PRAMANA
— journal of
physics

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pp. 1–7

NUSTAR and the status of the R3B project at FAIR

O. Tengblad for the R3B collaboration
1nstituto de Estructura de la Materia, Consejo Superior de Investigaciones Cientficas, Madrid ES-28006, SPAIN

Abstract. Over the last fifteen 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 branch.

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 analyze 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, 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, Fig. 1. The name FAIR stands for Facility for Antiproton and Ion Research. The construction of this facility and its experiments requires not only highest technological skills but will offer unique science opportunities.

One of the scientific pillars of the forthcoming FAIR facility [1] is the program centered 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 [4,5]. This program is governed

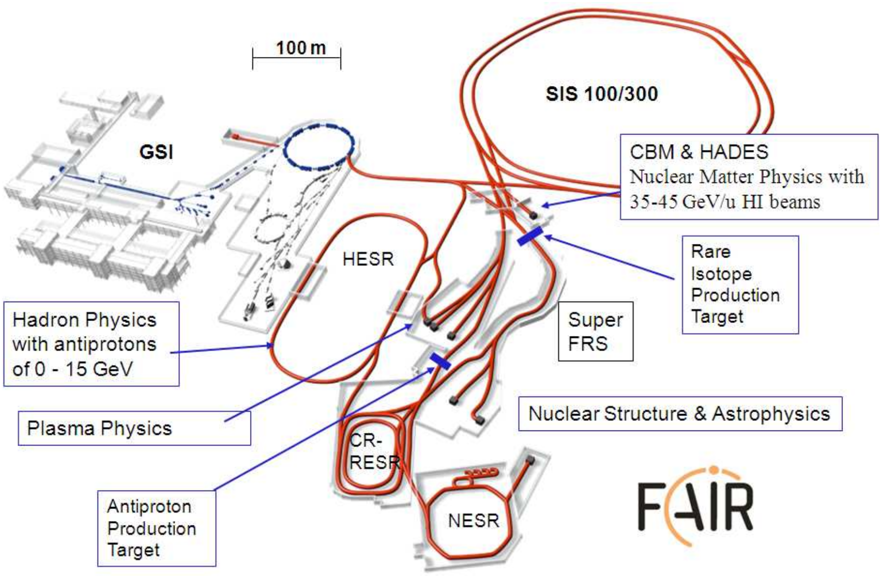

Figure 1. The FAIR facility with the research communities indicated

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 [2]. One of the emblematic experiments within NUSTAR is the R3B (Reactions with Relativistic Radioactive Beams) project [3], a fixed-target experiment that is the sole occupant of the high-energy branch. The FAIR project is moving forward, the final signatures on the formal agreement between the participating countries are expected to be placed during 2010. One has so far agreed on a modular structure 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 4 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 to the financing available.

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

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. A selection of issues to be addressed within NUSTAR:

- *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 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 dripline 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 interesting parameters.

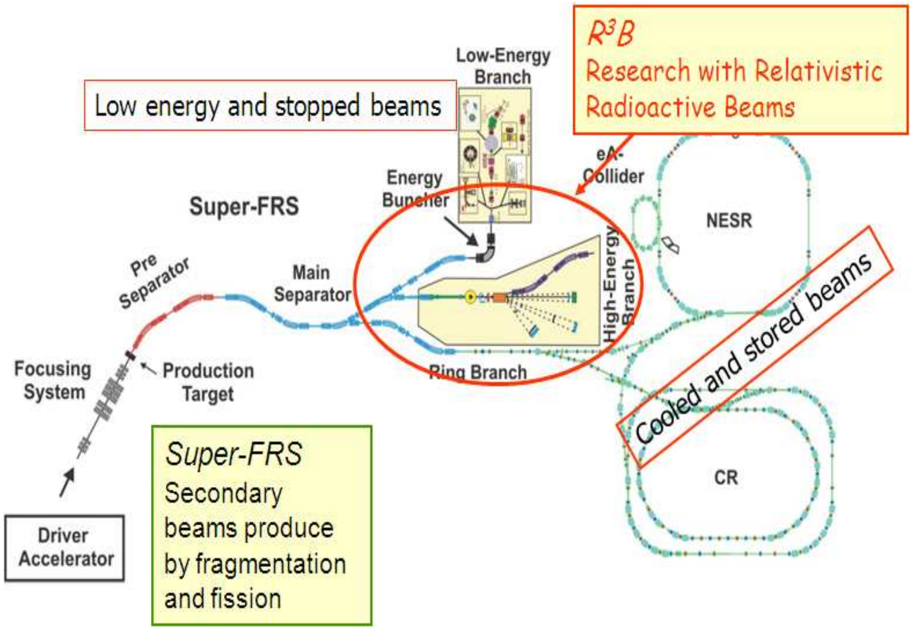

Figure 2. Within the FAIR complex, NUSTAR defines a facility where the heart is the Super - Fragment Separator (Super-FRS), which serves three experimental branches: The RING, the LOW- and the HIGH-ENERGY branch.

3. R3B Reactions with Relativistic Radioactive Beams

Reaction experiments at relativistic energies have proven extremely useful as a tool for nuclear structure investigations since decades. Here, a large range of reaction types are accessible and the intrinsic structure can normally readily be 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 experiment match 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 setup 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.

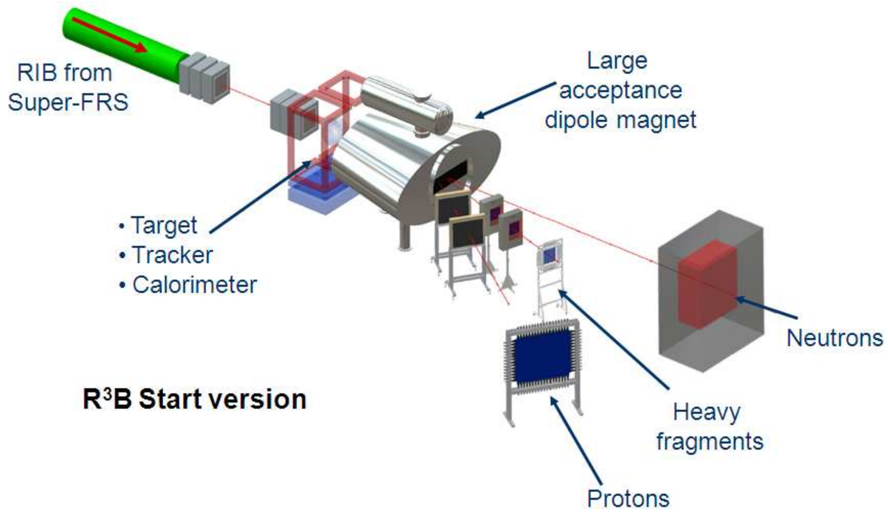

Figure 3. Schematic drawing of the R3B experimental setup comprising γ-ray and target recoil detection, a large-acceptance dipole magnet, a high-resolution magnetic spectrometer, neutron and light-charged particle detectors, and a variety of heavy-ion detectors.

R3B builds directly on the existing ALADIN-LAND reaction set-up (see fig. 4) which has successfully investigated light nuclear systems at and beyond the driplines, collective excitations in unstable nuclei and astrophysical 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, i.e., such as heavy-ion induced electromagnetic excitation, knockout and breakup reactions, or light-ion (in)elastic and quasi-free scattering in inverse kinematics. This will enable an unprecedented broad physics program 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 structure of exotic nuclear systems and their role in astrophysical processes. A survey of reaction types and associated physics goals that can be achieved is given below. The collaboration envisages a large range of state-of-the-art detectors, either as major upgrades or 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 detection of forward-going neutrons. The target area, with the possibility of using a liquid hydrogen target, will be surrounded by a silicon micro-vertex tracker and a combined gamma and charged-particle calorimeter. This will permit taking established methods like quasi-free 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.

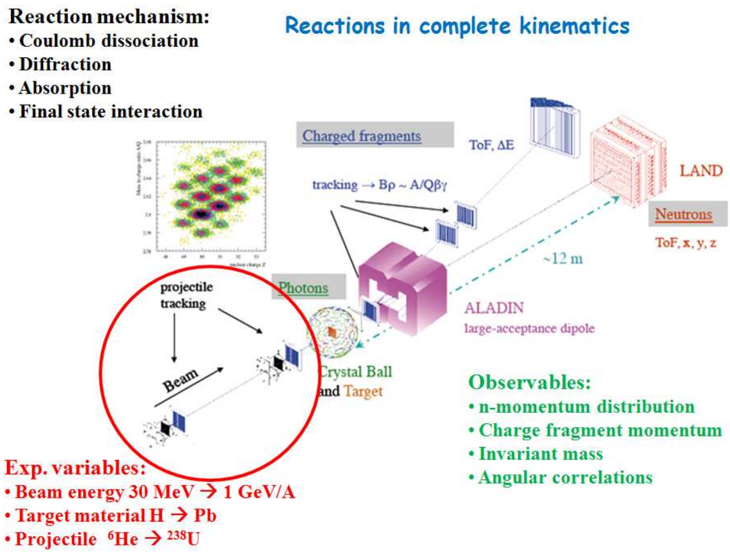

Figure 4. Schematic drawing of the LAND experimental setup, indicating the parameters in a Kinematically Complete Reaction Experiments: The Experimental variables, the observables and the information aimed for.

Table 2. Physics to be adressed at NUSTAR

Reaction type	Physics goals
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, 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 phase. One of the main collaborations is the Nuclear Structure and Astrophysics NUSTAR, which compromises 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 gamma 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] $http://www.gsi.de/fair/index_e.html$
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