Contribution to the future of GANIL

S^3 at SPIRAL2/GANIL

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The Super Separator Spectrometer (S^3) facility is developed in the framework of the SPIRAL2 (Phase 1) project. S^3 has been designed to extend the capability of the facility to perform experiments with extremely low cross sections, taking advantage of the very high intensity stable beams of the superconducting linear accelerator of SPIRAL2.

The S^3 project involves the coordinated participation of a large international collaboration including 28 partner laboratories gathered around a common physics ambition through Letters of Intent (LoI) and innovative technological developments. The research programs are structured by 18 LoIs, which were signed by 170 physicists, covering a wide range of physics topics and aimed at reaching extreme regions of the nuclear chart. The main focus of S^3 physics is the study of nuclei from medium-heavy mass at the proton drip line up to the super-heavy elements produced by fusion-evaporation reactions, by investigating the properties and the decays of their ground and isomeric states. In addition, the S^3 program covers the study of reaction mechanisms, especially for low cross-section channels, in nuclear but also in atomic physics (electron processes in beam-beam reactions).

The main areas of research fit into three broad categories:

1) Questions related to heavy and super-heavy element synthesis: Heavy and super-heavy nuclei, which form the upper end of the chart of nuclei, owe their stability, and for the heaviest systems (Z larger than 104) even their sheer existence, to quantal shell effects. Their study thereby offers unique insights into the quantal nuclear many-body problem. Due to the low cross sections, the nuclear properties and structure of these nuclei are still poorly known. For most isotopes, only the basic decay properties have been measured with low statistics experiments often hampered by the presence of a multitude of isomeric states, while their structure is expected to be complex. This complexity is due to the high single particle level density near the Fermi surface and the fact that the short-range nuclear force and the long-range Coulomb forces are of the same order of magnitude. The goal of S^3 is to obtain detailed measurements (through spectroscopy) on these nuclei by applying original and innovative methods.

2) Questions related to nucleon-nucleon interaction at the proton drip line: How do shell closures evolve far away from stability? Neutron deficient nuclei close to the proton drip line, in particular the doubly-magic ^{100}Sn and its neighbors along the N = Z line, have awakened the interest of the worldwide physics community thanks to the large variety of different nuclear phenomena occurring in this region. The fact that protons and neutrons occupy the same shell-model orbitals translates into a maximum overlap of the wave functions of the two fermionic systems; thus proton-neutron pairing plays a predominant role in this area of the nuclear chart. The inherent symmetry of these nuclei makes them excellent candidates for the study of proton-neutron pairing correlations and isospin-symmetry breaking. Moreover, the magicity of ^{100}Sn and close-by nuclei is decisive for the course and the end of the astrophysical rapid-proton capture process. In addition, the nuclei

in the region above ^{100}Sn are known for presenting different types of radioactivity; superallowed alpha emission, one or two proton emission, and cluster radioactivity predicted but not-observed so far in the region.

3) Questions related to energy deposition by ionic species in matter that takes place in irradiated materials when the ion stopping power is at its maximum: this collision regime is a hitherto unexplored regime since impossible to be studied in a precise way in ion-atom collisions. The various elementary electronic processes are, in fact, indistinguishable from each other and their probabilities are difficult to predict theoretically touching on the dynamics beyond the 3-body problem, notably in the range of a few MeV/u, provided by the Linac. The experimental program with S^3 is to investigate the collision dynamics of N-body systems by perfectly controlling the initial quantum states of the S^3 ion beam and of a low-energy ion beam. A better knowledge of the mechanisms involved in this regime would have undeniably important outcomes in different domains. These include inertial confinement fusion plasma; characterization of stellar and interstellar plasmas; impact on living cells for hadron therapy.

The common feature of these ambitious research programs is the requirement to separate very rare events from intense backgrounds. The development of S^3 required the solution of three major technological challenges: the need for very intense heavy ion-beams to access very low cross section reactions (picobarn and below), the need for a powerful recoil separator that can combine, thanks to its innovative superconducting multipole magnets, a large transmission with a high selectivity and the capability to perform in-flight mass-number determination of short-lived nuclei. All these features make S^3 unique in the world. In order to study these nuclei, the spectrometer is combined with high efficiency detection systems to select and study the nuclei of interest.

The interest of the S^3 physics is that the nuclear chart can be studied by different approaches depending on the experimental set-up placed at the end of the spectrometer. The S^3 project, considered as a “radioactive nuclei production facility”, has motivated the development of a broad range of innovative instrumentation setups, aiming at the study of those nuclei with different observables, namely:

- The SIRIUS setup is an implantation decay station focused on the decay spectroscopy of very heavy and super-heavy elements. The innovative character of SIRIUS lies in its highly pixelized compact Silicon box coupled to advanced front-end and back-end electronic technologies. This setup will provide a high efficiency and an excellent resolution in a large dynamic range for energy measurements to be capable of detecting heavy ions and subsequent decays. It is also foreseen to use pulse shape analysis on the signals from the silicon detectors to enable identification of the detected particle. In addition, germanium detectors in a close geometry around the implantation detector will be used for gamma-decay spectroscopy. This complex system composed of a variety of detectors in a compact geometry will enable to perform detailed precision measurements of the decay of ground and isomeric states to study fundamental properties like decay-modes, half-lives, branching ratio, spins and parities, and spectroscopy of these poorly known nuclei.

- The REGLIS setup couples a gas cell to stop the nuclei selected by S^3 and a Low Energy Branch for laser ionization/spectroscopy and mass measurements (MR-Tof-MS). The major attribute of REGLIS is to use atomic physics techniques - more specifically, high resolution spectral measurements of the atomic transitions – in order to provide fundamental and nuclear-model-independent data on the structure of ground and isomeric nuclear states. In this context, this setup will allow the measurements of static properties of exotic nuclei such as charge radii, electromagnetic moments, nuclear spins and atomic masses, giving information on the distribution of the nucleons inside the nucleus and providing information on structural changes throughout the chart of nuclei. This state-of-the-art technique will be used at S^3 with rare beams never studied by low-energy measurements.

- The FISIC setup is a bit apart from the others since it delves in the domain of atomic physics. This setup is coupled to S^3 with the goal to study atomic interactions in beam-beam collisions. A low energy beam is sent into S^3 at the achromatic point and interacts with the high-energy (few MeV/u) beam, whose charge state has been selected with the first half of S^3. The charge states after interaction will be measured after the collision point thanks to a dedicated beam line equipped with a magnetic dipole, quadrupoles and a beam dump. This will be a unique facility to study ion-ion interaction in this energy regime.

In addition, radioactive beams from S^3 will be sent in the future to the DESIR facility[1] equipped with complementary spectroscopy setups: The DETRAP facility for high-precision mass measurements and for the high-purity preparation of radioactive species for decay studies, the laser-spectroscopy facility LUMIERE for high precision laser spectroscopies and the BESTIOL facility to perform precision measurements in nuclear beta decay.

The S^3 project seeks to enable fundamental research breakthroughs in the study of the basic properties of the atomic nucleus and in elementary atomic processes. The nuclear physics program of S^3 is optimized for the study of neutron deficient and super-heavy nuclei, which makes it very complementary to the GANIL/SPIRAL1, as well as other international facilities or projects such as SPES (Italy), ARIEL (Canada), ISOLDE (CERN), FAIR (Germany), BigRips (Japan) or FRIB (U.S.), that have a large focus on the study of neutron-rich nuclei or cannot access the most extreme neutron deficient nuclei for detailed studies. Compared to other existing facilities in the world dedicated to super-heavy element research, such as FLNR (Russia), RIKEN (Japan), GSI (Germany) or LBNL (USA), S^3 has a unique combination of high transmission, high rejection and in-flight mass resolution. Combined with the decay spectroscopy station and a laser-based low-energy branch, it will be a very competitive and unique facility to perform ground and isomeric state studies, either for detailed investigations of nuclei that are produced today only at very low rates or to reach new unknown nuclei.

The upgrade of the Linac accelerator with a new generation superconducting ion source and the new A/Q = 7 injector is a critical improvement to strengthen the scientific program of S^3 and also indirectly the one planned at DESIR. Such an upgrade will provide unprecedented intensities for heavy ion beams (gain of the order of a factor 5-10 for $A \approx 40$-60), which are of paramount importance for the study of super-heavy nuclei for which the production cross sections decrease exponentially with the atomic number. Moreover, these intense beams will assure a leading position regarding the N = Z investigations worldwide in the ^{100}Sn region and beyond, in addition it will keep the competition on other regions of the nuclear chart[2]. **Therefore, the construction of a powerful new injector A/Q = 7 is the most urgent request of the S^3 collaboration as it will make SPIRAL2 the most intense heavy-ion accelerator in the world**.

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[1] See contribution entitled "DESIR@SPIRAL2"

[2] See contribution entitled: "RFQ injector A/Q = 7 for the production of exotic nuclei using fusion-evaporation and multinucleon transfer reactions"

The motivation of the scientific community has been unveiled recently by the many pre-proposals that already amount to a very important beam time for "Day1 experiments (~ 6800 hours requested). In that respect, we underline that **this innovative program could only be performed if a significant part of the Linac beam time is devoted to S^3**. **In addition, the availability of actinide targets will be required to produce and to study the heaviest nuclei.**

To summarise, the S^3 facility will be operational beginning 2023 at SPIRAL2. This new device was designed to study rare events thanks to the high intensity stable heavy ion beams. The beam intensities delivered by the Linac, combined with S^3 performances and state-of-the-art instrumentation will place the facility as the number one for the production of neutron deficient radioactive beams for decay, laser and mass spectroscopy studies and as one of the top facilities for the study of super-heavy nuclei.