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Low-energy experiments at the S3 spectrometer

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Abstract: With the advent of the Spiral-2 linear accelerator and the associated S3 spectrometer at the Ganil laboratory in France, new realms of intermediate-mass N=Z and very heavy nuclei will soon become available for research in nuclear structure. After their production and selection in the spectrometer, the ions of interest will be stopped in a buffer gas, neutralised, resonantly re-ionised, cooled and bunched. This will bring us in an adequate position to perform laser spectroscopy, mass measurements and decay spectroscopy of their ground and isomeric states. In this contribution we report on the ongoing commissioning of the detector set-up.

Keywords: *New facilities, laser spectroscopy, mass spectrometry, nuclear structure*

I. INTRODUCTION

Recent advances in nuclear theory are bringing ever heavier nuclei within reach of ab-initio techniques. The quantum many-body calculations naturally include three-nucleon forces, emphasising their influence for instance in the Gamow-Teller strength of ^{100}Sn [1]. Large-scale shell-model calculations are carried out in valence spaces that span complete shells and beyond, taking into account correlations that previously had to be left out. These in turn induce quadrupole deformation throughout the nuclear chart, affecting even the immediate vicinities of doubly magic nuclei such as ^{78}Ni [2]. The Monte-Carlo shell model puts in place a framework for exploring the sudden quantum phase transitions that are observed in exotic isotopes. Striving to unite single-particle and collective behaviours, it stresses the role of the central and tensor forces in the shell evolution of magic and near-magic nuclei such as zirconium, tin and mercury [3]. Reaction theory increasingly embraces structure models. By replacing both the optical and the shell-model potential by the nucleon self-energy, the dispersive optical model links energy states above and below the Fermi energy in a single description [4].

Experimentally, proton-induced fission at Isolde and Triumf gives access to the neutron-rich side of the nuclear chart. The particles diffuse out of the target as neutral atoms, they are ionised, extracted at low energy and eventually post-accelerated. At NSCL and Riken, fragmentation at high energy covers a broad spectrum of nuclei that are available for multinucleon transfer and knock-out reactions. In-flight spectroscopy of the emitted radiation relies on the development of multidetector arrays that provide the necessary granularity for event reconstruction. Fusion-evaporation reactions favour products rich in protons, recoiling into a spectrometer at threshold energies but setting aside for FLNR and S3 a range of experiments that would be difficult to perform elsewhere.

The S3 spectrometer for exotic radioactive ion beams is currently being installed at the Ganil laboratory in France and

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shall become operational in 2023. It offers novel opportunies to investigate isotopes produced in heavy-ion fusion-evaporation reactions, in particular for channels with low cross sections at the proton dripline and near the upper end of the nuclear chart. An approach based on laser spectroscopy in a swiftly expanding gas jet is adopted for the detection strategy, called Radioactive Elements in a Gas jet for Laser Ionisation and Spectroscopy (Reglis). It shall be coupled to a mass spectrometer that is built around a linear ion trap, referred to as Piège à Ions Linéaire du Ganil pour la Résolution des Isobares et la mesure de Masse (Pilgrim).

II. REPORT

A. Physics scope

The Reglis experiment focusses on two objectives, the isotopes near the N=Z line from Z=40 onwards and the very heavy nuclei with Z≥89. The first region allows to cover a broad range of physics issues that spans from collectivity and deformation over spin-aligned coupling schemes in nuclei such as ^{90}Rh and ^{94}Ag. Also the balance between isoscalar and isovector pairing interactions in ^{98}In and the evolution of single-particle structures in ^{99}In and ^{101}Sn attracts much interest. We shall shed light on quadrupole moments in the tin chain and investigate novel decay modes such as super-allowed α-decay in ^{112}Ba-^{108}Xe-^{104}Te and cluster radioactivity in ^{114,112}Ba. The measurement of masses will give access to binding energies and the role of the Wigner term. Among the heavy elements, we shall focus on the actinides. This includes the development of the N=126 shell closure in $^{210-213}$Ac and $^{213-215}$Th, the appearance of octupole deformation in $^{225-228}$U, and the possible emergence of a superheavy spherical shell gap as seen through K-isomers in $^{249-252}$Fm and $^{252-254}$No.

The mean-square charge radii, magnetic dipole and electric quadrupole moments can be extracted from the hyperfine interaction between the nucleus and its surrounding electrons, which is recorded by laser spectroscopy. The masses, spins and decay properties of their ground states and isomeric levels will be constrained by complementary measurements on the collected ions by means of time-of-flight mass spectrometry and decay spectroscopy.

B. The S3 spectrometer

A new superconducting linear accelerator has been constructed at Ganil, comprising 26 accelerating cavities housed in 19 cryomodules [5]. It will be able to deliver stable ion beams with intensities that are ten times larger than what is presently available. With a mass-to-charge ratio of 3, currents of 3 pμA for ^{40}Ar, 2 pμA for ^{40}Ca and 1 pμA for ^{48}Ca and ^{58}Ni at energies up to 14.5 MeV per nucleon are projected. With a later upgrade of the injector to a mass-to-charge ratio of 7, heavy beams up to uranium will become available.

These primary beams will make it possible to study fusion-evaporation reactions with cross sections down to picobarns, yielding neutron-deficient nuclei near the N=Z line and isotopes of very heavy elements. They will be separated from the intense background in the S3 recoil spectrometer [6]. The spectrometer consists of two stages, the first one of which is a momentum achromat that lets the reaction products pass through while the primary beam is suppressed with a factor of 10^3. Subsequently the ions of interest are selected in a mass separator with a resolution of 300. The combination of the momentum achromat and the mass separator results in a final rejection power of 10^{13}. An angular acceptance of ±50 mrad, a magnetic rigidity acceptance of ±7 % and a charge-state acceptance of ±10 % are aimed at. This means two charge states on either side of the centrally chosen charge state will be transmitted. A high-resolution mode that separates the charge states as well as a converging mode with a better transport efficiency at the price of a wider beam spot are proposed. To illustrate with an example, for the $^{208}Pb(^{48}Ca,2n)^{254}No$ reaction at 217 MeV a transmission efficiency of 56% is estimated for 5 charge states within a circular area of 50 mm diameter. The ^{254}No isotopes arrive with a mean energy of 37 MeV. In this mass region the ion rate amounts to 1 particle per second only but the beam would be almost 100% pure. For the $^{116}Sn(^{40}Ar,4n)^{152}Er$ reaction at 167 MeV, on the other hand, the expected rate reaches 8.6 10^4 particles per second yet with a purity of 1% only.

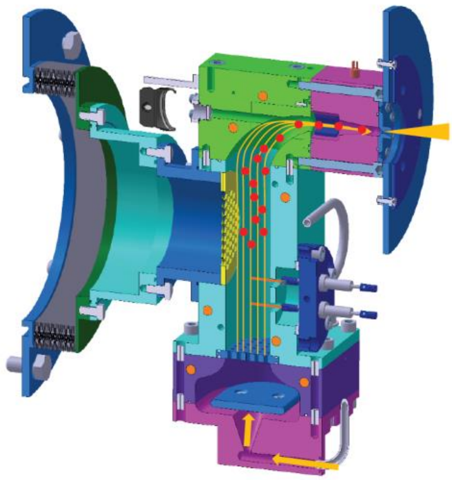

Fig. 1. Drawing of the Reglis gas cell. The S3 beam arrives from the left and the gas enters from below (orange). The stopped particles (red) are evacuated on the top right side

C. Principle of the detector

To take the best advantage of the capabilities of the accelerator and the spectrometer, a detection set-up with high efficiency is in order. The ions should be made available for several measurement set-ups so they should be transferable as a beam at low emittance. Moreover and in spite of the 10^{13} rejection power of S3, some secondary beams will still be significantly contaminated by their A±1 neighbours and additional selectivity is desirable.

We therefore aim to stop the reaction products in a buffer gas at high pressure [7]. They will be neutralised through collisions with the gas atoms, extracted from the gas cell in a well-defined cold and supersonic jet and resonantly re-ionised by laser light. They will then be sent through a series of radiofrequency quadrupoles (RFQ), in which their emittance is greatly reduced before being fed into various experimental set-ups. At the same time, we shall be able to instantaneously perform laser spectroscopy in the gas jet by scanning the resonance wavelength across the hyperfine structure. This is possible because the low density in the uniform jet keeps pressure broadening small such that sufficient resolution can be achieved.

D. Intrajet laser spectroscopy

The thickness of the entrance window is of the utmost importance as some of the secondary beams carry energies below as little as 1 MeV per nucleon. For critical cases we can afford not more than a couple of micrometers of material. On the other hand the window should span a diameter of 50 mm and remain rigid enough to withstand the pressure difference with the high vacuum inside S3. We choose a titanium foil that is supported by a honeycomb grid, both fused together by friction stir welding.

For the buffer gas a compromise is sought between the stopping power in the gas cell and the load on the pumping system. We use argon at 200 to 500 mbar purified to the part-per-billion level. Special care is taken for the mechanical design of the cell so we obtain a gas flow that is as laminar as possible, avoiding turbulences that would trap the particles. The flow transports the radioactive particles to the exit hole with an evacuation time of several hundreds of milliseconds, setting a limit for the shortest lifetimes we can efficiently measure. The exit hole takes the shape of a Laval nozzle. The thermodynamic properties of the jet are defined by the background pressure in the experimental chamber as well as the contour of the nozzle, the machining of which demands a dedicated effort with a precision of 5 µm. Several nozzles were tested, the latest design producing a homogeneous supersonic jet of Mach 8 at a temperature of 18 K over a distance of 25 mm. For development purposes the jet was visualised with Planar Laser-Induced Fluorescence and modelled with the Comsol and Ansys flow codes [8].

Laser ionisation happens in two or more steps. The last step may not be resonant and simply allow one of the atomic electrons to reach the continuum. One of the resonant steps is used for probing the hyperfine structure and requires a narrow bandwidth. It irradiates the gas jet perpendicularly and is expanded into a laser sheet to cover as large a section of the jet as possible. It is planned to implement a system of both solid-state as well as dye lasers at high repetition rate, the former being relatively free of safety constraints and the latter providing higher power levels. From a proof-of-principle experiment that was performed on $^{214\text{-}215}$At an overall efficiency of 10% and a selectivity of 3000 appears within reach [9]. The FWHM resolution of the hyperfine spectrum came down to 400 MHz during this measurement, but at S3 we intend to achieve 100 MHz, which will be essentially due to the gas temperature, the jet divergence and the laser linewidth. This number can be compared to the natural linewidth of the atomic transition of 4 MHz but remains amply sufficient to probe the hyperfine structures, the splittings of which typically amount to 300 MHz in the actinides.

E. Beam manipulation and mass spectrometry

The ions that emerge from the supersonic jet will be captured in a S-RFQ. The name derives from its geometrical shape, the purpose of which is to move the ions vertically out of the axis along which the broadband laser is sent in. A quadrupole mass filter (QMF) with a resolving power of 100 further cleans the beam. It is followed by a RFQ-buncher, which is filled with 10^{-2} to 10^{-3} mbar of helium and cools and prepares the beam for injection into a drift tube. The tube lifts the ions to 3 kV and transfers them to the Pilgrim multireflection time-of-flight mass spectrometer (MR-tof-MS) [10]. The latter basically comprises a linear trap with an electrostatic mirror on either end, between which the particles travel back and forth until they are spatially separated from isobaric contaminants because of their mass differences. A resolution of 10^5 can be achieved for an input emittance of 10 π.mm.mrad, corresponding to a flight path of some hundreds of meters in 10 ms. For a halflife of 100 ms, Pilgrim is expected to attain a sensitivity of one particle per ten seconds.

While the transmission through S3 can be evaluated at 50% on average, the thermalisation, neutralisation and transport of the particles in the gas cell are estimated at more than 25%. The rate of laser ionisation depends on the availability of a suitable scheme and can be taken at 50%, the capture efficiency in the RFQ sequence at 80%. The overall efficiency of our set-up before injection into Pilgrim would then reach at least 5%.

Reglis and Pilgrim are presently installed at the LPC laboratory nearby Ganil in Caen, where they can be commissioned over the next two years. Stable beams will be produced by heating a metallic filament that is mounted inside the gas cell. In order to mimimise adverse effects on the gas flow, the heat excess is removed by water cooling. One of the first elements to extract will be erbium, which is the chemical homologue of fermium. Since laser-ionisation schemes are poorly known for the actinides we are interested in at S3, they will be developed from better studied transitions in the lanthanides. According to the current timeline, S3 should become available for experiments in 2023.

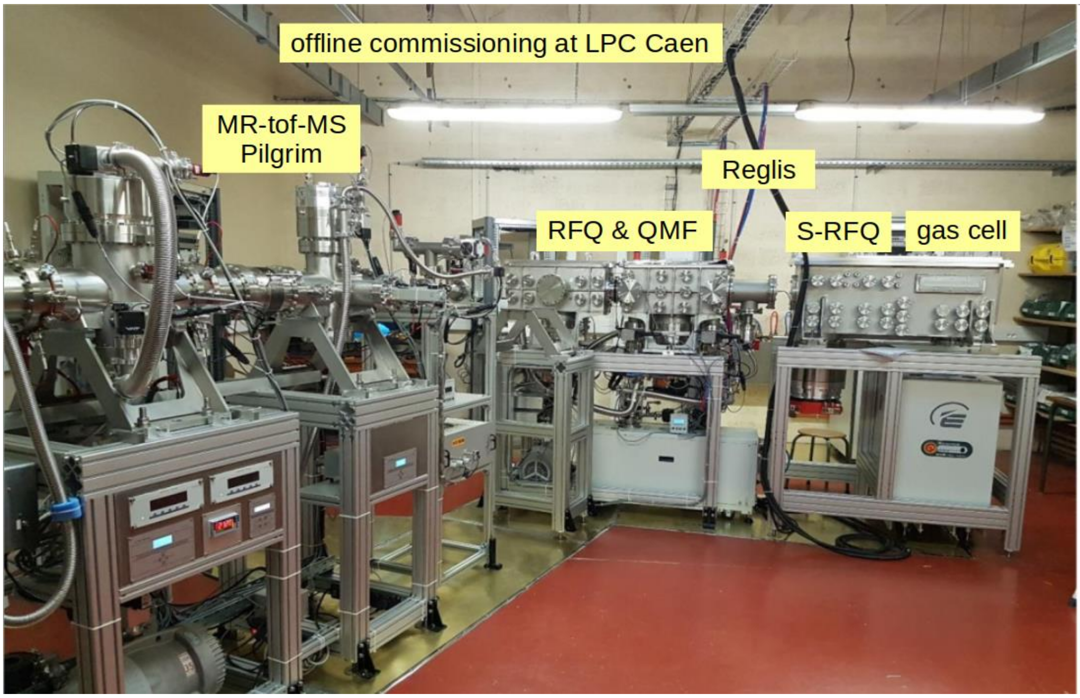

Fig. 2. The Reglis and Pilgrim set-ups as they are presently installed at the LPC laboratory in Caen for commissioning

F. Decay spectroscopy

The ions that emerge from Pilgrim will be implanted in a thin carbon foil that is surrounded by a small but segmented silicon array. Simple ion counting as well as decay spectroscopy through electron and α-radiation will be handled by a new generation of electronics with automatic gain switching. Particular attention will be paid to combining a high efficiency and resolution with a low energy threshold. Two germanium detectors can be integrated in a compact geometry for registering coincident γ-rays. The addition of a tape station for β-decay studies, which is helpful for those physics cases at N=Z, is also foreseen.

III. CONCLUSIONS

The new S3 spectrometer at Ganil shall unlock new N=Z nuclei and very heavy isotopes for experimental research. Because of the extraordinary low cross sections to produce these nuclei, a dedicated detector set-up that is sensitive to count rates of a few particles per second has been constructed and is now being commissioned. The Reglis gas cell provides the base for laser spectroscopy in a supersonic jet, probing the hyperfine structure to yield charge radii and electromagnetic moments. The Pilgrim trap is properly suited for mass measurements, recording the time of flight as the ion path is reflected between two electrostatic mirrors. In order to overcome the slow evacuation time of the gas cell, which constitutes the main limitation of our experiment when accessing the shortest lived isotopes, the development of a smaller gas volume that incorporates electrical radiofrequency fields is being considered.

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