.

The observation of high-momentum components of nucleons and/or correlated nucleons in nuclei will shed light on the effect of the tensor forces on nuclear structure. The recent reported possible signature of effect of tensor forces in ^{16}O observed via high-momentum one-neutron transfer (p,d) reaction marks an important milestone in the study of the roles of the tensor forces in atomic nuclei. Subsequent measurements at the FRS at around zero degrees have confirmed the earlier results, and dismissed any possible significant contributions from the reaction mechanisms. The Super-FRS will be the only facility in the world equipped with a high-resolution 0-degree spectrometer that provides high-energy stable and unstable ion beams. Hence, it is poised to be an ideal facility for the tensor-force experiments using highly momentum-mismatched transfer reactions such as (p,d), (d,t), and (d,^{3}He), both under normal and inverse kinematical conditions.

In the presence of the tensor forces, a high-momentum nucleon is strongly correlated with a non-identical nucleon counterpart. Therefore, the correlated nucleon may be emitted when a high-momentum nucleon is picked up by the incident particle. A measurement of the strongly correlated nucleon is possible by the coincidence measurements such as (p,pd), (p,nd), (d,pt), and (d, p^{3}He). Recently, an experiment using the (p,pd) and (p,nd) reactions has been successfully performed at the FRS of GSI using GeV proton beams to study the pn and nn pairing in ^{12}C and ^{16}O. While the data analysis is still in progress, a comparison of the (p,pd) and (p,nd) cross sections provides a handle to isolate the effect of tensor forces. Taking advantage of the high momentum resolution capabilities of the FRS/Super-FRS, which are of the order of p/Δp~10,000 or better, it is clear that the measurements are complementary to the quasi-free scattering experiments performed at the R3B setup.

Experimental setup:

The feasibility of the planned experiments has been demonstrated at the FRS in a pilot experiment of the collaboration in year 2014. A publication is in preparation. Here, the setup at Super-FRS is depicted in figure 7, and the table below gives a detailed overview of the new equipment that will be used. Otherwise, the experiments will use the standard equipment of Super-FRS.

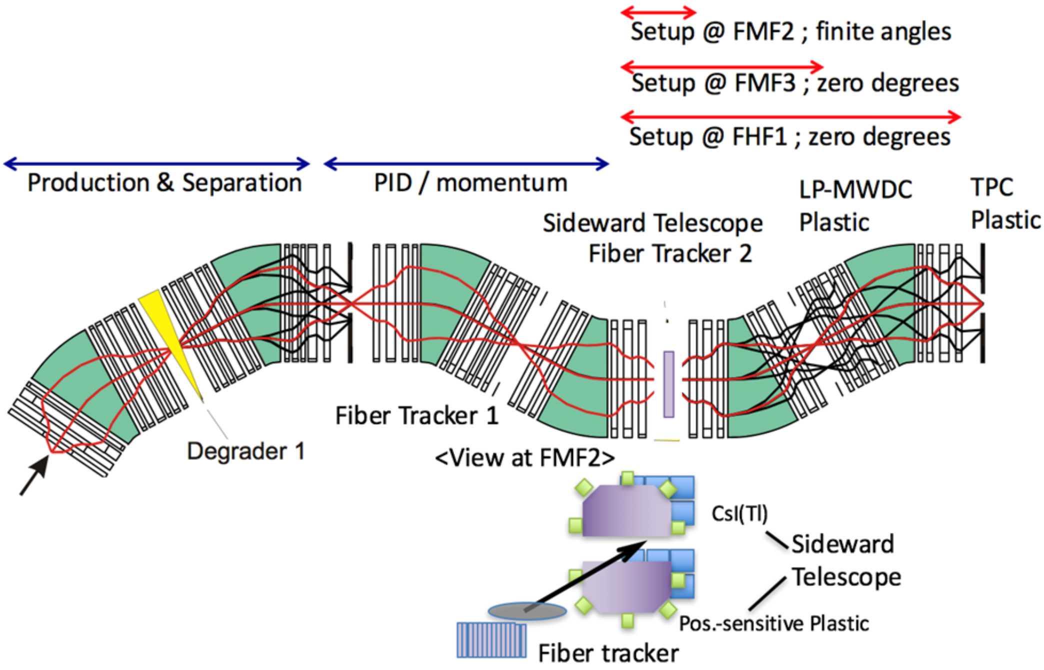

Fig. 7: Setup for tensor force and short-range correlation studies by high-momentum nucleon transfer reactions: the ancillary equipment will be located at the focal planes of the main separator.

Ancillary equipment	Location at FRS/Super-FRS
1. Ice target system	FMF2
2. Plastic-scintillator-based active hydrogen target	S2/FMF2
3. Beam current monitor	FMF2
4. Fiber trackers x 2	S1/FMF1, S2/FMF2
5. Multi-Wire Drift Chambers x 2	S3 or S4/FHF1
6. Sideward (charged- particle) telescope	FMF2
7. Backward-Angle Neutron Detector Array (BAND)	FMF2
8. Gamma-ray detector	FMF2
9. Liquid hydrogen target	FMF2

Topic 6: In-medium excitation of nucleon resonances probing nuclear structure

Physics Case: The Δ-resonance is a $\Delta S = 1$; $\Delta I = 1$ spin- and isospin-flip intrinsic excitation of the nucleon. As such it is a partner of the corresponding $\Delta S=1$; $\Delta I=1$ excitation of the nuclear medium, known as the Gamow-Teller resonance. This resonance is largely produced in relativistic heavy-ion collisions and could appear in the core of neutron stars at densities around 2 or 3 times the nuclear matter saturation density. Nucleon resonances also play a significant role in the understanding of three-body nuclear forces or the quenching of the Gamow-Teller strength.

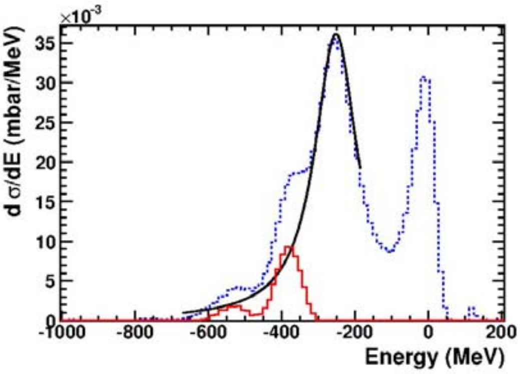

Fig. 8: Measured energy loss spectrum of ^{112}Sb projectile residues produced in isobaric charge exchange collisions induced by ^{112}Sn projectiles with copper targets at 1,000*A* MeV.

Studies with the Super-FRS present unique possibilities to study the Δ and other baryon resonances in stable and in exotic nuclei by using isobaric charge-exchange reactions in relativistic heavy-ion collisions. Pilot experiments have already been performed with the FRS and reveal that the high resolution of the spectrometer makes it possible to identify in the missing energy spectra of the forward-emitted projectile ejectiles the in-medium excitation of Delta and Roper resonances, as demonstrated in the figure 8.

This kind of measurements are expected to contribute to open a new field linking subnucleonic and nucleonic degrees of freedom through the production of resonant nuclear matter. In particular, these experiments should help constraining the in-medium NΔ and NR potentials above the 400 MeV range covered by electron-nucleus and pion-nucleus scattering experiments and to address the possible in-medium mass modification of nuclear resonances. These reactions may also provide an opportunity to study two Δ's in nuclei and provide a chance to study ΔΔ interactions and the recently observed $d^*(2380)$ resonance. Moreover, the use in these experiments of relativistic nuclei far off stability allows to explore the isospin degree of freedom enlarging in this way our present knowledge of the properties isospin-rich nuclear systems. Particularly, one could also take advantage of the strong absorption of the resonance decay pions to probe the relative abundances of protons and neutrons at the nuclear periphery. A large discovery potential, extending also to astrophysics, can be expected from studies of nucleon resonances in exotic nuclei, which were never possible in the past and will not be possible by other lower-energy facilities.

Experimental: Very similar to the pilot experiments at the FRS, the proposed experiments on Δ-excitations in exotic nuclei can be realized by using the Super-FRS with its standard tracking detector systems measuring the momentum distribution of the isobaric projectile residues created via charge-exchange reactions. The interaction target will be located at the central focal plane of the main separator, so that the experiments can be performed with stable ion beams as well as with secondary beams that are separated in-flight by the pre-separator and the first stage of the main separator. In addition, measuring the charged pions emitted in the decay of the nucleon resonances in coincidence will allow to separate resonance excitations in the projectile and target nuclei remnants. The use of a liquid hydrogen target will also contribute to isolate the excitation of particular resonances. In the next stage of these studies, one could use an advanced setup providing 4π detection capability with a complete tracking of all pions in the magnetic field. The proposed setup has many common issues with the one proposed for the investigations of the mesonic atoms (topic 4) and hypernuclei (topic 4). Therefore, synergies have been identified and detailed simulations are still underway with the goal to design a common setup.

In figure 9 a schematic view of a possible setup for pion detection for a FAIR Phase-0 experiment is presented. In this setup there is a liquid hydrogen target, a dipole magnet and tracking and time of flight detectors to determine the momentum of the emitted pions. In order to kinematically separate pions coming from projectile or target charge-exchange remnants, an angular range between 5° and 60° needs to be covered and the momentum of the pions needs to be determined with a resolution better than 10%.

Another interesting option is the identification of decays to a charged and a neutral pion because this possibility would allow us to isolate the Roper resonance excited in isobaric charge-exchange reactions. One can foresee two experimental scenarios, the detection of the neutral pions via their decay into two energetic gamma rays or the indirect identification of this decay channel from an energy shift in the missing energy spectra, which are obtained from the detection of the projectile remnant and the charged pion. In the first case one needs a forward-placed gamma calorimeter, in the second one the detection of the charged pions.

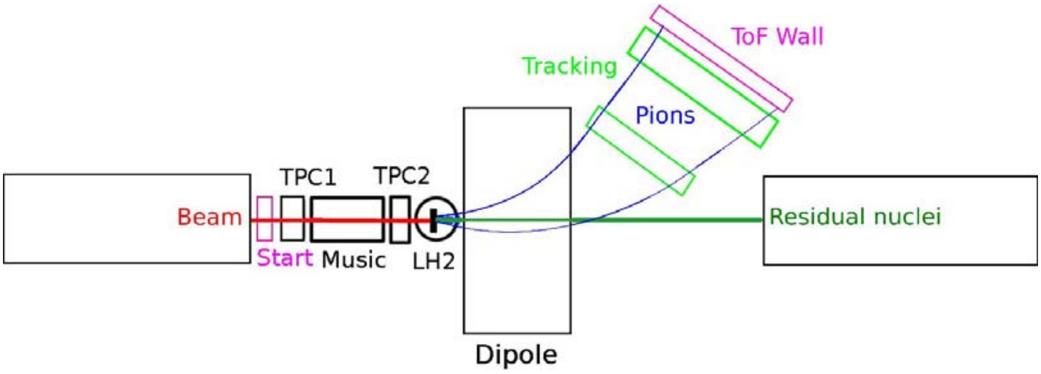

Fig. 9: Schematic representation of the setup for pion detection proposed for the first phase of the experimental program. The setup is simliar like the one planned for hypernuclei studies (see topic 4) and for exotic atoms (see topic 3).

In the third stage of these studies, one could use an advanced setup providing 4π-detection capability with a complete tracking of all pions in the magnetic field using a WASA-type detector. This is presently studied and simulations are underway. In any case, the proposed setups have many common issues with the ones designed for the investigations of the mesonic atoms and hypernuclei. Many synergies have been identified and the design of a common setup is underway.

3.4 Experiments taking advantage of multi-stages and high-resolution of the Super-FRS

The experiments that take advantage of the Super-FRS characteristics are listed here. They might be possible in other NUSTAR experimental areas, too, but the multi-stage and high-resolution spectrometer capabilities of the Super-FRS, have specific advantages. A case-to-case analysis and in depth discussion as to where such experiments can be performed in the best manner (performance, effectiveness of time and budget usage etc.), will take place within the NUSTAR collaboration. It is noted that in some cases complementary approaches and cross checks with different techniques might be advantageous.

Topic 7: Nuclear radii and momentum distributions

Physics case: The discoveries of exotic forms of nuclei such as neutron and proton halos, neutron skins, and new magic numbers mostly originated from measurements of nuclear radii by the interaction-cross-section measurements and subsequent fragmentation measurements.

(i) Matter and proton radii: The interaction cross section (σ_I) has been well established to be an efficient method to determine nucleon radii of unstable nuclei. It has been applied for elements up to argon. The nucleon density distributions have also been determined by the energy and the target dependences of the σ_I. Halo nuclei have been discovered in nuclei near the drip lines but the neutron drip line is reached only up to oxygen isotopes (Z=8) so far. Giant neutron halos including more than two neutrons are also predicted in heavier elements. It is of great importance to search for such a new structure in nuclei. Halos revealed a new quest on the coupling of continuum and discrete states. It prompted studies of nuclear theories to understand bound and unbound objects from first principles.

The thickness of neutron skins is one of the sensitive ways to determine the equation of state (EOS) of asymmetric nuclear matter. The EOS for asymmetric nuclear matter is of upmost importance for understanding the stellar objects (such as neutron stars) and their dynamic changes (such as supernovae). Neutron skin thicknesses are mostly determined by combining the matter radii extracted from σ_I and the proton-distribution radii deduced from charge radii. For isotope chains, charge radii are mostly determined by laser spectroscopy methods, such as isotope shift measurements.

In case of isotopes where charge radii are difficult to determine by isotope shifts measurements, a nuclear charge changing cross section (σ_{cc}) can provide a mean to determine the proton distribution radius. Determination of proton distribution radii by σ_{cc} measurements is still under development but there have been several successes in light elements. A particular advantage of this method is that it can be applied for very short-lived and weak intensity nuclides and thus has the possibility to reach the most neutron-rich isotopes.

The Super FRS is the ideal instrument in the world to perform the σ_I and σ_{cc} measurements due to the desired high energy coupled with the advantages of high mass resolution and transmission.

(ii) Momentum distribution of fragments: The momentum distributions of fragments following one- or two-nucleon removal was one of the early spectroscopic methods that gave knowledge on the wave function of the initial nucleus. It is of great importance to extend these studies to higher-mass regions in order to probe whether magic numbers 50, 82, 128 still persist and whether new magic numbers will appear.

The advantage of the present method is that a very low intensity beam (~10 /s) can be used for detailed spectroscopy. High-resolution momentum measurements are possible by applying the dispersion-matching mode. The usage of R3B for this type of experiments is also under discussion, especially with γ-rays from excited states of the fragment observed in coincidence. While this has potential to provide a more detailed knowledge on the final states, it requires higher intensity beams. The large acceptance of the R3B-dipole magnet may have advantages, for example, for the detection of multi-particle final states. Careful examinations are expected among experimentalists.

Experiment procedure and setup at the Super FRS

The matter radii of neutron-rich nuclei will be derived by measuring the interaction cross sections (σ_I). This allows reaching nuclei with beam intensities as small as ~ 0.5 pps. The charge changing cross sections (σ_{cc}) will be measured to determine the proton radii. To measure σ_I and σ_{cc} the transmission technique will be used. Here we need to identify and count the number of incident beam particles (^{A}Z) event-by-event and after the reaction target we count the number of non-interacted ^{A}Z for measuring σ_I while for measuring (σ_{cc}) the number of particles with same Z are counted. The root mean square point matter and point proton radii are extracted from a Glauber model analysis of the measured cross sections. Elastic scattering measurements, requiring higher beam intensity, can complement the interaction cross sections for deriving the matter radii for certain specific cases.

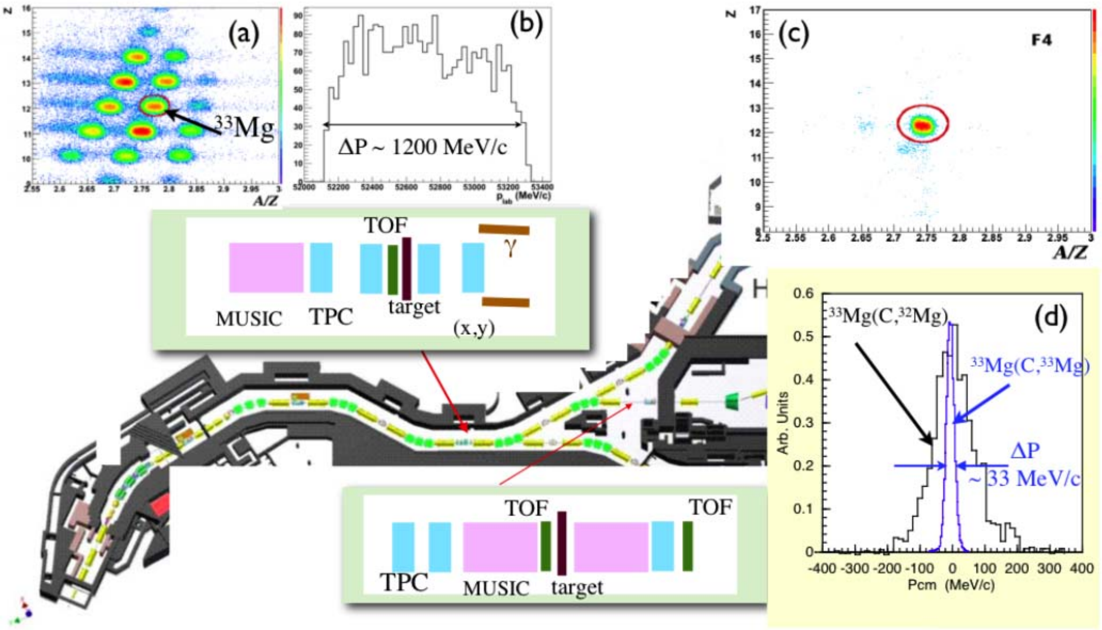

Fig. 10: Schematic of experimental layout. The main separator will be used in similar way to the FRS. The blue/pink/green boxes represent TPC/MUSIC/Scintillator detectors. Example figures of momentum distribution measurement from an FRS experiment (a) Incoming (^{33}Mg) beam identification (b) The beam momentum from position at the dispersive focus (c) One-neutron knockout residue identified at final focus (d) Momentum distribution of ^{33}Mg→^{32}Mg (black) from position distributions at the final focus due to dispersion-matched operation. ^{33}Mg→^{33}Mg (blue) shows the momentum resolution (including target effects).

The information on nucleon orbitals can be obtained from the shape of the momentum distribution measured after nucleon removal from the nucleus of interest. This momentum distribution will be measured by operating the Super-FRS in a dispersion-matched mode. The reaction target being placed at the dispersive midplane and the dispersion of first section of the Super-FRS is matched by the second section. The position measurement at final achromatic focus will provide a measure of the momentum distribution from nucleon removal.

The schematic of an experimental setup for these measurements at the Super-FRS is shown in figure 10. The reaction target will be located at the dispersive mid-plane, MF2, for the σ_I , $P_\parallel$ and $\sigma_{-n/-p}$ measurements and at the final focus MF4, for the σ_{CC} measurements. The high resolution (~ 10^{-4} – $6\text{x}10^{-4}$) of the Super-FRS makes it the device of choice for these measurements. The identification of nuclei before and after the target require magnetic rigidity, time-of-flight and energy loss measurements that will be done using TPC tracking detectors, fast plastic scintillators and multi sampling ionization chambers (MUSIC). A gamma array, GADAST, with four clusters, each having sixteen CsI(Tl) crystals is available to tag gamma rays from nucleon knockout. Some LaBr crystals are currently available to augment further and could potentially be increased in the future. This gamma detection can provide knowledge on the bound state of the final nucleus after nucleon removal. In very neutron-rich regions we do not expect that the density of states to be too high and hence this moderate gamma detection capability should suffice to get the main discovery information on unexpected orbitals. High precision gamma spectroscopy of excited states is not the aim of this program. The Super FRS high-resolution spectrometer allows good momentum resolution and cane hence discriminate between the different orbitals.

This experimental program at the Super FRS has competitive and complementary advantages that stem from the combination of high-energy beams with a high-resolution spectrometer at FAIR. The beam energy of 800...1500 *A* MeV at the Super FRS is an important advantage since multiple charge states of heavy fragments produced in fission of the ^{238}U beam (figure 11) at lower energies causes challenges in accurate particle identification which is crucial to the radii measurements in particular. Furthermore, contaminant/beam ratio increases much making it often difficult to study extremely neutron-rich nuclei with low beam intensity. The large acceptance of Super FRS together with the forward focusing of the RI beam at high energies also gives a competitive advantage of higher transmission efficiency that is another key point for the cross section measurements.

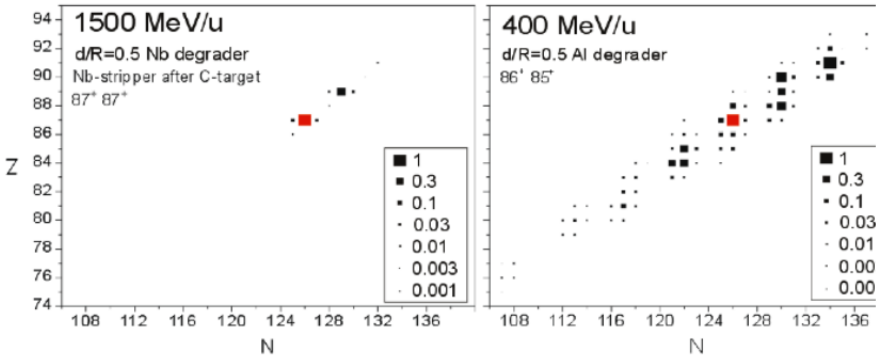

Fig. 11: Example showing the multiple charge states produced at different beam energies for example of ^{213}Fr produced from ^{238}U.

The much smaller energy-loss in target and beamline matter at high energies also contributes to attaining a better momentum resolution in addition to the advantage of high resolution of the Super FRS. For heavy nuclei, reactions at intermediate energies will lead to higher percentage of multiple charge states after the reaction target. This complicates the measurement of σ_I, σ_{CC} and nucleon removal reactions, where Super-FRS is advantageous with its high energy.

The time-of-flight resolution (σ) required for 3σ separation of Ni and Sn isotopes for a flight path of 60 m [PF4-MF2] is 133 ps and 66 ps respectively. The path from MF1-MF2 is half of this requiring factor 2 better resolution. A 3σ separation of charge requires a resolution of $\sigma_Z = 0.16$. Assuming a position resolution of 0.5 mm (σ_x) the expected momentum resolutions is $\sigma(P_{\|}^{cm})$ = 10 - 20 MeV/c with 1 – 4 g/cm^2 carbon reaction target respectively. The same for Sn isotopes shows expected resolution ~ 20 - 30 MeV/c. The test measurements with the GEM TPC have shown a resolution of 0.2 mm (σ_x). A rough estimate on expected resolution for gamma detection with Doppler correction, at beam energy of ~ 900*A* MeV is ~10-15% (FWHM) with 5% (FWHM) of intrinsic Eγ resolution as measured using the CsI(Tl) crystals.

Topic 8: Radioactive in-flight decays and continuum spectroscopy by EXPERT (EXotic Particle Emission and Radioactivity by Tracking)

Science case and motivation for EXPERT: The existence of nuclei is not restricted to the stable and β-decaying nuclei only. The limiting line of bound nuclei is called drip-line, and it is one of the goals of modern nuclear physics to explore the location of the drip-line. However the drip-line is not the end of the existence of nuclei, and nuclei beyond the proton and neutron drip-lines show interesting phenomena and they can have half-lives exceeding the characteristic time of nucleon orbital motion in nuclei (10^{-21} s). These nuclei are called resonances and their lifetimes are determined by the centrifugal and Coulomb barriers; their structure and properties are strongly affected by nucleon correlations. These nuclear resonances can be studied by exclusive reactions or invariant-mass methods (as is the goal of the R3B collaboration), which complement each other. In particular, they can be studied by their emission of proton(s) or neutron(s) (i.e., proton (*p*) or neutron (*n*) radioactivity, respectively). Because of their special properties and the fine balance of nuclear forces, these nuclei are subject of high interest for modern nuclear theory.

Beyond the proton drip-line, *p* radioactivity prevails and some nuclides with *2p*-decays have been observed. They allow studying *2p* correlations in nuclei. Four-proton decay is also expected in some cases of proton-rich nuclei. Neutron radioactivity has not been observed yet, mainly due to the fact that the drip line is reached only for light elements where only orbitals of low angular momentum are involved, and thus the centrifugal barrier is not high enough to retard the decay. Because of the pairing interactions of neutrons in nuclei, *2n* decays are predicted to have longer half-lives. If such long-lived systems exist which decay via neutron radioactivity, *2n* correlations in nuclei can be studied in a direct way.

Experimental Setups: Such decays and angular correlations can be studied ideally at high kinetic energy and directly at the Super-FRS, where highest transmission is obtained and where the most exotic species can be reached. The in-flight decay technique with relativistic exotic nuclei was pioneered at the FRS by Mukha *et al.* Also the Optical-TPC (OTPC) was used effectively in a recent experiment, where the beta-delayed *3p*-decay of the very exotic nucleus ^{31}Ar was studied by Pfützner *et al.* (figure 12). The Super-FRS will provide even more exotic nuclei and dripline nuclei for heavier elements.

For studies of *p*- and *n*- decays near and beyond the driplines, it is necessary to produce the tertiary nucleus of interest in a reaction from a nearby secondary beam (relatively large cross section, simple identification, high transmission) and provide low background conditions (for example, the *2p*-emitter ^{26}S can be produced by neutron removal reaction of ^{27}S, a possible *4n*-decay nucleus ^{28}O could be produced by *1p* removal from ^{29}F, etc.). Therefore, the Super-FRS facility is essential and most suitable for the study of tertiary nuclei. The detection schemes employed cover half-life ranges from ~1ps to 100 ns (in-flight decay technique) and ~100 ns to 1 s (implantation-decay technique). Based on angular correlations, these experiments will provide important information and be complementary to other NUSTAR activities.

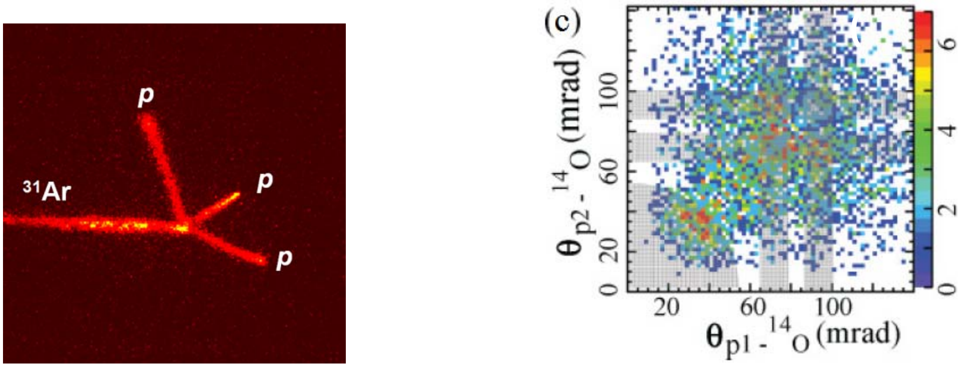

Fig. 12: Exotic radioactive decays: Left: 3-proton-emission following beta-decay in ^{31}Ar observed with the Optical-TPC in an FRS experiment (published in [Lis-15]). Right: The measured correlation plot of 2*p* decays of ^{16}Ne states populated in a neutron knockout from ^{17}Ne projectiles. Shaded areas of the circular sector and bands indicate the true 2*p* decay of the ground state and the sequential decays of excited states via the intermediate ^{15}F states.

Conceptual design of EXPERT: The exotic nuclei of interest will be produced by utilizing secondary reactions with radioactive ion beams of energies up to 1.5 *A* GeV impinging on a secondary target at the middle focal plane of the main separator of the Super-FRS. Thus the Super-FRS pre-separator and the first half of the main separator will be used as a radioactive-ion beam separator and as reaction spectrometer in its second half, which is set for identification and high-resolution momentum measurements of the secondary-reaction fragments. The ancillary detectors of the EXPERT setup will be located in the middle FMF2 and final FHF1, FRF1 focal planes of the main separator of the Super-FRS, see figure 13.

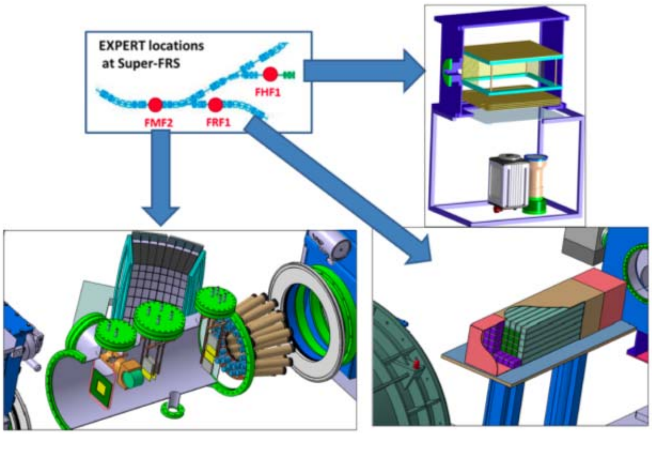

Fig. 13: Locations of the EXPERT detectors at the Super-FRS focal planes indicated by the red dots (in top left panel), and sketches of the respective detectors: the Si-trackers of charged particles and gamma-ray detector GADAST (bottom left), neutron detector NeuRad (bottom right), and implantation-decay chamber OTPC (top right). Details can be found in the TDR which is ready for submission.

Unbound nuclei beyond the drip lines either decay in flight or are radioactive by emitting protons or neutrons. Their decay products to be measured by a combination of 2-3 compact experimental installations in addition to the standard beam detectors of Super-FRS by applying the decay-in-flight and implantation-decay techniques. The EXPERT setup has a modular structure allowing adaptation to a number of experimental conditions and a multi-purpose operation mode needed in exploratory studies beyond the drip lines.

There are three main detector arrays for measurements of decays-in-flight of exotic nuclei: 1) Silicon (Si) fast-operating beam detectors which provide information on time-of-flight, position and energy loss of ions impinging the secondary target. 2) Micro-strip Si tracking detectors for high-precision measuring trajectories of all charged decay products as well as of decay energy and angular correlations of decay products. 3) The NeuRad (Neutron Radioactivity) fine-resolution detector of neutrons. Together with Si detectors, this small-size detector can provide precise information on angular correlations of decay neutrons with a charged fragment, which is used to derive the decay energy of exotic neutron radioactivity in the range of 0.1-100 keV. The EXPERT components augmenting the tracking subsystem are: i) The GADAST (Gamma-ray Detectors Around Secondary Target) array. It measures prompt gamma-rays and light particles, which allow disentangling the decay channels with gamma-ray emission); ii) The OTPC (Optical Time Projection Chamber) for radioactivity studies by the implantation-decay method. The EXPERT pilot experiment has been successfully performed during the FRS experiment "Two-proton decay of ^{30}Ar" in 2012 (see [Mukha-15] in Appendix I).

Topic 9: Low-q experiments with an active target

Proton scattering or light particles scattering with low-momentum transfer provides important information on the structure of nuclei as well as on the Equation of State (EOS) for asymmetric nuclear matter. For example the nucleon density distribution of a neutron-rich nucleus can be studied by elastic proton scattering. Combining the information of proton-distribution radii determined by other methods, one can systematically study the thicknesses of neutron skins. A systematic change of neutron skin thicknesses along an isotope chain is a sensitive tool to study the EOS of neutron-rich matter and in particular the saturation density.

Also the nuclear density near the maximum of $r^2\rho(r)$ is sensitive to the saturation density of nuclear matter. The N/Z ratio dependence of the saturation density of nuclear matter can therefore be studied from the systematic change of the nuclear density in a wide range of isotopes from the stability line to very neutron-rich nuclei. The cross section is most sensitive to the part of nuclei where $r^2\rho(r)$ has its maximum. Therefore the measurement can be made with weak-intensity radioactive beams when an active target is used. Inelastic scattering with ^{4}He target provides unique information on the incompressibility of the incident nucleus. The incompressibility is also an important property of nuclear matter.

In such a measurement, a low-energy recoil particle has to be detected in coincidence with the forward-emitted residual nucleus to identify the reaction channel. The clear identification of the forward-going residual nucleus is inevitable. The part of the Super-FRS after a secondary target provides high particle-identification power and thus it is most efficient to put an active target in the middle focus of the Super-FRS. It is considered to construct an active target, e.g. based on the design of the IKAR setup which was successfully used in the past for experiments on light halo nuclei, but with substantial improvements in performance. For illustration, some important data obtained at FRS are shown in figure 14 in which the obtained density distributions of ^{8}He and ^{11}Li are shown.

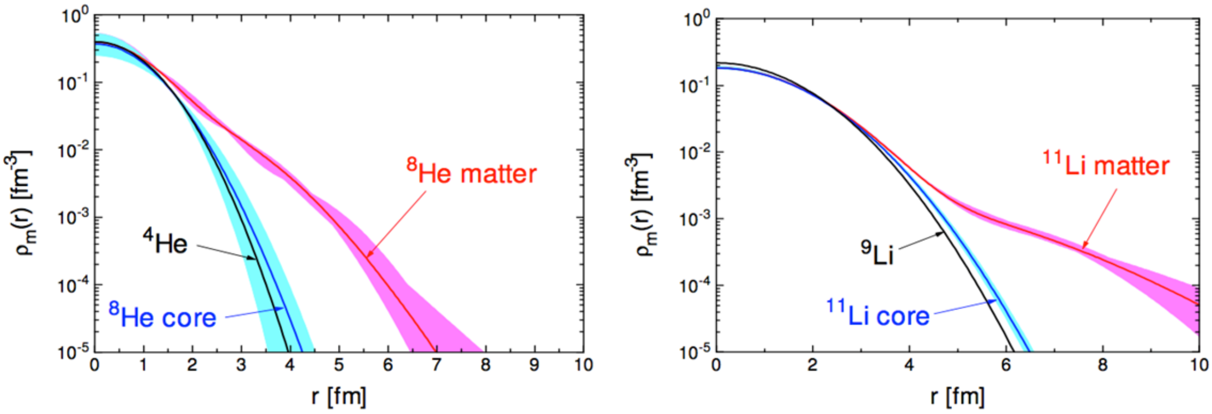

Fig. 14: Examples of the density distributions determined by IKAR experiments. A difference of neutron skin and neutron halo distributions is clearly seen by the proton elastic scattering experiment.

The application of an active target at the Super-FRS may profit from the fact that the scattered beam-like particle may be detected with a momentum resolution down to 10^{-4} in the Super-FRS section downstream of the active target. For the case of elastic proton scattering this will have the advantage that for the angular region where the light recoil particles are not stopped in the active target volume, but are only detected with much worse resolution via their energy loss signal, the high resolution detection of the scattered projectile will allow to cover this part of the angular distribution near the first diffraction minimum with higher resolution. As a pilot experiment one may consider to investigate the neutron skin in ^{132}Sn by elastic proton scattering at 700 A MeV, which is on the one hand a case of most physics interest, and, on the other hand, due to its high lying first excited state around 4 MeV, a case where the separation of the excited states should be most feasible. First simulations have shown that the energy resolution for the scattered projectile will not be affected by the energy straggling in the gas and the exit window of the active target for incident energies above about 600 A MeV. The active target will be operated with hydrogen or helium gas at 1...25 bar pressure and contain multiple anodes; a grid for shielding the ionization cloud of the penetrating beam will allow to detect the scattered protons even for penetrating high-Z projectiles. A schematic view is depicted in figure 15.

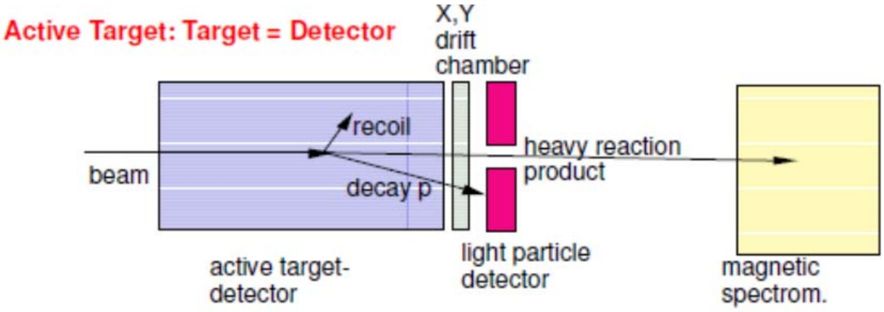

Fig. 15: The active target will be located at FMF2 of the Super-FRS. The recoil measurement will be combined with the high-resolution momentum analysis of the scattered fragment.

Topic 10: Nuclear reaction studies and synthesis of isotopes with low-energy RIBs

Radioactive ion beams at Coulomb barrier energies will open a wide field for the study of deep-inelastic reactions of heavy nuclei and their application for the synthesis of new exotic heavy and superheavy isotopes. Deep inelastic reactions are characterized by a large amount of energy dissipation, a large flow of nucleons between the interacting nuclei and a noticeable time delay in the reaction, in contrast to direct or quasi-elastic reactions. Typical examples are deep inelastic transfer, quasi-fission or complete fusion. Experiments in this field can be divided in two main groups: (i) Study of the process of deep inelastic reactions, starting with the mutual capture of projectile and target nucleus up to the formation of certain residual nuclei, and (ii) If favorable reactions were discovered in the reaction studies, applications of such reactions for the production of new exotic isotopes would be possible. However such a study is considered to be one of the long-term goals.

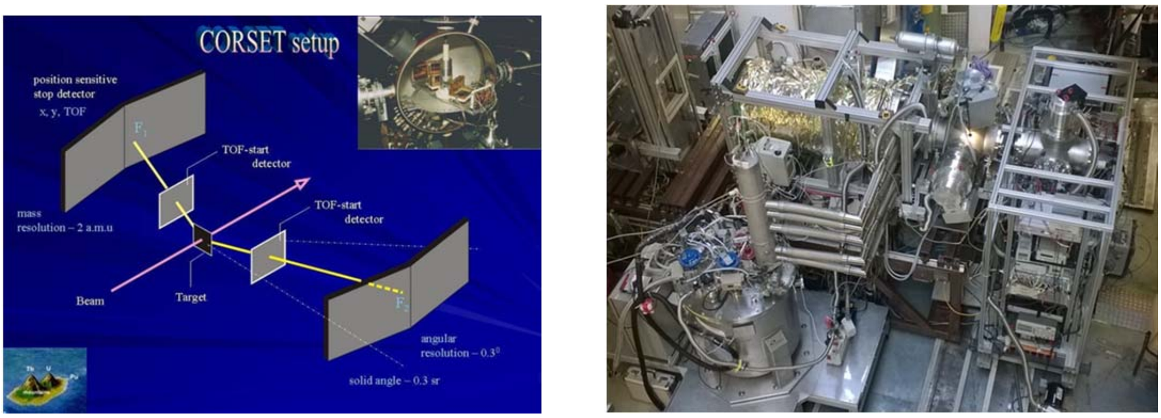

Fig. 16: Experimental setups that are presently considered for low-energy reaction studies using radioactive beams: CORSET (left) is an example of an existing detection system for the study of deep inelastic reactions with some important parameters (http://flerovlab.jinr.ru/flnr/corset.html). Next generation setups should cover a larger solid angle (ideally up to 4π coverage) to achieve highest sensitivity and efficient use of the weak radioactive beams. The FRS Ion Catcher (right) is shown at its present location at the final focal plane of the FRS.

At the Super-FRS, the possibility for a systematic study of the different steps of deep-inelastic reactions will open in a wide range of projectile isospin, binding energy, deformation and other degrees of freedom as well as the influence of shell effects. The information obtained from such a systematic study is decisive for the advancement of theoretical models which describe the process of deep inelastic reactions. One of the important goals is to find suitable reactions or find new reactions for the production of neutron-rich as well as neutron-deficient heavy nuclides and eventually superheavy elements which are not accessible in fragmentation reactions or in fusion reactions with stable beams.

The Super-FRS will offer the option of “cocktail” beams which will allow for the efficient use of the relatively small radioactive ion beam intensities for certain experiments. Beams from the Super-FRS could complement those possible with reaccelerated ones at ISOL facilities, where beam availability is limited by chemical properties. A presently unique feature of the LEB of Super-FRS is the energy buncher, which can be applied to significantly reduce the relatively large energy spread of the beams after deceleration to Coulomb barrier energies by degrader wedges. Although it extends out of the scope of the Super-FRS Experiment Collaboration, the possibility of applying a storage ring for deceleration, a unique option offered at FAIR, will be investigated.

The upgraded version of the TOF-E detection system CORSET from JINR Dubna and the Super-FRS Ion Catcher will be used for the study of deep inelastic transfer, quasi-fission and fusion-fission reaction for the synthesis of new isotopes. The Super-FRS Ion Catcher can also be used for in-cell decay studies (see also topic 1 above). CORSET and the Super-FRS Ion Catcher will be used at the LEB at the focus FLF6 with the buncher/spectrometer in mono-energetic mode. For high-intensity studies, not possible at the LEB, the Super-FRS Ion Catcher will be used at the High Energy Branch at the focus FHF1. In the latter case the main separator will be operated in mono-energetic mode. Existing versions of both detection systems, which will be upgraded for the Super-FRS, are shown in figure 16.

4. Conclusion

The present CDR describes the conceptual design of the planned experiments of the Super-FRS Experiment Collaboration at the Super-FRS facility. It is obvious that the physics topics and their implementation are complementary to those of the other sub-collaborations within NUSTAR. The principal feasibility of such experiments has been demonstrated in the last 25 years at the FRS of GSI. With dedicated new ancillary equipment, more detailed studies and some completely new experiments will become possible, offering great scientific potential, in addition to the previous science programs. Overall, the physics program is original and will have high scientific impact, even in several years from now, as it deals with experiments, which are intrinsically characteristic for the Super-FRS separator-spectrometer and which touch basic questions of modern nuclear, atomic and hadron physics. Moreover, it comprises experiments, which can be done during the commissioning and start-up phase of the FAIR facility, i.e., in principle already with the Super-FRS coupled to the SIS-18. In this context, it is interesting to note that several of the experiments described here do not require highest beam intensities. Although there is strong international progress in the field, the collaboration is guided by the “uniqueness criterion”, which guarantees that by the start of FAIR the physics program will still be competitive on the world scene. Furthermore, the target scientific programs will be timely even in the years around 2020 and beyond.

In conclusion, the activities of the Super-FRS Experiment Collaboration will neither delay the progress of the Super-FRS project nor deteriorate the performance of separation and identification of the whole in-flight separator, in particular, there will be no loss in beam quality (phase space or intensity) of the beams delivered to its end stations. Contrariwise, it might be worth mentioning that there is a significant added value when working at the interface between the experiments and the Super-FRS project. This is important, in particular, at the commissioning phase of the program. As the present detectors are often going beyond the standard identification and detection and aim at the highest possible momentum resolution, the whole NUSTAR collaboration will benefit, e.g., in terms of separation power, background suppression, etc. Needless to say that the “exclusive use” of the Super-FRS can not even be considered. Rather, harvesting the “early fruits” needs to be discussed and agreed within the NUSTAR collaboration with the goal to optimize the physics output under commissioning conditions while using equipment of potentially all NUSTAR sub-collaborations; the NUSTAR groups are used to mutual collaboration.

The ancillary systems (detectors, targets, degraders, etc.) needed to perform the separator-spectrometer experiments and their implementation have been described. Details of the various ancillary systems have been outlined and their external funding being cost neutral to FAIR Cost Book has been discussed. The ancillary detectors are relatively small, compact and moveable and can be fit to the modular focal-plane standard equipment of the Super-FRS. This includes transport ways, storage places etc. inside the Super-FRS tunnel, so that the presented experiments will not require changes of the civil construction.

The Super-FRS Experiment Collaboration will be grateful if the proposed concepts are accepted and an official acknowledgement of the Joint Scientific Council of the inclusion of this activity in the FAIR MSV experiment portfolio will be appreciated. Then the TDRs, which are in preparation or ready for submission, can be processed further.

Appendix I. Goals of the Super-FRS Experiment Collaboration

The experimental program of the Super-FRS Experiment Collaboration emerges from the experiments performed at the present FRS. It will exploit the Super-FRS as flexible, high-resolution ion-optical device. Similar categories of experiments were partly performed already at the present FRS since 1990. Highlights of experimental studies performed at the FRS with direct bearing only on future research program of Super-FRS Experiment Collaboration are illustrated in figure A1. More than 200 new rare isotopes including the doubly magic nuclei ^{100}Sn and ^{78}Ni have been identified and studied. FRS results have shown that fission of relativistic uranium ions provides a rich source for the most neutron-rich nuclides of medium mass. Other discoveries from such separator-spectrometer experiments are, for example: the two-proton radioactivity of ^{45}Fe nucleus, the first proton halo (^{8}B), the neutron skin in Na isotopes, a new magic number N=16, and the deeply-bound pionic states in heavy atoms.

These categories of experiments were also considered from the very beginning of the Super-FRS project. These separator-spectrometer experiments with the FRS are well established. They formed the backbone of the scientific program of the group who had proposed, built and operated the separator. The Super-FRS Experiment Collaboration takes advantages of the experiences with FRS to expand the scientific and technical knowledge for the next-generation experiments.

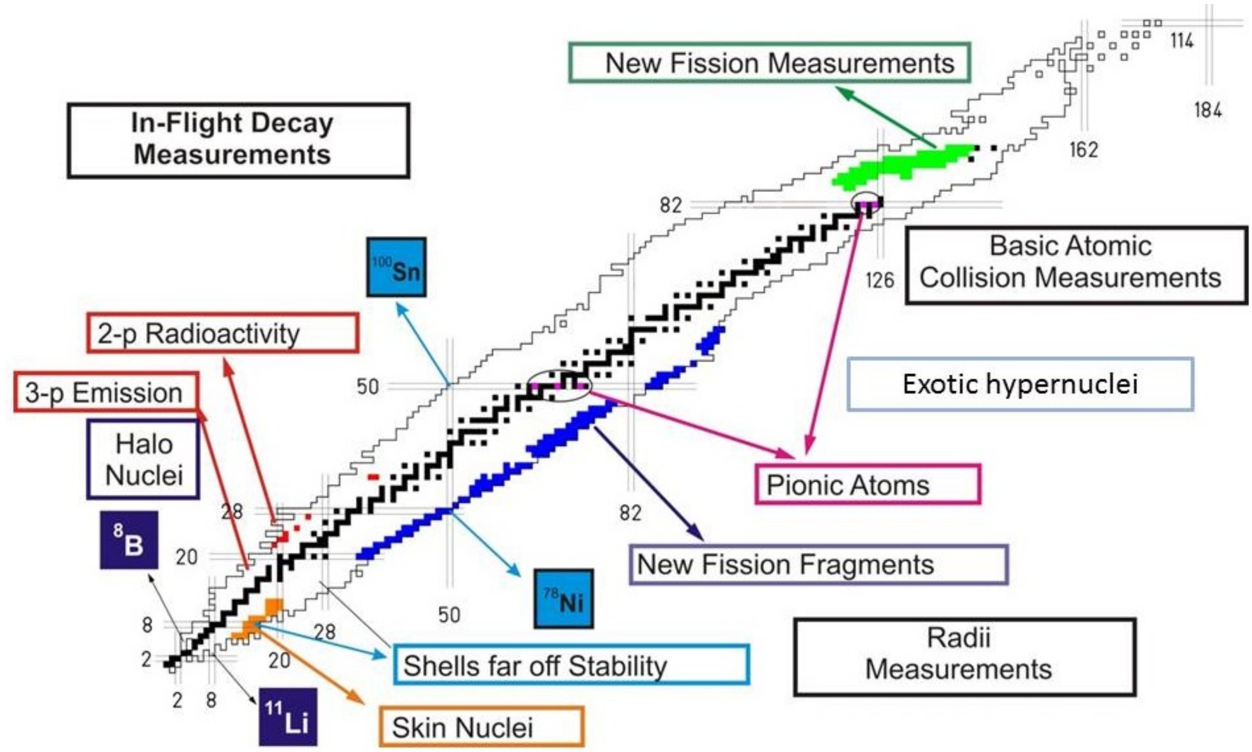

Fig. A1: Scientific highlights from separator-spectrometer experiments with the FRS. Several experimental discoveries made with the present FRS are illustrated on the schematic Chart of Nuclides. Also, new directions (such as hypernuclear studies) are shown.

Table A1: Experimental highlights from FRS experiments.

The research topics related to the future Super-FRS Experiment Collaboration scientific program: the experimental conditions and references are listed in the table below.

Research Topic	Experimental Conditions	Reference
New Isotopes	Spectrometer-Separator Setup Production Cross Section Projectile Fragments Projectile Fission, Fragmentation-Fission	Schmidt-93 Bernas-97 Pfützner-98 Kurzewicz-12
Doubly Magic Nucleus 100Sn	Identification and Decay Measurements	Schneider-94
Doubly Magic Nucleus 78Ni	Production Cross Section	Engelmann-95
New magic shell N=16	Radii Measurement and Momentum	Ozawa-00

Doubly Magic Nucleus 24O	Measurements Removal Cross Sections	Cortina-04 Kanungo-09 Kanungo-10 Rodrigues-10
New Fission Studies, Spallation	Z-Distribution of Fission Fragments from Exotic Nuclei	Schmidt-94 Ricciardi-03 Armbruster-04
Isomer studies, isomeric ratios	FRS Ion Catcher	Dickel-15
Radii-Measurements, Neutron Skin	Interaction Cross Sections	Suzuki-95
Hyperons in stable and exotic nuclei	Invariant mass spectroscopy, Pion spectrometer and decay residue measurements	Saito-16
Radii-Measurements	Elastic Proton Scattering FRS + IKAR	Kraus-94 Alkhazov-97
Proton Halo 8B	Momentum Measurements	Schwab-95 Smedberg-99 Iwasa-99 Cortina-02
Neutron Halo nuclei 11Li, 19C	Longitudinal momentum distribution Nucleon removal cross sections	Baumann-98
2-Proton Radioactivity 45Fe	Identification & Decay Measurements	Pfützner-02
2-Proton Radioactivity 19Mg	In-Flight Decay	Mukha-07, Mukha-15
3-Proton Emission 31Ar	Identification & Decay Measurements	Lis-15
Tensor force and short-range correlations	Momentum Spectroscopy after High momentum Nucleon Transfers	Ong-13 Tanihata-13
Deeply Bound Pionic States	Momentum Measurements	Yamazaki-98 Geissel-02a Geissel-02b Suzuki-04
Atomic Collision Studies Deviation from Bethe theory Enhanced Energy Straggling Charge-changing contributions	Momentum Measurements	Stöhlker-92 Scheidenberger-94 Dauvergne-99 Stöhlker-94 Kandler-95 Scheidenberger-96 Stöhlker-98 Weick-00

Alkhazov-97 G. D. Alkhazov et al., Phys. Rev. Lett. 78 (1997) 2313-2316: “Nuclear matter distributions in ^{6}He and ^{8}He from small angle *p*-He scattering in inverse kinematics at intermediate energy”

Armbruster-04 P. Armbruster et al., Phys. Rev. Lett. 93 (2004) 212701-4: “Measurement of a complete set of nuclides, cross sections, and kinetic energies in spallation of ^{238}U 1A GeV with protons”

Baumann-98 T. Baumann et al., Phys. Lett. B439 (1998) 256-261: “Longitudinal momentum distributions of ^{16,18}C fragments after one-neutron removal from ^{17,19}C”

Bernas-97 M. Bernas et al., Phys. Lett. B 415 (1997) 111-116: “Discovery and cross-section measurement of 58 new fission products in projectile-fission of 750 A MeV ^{238}U”

Cortina-02 D. Cortina-Gil et al., Phys. Lett. B 529 (2002) 36-41: “Experimental evidence for the ^{8}B ground state configuration”

Cortina-04 D. Cortina-Gil et al., Phys. Rev. Lett. 93 (2004) 062501-4: “Shell structure of the near-dripline nucleus ^{23}O”

Dauvergne-99 D. Dauvergne et al., Phys. Rev. A 59 (1999) 2813-2826: “Charge states and energy loss of 300 MeV/u U^{73+} ions channelled in a silicon crystal”

Dickel-15 T. Dickel et al., Phys. Lett. B744 (2015) 137–141: “First spatial separation of a heavy ion isomeric beam with a multiple-reflection time-of-flight mass spectrometer”

Engelmann-95 Ch. Engelmann et al., Z. Phys. A 352 (1995) 351: “Production and identification of heavy Ni isotopes: evidence for the doubly magic nucleus ^{78}Ni”

Geissel-02a H. Geissel et al., Phys. Lett. B 549 (2002) 64-71: “Experimental indication of a reduced chiral order parameter from the 1s π^{-} state in ^{205}Pb”

Geissel-02b H. Geissel et al., Phys. Rev. Lett. 88 (2002) 2301-2304: “Deeply bound 1s and 2p pionic states in ^{205}Pb and determination of the s-wave part of the pion-nucleus interaction”

Humbert-95 F. Humbert et al., Phys. Lett. B347 (1995) 198-204: “Longitudinal and transverse momentum distributions of ^{9}Li fragments from break-up of ^{11}Li”

Iwasa-99 N. Iwasa et al., Phys. Rev. Lett. 83 (1999) 2910-2913: “Measurement of the Coulomb dissociation of ^{8}B at 254 MeV nucleon and the ^{8}B solar neutrino flux”

Kandler-95 T. Kandler et al., Phys. Lett. A204 (1995) 274-280: “Transition selective investigation of the resonant transfer and excitation in $U^{90+} \rightarrow$ C collisions”

Kanungo-10 R. Kanungo et al., Phys. Lett. B 685 (2010) 253-257: “Structure of ^{33}Mg sheds new light on the N=20 island of inversion”

Kanungo-09 R. Kanungo et al., Phys. Rev. Lett. 102 (2009) 15201-4: “One-neutron removal measurement reveals ^{24}O as a new doubly magic nucleus”

Kraus-94 G. Kraus et al., Phys. Rev. Lett. 73 (1994) 1773-1776: “Proton inelastic scattering on ^{56}Ni in inverse kinematics”

Kurcewicz-12 J. Kurcewicz et al., Phys. Lett. B717 (2012) 371-375: “Discovery and cross-section measurement of neutron-rich isotopes in the element range from neodymium to platinum with the FRS”

Lis-15 A.A. Lis et al., Phys. Rev. C 91 (2015) 064309: “Beta-delayed three-proton decay of Ar-31”

Mukha-07 I. Mukha et al., Phys. Rev. Lett. 99 (2007) 182501-4: “Observation of two-proton radioactivity of ^{19}Mg by tracking the decay products”

Mukha-15 I. Mukha et al., Phys. Rev. Lett. 115 (2015) 202501: “Observation and spectroscopy of new proton-unbound isotopes ^{30}Ar and ^{29}Cl: an interplay of prompt two-proton and sequential decay”

Ong-13 H.J. Ong et al., Phys. Lett. B 725 (2013) 277: “Probing effect of tensor interactions in ^{16}O via (p,d) reaction”

Ozawa-00 A. Ozawa et al., Phys. Rev. Lett. 84 (2000) 5493-5496: “New magic number, $N = 16$, near the neutron drip line”

Pfützner-98 M. Pfützner et al., Physics Letters B 444 (1998) 32–37: “New isotopes and isomers produced by the fragmentation of ^{238}U at 1,000 MeV/nucleon”

Pfützner-02 M. Pfützner et al., Eur. Phys. J. A 14 (2002) 279-285: “First evidence for the two-proton decay of ^{45}Fe”

Ricciardi-03 M.V. Ricciardi et al., Phys. Rev. Lett. 90 (2003) 212302: “Experimental indications for the response of the spectators to the participant blast”

Rodrigues-10 C. Rodríguez-Tajes et al., Phys. Lett. B 687 (2010) 26-30: “One-neutron knockout from $^{24–28}$Ne isotopes”

Saito-16 T.R. Saito et al., Nucl. Phys. A954 (2016) 199-121: “Summary of the HypHI Phase 0 experiment and future plans with FRS at GSI (FAIR Phase 0)”

Scheidenberger-94 C. Scheidenberger et al., Phys. Rev. Lett. 73 (1994) 50-53: “Direct observation of systematic deviations from the Bethe stopping theory for relativistic heavy ions”

Scheidenberger-96 C. Scheidenberger et al., Phys. Rev. Lett. 77 (1996) 3987-3990: “Energy-loss straggling experiments with relativistic heavy ions in solids”

Schmidt-93 K.-H. Schmidt et al., Physics Letters B 300 (1993) 313-316: “Distribution of Ir and Pt isotopes produced as fragments of 1 A GeV ^{197}Au projectiles: a thermometer for peripheral nuclear collisions”

Schmidt-94 K.-H. Schmidt et al., Physics Letters B 325 (1994) 313-316: “Low-energy fission studies of neutron-deficient projectile fragments of ^{238}U”

Schneider-94 R. Schneider et al., Z. Phys. A348 (1994) 241-242: “Production and identification of ^{100}Sn.”

Schwab-95 W. Schwab et al., Z. Phys. A350, (1995) 283: “Observation of a proton halo in ^{8}B”

Smedberg-99 M.H. Smedberg et al., Phys. Lett B 452 (1999) 1-7: “New results on the halo structure of ^{8}B”

Stöhlker-92 Th. Stöhlker et al., Phys. Lett. A 168 (1992) 285-290: “Ground-state transitions in one- and two-electron Bi projectiles”

Stöhlker-94 Th. Stöhlker et al., Phys. Rev. Lett. 73 (1994) 3520-3523: “L-subshell resolved photon angular distribution of radiative electron capture into He-like uranium”

Stöhlker-98 T. Stöhlker et al., Phys. Lett. A 238 (1998) 43-48: “Interference between electric and magnetic amplitudes for K-shell excitation of high-z H-like projectiles”

Suzuki-95 T. Suzuki et al., Phys. Rev. Lett. 75 (1995) 3241-3244: “Neutron skin of Na isotopes studied via their interaction cross sections”

Suzuki-04 K. Suzuki et al., Phys. Rev. Lett. 92 (2004) 2302-2305: “Precision spectroscopy of pionic 1s states of Sn nuclei and evidence for partial restoration of chiral symmetry in the nuclear medium”

Tanihata-13 I. Tanihata, Physica Scripta T152 (2013) 014021: “Effect of tensor forces in nuclei”

Weick-00 H. Weick et al., Phys. Rev. Lett. 85 (2000) 2725-2728: “Drastic enhancement of energy-loss straggling of relativistic heavy ions due to charge-state fluctuations”

Yamazaki-98 T. Yamazaki et al., Phys. Lett. B 418 (1998) 246–251: “Effective pion mass in the nuclear medium deduced from deeply bound pionic states in ^{207}Pb”

Appendix II. Detectors and equipment

The experiments of the Super-FRS Experiment Collaboration range up to the highest available energies (restricted by SIS-100 energy and/or the Super-FRS magnetic rigidity of 20 Tm) and use beams of all elements ranging from protons up to uranium (and possibly higher atomic numbers, which can be produced in charge pick-up reactions). The experiments outlined above will use the Super-FRS up to its final foci as integral part of their measurements. The collaboration will use the standard detectors and standard equipment of the Super-FRS (2.4.6), which is used for beam diagnostics and for production, in-flight separation and identification of the exotic nuclear beams, as specified in the TDR-2007 and comprised in the MSV. These standard detectors (2.4.6.1) will cover the whole acceptance, a large dynamic range and they will operate at rates as high as possible, typically at 1-10 MHz. The separation and the identification are accomplished by a combined even-by-event analysis of magnetic rigidity[1] ($B\rho$), time-of-flight[2] (ToF) and energy deposition[3] (ΔE). All the parameters and features are in line with the specifications of the Super-FRS detectors, as outlined in the Super-FRS parameter list V3.07. However, as the collaboration aims at dedicated measurements beyond the standard separation and identification, planned measurements employ additional ancillary equipment, as listed in table A2. Among this ancillary equipment (detectors, targets, degraders, etc.) one may distinguish (a) pre-existing equipment and (b) new equipment.

(a) Pre-existing equipment: Among the ancillary detectors, some were or are already in use at the FRS and can be transferred to the Super-FRS. Possibly some upgrade activities can be considered, as well as the regular maintenance or improvement measures. These are the optical TPC (O-TPC, topic 8), the tracking detectors of the HypHi experiment, which will be used for the pion detection in the exotic hypernuclei experiments (topic 4) and the IKAR scattering chamber (topic 9). Other detectors are in routine operation and need to be adapted to the larger apertures of the Super-FRS beams. They are the alpha and isomer tagger (topic 1), the Super-FRS Ion Catcher[4] (topics 1, 2, and 10), the atomic collision targets including gas targets and a complete vacuum chamber/goniometer setup[5] (topic 2), the IKAR active target detector[6] (topic 9) and fiber trackers[7] (topic 5). Additional detectors accounted for in this category are NeuRad and GADAST[8] (topic 8), both currently under development, and CORSET (topic 10).

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[1] Via GEM-Time Projection Chambers (GEM-TPC, Finnish in-kind contribution to FAIR), for position and angle measurements with a position resolution of about 1 mm, at maximum rate capabilities up to 10 MHz at the central focal plane of the main separator.

[2] Via plastic scintillation detectors or alternatively silicon (Russian EoI), diamond and Cerenkov detectors (under development), with a ToF (FWHM) resolution of less than 50 ps for mass identification of the heaviest fragments.

[3] Via Multi-Sampling-Ionization Chambers (MUSIC), with few percent energy resolution for unambiguous identification in charge of the heaviest fragments.

[4] A prototype has been built and tested by the KVI-GSI-JLU-JYFL collaboration; a TDR for the LEB device is in preparation; the stopping cell has PSP-codes in the Accelerator Costbook and in the Experiment Costbook, 1 MEuro has been requested in 2011 by the GSI PMA (“Projektmittelantrag”); JLU receives BMBF funds via “Verbundforschung” for development and construction investment.

[5] For FRS experiments various multi-fold target ladders, including the equipment for a variable-thickness gaseous target, vibration-damped support and vacuum chamber for channeling experiments, a large variety of precision collimators and high-quality targets covering a large range of elements and thicknesses, are available.

[6] The Active Target Collaboration, which emerges from various activities in European funding programs; it makes a dedicated effort to develop and construct active target detectors for various facilities in Europe, such as HIE-ISOLDE, SPIRAL-II, FAIR. The IKAR Collaboration, which has performed experiments at the FRS since the early 1990s, will support the efforts for building an active target for Super-FRS and R3B.

[7] The fiber scintillator detectors for tracking (“fiber trackers”) have been developed by a Japanese-Chinese consortium, and have been tested at the FRS; they operate at rates up to the MHz regime and provide position resolution of few millimeters; units are ready for use.

[8] The NeuRad and GADAST prototypes have been funded from the GSI budgets and BMBF GSI-JINR (Dubna) grants; scintillator fibers and CsI crystals have been purchased and detector modules are presently being assembled; a FAIR-Russia research group has been approved in 2013-2016.

[8] CORSET will be upgraded by JINR-Dubna (Russia) as part of the HIE-ISOLDE experiment at CERN.

(b) New equipment:

New equipment is needed for the experiments, which benefit from the pion detection, i.e. exotic atoms, hypernuclei, and the nucleon resonance studies (topics 3, 4, and 6). To some extent also cryogenic targets can be considered in this category (although they have been used at the FRS in several experiments, see below), which will be used for, e.g., the tensor-force studies (topic 5).

For the pion detection, two directions are presently pursued: one is additional dipole magnets, and the other is a solenoid-type detector. Suitable dipole magnets have been identified in Japan, which could become available for the present purposes (for details see topic 4). Ion-optical calculations have been performed and solutions have been obtained to integrate these additional magnets in the FRS and Super-FRS while maintaining transmission, resolving power, etc. For the execution of these experiments at Super-FRS, a WASA-type 4π-detector will be most suitable and highly efficient. The collaboration is seriously looking into the possibility of using the WASA detector itself, which is presently installed at COSY (Jülich). This detector system has proven its effectiveness for the COSY scientific program. Discussions with the WASA Collaboration are now ongoing to agree on the conditions and terms for moving WASA to GSI/FAIR to pursue the foreseen program.

Cryogenic targets (like liquid or solid hydrogen targets) have been used at the FRS for many years, the infrastructure (lines, compressors, safety installations, etc.) are available. Nevertheless, to adapt to the experimental requirements and different conditions at the Super-FRS (e.g., larger apertures), dedicated new targets need to be developed and implemented.

The Super-FRS Experiment Collaboration will coordinate these developments, also with other sub-collaborations within NUSTAR; it will avoid duplication of equipment and exploit synergies wherever possible. Finally, the collaboration injects new expertise and partly new concepts for high-rate/high-resolution detectors, which could be beneficial for the Super-FRS operation and thus for the whole NUSTAR Collaboration.

Concerning the funding, the collaboration is looking for solutions, in particular, it makes efforts to raise support, involve new funding sources, and attract additional partners. Already now, many members of the present collaboration invest large resources (manpower, time, money) to realize the ancillary equipment. There are many new partners among the contributing countries and institutions, as can be seen from Appendix IV.

	Pilot experiment with FRS	**Experiment with Super-FRS**
Topic 1 (isotopes)	alpha- and isomer-tagger, FRS Ion Catcher	alpha- and isomer-tagger to be adapted to Super-FRS, Super-FRS Ion Catcher
Topic 2 (atomic collision)	precision targets, gas targets, FRS Ion Catcher	dto., Super-FRS Ion Catcher
Topic 3 (exotic atoms)	inclusive measurements	exclusive measurements with detector surrounding the target
Topic 4 (exotic hypernuclei)	pion detectors, HypHI tracking detectors, dipole magnets	pion detectors adapted to Super-FRS, HypHI tracking detectors and dipole magnets adapted to Super-FRS
Topic 5 (tensor force)	fiber trackers	fiber trackers to be adapted to Super-FRS
Topic 6 (Delta resonances)	pion detector	pion detector adapted to Super-FRS
Topic 7 (radii and momentum distribution)	GADAST prototypes	full-size GADAST array
Topic 8 (exotic decays)	O-TPC, NeuRad and GADAST prototypes	O-TPC, full-size NeuRad and GADAST
Topic 9 (low-q)	IKAR	active target
Topic 10 (low-energy reaction studies)	CORSET, FRS Ion Catcher	Super-FRS Ion Catcher, CORSET adapted to Super-FRS

Table A2. Ancillary equipment for pilot experiments at the FRS and Super-FRS experiments. A stepwise approach is considered, where prototypes can be tested at the FRS, experience can be gained, and first scientific output can be realized, while the full-scale detectors will be used for experiments at the Super-FRS.

The implementation of the ancillary equipment is planned to be pursued along the following lines. The collaboration has identified the following work packages and plans to produce the following TDRs:

Work package number in NUSTAR	Work package name	Will be treated in planned TDR ... (working title)	Expected submission date	Estimated investment costs (in k€)
1.2.10.1	Infrastructure, DAQ, ancillary systems	Infrastructure	2017	100...500
1.2.10.2	Cylindrical Detector System (CDS)	Pions	2018	600...1,000
1.2.10.3	Pion detection system	Pions	2017	
1.2.10.4	Liquid hydrogen target	Tensor	2017	500
1.2.10.5	Tensor force detection system and chamber	Tensor	2017	
1.2.10.6	Ice target	Radii	t.b.d.	200
1.2.10.7	EXPERT	EXPERT	Ready for submission	2,000

Table A3. Work packages for ancillary equipment and related TDRs. Work packages 1.2.10.4 and 1.2.10.5 will be combined in submitting one TDR since they address the same physics program. Work packages 1.2.10.2 and 1.2.10.3 will be combined if it is decided to bring the WASA detector from COSY, Jülich, to (Super-)FRS at GSI/FAIR.

As can be seen from table A3, the costs of some ancillary items have not been reliably estimated at this point, as can be seen from the large uncertainty in estimated costs, e.g. for work package 1.2.10.1. However, it is also seen that the overall costs are in the single-digit M€ range. In any case, it is clear to the present collaboration that applications for money will be submitted to national funding agencies of the involved international groups within the Super-FRS Experiment Collaboration and thus the TDRs will be cost neutral for the FAIR Experiment Cost Books.

Appendix III: Organization and scope of the Super-FRS Experiment Collaboration

This section reflects the present organization and scope of the Super-FRS Experiment Collaboration, as far as is agreed within the collaboration.

Relation to NUSTAR

Within NUSTAR, the Super-FRS Experiment Collaboration is one among the other sub-collaborations; its organization and role will be similar to all other NUSTAR experiments. The Super-FRS Experiment Collaboration is integrated since the beginning of NUSTAR existence, in a similar way as the other NUSTAR sub-collaborations. The relation to the NUSTAR bodies and the communication lines are similar, too. Details will be formulated in the corresponding MoUs, which are in preparation and similar for all NUSTAR sub-collaborations. The Super-FRS Experiment Collaboration will use the Super-FRS itself for its physics program. Furthermore, it will support the realization of the Super-FRS facility.

Scope, tasks and role

The Super-FRS Experiment Collaboration main activity and mission is to pursue and execute the scientific program, which is outlined in its scientific case document (GSI-Report 2014-4). To achieve this goal, two types of technical components are needed, the Super-FRS itself and the ancillary components. The realization of the Super-FRS project[9] is the responsibility of the Super-FRS department in the GSI project division. The machine project leader supervises the realization of all cost book items 2.4.X (accelerator costbook) which are done within the FAIR project organization at GSI together with the in-kind partners. The Super-FRS Experiment Collaboration will provide additional support, for instance by contributing to R&D work, simulations or support of in-kind partners for the Super-FRS components. The development, design and realization of the additional experimental equipment for the outlined program (experiment Cost Book items 1.2.10.X) are the responsibility of the collaboration. During the R&D effort and the construction phase of the Super-FRS the FRS will continue to be used for both, Super-FRS development tests and pilot experiments of the Super-FRS Experiment Collaboration. The Super-FRS Experiment Collaboration will continue, while pursuing its physics program with the FRS, to secure support and beam time for experiments and tests to be carried out at the FRS in order to assure developments for the Super-FRS.

Organization and governance of the Super-FRS Experiment Collaboration

The internal organization of the Super-FRS Experiment Collaboration has been set up in line with similar collaborative efforts. An overview of the bodies of the Super-FRS Experiment Collaboration is shown in figure A2. The main bodies of the collaboration are described briefly in the following:

Collaboration Board: The Super-FRS Collaboration Board defines the policy of the collaboration and monitors the physics projects and the efforts towards the construction of the ancillary equipment. The members of the Collaboration Board are representatives from the contributing institutions (later: signatories to the MoU). The Collaboration Board members elect a Chair and a Vice-Chair for a period of three years. The Collaboration Board meets at least once per year.

Management Board: The Super-FRS Management Board acts as executive committee of the Collaboration and is responsible for the management of the physics program and the support towards the construction and operation of the Super-FRS. The Super-FRS Management Board is composed of the Spokesperson and the Deputy Spokesperson, the Technical Director and two Deputy Technical Director (all have been elected by the Collaboration Board) the Chair of the Collaboration Board, as well as several scientific and technical experts from the member institutions. Representatives of major work packages of the Super-FRS project organization (presently these are: buildings, target, separator, detectors) are “ex-officio” members of the Management Board. The Management Board prepares the topics to be decided by the Collaboration Board, it prepares the collaboration meetings, policies on general publications, etc.

Executive Board: The Executive Board, comprised of the Spokesperson, Deputy Spokesperson, Technical Director and Deputies of Technical Director, is for rapid interaction within the collaboration, with the Collaboration Board and the Management Board and is the interface with existing committees at NUSTAR, FAIR, etc.

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[9] The Super-FRS project is specified in the TDR (submitted and approved in year 2008) and the project plan.

Members, institutes, resources

The participating persons and institutes of the Super-FRS Experiment Collaboration are listed in Annex IV. The group of institutes and members is open to be extended in the future. Several of the participating institutes already contribute in-kind to the Super-FRS project.

Some of the activities described above will require resources that are presently not listed in the experiment cost book. These resources are specified in detail in the context of TDR's, which are in preparation or which have already been completed and submitted (EXPERT TDR). The Super-FRS Experiment Collaboration is aware of the present funding scheme of FAIR experiments, and thus it will make every effort and do its utmost to raise additional funds, and to provide additional resources with respect to R&D, simulations and other contributions. Actually, already now, and partly since many years, the members of the Super-FRS Experiment Collaboration bring in not only their expertise, but also financial contributions of their groups/institutes, capacities of electronics/mechanical workshops of their home institutes, installations for producing/testing the equipment, etc. Their expertise, efforts and additional resources will be beneficial not only for the ancillary components, but also for the Super-FRS standard equipment and finally for the overall performance of the whole NUSTAR facility at FAIR. It should be stressed here that the TDRs of the Super-FRS Experiment Collaboration will be cost neutral for the FAIR Experiment Cost Book.

MoUs

The first Super-FRS MoU was completed in 2007 within NUSTAR (at that time there was no distinction between the Super-FRS Project and the Collaboration). Presently, a MoU for the Super-FRS Experiment Collaboration is in preparation in line with other NUSTAR MoUs.

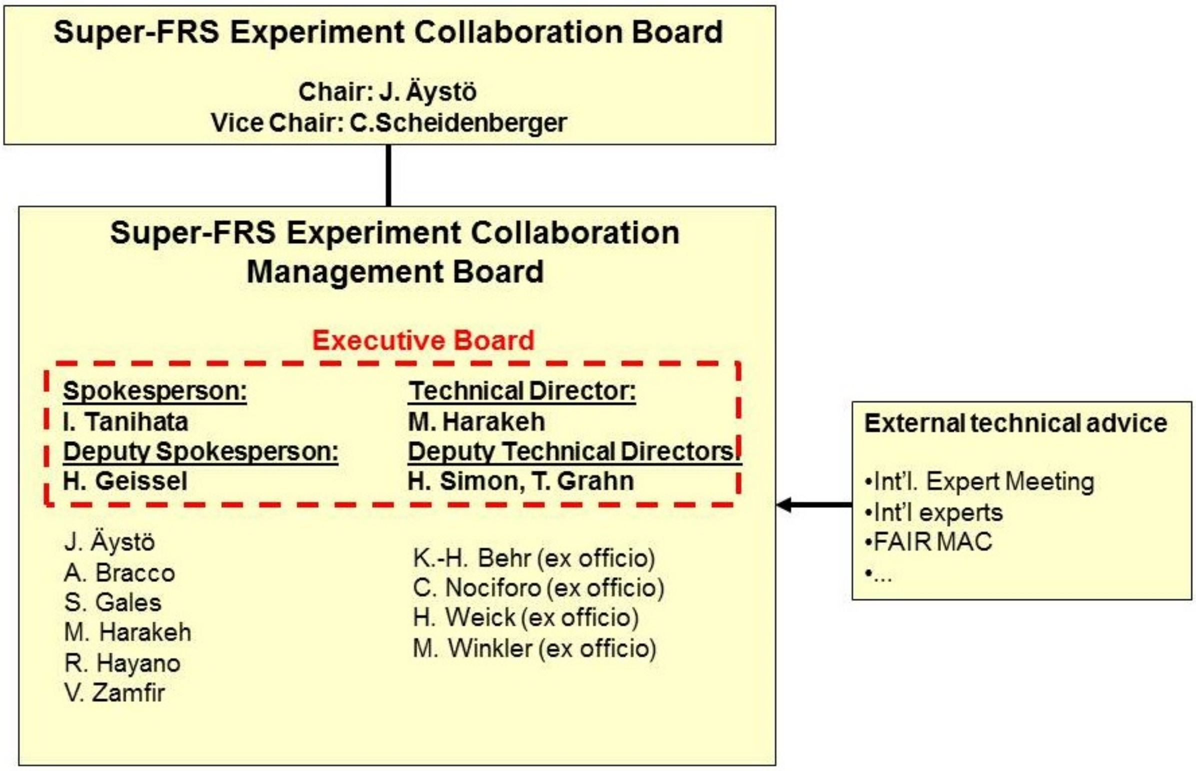

Fig.: A2: Bodies of the Super-FRS Experiment Collaboration; their functions and interaction are described in the text.

Appendix IV: Members of the Super-FRS Experiment Collaboration

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