Progress on the Super-FRS Experimental Program

J. Äystö[1], *K. Gales*[2], *H. Geissel*[3,4], *C. Nociforo*[3], *C. Scheidenberger*[3,4], *H. Simon*[3], *I. Tanihata*[5,6], *H. Weick*[3], *M. Winkler*[3], *and for the Super-FRS Collaboration* [1]

[1]Helsinki Institute of Physics, FI-00014 University of Helsinki, Finland; [2]IPN Orsay/IN2P3-CNRS and University Paris XI, 91406 Orsay Cedex, France; [3]GSI Helmholtzzentrum für Schwerionenforschung GmbH, 64291 Darmstadt, Germany; [4]Justus-Liebig-Universität Gießen, 35392 Gießen, Germany; [5]Research Center for Nuclear Physics, Osaka University, Osaka 567-0037, Japan; [6]School of Physics and Nuclear Energy Engineering, Beihang University, Beijing, China

The superconducting fragment separator (Super-FRS) will not only provide several thousand different short-lived isotopes to the experimental destinations of its three branches, but, taking advantage of its nature being a high-resolution spectrometer [1], it will enable a variety of unprecedented, unique nuclear physics experiments, too. The key feature common to these "spectrometer experiments" is the high-resolution momentum measurement. The highest possible momentum resolution will be reached with the energy-buncher/spectrometer [2] at the LEB when this is coupled to the main separator in a dispersion-matched ion-optical mode: to first order, this combination will yield a momentum resolving power up to $p/\Delta p \sim 20,000$. Another important trait is the multi-stage operation, where the separator-spectrometer capabilities as such are a comprising and integral part of the measurement. With this intention, the Super-FRS Collaboration has identified experiments, which are complementary to the other NuSTAR experiments and emerge as new physics opportunities with the Super-FRS instrument. The common feature is that these experiments will employ

- individual stages of the Super-FRS (roughly speaking: pre-separator, first and second half of the main separator, spectrometer/energy buncher at the Low-Energy Branch)

- different ion-optical modes of the Super-FRS (achromatic, mono-energetic, dispersive)

- several target and degrader stations at the major focal planes (including secondary or tertiary targets)

- various functions (separation including the suppression of the primary beam or unwanted species, identification, momentum measurement).

This opens up a large variety of experimental conditions, customized for the specific goals of the measurement, including new measurement concepts, not fully explored yet. For most of the experiments, the standard equipment of the Super-FRS can be used, while some experiments will need additional ancillary detector setups, which are currently under development. Scientific contributions to the following main topics can be expected:

Basic studies: this category of Super-FRS experiments goes hand in hand with the performance verification of the separator and its standard detector systems; ion-optical measurements will also include atomic collision experiments of ions penetrating (shaped) matter over the full energy range down to thermalized reaction products (e.g. in the cryogenic gas-filled stopping cell of the Low-Energy Branch [3]). These studies will also aim at the search for new isotopes, production cross section and rate measurements and provide data needed for all other NuSTAR experiments.

Nuclear structure and nuclear matter: the structure of nuclei far off stability is a major topic of modern nuclear physics and a central pillar of all next-generation radioactive beam facilities. The present approach is associated with nuclear reactions at relativistic speed and subsequent high-resolution longitudinal momentum-distribution measurements that give access to nuclear radii and matter distributions of the most exotic nuclei. The discoveries of neutron and proton halos, neutron skins and new "'magic numbers"' originated from such inclusive experiments. The experiments will provide information on the equation-of-state (EOS) of cold asymmetric matter by nuclear density distributions and neutron skin thicknesses, where the saturation density of asymmetric nuclear matter can be extracted from systematic data on interaction cross sections, charge changing cross sections, and proton elastic scattering of neutron rich nuclei. Exotic decay modes, such as 2-proton radioactivity, appear near the drip-lines at the limits of stability. Multiple neutron or proton radioactivity, appearing in extremely short-lived nuclei ($T_{1/2} \sim 10^{-10} s$), can only be studied with the in-flight decay technique, which was pioneered at the FRS [4], and which is based on relativistic exotic nuclei impinging on a secondary target within a fragment separator and subsequent identification. Also beta-delayed ternary fission is so far unobserved, but with the sensitivity of novel detector systems, such as an O-TPC [5], combined with the universal isotope production capabilities, short separation times and the selectivity of Super-FRS, even very weak decay branches can be identified. Finally, the study of tensor forces is an important new direction in nuclear physics [6]. The tensor interaction introduces a high-momentum component in the nucleus through specific proton-neutron correlations, which can be "visual-

doi:10.15120/GR-2014-1-NUSTAR-FRS-02

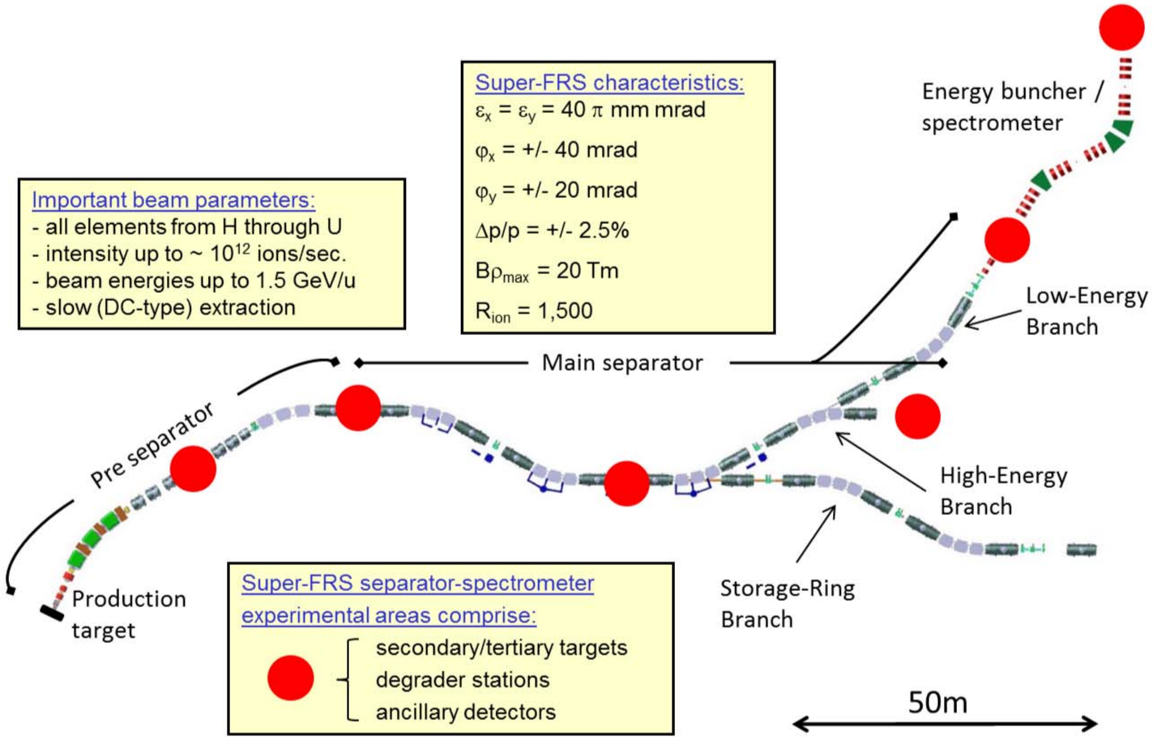

Figure 1: Schematic view and characteristic features of the Super-FRS with its three branches and the LEB energy-buncher/spectrometer system. The different separator stages and the experimental areas, which will be used for high-resolution separator-spectrometer experiments, are indicated.

ized” by high-momentum transfer reactions and subsequent high-resolution momentum analysis of the beam-like reaction product at beam energies above 400 A MeV.

Exotic atoms: at relativistic energies and with sufficiently intense beams (typically in excess of $\sim 10^5$ ions per second), various exotic atoms can be produced, for instance hypernuclei or Δ and N* excitations in nuclei, or mesic nuclei respectively mesic atoms. Both are of interest to study chiral symmetry breaking via direct measurements of in-medium mass modifications. Also interactions between such exotic particles and nucleons or nuclear matter are subjects of interest. Resonance physics in radioactive nuclei is completely unexplored. A recent pilot experiment [7] with the FRS has demonstrated that new properties of the Δ resonances can be observed in charge-exchange reactions of heavy ions. Also the possibility to produce (multiple) strangeness in nuclei by coalescence in fragmentation reactions, recently demonstrated [8], opens up a completely new and wide field of studies. Production rates for exotic atoms are sufficiently high in the region of $1 \ldots 1.5$ A GeV (cross sections are at the micro-barn level), and the Super-FRS with its capability to serve as zero-degree spectrometer, its momentum resolution down to $\delta p \sim 10^{-4}$ (essential for missing-mass measurements of bound states with a precision of $\sim$ MeV/c2), and its high primary-beam or contaminant suppression will allow unique experiments in this emerging field.

References

[1] H. Geissel et al., Nucl. Instr. Meth. B204 (2003) 71.

[2] H. Geissel et al., Nucl. Instr. Meth. B317 (2013) 277.

[3] W. R. Plaß et al., Nucl. Instr. Meth. B317 (2013) 457.

[4] I. Mukha et al., Phys. Rev. Lett. 99, 182501 (2007).

[5] M. Ćwiok et al, IEEE TNS 52, 2895 (2005),
K. Miernik et al., Nucl.Instr.Meth. A581, 194 (2007).

[6] H. J. Ong et al., Phys. Lett. B725, 277(2013).

[7] J. Benlliure et al., publication in preparation.

[8] C. Rappold et al., Nucl. Phys. A 913, 170 (2013).