ISOBAR SUPPRESSION BY PHOTODETACHMENT IN A GAS-FILLED RF QUADRUPOLE ION GUIDE*

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Abstract

A novel technique based on selective non-resonant laser photodetachment in a radio frequency quadrupole ion guide is demonstrated for efficient suppression of isobaric contaminants in negative ion beams. The use of the quadrupole ion guide substantially increases the interaction time of the ions with the laser, significantly increasing the efficiency of the photodetachment process. In a proof–of-principle experiment, we achieved 95% suppression of $^{59}Co^-$ ions by photodetachment while under identical conditions only 10% of $^{58}Ni^-$ ions were neutralized.

INTRODUCTION

Selectively removing unwanted negative ion species by photodetachment has been suggested for applications in accelerator mass spectrometry [1,2], as well as radioactive ion beam purification [3]. D. Berkovits, et al. [1,2] used a pulsed Nd:YAG laser of 10 ns pulse width and 30 Hz pulse repetition rate to neutralize S and Co negative ions, while leaving the Cl and Ni negative ions unaffected. In their experiment, the negative ions were traveling with ~100 keV energies, interacting with the laser beam over a distance of about 1.2 m. Therefore, the overall degree of isobar suppression obtained by D. Berkovits, et al. [1,2] was too small for practical uses due to the very short interaction time (a few μs) between the pulsed laser beam and the fast moving negative ion beams.

We report a novel technique that promises near 100% efficiency of photodetachment and, consequently, near 100% suppression of isobar contaminants in negative ion beams. The new technique is based on non-resonant photodetachment with lasers in a gas-filled radio-frequency quadrupole (RFQ) ion guide. The principle of operation and the results of a proof-of-principle experiment are presented.

PRINCIPLE OF OPERATION

Photodetachment

The probability of photodetachment, η, is related to the incident photon flux Φ (photons cm^{-2} s^{-1}), through the photodetachment cross section, σ (cm^2), and the laser-ion interaction time, *t* (s).

$$\eta = 1 - \exp(-\sigma\Phi t) \tag{1}$$

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Photodetachment cross sections are typically on the order of 10^{-17} cm^2. One needs either a large photon flux or a long laser-ion interaction time in order to obtain high photodetachment efficiency. For example, to obtain 90% photodetachment efficiency for a cross section of 10^{-17} cm^2 and a 1 eV photon energy, one estimates (Φt) ~0.04 (Ws/cm^2) (i.e. a 0.4 ms interaction time for a 100 W/cm^2 laser power density). This implies a spatial overlap extending more than 200 m for a 100 keV $^{56}Co^-$ beam.

Gas-Filled RF Quadrupole Ion Guide

RF quadrupoles have been widely used as mass analyzers or ion beam guides [4]. A RF-only quadrupole acts as a high mass pass filter or ion guide. Ions with mass larger than a certain value are radially confined within the quadrupole while proceeding in the axial direction and transported through the device. Gas-filled RFQ ion guides have been used extensively for ion beam cooling and bunching [5-7]. When a buffer gas is introduced, ions suffer collisions with the gas molecules. If the gas molecules are significantly lighter than the ions, ion energies can be effectively dissipated in the collisions and the ions can be cooled close to the thermal energies of the gas molecules. A Monte Carlo code has been developed to simulate ion motions through gas-filled RFQ ion guides [5]. Fig. 1 displays the calculated trajectories of negative F ions during transit through a 10 cm long RFQ ion guide with He pressure of 1.33 Pa and driven by a RF field of V_{rf} = 300 V at 5 MHz. As shown, when cooled, the ion trajectories are confined to a small region near the longitudinal axis of the device.

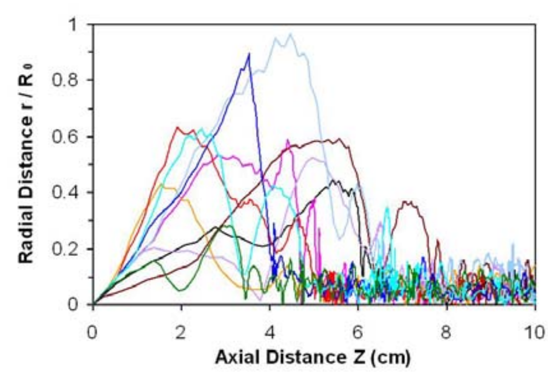

Figure 1: Monte Carlo simulation of trajectories of F^- ions in a RF quadrupole filled with 1.3 Pa He buffer gas. The ions have initial energy of 40 eV and enter the RFQ at an angle of 10 degrees.

After cooling to near thermal energies, the motion of the ions along the axis is essentially governed by diffusion and thus it is necessary to provide a longitudinal field to direct them towards the exit. With appropriate longitudinal field, ion residence time in the 40 cm long RFQ ion guide can be on the order of milliseconds. Fig. 2 shows the calculated residence time of Co^- ions entering a 40 cm long RFQ with 17 eV initial energy, as a function of the He gas pressure and different longitudinal field gradients.

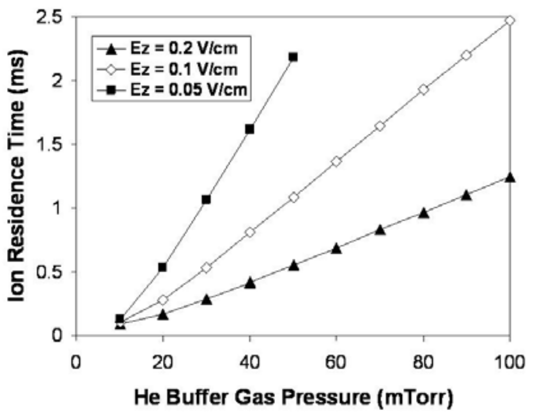

Figure 2: Calculated residence time of Co^- ions in a 40 cm long RFQ ion guide. The operation parameters of the RFQ are $f = 2.76$ MHz, $V_{rf} = 160$ V.

Photodetachment in Gas-Filled RFQ Ion Guide

The combination of small transverse dimension and long residence time in a gas-filled RFQ ion guide provides ideal conditions for photodetachment. Substantially longer interaction time and better special overlapping between the laser beam and the ions can be obtained in the RFQ. Consequently, the efficiency of photodetachment can be dramatically improved. For laser-ion interaction time on the order of milliseconds, it is possible to achieve high photodetachment efficiency with commercially available continuous wave (CW) lasers. This concept is tested in a proof-of-principle experiment using negative ion beams of stable isotopes of Ni and Co and a CW Nd:YAG laser beam at 1064 nm wavelength to selectively remove Co^- ions in a RFQ ion guide filled with helium gas. The energy of the 1064 nm photon, 1.165 eV, is much larger than the electron affinity of Co (0.661 eV), and slightly above the electron affinity of Ni (1.156 eV). Therefore, a much higher photodetachment probability for Co is expected.

EXPERIMENTAL SETUP

Negative Ni and Co ion beams were produced by a cesium sputter negative ion source, extracted from the ion source at about 5 keV energies, and mass separated with a 90° dipole magnet. After mass separation, the ion beams were decelerated to energies less than 50 eV and focused into a RFQ ion guide with helium buffer gas. The beam intensity before entering the RFQ was measured with a Faraday cup. A schematic view of the RFQ ion guide is shown in Fig. 3. The RFQ is 40 cm long, with a 3 mm diameter entrance aperture and a 2 mm diameter exit aperture, operating at 2.76 MHz and $V_{rf} \sim 200$ V. A detailed description of the RFQ ion guide can be found elsewhere [5]. Ions extracted from the RFQ were re-accelerated to an energy of 5 keV and deflected by an electrostatic deflector to an off-axis Faraday cup. Cooling of Ni and Co negative ions in the RFQ ion guide with He were confirmed by measuring the energy spread of the ion beams using an electrostatic energy analyzer system. The transmission efficiency of the RFQ for cooling Ni^- ions was measured to be ~17%.

The fundamental output of a CW Nd:YAG laser at 1064 nm was focused over a distance of about 2 meters into the RFQ from the ion extraction side, passing through the ion guide in opposite propagation of the ion beams. The laser beam was well-collimated with an angular divergence of ~1 mr. Limited by the 2 mm diameter entrance aperture, the laser beam transmission through the RFQ was measured to be about 50%.

RESULTS

In the experiment, the intensity of ion beams extracted from the RFQ was monitored with the off-axis Faraday

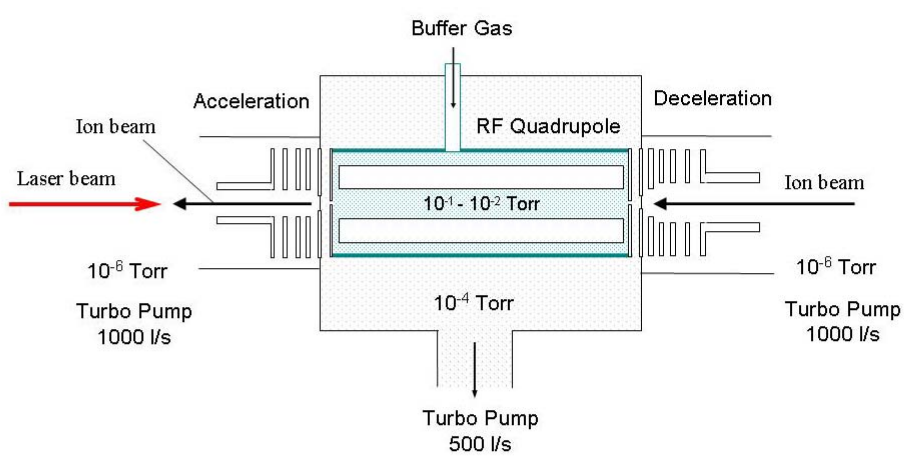

Figure 3: Schematic view of the gas-filled RF quadrupole ion guide.

cup. When the laser beam was turned on, an immediate decrease by 95% in the Co^- current was observed, while under the same condition, only ~10% drop in Ni^- current was seen. The ion currents immediately returned to the initial values when the laser beam was interrupted. As shown in Fig. 4, the changes in the ion currents are reproducible for laser on and off.

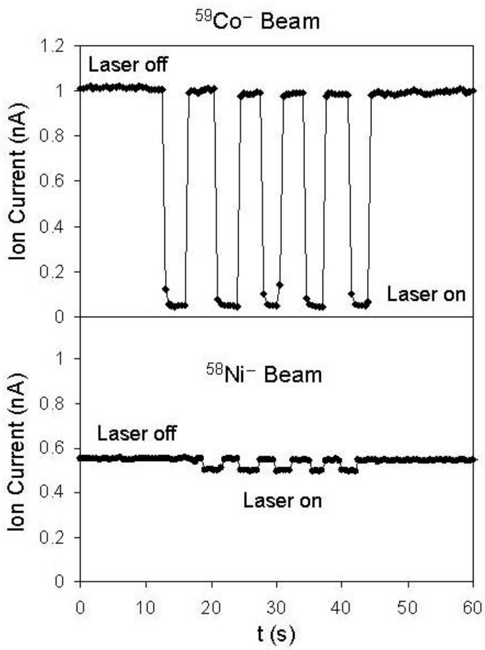

Figure 4: Measured intensities of ion beams accelerated from the RFQ with He pressure ~6 Pa. When the laser beam is turned on, 95% of $^{59}Co^-$ and 10 % of $^{58}Ni^-$ ions are neutralized.

The 95% photodetachment efficiency for Co^- was obtained with fairly low laser power: 5W measured at the laser output and ~2.5 W injected into the RFQ. Using Equation (1) and the experimental photodetachment cross section, $6.8x10^{-18}$ cm^2, for Co^- [2], the ion residence time in the ion guide is estimated to be ~1.2 ms. The detachment efficiency is limited by the laser power available in the experiment. Assuming t = 1.2 ms in Equation (1), one can scale the photodetachment efficiency to higher laser powers. Increasing the laser power to 5.7 W injected through the ion guide would remove 99.9% of Co^-, with only ~21% reduction of the Ni^- intensity due to photodetachment. Such laser power is available with existing commercial lasers.

This technique is applicable to purifying isobaric contaminants in radioactive ion beams for research at the Holifield Radioactive Ion Beam Facility (HRIBF) at the Oak Ridge National Laboratory or other isotope separator on-line (ISOL) facilities, or removing unwanted stable isobars in radioisotope ion beams for accelerator mass spectrometry analyses. An example of practical importance for research at HRIBF is suppressing the $^{56}Co^-$ isobar contaminant in a mixed $^{56}Ni^-$ + $^{56}Co^-$ radioactive ion beam. The RFQ ion guide employed in this work is not optimized for this application. Improvement in ion guide performance, and in coupling of the laser into the ion guide should be straightforward and is in progress.

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