S^3: PUSHING SPECTROSCOPY FORWARD*

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Spectroscopy in the region of high masses is performed at the limits of the existing detection systems. Observation limits were recently pushed down to 11 nb with the prompt gamma-ray spectroscopy of ^{246}Fm and ^{256}Rf. The very high intensity beams that will be provided by the new SPIRAL2 LINAC accelerator, combined with the high transmission and selectivity power of the Super Separator Spectrometer S^3, will provide an unprecedented access to nuclei with cross-sections in the nanobarn region. Using the latest technologies, the S^3 Collaboration is designing a detection system based on recoil-decay tagging that will enable a major step in these physics cases.

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1. Introduction

The upcoming SPIRAL2 [1] facility at GANIL, Caen, will provide intense beams of radioactive species through fission induced by deutons in a uranium-carbide target. The latest generation A-PHENIX ECR ion source will also provide stable beams for ions with $A < 40$–50 with intensities reaching 100 pμA. These stable beams will be accelerated by the supraconducting linear accelerator (LINAC) and distributed to two experimental halls hosting the Neutron For Science (NFS) project and the Super Separator Spectrometer S^3 that has been recently selected and funded as an Equipment of Excellence (EQUIPEX) by the French National Research Agency.

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This latter device will provide access to spectroscopic studies for nuclei with cross-sections in the sub-nanobarn region. The presence of a Momentum Achromat followed by a Mass Spectrometer (MAMS) with a mass resolution nearing $1/400$ will achieve a 10^{14} beam rejection power [2]. The intermediate focal plane between the two achromats will be available for a secondary target in order to study Coulomb excitation and deep inelastic reactions. Several γ-ray detectors could be placed at this position, such as PARIS [3], EXOGAM2 [4] or AGATA [5].

The detection at the final focal plane of S^3 will enable Recoil-decay tagging [6] by means of a dedicated detection setup discussed below. This device — meant to overcome the present limitations due to low production cross-section far from stability — will offer a unique possibility to access to present spectroscopic no man's land such as the vicinity of the superheavy nuclei and areas beyond drip lines.

2. Limits of the spectroscopy techniques

The limit in cross-section for prompt in-beam γ-ray spectroscopy has recently been pushed down to 11 nanobarns with the spectroscopic study of ^{246}Fm [7] using the JUROGAM2 array [8]. Thanks to this progress, the region of superheavy nuclei has been reached using prompt in-beam spectroscopy with the study of the ^{256}Rf. The nuclei have been unambiguously identified through tagging on the fission decay of ^{256}Rf. A rotational band based on the ground-state of the heaviest nucleus studied in spectroscopy has been observed.

The present focal-plane decay spectroscopy limit is lower with fusion-evaporation experiments performed with cross-sections down to a few nanobarns. This is due to the higher beam intensities that can be sent on target since no detectors are used at this position. The aim of S^3 is to significantly lower this limit thanks to the high stable beam intensities provided by the SPIRAL2 LINAC. The optimized design of the two stages separator will allow a mass resolving power close to $1/400$ with a high transmission ranging from 10 to 60% depending on the reaction. The beam rejection of 10^{14} will improve the detection limits by one order of magnitude.

3. R&D for the S^3 focal plane

The development of the detection system at the focal plane of S^3 is ongoing. A report on the previous developments and the general physics case of this setup can be found in [9, 10]. This article will mainly focus on the latest developments of this project.

3.1. Tracking and Time-of-Flight detectors

The tracking and Time-of-Flight are crucial for the setting and calibration of the separator as well as for the identification of ions in dispersive mode. The ongoing developments aim at reaching a spatial resolution lower than 1.5 mm for the tracking and a time resolution lower than 400 ps for the Time-of-Flight measurement. Secondary Electron Detectors using a 2D cathode associated to wire chamber or micromegas at low pressure will ensure good time and position resolution. This concept is based on the existing device SED used on the VAMOS spectrometer [11]. The two solutions are being developed to ensure the coherence with the specifications asked for S^3. Tests on the detectors are ongoing. The different Physics Cases to be studied with S^3 require detectors with a size of 20×10 cm^2 with emissive foils thinner than 100 μg/cm^2 to avoid stopping nuclei with recoiling velocities of the order of 0.5 cm/ns. Various techniques are being tested for the production of self-supporting foils in order to bring the thickness to the required level.

3.2. Implantation and tunnel Si detectors

The implantation detector will be a Double Sided Silicon Strip Detector (DSSD) of 10×10 cm^2 active area with 128 strips on each side. This detector is dedicated to spectroscopy experiments with an active area covering the implantation pattern for both the high transmission and the dispersive modes of the separator. The granularity of the detector has been defined to optimize both the counting rate in each strip and the position resolution for the mass identification of recoiling nuclei. A new generation windowless prototype has been received this summer. The test bench has been coupled to the acquisition system and is ready for use. The tests of the detector are scheduled for the end of 2011.

The detection for the conversion electrons will be provided by four dedicated 700 μm thick 10×10 cm^2 windowless silicon detectors. A prototype of single-sided windowless high resistivity silicon crystal has been ordered for further tests. The detector prototype will be segmented into 64 pads of equal size. This segmentation was chosen so that pads could be coupled using different configurations to test the optimal granularity of the tunnel detectors. Tests will be performed to adapt the granularity of the actual detector for an optimal reconstruction of escape α particles and electrons.

The support for these detectors will be made out of ceramic in order to cool directly the silicon detectors at the optimal temperature with as little material as possible in the chamber. The design of the detectors is in the final validation process and is expected for test in early spring 2012.

3.3. Front and back-end electronics

The detection of implanted nuclei and their decay by α-particles, conversion electron or spontaneous fission requires different gains on the silicon detectors at the focal plane. The energy ranges are defined from 100 keV to 15 MeV (High gain) for α-particles and conversion electrons ($\sigma_{\mathrm{E}} = 15$ keV FWHM) and from 10 MeV to 500 MeV (Low gain) for implantation and fission ($\sigma_{\mathrm{E}} = 1\%$ FWHM). Therefore, three types of preamplifiers have been developed and are under test for this project:

- Floating point preamplifier based on microelectronics;
- Double pole zero preamplifier;
- Feedback loop preamplifier for fast baseline recovery after high energy signal.

Simulations of the floating point preamplifiers provide equivalent noise charges of 7.2 keV FWHM and 23 keV FWHM and absolute integral non linearity of 8.6 keV and 0.33%, respectively, for the High gain and Low gain. The measurement of a decay signal following the implantation signal by at least 10 μs is possible while keeping the energy resolutions indicated. Prototypes are expected to be ready for test at the beginning of 2012, followed by the characterization of the preamplifier in the first trimester of 2012.

The simulations for the behaviour of the double Pole Zero preamplifier show expected energy resolutions of 7.5 keV at 10 MeV and 15 keV at 100 MeV. The preamplifier is able to record a decay signal with the expected energy resolution after the high energy signal of an implantation if they are at least 10 μs apart.

The feedback loop preamplifier is an adaptation of the preamplifier from EXOGAM for the two gain constraint of S^3. A test bench was built using a modified existing Exogam Preamplifier with 3 evaluation boards under a programmed arbitrary generator to simulate a detector. The tests performed on this preamplifier show energy resolutions stable around 8 keV negative signal up to 7.5 keV and positive signals up to 30 MeV. The Low gain part shows an energy resolution lower than 1% from 30 MeV to 500 MeV. The behaviour of the preamplifier is stable if the time difference between the implantation of the nucleus and its decay is longer than 14 μs. A new prototype of the S^3 preamplifier is being built and the tests are scheduled for the beginning of 2012.

The back-end electronics will be fully digital and triggerless in order to perform experiments on nuclei with very short lifetimes (below 100 μs) and the presence of isomeric states. Two options are considered at the moment for this electronics, based on parallel developments. The first solution is based on a collaboration between the CSNSM and the CAEN company to produce the back-end electronics for the digital feedback amplifier. This solution is based on modified commercial motherboards from CAEN using one ADC and one DAC output per channel for fast compensation after high energy signal through the feedback loop preamplifiers. The second solution uses the NUMEXO2 boards being developed at GANIL in the framework of EXOGAM2 [4]. The final decision on the optimal back-end solution for S^3 should be reached soon.

3.4. Gamma-ray array

The detection of gamma-ray decay is the crucial part of spectroscopy. The choice of the detectors and geometry has a strong impact on the efficiency of the detection setup. The solution foreseen for the first phases of S^3 is based on the existing EXOGAM [12] detectors in a star configuration around the implantation point (see Fig. 1). Simulations using the code GEANT4 [13] taking into account the use of anti-Compton shields are ongoing and show that half of the efficiency comes from the germanium at the back of the implantation DSSD [14]. Therefore, the use of a dedicated large volume germanium detector is foreseen. Further developments for a custom solution are considered for the later phases of the project.

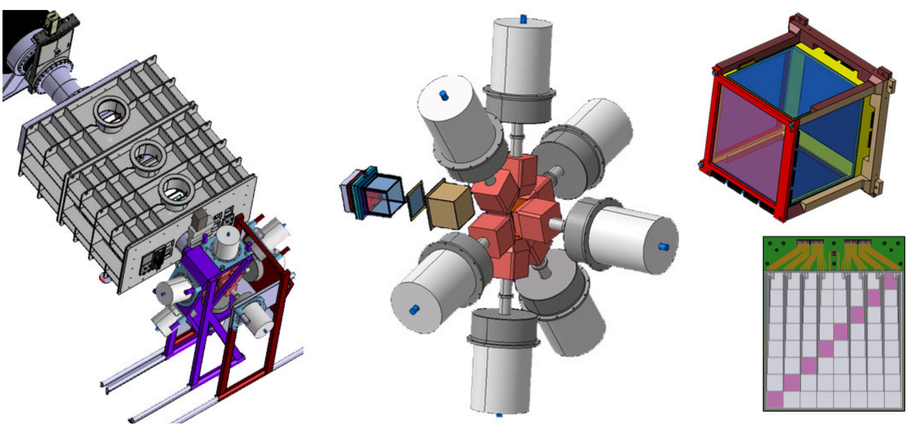

Fig. 1. Integration of the detection system at the focal plane of S^3 with a box for two Time-of-Flight detectors (left). Exploded diagram of the foreseen focal plane geometry (center). View of the detail of the Silicon detectors assembly as foreseen for the day 1 set up (top right). Tunnel detector prototype (bottom right).

4. Conclusions and perspectives

The development phase of the detection system at the focal plane of S^3 is ongoing. The prototypes of the silicon detectors will be ready for testing at the end of 2011. Operational tests of the different part of the detection systems will be performed during 2012. This crucial part of the conception will provide important information on the expected behaviour of the future detector array. The completion of the detection system is expected for the beginning of 2015, pending the first phases of the commissioning of S^3.

The author emphasizes that S^3 is the work of a wide collaboration from which he is only representatives. He thanks all the present and future contributors of this project. A special thank goes for E. Gamelin for the 3D conception of the focal-plane elements as well as all the engineers involved in the project.

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