Slow or trapped RI-beams from projectile fragment separators and their laser spectroscopy

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A new idea to obtain slow or trapped unstable nuclear ions which are primarily produced by a projectile fragment separator is presented. The energetic unstable nuclear ion beams are, firstly, degraded by an energy degrader, then, injected into an RF ion-guide gas cell. A certain fraction of ions are thermalized in the gas cell as singly charged ions. They are rapidly and efficiently transported to an exit by DC and RF electric field. An off-line test experiment for the RF ion-guide is briefly described.

Introduction

The projectile fragment separator provides a wide variety of radioactive nuclear ions without any restrictions on chemical property or lifetime limit of the ions, which are unavoidable problems in the ordinary ion-source-based ISOL (isotope separator on-line) facilities. The beam energy and quality in terms of the longitudinal and transverse emittance is, however, not adequate for low-energy beam experiments, in particular for trapping experiments. Trapped unstable nuclear ions enable us to perform a variety of high precision experiments. We will primarily apply this method to the precision spectroscopy of the hyperfine structure.[1] The magnetic hyperfine constant A shows a weak but finite isotope dependence called hyperfine anomaly, the main part of which stems from the finite size of the magnetization distribution in the nucleus (Bohr-Weisskopf effect). This effect affords a unique and interesting probe for valence neutron distribution in a nucleus, particularly in a neutron halo nucleus such as ^{11}Be.[2]

We have proposed a new scheme to provide low-energy high-quality beams from such fragment separators.[3,4] The system comprises a primary degrader, a large He gas cell and a beam guide (Fig. 1).

The degrader reduces the beam energy to about 5 MeV/u. If the primary energy of a beam is 100 MeV/u, more than 50% is in the energy range of 0 to 5 MeV/u after passing through a degrader foil of suitable thickness. The medium energy beam thus obtained is then injected into the He gas cell. In order to stop the 5 MeV/u beams, the cell is required to be 2 m in thickness with 0.2 atm of He. The thermalized ions should be extracted from the exit of the cell and then guided to a high vacuum region by the RF sextupole ion beam guide (SPIG) through multiple skimmers.[5,6]

The main part of the system is the He gas cell. The system is based on the same principle as that of the ion guide ISOL(IGISOL), but a significant difference is in the cell size. In the ordinary IGISOL, a typical cell size is 1 cm which corresponds to a stopping capability of 10 keV/u. This limits the effective thickness of the target and the corresponding yield. The reason a small cell size is used in the IGISOL is that the transport of the ions in the cell is performed only by the gas flow. If a large cell were used in the ordinary IGISOL, it would take many minutes to extract ions which would cause severe loss of ions due not only to the lifetime limit but also to other processes such as neutralization and diffusion. In the proposed system, on the other hand, ions in the cell are totally under the control of an electric field. Many ring

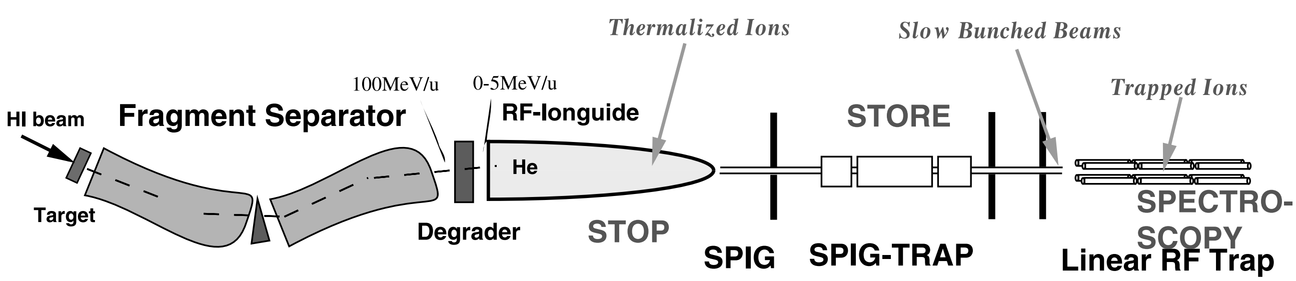

Fig. 1. Overview of the proposed scheme.

electrodes are placed in the cell, which produces a superposition of a DC field and an RF field (RF ion guide). The DC field gives the ions a relatively high velocity in order to quickly exit the cell and the RF field focuses the ion beam to the small exit hole. This allows the use of a large-size gas cell and a small exit hole.

Simulation

An analytical evaluation based on the pseudo potential method was performed for an estimation of the average focusing effect of the RF field. The equation of the motion of an ion in the RF ion guide in friction model is

$$m\ddot{r} + \frac{e}{\mu}\dot{r} = -e\nabla\phi\cos\Omega t, \tag{1}$$

where m is mass, r coordinate, e charge, μ mobility, ϕ potential of the RF field and Ω angular frequency of the RF. The velocity relaxation time τ_v is

$$\tau_v = \mu\frac{m}{e} = \mu_0\frac{760}{P}\frac{m}{e}, \tag{2}$$

where μ_0 is the normalized mobility. The μ_0 of ions in He gas is experimentally known to be $\sim$20 cm^2/Vs. Thus Eq. (1) is rewritten in

$$\ddot{r} + \frac{1}{\tau_v}\dot{r} = \frac{e}{m}E\cos\Omega t. \tag{3}$$

The average motion is described to be

$$\ddot{r}_{av} + \frac{1}{\tau_v}\dot{r}_{av} = -\frac{e^2}{4m\Omega^2}\nabla E^2\left(\frac{1}{1+1/(\tau_v^2\Omega^2)}\right). \tag{4}$$

If we assume the form of the RF potential as a quadrupole with a distance of adjacent electrodes r_0 and terminal voltage V, the effective electric field due to the RF potential is

$$E_{\text{eff}} = \frac{8e\tau_v^2}{m(\Omega^2\tau_v^2+1)}\frac{V^2}{r_0^3}\left(\frac{r}{r_0}\right). \tag{5}$$

In the present case the relaxation time is the order of ns, much shorter than the period of RF. Then the effective field is

$$E_{\text{eff}} \approx \frac{8e\tau_v^2}{m}\frac{V^2}{r_0^3}\left(\frac{r}{r_0}\right) = \frac{8m\mu^2}{e}\frac{V^2}{r_0^3}\left(\frac{r}{r_0}\right). \tag{6}$$

It is not dependent on the frequency. In general, heavier ions in lower pressure can be driven in an weaker RF field.

Numerical simulations were performed for the RF ion-guide system. A single ion motion in the electric field was traced by the Runge-Kutta integration method. The effect of gas collision was taken into account by the Monte Carlo method. The kinematics of each collision was simulated in two different ways. In the simpler one, isotropic scattering at the center of the mass system was assumed and the mean free path was chosen to emulate the experimental value of the ion mobility in He gas ($\sim$20 cm^2/Vs at 760 Torr). In the more complex one, a classical scattering model in a semi-empirical potential, which was determined by Mason and Schamp from their mobility measurements,[7] was used. A typical trajectory of an ion in the RF ion guide is shown in Fig. 2.

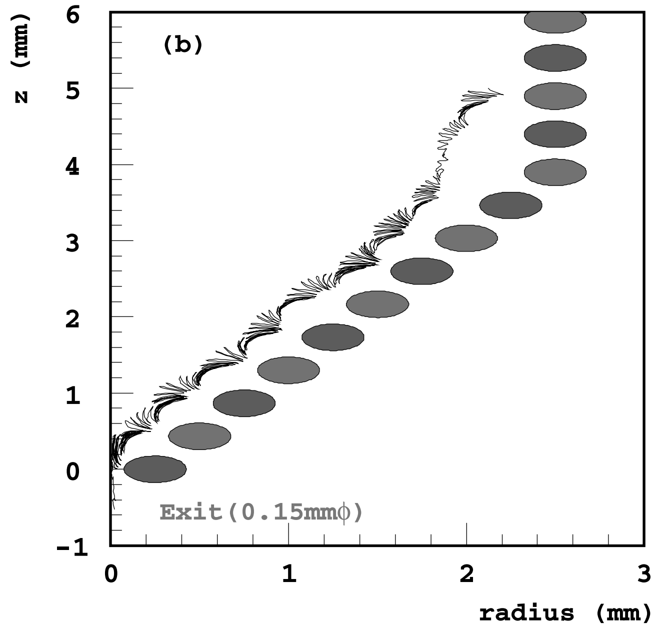

Fig. 2. Typical ion trajectry in the RF ion-guide.

Test experiment

A test bench for the RF ion-guide system with a gas cell of 60 cm in length has been constructed at KEK-Tanashi and then moved to RIKEN. In order to clarify the effect of RF electric field in the ion-guide gas cell, a test gas cell of 30 cm in length was prepared. In the test cell, 80 pieces of electrodes with an interval of 2.5 mm are placed and an RF voltage with a different DC offset is applied to the each electrode. Figure 3 shows a schematic diagram of the gas cell. Metallic ions were created in the small cell by irradiation of a pulsed YAG laser. The ions are, then, injected into the RF ion-guide cell by a gas flow. The source ion current was monitored throughout the measurement for normalization. A typical current of 100 pA was obtained under an irradiation frequency of 10 Hz and a gas flow rate of 3 Torr l/s. The transported ions were detected by a Faraday cup which is located at the downstream of the RF electrodes.

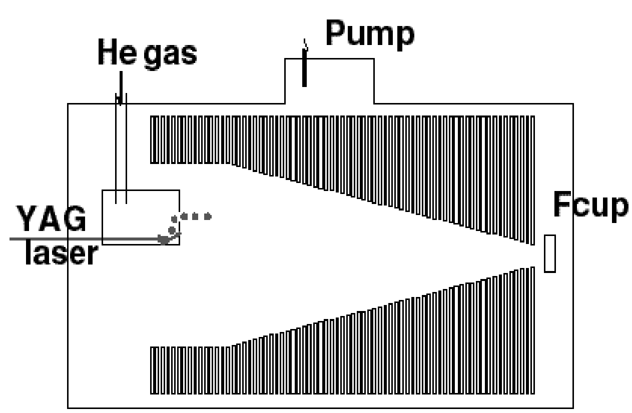

Fig. 3. Test RF ion-guide gas cell.

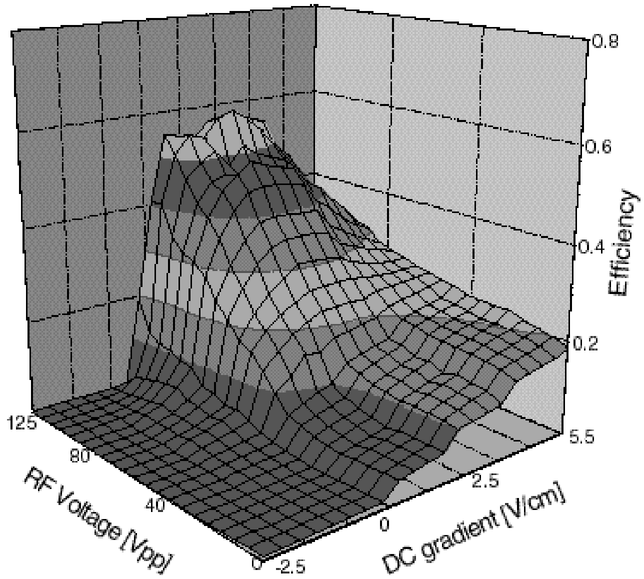

Fig. 4. Experimental result of ion transport in the RF ion-guide.

A typical experimental result is shown in Fig. 4. The effect of RF electric field was clearly indicated. A transmittance of 60–80% was obtained in the test under a condition of 20 Torr He gas pressure and an RF voltage of 150 V_{pp}. The voltage was limited by a discharge which occurred around feed throughs. The transmittance decreased when increasing the gas pressure. For a higher pressure, a higher RF voltage is required.

Discussion

The gas pressure of 20 Torr which was used in the test experiment is too low for realistic applications. In order to stop the radioactive beam of 5 MeV/u in the gas cell, a pressure of 150 Torr and a thickness of 2 m is required.

According to Eq. (6), an effective way to increase the operation pressure is to decrease r_0, which corresponds to the interval of the electrodes. If we could use a fine electrode structure with an interval of 0.5 mm, a similar transmittance would be achieved in high pressure He gas of 150 Torr. Such a fine structure electrode could be fabricated by using a flexible printed circuit.

An on-line test is scheduled in summer 2000 at the RIKEN ring cyclotron facility, where a half part of the fragment separator RIPS will be used.

References

1) M. Wada et al.: Nucl. Phys. A **626**, 365c (1997).
2) T. Fujita et al.: Phys. Rev. C **59**, 210 (1999).
3) M. Wada et al.: presented in the Int. Workshop on Ion Guide Isotope Separator On-Line (IGISOL-6), Dubna 1997, unpublished.
4) I. Katayama et al.: Hyperfine Interact. **115**, 165 (1998).
5) H. Xu et al.: Nucl. Instrum. Methods Phys. Res. A **333**, 274 (1993).
6) S. Fujitaka et al.: Nucl. Instrum. Methods Phys. Res. B **126**, 386 (1997).
7) E. A. Mason et al.: Phys. Rev. **112**, 445 (1958).