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A new in-gas-laser ionization and spectroscopy laboratory for off-line studies at KU Leuven

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ABSTRACT

The in-gas laser ionization and spectroscopy (IGLIS) technique is used to produce and to investigate short-lived radioactive isotopes at on-line ion beam facilities. In this technique, the nuclear reaction products recoiling out of a thin target are thermalized and neutralized in a high-pressure noble gas, resonantly ionized by the laser beams in a two-step process, and then extracted from the ion source to be finally accelerated and mass separated. Resonant ionization of radioactive species in the supersonic gas jet ensures very high spectral resolution because of essential reduction of broadening mechanisms. To obtain the maximum efficiency and the best spectral resolution, properties of the supersonic jet and the laser beams must be optimized. To perform these studies a new off-line IGLIS laboratory, including a new high-repetition-rate laser system and a dedicated off-line mass separator, has been commissioned. In this article, the specifications of the different components necessary to achieve optimum conditions in laser-spectroscopy studies of radioactive beams using IGLIS are discussed and the results of simulations are presented.

1. Introduction

The in-gas laser ionization and spectroscopy (IGLIS) technique developed at KU Leuven has been used at the Leuven isotope separator on line (LISOL) facility to produce short-lived radioactive beams in different regions of the chart of nuclei using light and heavy-ion induced fusion or fission reactions [1–5]. In this technique, the nuclear reaction products recoiling out of a thin target are thermalized and neutralized in a high-pressure noble gas, resonantly ionized by the laser beams in a two-step process [6], and then extracted from the ion source to be finally accelerated and mass separated. In this way isobaric and isotopic selectivity can be achieved. High efficiency and selectivity of the ion source by a dual chamber approach [7] allows performing in-gas cell resonance ionization spectroscopy of exotic atoms. Using this method ground- and isomeric-state properties, such as isotope or isomer shifts, charge radii and nuclear magnetic moments of isotopes produced in fusion evaporation reactions have been measured in copper [8], silver [9] and actinium. The achievable spectral resolution of the original method, whereby resonant laser ionization is performed inside the buffer gas cell, is limited by the collision broadening mechanism to values not better than 3–5 GHz. Implementation of resonance laser ionization in the supersonic gas jet overcomes this limitation and allows increasing the spectral resolution by more than one order of magnitude in comparison with in-gas-cell ionization spectroscopy [10–12]. In recent on-line experiments with radioactive actinium isotopes the spectral line width has been reduced down to 300 MHz [13]. Further improvements can make it possible to obtain a resolution of the same order of magnitude as with other high-resolution laser photoionization technique, such as collinear resonance ionization spectroscopy (CRIS) [14,15]. To obtain the maximum efficiency and the best spectral resolution, properties of the supersonic jet and the laser light must be optimized [12]. To perform these studies a new off-line IGLIS laboratory, including a new high-repetition-rate laser system and a dedicated off-line mass separator, has been commissioned. In this article, the specifications of the different components necessary to achieve optimum conditions in laser-spectroscopy studies of radioactive beams using IGLIS will be discussed and the results of simulations will be presented. An optimized IGLIS setup to perform laser ionization

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spectroscopy including high repetition lasers will be installed at the focal plane of the Super Separator Spectrometer (S^3) [16], which will be coupled to the superconducting linear accelerator of the SPIRAL2 facility at GANIL [17]. An international network that includes 14 research groups [18] with the common goal of implementing and/or developing the IGLIS technique is currently established to inform about their progress and coordinate the collaboration among them to further optimize the IGLIS method.

2. General description

A schematic layout of the laboratory is shown in Fig. 1. It is distributed in two rooms, being the first a temperature stabilized (±0.5 °C) clean room (ISO8) with a Safety Access System (SAS). This room houses the laser system that provides several beams to perform high-resolution laser photo-ionization spectroscopy in a supersonic gas jet. The laser beams, indicated with λ_1 and λ_2 representing their respective wavelength, are sent to the front-end of the separator situated in the mass-separator room. The front-end hosts a gas cell coupled to a de Laval nozzle to create the gas jet [19]. The gas handling system provides purified noble gases into the gas cell. Laser produced ions are transported by radio frequency quadrupole (RFQ) ion guides up to an extraction electrode. Subsequently, ions are focused by an electrostatic Einzel lens and are sent towards a dipole magnet. The frontend of the separator is at ground potential, but the separator itself is placed on a high voltage (−40 kV) platform. Before and after the dipole magnet the ion beam is monitored in beam diagnostic chambers which include Faraday cups and a beam profile meter based on multichannel plates (MCP) and phosphor screens.

2.1. In-gas jet laser ionization spectroscopy: general principle

The basic principle of the in-gas jet laser ionization consists in the resonance excitation of seeded atoms to an intermediate atomic level with subsequent ionization of excited atoms via continuum- or autoionizing states. A de Laval nozzle is used to create an axisymmetric supersonic gas jet. This gas jet is characterized by a low atom density and a low temperature, which result in a strong reduction of the collision- and Doppler broadening mechanisms in comparison with those existing in the gas cell. Ionization takes place in the volume defined by the overlap of the two laser beams with the jet. To obtain optimum spectral resolution as well as to avoid ionization inside the gas cell, a cross laser beam interaction with the gas jet has to be used, as pointed out in [12]. The main parameter that characterizes the property of the jet is the Mach number (M). Fig. 2 shows the contribution of the Doppler broadening to the spectral line width (438 nm) for actinium atoms and the diameter of the jet as a function of the Mach number. At a Mach number 12 the jet diameter is 10.5 mm and the spectral resolution is limited to 80 MHz. To achieve this resolution, the laser system must operate with a suitable laser bandwidth and the ion guide system should be able to accept the ion beam formed at the interaction region with the required diameter.

2.2. Laser system

Two step ionization schemes are frequently used for selective ionization of atoms in the gas cell and in the supersonic gas jet [6]. The laser system consists of two Nd:YAG INNOSLAB lasers (EdgeWave GmbH) with a maximum repetition rate of 15 kHz that pump two dye lasers and a dye amplifier, see Fig. 1. The average output power of each pump laser is 90 W with a frequency doubling module at 532 nm (green) or 36 W with a frequency tripling module at 355 nm (UV) and a pulse length of 8–10 ns. The radiation of the Nd:YAG laser 1 is split to pump the first step dye laser and the pulsed dye amplifier. The radiation of the Nd:YAG laser 2 is used only to pump the second step dye laser. Both lasers are time-synchronized with a jitter better than 3 ns.

Dye lasers (CREDO, Sirah Lasertechnik GmbH) cover the tuning range of the fundamental wavelength from 375 to 900 nm. Both dye lasers are equipped with a grating lift option that allows changing between two gratings of 1800 lines/mm and 3000 lines/mm inside the laser cavity to be used with the green or the UV pump wavelengths, resulting in a laser bandwidth of 0.08 cm^{-1} and 0.05 cm^{-1}, respectively. Additionally, the bandwidths can be increased by a factor of four by changing an intracavity prism expander. This option can be useful to search for unknown atomic transitions of rare isotopes in on-line experiments. Frequency conversion units (FCU) in both dye lasers allow frequency doubling of the fundamental wavelength insuring an continuous tuning range of the laser system from 215 nm up to 900 nm. The laser pulse width of fundamental and second harmonic laser beams is 7–9 ns.

To perform high-resolution spectroscopy in the supersonic gas jet, laser radiation with a bandwidth smaller than the residual Doppler broadening is required. This light is obtained by seeding of a single mode continuous wave (CW) tunable laser beam in a pulsed dye amplifier. The narrow bandwidth (1 MHz at 5 μs and 654.8 nm) laser light from the TA Pro (TOPTICA Photonics AG) Master Oscillator Power Amplifier (MOPA) design is focused into a one- or two stage dye amplifier. The amplified pulsed radiation is then frequency doubled in a frequency conversion unit to get a wavelength of λ_1 = 327.4 nm that can be used for the first step excitation of copper atoms. The spectral line profile, obtained as the Fourier transform of the pulse time profile, has a full width at half maximum (FWHM) of 63 MHz for a laser pulse length of 7 ns. The spectrum of the CW laser is monitored by a scanning Fabry–Perot interferometer (SFPI) with a free spectral range (FSR) of 4 GHz and finesse better than 400. Fundamental wavelengths of the dye lasers and the amplifier are measured in sequence by a wavelength meter HF-ANGSTROM WS/7 (HighFinesse GmbH) with an absolute accuracy of 60 MHz. The wavelength meter has an internal calibration option and additionally can be externally calibrated by a frequency stabilized He/Ne laser. The laser bandwidth of the dye lasers is measured by a homemade air-spaced Fabry–Perot Interferometer (FPI). The time synchronization of the laser beams that are sent towards the separator is controlled by fast photodiodes.

The diameter of the gas jet is defined by the Mach number of the nozzle, see Fig. 2. The saturation energy fluence needed for the first excitation step [12] can be easily provided by the present laser system for Mach number lower than 15. The saturation fluence of the second ionization step is about 0.4 mJ/cm^2 for an autoionization cross section of $1 \cdot 10^{-15}$ cm^2. The argon jet velocity is 560 m/s and to ensure interaction of all atoms with lasers operated at 10 kHz pulse repetition rate the size of the laser beam along the jet axis (λ_2 in Fig. 3) should be at least 5.6 cm [12]. The jet diameter with M = 7 is about 0.5 cm. To provide complete spatial overlapping and saturation of the second step, a pulse energy of 1.2 mJ is required for a laser with a beam are of 0.5 cm × 5.6 cm ≈ 3 cm^2. A way of reducing the required pulse energy would be to use a multipath laser beam (0.5 cm in diameter) arrangement, which consists of two mirrors at a small angle along the gas jet.

A fraction of both laser beams is deflected by beam splitters towards an atomic beam unit (ABU). Here, laser ionization of the same atoms as those seeded in the gas jet is carried out in a 90° cross-beam geometry that provides a spectral resolution closed to the laser bandwidth. The laser-produced ions are mass separated in a time of flight mass spectrometer (TOF MS). The atomic beam is produced by resistive heating of a graphite crucible and

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