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Super-FRS Collaboration

Scientific Program of the Super-FRS Collaboration: Report of the collaboration to the FAIR management

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GSI Helmholtzzentrum für Schwerionenforschung GmbH
Planckstraße 1 · D-64291 Darmstadt · Germany
Postfach 11 05 52 · D-64220 Darmstadt · Germany

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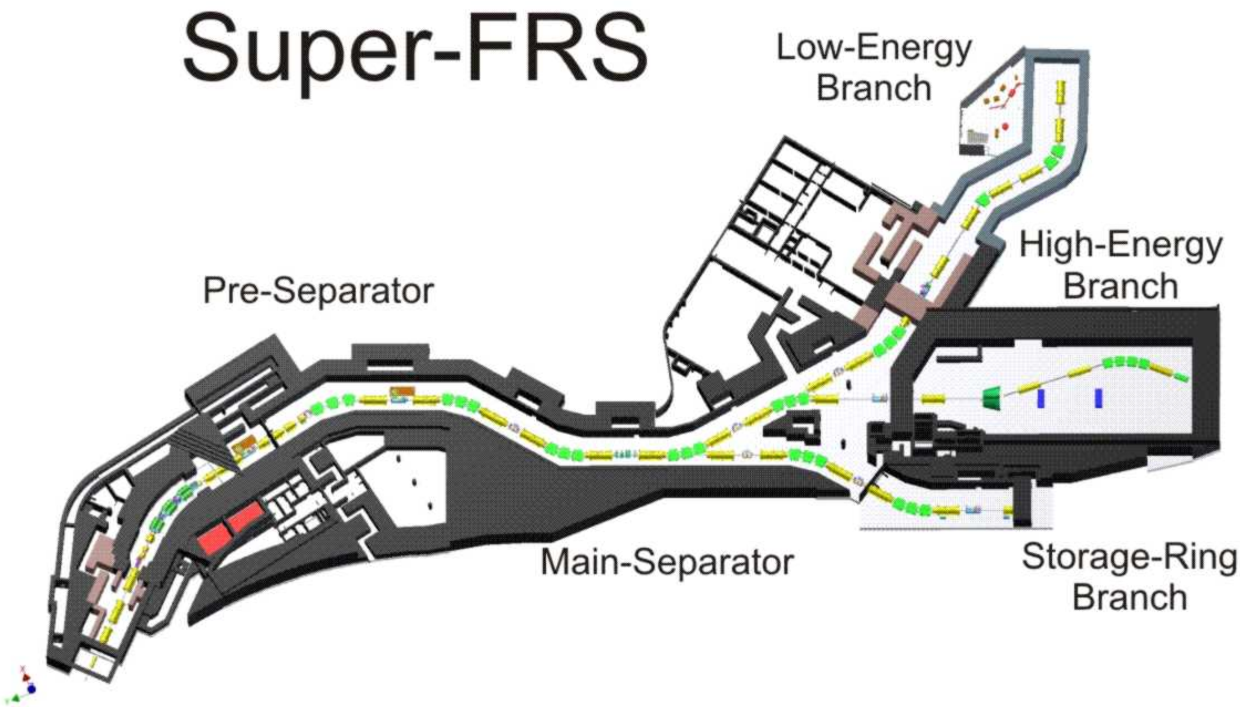

Darmstadt, May 26th, 2014

Abstract:

A series of experiments, which use the versatile high-resolution separator-spectrometer performance of the Super-FRS have been proposed. A large variety of modern nuclear physics experiments with new scientific possibilities and outstanding scientific potential are presented. In addition to the uniqueness of FAIR, the science program takes advantages of the unique features of the Super-FRS and in particular the high momentum resolution capabilities of the multiple-stage separator-spectrometer including the energy-buncher system of the Low-Energy Branch. The experimental program utilizes flexible ion-optical operating modes and standard focal-plane equipment (detectors, target and degrader systems) together with a few dedicated ancillary detectors.

The present document is the result of an effort to re-define a high-level experimental program. The pilot experiments with the Super-FRS testing the performance of the production and in-flight separation of exotic nuclei will be of general benefit for the whole NUSTAR collaboration. The present experimental program is complementary to other NUSTAR sub-collaborations and will be outstanding on the worldwide scene, in particular with respect to other second-generation radioactive beam facilities. R&D works and some pilot experiments can already be carried out at the existing FRS of GSI (see Appendix I). In this sense, the present science case is a continuation and extension of the spectrometer experiments performed successfully at the FRS in the past. The science program of this collaboration with the Super-FRS can start at the commissioning phase and will continue with the established full performance. Detector developments and organization of the Super-FRS Collaboration are described in Appendices II and III, respectively; the collaboration partners and institutes are listed in Appendix IV.

The Super-FRS Collaboration has been formally established based on the scientific proposal shown here. It is open to new ideas and new active collaborators.

Spokesperson: Isao Tanihata, Beijing and Osaka (tanihata@rcnp.osaka-u.ac.jp)

Deputy Spokesperson: Hans Geissel, Darmstadt (h.geissel@gsi.de)

Technical Director: Sydney Galès, Paris (gales@in2p3.fr)

Deputy Technical Director: Haik Simon, Darmstadt (h.simon@gsi.de)

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Ryu Hayano, Tokyo (hayano@phys.s.u-tokyo.ac.jp)

Chiara Nociforo, Darmstadt (c.nociforo@gsi.de)

Helmut Weick, Darmstadt (h.weick@gsi.de)

Martin Winkler, Darmstadt (m.winkler@gsi.de)

Victor Zamfir, Bucharest (zamfir@tandem.nipne.ro)

1. Preamble

The Super-FRS Collaboration is one of the science pillars of NUSTAR. The presently defined Scientific Program of the Super-FRS Collaboration is described in this document. Super-FRS is the world-unique facility as compared to any yet existing or planned next-generation facility. Its unique properties are:

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.
2. It is a unique high-energy, high-resolution spectrometer with a large acceptance and with flexible ion-optical settings, in particular with dispersion-matching capabilities.
3. It provides high primary-beam suppression power and high separation power of nuclides up to Z=92, and also provides fully stripped ions of all elements.
4. It provides versatile spectrometer modes by different combinations of separator sections.

The scientific program presented here is largely unique or complementary within the NUSTAR collaboration. It is unique in the world when compared with the goals of other next-generation exotic nuclear beam facilities. It is in line with the scientific goals of FAIR and with the proposed scope of the Modularized Start Version. The collaboration is open to, and exploits synergies with the scientific and technical programs of the other FAIR collaborations, in particular with APPA, CBM and PANDA. It is not intended to duplicate equipment within the NUSTAR collaboration.

2. Identity of the Super-FRS Collaboration

The Super-FRS Collaboration is guided by its physics goals: Research with exotic nuclei using the high-resolution spectrometer performance of the FRS and later the Super-FRS. The FRS serves as a platform for R&D and for pilot experiments before the start of FAIR. Later the collaboration will use the Super-FRS mostly with the standard instrumentation. The Super-FRS provides high quality radioactive ion beams for the whole NUSTAR collaboration, but in addition the present collaboration aims to use only the Super-FRS, and for the first time in different operation modes, namely for instance high-resolution spectrometer and dispersion-matched modes for studies with exotic nuclei.

Following this approach, the collaboration has identified a number of experiments, which address excellent science. 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, which also means that all NUSTAR colleagues are invited to contribute to the present program and its practical preparation. From the organizational point of view, the role of the Super-FRS Collaboration is similar to the other sub collaborations of NUSTAR. The organization and governance of the Super-FRS 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. The separator will provide beams of exotic nuclei ranging from hydrogen up to uranium over a large energy range equivalent to a maximum magnetic rigidity of up to 20 Tm. 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 planned within the Modularized Start Version of FAIR which 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 mrad and a longitudinal momentum acceptance of $\Delta p/p$=±2.5%. Properties of the Super-FRS are summarized in Fig. 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 detector system, placed at the different focal planes of the Super-FRS, can also be used advantageously for high-resolution momentum measurements after e.g. secondary reactions.

These features are the very characters that make the Super-FRS unique also for stand alone experiments. In addition, 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.

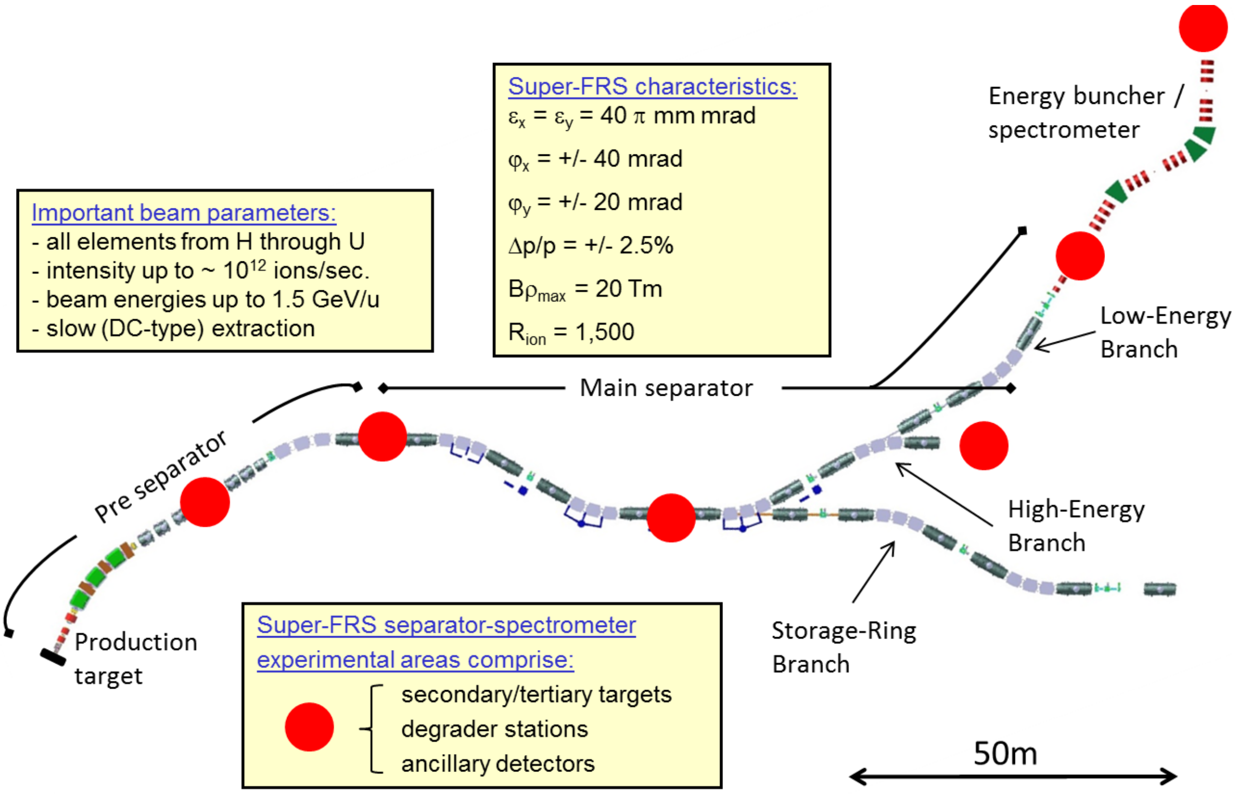

Fig. 1: Characteristics of the Super-FRS with its three branches and the LEB spectrometer-energy-buncher system. The experimental areas used by the present collaboration are indicated.

3. Experiments at Super-FRS

In this section the proposed physics program is outlined.

3.1 Physics goals

The Super-FRS Collaboration is one of the NUSTAR 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. However these experiments use the unique characteristics of Super-FRS, as is described below.

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 radii, and the atomic interaction of highly-charged atoms of heavy elements. Although these studies were discussed in a series of Super-FRS Collaboration meetings, 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 ion-optical performance is practically an integral part of the measurement. 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 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 TDR, will be used; only some experiments will need new, additional dedicated detector setups.

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 ground-state properties

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.

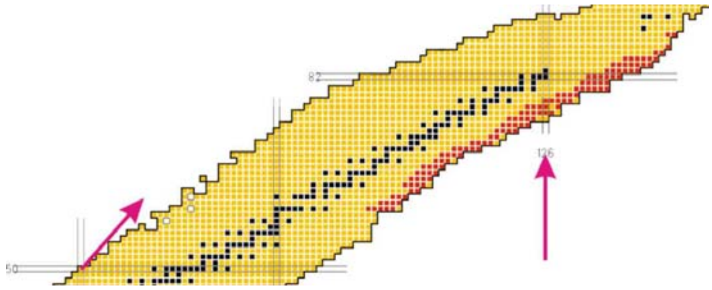

Fig. 2: Region of recently discovered neutron-rich isotopes with the FRS illustrated in the chart of nuclides (the new nuclides are marked in red color). Arrows indicate future directions of the proposed isotope search experiments.

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. First of all, 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 Fig. 2.

Topic 2: Atomic collisions

Accurate knowledge of the atomic interaction or energy loss of heavy ions penetrating through matter is essential for the successful operation of the in-flight separator Super-FRS. An uncertainty of one percent in the momentum prediction would already cause difficulties for the identification of rare isotopes at the outskirt of the chart of nuclides where no guidance of reference isotopes is comprised in the spectrum. The operating domain with the Super-FRS extends more than 500*A* MeV higher than the present FRS. In this new energy range no data for stopping powers, energy and angular straggling and charge-state distributions of heavy ions exist. An additional challenge comes from the predicted large mean free path lengths for charge-changing collisions. This will cause that the resulting contribution to the energy-loss straggling will become larger than the collisional part. The theoretical uncertainties are presently too large. Therefore, basic atomic collision processes have to be measured in an early stage of the Super-FRS operation.

The complete slowing down in a gas-filled stopping cell (for instance at the LEB of the Super-FRS) is another challenging task because of the large momentum spread of the fragments emerging from the production target. 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 experiments with such a gas cell the atomic interaction of heavy ions has to be known with high accuracy over the full energy range down to thermalization. Especially the different contributions to the range straggling have to be correctly predicted to perform efficient experiments with very exotic nuclei stopped in such a gas cell.

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). 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. 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.

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). 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 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. The η′ meson has a peculiarly large mass compared with other mesons in the pseudo-scalar nonet. This large mass can be theoretically understood in terms of the chiral symmetry breaking and the $U_A(1)$ quantum anomaly of non-perturbative gluon dynamics which induces the non-trivial vacuum structure of QCD. 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.

Topic 4: Exotic hypernuclei and their properties

Lambda (Λ) particles can be produced by peripheral collisions at incident energies around 1…2 *A* GeV. These Λ-particles may coalesce with the projectile fragments to form Λ-hypernuclei. The invariant mass of the final state, for example a π^- and a nuclear fragment after weak decay of hypernuclei, gives an effective signature for identifying a hypernucleus.

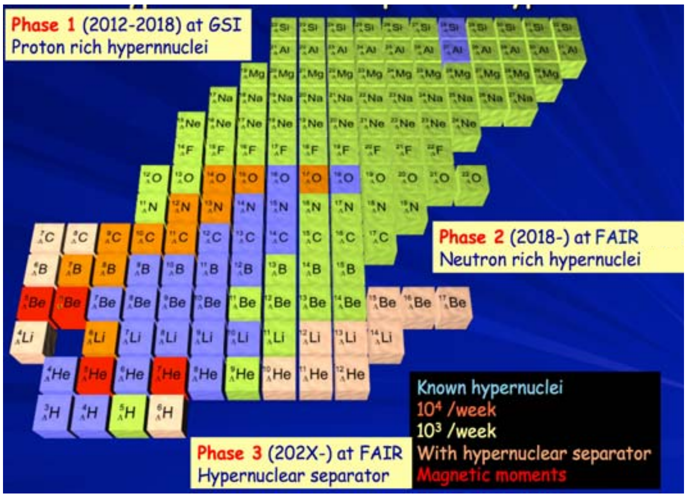

Fig. 3: Hypernuclear landscape reachable with the fragmentation-coalescence method. Purple colored are known hypernuclei. Hypernuclei whose magnetic moments can be measured are shown by red color.

One of the unique features of hypernuclear spectroscopy with projectile fragmentation is that, due to a large Lorentz factor of the produced hypernuclei, the decay can be observed in flight behind the production target. The half-life of an observed hypernuclei can be determined from the distribution of the flight length before it decays. Heavy-ion collisions also provide a possibility for forming multi-Λ hypernuclei. As a further development, the Super-FRS with addition of a pion detector just downstream of the target at the central focal plane of the main separator, would provide efficient and high-mass resolution measurements.

Such a method of production of hypernuclei has been already demonstrated at GSI facility by the HypHI collaboration. They performed the first experiment with ^{6}Li projectiles at 2 *A* GeV on a carbon target. Signals indicating the production of light hypernuclei $^3_\Lambda$H and $^4_\Lambda$H were observed. The half lives were also extracted. The hypernuclei which could be produced at FAIR are shown in Fig. 3. A drastic expansion of the hypernuclear chart is expected.

Topic 5: Importance of tensor forces in nuclear structure

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 force has not been explicitly handled 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 of 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 the observation of correlated nucleons in nuclei are essential to clarify the importance of the tensor force. Zero-degree scattering is best way to get rid of possible difficulties from reaction mechanisms. The Super-FRS is the only facility in the world that provides high-energy incident beams with a high-resolution 0-degree spectrometer. Nucleon-transfer reactions such as (p,d), (d,t), and (d,^{3}He) are relevant reactions to be measured for this purpose.

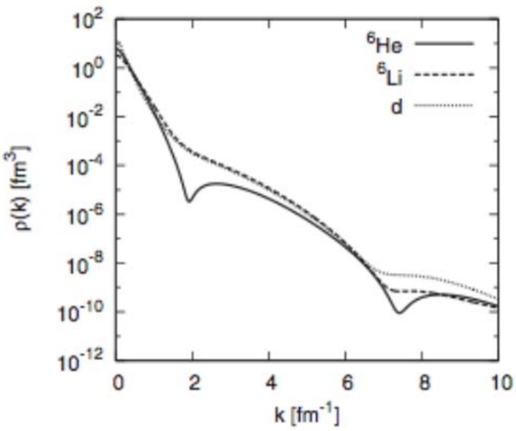

Fig. 4: High momentum components in nuclei predicted by the cluster model calculation of ^{6}He and ^{6}Li. (W. Horiuchi and Y. Suzuki., Phys. Rev. C 76 (2007) 024311). Valence nucleons in ^{6}Li are a pn pair that receive strong contributions from tensor forces. On the other hand, valence nucleons in ^{6}He are an nn pair that has no effect of tensor forces. The momentum distributions of such nucleons show a clear difference around 2 fm^{-1}. The observation of this difference isolates the effects of tensor forces in nuclei.

A high-momentum nucleon is strongly correlated with a non-identical nucleon pairs by the tensor forces.(see Fig. 4) Therefore the correlated nucleon may be emitted also when the 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). A comparison of correlations between pn pairs and pp(or nn) pairs provides a good means to isolate the effect of tensor forces.

The transfer-reaction experiments definitely take advantage of the Super-FRS, however quasi-free scatterings, such as (p,pd) and (p,nd) experiments are subject of a future discussion as to whether R3B in NUSTAR has advantages in performing such experiments or not.

Topic 6: Delta resonances probing nuclear structure

In high-energy heavy-ion collisions, in particular in charge-exchange reactions, there is clear evidence for Δ-resonance in nuclei. Also the three-body force in nuclear systems could originate from Δ-resonances. The Δ-resonance is a ΔS =1; ΔI =1 spin- and isospin-flip intrinsic excitation of the nucleon. As such it is a partner of the corresponding ΔS=1; ΔI=1 excitation of the nuclear medium, known as the Gamow-Teller resonance. Studies with the Super-FRS present unique possibilities to study the Δ and other baryon resonances in stable and in exotic nuclei. Pilot experiments of isobaric charge-exchange reactions have already been performed with the FRS and reveal interesting results as demonstrated in the Fig. 5.

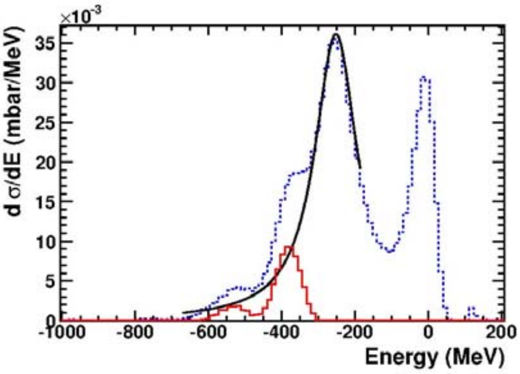

Fig. 5: Measured energy loss spectrum of ^{112}Sb projectile residues produced in isobaric charge exchange collisions induced by ^{112}Sn projectiles with copper targets at 1,000*A* MeV.

Heavy-ion collisions with heavy target nuclei also provide an opportunity to study two Δ's in nuclei. It may also provide a chance to study ΔΔ interactions. 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 nuclides created via charge-exchange reactions. In addition, measuring the charged pions emitted in the decay of the nucleon resonances in coincidence will provide a clear signature for the Δ-resonance excitation. 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. The proposed setups have many common issues with the ones proposed for the investigations of the η' mesonic states and hypernuclei. Therefore, synergies should be identified in order to design a common setup.

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. The advantages of Super-FRS are clear for the first stage experiments. However, serious considerations of advantages of other NUSTAR setups for the later stages with more complicated settings are a subject of forthcoming discussions.

3.4 Experiments taking advantages 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, may 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

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.

Topic 8: Radioactive in-flight decays and continuum spectroscopy by particle emission

The existence of nuclei is not restricted to the stable and β-decaying nuclei only. The limiting line of bound nuclei is the so-called drip-line and it is one of the goals to explore the drip-line for as many elements as possible. 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 may 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 and also strongly affected by nucleon correlations. Nuclear resonances can be studied by exclusive reactions or invariant-mass methods (as is the goal of the R3B collaboration). Alternatively, they can be studied by their decays (emission of proton(s) or neutron(s), so called proton radioactivity and neutron radioactivity, respectively). Because of their special properties and the fine balance of nuclear forces, these nuclei are subject of high theoretical interests.

Outside the proton drip-line, proton radioactivity prevails and some nuclides with two-proton decays have been observed. They allow studying two-proton 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, it is expected that two-neutron decays have longer half-lives. It is interesting to see whether such long-lived neutron radioactivity exists; if so, two-neutron correlations in nuclei could be studied in detail.

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 (O-TPC) 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. (Fig. 6). The Super-FRS will provide even more exotic nuclei and dripline nuclei for heavier elements.

For the study of proton and neutron 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 two-proton emitter ^{26}S can be produced by neutron removal reaction of ^{27}S, a possible four-neutron decay nucleus ^{28}O could be produced by one-proton 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 100ns (in-flight decay technique) and ~100ns to 1s (O-TPC). Based on angular correlations and with more inclusive measurements, these experiments will provide important information and be complementary to other NUSTAR activities.

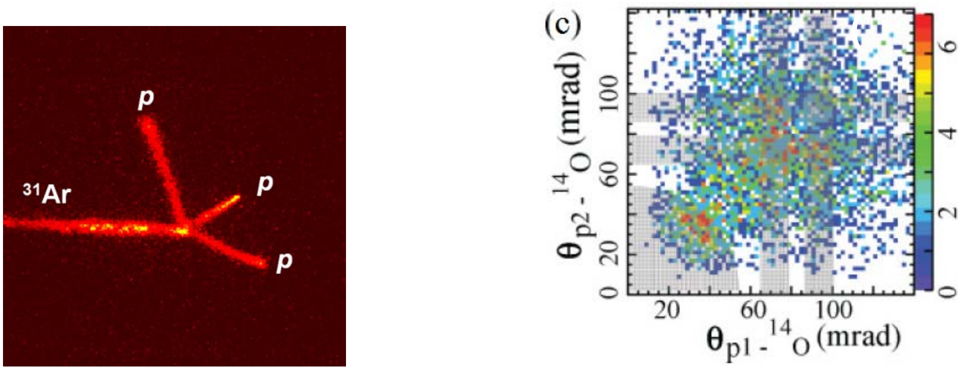

Fig. 6: Exotic radioactive decays: Left: 3-proton-emission following β-decay in ^{31}Ar observed with the Optical-TPC. Right: The measured correlation plot of 2*p* decays of ^{16}Ne states populated in a neutron knockout from ^{17}Ne projectiles. Shaded areas of the circular sector and bands indicate the true 2*p* decay of the ground state and the sequential decays of excited states via the intermediate ^{15}F states.

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 Fig. 7 in which the obtained density distributions of ^{8}He and ^{11}Li are shown.

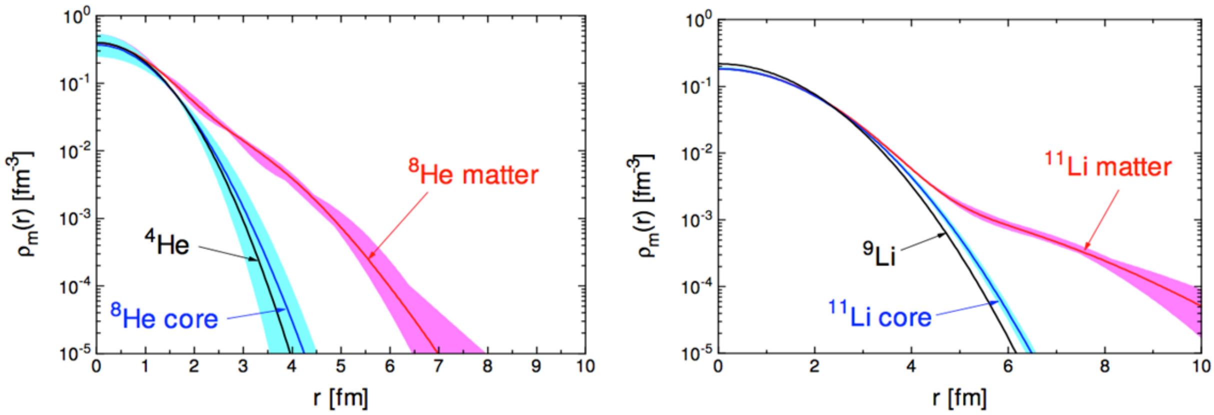

Fig. 7. Examples of the density distributions determined by IKAR experiments. A difference of neutron skin and neutron halo distributions is clearly seen by the proton elastic scattering experiment.

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.

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 heavy and superheavy exotic 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.

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 trans-uranium nuclides (Z>92) 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. 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 collaboration, the possibility of applying a storage ring for deceleration, a unique option offered at FAIR, will be investigated.

The TOF-E detection system CORSET from JINR Dubna will be used for the study of deep inelastic transfer, quasi-fission and fusion-fission, where an upgraded version of CORSET will allow covering a significantly larger solid angle. For synthesis reactions, the existing setup consisting of a gas-catcher, RFQ and Multiple-Reflection ToF-Mass-Spectrometer (MR-ToF-MS) can be used for particle identification. At a later stage, a velocity filter or a gas-filled separator can be employed for separation of rare reaction products.

4. Conclusion

The present document outlines the present experimental program, new opportunities, uniqueness, challenges with the Super-FRS facility. The Super-FRS Collaboration is complementary to other sub-collaborations within NUSTAR, their setups and science topics. Some completely new experiments have been identified, which offer great scientific potential in addition to previous science programs. Overall, the physics program is original and will have high scientific impact, as it deals with experiments which are intrinsically characteristic for the Super-FRS separator-spectrometer and which touch basic questions of modern nuclear science. Therefore, it is an important asset for FAIR overall and for NUSTAR in particular. Moreover, it comprises experiments, which can be done during the commissioning and startup phase of the FAIR facility, partly already with the Super-FRS coupled to the SIS-18. Although there is strong international progress in the field, the collaboration is guided by the “uniqueness criterion”, which guarantees that by the start of the FAIR the physics program will still be competitive on the world scene, also the activity will be timely even in the years around 2020 and beyond.

The Super-FRS Collaboration will be pleased if the proposed activity is taken up by FAIR. If this is the case, official acknowledgement and feedback on a clear roadmap towards the inclusion of this activity in the FAIR experiment portfolio will be appreciated.

The collaboration is open to any scientists and exploits synergies with the scientific and technical programs of the other FAIR collaborations. The priorities within NUSTAR and day one experiments could be discussed along with the road map of the Super-FRS Collaboration. The road map for coming few years for developments using present FRS has been made, but the road map for longer term until the completion of FAIR construction and after the commissioning is still under discussion within NUSTAR.

Appendix I. Motivation of the Super-FRS Collaboration

The experimental program of the Super-FRS 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. Highlights of experimental studies performed at the FRS with direct bearing only on future research program of Super-FRS Collaboration are illustrated in Fig. 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 discovery 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 of also considered from the very beginning of the Super-FRS project. These separator-spectrometer experiments with the FRS are so well established and formed the scientific backbone of the group who had proposed, built and operated the separator. The Super-FRS Collaboration takes advantages of the experiences in FRS to expand scientific and technical knowledge for the next generation experiments.

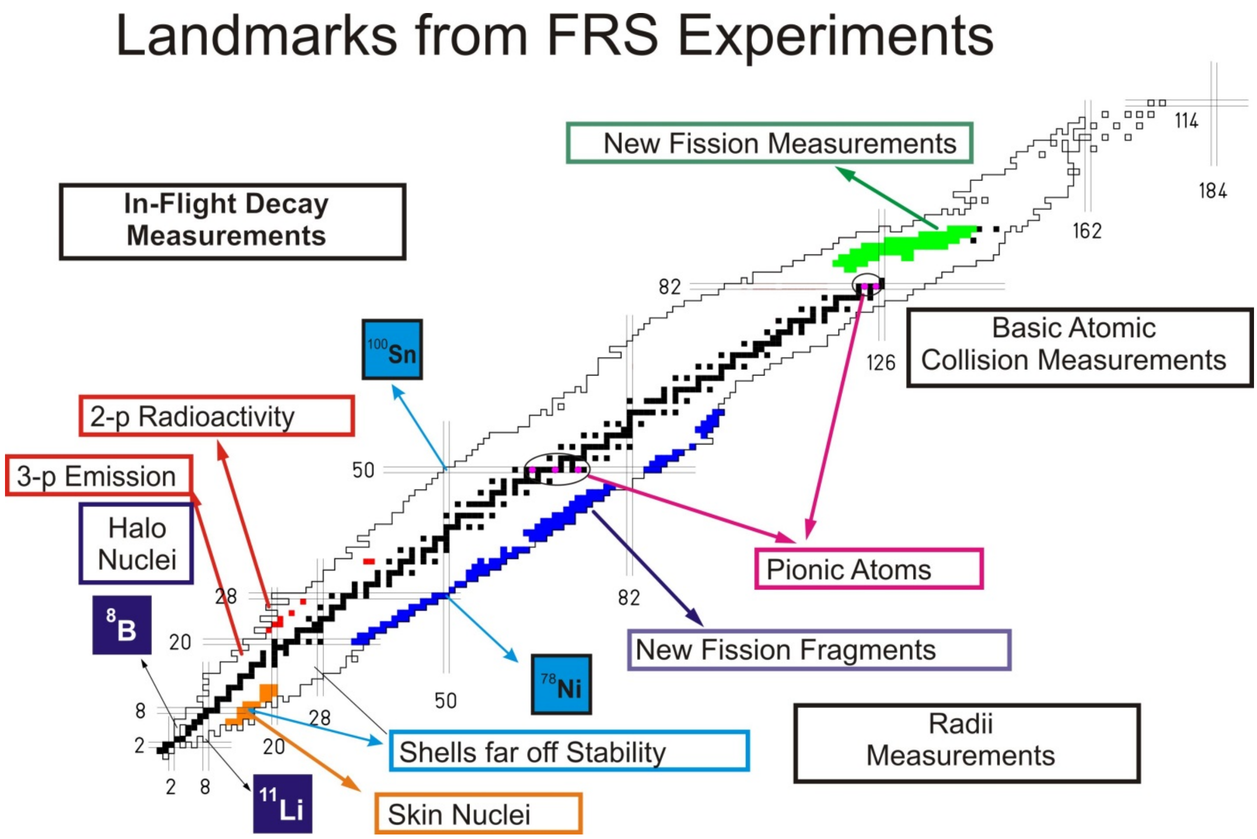

Figure A1: Scientific highlights from separator-spectrometer experiments with the FRS. Several experimental discoveries made with the present FRS are illustrated on the schematic Chart of Nuclides.

Table A1: Experimental highlights from FRS experiments.

The research topics related to future Super-FRS Collaboration , 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, Fragmenta-tion-Fission	Schmidt-93 Bernas-97 Pfützner-98 Kurzewicz-12
Doubly Magic Nuclei 100Sn	Identification and Decay Measure-ments	Schneider-94

Doubly Magic Nuclei 78Ni	Production Cross Section	Engelmann-95
New magic shell N=16 Doubly Magic Nuclei 24O	Radii Measurement and Momentum Measurements Removal Cross Sections	Ozawa-00 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
Radii-Measurements, Neutron Skin	Interaction Cross Sections	Suzuki-95
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 11-Li, 19-C	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
3-Proton Emission 31Ar	Identification & Decay Measurements	Pfützner, in preparation
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

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"

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

Kanungo-10 R. Kanungo et al. Phys. Lett. B 685 (2010) 253-257: "Structure of 33Mg 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 24O as a New Doubly Magic Nucleus"

Mukha-07: I. Mukha et al., Phys. Rev. Lett. 99 (2007) 182501-4: "Observation of Two-Proton Radioactivity of 19Mg by Tracking the Decay Products"

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

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"

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 238U 1A GeV with protons"

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"

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

Geissel-02a H. Geissel et al., Phys. Lett. B 549 (2002) 64-71: "Experimental indication of a reduced chiral order parameter from the 1s $\pi-$ state in 205Pb"

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

Geissel-02b H. Geissel et al., Phys. Rev. Lett. 88 (2002) 2301-2304: "Deeply Bound 1s and 2p Pionic States in 205Pb and Determination of the s-Wave Part of the Pion-Nucleus Interaction"

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"

Ozawa-00 A. Ozawa et al. Phys. Rev. Lett. 84, (2000) 5493-5496: “New Magic Number, N = 16, near the Neutron Drip Line”
Iwasa-99 N. Iwasa et al., Phys. Rev. Lett. 83 (1999) 2910-2913: “Measurement of the Coulomb Dissociation of 8B at 254 MeV nucleon and the 8B Solar Neutrino Flux”
Dauvergne-99 D. Dauvergne et al. Phys. Rev. A 59 (1999) 2813-2826: “Charge states and energy loss of 300MeV/u U73+ ions channeled in a silicon crystal”
Smedberg-99 M.H. Smedberg et al., Phys. Lett B 452 (1999) 1-7: “New results on the halo structure of 8B”
Pfützner-98 M. Pfützner et al., Physics Letters B 444 (1998) 32–37: “New isotopes and isomers produced by the fragmentation of 238U at 1,000 MeV/nucleon”
Baumann-98 T. Baumann et al., Phys. Lett. B439 (1998) 256-261: “Longitudinal momentum distributions of 16,18C fragments after one-neutron removal from 17,19C”
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 207Pb”
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-2 H-like projectiles”
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 238U”
Alkhazov-97 G. D. Alkhazov et al., Phys. Rev. Lett. 78 (1997) 2313-2316: “Nuclear matter distributions in 6He and 8He from small angle p-He scattering in inverse kinematics at intermediate energy”
Scheidenberger-96 C. Scheidenberger et al., Phys. Rev. Lett. 77 (1996) 3987-3990: “Energy-loss straggling experiments with relativistic heavy ions in solids”
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 78Ni”
Suzuki-95: T. Suzuki et al., Phys. Rev. Lett. 75 (1995) 3241-3244: “Neutron skin of Na isotopes studied via their interaction cross sections”
Schwab-95: W. Schwab et al., Z. Phys. A350, (1995) 283: ”Observation of a Proton Halo in 8B”
Kandler-95 T. Kandler et al., Phys. Lett. A204 (1995) 274-280: „Transition selective investigation of the resonant transfer and excitation in U90+ → C collisions”
Humbert-95: F. Humbert et al., Phys. Lett. B347 (1995) 198-204: „Longitudinal and transverse momentum distributions of 9Li fragments from break-up of 11Li“
Schmidt-94: K.-H. Schmidt et al., Physics Letters B 325 (1994) 313-316: „Low-energy fission studies of neutron-deficient projectile fragments of 238U“
Schneider-94 R. Schneider et al., Z. Phys. A348 (1994) 241-242: “Production and identification of 100Sn.”
Scheidenberger-94 C. Scheidenberger et al., Phys. Rev. Lett. 73 (1994) 50-53: „Direct oberservation of systematic deviations from the Bethe stopping theory for relativistic heavy ions”
Kraus-94: G. Kraus et al., Phys. Rev. Lett. 73 (1994) 1773-1776: „Proton inelastic scattering on 56Ni in inverse kinematics“
Stöhlker-94: Th. Stöhlker et al., Phys. Rev. Lett. 73 (1994) 3520-3523: „L-subshell resoved photon angular distribution of radiative electron capture into He-like uranium”
Schmidt-93: K.-H. Schmidt et al., Physics Letters B 300 (1993) 313-316: „Distribution of Ir and Pt isotopesproduced as fragments of I A GeV 197Au projectiles: a thermometer for peripheral nuclear collisions“
Stöhlker-92: Th. Stöhlker et al., Physics Letters A 168 (1992) 285—290: „Ground state transitions in one- and two-electron Bi projectiles“

Appendix II. Detectors and equipment

The experiments of the Super-FRS 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). All of them require full or partial use of the beam diagnostics of the Super-FRS (2.4.6) as specified in the TDR-2007 and comprised in the MSV. The 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] (Bρ), 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. Furthermore, some of the planned measurements employ additional (a) ancillary detectors or/and (b) new equipment, as listed in Table A2.

(i) Ancillary detectors: Among the ancillary detectors, some are already in use at the FRS or Cave C and can be transferred to the Super-FRS. They 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). Others 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 cryogenic stopping cell[4] (topic 10), the atomic collision target[5] (topic 2), active target[6] (topic 9) and fiber trackers[7] (topic 5). Additional detectors accounted for this category are NeuRad and GADAST[8] (topic 8), both currently under development, and CORSET (topic 10).

(ii) New equipment: Additional devices are the dipole magnets for pion identification (topics 4 and 6), the target ejectile detectors (topic 3) and the velocity filter (topic 10). Suitable dipole magnets have been identified in Japan, which could become available for the present purposes (for details see topic 4). Otherwise the collaboration is looking for solutions, in particular it makes efforts to raise support, involve new funding sources, and attract additional funds.

The Super-FRS Collaboration will coordinate these developments with other sub-collaborations within NUSTAR, 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.

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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 (FWMH) 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" and will submit an additional request in 2014 for 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 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, which has been tested at the FRS; it operates at rates up to the MHz regime and provides 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; investments have been requested by the FAIR-Russia STC.

	Pilot experiment with FRS	Experiment with Super-FRS
Topic 1 (isotopes)	alpha- and isomer-tagger, cryogenic stopping cell	alpha- and isomer-tagger to be adapted to Super-FRS
Topic 2 (atomic collision)	precision targets, gas targets	dto.
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
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, 2nd half of FRS as energy buncher	ion catcher adapted to the Super-FRS, MR-ToF-MS, Super-FRS in mono-energetic mode, CORSET adapted to Super-FRS, velociy filter

Table A2. Pilot experiments at the FRS and Super-FRS experiments.

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

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

Relation to NUSTAR

Within NUSTAR, the Super-FRS Collaboration is one among the other sub-collaborations; its organization and role will be similar to all other NUSTAR experiments. The Super-FRS 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 Collaboration will use the Super-FRS itself for its physics program. It will support the realization of the Super-FRS.

Scope, tasks and role

The Super-FRS Collaboration main activity and mission is to pursue and execute the scientific program, which is outlined in this document. To achieve this goal, two types of technical components are needed, the Super-FRS itself and ancillary detectors, to perform science program listed in this document. The realisation of the Super-FRS project[9] is the responsibility of the Super-FRS department in the FAIR@GSI project branch. The machine project leader supervises the realisation of all cost book items 2.4.X which are done within FAIR@GSI together with in-kind partners. Additional support can be, for instance, R&D work or support of in-kind partners for the Super-FRS components. The development, design and realisation 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 be used for both, Super-FRS development tests and in parallel pilot experiments of the Super-FRS Collaboration. The Super-FRS collaboration will take care, that while pursuing its physics program with the FRS, it will secure support and beam time to be carried out at the FRS in order to assure developments for the Super-FRS.

Organization and governance of the Super-FRS Collaboration

The internal organization of the Super-FRS Collaboration has been set up in line with similar collaborative efforts. An overview of the bodies of the Super-FRS 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 detectors. 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 the 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 within FAIR@GSI (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 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.

Members, institutes, resources

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

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[9] The Super-FRS project is specified in the TDR and the FAIR@GSI project plan.

Some of the activities described above will require resources that are presently not listed in the experiment cost book. These resources will be specified in the context of TDR's, which are in preparation. The Super-FRS Collaboration will make an effort to raise additional funds.

MoUs

The first Super-FRS MoU was completed in year 2007 within NuSTAR. Presently, a MoU for the Super-FRS Collaboration is in preparation in line with other NUSTAR MoUs.

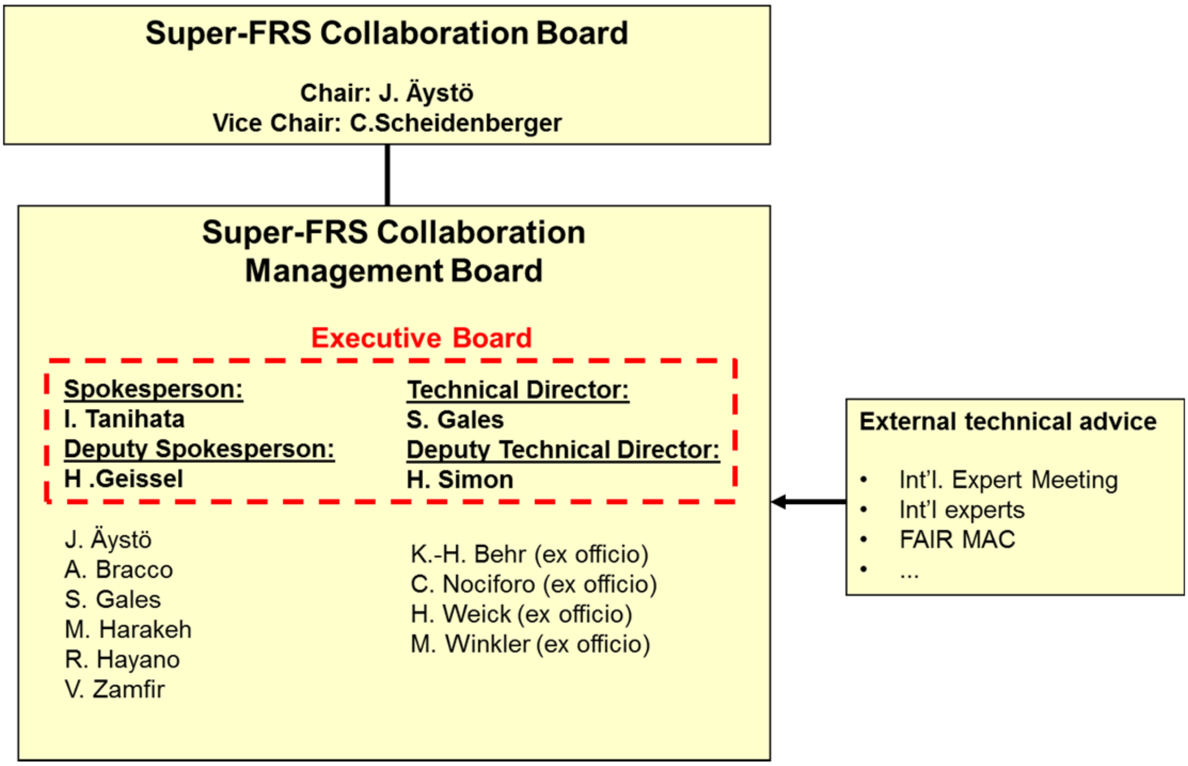

Figure A2: Bodies of the Super-FRS Collaboration; their functions and interaction are described in the text.

Appendix IV: Members of the Super-FRS Collaboration

Aarhus University, Aarhus, Denmark
A. H. Sørensen

Beihang University, Beijing, China
J. Meng, S. Terashima

Bogolyubov Laboratory of Theoretical Physics, JINR, Dubna, Russia
I. A. Egorova, S. N. Ershov, A. K. Nasirov

CEA/DAM/DIF, Bruyères-le-Châtel, France
J. Taieb

CEA Saclay, France
N. Alamanos

Chalmer's University of Technology, Göteborg, Sweden
A. M. Heinz, B. Jonson, T. Nilsson

Comenius University, Bratislava, Slovakia
B. Sitar, P. Strmen

Department of Physics, University of Tokyo, Tokyo, Japan
R. Hayano

Faculty of Physics, University of Warsaw, Warsaw, Poland
W. Dominik, Z. Janas, C. Mazzocchi, S. Mianowski, M. Pfützner

FAIR Facility for Antiproton and Ion Research in Europe GmbH, Darmstadt, Germany
J. Gerl, A. Herlert

Flerov Laboratory of Nuclear Reactions, JINR, Dubna, Russia
S. A. Baraeva, A. A. Bezbakh, A. Fomichev, L. V. Grigorenko, M. S. Golovkov, A.V. Gorshkov, A. M. Itkis, A. G. Knyazev, G. Knyazheva, E. Kozulin, S. A. Krupko, D. Kulik, S. I. Sidorchuk, P. G. Sharov, R. S. Slepnev, G. M. Ter-Akopian, V. Zagrebaev

Frank Laboratory of Neutron Physics, JINR, Dubna, Russia
Y. Kopatch

GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany
S. Ayet, K.-H. Behr, T. Dickel, P. Egelhof, E. Fiks, H. Geissel, E. Haettner, S. Heinz, A. Kelic, O. Kiselev, R. Knöbel, G. Münzenberg, I. Mukha, C. Nociforo, S. Pietri, A. Prochazka, S. Purushothaman, C. Rappold, C. Scheidenberger, H. Simon, T. Stöhlker, M. Takechi, H. Weick, J. S. Winfield, M. Winkler

Helsinki Institute of Physics, Helsinki, Finland
J. Äystö, F. Garcia

Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania
N. Marginean, L. Trache, V. Zamfir

Institute of Modern Physics, Lanzhou, China
X. Ma

Institut de Physique Nucléaire Orsay, Orsay, France
L. Audouin, F. Azaiez, S. Galès

Institute of Nuclear Physics PAN, Krakow, Poland
G. Kaminski

Institute of Physics, Silesian University Opava, Opava, Czech Republic
V. Chudoba

Ioffe Physical-Technical Institute, Russian Academy of Science, St. Petersburg, Russia
I. Eremin, V. Eremin, N. Fadeeva, E. Terukov, Yu. Tuboltsev, E. Verbitskaya

ISOLDE, Cern, Geneva, Switzerland
J. Kurcewicz

Istituto Nationale di Fisica Nucleare, Milano, Italy
A. Bracco, G. Benzoni, A. I. Morales

Johannes-Gutenberg-Universität Mainz, Mainz, Germany
T. Saito

Justus-Liebig-Universität, Gießen, Germany
J. Ebert, C. Hornung, H. Lenske, V. Metag, M. Nanova, W.R. Plaß, M. P. Reiter, A.-K. Rink, X. Xu

KVI Center for Advanced Radiation Technology, Groningen, The Netherlands
M. N. Harakeh, N. Kalantar

Kyoto University, Kyoto, Japan
H. Fujioka

Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia
V.P. Shevelko

National Center for Nuclear Research NCBJ, Swierk, Poland
Z. Patyk

National Research Center “Kurchatov Institute", Moscow, Russia
A. A. Korsheninnikov, E. A. Kuzmin, E. Yu. Nikolskii

National Research Tomsk Polytechnic University, Tomsk, Russia
Y. Pivovarov

Petersburg Nuclear Physics Institute, St. Petersburg, Russia
G. D. Alkhazov, A. V. Dobrovolsky, A. V. Khanzadeev

Research Center for Nuclear Physics, Osaka University, Osaka, Japan
H. J. Ong, I. Tanihata, H. Toki

RIKEN Nishina Center, Wako, Japan
K. Itahashi, T. Kubo

Saint Mary's University, Halifax, Canada
R. Kanungo

School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
A. Estrade, P. Woods

Skobel'tsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
Yu. L. Parfenova

Technische Universität Darmstadt, Darmstadt, Germany
J. Enders

Universidad de Santiago de Compostela, Santiago de Compostela, Spain
J. Benlliure, D. Cortina-Gil

University of Jyväskylä, Jyväskylä, Finland
T. Grahn, A. Jokinen, S. Rinta-Antila

University of Manipal, Manipal, India
M. Gupta

Veksler and Baldin Laboratory of High Energy Physics, JINR, Dubna, Russia
V. B. Dunin