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Super-FRS Collaboration

Published in:
JPS Conference Proceedings

DOI:
[10.7566/JPSCP.6.020035](https://doi.org/10.7566/JPSCP.6.020035)

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
2015

[Link to publication in University of Groningen/UMCG research database](#)

Citation for published version (APA):
Super-FRS Collaboration (2015). Unique spectrometer experiments with the Super-FRS at FAIR. *JPS Conference Proceedings*. <https://doi.org/10.7566/JPSCP.6.020035>

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Unique Spectrometer Experiments with the Super-FRS at FAIR

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(Received July 31, 2014)

The Super-FRS at FAIR is a powerful superconducting in-flight separator and also a versatile high-resolution spectrometer system for exotic nuclei over a large energy range equivalent to a maximum magnetic rigidity of 20 Tm. In this contribution we present the physics program of the Super-FRS Collaboration. This program is partially based on the previous experimental results obtained with the FRS of GSI, but will also extend the research to directions not considered before.

KEYWORDS: exotic nuclei, Super-FRS, high momentum resolution, isotope search, tensor force, mesonic atoms, hypernuclei, atomic collisions, delta resonances, nuclear radii, momentum distributions, neutron radioactivity, proton radioactivity, super-heavy elements, fusion reactions with exotic nuclei

1. Introduction

The Superconducting FRagment Separator of FAIR [1], which will supersede the FRS of GSI [2], profits from increased primary-beam intensities, higher acceptance for projectile and fission fragments and new components: it comprises more separation stages and a high-resolution energy-buncher-spectrometer at its Low-Energy Branch (LEB). The goal of the Super-FRS Collaboration is to exploit the Super-FRS as a flexible, high-resolution ion-optical instrument and to take advantage of the high-energy beams of fully stripped for all elements up to uranium. The experiments are performed in a large energy range, for example, the maximum kinetic energy for $^{238}\text{U}^{92+}$ ions will be 1560 A·MeV, whereas in experiments with a gas-filled ion catcher the in-flight separated exotic nuclides are thermalized and manipulated in the keV regime.

2. Planned experiments

2.1 General concept

Unique features of Super-FRS as a device for a variety of discovery experiments are its use

- with high-energy and -intensity primary and secondary nuclear beams with energies up to 1560 A·MeV for $^{238}\text{U}^{92+}$, equivalent to a maximum magnetic rigidity of 20 Tm.
- as a high-resolution spectrometer with a large acceptance and with flexible ion-optical settings, in particular with dispersion-matching capabilities,
- with high primary-beam suppression power and high separation power for nuclides up to $Z=92$, with fully stripped ions of all elements,
- in versatile spectrometer modes by different combinations of the separator sections.

The high separation power is achieved under the phase-space condition of $40 \pi \text{ mm mrad}$ and a longitudinal momentum acceptance of $\Delta p/p = \pm 2.5\%$. Properties of 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. Detector systems, placed at the different focal planes of Super-FRS, can also be used advantageously for high-resolution momentum measurements e.g. after secondary reactions. These features make 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 [3]. This yields a high momentum resolving power of up to 20,000 for a 1 mm object size.

2.2 Experiments using the Super-FRS for spatial isotopic separation

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, Super-FRS will be 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 [4].

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. 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.

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

Atomic collisions

Accurate knowledge of the atomic interaction or energy loss of heavy ions penetrating through matter is essential for the successful operation of Super-FRS. In the new energy range no experimental data for stopping powers, energy and angular straggling and charge-state distributions of heavy ions exist. The corresponding 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 up to the thermalization in a gas-filled stopping cell [5] (for instance at the LEB of the Super-FRS) will be challenging due to the large momentum spread of fragments emerging from the production target. Adequate stopping efficiencies can be achieved only by reducing the energy spread in a dispersive magnetic stage combined with a mono-energetic degrader system. Atomic interaction of heavy ions in a cryogenic gas-filled stopping cell 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 predicted correctly to perform efficient experiments.

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) [6]. The feasibility of channeling experiments in this energy range has been successfully demonstrated with pilot experiments at the FRS many years ago. At Super-FRS, it is planned that RCE experiments will be performed with radioactive nuclei.

Finally, the 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 [7]. Experiments with Super-FRS will contribute to a refined understanding of Cherenkov radiation of heavy ions and may lay the grounds for novel detector developments.

2.3 Unique experiments with Super-FRS as high-energy, high-resolution spectrometer

Spectroscopy of meson-nucleus bound system (“mesonic atoms”)

The discovery of deeply-bound pionic states in heavy atoms at FRS [8] 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 ion-optical multiple-stage operation of the Super-FRS are essential key features for these experiments. The first planned experiment is on η' -bound nuclei [9]. The (p,d) reaction at 2500 MeV is suitable for producing and observing the first η' -bound nuclei. The next candidates will be η -bound nuclei. The latter nuclei can be produced either by the $(d,^3\text{He})$ reaction or by the $(p,^3\text{He})$ reaction.

Exotic hypernuclei and their properties

Lambda (Λ) hyperons can be produced in peripheral collisions at incident energies around 1 to 2 A·GeV. The 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.

Such a method of production of hypernuclei has been demonstrated recently at GSI by the HypHI collaboration [10]. They performed the first experiment with ^6Li projectiles at 2 A·GeV on a carbon target. Signals indicating the production of light hypernuclei $^3_\Lambda\text{H}$ and $^4_\Lambda\text{H}$ were observed. The half-lives were also extracted. With this feature, a dramatic expansion of the hyper-nuclear chart is expected.

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. Heavy-ion collisions also provide a possibility for forming multi- Λ hypernuclei. As a further development, Super-FRS equipped with additional pion detectors just downstream of the target at the central focal plane of the main separator, would provide efficient measurements with high-mass resolution.

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 tensor force has not been explicitly handled in nuclear models except for the lightest nuclei such as the deuteron and ^4He . 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 (p-n pairing) in a nucleus and introduces high-momentum nucleons in nuclei. Most of the 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 [11]. Zero-degree scattering is the best way to get rid of possible difficulties from reaction mechanisms. Super-FRS will be the only facility in the world that can provide high-energy incident beams with a high-resolution zero-degree spectrometer. Nucleon-transfer reactions such as (p,d) , (d,t) , and $(d,^3\text{He})$ are relevant reactions to be measured for this purpose.

Delta resonances probing nuclear structure

In high-energy heavy-ion collisions, in particular in charge-exchange reactions, there is clear evidence for Δ -resonances in nuclei. Also, the three-body force in nuclear systems could originate from Δ -resonances. 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. Studies with the Super-FRS will 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 a contribution to this conference [12].

Heavy-ion collisions with heavy target nuclei also provide an opportunity to study two Δ 's in nuclei and a chance to study Δ - Δ -interactions. The proposed experiments on Δ -excitations in exotic nuclei can be realized by 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 a setup providing 4π detection capability with a complete tracking of all pions. A large discovery potential, extending also to astrophysics, can be expected from studies of nucleon resonances in exotic nuclei, which were not possible in the past and will not be possible at other facilities due to the limited energy range.

2.4 Experiments taking advantages of multi-stages and high-resolution of the Super-FRS

Nuclear radii and momentum distributions

The measurement of total interaction cross sections (σ_I) is a well-established and efficient tool to derive matter radii of unstable nuclei [13]. It has been applied mainly for light elements. Halo nuclei have been discovered in nuclei near the drip lines but the neutron drip line is reached only up to oxygen isotopes so far. Giant neutron halos including more than two neutrons are also predicted in heavier elements.

The thickness of neutron skins is one of the sensitive ways to determine the equation of state (EOS) of asymmetric nuclear matter. Neutron-skin thicknesses can be 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 means to determine the proton distribution radius. Determination of proton distribution radii by σ_{cc} measurements is still under development but there have been several successful cases in light elements. A particular advantage of this method is that it can be applied for very short-lived and low intensity nuclides and thus has the possibility to reach the most neutron-rich isotopes. Super-FRS will provide an ideal instrument to perform the σ_I and σ_{cc} measurements due to the desired high energy coupled with the advantages of high mass resolution, transmission and identification.

Following the successes of momentum distribution measurements of knocked-out nucleons with light nuclei, it is of 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.

Radioactive in-flight decays and continuum spectroscopy by particle emission

Unbound nuclei beyond the proton and neutron drip-lines show interesting phenomena and may have half-lives as short as those exceeding the characteristic time of nucleon orbital motion in nuclei ($\sim 10^{-21}$ s). These nuclei form resonances whose lifetimes are determined by the centrifugal and Coulomb barriers and are also strongly affected by nucleon correlations. Nuclear resonances can be studied by exclusive reactions or invariant-mass methods. Alternatively, they can be studied by their decays, e.g., the 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 interest [14].

Such decays and angular correlations can be studied ideally at high kinetic energy and directly with 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 [15]. Also, an Optical-TPC (O-TPC) [16] was used effectively in a recent experiment, where the beta-delayed 3p-decay of the very exotic nucleus ^{31}Ar was observed [17]. The Super-FRS will provide even more exotic nuclei and drip-line nuclei up to heavy elements.

Furthermore, the Super-FRS will be suitable for the study of tertiary nuclei. The detection schemes employed cover half-life ranges from ~ 1 ps to 100 ns (in-flight decay technique) and ~ 100 ns to 1 s (O-TPC). Based on angular correlations and with more inclusive measurements, these experiments will provide important information and be complementary to other NUSTAR experiments.

Low-q experiments with an active target

At Super-FRS the N/Z ratio dependence of the saturation density of nuclear matter can 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 a ^4He target provides information on compression modes in nuclei and thus 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 section of Super-FRS after a secondary target will provide high particle-identification power and thus it is most efficient to put an active target in the middle focus of Super-FRS. A novel-design active target, e.g. based on the IKAR setup [18] used in FRS experiments on light halo nuclei will be used. The scattered beam-like particle can 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 feature will allow to cover an important 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.

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 potential for the synthesis of new heavy and super-heavy isotopes. 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 to produce neutron-rich trans-uranium nuclides ($Z > 92$) and eventually heavy nuclides 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 selected experiments. A presently unique feature of the LEB of Super-FRS is the energy-buncher-spectrometer, which can be applied to reduce the relatively large energy spread of the beams after deceleration to Coulomb barrier energies by degrader wedges.

3. Conclusion

The present contribution outlines the experimental program of the Super-FRS Collaboration demonstrating new opportunities, uniqueness and challenges. New experiments are identified, which will offer a high scientific discovery potential. The collaboration is guided by the “uniqueness criterion”, which guarantees that by the start of the FAIR facilities will still be competitive on the world scene, even in the years around 2020 and beyond.

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