PRAMANA — journal of physics | © Indian Academy of Sciences | Vol. 75, No. 2 August 2010 pp. 355–361

NUSTAR and the status of the R3B project at FAIR

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Abstract. Over the last 15 years, reaction experiments on fixed targets using secondary beams of high energy have developed a potential as exploratory tool to study the properties of nuclei far from stability. NUSTAR (nuclear structure, astrophysics and reactions) is a collaboration of the international nuclear structure and astrophysics community with the aim to further explore this method at the FAIR Facility. Within the FAIR complex, NUSTAR defines a facility where the heart is the super-fragment separator (Super-FRS), which serves three experimental branches: The RING, the LOW- and the HIGH-ENERGY branches.

Keywords. Fair; Nustar; R3B; radioactive ion beam; nuclear structure.

PACS Nos 20; 21; 24

1. Introduction

Research in natural sciences has provided us with an increasingly detailed picture of the structure of matter. This search is ongoing and we continue to analyse the elementary building blocks of matter and the fundamental forces acting between them on an increasingly deeper level. Particle accelerators have and will continue to play a key role in those efforts. Next-generation facilities will allow us an even deeper probing into the structure of matter and the structure of the Universe.

The above general reasoning has let the German Government to approve a completely new accelerator complex, named FAIR (facility for antiproton and ion research), on the site of the current GSI Laboratory. FAIR will be an international facility with a broad scientific base in nuclear and hadron physics, atomic physics, astrophysics, plasma research, biophysics and materials research (figure 1). The construction of this facility and its experiments require the highest technological skills and this facility will offer unique science opportunities.

One of the scientific pillars of the forthcoming FAIR Facility [1] is the program centred around the unprecedented range of exotic, radioactive beams, with several orders of magnitude higher intensities than currently available that will be delivered from the planned Super-FRS fragment separator [2,3]. This program is governed

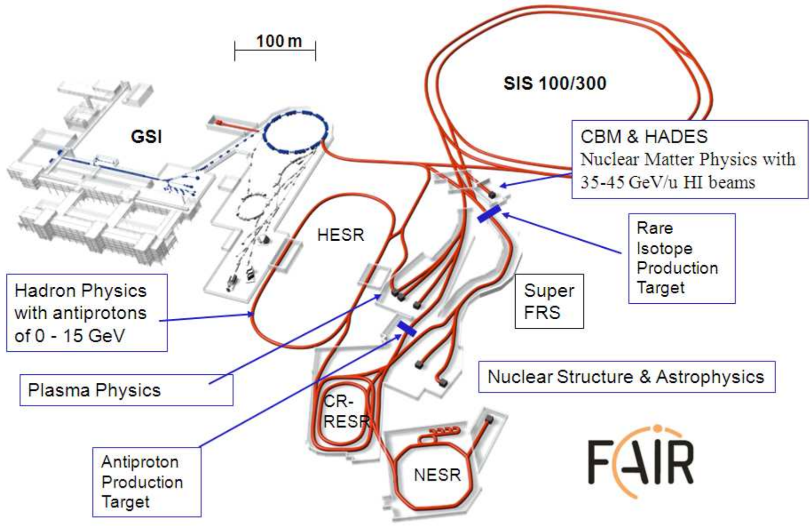

Figure 1. The FAIR Facility with the research communities indicated.

Table 1. Modular construction of FAIR phase one.

Module	Decision (year)	Construction time (month)	Start construction (year)	Operational (year)
0	2009	72	2010/11	2015/16
1	2009	28	2010/11	2015/16
2	2010/11	60	2012	2016
3	2010/11	60	2012	2016

by the NUSTAR (nuclear structure, astrophysics and research) Collaboration. The NUSTAR Collaboration covers all planned experiments following the Super-FRS fragment separator, situated at the high-energy, low-energy and ring branch respectively. An overview of the NUSTAR program can be found in [4]. One of the emblematic experiments within NUSTAR is the R3B (reactions with relativistic radioactive beams) project [5], a fixed-target experiment that is the sole occupant of the high-energy branch (see figure 2). The FAIR project is moving forward, and the final signatures on the formal agreement between the participating countries are expected to be reached during 2010. A modular structure has been agreed upon for the construction of FAIR, taking into consideration the setting up of relatively independent construction groups serving experiments from the four scientific pillars of FAIR (APPA, CBM, NUSTAR and PANDA).

- Module 0: Heavy-ion synchrotron SIS100, basis and core of FAIR, required for all the physics program
- Module 1: Experimental areas at SIS100 for extracted beam diagnostics, HADES/CBM, APPA

- Module 2: Super-FRS for NUSTAR and a fixed target area
- Module 3: Antiproton facility for PANDA
- Module 4: Additional low-energy caves for NUSTAR, NESR storage ring, building for FLAIR and plasma physics cave for APPA
- Module 5: RESR storage ring for higher beam intensity for PANDA and time-sharing operation with NUSTAR and APPA

In the present money matrix the first four modules (0–3) are covered and can thus enter in the phase one of the construction (see table 1). The configuration of the modules will be adjusted according to the financing available.

2. NUSTAR (nuclear structure and astrophysics research) at FAIR

Physics using radioactive ion beams (RIB) has progressed in recent years, as physics-driven technical developments have given access to an increased range of nuclei far from stability, improved beam intensity and quality. The scientific scope of RIB is extensive and encompasses nuclear structure, atomic, solid-state, surface and fundamental-interaction physics and medical applications. However, the existing RIB facilities are still to be considered as first-generation or upgraded first-generation facilities. The issues to be addressed within NUSTAR are:

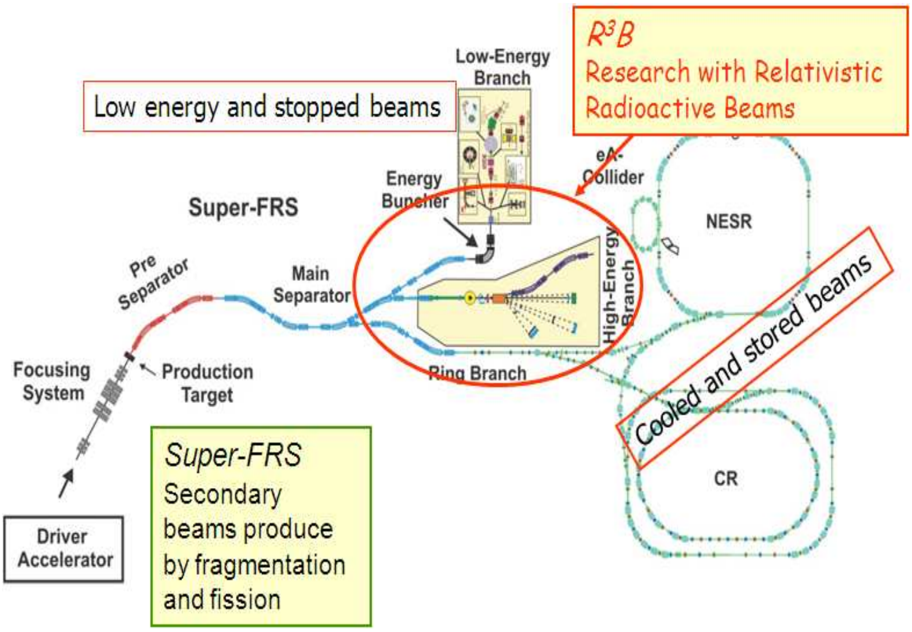

Figure 2. Within the FAIR complex, NUSTAR defines a facility where the heart is the super-fragment separator (Super-FRS), which serves three experimental branches: The RING, the LOW- and the HIGH-ENERGY branches.

- Exotic structures in nuclei at or beyond the limits of nuclear stability, the drip lines. The halo structure in light exotic nuclei is the best known case, but a range of new phenomena exists with strong coupling to continuum states and unbound resonances. The mass range constitutes a bridge between nucleons and nuclei where gradually *ab-initio* calculations, based on the first-principle two- and three-body nuclear interactions, become available. FAIR will provide access to the most exotic nuclear systems around the drip lines and enlarge the scope towards heavier nuclei.
- Weakening of shell structures, evolution of single-particle structure and onset of nuclear deformation, signalling fundamental changes as the neutron drip line is approached. The unique choice of isotopes, available beam energies together with advanced experimental devices will make detailed studies of structural evolution with isospin possible. FAIR will open the possibility to study neutron-rich nucleonic matter with properties that are largely unknown, e.g. exotic collective excitation modes. The study of these nuclear systems may greatly enhance our understanding of nuclei by imposing strong constraints on theory.
- Several of the topics listed above are directly relevant within nuclear astrophysics. The $N = Z$ region coincides with the *rp*-process path (rapid proton capture), the structure of neutron-rich nuclei significantly influences the *r*-process (rapid neutron capture) with its waiting-points and energetic RIBs allow studies of neutron and proton capture rates, the Gamow–Teller resonance and astrophysical parameters.

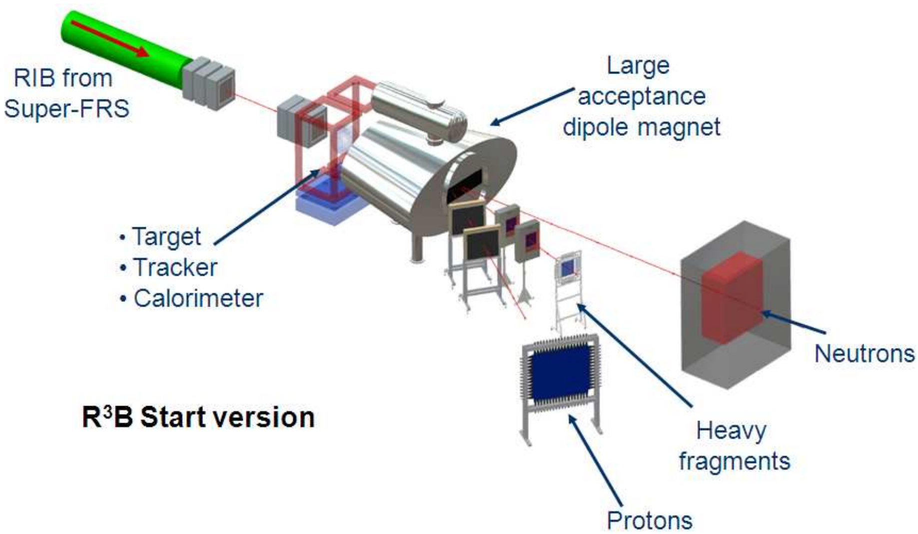

Figure 3. Schematic drawing of the R3B experimental set-up comprising γ-ray and target recoil detection, a large-acceptance dipole magnet, a high-resolution magnetic spectrometer, neutron and light-charged particle detectors and a variety of heavy-ion detectors.

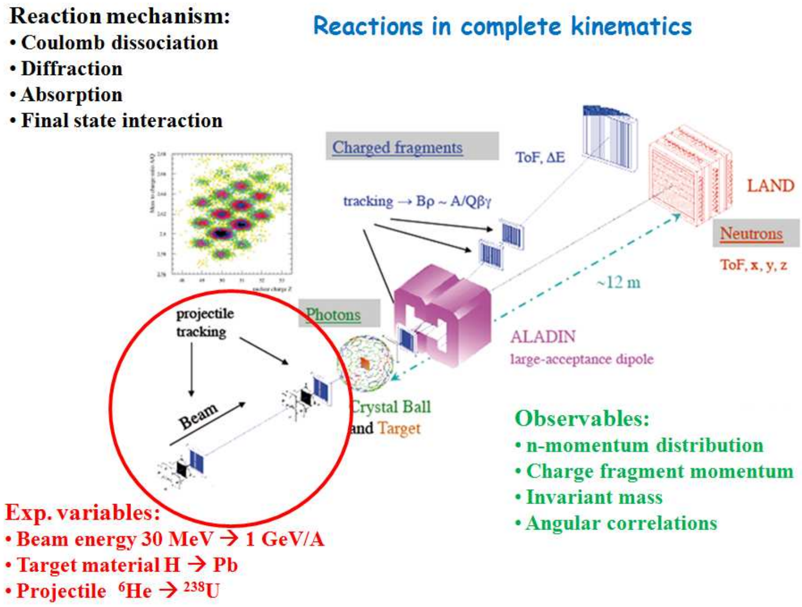

Figure 4. Schematic drawing of the LAND experimental set-up, indicating the parameters in a kinematically complete reaction experiment.

3. R3B Reactions with relativistic radioactive beams

For decades, reaction experiments at relativistic energies have been proven extremely useful as a tool for nuclear structure investigations. Here, a large range of reaction types are accessible and the intrinsic structure can normally be readily disentangled from the reaction mechanism. Furthermore, the possibility of using thick secondary targets and large, efficient coverage of a wide variety of detector types makes such experiments matches the scarce, most exotic nuclear species excellently. All the burning questions listed in the previous section can be addressed through such experiments.

The R3B Collaboration (180 members from 50 institutes) has designed an experimental set-up capable of fully benefiting from the Super-FRS beams (0.32 GeV/u) with the characteristics inherent to the in-flight production method. Located at the focal plane of the high-energy branch of the Super-FRS, R3B is a versatile fixed-target set-up with high efficiency, acceptance and resolution for kinematically complete measurements of reactions with high-energy radioactive beams. The heart of the R3B set-up is a large-acceptance superconducting dipole magnet, permitting identification and momentum analysis of the reaction products with a coverage approaching 4π due to the forward-directed Lorenz boost (see figure 3).

R3B builds directly on the existing ALADIN-LAND reaction set-up (see figure 4) which has successfully investigated light nuclear systems at and beyond the drip lines, collective excitations in unstable nuclei and astrophysically relevant reactions e.g. through studies of Coulomb break-up, using the (γ, n) reaction to study the

(n, γ) cross-sections. R3B will further widen this scope by a variety of scattering experiments, such as heavy-ion induced electromagnetic excitation, knock-out and break-up reactions, or light-ion (in)elastic and quasifree scattering in inverse kinematics. This will enable an unprecedented broad physics program (see table 2) with rare-isotope beams to be performed. It will be the prime program at FAIR for investigating the isospin frontier, i.e. the most exotic nuclei produced with the super-FRS, to gain information on the structure of exotic nuclear systems and their role in astrophysical processes. A survey of the reaction types and the associated physics goals that can be achieved is given. The collaboration envisages a large range of tate-of-the-art detectors, either as major upgrades or as completely new extensions to the existing set-up; resistive plate chambers (RPCs) will be used for ion detection and constitute a promising option for substantial resolution improvement for the detection of forward-going neutrons. The target area, with the possibility of using a liquid hydrogen target, will be surrounded by a silicon microvertex tracker and a combined γ and charged-particle calorimeter. This will permit taking established methods like quasifree hadronic scattering, e.g. $(p, 2p)$ and (p, pn), to investigations of RIBs in inverse kinematics, but with the additional advantage of being able to also measure the forward-directed heavy fragments.

Table 2. Physics to be adressed at NUSTAR.

Reaction type	Physics goals
Knock-out	Shell structure, valence-nucleon wave function, many-particle decay channels, unbound states, nuclear resonances beyond the drip lines
Quasifree scattering	Single-particle spectral functions, shell-occupation probabilities, nucleon–nucleon 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 transition 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, neutron spallation sources
Projectile fragmentation and multifragmentation	Equation-of-state, thermal instabilities, structural phenomena in excited nuclei, γ-spectroscopy of exotic nuclei

4. Summary

The FAIR project has started its construction. One of the main collaborations is the nuclear structure and astrophysics (NUSTAR) Collaboration, which comprises a vast number of experiments to be performed using radioactive beams from stopped up to relativistic energies. At the high-energy branch, the R3B concept builds upon an ion-by-ion identification and momentum analysis with maximum precision of the incoming and outgoing ions, in addition to detection of all other reaction products (light ions, protons, neutrons and γ-rays). This permits precision experiments with the relativistic radioactive species with beam characteristics as produced in-flight in the super-FRS and allows studies of the most exotic nuclei that the future facility will be able to produce.

References

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[2] H Geissel *et al*, *Nucl. Instrum. Methods* **B204**, 71 (2003)
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[5] http://www.gsi.de/fair/experiments/NUSTAR/R3b.html