PUSHING THE LIMITS OF SPECTROSCOPY WITH S^{3*}

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Designed in the framework of the SPIRAL2 project, the Super Separator Spectrometer (S^3) will benefit from unprecedented high intensity stable beams available at the new LINAG accelerator. It will open new horizons for the physics of rare nuclei and low production cross-section nuclei at the extreme limits of the nuclear chart. A research and development program has been launched in order to optimize the S^3 focal-plane detection according to the three main physics cases: Synthesis of new Super Heavy Elements, Spectroscopy of Very and Super Heavy Elements and Spectroscopy of neutron-deficient nuclei around ^{100}Sn.

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1. Introduction

A new generation of nuclear experimental facilities is under construction at GANIL within the SPIRAL2 [1] international project. Intense beams of radioactive species will be produced by means of fission induced by deuterons in a uranium–carbide target. The injector of this installation will be constituted of a latest generation A-PHENIX ECR ion source coupled to a superconducting linear accelerator (LINAG). In addition to this deuterons

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beam, this device will be able to provide beam intensities up to 100 pμA for ions with $A < 40$–50. This opens up a unique opportunity to use unprecedented intensities of stable beams. Therefore, the project includes, in addition to the radioactive beams facility, two experimental halls. The first dedicated to Neutrons For Science (NFS) and the second to the Super Separator Spectrometer (S^3).

This latter device — meant to overcome the present limitations due to low production cross-sections far from stability — offers a unique possibility to access the present spectroscopic no man's land such as the vicinity of the Super Heavy Elements and areas beyond the drip lines, especially around ^{100}Sn. In order to achieve a 10^{13} beam rejection power, S^3 [2] will be constituted of a high acceptance momentum achromat followed by a mass spectrometer (mass achromat) with a mass resolution approaching 1/400. It is foreseen to enable the use of a secondary target at the intermediate focal-plane for Coulomb excitation studies, deep inelastic reactions and the study of reaction mechanisms. Beam limitations may be set for physical reasons for this target as it could be the case for some beams in the primary target. For these latter studies a γ-ray detector array will be necessary around this secondary target. Several possibilities such as PARIS [3], EXOGAM2 [4] or AGATA [5] have been proposed.

In addition to the detection in the intermediate focal-plane, there will be a need for specific identification device at the final focal-plane of S^3. This can be achieved by an implantation device (S^3 focal-plane detection system) or a Gas-Catcher sending selected ions to dedicated area such as the DESIR facility [6].

2. Limits of spectroscopy techniques

2.1. Prompt spectroscopy, example of the ^{246}Fm

The present prompt spectroscopy limit has been recently pushed down by one order of magnitude with the study of ^{246}Fm [7] at the University of Jyväskylä using the association of JUROGAM2, RITU and GREAT [8]. A 70 pnA ^{40}Ar beam impinging on a ^{208}Pb target has been used in order to overcome the 11 nb production cross-section. The germanium array JUROGAM2 was fully digital instrumented with TNT2 [9] cards to sustain the counting rates in the detectors. Recoiling nuclei of interest were selected with GREAT at the focal-plane of RITU.

It has been possible to establish for the first time a rotational band in this nucleus with only 10 days of beam time (see figure 1). Spin and parities have been successfully assigned on the basis of the Harris method [10]. Good agreement has been found in the comparison with neighbouring nuclei of the obtained level scheme and the behaviour of dynamical moment of inertia.

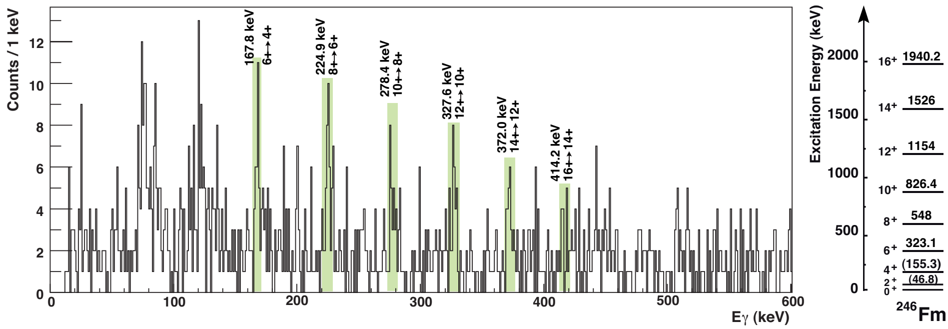

Fig. 1. Single γ-ray spectrum unambiguously attributed to ^{246}Fm and associated level scheme [7].

2.2. Focal-plane spectroscopy

The present focal-plane decay spectroscopy limit is around 1 nb for fusion–evaporation cross-section of heavy elements. It will be significantly reduced in the framework of S^3. The use of the SPIRAL2 LINAG induces for some beams an increase of one to two orders of magnitude in intensity. In addition, the developments done in the framework of S^3 — significant increase in the transmission of the separator and optimization of the efficiency of all the key detectors at the focal-plane of S^3 are estimated to induce an additional order of magnitude step in detection limits.

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

3.1. The focal-plane detectors

Decay studies need a combination of several detection devices at the focal-plane of S^3. The total detection efficiency is driven by the product of the individual efficiency of these detectors. To define the best setup for the three physics cases of S^3, optimization will be done in each case.

Reaction products transported and separated through S^3 will first pass through a Time-of-Flight (ToF) device. It will be constituted from 1 to 2 ToF elements based on Secondary Electron Detectors (SED) [11]. It will contribute to select the recoiling nuclei and the discrimination between implantation and decay events in the silicon detector downstream.

Recoiling nuclei are then implanted in a Double Sided Silicon Strip Detector (DSSSD). Its thickness and granularity will be adapted to the physics case. This detector will be surrounded by a tunnel of silicon detectors for charged particles (alpha particles, electrons and protons) emitted during the decay process of the implanted recoil nuclei and escaping the implantation detector. A thin veto silicon detector is foreseen behind the implantation

DSSSD in order to suppress events induced by light punch-through particles. The silicon detectors will be surrounded by a germanium array constituted by EXOGAM2 Clovers [4].

Each of these detectors will be associated to the acquisition system via optimal electronics. The geometry will be as compact as possible for efficiency reasons. Cross influence between detectors or shadowing effect due to positioning will at the same time be minimized. Figure 2 shows the compactness of the geometry of the silicon detector arrangement for the "Day 1" experiments and the right part of this figure show the positioning with respect to the germanium array.

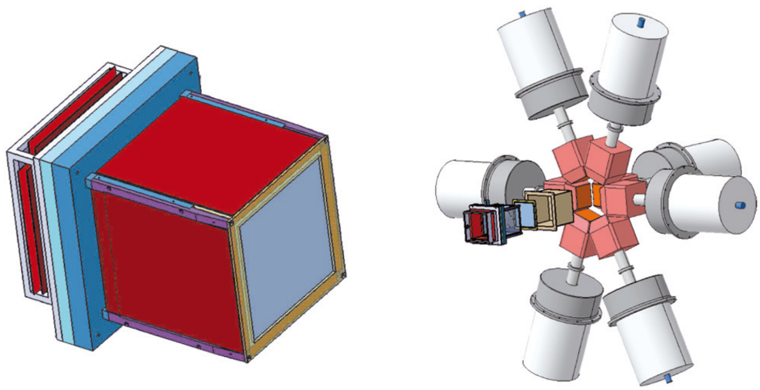

Fig. 2. View of the detail of the silicon detectors assembly as foreseen for the "Day 1" setup (left). Schematic view of the foreseen S^3 focal-plane geometry (right).

3.2. Tracking and time-of-flight detectors

The first focal-plane element hit by the recoiling nuclei will be a ToF tracking detector. The constraints and limitations on the design and operation of this device strongly depend on the physics case. In the case of heavy elements, where the recoils can be quite slow, it may be necessary to use only one ToF element with the thinnest possible emissive foil since straggling in this foil may be a key issue.

For faster recoiling nuclei, angular straggling is not a key issue since the detectors give the position with enough precision to enable trajectory reconstruction through the association of the ToF elements.

A research and development program is ongoing to define the best solution for each physics case and to meet the S^3 and NFS specifications. Several prototypes have been tested: 1 or 2 dimension SED and also a low-pressure micromegas solution [11]. Time resolution is important for the determination of the M/Q ratio. After some beam tests, the 2D SED solution seems to be the most promising one.

3.3. Implantation and tunnel silicon detectors

The implantation DSSSD will be based on the MUSETT [12] 10×10 cm^2 detector with 128 strips per side. The version for S^3 will benefit from the latest technological developments through the windowless technology that ensures a silicon entry window thinner than 50 nm. This allows to work with slow recoils, which implant shallowly into the DSSSD.

The tunnel detector, surrounding the implantation detector, is based on 1 mm thick 10×10 cm^2 windowless high resistivity silicon detectors. This choice is the result of a GEANT4 simulation [13] showing that very little is gained by taking a longer tunnel. Since both the Tunnel and the implantation DSSSD detectors will be windowless, more accurate energy reconstruction for DSSSD-tunnel coincidences will be possible due to the reduction of energy losses of the escaping α in dead silicon zones.

There are up to now two options: optimized geometry pads on a single sided silicon wafer or "pixels" generated by wide strips on a double sided silicon detector. In both cases the lithography will be done in order to get all the signals out from one side of the silicon crystal.

Following a simulation of the angular effects on the resolution due to the effect of dead layers in the implantation and tunnel silicon detectors for escaping αs [14], it can be seen in figure 3 that the reconstruction of α energy in this case is mainly affected in the 2 first centimetres of the tunnel detector by the energy-loss variation in the two silicon detector dead layers. It has been proposed to reduce the number of pads far from DSSSD, keeping a good granularity close to the DSSSD, where the effects are the largest. One of the proposed geometry is shown in the right part of figure 3.

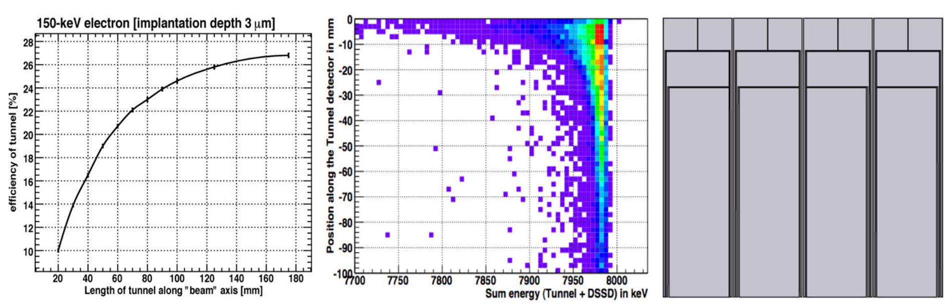

Fig. 3. GEANT simulation of the optimal length of the tunnel detectors [13] (left). GEANT simulation of the influence of the dead layers of the silicon detectors on a 8 MeV α escaping from the implantation DSSSD with respect to the tunnel hit position [14] (centre). Proposed stripy-pads geometry for the tunnel detector (right). For these two illustrations, the DSSSD is situated on the top edge of the figure.

The R&D program will be done for ceramic support for these detectors in order to cool directly the silicon detectors at the optimal temperature with as little material as possible in the chamber. Study of optimal silicon detector operation temperature and optimization of cooling process is ongoing [15]. The ceramic parts supporting the silicon crystals will be designed in order to enable the use of either 10×10 cm^2 or 10×20 cm^2 focal-planes.

3.4. Front and back-end electronics

The S^3 project aims at an energy resolution of 15 keV for 8 MeV α particles. This implies the use of optimized front and back-end electronics. Important efforts are set in the project in order to develop a new preamplifier with two gains that can reach this performance while keeping the ability to process with equal quality the wide amplitude range necessary for this type of studies and fast response ability. Discrete charge preamps as well as integrated solutions are studied.

The two physics cases dedicated to SHE synthesis and spectroscopy will generate low counting rates at the focal-plane. From this point of view they do not explicitly need digital back-end electronics. Nevertheless, they require the ability to distinguish rare events from transfer reaction products and to trig on fast decay following implantation. Triggerless operation with as low as possible dead time is necessary for this system. Digital electronics fits well this requirement and opens up possibility of specific data processing.

Physics around ^{100}Sn implies much higher recoils flux. This latter case will therefore need a much higher granularity of the implantation silicon detectors resulting in a large number of electronics channels. It will imply the use of a dedicated digital electronic based solution.

3.5. Gamma-ray array

The γ-ray efficiency plays a major role for the physics cases based on focal-plane spectroscopy. The detector situated directly behind the implantation silicon detector gives the major part of the total γ-ray efficiency. The size and geometry of this detector are of the utmost importance. A ring of γ-ray detectors surrounding this system accounts for the complementary efficiency.

In a first phase, optimization of possible geometries with new dedicated gamma detectors was done with the GEANT4 code [16]. A maximum efficiency of 63% (see Fig. 4) for low energy γ-rays has been determined for optimal focal-plane gamma detection geometry [17]. Even if this ideal case is not fully realistic, it gives an upper limit to the realistic efficiencies we may obtain with existing detectors where the geometry was not optimized for S^3 configurations.

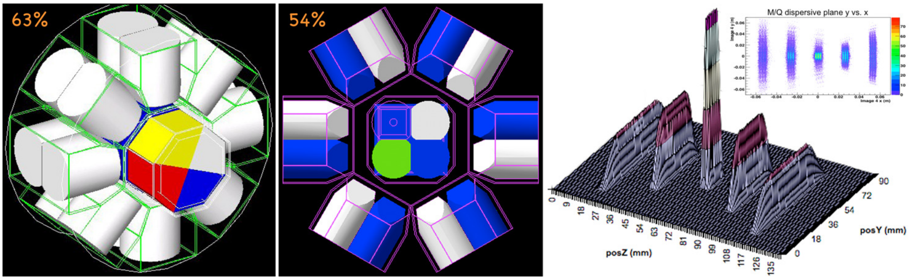

Fig. 4. Optimal geometry with a γ-ray array based on new dedicated germanium detectors (left), existing EXOGAM Clovers (middle) [17]. Simulated realistic implantation distribution of the five charge-states transported up to S^3 focal-plane (right) [20].

In a second phase, optimization has been performed for different geometries based on existing detectors. Several arrangements of EXOGAM clovers were compared. These γ-ray arrays were based on one clover in the back of the DSSSD associated to a ring of 4, 6 or 8 clovers surrounding the focal-plane silicon detectors. With 54%, the "1+6" Clovers was found to give the best total gamma efficiency for low energy γ-rays. One can see in figure 4 that this geometry also leaves enough space for mechanics and cabling between the silicon detectors and the gamma-array.

Even if we still need more realistic simulations, we can consider that this represents more than a factor of 2 with respect to existing focal-planes such as GABRIELA@VASSILISSA (JINR, Dubna) [18] and GREAT@RITU (JYFL, Jyväskylä) [19] .

More recently, realistic recoil implantation distributions coming from S^3 optics were introduced as emission source for particles and photons at the focal-plane [20]. All of this gives a perfect framework for the last phase of simulation based on the real 3D solution taking into account all the elements that will generate absorption or scattering. These simulations will guide our mechanical choices and conduct to realistic simulation of "Day 1" experiment.

4. Conclusions and perspectives

Designed to make the best use of unprecedented high intensity stable beams available from the SPIRAL2 injector, the Super Separator Spectrometer is now in construction phase and should start commissioning in GANIL early 2013. The focal-plane detection system described in this paper is in study phase on the basis of the strong expertise of designing and running focal-planes within the S^3 collaboration.

Time of flight detectors, implantation DSSSD, tunnel silicon detector, veto silicon, associated electronics and γ-ray array are in study in order to design the best possible detection system with respect to the physics cases.

This ongoing process will lead to opening of new horizons for the physics of rare nuclei and low cross-section reactions at the extreme limits of the nuclear chart.

The authors emphasize that S^3 is the work of a wide collaboration from which they are only representatives. They thank all the present and future contributors of this project. A special thanks goes for E. Gamelin for the 3D conception of the focal-plane elements.

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