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NUSTAR – The teenage years

Towards operation at FAIR

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Abstract The "NUclear STructure, Astrophysics and Reactions" (NUSTAR) Collaboration was formed at the end of 2003. More than ten years later, a good fraction of the envisaged experimental equipment has been successfully developed and constructed. While the NUSTAR community is looking forward to the start of the civil construction for the new FAIR facility, existing NUSTAR equipment is tested and operated at radioactive ion beam facilities worldwide. The status of the project is briefly described at the stage when it enters the teenage years.

Keywords NUSTAR · FAIR · Nuclear structure · Nuclear reactions · Nuclear astrophysics

PACS 29.38.-c Radioactive beams · 29.25.Rm Sources of radioactive nuclei · 29.40.-n Radiation detectors · 29.20.-c Accelerators · 21.10.-k Properties of nuclei · Nuclear energy levels

1 Introduction

NUSTAR is one of the four experimental pillars at the Facility for Antiproton and Ion Research in Europe (FAIR) which is being constructed next to the existing GSI facility in Darmstadt, Germany. An overview of NUSTAR has been given on various occasions (see

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e.g. [1–3] and references therein). It comprises all relevant aspects of the investigation of short-lived nuclides, for example measurements of masses, lifetimes, matter and charge radii, as well as the structure of excited states. To this end, several experimental setups located in different experimental caves will be used to unravel the properties of the exotic ions produced at FAIR.

In general, FAIR will employ the present GSI linear accelerator UNILAC and the synchrotron SIS18 for injection of highly charged ion bunches into the new SIS100 synchrotron. In particular, NUSTAR will make use of the Super-FRS fragment separator, where, e.g., uranium ions at 1 GeV/u will impinge on a target and the products from in-flight fragmentation and fission will be separated with high resolution and contaminating isotopes will be efficiently suppressed [4, 5]. Together with the primary beam intensities achievable at SIS100, the Super-FRS will provide several orders of magnitude higher yields of exotic nuclides [4] as compared to the present fragment separator FRS which receives ions accelerated by the SIS18 on its target.

Although the NUSTAR experiments are somewhat independent from each other, there is a large synergy in the physics questions raised and they all share the need for an operational Super-FRS. Therefore, the planning of the construction of components and installation of the experimental systems in the new experimental caves at FAIR depends very much on the time schedule of civil construction of the new facility and the construction and commissioning of the accelerator infrastructure and the Super-FRS. Since the construction of the facility is about to start, NUSTAR enters a very exciting phase of the project. In this paper, the present status of the NUSTAR experiments is given.

2 Project time line

NUSTAR has seen more than a decade of major milestones along the project timeline: The Conceptual Design Report of FAIR was published in 2001 and presented the science case as well as technical aspects of the proposed facility [6]. Following this preparatory phase with further discussions on the possibilities at FAIR, the NUSTAR Collaboration was formed in 2003. Details of the experimental equipment and the physics program were outlined in the FAIR baseline technical report for the full FAIR facility [7]. This baseline also provided a first detailed financial estimate of the many work packages of NUSTAR.

The first technical design reports appeared in 2008 for the LYCCA calorimeter [8] and the AIDA implantation and detection system [9], followed shortly after by the description of the MATS and LaSpec experimental setups [10]. In 2009, the Modularized Start Version (MSV) of FAIR was defined [11], mainly shifting the SIS300 accelerator and the NESR storage ring to a later stage of the FAIR project. For the NUSTAR Collaboration this had the consequence that some initially planned experiments (EXL and ELISe as well as some parts of ILIMA) were put on standby, albeit research and development continued throughout the following years.

With the founding of FAIR in 2010 as an international organization with presently nine shareholder countries and one associate member country, the project started to take shape with respect to advancing the civil construction planning and project planning of the experiments as laid out in the FAIR MSV. First components of NUSTAR were ready a few years later. For example the LYCCA calorimeter was employed, together with a subset of the AGATA gamma spectrometer array, for a precursor campaign at GSI of HISPEC/DESPEC in 2012 and 2014 (called PreSPEC [12]).

The FAIR civil construction started off in 2013 with the site preparation (more than 1300 stabilizing concrete piles were put in the ground) which was finished in summer 2014. In 2013 the monitoring of the cost of the experiments was started by the FAIR Resources Review Board. Throughout the subsequent years, more and more TDRs were submitted and the cost estimate as well as the technical description of NUSTAR components was further refined. The last main TDRs are expected in 2017 and then the work on a Memorandum of Understanding can be completed for the construction phase of NUSTAR at FAIR.

Finally, in 2015, the Super-FRS has seen a major milestone with the conclusion of a contract for the construction of more than 30 multiplet magnets to be built over the next years. The civil construction of FAIR also enters a new phase, as civil construction planning for the buildings, accelerator tunnels and experiment caves comes to an end. A call for tender was recently published for a first batch of the construction of the SIS100 ground preparation and buildings. Construction is supposed to start in the middle of 2017. For the NUSTAR experimental caves the planning is also in the final stage and construction is expected to start around 2019.

3 Physics program for start phase

In 2014, the NUSTAR Collaboration decided at a meeting in Valencia [13] to stage the whole project into phases. Phase 0 comprises the operation of NUSTAR equipment at GSI and other international ion beam facilities for tests or first experiments using already built NUSTAR equipment. Phase 1 describes the period when first beams from Super-FRS at FAIR will be available. In Phase 2 the NUSTAR detectors will be completed in terms of their definition within the MSV and the full intensity of FAIR beams. Additional Phases 3 and 4 are dedicated for projects beyond FAIR MSV and large scale upgrades, respectively.

During a review in early 2015, the key physics topics of NUSTAR have been outlined, which shall be pursued in the first years of FAIR operation: (1) Understanding of the third r-process peak by means of comprehensive measurements of masses, lifetimes, neutron branchings, dipole strength, and level structure along the $N = 126$ isotones; (2) Investigation of the Equation of State (EoS) of asymmetric matter by means of measuring the dipole polarizability and neutron skin thicknesses of tin isotopes with N larger than 82; and (3) Study of exotic hypernuclei with very large N/Z asymmetry.

4 Status of experiments

NUSTAR, as defined in the Modularized Start Version of FAIR, consists of the low-energy experiments MATS and LaSpec, the nuclear spectroscopy experiment HISPEC/DESPEC, and R^3B for reaction experiments at high beam energies. Furthermore, ILIMA will be implemented in the CR storage ring to measure ground state properties and isomers of exotic nuclei. More recently, additional programs have been added to the NUSTAR portfolio, for example the Super-FRS Experiment collaboration which plans to employ the Super-FRS together with additional detectors and setups at various focal planes for experiments, employing the Super-FRS as a high-resolution particle spectrometer. Recently, the EXL Collaboration discussed options to run part of its program at the HESR storage ring. In the following, a brief update of the status of the NUSTAR experiments will be given.

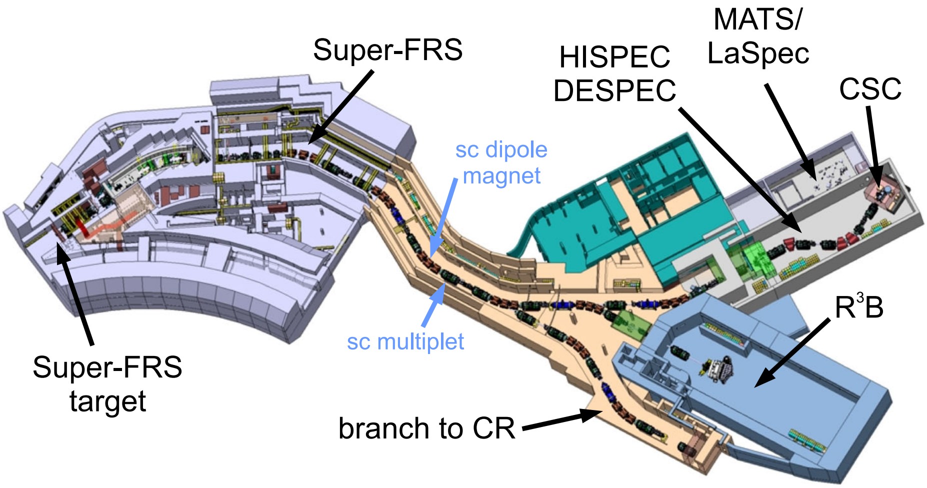

Fig. 1 Super-FRS tunnel and adjacent experimental caves: HISPEC/DESPEC with the energy-buncher /spectrometer, MATS and LaSpec in the low-energy branch, receiving beam from the cryogenic stopping cell (CSC), R^3B in the high-energy branch, and ILIMA in the Collector Ring (CR) where only the beamline toward the CR is shown

4.1 Super-FRS

The Super-FRS [4] is part of the accelerator infrastructure of FAIR, providing exotic nuclides with a high degree of purity to the subsequent experiments. Figure 1 shows a technical drawing of the Super-FRS with its target area, the tunnel where the superconducting magnets are placed and the adjacent experimental caves at the end of the low-energy branch, the high-energy branch and the ring branch. The drawing gives the status of planning in mid-2016, i.e. parts of the civil construction planning were not completed at this stage.

While the multiplet magnets are in production, the superconducting dipoles are in the final phase of design planning (in cooperation with CEA Saclay). Besides the careful planning of the cryogenics system for the Super-FRS [14], the design of the target area and the target wheel as well as the beam diagnostics are challenging work packages for the participating in-kind partners. In the low-energy branch, it is planned to have the so-called energy-buncher/spectrometer as an in-kind contribution from India to the FAIR accelerator infrastructure, where a new layout [5] has been taken into account as compared to the initial design as given in the technical proposal.

In addition to being a high-resolution separator with dedicated beam tracking and detection systems, the Super-FRS can also be employed as an experiment, which is pursued by the Super-FRS Experiment Collaboration [15]. Besides the support for the construction of the Super-FRS, a physics case has been formulated and the various physics ideas are structured in several work packages [16]. The implementation into the MSV of FAIR is in the pipeline and first TDRs are prepared to define the future experimental setups.

4.2 HISPEC/DESPEC

The HISPEC/DESPEC Collaboration is a joint effort of two communities, for high-resolution in-beam spectroscopy and decay spectroscopy. Both share the same experimental area in order to use dedicated detector systems for the various specific investigations of the radionuclides delivered by the Super-FRS. In the case of HISPEC, the core detector setup comprises the AGATA Germanium detector array [17] around a target and the LYCCA calorimeter [8] for particle identification. Additionally, the MONSTER neutron detector array [18] can be mounted around AGATA. See [1] for further details.

For DESPEC, the ions have to be stopped in order to perform the envisaged experiments. To this end, the AIDA implantation and decay detector is employed. Depending on the specific needs of a particular decay experiment, the neutron detector systems BELEN and NEDA as well as the gamma detector systems DEGAS, FATIMA [19], and DTAS [20] can be used in various combinations.

Many detectors are ready for operation, for example first results have been obtained with DTAS [21] and AIDA is presently operated at the radioactive ion beam facility RIKEN in Japan. The present planning focusses on the infrastructure especially for the installation into the future experimental cave of the low-energy branch. With the PreSPEC campaign and the envisaged Phase 0 program at GSI, HISPEC and DESPEC are well underway for the transition to the operation at FAIR [22].

The Phase 0 program of DESPEC comprises the investigation of heavy nuclei around $N = 126$ close to the third r-process waiting point. To this end, the systems AIDA, DEGAS, DTAS and FATIMA will be used for the experiments at GSI. HISPEC, with AGATA being the core equipment, will only start in Phase 1 of NUSTAR.

4.3 MATS and LaSpec

Although MATS [10] and LaSpec [10, 23] are two distinct experimental setups specialized for mass spectrometry and laser spectroscopy, respectively, they both share a common beam line for the stopping and preparation of the exotic nuclides delivered from the Super-FRS target. For the injection of radionuclide ions into ion traps and to obtain suitable overlap with laser beams, the beam emittance has to be sufficiently low which is achieved by the use of a radiofrequency quadrupole cooler and buncher (RFQ) (see [10] for details). The latter is operated at a few tens of kilovolts potential and therefore, the initial incoming ion beam from Super-FRS has to be reduced in energy for an efficient injection into the RFQ. This task is performed by a cryogenic stopping cell (CSC) at the final focal plane at the end of the energy-buncher/spectrometer. The product ions from Super-FRS are stopped in helium gas and extracted from the cell by use of rf carpets toward the MATS and LaSpec RFQ. A prototype stopping cell system has already been built and successfully tested and the technical design of the final CSC is in progress [24, 25].

For MATS and LaSpec initial experimental setups exist at the University of Mainz, where the respective prototype beam lines are connected to the TRIGA reactor in order to receive fission product ions via a capillary transport system [26, 27]. Also off-line operation is performed to test the components prior to the move to the FAIR facility. For example, the precision that can be obtained with the existing collinear laser-spectroscopy setup has been demonstrated with stable Ca isotopes [28]. Furthermore, the technical development on the control and data acquisition system is ongoing [29].

During the Phase 0 of NUSTAR, MATS will continue to pursue technical developments in cooperation with other Penning trap mass measurement systems as well as the prototype setup at the TRIGA reactor at Mainz University, where first results have already been obtained [30–32]. In the case of LaSpec, it is planned to move part of the existing equipment to Argonne National Laboratory for laser-spectroscopy experiments on ^{8}B [33]. In addition, LaSpec Phase 0 will be coupled to the CARIBU facility [34] in order to continue systematic studies of the experimental setup for the future use at the FAIR facility. This will also serve as a test for the coupling of LaSpec to a gas catcher system [35].

4.4 R^{3}B

The R^{3}B experiment is dedicated to the investigation of radionuclides by use of kinematically complete measurements of reactions in a target at high energies [36, 37]. Right after the target the charged products pass through the large dipole magnet GLAD [38] and are monitored with tracking detectors. The neutrons are unaffected the GLAD magnet and are measured with the NeuLAND neutron detector [39, 40] which has the capability (once fully built) to disentangle up to 5-neutron events.

The GLAD magnet has been delivered to GSI at the end of 2015 and has meanwhile been placed in the experimental hall "Cave C" of GSI (see Fig. 2) in order to be employed for an experimental campaign (Phase 0 program at GSI) before the start of FAIR and Super-FRS beams become available. Out of the 30 double planes of NeuLAND (one double plane consists of two layers of 100 scintillator bars each) up to 12 are funded and will be operational for Phase 0. Four of those NeuLAND double planes were recently shipped to the RIKEN facility in Japan to perform first tests and conduct experiments.

The other main detector system is the calorimeter CALIFA [41–45] which surrounds the target area with the target recoil ion detector [46]. While CALIFA is partly funded and construction has started, the silicon tracker system will be completely available for Phase 0. Thus parts of CALIFA and NeuLAND as well as tracking detectors and of course the GLAD magnet will be available for the Phase 0 program at GSI, where experiments similar to the measurement of two-neutron knockout reactions [47] are planned in the period 2018-2020.

4.5 ILIMA

The ILIMA experiment [48] wants to study isomeric states, lifetimes, and masses of short-lived nuclides. Although the NESR storage ring will not be built as part of the FAIR MSV, the core program can be pursued in the CR storage ring. It is also planned to employ the HESR and the ESR at a later stage. Three main types of detectors will be used: Schottky pick-up systems, ToF detectors for time-of-flight measurements, and particle detectors to study the decay of the short-lived ions in the storage ring. For all detectors, prototype systems are available and the final design for the operation in the CR is in progress.

4.6 ELISe

The ELISe experiment [49, 50] aims at the investigation of nuclear structure by use of electron scattering. ELISe was supposed to be mounted at the NESR storage ring in order to overlap the stored and cooled exotic ion beams with electrons circulating in an adjacent electron storage ring (filled with electrons from a pulsed linear accelerator). The scattered electrons and the reaction products will be detected with an in-ring spectrometer.

Since the NESR will not be realized in the FAIR MSV, the ELISe collaboration is looking for alternatives in order to run ELISe at FAIR. One possibility is to use the ESR storage ring, albeit some modification of the storage ring is required, in order to match the requirements of ELISe and the additional electron storage ring, and further space would be needed for an electron linear accelerator. Furthermore, a connection of the ESR to the Super-FRS beams (via a new beam line connecting the chain CR and HESR with the ESR) is desirable, which would be also a project beyond the FAIR MSV. Therefore, the ELISe collaboration

Fig. 2 GLAD magnet shortly after its move into Cave C of GSI. It will stay at this position until the final move to the high-energy cave of the FAIR facility

continues with the preparatory work and design studies and keeps its physics case up to date in order to be ready once funding will be available.

4.7 EXL

Similar to ELISe, EXL [51] requires the NESR for reaction studies on cooled and stored exotic nuclides. However, in contrast to ELISe, FAIR will offer a variety of storage rings, in particular the HESR, where part of the EXL science program can be performed. The EXL collaboration is presently investigating these possibilities and a conceptual design report is in the making. First results have already been obtained with a prototype system at GSI using the ESR storage ring [52, 53]. It is planned to continue the scattering experiments at the ESR and proton-induced reactions in CRYRING [54] during the Phase 0 of NUSTAR at GSI.

4.8 SHE

The research program of the super-heavy element (SHE) community at GSI has a long history [55, 56]. Both physics and chemistry of super-heavy elements are investigated with tailored experiments, where the UNILAC is the work horse for the production of super-heavy nuclides. Recently, the SHE Collaboration joined NUSTAR in order to continue all facets of super-heavy element research including mass measurements [57, 58], laser spectroscopy [59, 60], and chemistry [61] at FAIR.

In course of the adaption of the injector chain of GSI for FAIR, the UNILAC will most likely change its parameters such that it cannot be used for SHE research in the near future. With the present UNILAC it is planned to study chemical properties of elements beyond $Z = 112$ and nuclear structure and atomic properties beyond element $Z = 102$ at GSI during Phase 0 of NUSTAR. This will bridge the time until a continuous wave (cw) linear accelerator has been built. At present, it is planned to construct such a dedicated cw linear accelerator [62] in order to serve the SHE community as well as other experiments with the required beams.

5 Conclusion

In general, the NUSTAR experiments are very much advanced with respect to the main detector systems. Presently, the infrastructure of the experiments is defined as part of the final work in the building planning. While the NUSTAR Collaboration is eagerly awaiting the start of the construction of the FAIR facility, it plans to perform experiments at GSI and other facilities in order to test their systems and to train students and young scientists for the future tasks and operation at FAIR. In paticular, a Phase 0 program at GSI is envisaged, starting in the year 2018.

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