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Studying Nuclear Structure at the extremes with S^3

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Abstract. The in-depth study of the regions of Superheavy elements and the proton drip line around ^{100}Sn are two major challenges of today's Nuclear Physics. Performing detailed spectroscopic studies on these nuclei requires a significant improvement of our detection capabilities. The Super-Separator-Spectrometer S^3 is part of the SPIRAL2 facility at GANIL. Its aim is to use the high stable beam currents provided by the new LINAC to reach rare isotopes by fusion-evaporation.

1 Introduction

The SPIRAL2 project [1] will be a breakthrough for the study of nuclei far from stability. This large scale international instrument belongs to the new generation of nuclear experimental facilities and is presently under construction at GANIL. Its injector will be constituted of a latest generation A-PHENIX ECR ion source coupled to a superconducting linear accelerator (LINAG). This device will be able to provide, in addition to its proton and deuteron beam, stable beams with intensities up to 100 pμA for ions with $A < 60$. The Phase 1 of the project is now under tests. Proton beams have been successfully delivered to the exit of the Radio Frequency Quadrupole and deuteron beams are now being tested. The cryogenic accelerating cavities have been cooled down and are being proven for temperature stability.

The LINAG will provide beams to two experimental halls in the first phase. The first is dedicated to Neutrons For Science (NFS) and the second, the Super Separator Spectrometer (S^3) [2], to synthesis and study of the heaviest elements and N=Z nuclei around ^{100}Sn.

2 The Super Separator Spectrometer

S^3 will use the high intensity stable beams of the LINAG to produce exotic nuclei through fusion-evaporation reactions and select them. Thus, S^3 is designed to offer the possibility to access the present spectroscopic no man's land such as the vicinity of the Superheavy Elements and areas beyond the drip lines, especially around ^{100}Sn.

2.1 Physics Cases

The design of S^3 was guided by its general purpose : studying rare isotopes and phenomena in nuclei produced by fusion-evaporation reactions. Two regions of interest can be reached through these reactions : Transactinide and Superheavy nuclei and N=Z isotopes near ^{100}Sn. The study of Transactinide and Superheavy nuclei has been pursued for many decades now and yet our understanding of this region remains limited. The objectives of S^3 are to provide production yields increased by a factor of 10 to 100 compared to the current capabilities. Under these conditions, decay spectroscopy of nuclei with production cross-sections of the order of the picobarn become possible. Therefore the investigation of nuclear structure closer to the so-called Island of Stability becomes possible and with it the availability of models with an increased predictive power.

The region of ^{100}Sn is equally challenging if not more. In addition to the extremely low cross-sections, the multiplicity of the evaporation channels produced a background that clouds the identification of the nuclei of interest. Access to the nuclear structure information in this region is however very much of interest regarding the double magicity of ^{100}Sn. Isomersim, shape and exotic decay modes all command an in-depth study.

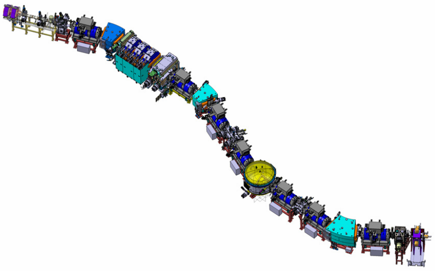

Figure 1. CAD layout of S^3 with the decay spectroscopy setup SIRIUS.

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2.2 Instrumentation

In order to achieve these objectives, the present limitations due to low production cross-sections far from stability need to be overcome. The design of S^3 was focused on maximizing the transmission of fusion-evaporation products to the final focal plane. It is constituted of a momentum achromat followed by a mass spectrometer with a mass resolution approaching 1/400 and a beam rejection power of 10^{13}. For this reason triplets of cryogenic multipoles are used for the optics to enhance the opening gap and provide corrections up to the octupolar level. Seven of these modules make the optical lattice of S^3. They are powered by custom made power supplies designed for quench protection. In addition to these elements, the selection is made by three room-temperature magnetic dipoles and an electric dipole.

In order to handle the high power deposition generated by the beams driven by the LINAG, the targets are mounted on a 70 cm wheel to maintain the temperature of the target material below the melting point. This large wheel will be used for stable targets such as Lead or Bismuth and Uranium. The control of the thickness and integrity of the target throughout the experiment will be done by three complementary diagnostics : an electron-gun, an alpha source and a thermal camera. The use of actinide targets is obviously foreseen to reach the heaviest elements. The scarcity of these material and their radioactivity impose the design of a smaller wheel with a dedicated handling procedure to ensure the confinement of the radioactive material. A prototype of this target station has already been tested.

S^3 has been designed to accommodate different working modes depending on the experimental requirements. The first mode to be commissioned and used is the Convergent Mode that focuses on the efficiency by maximizing the transmission. This mode uses the Mass spectrometer to focus all five transmitted charge states into a 5 cm spot at the final focal plane. Relaxing the ion optics in the second part of the spectrometer provides an enhanced transmission up to 68 % for the reaction $^{58}Ni+^{40}Ca \rightarrow^{94} Ag+p3n$.

The second mode is the High-Resolution Mode where the emphasis is put on the Mass separation at the final focal plane. The Mass resolution of $\Delta M/M = 1/460$ will allow to separate 3 or 5 charge states and three mass-units for identification by the position on the final focal plane. The simulated transmission is 50% for the reaction $^{58}Ni +^{46} Ti \rightarrow^{100} Sn + 4n$. This Mode will be used to identify or select by mass the ions in addition to decay-tagging or laser ionization.

The final mode, called High Transmission Mode is a compromise between the two previously cited. It aims at maximizing the transmission while maintaining a mass resolution of $\Delta M/M = 260$ for low velocity recoiling nuclei from asymetric reactions such as $^{22}Ne +^{238} U \rightarrow^{255} No + 5n$. In this case where the recoiling velocity is of the order of 10 MeV, the transmission of S^3 will be between 15 and 20 %.

The full power of S^3 will be used at focal plane where it will be possible to select precisely incoming ions with a gas-cell for laser spectroscopy or to implant the selected recoiling nuclei at focal-plane for nuclear structure studies.

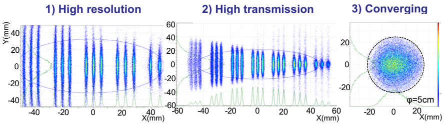

Figure 2. Simulated emittance at the final focal plane for the three operating modes of S^3.

3 Detection setups

From the start of the operation, S^3 will be equipped with two complementary detection setups. The first one will be dedicated to decay spectroscopy with alpha particles, gamma-rays, conversion electrons and spontaneous fission. It is called SIRIUS for System for the Identification of Recoiling Ions Using S^3. The second one will be dedicated to the selection and study of ground-state properties through laser spectroscopy. It is called S^3 Low Energy Branch (S^3-LEB).

3.1 Decay spectroscopy with SIRIUS

SIRIUS is designed to perform the most efficient recoil-decay tagging for nuclei separated by S^3. Its configration is based on the time-proven achitecture of detection setups such as GABRIELA [3], GREAT [4] or the focal plane of SHIP [5]. Nuclei are implanted in the 128x128 channels Double Sided Silicon Strip Detector (DSSD) with a thin entrance window (inferior to 50nm). Their decay is recorded at the same pixel as the implantation site, allowing a time correlation with little possibility of contamination. Four custom made "Strippy-pad" silicon dectectors [8] are placed upstream in a tunnel configuration to recover escaping alpha particles, conversion electrons and spontaneous fission products. The time correlation between the implantation event and its decay recorded by all silicon detectors provide the recoil-decay tagging identification and the spectroscopy. An array of five EXOGAM clover detectors with BGO Shields [6] complete the system for gamma-ray detection. Upstream a Secondary electron detector (SeD) is used to provide time and position information [7]. In conjunction with the DSSD, it provides the time of flight of the recoiling ions and their tracking thanks to its position resolution.

The acquisition of SIRIUS is based on the NUMEXO digitizers adapted to our needs. The preamplifiers of the DSSD are using ASIC chips accommodating a Floating Point Charge Sensitive Amplifier (FPCSA) to accommodate high-energy implantation events followed rapidly by low energy decay. The tunnel detectors use a preamplifier compensated by a feedback loop to accommodate the two gains. The preamplifier uses a high gain by default and will be sent successive step functions in the case of a saturation to restore the baseline in the dynamic range of the amplifier.

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The chambers hosting the detector have been designed to shorten as much as possible the distance between the exit of S^3 and the DSSD and to enhance the efficiency and energy resolution of the gamma-ray detection (see fig.3). The preamplifiers are housed outside the chamber on a dedicated flange as close as possible to their respective detectors to reduce the noise contribution of the cabling.

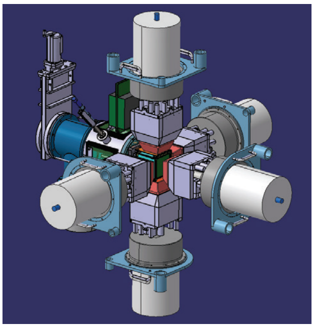

Figure 3. Layout of SIRIUS.

3.2 Laser spectroscopy with S3-LEB

$S^3 - LEB$ is the versatile combination of multiple but complementary detectors (see fig.4) [9, 10]. Its aim is to measure the ground state properties (mean square charge radii differences, magnetic dipole and quadrupole moments) of exotic nuclei using laser ionization spectroscopy. Thanks to the selectivity and efficiency of in-gas jet laser ionization spectroscopy in combination with S^3, studies of transactinide nuclei, refractory elements and medium-mass N=Z nuclei is reachable.

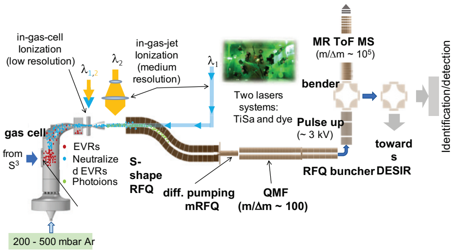

Figure 4. Schematic drawing of the Low Energy Branch of S^3.

The first part is the laser ionization spectroscopy setup installed at the final focal plane of S^3 to selectively ionize the atoms of interest. It consists in a gas-cell separated from the spectrometer by a thin foil, a laser system for the ionization and radio frequency based ion optical elements to prepare the ion bunches for further studies. The nuclei are thermalised in the gas cell and evacuated with the gas flow to a de Laval nozzle designed to accelerate the gas jet up to mach 7. The size and shape of the gas jet is optimized to maximize the interaction of the nuclei with the lasers. Titanium-Sapphire or Dye Lasers can be used depending on the frequency range of the ionization scheme of the ion of interest. The ionized atoms are then extracted to a S-shaped RFQ followed by a Quadrupole Mass Filter (QMF) and a buncher. The selected ion bunches can then be sent for ion counting to a silicon detector, to a Multi reflection Time of Flight Mass Spectrometer or to another detection facility such as the DESIR hall.

4 Conclusions

The Super Separator Spectrometer is designed to make the best use of the high intensity stable beams available from the SPIRAL2 injector. It is designed for the selection and identification of rare ions produced by fusion-evaporation. Two complementary detection systems are constructed to study the nuclei selected by S^3 : SIRIUS to investigate nuclear structure using decay-tagging and S^3-LEB to measure ground state properties using laser spectroscopy. These two complementary devices will allow to investigate rare nuclei regions such as Superheavy Elements or neutron-deficient nuclei close to ^{100}Sn.

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