Perspectives of Super-Heavy Nuclei research with the upcoming separator-spectrometer setup S^3 at GANIL/SPIRAL2 - The VAMOS Gas-Filled separator and AGATA

Christophe THEISEN[1],[*] on behalf of the S^3 and VAMOS-GFS collaborations

[1]*Irfu, CEA, Université Paris-Saclay, 91191 Gif-sur-Yvette, France*

Abstract. Several facilities or apparatus for the synthesis and spectroscopy of the Super-Heavy Nuclei (SHN) are presently under construction in the world, which reflect the large interest for this region of extreme mass and charge, but also for the need of even more advanced research infrastructures. Among this new generation, the GANIL/SPIRAL2 facility in Caen, France, will soon deliver very high intense ion beams of several tens of particle μA. The Super Separator Spectrometer S^3 has been designed to exploit these new beams for the study of SHN after separation. It will provide the needed beam rejection, mass selection and full arsenal of state-of-the art detection setups. Still at GANIL, the AGATA new generation gamma-ray tracking array is being operated. The VAMOS high acceptance spectrometer is being upgraded as a gas-filled separator. Its coupling with AGATA will lower the spectroscopic limits for the prompt gamma-ray studies of heavy and super-heavy nuclei. In this proceeding, these new devices will be presented along with a selected physics case.

1 Introduction

The synthesis of new elements has reached up to $Z = 118$ with the IUPAC/IUPAP recently assigning the naming rights for the elements 113, 115, 117 and 118 to groups at the FLNR Dubna, Russia and at RIKEN, Japan [1–4]. Despite tremendous worldwide efforts in the production of the heaviest nuclei, the region of SHN is still not well known nor delineated. Indeed, the production cross-sections of the heaviest known nuclei are extremely low, at the pb level in the $Z = 114 - 118$ region, which corresponds with present state-of-the-art facilities to the synthesis of a few atoms per month. This low production is itself related to the extreme fragility of the species: the nuclei beyond rutherfordium ($Z = 104$) are solely stabilised by quantum mechanics. A charged liquid drop would fall apart due to Coulomb repulsion. Therefore those species provide an ideal laboratory for nuclear structure studies. On the theoretical side, there is not yet any consensus concerning the position and properties of an hypothetical island of stability around a doubly magic spherical nucleus. While microscopic-macroscopic models predict $Z = 114$, $N = 184$ as doubly magic numbers, models based on effective forces predict either $Z = 120$ or 126, $N = 172$ or 184: see e.g. [5, 6]. These nuclei are however inaccessible using a stable beam, even when using a radioactive actinide target.

Besides the synthesis of the heaviest species approaching the island of stability, advances in the field can be made performing detailed studies of lighter nuclei for which production cross-sections are higher. Decay spectroscopy after separation of deformed nuclei around $(N, Z) = (152, 100)$ and $(162, 108)$ provides direct links to the next heavier spherical closed shell nuclei, by investigating single particle levels which are, according to model calculations, relevant in both regions [7, 8]. A particularly interesting feature, accessible with this experimental approach, are meta-stable states created by nuclear deformation, so called K isomers. Following the trend of vanishing deformation they can be used to trace the spherical SHN and to locate the island of stability. A second route consists in prompt spectroscopy studies of deformed nuclei, still with the idea to trace orbitals active both in deformed nuclei and in heavier spherical nuclei [9]. Such studies can be made down to the 10 nb level, ^{256}Rf being the heaviest nuclei for which collective properties have been deduced so far [10].

Progress and success in the field will be obtained by lowering the cross-section limits to reach heavier nuclei in the direction of the island of stability, and by performing detailed studies. This will be done improving experimental means like new high intensity ion accelerators, efficient in-flight separators and spectrometers, and highly efficient detector systems with fast electronics. The new SPIRAL2 facility and, in particular, the separator-spectrometer setup S^3, presently under construction at the accelerator laboratory GANIL in Caen, France, will offer great perspectives for the field. Still at GANIL, the upgrade of the VAMOS vacuum spectrometer as a Gas-Filled Separator (GFS) will provide, when coupled to e.g. AGATA, a very efficient tool for prompt spectroscopy.

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[*]e-mail: christophe.theisen@cea.fr

2 The GANIL/SPIRAL2 facility

The "historical" part of the GANIL facility is based on three cyclotrons, 2 of which serve for stable beams acceleration, plus the CIME cyclotron for reacceleration of radioactive species using the ISOL method (SPIRAL1 facility). Among the different instruments, the AGATA gamma-ray spectrometer is hosted at GANIL until 2019 and will be coupled to the VAMOS-GFS high acceptance separator, as detailed in section 4.

The new forthcoming SPIRAL2 facility is based on a superconducting linear accelerator that will deliver ions up to $\approx$ 15 MeV/A. The S^3 Super Separator Spectrometer is one of the major experimental device that will benefit from the high intense beams. In the first phase of the project "phase1", the RFQ injector $A/Q = 3$ will allow production of mostly $A \lesssim 50$ beams. This RFQ has been optimised for the deuterium beams used for neutron production at the Neutrons For Science facility, and for the "phase2" of the project. In the "phase1++" stage, a second RFQ $A/Q = 7$, which construction is foreseen from 2019, will deliver ultra-high intense beams up to uranium. This phase will provide a world-class facility for SHN research, competitive with other ongoing projects such as the SHE factory in Dubna [1]. As an example, ^{48}Ca beam of $\approx$ 2.5 pμA intensity will be available with the RFQ $A/Q = 3$, raised up to $\approx$ 15 pμA with "phase1++".

The 30 meter long S^3 Super Separator Spectrometer, shown in figure 1, has been optimised for selecting from the high background of parasitic reactions the rare heavy nuclei produced after fusion-evaporation reactions. In order to sustain the beam intensity, targets will be arranged on a rotating wheel installed in the target cave, with the possibility of using actinide material. The first separator section, a momentum achromat, has a QQQDQQQ-QQQDQQQ optics configuration with the purpose of getting rid of most of the direct beam (more than 99.9 %). The spectrometer section with a QQQEQQQ-QQQDQQQ configuration, combining an electric and a magnetic dipole, acts as a mass separator. The electric dipole will also separate the fusion-evaporation residues from the direct beam according to their electric rigidity. According to simulations, the direct beam should be fully suppressed. A rejection factor of about 10^{12} is expected for the beam-like particles. Ions will be dispersed at the focal plane according to their mass over charge state ratio and provide a resolution $\Delta M/M \approx 1/300$. A transmission of $\approx$ 40% is expected for asymmetric reaction such as ^{208}Pb(^{48}Ca,2n)^{254}No while a lower transmission of $\approx$ 15% is expected for more asymmetric reactions such as ^{238}U(^{22}Ne,5n)^{255}No.

As an option, devices can be installed at the achromatic point of S^3, such as the Fast Ion-Slow Ion Collision (FISIC) station for atomic ion-ion collisions studies, or a target surrounded by a photon detection array for prompt studies of exotic nuclei produced after two-step reactions. Decay spectroscopy after separation will be performed at the focal plane using an array known as SIRIUS (Spectroscopy and Identification of Rare Ions Using S^3). The first detection stage consists of one or two trackers that will provide the time-of-flight measurement for kinematic selection, and the position needed for the M/Q identification. Ions will be implanted in a segmented 10×10 cm^2 double-sided silicon strip detector (128 strips on both vertical and horizontal directions) 300 μm thick, where subsequent decays will also be measured (alpha, fission, electrons). A tunnel made of four 1 mm thick, 10×10 cm^2 Si pad detectors will be placed upstream for conversion-electron spectroscopy, escaped alpha and fission fragments detection. The Si detectors will be surrounded by 5 HPGe detectors for gamma-ray spectroscopy. All detectors will be equipped with digital, fully time stamped electronics to minimise the dead-time and allow measurement of fast decays. The S^3 and SIRUS coupling is expected to be completed in 2018 and then will be ready for commissioning. More details can be found in [11]. As an alternative to SIRIUS, it will be possible to send ions in a gas cell. There, in-gas jet laser spectroscopy can be performed with a very high resolution (200 MHz). Isotopic shifts, electric or magnetic moments can be measured. Provided the atomic scheme is known or measured, laser ionisation can selectively send the nuclei of interest (or their isomers) to a low energy line. Their mass can be measured with high precision with a multi-reflection time-of-flight spectrometer [12]. In a latter phase expected in 2023, the option to send the ions in the DESIR hall [13] will be available for ground state and atomic properties studies: mass measurement, decay studies, collinear laser spectroscopy, etc. S^3 is not only designed for SHN, but for other regions where mass selection and/or tagging is needed for the spectroscopy and synthesis of rare nuclei, which corresponds to a large panel of isotopes from $N \sim Z$ nuclei up to the heaviest nuclei.

3 Selected physics case with S^3

3.1 "First day" experiments

As "first day" experiments following the commissioning phase, physics cases of technically moderate difficulty but with potentially high scientific outcome have been selected by the collaboration. Among the possible candidates, there is a strong interest in the study of high-K isomers in ^{254}No and ^{256}Rf. High-K isomerism is a rather general phenomenon in the transfermium region due to the presence of high-K single particle states around the Fermi level. In even-even deformed nuclei, it corresponds to the breaking of a pair promoted towards two different single-particle states coupled with a high-K projection along the symmetry axis. Therefore their study allows to track the properties of the corresponding orbitals, to provide information on pairing correlations, and eventually allows the spectroscopy of states fed along the isomer decay path. Because of the K-forbiddness, the decay of these states is largely hindered and provides a clear experimental signal that allows to isolate the corresponding exotic states using the so-called calorimetric technique [14]. Isomeric states in the transfermium region were first postulated in ^{254}No and ^{250}Fm by A. Ghiorso et al. in the early 1970's at the Lawrence Berkeley National Laboratory (LBNL) [15].
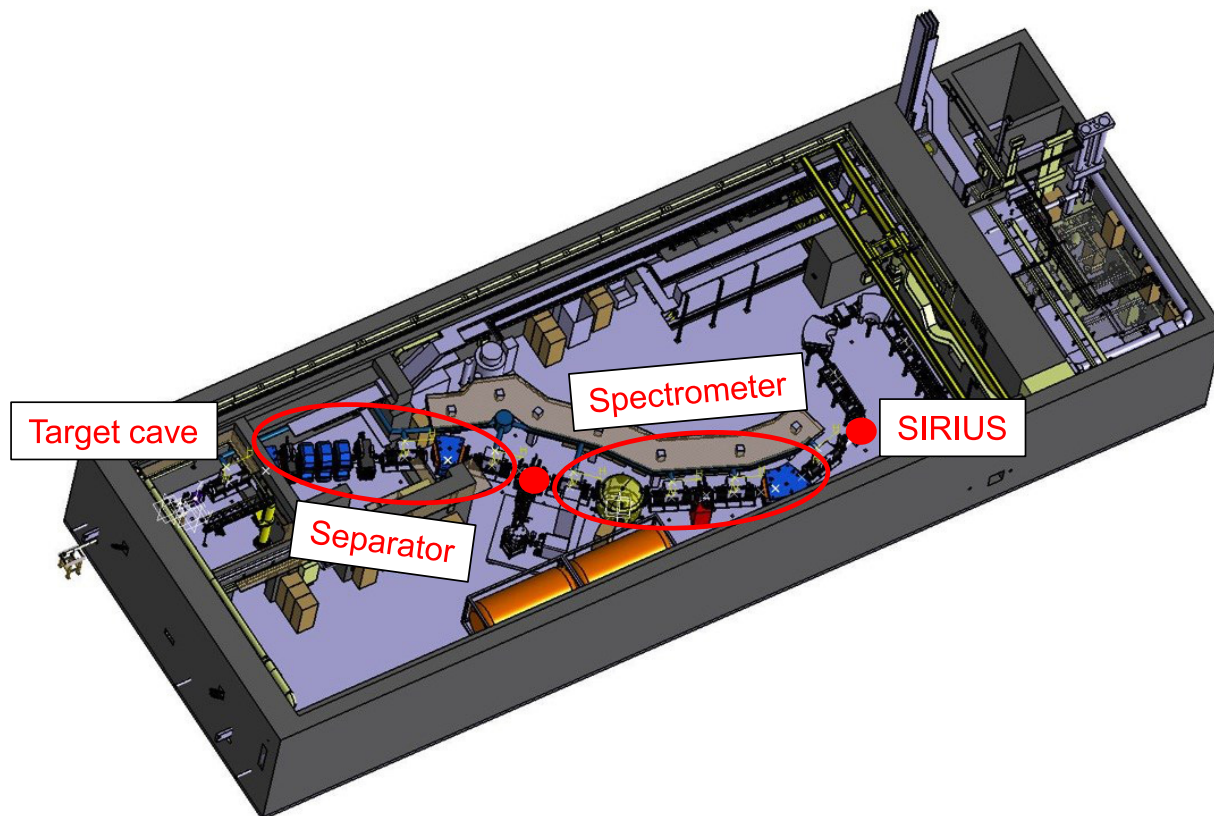
Figure 1. Design view of S^3. The position of the achromatic point between the separator and spectrometer sections, and of the SIRIUS station, are represented by red dots.

While the correct half-life was deduced, neither the excitation energy nor the decay path could be measured. It is only in 2006 that a detailed level scheme could be obtained in two experiments performed at the University of Jyväskylä [16] and at the Argonne National Laboratory (ANL) [17]. The experiment was later repeated at GSI and LBNL [18, 19]. Despite the large cross section of about 2 μb, there are significant differences in the level schemes and interpretations: the isomer is either understood as the breaking of a pair of protons $\pi[514]7/2^- \otimes \pi[624]9/2^+$ or neutrons $\nu[613]7/2^+ \otimes \nu[734]9/2^-$, which has consequences on the underlying single-particle scheme and deformed shell gap. Also a higher-lying isomeric state presumably of 4qp character has been measured in the four above-mentioned experiments, but without precise excitation energy, only tentative decay scheme, spin, parity and single-particle configuration. In the same mass region, three isomeric states have been observed recently at LBNL in ^{256}Rf [20]. Due to the lower cross-section of $\approx$ 17 nb, only tentative placement and single-particle configuration could be proposed. Moreover an experiment performed at ANL provides a different interpretation [21].

Consequently, the two $N = 152$ isotopes ^{254}No and ^{256}Rf deserve comprehensive new investigations. These cases are feasible already in the first operation period of S^3, using the reactions ^{208}Pb(^{48}Ca,2n)^{254}No and ^{208}Pb(^{50}Ti,2n)^{256}Rf, respectively. Assuming a beam intensity of $\approx$ 2 pμA with the $A/Q = 3$ RFQ, targets of

500 μg/cm^2 and a transmission of 50%, a statistics of 10^7 and 90×10^3, respectively, is expected in a one week experiments, which exceeds the previous obtained figures by more than one order of magnitude.

3.2 Further studies with S^3

With the availability of the RFQ injector $A/Q = 7$, a large panel of nuclides will be accessible with decent statistic for spectroscopic studies. To take an example, cross-sections at the 10 pb level reached for some nuclides in the $Z = 114 - 116$ region will correspond to a statistics of several hundred tagged nuclei per week at S^3, assuming a transmission of $\approx$ 15% for very asymmetric reactions using actinide targets.

Besides single-particle spectroscopy, direct experimental proof of the atomic number could also be the measurement of characteristic X-rays where attempts have been recently made with limited success so far for e.g. $Z = 115$ [22, 23]. In the case of ^{288}Mc ($Z = 115$) synthesised using the reaction ^{48}Ca+^{243}Am, about 1800 L X-rays are expected in a one week experiment using S^3 [8].

Returning to the K-isomer cases, their role in an enhanced stability of SHN has been pointed-out [24]. In several cases, nuclides are characterised by a higher stability and longer lifetime of the metastable state compared to the ground-state. Such an inversion was observed in ^{270}Ds already during its first synthesis experiment: isomer half-

life $t_{1/2} = 6.0^{+8.2}_{-2.2}$ ms compared to $t_{1/2} = 100^{+140}_{-40}$ μs for the ground-state [25]. Because of the low cross-section of 15(5) pb, only 3 events were observed for each decaying state, which does not allow a robust interpretation. With S³, a total of ≈ 400 implanted nuclei are expected per week. Other examples of recently observed isomer – ground state lifetime inversion are ²⁵⁴Rf and ²⁵⁰No.

The nuclide ²⁵⁴Rf has been recently studied at ANL and LNBL [26]. Two isomeric states with half-lives of 4.7(1.1) μs and 247(73) μs have been observed, and interpreted as 2qp neutron $K^\pi = 8^-$, and 4qp $K^\pi = 16^+$ configuration, respectively. Surprisingly, the half-live of the 4qp isomer exceeds that of the ground-state by one order of magnitude. Because of the short half-live of the 2qp isomer, utilisation of digital signal processing was a key of the success in order to disentangle the signals corresponding to the implantation, electromagnetic and alpha decays. Because of the modest cross-section of ≈ 2.4 nb for the fusion-evaporation reaction ⁵⁰Ti(²⁰⁶Pb,2n)²⁵⁴Rf, neither the precise excitation energy of the isomer nor their de-excitation could be measured. With S³ in the 1++ phase, an implantation rate of ≈ 8/min is expected corresponding to ≈ 80 × 10³ events per week, which is comfortable for decay studies after separation.

The lifetime of ²⁵⁰No has been a long-standing puzzle since its first synthesis by Oganessian et al. with the Dubna gas-filled recoil separator [27], studies by Belozerov et al. using VASSILISSA [28], and by Peterson et al. using the fragment mass analyser at ANL [29]. The first experiment by Oganessian et al. gave the surprising result that going from ²⁵²No to ²⁵⁰No, the spontaneous fission half-life drops by seven orders of magnitude. In the subsequent experiment using VASSILISSA, two spontaneous fission half-lives $t_{1/2} = 5.9$ μs and 54 μs were measured but it was not clear whether the long component was due to the neighbouring ²⁴⁹No or to an isomeric state. Finally, Peterson et al. assigned the shorter-lived decay ($t_{1/2} = 3.7^{+1.1}_{-0.8}$ μs) to the ground state and the longest to a $K^\pi = 6^-$ isomer ($t_{1/2} = 43^{+22}_{-15}$ μs). It is only recently in an experiment performed at the University of Jyväskylä that the electromagnetic branch from the isomeric state could be detected [30]. Again, using digital signal processing was a key ingredient for disentangling the implantation, de-excitation and decay. In the phase1++ of SPIRAL2, about 40 implanted nuclei are expected per minute, leading to a statistics of ≈ 420 × 10³ implanted nuclei in a one week experiment.

There are obviously a wealth of other interesting studies to be performed with S³ using either the SIRIUS decay station, the low energy branch or the forthcoming DESIR hall, not only in the region of the heaviest elements, but along the nuclear chart where separation selection and/or tagging techniques are required to study rare nuclei immersed in a dominant background of parasitic reactions. More details can be found in e.g. [8, 31].

4 The VAMOS Gas-Filled Separator and AGATA

The decay spectroscopy after separation discussed above is an ideal tool for the study of isomeric and low-lying single-particle states, since the decay process selectively populates states in the daughter nucleus at low excitation energy and low angular momentum. On the other hand, fusion-evaporation reactions populate medium to high spin states. Therefore prompt spectroscopy of the transitions emitted straight after the collision allows to study collective properties. However, using a detection array at the target position induces severe restrictions on the beam intensity and therefore on the cross-section limits for the nuclei to be studied. So far ²⁵⁶Rf is the heaviest nucleus for which collective properties have been studied using prompt gamma-ray spectroscopy [10]. Lowering the spectroscopic limits can be done in three directions: improving the transmission for the recoiling nuclei, increasing the prompt array efficiency, and improving the prompt array counting rate capabilities.

The VAMOS-GFS project is an upgrade of the existing VAMOS spectrometer [32] that adds a Gas-Filled Separator (GFS) mode. This upgrade was guided by mainly two motivations. First VAMOS is a large acceptance device therefore a huge transmission is expected in particular for the heaviest elements leaving the target with a large angular distribution. The second motivation is related to the opportunity for its coupling with state-of-the-art gamma-ray detectors (the new generation gamma-tracking array AGATA [33, 34], and other arrays such as EXOGAM2, PARIS...). Hence VAMOS-GFS and AGATA which is operated at GANIL until 2019, should provide one of the most efficient devices (in terms of transmission and selectivity) for the spectroscopy of rare nuclei produced by fusion-evaporation reactions. Thanks to the concept of tracking and fully digital signal processing, AGATA will provide a large efficiency and a high counting rate capability. The feasibility and the potential of VAMOS-GFS have been established in a test experiment performed in 2009 [35]. Excellent performances in terms of fusion-evaporation residue transmission and background rejection have been obtained for the ⁴⁰Ca + ¹⁵⁰Sm collisions around the Coulomb barrier: a large transmission of ≈ 95% was measured for the neutron evaporation channels. However, the modifications, mandatory to transform the vacuum VAMOS spectrometer into a gas-filled separator, were of provisional character. The aim of the VAMOS-GFS project is to make available to a widespread community a fully operational device, with the best performances for a large range of reactions and a smooth operation.

A sketch of the VAMOS-GFS upgrade is shown in Fig. 2. VAMOS has natively a $Q_v Q_h (E \times B) D$ optics configuration, restricted in most experiments to $Q_v Q_h D$. Since the dipole is the last optics element, the magnetic field, focal plane detection and beam dump geometries can be optimised for each reaction such as to increase the physical separation between the beam and the fusion-evaporation residues. In practice, the beam dump will be at a fix position on the low magnetic rigidity side, namely ≈ 30° with
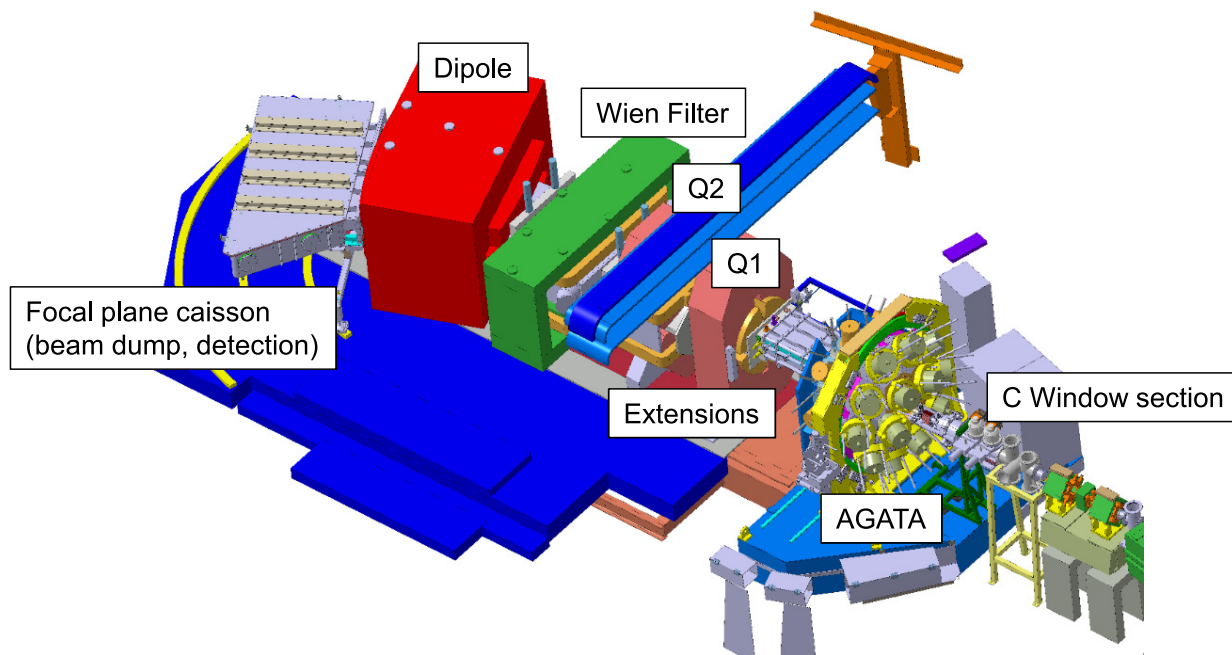
Figure 2. Design view of the VAMOS Gas-Filled separator coupled to the AGATA gamma-ray tracking array.

respect to the dipole exit central angle (therefore constraining the magnetic field to be used), while the recoil detection will be placed according to the magnetic rigidity of the fusion-evaporation residues. This contrasts with existing or foreseen separators for which the detection is at a fixed position on the optics axis. To give an example, the optimum detection position for VAMOS-GFS is at $\approx -5°$ and $\approx 15°$ with respect to the dipole exit central angle for the fusion-evaporation reactions ^{208}Pb(^{48}Ca,2n)^{254}No and ^{58}Ni(^{54}Fe,2n)^{110}Xe, respectively. The beam rejection and transmission will be optimised in such manner. A transmission of $\approx 70\%$ is expected for the two reactions mentioned above.

The physics case covered by VAMOS-GFS includes experiment where it is mandatory to physically filter the nuclei of interest lost in a huge background of parasitic reactions, plus eventually to tag the nuclei using their characteristic decay (Recoil Tagging and Recoil Decay Tagging techniques). Besides the region of the actinides and SHN, the foreseen experiments will also cover the ^{100}Sn region, nuclei at the proton drip-line, and the neutron-deficient lead region. The physics case gathering a large community has been discussed in several collaboration meetings and reviewed by the GANIL program advisory committee. In a longer term, fusion-evaporation reactions used in conjunction with exotic beams will permit to reach exotic isotopes, and/or still un-explored regions of the (angular momentum L, excitation energy E^*) phase space. The interest in fusion-evaporation for reaction dynamics studies is obvious, giving access to the evolution of the system as driven by rotation and/or temperature.

The modifications to upgrade VAMOS imply the following items. The separation between the incoming vacuum beam line and the gas-filled region is performed using a thin Carbon window. At its nominal position, the angular

acceptance of VAMOS is ≈ 70 msr. Pushing VAMOS-GFS back with respect to the target position using extensions will help to achieve a better beam control and to increase the maximum $B\rho$ capability, with only a slight decrease of the transmission. The transmission of $\approx 70\%$ quoted above is estimated pushing VAMOS-GFS back by 60 cm. The new focal plane chamber needed to accommodate the variable detection angle has been built. The detection will be based on a modified version of MUSETT, an array of segmented double-sided silicon strip detectors [36], and on a multi-wire proportional chamber for time-of-flight and energy loss measurements. A set of masks will be used to minimise the parasitic ions reaching the detection. Moreover, a shield will be placed between the tantalum beam dump and the focal plane detectors to avoid contamination from the radiations coming from the beam dump. The shield will stop all charged particles, and the fraction of 100 keV photons transmitted will be less than 10^{-6}. No contamination of the prompt detection array by the beam dump is expected since the latter is placed at ≈ 8 m from target point, and since it is shielded by the VAMOS two quadrupoles and by the Wien filter. The VAMOS-GFS project is in its last completion phase.

It should be noted that the VAMOS-GFS project has large similarities with the AGFA project (see the contribution of B.B. Back in these proceedings), with also the magnetic dipole being the last optics element, a similar transmission, and the opportunity to be coupled with the GRETA gamma-ray tracking array.

The laboratories primarily involved in this work are: Grand Accélérateur National d'Ions Lourds (GANIL), Institut de recherche sur les lois fondamentales de l'Univers (CEA, Irfu), Institut de Physique Nucléaire d'Orsay

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