

Studies of exotic nuclei: state-of-the-art experimental tools and techniques

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Abstract. As new radioactive-ion beam facilities are coming online there is an even growing need for advanced experimental apparatuses that offer unprecedented resolution and efficiency and can fully exploit the physics opportunities that open up in this new for the nuclear physics community era. In this contribution state-of-the-art equipment and techniques for nuclear physics experiments are presented.

1. Introduction

The study of the atomic nucleus dates more than a hundred years back, when early experiments indicated that an atom has a small, central, dense and positively charged core. Since then, there has been a tremendous progress in understanding the structure and properties of the atomic nucleus. The vast majority of our knowledge originates from studies of a few hundred nuclei at or near the valley of β stability. There is, however, an even larger number of nuclei that are short lived (radioactive or exotic) and do not naturally occur on earth. It is only in the last decades that the nuclear physics community gained access to this unknown territory of the nuclear chart, which became available with the advent of radioactive-ion beam (RIB) facilities. Recent major upgrades in the world's most powerful facilities opens up the way for studies of even more exotic systems and in much greater detail.

Some of the strongest motivations to extend our studies to the most exotic nuclear systems include the fact that although they are not found on earth, they play an important role in the cosmos as they are constantly created in stars. Furthermore, exotic nuclei provide a fertile ground to study quantum phenomena such as clustering, quantum dots and phenomena unique to weakly bound systems. Such phenomena are also important in other fields of physics today and in many cases a universal description can be applied. Finally, major advances in many-body theory result from investigations of nuclei with very different proton-to-neutron admixtures, since certain parts of the nucleon-nucleon interaction are particularly sensitive to the proton-to-neutron asymmetry.

2. Production of exotic nuclei

The two most popular methods to produce exotic nuclei are:

- the production at rest followed by Isotope-Separation-On-Line (ISOL-technique)
- the production and separation in flight using heavier ions (fragmentation technique)

In the fragmentation technique, a high-energy primary beam impinges on a production target and gets fragmented. In this process many different nuclei are produced including some which are very exotic – typically the cross-section for producing exotic nuclei falls rapidly as a function of their distance from the stability line. These fragments are then flying in forward angles, due to the high beam energy, and can be separated and identified through a magnetic spectrometer (commonly referred to as fragment separator). The selected and identified species (constituting the secondary beam) are then transported to the experimental halls where they are probed using a secondary target. The primary beam intensity and the acceptance of the fragment separator are two of the most important factors that determine the secondary beam intensity and thus define how far exotic systems can be probed.

Some of the largest fragmentation facilities worldwide include the GSI/FAIR facility in Germany, the NSCL/FRIB facility in the United States and the RIKEN/RIBF facility in Japan. Recent or ongoing upgrades in these facilities enable studies of exotic systems which were not feasible before. Besides the major upgrades in the production of the secondary beams, the experimental apparatuses are also being significantly improved in terms of resolution, detection efficiency and rate capability.

3. State-of-the-art experimental tools and techniques for nuclear structure studies

3.1. NUSTAR (Nuclear Structure and Astrophysics Research) at FAIR (Facility for Antiproton and Ion Research)

The NUSTAR collaboration aims at exploring the structure and properties of the atomic nuclei by exploiting the high-intensity radioactive-ion beams that will become available at FAIR. The collaboration utilises different and complimentary ways to probe the nucleus. The main experiments planned within the NUSTAR collaboration at FAIR are the following:

- Super-FRS (RIB production, identification and high-resolution spectroscopy),
- DESPEC (γ -, β -, α -, proton- and neutron-decay spectroscopy),
- HISPEC (in-beam γ -ray spectroscopy at low and intermediate energy),
- ILIMA (masses and lifetimes of nuclei in ground and isomeric states),
- LaSpec (laser spectroscopy),
- MATS (in-trap mass measurements and decay studies) and
- R³B (kinematically complete reactions at high beam energy),

which are currently being built in the first phase of the project and the experiments:

- ELISE (elastic, inelastic, and quasi-free e^- -A scattering) and
- EXL (light-ion scattering reactions in inverse kinematics),

which are foreseen in the second phase.

Some of the highlight physics questions that these experiments are aiming to address include:

- the changes in the nuclear structure as one moves away from the valley of stability; the evolution of the single-particle structure and the onset of deformations will be probed as a function of isospin,
- quantum phenomena that occur at extreme isospin values, such as neutron halos and neutron skins,
- pin down components of the nuclear force that become more prominent as the neutron-to-proton asymmetry increases,
- systematic studies of the collective response of exotic nuclei.

In the following section the R³B experiment is discussed in more detail.

3.2. The R^3B (Reactions with Relativistic Radioactive Ion Beams) experiment

The strength of the R^3B experiment is the kinematically complete measurement of reactions with relativistic short-lived ions with energies of up to 1 AGeV. These rare radioactive isotopes are produced at the beginning of the Superconducting Fragment Separator (Super-FRS) when the high-energy primary beam is fragmented on the production target. The separator selects and identifies on an event-by-event basis the ions of interest and measures their momentum to a 10^{-4} precision. The maximum beam rigidity that it can accept is 20 Tm. The R^3B experiment is planned at the high-energy branch of the Super-FRS.

The key constituents of the R^3B setup, shown in Fig. 1, are:

- the large-acceptance superconducting dipole magnet (GLAD). Its construction is completed at CEA Saclay and will be installed in cave C at GSI with all its cryogenic components beginning of 2015.
- The New Large Area Neutron Detector (NeuLAND). It is currently being built and 20% is completed already.
- The silicon tracker (R^3B -Si-Tracker). It has all components developed and is expected to be fully completed by the end of 2015.
- The photon and particle calorimeter and spectrometer (CALIFA). It is under construction with the goal to reach 20% in the year 2015.
- The in-beam tracking detectors for the heavy fragments and evaporated protons. It is under construction with the goal to be completed in 2017.

For more details on these systems the reader is referred to the corresponding Technical Design Report of each system [1, 2] and also to the R^3B Technical Proposal [3]. Once the individual

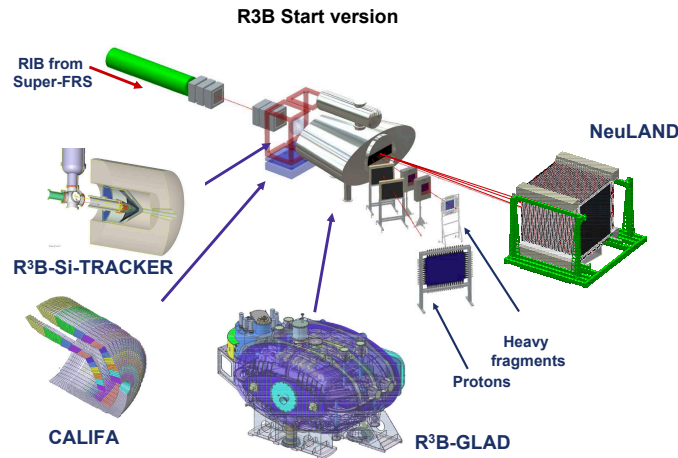


Figure 1. The R^3B setup in its startup version with its main components: the silicon tracker R^3B -Si-TRACKER, the calorimeter CALIFA, the dipole magnet R^3B -GLAD and the neutron time-of-flight spectrometer NeuLAND.

detection systems are complete, the apparatus will be able to measure all particles emerging from a reaction with high efficiency and resolution. A typical scenario would be as follows: the high-energy (1 AGeV) radioactive-ion beam, which is selected and identified through the fragment separator (Super-FRS), impinges on the secondary target and the beam-like fragments are moving at small forward angles and fly through the large acceptance dipole magnet GLAD. The trajectory and time of flight of the fragments is measured by the in-beam tracking detectors before and after the dipole magnet to a precision that corresponds to about 10^{-3} momentum

resolution. The light charged particles that scatter at large angles are tracked precisely with the finely segmented three-layer Si-R³B tracker. It is designed to offer, for example, precise tracking and vertex reconstruction by detecting the two protons originating from a (p,2p) quasifree scattering reaction (QFS). A total energy measurement of the target recoil charged particles is performed in the CALIFA calorimeter. The γ rays emerging from the excited nuclei are also measured by the CALIFA detector with very high efficiency due to its large geometrical coverage and minimum dead layers between the crystals. Its high crystal granularity allows for a precise Doppler correction; Doppler broadening is the dominant factor of the energy resolution at these relativistic energies. An unbound daughter nucleus – either excited in the continuum or lie beyond the neutron driplines – is likely to decay via neutron decay or evaporation. In this case, the in-flight emitted neutrons fly at forward angles through the dipole magnet and hit a large neutron time-of-flight wall (NeuLAND), where they are measured with very high efficiency. The high granularity of the neutron detector allows also for high neutron multiplicity measurements, which enables the study of very exotic systems and the poorly known multi-neutron correlations. In particular, once fully built it will provide an unprecedented detection efficiency of more than 50% for four neutrons evaporated from a fast moving fragment.

These kinematically complete measurements enable a rich and versatile physics program:

- QFS reactions, in which a bound nucleon is knockout out at high momentum transfer, offer a sensitive probe to study the single particle structure of exotic nuclei and also constitute an effective way to populate unbound nuclei. For example, when starting from very neutron rich nuclei as beam particles and knocking out a proton.
- Systematic studies of collective degrees of freedom in nuclei and their evolution towards more exotic systems. For instance, the low-lying strength below the Giant Dipole Resonance (GDR) identified as Pygmy Dipole Resonance (PDR), carries information about the neutron skin thickness of nuclei, which in turn is used in calculations of the symmetry term coefficient in the equation of state.
- The R³B setup will also be well suited to study total reaction cross section, as well as total charge-changing and total neutron-removal cross sections. This information can be associated to the nuclear and charge radii and the thickness of the neutron skin.

3.3. *The high-resolution γ -ray tracking arrays*

High resolution γ -ray spectroscopy has been and still is one of the most powerful ways to probe the structure of the atomic nucleus. This is reflected in the tremendous improvement of the γ -ray spectrometers over the last decades, in terms of resolution, efficiency, peak-to-total (P/T) ratio and γ -ray multiplicity.

The Ge detectors with their unprecedented resolution are at the forefront of γ -ray spectroscopy. One of the main limitations of the Ge detectors has been the relatively low P/T ratio for a typical coaxial geometry Ge crystal, e.g. only about 1 out of 5 γ -rays of 1 MeV energy that enter the crystal will deposit their full energy in this crystal. The rest of the γ rays will deposit only part of their energy - mainly through single or multiple Compton scattering - in the crystal, before escaping. These events generate a significant background at lower energies in the crystal's energy spectrum. The identification of other smaller energy γ rays is hindered by this background. For low γ -ray multiplicity events a solution to increase the P/T ratio is to pack several crystals next to each other in a clover geometry. However, for high multiplicity events this solution is not ideal. A very effective solution to increase the P/T ratio, which has been used in the past decades, is to Compton-shield the Ge crystal with fast scintillator detectors that veto the escaping γ rays. Combining many of such Compton-suppressed modules full four- π arrays have been built. These arrays have been used very successfully over the past two decades and have served a broad physics program with an important impact for nuclear physics.

The use of the suppression shields, however, limits the solid angle that can be covered by Ge detectors and thus limits the efficiency of the array. A pioneering solution to maintain the good P/T ratio offered by the Compton suppression and at the same time increase the efficiency is γ -ray tracking (see for example Ref. [4]). Instead of tagging on the escaping γ rays using Compton shields, one can fill the full four- π solid angle with Ge detectors and track the γ rays that scatter into the neighbouring crystal. In this way, the full γ -ray energy can be reconstructed and both the efficiency and the P/T ratio of the array improve drastically. Two such arrays have been specifically designed and built as γ -ray energy tracking arrays over the past decade: the GRETINA [5] and the AGATA [6] arrays. Both arrays cover a one π of the full solid angle and have been successfully completed. In the last couple of years they have started serving the nuclear physics community around the world.

Gamma-ray tracking uses the Compton relation to group and order the individual γ ray interaction positions inside the crystals for each γ ray. In order to perform γ ray tracking, it is required to know precisely the coordinates of each γ ray interaction position and the deposited energy in this position. In the 3D volume of large coaxial detectors with high electrical segmentation this can be achieved by recording the pulse shapes of the signals that are generated as the charge drifts towards the electrodes. The rise time of the signal depends on the drift distance between the segment (or central contact) electrode and the interaction position. In addition, the neighbouring segments see an image charge of opposite polarity during the drift of the charge in the hit segment. The magnitude of the image charge is related to the distance between this segment and the hit position inside the segment where the interaction occurred. In reality, the final signal shapes that the electrodes record for each event become rather complicated as they are folded with cross-talk effects, multiple interactions inside one segment, electronic shaping and noise. The event-by-event on-line reconstruction of the interaction positions is performed by comparison of the measured pulse shapes with a basis of simulated pulses. This is a computationally intense task and such arrays are coupled to dedicated computer farms that perform the reconstruction in real time.

4. Summary

The high-intensity radioactive-ion beams from the upgraded accelerator facilities coupled to the state-of-the-art experimental tools and techniques that are currently being developed open up the way for the nuclear physics community to explore the structure and properties of exotic nuclei that were not accessible so far. The FAIR facility and the NUSTAR experiments will play a leading role in these investigations.

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