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A study of on-line gas cell processes at IGISOL

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ABSTRACT

The laser ion source at the IGISOL facility, Jyväskylä, has been used to study the effects of the passage of a primary beam through an ion guide via the dynamic time profiles of yttrium and related molecular compounds. The accessibility of a neutral fraction for laser ionization is shown to be restricted to the nozzle region in the presence of a weak plasma. The survival of this neutral fraction cannot be explained by recombination of the buffer gas alone and perhaps indicates a suppression of the transport of ions due to a plasma-generated electric field. The concept of a competition between the processes that create and destroy the ion of interest is used to explain the different trends in the ratio of yttrium to yttrium oxide following the extraction of a stopped primary beam of $^{89}Y^{21+}$ in both helium and argon buffer gases.

1. Introduction

In our previous article we presented the first detailed off-line studies using the new laser ion source at the IGISOL facility, Jyväskylä [1]. The flexibility of the dye-Ti:Sapphire laser system was illustrated using the laser ionization of yttrium atoms produced in an ion guide via the resistive heating of a filament. A careful study was undertaken to understand the effects of gas purity on an element that exhibits strong molecular formation in the presence of impurities within the gas. In order to decouple the competition between the molecular formation process and evacuation from the ion guide we analyzed the experimental data in the framework of a series of molecular rate equations in order to extract time profiles of single laser shots. With good control over the gas purification a sub-ppb level of impurities was demonstrated. The importance of the baseline vacuum pressure in the immediate vicinity of the ion guide was apparent after a controlled leak was added to the IGISOL chamber. Within the experimentally determined flight time of ~100 μs through the rf sextupole ion beam guide (SPIG) [2], a fast redistribution of atomic ions into molecular forms can occur after leaving the exit nozzle of the gas cell highlighting the importance of having a clean environment not only within the gas cell but through which the ions are electrostatically guided following extraction.

In this follow-up paper the results of our first set of on-line experiments undertaken in conditions of high ion-electron density are presented. On-line experiments pose an additional set of challenges to attaining that of sub-ppb purity conditions. One of the most important loss mechanisms for the ion of interest on-line is that of neutralization. This is due to the density of ionization created either by the passage of a primary beam or via the extraction of recoils out from the gas cell from a fixed target such as in a light-ion induced fusion-evaporation reaction or that of a fission reaction. The effects associated with the presence of a large density of ion-electron pairs have been discussed previously [3,4]. The resultant reduction in extraction efficiency as a function of the implantation rate has been observed at all gas catcher facilities [5–8] which incorporate different volumes, buffer gases, projectile energies and electric fields. A review of the most recent results highlighting the decline in extraction efficiency and possible solutions to tolerate higher primary beam intensities can be found in [9].

The experiments discussed in the present work continue the studies utilizing the yttrium atomic system. As an intermediate step towards an operational ion guide laser ion source facility it is important to understand the competing processes occurring in the gas cell under on-line conditions. The effects of the passage of a primary beam through the ion guide have been studied using the time distribution profiles of yttrium and associated molecules.

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Information has been extracted from both the equilibrated processes and the dynamic effects, with the latter discussed using two different models. Additionally, a stopped primary beam of yttrium has been extracted from the ion guide and the ratio of yttrium to yttrium oxide as a function of gas pressure has been studied in both helium and argon. The ratio has been explained using a simple model of creative and destructive processes within the gas cell. Although our goal is not to produce detailed simulations of the ion guide processes, in order to provide a more efficient and selective means of producing low-energy radioactive ion beams via laser ionization, a reasonable understanding of the ion guide plasma is required. Finally, we note that in those instances in which laser ionization has been used in the current studies, the laser ionization efficiency is not a subject of discussion. The choice of laser ionization scheme included a non-saturated intermediate excitation step and a non-resonant ionization step. Without the use of Rydberg- or auto-ionization states the cross section for ionization is reduced by a factor of ~1000. Future radioactive ion beam production with the laser ion source will utilize the most efficient ionization scheme.

2. Experimental set-up

The laser system used in this work has been described in detail in our previous article [1] therefore we concentrate here on the IGISOL front-end. It is informative to briefly mention the present ion guides in regular use at IGISOL, in order to explain the differences between these and the gas cells designed for the purpose of laser ionization studies. There are three main types of ion guide: light-ion ion guide, heavy-ion ion guide and a fission ion guide. The differences between each relate to the choice of reaction kinematics needed for a particular experiment. In addition, two other ion guides have been developed for specific purposes. The first has been designed for quasi- and deep-inelastic reactions [10], and the second for the production of a low-energy ion beam of daughter products of α-emitters [11].

The light-ion ion guide has been designed for use with H and He primary beams. In this guide the target is mounted directly in the stopping volume of the cell as the recoil energy of the reaction products is small. The effective stopping volume for the recoils is $\sim 3\ \mathrm{cm}^3$ and with a typical exit nozzle diameter of 1.2 mm, the extraction time can be as short as one millisecond. A typical ion guide efficiency (ions detected in the separator focal plane compared to those recoiling out of the target into the stopping volume) varies between 1% and 10% [12].

The heavy-ion ion guide (HIGISOL) is used in heavy-ion induced fusion-evaporation reactions. As the reaction product distribution is forward peaked a special arrangement is needed to reduce the strong ionization of the helium gas by the accelerator beam. The so-called "shadow method" is employed which takes advantage of the difference between the primary beam angular distribution and that of the reaction products after passing through a relatively thick target (few $\mathrm{mg/cm}^2$) [13–15]. The stopping volume is considerably larger than that of the light-ion ion guide, typically $120\ \mathrm{cm}^3$. With a similar size exit nozzle an average evacuation time of 185 ms can be estimated by dividing the stopping chamber volume with the exit-hole conductance. Targets are installed on a water cooled frame outside the stopping volume, with a variable distance relative to the ion guide along the cyclotron beam axis. Recently, a rotating target wheel was installed and used in combination with the HIGISOL system. Ion guide efficiencies are rather low, on the order of 1×10^{-3}.

Many of the experimental studies at IGISOL use the fission ion guide. The guide has been designed for use in proton-induced fission of uranium (or other actinide) targets. A $15\ \mathrm{mg/cm}^2$ uranium target is mounted within the ion guide volume at an angle of 7° with respect to the primary beam to increase the effective thickness of the target to $123\ \mathrm{mg/cm}^2$. In order to reduce the beam-related plasma, the primary beam is shielded from the stopping chamber with a thin foil. The volume of this chamber, $130\ \mathrm{cm}^3$, is comparable to that of the HIGISOL ion guide. The separation foil may be made of an element of choice to provide sputtered material for use as a stable ion beam for on-line experimental calibrations.[2] Although the fission fragments can be separated from the primary beam due to the isotropic emergence from the target, an intense plasma effect remains, generated by the fission fragments themselves passing through the stopping gas. Combining the recombination losses with a relatively low fission fragment stopping efficiency of ~1% in 200 mbar helium, typical absolute efficiencies are rather low, only a few $\times 10^{-4}$, and very often the isotope of interest is dominated by less exotic, unwanted isobars. It should be noted, that the fission rate in the target is $\sim 2 \times 10^9$ fissions/μC. Despite this, maximum intensities of $\sim 10^5$ fission products per second can be achieved with the ion guide technique.

Two laser ion guides have been used in studies of laser ionization at the IGISOL facility. The first, used in the present work and on loan from the LISOL group at the University of Leuven, has been described in detail in [1]. Briefly, the volume of the gas cell can be divided into two parts, the main cell and a channel of 10 mm in diameter and 26 mm in length leading to the exit nozzle. The conductance of the 0.5 mm diameter exit hole for helium is equal to 0.112 l/s. The evacuation time of the whole guide is ~480 ms and that of the exit channel ~18 ms. Compared to the ion guides described above these extraction times are considerably longer due to the smaller exit hole. This is necessary in order to achieve neutralization of the recoiling nuclei. The second ion guide is a modified version of the HIGISOL gas cell, built for both the laser ion source project in Jyväskylä and standard heavy-ion fusion-evaporation reactions. The guide has been optimized for efficient gas flow transport, water cooling and baking capabilities have been added and the design is modular such that filaments and dc electrodes can be installed. The ion guide has three main components: a gas feeding part, the main body and a removable exit nozzle, all of which are sealed with indium. A beam window of 48 mm in diameter can be added for standard HIGISOL reactions. A schematic picture of both the LISOL ion guide and the JYFL laser ion guide is shown in Fig. 1. The volume of the main body of the JYFL ion guide up to the exit nozzle is $\sim 252\ \mathrm{cm}^3$, almost a factor of five larger than the LISOL guide. The evacuation time of the ion guide volume for an exit hole of 0.5 mm diameter is 2.25 s, and for a standard exit nozzle diameter of 1.2 mm, 390 ms.

3. Processes within the gas cell under on-line conditions

On-line experiments provide an additional set of complex processes to those of the off-line conditions discussed in our earlier work [1]. In this section we present an overview of processes occurring within the ion guide, often in parallel, relevant to the experimental results presented in later sections.

The monomer buffer gas ions B^+ created by the passage of a primary accelerator beam through an ion guide, or in the passage of energetic highly-charged fragment recoils, rapidly dimerize to B_2^+ in the three-body reaction:

$$B^+ + 2B \rightarrow B_2^+ + B. \quad (1)$$

[2] In collinear laser spectroscopy of neutron-rich fission fragments a stable calibration is often required to connect the change in mean-square charge radii of radioactive isotopes to stable isotopes.