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Nuclear few-body physics at FAIR*

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Abstract The FAIR facility, to be constructed at the GSI site in Darmstadt, will be addressing a wealth of outstanding questions within the realm of subatomic, atomic and plasma physics through a combination of novel accelerators, storage rings and innovative experimental set-ups. One of the key installations is the fragment separator Super-FRS that will be able to deliver an unprecedented range of radioactive ion beams (RIBs) in the energy range of 0-1.5 GeV/u to the envisaged experiments collected within the NuSTAR collaboration. This will in particular permit new experimental investigations of nuclear few-body systems at extreme isospins, also reaching beyond the drip-lines, using the NuSTAR-R^{3}B set-up. The outcome of pilot experiments on unbound systems are reported, as well as crucial detector upgrades.

Keywords FAIR · NuSTAR · radioactive beams · unbound nuclei

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1 Introduction

The issues addressed within nuclear structure, astrophysics and reactions are of fundamental importance for our understanding of the subatomic world and numerous aspects of our universe. Unlike many other branches of science, there are not only a few, critical problems to be attacked but rather a multitude of interconnected questions, each highly relevant in its own respect. A few examples of these are:

- How are complex nuclei built from their basic constituents?
- What are the limits for existence of nuclei?
- How does the nuclear force depend on varying proton-to-neutron ratios?
- How to explain collective phenomena from individual motion?

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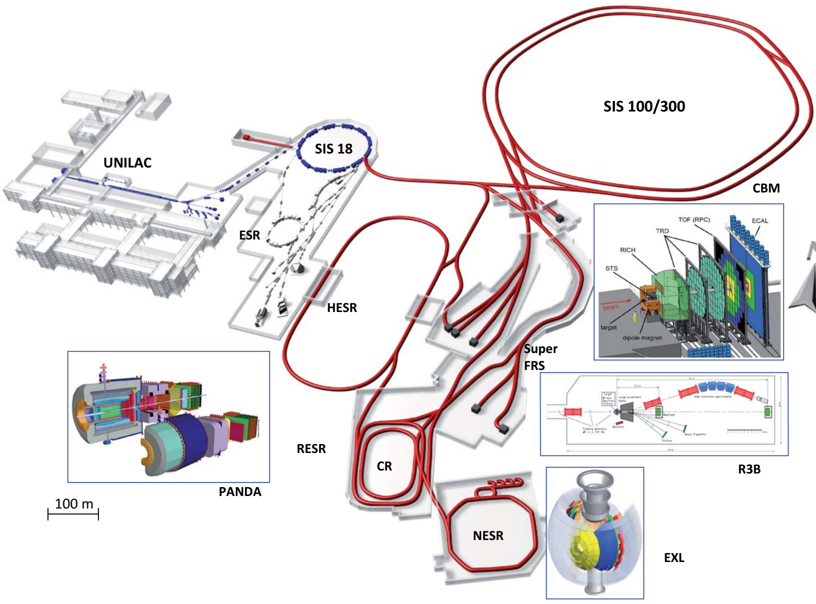

Fig. 1 Schematic view of the FAIR facility layout showing the complex of accelerators, storage rings and the Super-FRS. A few experiments are as well indicated: the CBM detector following the SIS100/300 synchrotrons, the PANDA experiment located in the HESR storage ring, the R^3B setup behind the Super-FRS and the EXL central detector located in the NESR storage ring.

– Which are the nuclei relevant for astrophysics and what are their properties?

Radioactive ion beams (RIBs) covering a variety of nuclear species and energies as well as state-of-the art instrumentation are indispensable tools in the endeavour of attacking the issues above, as well as several additional burning topics within subatomic physics. It is therefore natural that the conception and construction of new and upgraded facilities providing RIBs is a major concern for science worldwide. In particular, the in-flight fragmentation method (see e.g. [1]) can provide energetic beams of exotic isotopes, regardless of chemical properties. It is the method of choice for RIB production at FAIR, using the fragment separator Super-FRS, being able to deliver an unprecedented range of radioactive ion beams (RIBs) in the energy range of 0-1.5 GeV/u. Consequently, a broad experimental programme utilising these beams are envisaged, under the umbrella of the NuSTAR (Nuclear Structure, Astrophysics and Reactions) collaboration.

2 FAIR - Facility for Antiproton and Ion Research

The FAIR facility aims at being a world-leading facility within large domains of accelerator-based research with broad international participation. Through a complex

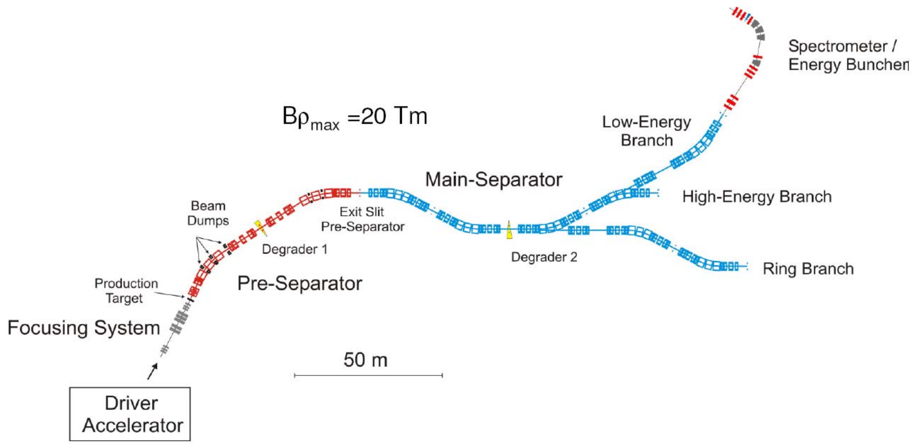

Fig. 2 The Super-FRS with pre- and main separator and the three branches.

of linear accelerators, synchrotrons, fragment separator and storage rings (see fig. 1), beams of unprecedented intensity and quality of heavy ions, antiprotons and radioactive ions will be produced. The facility and all envisaged experiments are described in detail in [2]. FAIR will allow advancing the scientific frontier concerning our understanding of hot and dense nuclear matter (within the CBM project), the internal structure of hadrons (PANDA) and the structure of nuclei all the way out to extreme isospin (NuSTAR). Furthermore, the access to the high electromagnetic fields by relativistic heavy ions (HEDgeHOB/WDM) and highly charged ions (SPARC) will open up completely new avenues for atomic physics studies. A rich programme using slow antiprotons (FLAIR) is as well foreseen.

However, the financial constraints will not permit constructing the full FAIR infrastructure at once. Parts of the programme has been shifted to a later Phase B, and a recent modularisation scheme [3] will permit the step-wise construction of Phase A in six modules while already from an early stage involving virtually all scientific communities around FAIR.

3 Rare-ion production with the Super-FRS and the NUSTAR programme

The existing FRS facility at GSI provides already today relativistic beams of exotic species through in-flight fragmentation of heavy ions. To be able to substantially improve the secondary beam intensities, a two-fold development is necessary: Firstly to increase the primary beam intensities by faster cycling and by using lower charge states (thus decreasing the space-charge effects) in the SIS100/300 synchrotrons to be constructed. Secondly, by increasing the acceptance of the separator device, the Super-FRS. This is being achieved by substantially larger apertures of all ion-optical stages of the separator compared to the FRS which necessitates the use of superconducting magnets. For the "hot" fission process where the fragments have a large transversal momentum, a total gain of 3-4 orders of magnitude in secondary beam intensities is expected compared to the existing facility.

The Super-FRS will be able to deliver the secondary beams to three main experimental areas, namely the low-energy, the high-energy and the ring branch, as shown in fig. 2. The three areas have, as their names indicate, different foci on the beam properties which have to be handled by the SIS-100/300 in conjunction with the Super-FRS. The fixed-target type experiments in the first two branches require that the ions are well distributed in time, approaching a DC beam. This necessitates slow extraction of the primary beam from the synchrotron. On the contrary, injection into the ring branch requires an ion pulse that is strongly focused in time, achieved by fast extraction. Furthermore, in the low-energy branch, the ions are to be degraded in energy shortly before the experimental set-up. Due to the distribution of charge states following the energy degradation, no subsequent separation is possible which puts stringent demands on the ion-optical properties of the preceding mass separation.

3.1 Experiments at the Low-energy branch

The low-energy branch collects experiments making use of ion beams at a lower energy than intrinsically produced in the Super-FRS. This encompasses several energy domains; stopped beams, energetic beams (3-150 MeV/u), and stopped and re-accelerated beams (0-60 keV). The directly stopped beams constitute the domain of the DESPEC experiment, concentrating on decay spectroscopy of the most exotic species. The DESPEC set-up is consisting of several detection systems optimised for gamma ray, charged particle and neutron detection. The energetic beams will make in-beam studies with highest resolution feasible, being the aim of the HISPEC set-up. HISPEC has as its main detection system the AGATA [4] advanced gamma-ray tracking array.

By stopping the radioactive ions in a gas volume, extracting and reaccelerating them using electrostatic devices, it is possible to convert the high-energy beam with large emittance to a low-energy and low-emittance beam of radioisotopes. These low-energy beams will be exploited by the experiments LaSPEC and MATS, concentrating on laser spectroscopy and high-precision mass Penning-trap measurements, respectively, in order to investigate ground-state properties of exotic nuclear species. A further area of study is trap-assisted decay spectroscopy with MATS. The Technical Design Report for the MATS and LaSPEC set-ups has recently been published in [5].

3.2 The High-energy branch and the R^3B experiment

The high-energy branch at the Super-FRS will house only one experiment, the R^3B (Reactions with Relativistic Radioactive Beams) set-up. The R^3B set-up is a generic fixed-target device optimised for RIBs as they are produced from the Super-FRS, i.e. in the energy range of 0.3 - 1.5 GeV/u. The width of the reaction programme at R^3B is demonstrated in table 1. The set-up is based on the existing ALADIN-LAND experiment which has been used for inverse-kinematics reaction studies with RIBs since 1992. The R^3B project aims at upgrading all existing detector systems, as well as adding substantial new developments. A schematic picture is shown in figure 3, indicating the various detector systems to be used for neutrons, charged particles, ions and gamma rays. The reaction target will be surrounded by a silicon micro-vertex tracker followed by the CALIFA calorimeter (shown in inset) with the dual use for gamma ray and light-ion detection. This puts large demands on e.g. granularity and resolution since

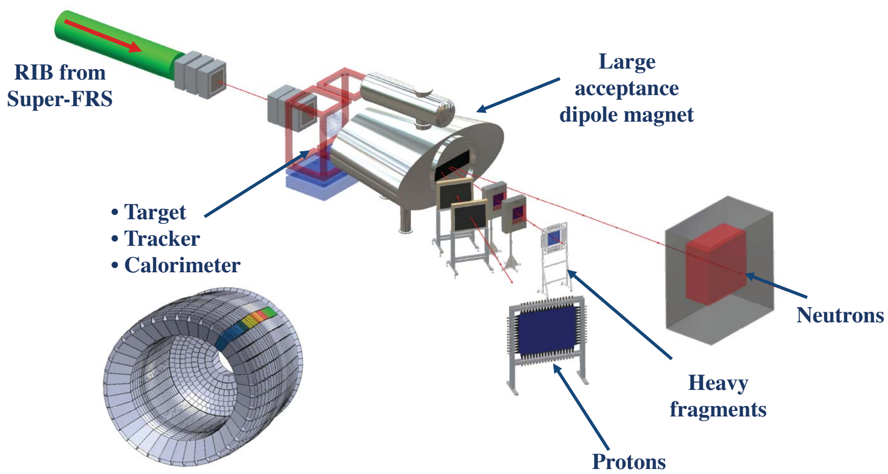

Fig. 3 Schematic view of the R^3B set-up in the start version. The lower left inset shows the CALIFA calorimeter.

Table 1 Reaction types with high-energy beams measurable with R^3B and corresponding achievable information.

Reaction type	Physics goal
Knockout	Shell structure, valence-nucleon wave function, many-particle decay channels, unbound states, nuclear resonances beyond the drip lines
Quasi-free scattering	Single-particle spectral functions, shell-occupation probabilities, n-n correlations, cluster structures
Total-absorption measurements	Nuclear matter radii halo and skin structures
Elastic p scattering	Nuclear matter densities, halo and skin structures
Heavy-ion induced electromagnetic excitation	Low-lying strength, single-particle structure, astrophysical S factor, soft coherent modes, low-lying resonances in the continuum, giant dipole (quadrupole) strength
Charge-exchange reactions	Gamow-Teller strength, soft excitation modes, spin-dipole resonance, neutron skin thickness
Fission	Shell structure, dynamical properties
Spallation	Reaction mechanism, astrophysics, applications: nuclear-waste transmutation, spallation sources
Projectile fragmentation and multifragmentation	Equation-of-state, thermal instabilities, structural phenomena in excited nuclei, γ-spectroscopy of exotic nuclei

the Doppler-boosted gamma rays can have energies exceeding 10 MeV and typical recoil protons energies of several hundred MeV. In order to achieve maximum time resolution, RPC technologies are planned for heavy ions and constitutes as well the base-line option for detection of fast neutrons in the NeuLAND detector. In a later stage, a high-resolution spectrometer will be added to achieve optimum momentum resolution of the recoiling ions.

3.3 The Ring branch

The ring branch allows injecting the rare isotopes from the Super-FRS into the complex of storage rings to be constructed at FAIR. RIBs at 740 MeV/u will be collected and cooled through stochastic and electron cooling in the CR (Collector Ring) and subsequently be transferred to the experimental storage ring NESR (New Experimental Storage Ring). The CR and NESR are themselves experimental devices for mass measurements within the ILIMA project. The methods of Schottky and isochronous mass measurements are adapted to high precision and shortest half-lives respectively, thus complementing the MATS project.

The NESR, shown in fig. 4, will be the venue of three further experiments, using cooled beams. Light-ion induced reactions using a gas-jet target will be performed within the EXL experiment, where precision measurement will be attainable through the cooled rare-isotope beam. Here, e.g. (in)elastic scattering, charge-exchange and, following deceleration, transfer reactions will be feasible also at very low momentum transfer due to the thin target. The loss in luminosity from the small target thickness can largely be regained by recirculating the beam.

In the ELISe experiment, the well-proved precision method of electron scattering will for the first time be used for studying short-lived nuclei. This is being achieved by combining the stored RIBs in the NESR with electrons in a small intersecting storage ring, in collider geometry. The obvious experiment here is elastic electron scattering to map out charge radii of exotic isotopes, but also inelastic scattering, electrofission and quasi-free scattering (e,e'X) can be addressed with pure leptonic probes.

The ELISe electron ring will in a later stage also serve in the AIC (Antiproton-Ion Collider) as storage ring for antiprotons. The cross-section for annihilation of nucleons in nucleus-antiproton collisions depends strongly on the matter distribution, thus the difference in matter radii between neutrons and protons in exotic systems can be determined.

All experiments situated in the NESR storage ring extend the scientific scope compared to the fixed-target experiments through their additional observables and increased precision. However, due to the time needed for beam cooling which is in the order of a few seconds, the most short-lived nuclei will remain the domain of the latter, yielding a true complementarity.

4 Precursor experiments probing exotic few-body systems

Nuclear few-body physics is evidently connected to the properties of light nuclear systems, being the natural testing ground for linking nucleons and sub-nucleon degrees of freedom with complex nuclei. Here, specific phenomena like haloes, clusters and nuclear molecules appear in the vicinity of the drip-lines and/or in excited states that poses the additional complexity of finding the correct degrees of freedom describing the system. The intensity increase of RIBs from Super-FRS will permit a major quality increase in the studies of such systems, permitting precision experiments at and beyond the neutron and proton drip-line in many cases.

Exotic nuclear systems have been studied at the R^3B predecessor set-up ALADIN-LAND for almost two decades, generating information concerning the structure of light neutron-rich nuclear systems at and beyond the drip-lines, e.g. [6–10]. Recent experiment [11–14] have been able to focus on detailed properties of nuclei beyond the

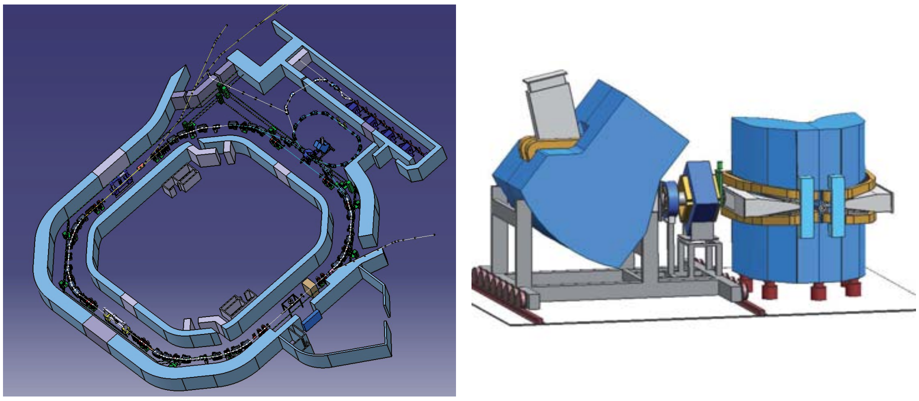

Fig. 4 The NESR storage ring (left) which will host the experiments ILIMA, EXL, ELISe and AIC. The ELISe electron spectrometer situated in the RIB-electron interaction zone (right). A horizontal pre-deflector is followed by a vertical momentum-analysing stage.

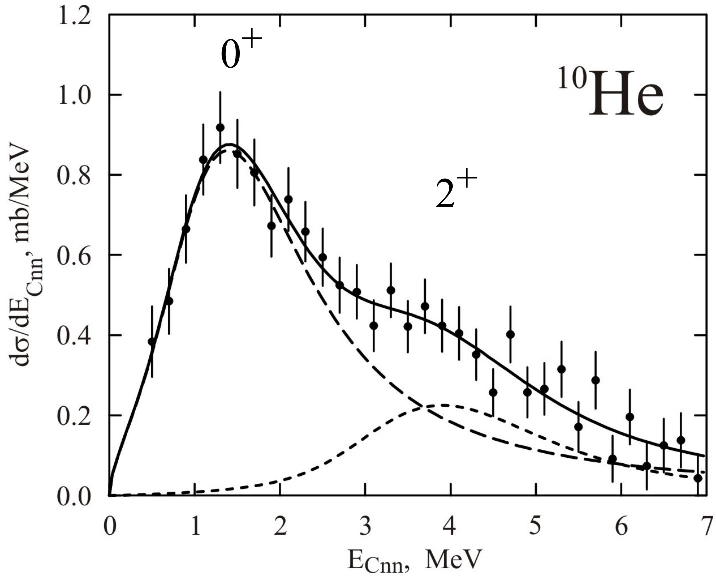

Fig. 5 Relative energy spectrum of the $^8He{+}2n$ system from the $^1H(^{11}Li, 8He{+}2n)$ reaction. From [14].

neutron drip-line through few-nucleon knock-out reactions on very exotic secondary beams like ^{14}Be and ^{11}Li. One highlight in this campaign, paving the way for experiments at R^{3}B, was the first observation of the unbound $^{12,13}Li$ systems [11]. As a further example, the results from break-up reactions of ^{11}Li on a hydrogen target at 287 MeV/u, selecting the $^8He + n + n + X$ decay channel are shown in 5. Through a careful analysis of the three-body correlations through expansion in hyperspherical harmonics, it was possible to draw spectroscopic conclusions on the low-lying structure of states in ^{10}He, identifying a $I^\pi = 0^+$ ground state and a $I^\pi = 2^+$ excited state.

This paves the way for improved investigations of similar type at FAIR, in particular using the R^3B installation which will be optimised for detecting outgoing gamma rays, charged fragments and neutrons stemming from reaction with ion beams in the 0.3-1.5 GeV/u range. Energies of several hundreds of MeV/u are perfectly matched to the production method of high-energy fragment separation in the Super-FRS and the reaction mechanisms are typically clear-cut, permitting a separation from structural features. In studies of bound and unbound nuclear few-body systems, the CALIFA calorimeter and the micro-vertex tracker (see 3.2) in conjunction with a liquid hydrogen target, will open completely new possibilities of reaction tagging through detection of ejectiles and/or excited residual nuclei. In particular, the class of **quasi-free reactions**, e.g. $(p, 2p)$, (p, pn), $(p, p$ cluster) in inverse kinematics will become available for studies of a large range of exotic projectiles. Since these reactions constitute the dominant process involved in the creation of unbound systems, this will crucially improve selectivity to this kind of studies. First experiments using prototype systems for detection of recoil protons are currently underway.

5 Conclusions

The field of nuclear few-body physics concerning exotic nuclei at and beyond the limits of nuclear binding will be able to make major progress following the completion of the FAIR facility including the Super-FRS and the NuSTAR experimental programme. In particular the high-energy reactions in fixed-target as well as ring/collider geometry opens up completely new prospects. For the former class of experiments, the programme already pursued with the ALADIN/LAND set-up will be much enlarged at R^3B through increased secondary beam intensities and more selective reactions.

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