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The in-gas-jet laser ion source: Resonance ionization spectroscopy of radioactive atoms in supersonic gas jets

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ABSTRACT

New approaches to perform efficient and selective step-wise resonance ionization spectroscopy (RIS) of radioactive atoms in different types of supersonic gas jets are proposed. This novel application results in a major expansion of the in-gas laser ionization and spectroscopy (IGLIS) method developed at KU Leuven. Implementation of resonance ionization in the supersonic gas jet allows to increase the spectral resolution by one order of magnitude in comparison with the currently performed in-gas-cell ionization spectroscopy. Properties of supersonic beams, obtained from the de Laval-, the spike-, and the free jet nozzles that are important for the reduction of the spectral line broadening mechanisms in cold and low density environments are discussed. Requirements for the laser radiation and for the vacuum pumping system are also examined. Finally, first results of high-resolution spectroscopy in the supersonic free jet are presented for the 327.4 nm $3d^{10}4s\ ^2S_{1/2} \rightarrow 3d^{10}4p\ ^2P_{1/2}$ transition in the stable ^{63}Cu isotope using an amplified single mode laser radiation.

1. Introduction

The method of laser resonance ionization spectroscopy (RIS) [1,2] was developed at the end of the last century. Nowadays resonance photoionization with pulsed lasers is widely used or planned, in particular, for the production of pure beams of short-lived isotopes at several on-line radioactive ion beam (RIB) facilities [3–18]. In addition to the production of element-pure or isomeric-pure beams, RIS can be used to obtain nuclear-model independent information on the properties of nuclear ground and long-living excited states such as nuclear spins, nuclear magnetic dipole moments, quadrupole moments, and changes in the mean-square charge radii from atomic spectra [19–25]. Numerous two- and three-step ionization schemes have been proposed to produce and investigate radioactive nuclei using resonance ionization techniques [26]. Since the radioactive isotopes of interest are created in nuclear reactions in very small quantities, together with a huge background of contaminating nuclei, the RIB production and detection methods have to be sensitive, efficient, selective, and fast. Currently, collinear resonance ionization spectroscopy (CRIS) in an accelerated atomic beam (>10 keV) [27–31] is one of the most sensitive detection methods. Owing to the reduction of the Doppler width by the electrostatic acceleration [32], a high spectral resolution and a high selectivity can be provided for the detection of short-lived- and low-abundant long-lived radioactive isotopes [33–35].

Another sensitive atomic spectroscopy and selective production method is in-source laser resonance ionization spectroscopy. This method has been implemented in two distinctly different ways at isotope separator on line (ISOL) systems to produce RIBs and to perform laser spectroscopy measurements. The two approaches are based on resonance ionization either in a hot cavity [36–38] or in a buffer gas cell [5–7,39]. The spectral resolution in a hot cavity is limited by Doppler broadening as the temperature has to be above 2000 K in order to keep the reaction products volatile and in their atomic form. In a gas cell, additionally to the room temperature Doppler broadening, the spectral resolution is limited by collision broadening with the buffer gas atoms. In spite of the limited spectral resolution in comparison with the collinear photo ionization spectroscopy, the in-source technique is very sensitive; results have been obtained with beams of less than 1 atom per second [40,41], and it can be applied for the study of isotopes with a large hyperfine splitting [42–44].

The in-gas laser ionization and spectroscopy (IGLIS) technique, developed at KU Leuven since the late 1980s [5,6,45,46], is used at the Leuven isotope separator on line (LISOL) facility [47] to produce short-lived radioactive beams in different regions of the chart of nuclides using light and heavy-ion induced fusion or fission reactions. The basic principle of the IGLIS method can be summarized as follows. Nuclear-reaction products are thermalized and neutralized in the high-pressure noble gas in their ground- and possibly in low-lying metastable atomic states (see Fig. 1a). They

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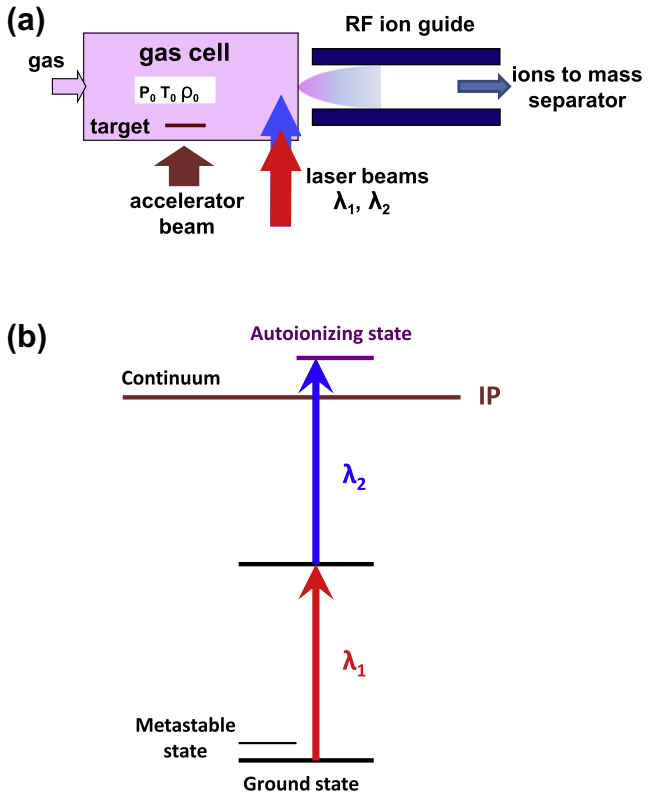

Fig. 1. (a) Layout of the in-gas-cell laser ion source for the production of radioactive ion beams, (b) two step laser resonance ionization scheme. P_0, T_0, and ρ_0 represent the stagnation conditions of pressure, temperature, and density in the gas cell, respectively.

are subsequently transported by the gas flow towards the exit orifice. Shortly before leaving the gas cell, the atoms undergo element-selective two-step resonance laser ionization (Fig. 1b). Outside the gas cell the laser-produced ions are captured by the radio frequency (RF) field of a SextuPole Ion Guide (SPIG) for further transport towards the mass separator [48]. The use of a repelling voltage to suppress unwanted ions and laser ionize the nuclei of interest in an RF trap, the so-called laser ion source trap (LIST) technique, was first proposed for the hot cavity approach [49] and recently successfully applied in on-line conditions [50]. The coupling of the LIST method to the gas cell approach was suggested at Jyväskylä [51]. In order to improve the spectral resolution and the selectivity, the possibility of laser ionization in the free gas jet has been investigated at LISOL with 200 Hz [52] and 10 kHz [53] pulse repetition rate lasers. In these experiments, the ionizing laser beams passed through the gas cell and the exit orifice to reach the expanding free gas jet. By applying a positive potential to the SPIG rods relative to the gas cell the ions created in the gas jet could be separated from those created in the gas cell. Compared to in-gas cell ionization an improved spectral resolution down to 2.6 GHz was achieved for in-gas jet ionization owing to the low pressure and low temperature environment of the supersonic gas jet, however, major developments were required in order to improve the efficiency, selectivity, and spectral resolution to be able to perform spectroscopic studies of the nuclei. The supersonic gas jet can be a natural part of the target-ion-source system for on-line mass separators. In this paper we propose new approaches for high-resolution, efficient, and selective step-wise laser resonance ionization of radioactive atoms using different types of supersonic jets. The spectral resolution that can be reached in the supersonic gas jet is calculated and found to be far superior to that in the gas cell. The requirements for the laser radiation and for the vacuum pumping system are also discussed. Finally, first off-line results of two-step high resolution laser resonance ionization spectroscopy in the supersonic free jet that show the feasibility of this method are presented.

2. Brief introduction to the different jet-formation schemes

Three different approaches for gas-jet formation suitable for resonance ionization are considered in this article and can be found schematically illustrated in Fig. 2.

- The supersonic free-jet expansion technique, Fig. 2a, proposed in [54] is used nowadays in different fields of research involving cold atoms and molecules. Effective translation, rotation, and vibration cooling of the molecules seeded into the jet allow to perform fluorescence spectroscopy of complex molecules with very high resolution [55,56]. Sub-Doppler resolution was achieved with very well collimated beams, where owing to the strong collimation only a small part of all atoms coming out the gas cell were used. The most important advantage of this low-temperature molecular spectroscopy consists in the simplification of the spectra due to the compression of the population distribution in low-lying vibration and rotational levels.

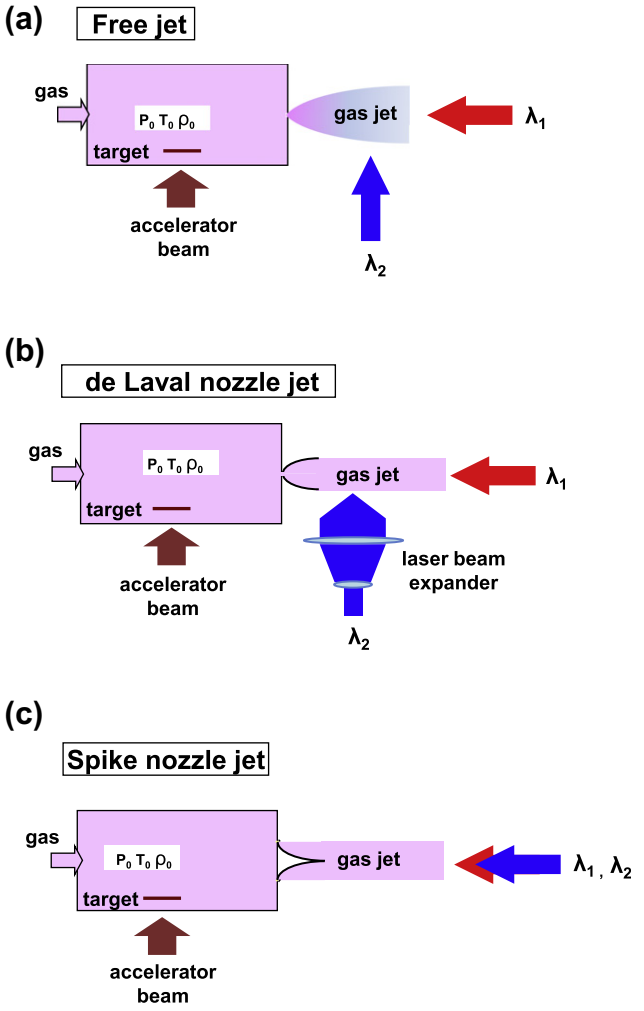

Fig. 2. Proposed setup layouts for the production and spectroscopy of radioactive isotopes in (a) a free jet, and in jets produced by (b) a de Laval nozzle and (c) a spike nozzle. The production target is here located in the gas cell and the primary beam from the accelerator is therefore entering the cell.