Nuclear Instruments and Methods in Physics Research B 126 (1997) 194–197

ELSEVIER

NIM B
Beam Interactions with Materials & Atoms

The SPIG, improvement of the efficiency and beam quality of an ion-guide based on-line isotope separator

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Abstract

A SPIG (Sextupole Ion Beam Guide) has been constructed and tested to couple an ion-guide based ion source to an on-line isotope separator. In comparison to a skimmer, the SPIG offers both an increased beam quality and the possibility to operate the ion-guide at higher buffer gas pressures.

PACS: 29.25.Ni, 41.85.Ar
Keywords: Ion-guide; Multipole ion beam guide; Ion trap

1. Introduction

The ion-guide technique uses a gas cell to thermalize the reaction products recoiling out of the target in a buffer gas [1]. The recoil ions are then transported by the gas flow through the exit hole of the cell. In most IGISOL systems (Ion-Guide Isotope Separator On Line), a skimmer is used to separate the ions from the gas jet and to inject them in the acceleration stage of the separator. In order to focus the ions through the skimmer, an electric field of typically 400 V/cm is applied between the cell and the skimmer plate. Two problems of the current IGISOL technique are directly related to the skimmer:

(1) In order to obtain a good transmission of the ions through the skimmer, the skimmer plate has to be positioned close to the exit hole of the cell. A distance of about 9 mm was found to be optimal [2]. The pressure at such a short distance from the exit hole is still quite high and this results in a considerable throughput of the gas to the high vacuum sections of the separator. This limits the maximum allowable pressure in the gas cell. For fission and heavy-ion fusion reactions, however, higher buffer gas pressures could significantly increase the efficiency because of the high recoil energies of the reaction products

(2) The quality of the extracted beam is usually poor in IGISOL systems. This is mainly due to the acceleration of the ions in the skimmer field. The ions gain energy from the field, but part of the energy is lost in frequent collisions with the gas atoms. On the other hand, the gas collisions lead to the dissociation of molecular ions which, as we will show later, is crucial for a proper operation of the ion-guide. Furthermore, because of the high throughput of gas through the skimmer, the pressure in the acceleration stage of the separator is usually high and collisions are also likely to happen here. This results in a large energy spread of the extracted ions and, consequently, in a poor mass resolution and a reduced efficiency of the beam transport through the separator.

Iivonen et al. [3] developed the squeezer ion-guide to solve this problem. Another approach was suggested by Xu et al. [4] They proposed to use a SPIG (sextupole ion beam guide) instead of a skimmer to transport the ions from the exit hole of the gas cell to the extraction electrode. The SPIG does not only reduce significantly the spread of the extracted ions with respect to energy and space distribution, but also offers the possibility for efficient differential pumping and consequently the use of higher buffer gas pressures. A SPIG was constructed and tested in the framework of the development of the Ion-Guide Laser Ion Source (IGLIS) [5–7], with the aim of coupling the IGLIS to the LISOL (Leuven Isotope Separator On Line) separator [8] at Louvain-la-Neuve.

2. The IGLIS

The IGLIS, shown in Fig. 1, is similar to more common ion-guides in the sense that it consists of a gas cell to thermalize the recoil products. The principle of the IGLIS is based on resonant photo ionization of the neutralized

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PII S0168-583X(96)01011-7

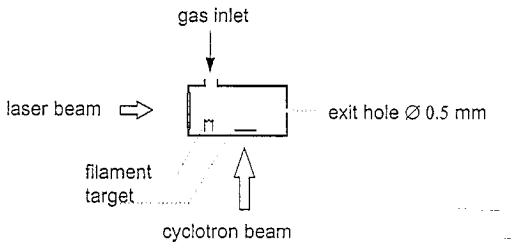

Fig. 1. Schematic drawing of the IGLIS.

reaction products in the gas cell. The diameter of the exit hole of the cell is 0.5 mm, whereas 1 to 1.5 mm is more common in normal IGISOL systems. The IGLIS is typically operated with a buffer gas pressure of 50 kPa, which results in a gas flow through the exit hole that is comparable to the gas flow resulting from a buffer gas pressure of 10 kPa and an exit hole of diameter 1.2 mm.

3. The principle of the SPIG

A schematic drawing of the SPIG is shown in Fig. 2. It consists of 6 rods cylindrically mounted. They are on a hexagonal structure between the exit hole of the cell and the extraction electrode, the structure being oriented parallel to the beam path. An oscillating voltage (V_{rf}) is applied to the rods, with every rod in antiphase with the neighboring rods. If the amplitude and the frequency of the rf signal is well chosen, ions can be radially confined within the structure. This property of the so-called multipole ion beam guide with $2N$ parallel rods ($N = 3$ in case of the SPIG) is already well known and similar devices have been used in different applications, e.g. [9–11]. A description of the principle of multipole ion beam guides can be found in e.g. [4,9,10]. In combination with IGISOL systems, a SPIG can be used to transport the ions from the exit hole to the extraction electrode. The gas can expand through the gaps between the rods, while the ions are radially confined within the structure and are transported

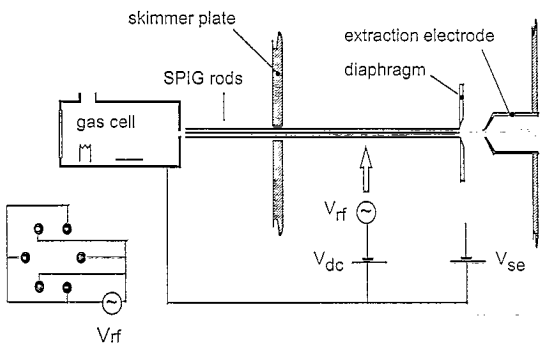

Fig. 2. Layout of the SPIG. The inset shows a cross-section of the 6 rods perpendicular to the beam axis with the way the rf voltage is applied.

to the extraction electrode with the velocity of the gas jet. This eliminates the need to accelerate the ions in a high pressure zone and consequently the spread of the ions with respect to energy and space will be much smaller. If the kinetic energy of the ions is higher than the energy of the gas atoms, the ions can even be cooled by collisions with the gas atoms inside the SPIG.

The skimmer plate separates the high vacuum chambers of the separator from the low vacuum around the gas cell. Since the position of this plate is no longer critical in the SPIG setup, its distance to the gas cell can be chosen to be much bigger than in the skimmer setup. Since the pressure on the symmetry axis drops very fast with increasing distance from the exit hole [3], differential pumping becomes much more efficient.

4. Description of the SPIG

We constructed a SPIG with 6 silver rods of diameter 1 mm (Fig. 2). The length of the rods is 124 mm and the diameter of the inner circle is 2.5 mm. The distance between the rods and the exit hole is 2.5 mm. The oscillator that supplies the rf signal (V_{rf}) has a fixed frequency of 4.7 MHz and a variable amplitude of 0...150 V. A dc voltage can be added to the rf signal (V_{dc}, 0...+/−300 V, relative to the potential of the cell). A diaphragm (diameter 2.5 mm) is mounted at the end of the rods. The potential of the diaphragm (V_{se}), relative to the cell can be varied from 0...+/−300 V. The plate between the low vacuum region and the extraction chamber is positioned at 30 mm from the gas cell.

5. Results

5.1. Differential pumping

Fig. 3 shows the pressure in the extraction region versus the pressure in the cell, both for the skimmer and

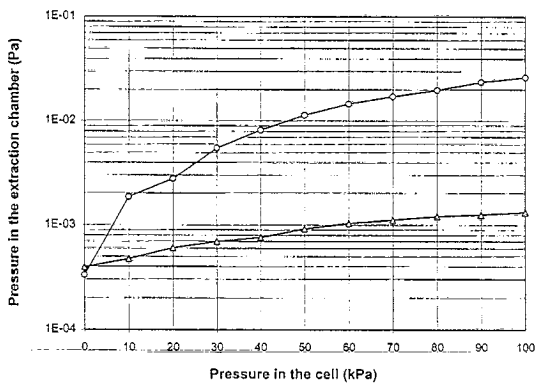

Fig. 3. The pressure in the extraction chamber of the LISOL separator as a function of the buffer gas pressure, both for the skimmer (○) and the SPIG (△), with He used as buffer gas.

the SPIG setup. It is clear that differential pumping has become much more effective. With the skimmer the maximum pressure of the buffer gas was limited to 50 kPa for helium and 15 kPa for argon. With the SPIG, pressures up to and exceeding 100 kPa are possible for both gases without any problems.

5.2. Transmission

In order to measure the transmission properties of the SPIG, a nickel filament inside the cell is heated (see Fig. 1) and the nickel atoms evaporating from the surface are ionized by resonant laser ionization [5–7]. The extracted beam can be measured in a Faraday cup, either before or after mass separation. During the first tests, V_{dc} and V_{se} were 0 V.

To obtain an efficiency of the transmission of the SPIG, the extracted current before mass separation was measured, both with the skimmer and with the SPIG. When the skimmer was installed, we measured an average current of 213 particle pA. This value increased to 237 particle pA with the SPIG ($V_{dc} = V_{se} = 0$ V), resulting in a 10% increase of the transmission efficiency compared to the skimmer with the same power deposition in the filament.

5.3. Beam quality

The Mass Resolving Power (MRP), defined as $M/\Delta M$, where M is the separated mass and ΔM the width of the mass peak at FWHM in the focal plane, was found to be in the order of 300 when the skimmer was installed. After mounting the SPIG, MRP values as high as 1450 were measured. Profiles of the extracted and mass-separated beam are shown in Fig. 4. Which clearly illustrates the improved beam quality. We were able to measure an upperlimit of 1 eV for the kinetic energy spread of the extracted ions along the axis of symmetry. This is in good correspondence with the value of 0.8 eV that was obtained by Xu et al. [4].

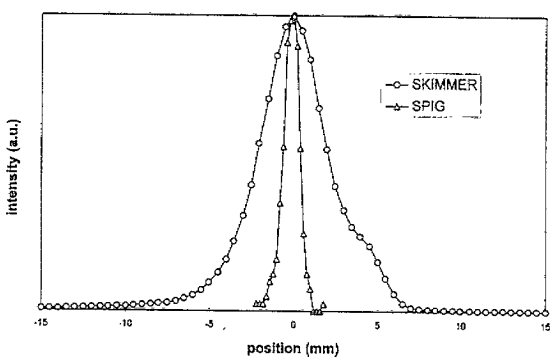

Fig. 4. The profiles of the mass-separated beams in the focal plane for skimmer and SPIG. These profiles were measured on a vertical wire (∅ 0.2 mm) that was moved through the beam in the focal plane. The curves are normalized to their maximum.

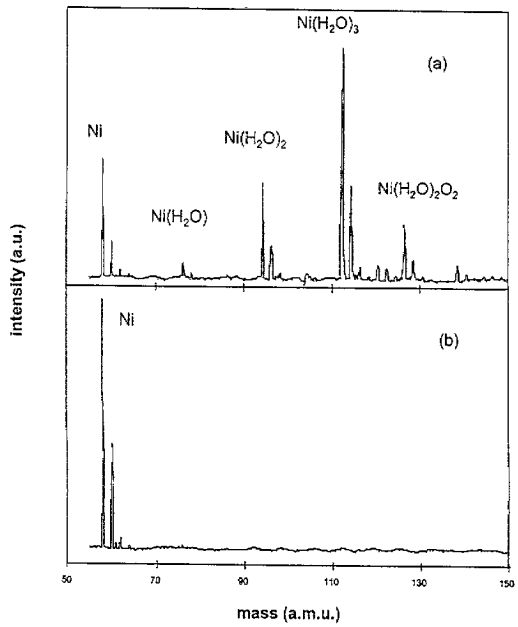

Fig. 5. Mass spectrum obtained with the laser ion source and the SPIG. (a) Without dissociation of molecules ($V_{dc} = 0$ V, $V_{se} = 0$ V). (b) With dissociation ($V_{dc} = -250$ V, $V_{se} = -250$ V).

5.4. Molecular sidebands

Fig. 5a shows a mass spectrum of the extracted beam, with both V_{dc} and V_{se} at 0 V. Since resonant laser ionization is a very element-selective ionization method, only nickel ions can be present in the beam. However, Fig. 5a shows that most of the ions are extracted as molecules. This is due to interactions between the nickel ions and the ppm impurities from the helium gas in the cell. Typically, most of the ions are separated as $Ni(H_2O)_3$, while only a small fraction is extracted as atomic ions. In the skimmer setup, these molecules are dissociated by collisions with the buffer gas atoms in the skimmer field. By applying an electric field between the rods (V_{dc}, typically -250 V) and the exit hole of the source, dissociation of the molecules can also be obtained with the SPIG. In this case, the potential of the diaphragm (V_{se}) must be equal to or below V_{dc} to enable the ions to pass the diaphragm. While acceleration in the high pressure region, i.e. the distance of 9 mm between exit hole and skimmer, was one of the main reasons for the poor beam quality obtained with the skimmer, this is no longer the case with the SPIG. This is due to the fact that the acceleration stops at the entrance of the SPIG (2.5 mm from the exit hole), leaving a sufficient

high-pressure region further down the SPIG to rethermalize the ions. This effect preserves the excellent beam quality. In fact the MRP, the energy spread and the beam profiles are hardly influenced by the acceleration between the cell and the SPIG. Fig. 5b shows a mass spectrum with $V_{dc} = V_{se} = -250$ V. Almost 100% of the molecules that were present in the spectrum of Fig. 5a, are now extracted as atomic nickel ions. The transmission efficiency was found to be 1.8 times higher when the dissociation voltage was applied, increasing the efficiency of the SPIG to 2 times the efficiency of the skimmer. This effect is not yet completely understood, but might be related to a better focusing of the ions towards the center of the SPIG.

5.5. Using the SPIG as an ion trap

When V_{dc}, the offset voltage on the SPIG rods, is negative, and V_{se}, the voltage on the diaphragm, is higher than V_{dc}, the ions can no longer leave the SPIG, and are thus trapped between the entrance and the exit of the SPIG. When V_{se} is lowered to a potential below or equal to V_{dc}, the SPIG is opened and the ions can be extracted by the extraction electrode. We measured that the stored ions are released within 150 μs. As a first information on the storage efficiency, which depends on the storage time and the number of stored ions, we determined that up to 10^7 ions could be stored efficiently for storage times in the order of 100 ms.

5.6. On-line results

The SPIG was successfully tested in an on-line experiment where the production of ^{69}Ni in a proton induced fission reaction of uranium was studied. With the SPIG, the intensity of the mass-separated ^{69}Ni beam was approximately 5 times higher compared to the same experiment with the skimmer, at equal buffer gas pressure (50 kPa). This improvement of the efficiency is partially due to the higher transmission of the SPIG, and the excellent quality of the extracted beam, which increases the transport efficiency through the beam transport lines. Between the two experiments, however, different efforts have been made to improve the overall efficiency of the IGLIS and the separator, and it is not clear how large the contribution of the SPIG is in this gain factor.

6. Conclusion

(1) Compared to the skimmer, the SPIG offers the possibility to use much higher buffer gas pressures. Pressures up to and above 100 kPa are possible, both with helium and argon as buffer gas. This extends the application possibility of IGISOL systems for heavy-ion fusion and fission reactions.

(2) Under the present circumstances, the efficiency of the SPIG is approximately 2 times higher than the efficiency of the skimmer.

(3) A considerable improvement of the beam quality is obtained. The MRP value increased from ~ 300 (skimmer) to ~ 1450 (SPIG). This also reduces transport losses through the separator.

(4) The SPIG can be used to store the ions for a limited amount of time. This offers the possibility to bunch the extracted beam.

Points (4) and (5) could be crucial for performing collinear laser spectroscopy measurements on radioactive isotopes.

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