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In gas laser ionization and spectroscopy experiments at the Superconducting Separator Spectrometer ($\mathbf{S}^3$): Conceptual studies and preliminary design

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ABSTRACT

The results of preparatory experiments and the preliminary designs of a new in-gas laser ionization and spectroscopy setup, to be coupled to the Super Separator Spectrometer $\mathbf{S}^3$ of SPIRAL2-GANIL, are reported. Special attention is given to the development and tests to carry out a full implementation of the in-gas jet laser spectroscopy technique. Application of this novel technique to radioactive species will allow high-sensitivity and enhanced-resolution laser spectroscopy studies of ground- and excited-state properties of exotic nuclei.

1. Introduction

Ever since the early days when step-wise resonance laser ionization was proposed as a selective and efficient ionization tool [1] for the production of isobaric-pure Radioactive Ion Beams (RIBs) [2,3] its usage has continued growing. It is such, that several on-line facilities worldwide use currently a Resonance Ionization Laser Ion Source (RILIS) [4], or plan to do so, as a powerful production mechanism of high-purity RIBs. In some cases, as e.g. RILIS-ISOLDE, this type of ion source is already used in more than half of the annually programmed beam times of the ISOLDE facility (a total of 3000 h in 2012 [5]).

Currently there exist two types of RILIS, one operating in a hot cavity [6] and the other in a gas cell [7]. While in the former radioisotopes diffuse out of a high temperature target ($T \sim 2000$°C), usually bombarded previously by high-energy protons, and are subsequently laser ionized in the ionizer cavity attached to it, in the latter the reaction products are thermalized and neutralized in a cell filled with a high pressure (p = 200–500 mbar) helium or argon buffer gas, where they are subsequently laser ionized. Owing to the thick targets used in the hot cavity approach, isotopic productions that are orders of magnitude higher than in the gas cell can be obtained. On the other hand, for the production of refractory elements or for some short-living isotopes, the gas cell approach is better suited.

Owing to its high selectivity, RILIS is not only constrained to the production of element-pure RIBs but also for producing pure isomeric RIBs [8–10] in those cases where the species of interest exhibit a suitable hyperfine structure splitting. This enhanced selectivity also confers RILIS the possibility of being used as a spectroscopy tool to perform in-source laser spectroscopy studies of rare species with a very high sensitivity, of a few [11,12] or less than one ion per second [13], although with only moderate resolution. As a matter of fact, both types of RILIS approaches suffer from either an inherent Doppler broadening or pressure broadening and shift of the resonance due to the high temperature of the hot cavity or the high pressure of the gas cell, respectively. This results in practice in a final spectral resolution not better than ~4 GHz, which in many cases is insufficient to fully resolve the atomic

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hyper**f**ine **s**tructure (HFS), although charge radii deduced from isotope shifts in heavy-mass nuclei can be determined with a reasonable accuracy [11,14].

In order to overcome the limited resolution and efficiency factors of in-source laser spectroscopy, a novel spectroscopic technique for rare isotopes has recently been presented [15] in which laser ionization, and therefore spectroscopy, is performed in the gas jet streaming out of the gas cell. The environmental conditions in the supersonic gas jet are such that after a careful choice of the ionization region a reduction of the spectral resolution down to a few hundred MHz can be achieved, as also demonstrated in [15] in a series of off-line experiments on the stable copper isotopes.

In this paper, we report on the results of a number of experiments and studies carried out at the Leuven Isotope Separator On-line (LISOL) facility that have served to investigate the requirements to perform in-gas jet laser spectroscopy studies [15] on rare isotopes at the future RIB facility SPIRAL2 (France) [16]. Results from a series of conceptual studies that have been used to prove the feasibility and to define the preliminary design of a novel In-Gas Laser Ionization and Spectroscopy (IGLIS) setup to be coupled online to the Super Separator Spectrometer (S^3) are presented. At $\mathbf{S}^3$, experiments will be performed with the high-current stable beams of LINAC (~1–5 mA), the superconducting linear accelerator currently being built in the framework of SPIRAL2. Commissioning and test of the complete IGLIS setup will be accomplished off-line in a new laser laboratory at KU leuven prior to on-line operation. With the IGLIS setup at $\mathbf{S}^3$, the production of selected pure ground- and isomeric states of very exotic RIBs will be possible. High-sensitivity and enhanced-resolution laser spectroscopy studies of ground- and excited-state properties of the $N = Z$ nuclei up to the doubly-magic ^{100}Sn and those of the very-heavy and superheavy (transfermium) elements will become accessible, overcoming thus the present experimental constraints of low-production rates and low-spectral resolution that currently prevent the study of these exotic nuclei.

2. IGLIS@LISOL: limitations of the gas cell approach

At the LISOL facility [7,17], located at the Cyclotron Research Center (CRC), Louvain-la-Neuve [18], purified RIBs are produced using a gas cell-based laser ion source. Fig. 1 shows a schematic layout of the facility. Two-step two-color ionization schemes are employed at LISOL to step-wise ionize the species of interest. The LISOL laser system consists therefore of two dye lasers each of them pumped by a XeCl excimer laser of 15 ns pulse length at a maximum repetition rate of 200 Hz [7]. The first step laser is typically frequency doubled in a second harmonic generation unit (SHG) to reach the required UV radiation. The laser frequency can be measured using a lambdameter calibrated by a single-mode frequency-stabilized He–Ne laser. Additionally, when stable beams are available, an atomic beam of the element under investigation can be used in the reference cell to tune both lasers in resonance and to monitor laser-frequency and laser-power systematic effects. In the dual-chamber gas cell [19] a primary ion beam, accelerated by the CYCLONE110 cyclotron, impinges on a thin target. The recoiling reaction products are thermalized and neutralized by collisions with the argon or helium buffer gas within the stopping chamber and then transported by the gas flow towards the ionization chamber. At this location, the atoms of interest interact with the laser beams (transported over an optical path of 15 m) and are resonantly ionized to a 1^+ charge state. The photoions are typically extracted through a 1 mm diameter exit hole and transported by a radio-frequency sextupole ion guide (SPIG) [20]. While neutralized reaction products are pumped away, the RIB is accelerated to an energy of 40 keV and mass separated according to its mass-to-charge ratio A/Q using a dipole magnet. The resulting isobaric beam of radioactive species is subsequently implanted, according to its characteristic decay radiation, either on the tape of a moving-tape station (β-γ emitters) or in the carbon foils of a windmill setup (rotating wheel for α emitters) placed at the measuring station. In addition, the ions can also be counted in a Secondary Electron Multiplier (SEM).

The enhanced sensitivity and selectivity of this apparatus, as well as the high contaminant suppression, have allowed in-gas cell laser spectroscopy experiments on the neutron deficient $^{57-59}$Cu [12,14] and $^{97-101}$Ag [13] isotopes with count rates as low as 6 ions/s in the case of ^{57}Cu ($t_{1/2} = 200$ ms) or ~1 ion/s for ^{97}Ag ($t_{1/2} = 25.3$ s), both semi-magic nuclei. The averaged spectral resolution in those experiments was found to be 4 and 10 GHz and the overall efficiency 0.3% and 3% for the experiments on copper and silver, respectively. The overall efficiency is defined as the ratio between the measured production rate and the fraction of recoiling isotopes from the target.

2.1. Experiments on the tin isotopes

Following up the good results obtained previously in this region for the silver isotopes [13], a new experimental campaign was dedicated at LISOL to study the production of purified RIBs of tin isotopes in the vicinity of A = 100. Besides the RIB production, these experiments aimed at studying the feasibility of laser spectroscopy on the tin isotopes in view of the future experimental activities with IGLIS@$\mathbf{S}^3$.

The tin isotopes were produced by fusion evaporation reactions of ^{16}O at an energy of 100 MeV on a ^{92}Mo target (3.3 mg/cm^2) at an angle of 20° with respect to a normal plane to the beam propagation. Two different ionization schemes were tested in these experiments. The scheme shown in Fig. 2a) was obtained at LISOL by

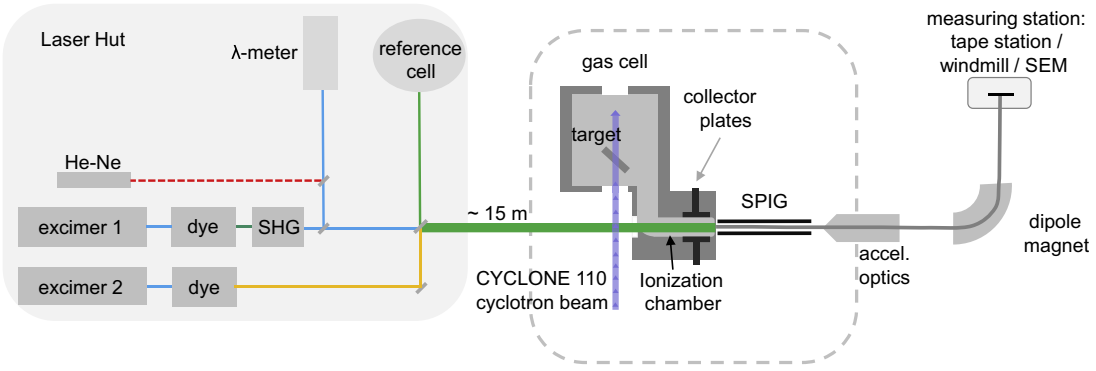

Fig. 1. Schematic view of the LISOL facility including the optical layout.