Eurasian Journal of Physics and Functional Materials
2017, **1**(1), 19-24

NUSTAR experiments on the way from GSI to FAIR

C. Scheidenberge
GSI Helmholtzzentrum fur Schwerionenforschung, Darmstadt, Germany
Justus-Liebig-Universitat, Giessen, Germany
e-mail: c.scheidenberger@gsi.de

Received 25.10.2017

The NUSTAR Collaboration will perform experiments with relativistic exotic nuclei and superheavy elements at GSI and FAIR. Presently, several new FAIR detector systems are under construction for high-resolution spectrometer experiments, decay spectroscopy, reaction studies with internal and external targets, and for experiments with stopped and re-accelerated beams. Due to the delayed start of the FAIR project, the new FAIR detectors will be used at GSI with beams from the existing accelerators (UNILAC, SIS-18/ESR) and set the scene for new experimental avenues, not existing so far. The planned intermediate research program and the new opportunities are outlined.

Keywords : relativistic exotic nuclei, superheavy elements, NUSTAR detector systems.

Introduction

FAIR, the international Facility for Antiproton and Ion Research next to GSI, builds on four major scientific collaborations: APPA (Atomic, Plasma Physics and Applications), CBM (Compressed Baryonic Matter experiment), NUSTAR (nuclear structure, astrophysics, reactions and superheavy element research), and PANDA (Anti-Proton Annihilation at Darmstadt). The major challenge is the civil construction of FAIR, which is presently underway. The key instrument of the NUSTAR Collaboration at FAIR is the super-conducting fragment separator, the Super-FRS. This instrument delivers beams of exotic nuclei to the experimental areas and detector systems HISPEC/DESPEC, MATS/LASPEC (all located at the Low-Energy Branch), R^3B (located at the High-Energy Branch) and ILIMA (Storage-Ring Branch); it will also provide opportunities for novel spectrometer experiments with ancillary detectors that are integrated in the main separator branch. While the construction of FAIR buildings and accelerators is ongoing, the NUSTAR collaboration exploits the beams of the existing GSI accelerator facilities, UNILAC and SIS-18/ESR, and the experimental areas to implement, test, and use their new NUSTAR-FAIR detector systems; with the start versions of the new detector systems, a variety of new and unique experiments can be performed in this so-called “FAIR Phase-0”.

Superheavy element research

*T*he search for the limits of existence of nuclei is one of the most prominent scientific pillars of GSI. In particular the search for the heaviest chemical elements persists as key research area in many other laboratories around the world. While beam time at GSI is scarce, time consuming experiments to synthesize new elements cannot be performed any longer under the present conditions. Instead, several shorter experiments are being performed, which take advantage of the unique combination of instrumental equipment that is available at GSI and its world-class separators SHIP and TASCA. This opens up excellent scientific opportunities in chemistry, atomic physics, nuclear spectroscopy, laser spectroscopy, mass measurements and other directions. Recent highlight examples are the first synthesis of the new compound molecule $Sg(CO)_6$ [1] and the chemical studies of Nh and Fl [2], high-precision mass measurements [3] and first laser-spectroscopic studies of No-isotopes, which yield ionization energies and details of atomic level schemes [4]. For details, the reader is referred to the contributions to these proceedings by A. Yakushev, V. Pershina and P. Chhetri. The new super-conducting continuous-wave linear accelerator (s.c. cw-linac) is presently under construction at GSI; it will deliver beams with kinetic energies up to 7 MeV/nucleon; first experiments (with about ten times increased intensity compared to the existing UNILAC) are expected in year 2022. Thereafter, the search for new elements will be continued with much increased efficiency, with the hope to open up a new period in the periodic table.

Spectrometer experiments at the borderline of atomic, nuclear and hadron physic

The Super-FRS is widely used as beam-delivery system for relativistic exotic nuclei (production, separation, identification). In order to separate the heaviest fragments up to uranium, a high momentum resolving power is needed at the corresponding phase space (induced by the fragmentation or fission reactions). This spectrometer capability can be used for a variety of atomic, nuclear and hadron physics experiments, where the separator-spectrometer is intrinsic part of the measurement. In the energy range >400 MeV/nucleon, the Super-FRS is the world- wide only separator-spectrometer experiment. Presently, several ancillary detectors are under construction and will be available for pilot experiments at the FRS in Phase-0 from 2018 onwards, and among several smaller pieces of equipment the most complex detectors are e.g.

- the EXPERT setup [5] for radioactive in-flight decays and continuum spectroscopy by particle emission, which aims at studies at the borderline between resonant behavior and continuum response of nuclei;
- a WASA-type detector [6] for pion detection and momentum measurement, which will be used for exotic hypernuclei experiments, for Delta-resonance excitation probing nuclear structure in peripheral collisions, and for production and study of exotic atoms (such as eta-prime mesic nuclei);
- highly segmented high-rate detectors for the observation of high- momentum components of nucleons and the observation of correlated nucleons in nuclei; zero-degree scattering in nucleon-transfer reactions such as (p,d), (d,t) and

(d,^{3}He) at beam energies $>> 400$ MeV/nucleon can contribute to clarify the importance of the tensor force;

• a cryogenic gas-filled ion catcher [7], that is a versatile instrument andthat opens up a variety of new experiments after in-flight separation, such as reaction studies in the gas with exotic nuclei around the Coulomb barrier, it can provide ISOL-type beams at keV-energies, it allows for direct mass measurements with an MR-ToF mass spectrometer, it provides isomerically pure beams, etc.

More examples and a more detailed description can be found in the proceedings of the EXON-2014 conference [8] and in [9].

Spectroscopy and nuclear data for understanding the 3 rd r-process abundance peak

Nuclear astrophysics as a cross sectional discipline, that aims for a detailed understanding of the different stellar and explosive nucleosynthesis processes, requires various basic nuclear physics data. A major challenge is the quantitative modeling of the 3rd r-process abundance peak. This area is difficult to reach with present day techniques at the existing radioactive beam facilities. Here, the high energies available at GSI and FAIR (which allow for an unambiguous identification) and the selectivity of the in-flight separation combined with highest sensitivity of event-by-event particle detection (which allows for experiments with rates as low as $\sim$1atom per day) provide the basis for dedicated measurements of nuclear data of neutron-rich nuclei around the N=126 shell closure. Especially with the experiments MATS/LASPEC [10] and HISPEC/DESPEC [11], which will be located at the Low-Energy Branch of the Super-FRS, the NUSTAR collaboration will explore masses, β-lifetimes, neutron-branching ratios, strength distributions and level structures of exotic nuclei. The setups are highly modular and comprise various sub-systems. Several of them have already been completed such as DTAS (a total absorption spectrometer), LYCCA (for particle identification), AIDA (for decay spectroscopy), BELEN (for low-energy neutron detection) and several others. The HISPEC/DESPEC collaboration is presently using them at various facilities around the globe, for instance at GANIL, ISOLDE, IFIN-HH, JYFL, RIKEN and other places for tests and first measurements under realistic experimental conditions. In the new campaigns from 2018 onwards, new territories, especially along N=126, are in reach and new isotopes can be accessed, which touch the r-process pathway, see figure 1.

New storage ring experiments for nuclear structure and nuclear astrophysics

Also at the storage ring branch there are new opportunities for experiments with stable and radioactive ion beams, especially with the recently installed CRYRING. During the commissioning, beams extracted from SIS and ESR have reached the CRYRING and beams from the internal ion source were circulating in the CRYRING. From year 2018 onwards, highly-charged ions and bare nuclei can be stored and studied in an energy domain from ~ 100 keV/nucleon to ~ 1 MeV/nucleon; atomic collision experiments, ion-surface interaction studies using the ultra-high electromagnetic fields and nuclear physics experiments become possible. This energy range is particularly interesting for direct capture reactions, such as (p,γ) on stable and unstable nuclei in inverse kinematics, as

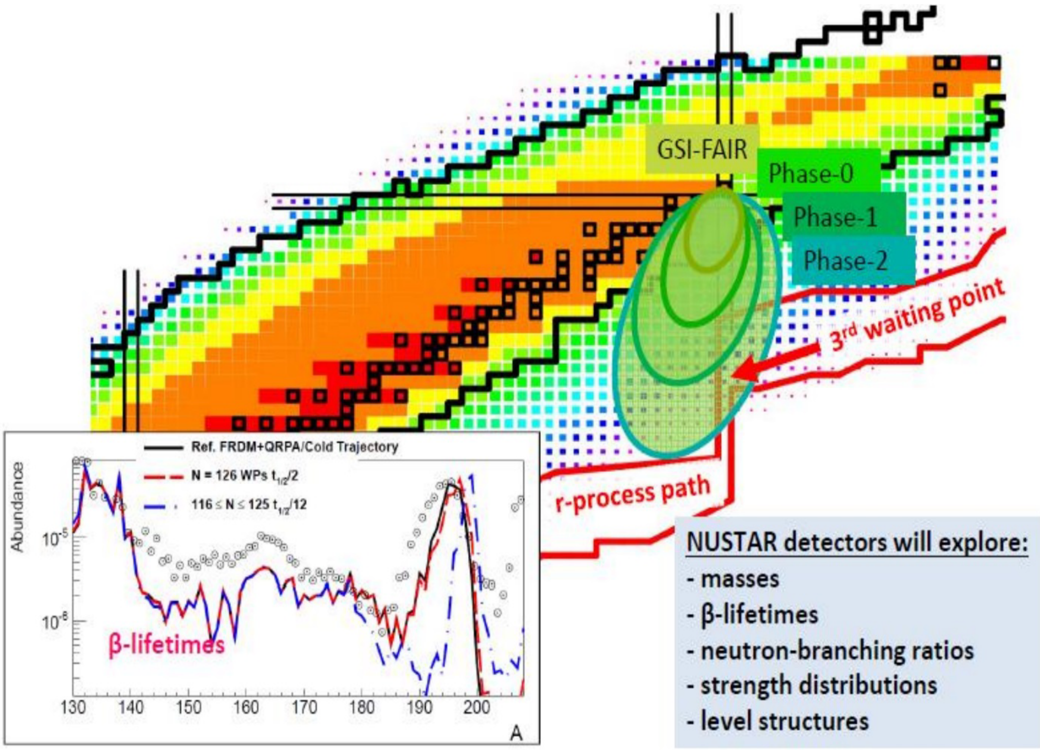

Figure 1. Nuclides of interest for r-process nucleosynthesis around the third abundance maximum. The inset shows the observed stellar abundances and the results of network calculations for different beta-decay lifetimes. With increasing beam intensities at GSI (Phase-0) and the availability of the Super-FRS at FAIR (Phase-1 and Phase-2) more and more nuclides along and around N=126 become accessible for obtaining the relevant nuclear data.

it covers the Gamow window of the rp-process for explosive nucleosynthesis. At higher energies, around 400 MeV/nucleon, pilot experiments on scattering of stored beams off internal targets have been performed recently in the ESR: primary ^{58}Ni and ^{56}Ni secondary beams have been accumulated, interacted with the H-atoms of the gas jet target, and the recoils have been detected with a prototype DSSD and Si(Li) detector of the EXL experiment. The window-less detectors, which are mounted directly into the ultra-high vacuum of the storage ring, probe direct reactions in inverse kinematics at very low momentum transfer q. This technique enables high-resolution measurements of the differential cross section for elastic proton scattering down to very low q. Experimental spectra have been obtained [12] and allow to determine the nuclear matter distribution of ^{56}Ni. In a pilot run, the feasibility of elastic α-scattering from ^{58}Ni in inverse kinematics was demonstrated [13]. This allows for studying the Giant Monopole Resonance in ^{58}Ni down to center-of-mass angles to 1 degree or even below, see figure 2. It is planned to perform such a measurement with doubly magic ^{56}Ni, which will then provide information on the EOS and the compressibility of nuclear matter.

Complete kinematics measurements for reactions with relativistic radioactive beams

In Cave C, the ALADIN-LAND setup has been dismantled and the new R^3B setup (for "Reactions with Relativistic Radioactive Beams") is under construction. It comprises the GLAD magnet (GSI Large Acceptance Dipole magnet), start versions of CALIFA (CALorimeter for In-Flight detection of gamma-rays and high energy charged pArticles) and NeuLAND (new Large-Area Neutron

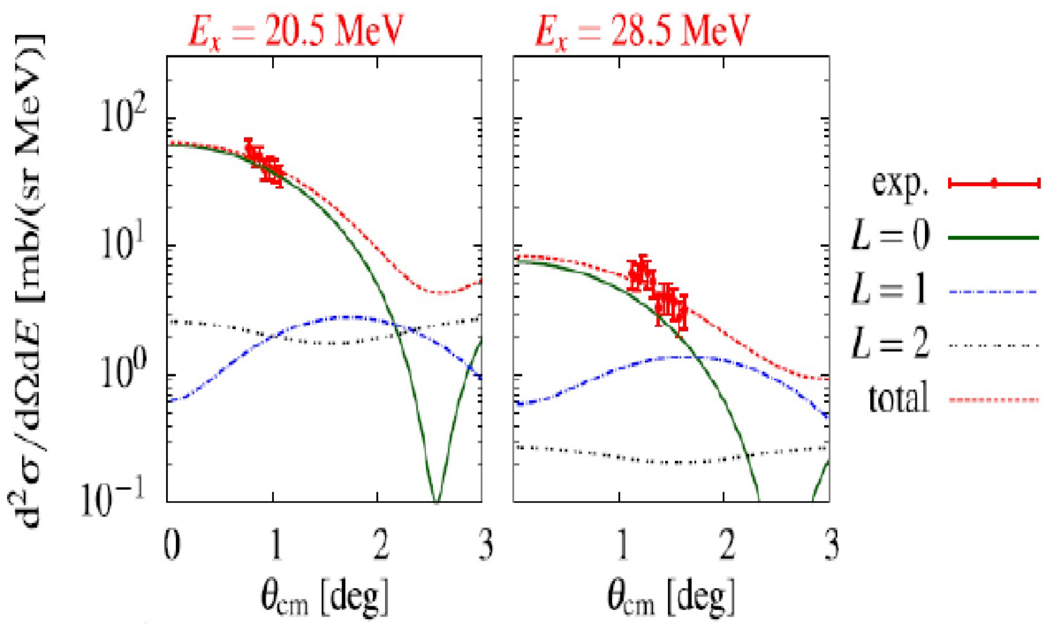

Figure 2. Multipole decomposition analysis of the measured double-differential scattering cross section of ^{58}Ni of an internal He-target in the ESR in inverse kinematics. The plots show angular distributions for different excitation energies. From ref. [13].

Detector) detector and various other sub-systems for reaction experiments using complete kinematics; the setup is optimized for large angular acceptance of all reaction products, high rigidity beams (i.e.: neutron-rich isotopes at ~ 1 GeV/nucleon) and multiple neutron detection capability. With this new setup, several experiments become possible for the first time and exploit the uniqueness of R^3B such as

- multiple neutron decays beyond the drip-line and for very heavy neutron-rich isotopes;
- kinematical complete measurement of quasi-free nucleon knockout reactions (at large momentum transfer);
- electric dipole and quadrupole response of Sn nuclei beyond N=82, and of neutron-rich Pb isotopes; the dipole polarizabilities along the chains up to very n-rich heavy nuclei will give tight constraints on the symmetry energy and its density dependence, which is relevant for neutron star physics.

As an example, the dipole strength distribution in neutron-rich nuclei can be probed by the interaction with the virtual photon spectrum of the Coulomb field of very heavy nuclei [14]. Presently, the maximum energy of the equivalent photon spectrum reaches a few MeV, while an extended range up to ~ 40 MeV can be reached with high-energy beams (1 GeV/nucleon), see figure 3. The classical giant resonance pattern with a single peak may exhibit more complex structures at higher excitation energies, which are the result of neutron halo's and the corresponding breakup of the neutron halo and the core. The R^3B experiment is an avenue to open up this new excitation energy domain, it will allow for an unique experimental program for nuclear structure and astrophysics using kinematical complete measurements of reactions with ~ 1 GeV/nucleon radioactive beams.

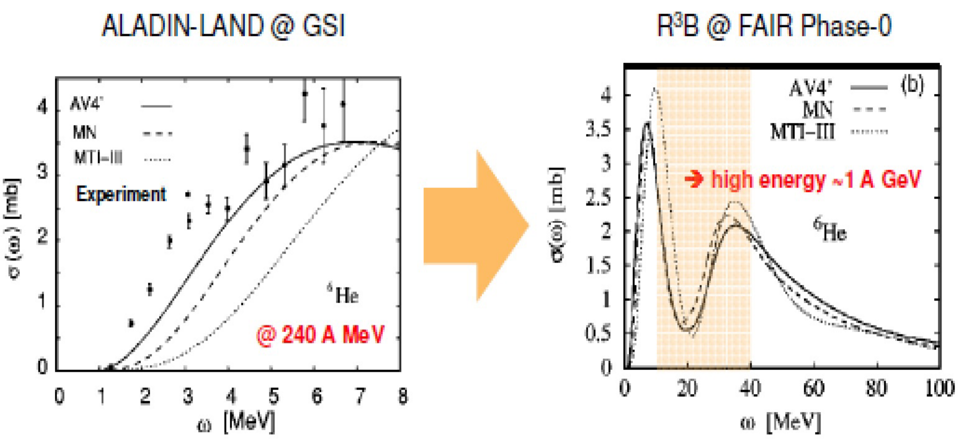

Figure 3. Dipole strength distributions in R^{3}He . The measured data have been obtained at a beam energy of 240 MeV/nucleon with the previous ALADIN-LAND setup of GSI and reach up to excitation energies around 7 MeV. Much higher excitation energies will become available with GeV/nucleon-beams and the new R^{3}B setup in Phase-0 of FAIR. Calculations are taken from ref. [15]

Summary and Conclusions

The merger of GSI and FAIR becomes manifest in the FAIR Phase-0 research program: the novel NUSTAR detector systems and equipment will be used together with the GSI accelerator facilities and beams from 2018 onwards for an original research program in nuclear structure and astrophysics, which builds on characteristic features such as high-energy beams, high-resolution momentum analysis, storage rings and high-energy reaction studies. Besides, the FAIR Phase-0 program will allow to construct, test and debug the complex detector systems of the NUSTAR collaboration; new concepts and algorithms can be implemented; when the Super-FRS is completed, the detectors will be moved from GSI to the FAIR site; this strategy avoids delays of a complicated start-up phase and will allow for harvesting physics results at an early stage of FAIR.

References

[1] J. Even et al., Science **345** (2014) 1491.
[2] A. Yakushev et al., Inorg. Chem. **53** (2014) 1624.
[3] E. Minaya Ramirez et al., Science **337**, No.6 (2012) 1207.
[4] M. Laatiaoui et al., Nature **538** (2016) 495.
[5] H. Geissel et al., Proceedings of EXON-2014, pp. 579 (2015).
[6] Chr. Bargholtz et al., Nucl. Instr. Meth **A594** (2008) 339.
[7] W.R. Plab et al., Nucl. Instr. Meth. **B317** (2013) 457.
[8] C. Scheidenberger et al., Proceedings of EXON-2014 (2015) pp. 491.
[9] J. Aysto et al., Nucl. Instr. Meth **B376** (2016) 111.
[10] D. Rodriguez et al., Eur. Phys. J. Special Topics **183** (2010) 1.
[11] S. Akkoyun et al., Nucl. Instr. Meth **A668** (2012) 26.
[12] J.C. Zamora et al., Phys. Lett. **B763** (2016) 16.
[13] M.v.Schmid et al., Physica Scripta **T116** (2015) 014005.
[14] D.M. Rossi et al., Prog. Theor. Phys. Suppl. **196** (2012) 465.
[15] S. Bacca et al., Phys. Rev. Lett. **89** (2002) 052502.