Nuclear Instruments and Methods in Physics Research B 295 (2013) 1–10

Contents lists available at SciVerse ScienceDirect

Nuclear Instruments and Methods in Physics Research B

journal homepage: www.elsevier.com/locate/nimb

Development of a resonant laser ionization gas cell for high-energy, short-lived nuclei

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A R T I C L E I N F O

Article history:
Received 7 August 2012
Received in revised form 10 October 2012
Available online 9 November 2012

Keywords:
Laser ion source
Gas jet
Resonant laser ionization
Laser spectroscopy

A B S T R A C T

A new laser ion source configuration based on resonant photoionization in a gas cell has been developed at RIBF RIKEN. This system is intended for the future PArasitic RI-beam production by Laser Ion-Source (PALIS) project which will be installed at RIKEN's fragment separator, BigRIPS. A novel implementation of differential pumping, in combination with a sextupole ion beam guide (SPIG), has been developed. A few small scroll pumps create a pressure difference from 1000 hPa–10^{-3} Pa within a geometry drastically miniaturized compared to conventional systems. This system can utilize a large exit hole for fast evacuation times, minimizing the decay loss for short-lived nuclei during extraction from a buffer gas cell, while sufficient gas cell pressure is maintained for stopping high energy RI-beams. In spite of the motion in a dense pressure gradient, the photo-ionized ions inside the gas cell are ejected with an assisting force gas jet and successfully transported to a high-vacuum region via SPIG followed by a quadrupole mass separator. Observed behaviors agree with the results of gas flow and Monte Carlo simulations.

1. Introduction

Radioactive ion beam (RIB) facilities based on the in-flight production technique provide a wide variety of exotic nuclei without restrictions on lifetimes or chemical properties. An essential requirement for present and future RIB facilities is to transform this high-energy beam into a low-energy, low-emmitance beam. Such low-energy beams open up opportunities to study ground state properties of exotic nuclei by experimental techniques such as laser spectroscopy and ion trapping. At RIKEN, a universal slow RI-beam facility, SLOWRI, based on a gas catcher cell with an RF-carpet ion guide [1,2], was assigned as one of the principal facilities of RIBF. A novel method, named PALIS (PArasitic RI-beam production by Laser Ion-Source) [3], was also approved for the construction, to expand the usability and reduce experimental costs by utilizing unused RI-beams produced by projectile fragmentation or in-flight fission. Using this scheme, it will be possible to perform low-energy RI-beam experiments alongside every on-line BigRIPS experiment.

At RIKEN RIBF, the RI-beams of highly exotic nuclei are available with the highest intensity in the world. However, the usability is restricted to short periods of beam time due to high demand and limited yearly operating hours due to the electrical cost for accelerator operation. To bring about the most effective utilization of such high-performance facility, parasitic production of unused RI-beams would be valuable. In-flight fission and fragmentation produces a beam which is a mixture of thousands of isotopes. A fragment separator selects one specific RI-beam by removing the vast majority of these isotopes. The removed isotopes still include many rare nuclei of interest for nuclear studies; wastefully, they are simply thrown away. Our method is to save these rare isotopes before their removal in a beam purification slit. By installing a gas catcher cell in the vicinity of the slit at the F1 or F2 focal plane in BigRIPS [4], the RI which would have been removed by the slit can be collected and salvaged as a low-energy RI-beam. A schematic

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0168-583X/$ - see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.nimb.2012.10.009

view of this setup is shown in Fig. 1. Due to space and accessibility constraints, a big gas cell such as the ones typically used in RIB facilities [1,5,6] is not possible. Instead, we must use a compact cell with a simpler mechanism. Such a compact gas catcher cell necessitates higher pressure in order to maintain enough stopping power for the high energy RI-beams. Therefore, we will use a laser ionization gas cell [7–10] which can be a few hundred cm^3 in volume with 1 bar argon gas. The thermalized ions are quickly neutralized in high-pressure argon gas and transported by gas flow toward the exit of the cell, where they are selectively re-ionized by resonant laser radiations in the vicinity of the exit. They can then be further purified by an electro-magnetic mass separator and transported to the low-energy experimental room. In this way, the parasitic low-energy RI-beams could be delivered whenever BigRIPS experiments are in operation.

In order to provide a high stopping efficiency for high-energy RI-beams, the pressure in the gas cell must be sufficient to ensure the stopping range is shorter than the finite length of the gas cell. Additionally, the transport of neutral atoms by gas flow constrains the volume of the gas cell due to diffusion loss. Thus, it is optimal to use the highest possible pressure to allow the smallest possible gas cell. Additionally, a fast evacuation time is necessary to avoid decay losses for short-lived nuclei during transportation inside the gas cell. This can be accomplished by enlarging the size of the exit hole. For dealing with such high gas throughput, while keeping a high-vacuum extraction beam line, large roots pumps with pumping speed of the order of 10^3 m^3/h are typically used in a differential pumping system. The radiofrequency sextupole ion beam guide (SPIG) [11–14] can moderate the pumping load by decreasing the conductance between the gas cell and the extraction chamber. Even using such high-throughput pumps and SPIG, however, there are limits to the allowable pressure and consequently the number of feasible RIs extracted from the gas cell due to a lack of stopping efficiency and a relatively slow evacuation time. In order to address such inherent limitations, while also miniaturizing the entire system to fit within the highly constrained space limitations of the PALIS installation, we have developed a new idea which is the stepwise differential pumping method by small pumping capacities. This enables use of an even larger exit hole, more than 1 mm in a diameter, with the use of pressures up to one atmosphere argon in the gas cell. For such a pressure and exit hole, RI-beams with energies up to 10 MeV per nucleon will have a stopping range within the length of the gas cell (25 cm), while the evacuation time of the cell (gas cell volume ~500 cm^3) will allow a half-life of 100 ms to be extracted with 20% efficiency.

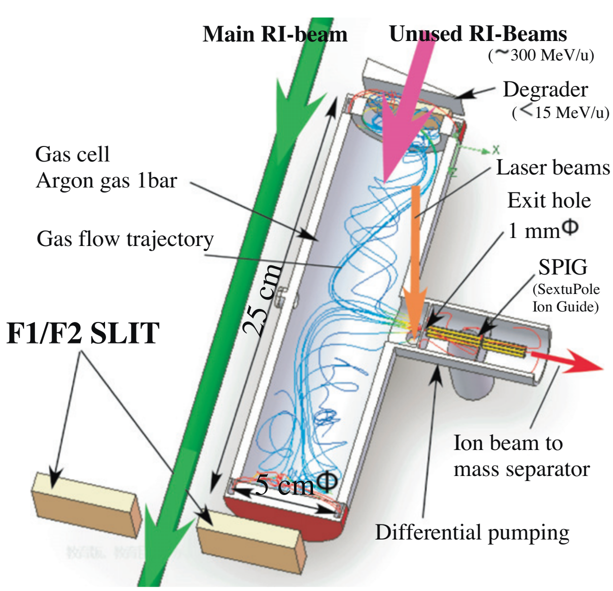

Fig. 1. Schematic of the laser ionization gas catcher setup. Without disturbing the main beam, an unwanted portion of the beam is stopped in the argon gas cell. Neutralized atoms are transported by gas flow towards the exit and re-ionized by resonant laser radiations. Thusly produced low-energy RI-beams can be utilized for slow-RI beam experiments.

To provide proof of principle for this new gas cell based laser ionization system, a prototype gas cell and a beam extraction system has been built for off-line experiments. The differential pumping capability of this new system has been verified; a pressure difference from 1000 hPa argon in the gas cell down to 10^{-3} Pa at the quadrupole mass filter has been achieved, while using a 1 mm diameter gas cell exit hole. This is the first result obtained in this mode: resonant laser ionization inside the gas cell, along with ion extraction from the gas cell and transport to high-vacuum. This has been experimentally confirmed off-line for several stable elements produced by filament evaporation or ablation by YAG laser. Resonant ionization has been performed using a two-step excitation scheme with an excimer–dye–laser combination. The extraction time profiles of the gas cell and the SPIG have been investigated and also examined by a Monte Carlo simulation combined with a gas flow calculation. The experimental results show that ions can be transported from a high pressure to a high-vacuum region via a long SPIG (253 mm) with an assisting force gas jet. This technique will relieve the inherent restrictions of conventional Ion Guide Isotope Separator On-Line (IGISOL) technique [15] based gas catcher cells, providing faster extraction times and improved stopping efficiency.

2. Prototype gas cell and a beam extraction system

A prototype gas cell and a beam extraction system has been developed. A conceptual sketch is shown in Fig. 2. The system is composed of four parts: a laser ionization gas cell, a differential pumping system, a quadrupole mass separator and a detector station comprising a Channel Electron-Multiplier (CEM). In this system, differential pumping – from the high pressure gas cell to the ion detector in a high-vacuum region – is achieved in just 1 m by applying our novel differential pumping method without using large roots pumps.

2.1. The gas cell

In the present off-line setup, a gas cell consisting of a simple cross chamber with dimension of $120 \times \phi$ 70 mm was used. It has an exit hole of 1 mm diameter and two feedthroughs to provide an electric current to a filament. In order to create a laminar gas flow inside the cell, the shape of the gas inlet was carefully fabricated by referencing flow simulation results. The gas inlet structure is shown in Fig. 3. The buffer gas is introduced via an inlet pipe of 6.35 mm diameter and spread with the conical structure. Laser beams can be introduced into the ionization region inside the gas cell via a quartz view port. Two alternative laser paths, transverse and longitudinal to the beam extraction axis, exist for ionization inside the gas cell. In the present experiment, however, only the transverse path was used. In the off-line setup, there are two methods available for producing atomic vapor inside the gas cell: evaporation of a filament or ablation by YAG laser. For laser ablation, the filament was replaced by a target which was irradiated by a YAG laser via a view port in the flange opposite the target. The gas handling system was specially designed to remove any impurity or contaminant from the argon buffer gas. Electro-polished stainless steel tubes and metal sealed valves were used. The gas