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Accumulation of ions from a recoil mass separator in a new type of linear ion trap

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A new type of linear ion trap system in combination with a sextupole ion beam guide (SPIG) has been developed for the accumulation of a continuous ion beam. An axial trapping potential is generated by three cylindrical electrodes mounted outside, but concentric to, the SPIG. The ions in a continuous beam are trapped in potential well via collisions with He gas. This linear ion trap is called 'SPIG-trap'. The properties of the SPIG-trap were tested off-line with a discharge ion source in a gas cell. Up to 10^6 ions were trapped and extracted as a bunch with an efficiency of 10% for 10 ms of accumulation. The SPIG-trap system was then connected to a gas filled recoil mass separator (GARIS) and tested with an energetic primary beam from a cyclotron (^{16}O , 107 MeV). The overall efficiency of SPIG-trap including ion losses in an energy degrader, which was placed in front of the He cell, was measured to be the order of 10^{-5} for 10 ms accumulation.

1. Introduction

Ion traps have played important roles in a wide variety of atomic and nuclear physics, in particular in precision measurements of atomic masses and hyperfine structures. We have been aiming at an investigation concerning nuclear magnetic moments and their distributions in nuclei, especially for unstable Be isotopes, through measurements of the hyperfine structures of the ground state ions trapped in an ion trap [1,2]. Trapping of ions in continuous ion beams from an on-line mass separator is an important practical concern when we want to apply the ion-trap technique to a study of unstable nuclear ions. For low energy, small emittance beams from an ISOL (isotope separator on-line), a system consisting of an electrostatic retardation and a large Paul trap with buffer gas cooling has been proposed by Moore et al. [3,4] and tested at ISOLDE at CERN. Another system using a long Penning trap has also been proposed for a pre-bunching device of an injector of a radioactive beam acceleration facility (REX-ISOLDE) [5,6].

These systems are meant for the so called ISOL-type mass separator. However, due to the limitations of ion-sources not all element species are obtained from such devices. On the other hand, the so called recoil type separator such as a projectile fragment separator and a gas filled recoil isotope separator (GARIS) are versatile separators for any kinds of element, but their

output ion beams are not easily trapped. This is because the energy is high ($> \text{MeV/u}$), the energy spread is large ($> \text{MeV}$), and the emittance is large ($\sim 500\pi \text{ mm mrad}$). However, we have developed a device for trapping such ions from the GARIS at the Institute for Nuclear Study (INS), University of Tokyo. This device consists of an Ion-guide gas cell and a RF multipole ion beam guide (sextupole ion beam guide – SPIG) [7] and a SPIG-trap.

Historically the ion guide method was developed as a kind of ion source for an on-line mass separator by Årje et al.[8,9]. In the original scheme, the ions extracted from the gas cell were accelerated towards a skimmer by an electric field, and the acceleration in the poor vacuum region caused a large energy spread of the extracted ion beam. We have proposed to use the SPIG right after the exit hole of the gas cell to extract the ions without any acceleration [7]. The SPIG consists of six parallel rods equally spaced around a circle. A radial confinement field is generated inside the SPIG by applying RF voltages between adjacent rods. The ions are thus radially focused and efficiently transported through a skimmer to a high vacuum region. The properties of the SPIG were tested in ref. [7], where the optimum transport efficiency is more than 90% and the energy spread of the transported ion beam smaller than 1 eV. Although an alternate device called a squeezer [10] has been proposed, the SPIG should be better for the present purpose.

We have also developed an accumulation system in the SPIG itself. This is because a continuous ion beam from the SPIG would be quite inefficient for capture in a subsequent trap. The short opening time compared to the holding time of the trap would allow capture efficiencies of at most about 10^{-5} even when the energy of ions is as low as 1 meV/u. If, however, we can accumulate continuous ion beam before delivery as a pulse into the time-window of the trap then the efficiency becomes 100%.

Figure 1. Schematic drawing of SPIG-trap. A RF sextupole field is produced by six rods for the radial confinement while three ring electrodes form an axial trapping field. The vacuum of each region separated by an exit nozzle and three skimmers (the 3rd one is not drawn) is of the order of 10 kPa, 10 Pa, 1 Pa, 10^{-2} Pa and 10^{-4} Pa, respectively.

The accumulation of the continuous ion beam was realized with the three ring electrodes shown in Fig. 1, which we call the SPIG-trap. By applying the appropriate DC voltages on these electrodes, an axial potential well is formed inside the SPIG. The ions in a continuous beam are trapped in the potential well through the process of collision with He buffer gas. The

trapped ions are extracted as an ion bunch in a short period, and then could be trapped quite efficiently in a subsequent ion trap connected in the downstream.

In the present paper the off-line tests on the properties of the SPIG-trap and the results of on-line tests in combination with the GARIS are described.

2. Principle of the SPIG-trap

Since a radial confinement field is already formed by the SPIG, we only need to add an axial confinement field in order to produce a three dimensional trapping potential. In an ordinary linear trap, the axial confinement field is formed by separating the electrodes into three sections and applying different DC offsets. In our case it is very difficult to cut the SPIG into three parts since the SPIG electrodes are too fine. We have therefore adopted the ring electrode geometry shown in Fig. 1.

We have calculated the penetration of the electric field for the geometry shown in Fig. 2(a). The ring electrode has 4.4 mm inner diameter. The SPIG comprises 6 rods of 0.5 mm diameter. The diameter of the inscribed circle of the SPIG is 2.8 mm. By applying a DC voltage on the outer ring electrode the mean potential at the center of the SPIG is shifted while a SPIG potential is maintained. A two-dimensional potential distribution calculated by POISSON [11] is shown in Fig. 2. When the voltage of the ring electrode is 100 V, the potential at the center is shifted by as much as 9 V from the average potential of the SPIG rods.

Figure 2. Calculation of the electric potential inside the SPIG with an outer ring electrode. (a) shows the potential map with the radial geometry of the SPIG and the ring electrode, (b) the potential distribution along the y and x axis. Thin lines are for y axis and thick lines for x axis. The outer ring electrode is kept at +100 V (solid lines) or 0 V (dotted lines), while the SPIG rods are connected alternatively and applied with a voltage oscillating from 0 to 160 V in opposite phase. The potential at the center is raised to 9 V when +100 V is applied to the ring.

The vacuum in the region of the three ring electrodes is of the order of 1 Pa, and the ions have a mean free path of approximately 10 mm. The result of a Monte Carlo simulation of

an ion motion in the SPIG-trap is shown in Fig. 3. An ion which drifts in the SPIG from the upstream gas cell passes through a potential well at $z = 55$ mm. The ion loses its energy through collisions with the He gas, and then is trapped. This result shows that by using the SPIG-trap we can accumulate ions in a continuous beam into the potential well.

Figure 3. Monte Carlo simulation of an ion motion in the SPIG-trap. An ion ($A = 32$, initial energy is 20 eV) from the gas cell flowing along z axis is cooled by gas (He, 300 K) collisions and trapped in the axial potential well at $z=55$ mm. The energy and the radius (root-mean-square radius) are averaged over $5 \mu\text{s}$.

3. Experimental

3.1. Apparatus

We present here further details of the apparatus shown in Fig. 1. The ions are extracted with the He gas flow through a 1.2 mm diameter exit hole of the gas cell. The gas cell was filled with He gas to about 10 kPa. The gas between the gas cell and the 1st skimmer is evacuated by a combination of mechanical boosters of 1200 and 330 ℓ/s backed by a rotary pump of 83 ℓ/s . The three ring electrodes are placed between the 1st and 2nd skimmer, where the gas is evacuated by a mechanical booster of 70 ℓ/s backed by a rotary pump of 8.3 ℓ/s . Beyond the 2nd and 3rd skimmer the gas is evacuated by two turbo-molecular pumps of 250 ℓ/s and 50 ℓ/s , respectively.

The radial dimensions of the SPIG and the ring electrode are presented in the previous section. The SPIG rods of 270 mm length are mechanically supported and electrically insulated by glass ceramics (Macor) and are supplied with RF voltages between adjacent pairs. These RF voltages are approximately 100 V_{pp} at 6.3 MHz. We also apply a DC voltage (V_g) to the gas cell and an average DC voltage (V_m) to the SPIG rods superimposed to the RF. The lengths of the three ring

electrodes are 5 mm, 10 mm and 5 mm, respectively. The voltage applied to the ring electrode is controlled sequentially within very short switching times ($< 1 \mu\text{s}$) by a fast high voltage ($\pm 200 \text{ V}$) amplifier made of the Apex PA85.

3.2. Results

3.2.1. Off-line test

In the off-line tests, a discharge ion source was used in the gas cell. During the measurements, the DC current of the ion beam transported by SPIG was of the order of 1 nA. The off-line test result is shown in Fig. 4. A signal of the trapped ions and the time sequence of the ring voltage are shown. The ion signal was detected with a Faraday cup located at the end of the SPIG. During the through ('Thru') period three rings were grounded, so the ions flew inside the SPIG continuously, and a DC current of 2 nA was observed. During the 9 ms accumulation period

Figure 4. Result of the off-line accumulation test with the SPIG-trap. The ion current detected at the Faraday cup and the sequence of the voltages applied to the three ring electrodes (R_u , R_c , R_d) are shown. The continuous ion beam of 2 nA was accumulated for 9 ms and held for 0.6 ms, and then extracted as a sharp bunch.

('Acc'), the downstream ring (R_d) was raised to 70 V and the central ring (R_c) was lowered to -5 V in order to produce a potential barrier and a well. The ions were accumulated in the central ring (R_c) region. During the 0.6 ms hold period ('H'), the upstream ring (R_u) was also raised to 100 V in order to stop the supply of the ions from upstream. During the 5 ms extraction period ('Ext'), R_d was grounded and R_c and R_u were raised to 80 V and 150 V respectively in order to extract the ions in the potential well as a bunch. The short signal pulse observed at the beginning of 'Ext' period corresponds to the trapped ion bunch. The number of ions in the bunch is estimated to be about 7×10^6 , which corresponds to 7% of the ions supplied during the accumulation period.

Some aspects of the performance of SPIG-trap were examined, in particular the trapping capacity and a life-time of the trapped ions. The trapping capacity of the SPIG-trap was measured by changing the accumulation time while the hold time was fixed to 1.2 ms. In Fig. 5(a), the number of trapped ions is plotted as a function of the accumulation time. At extended accumulation time, the number of the trapped ions saturates. This saturated number, 6×10^6 , shows the capacity of the SPIG-trap. This capacity is considered to come from a space-charge effect, i.e. charge saturation in the trapping region. The life-time of the trapped ions was measured by changing the hold time while the accumulation time was fixed to 24 ms. In Fig. 5(b), the

Figure 5. Characteristics of the present SPIG-trap. (a) shows the trapping capacity. The number of trapped ions for the ion beams of different DC current is plotted as a function of the accumulation time. The hold time was fixed at 1.2 ms. Different beams cause saturation at about the same number, 6×10^6 . (b) the trapping life time. The number of trapped ions is plotted as a function of the hold time. The accumulation time was fixed at 24 ms. The half-life of the accumulated ions was about 90 ms regardless of the DC beam current.

number of trapped ions is plotted as a function of the hold time. It decreases exponentially with the hold time. The half-life of the trapped ions is about 90 ms. The trapped ions are thought to be lost via collisions with impurities contained in the He gas and via RF heating. A fast decay component can be seen at the beginning of the decay curve. Since the ions are accumulated in the trapping potential to the limit of the space charge during the 24 ms accumulations, it would appear that this immediate rapid loss is due to space charge forces.

3.2.2. On-line test

In the on-line tests, the oxygen ion beam of 107 MeV from the SF cyclotron ($K = 67$) was injected into GARIS without a target and guided to the focal plane with an intensity of approximately 10 epA. No gas was used in GARIS. The energetic oxygen ion beam was degraded just in front of the gas cell by Al foils of 90 μm thickness (comparable to the range of the oxygen ion beam), and a 1.5 μm polyethylene film was used to separate the vacuum between the gas cell and GARIS. The ion beam was then injected into the gas cell filled with He gas with a pressure of 16-20 kPa.

The on-line test results are shown in Fig. 6. In Fig. 6(a), the number of ions extracted from the gas cell and transported by SPIG is plotted as a function of time. A secondary electron multiplier was used for the detection of the ions. The oxygen ion beam was chopped at the ion source of the cyclotron at 1 Hz with a 50% duty cycle. The average number of ions transported to the end of the SPIG was 700 per second. Figure 6(b) shows the result of the accumulation test of the SPIG-trap. The time sequence was the same as that of the off-line experiment (cf. Fig. 4). The signal of the trapped ions is observed at the beginning of the extraction period after 10 ms of accumulation and a 40 μs hold time. The average number of ions contained in the trapped ion signal is estimated to be 3, while the number of ions injected into the energy degrader during 10 ms is 8×10^4 , corresponding to an accumulation efficiency of the order of 10^{-5} .

Figure 6. Results of the on-line tests. (a) Measurement of the ion intensity transported by SPIG without trapping. The cyclotron ion beam was chopped at 1 Hz and the data are acquired over 20 cycles. The average number of transported ions was 7×10^2 per second. (b) Measurement of the trapped ion signal. The time sequence of the voltages of the ring electrodes was the same as that for the off-line experiments. The accumulation time was 10 ms and the hold time $40 \mu\text{s}$. The number of ions in one bunch was 3 averaged over 2000 cycles, which corresponds to an overall efficiency of the order of 10^{-5} .

4. Discussion

The trapping efficiency of the SPIG-trap itself was the order of 10% for 10 ms accumulation. It is strongly dependent on the accumulation time. In a very short accumulation period of 0.3 ms, a large efficiency of $>80\%$ was observed while a very low efficiency of $<10^{-3}$ was obtained in a long accumulation period of 1 s. This fact suggests that the trapping life-time should be improved to achieve high trapping efficiency for a long accumulation period. Since we aim at unstable nuclei of rather long half-life, more than 1 s, a longer accumulation period of >1 s with sufficiently high efficiency would be preferred. The present short trapping life-time of ~ 100 ms is thought to be mainly due to a poor background vacuum of 10^{-2} Pa.

The number of ions contained in one bunch in the on-line tests was 3 while the number of ions in a length of 10 mm in the energetic continuous beam was 2.6×10^{-3} , which corresponds to an enhancement factor of 10^3 . If the transversal distribution is taken into account, spatial compression of 10^3 ($\sim 30 \text{ mm}\phi$ to $\sim 1 \text{ mm}\phi$) was also achieved. If energy spread is also taken into account, a large cooling effect ($\Delta E \approx 1 \text{ MeV}$ to thermal) was achieved.

Although the present trapping efficiency of the entire system is not so high, such large enhancements help to realize on-line experiments. Furthermore, a realistic beam energy from GARIS is lower than the present test. It may lead to much higher trapping efficiency, since the dominant loss of ions is in the energy degrader. For example, in a past GARIS-IGISOL experiment at INS [12], the maximum energy of ^{28}Al produced in the reaction $^{27}\text{Al}(\alpha, 2p\text{n})$ is 110 keV/u at the focal plane of the GARIS and the overall efficiency was about 1%. If the present SPIG-trap were coupled with it, an overall trapping efficiency of 10^{-3} for 10 ms accumulation would be expected.

The capacity of the present trap, 10^6 , is quite large for trapping unstable nuclear ions. If, however, greater capacity is needed, it could be easily increased by extending the length of the trapping electrode. Since the ring electrode is very simple, it is also easy to make additional trapping regions by increasing the number of rings. In such multi-ring configuration, a versatile time sequence and trapping scheme can be used. A long trapping region can be made by using many rings together as a central ring which allows us to use lower gas pressure to cool the incoming ions. Then, ions in the long trap region can be squeezed to make a sharp bunch by pulsing the potential of the rings one by one from upstream to downstream. A new accumulation can also be started in the upstream region during the squeezing period.

Figure 7. Mass spectrum of ions in the off-line setup. The ions were produced by an arc discharge in the He buffer gas cell. The mass spectrum was taken by a quadrupole mass filter at the end of the SPIG.

Cluster formation of incoming ions in a He buffer gas cell has been reported as a drawback of using SPIG [13]. Reactions between the incoming ions and impurity molecules in the He, mainly water, occur. In an ordinary IGISOL the clusters are thought to dissociate when they collide with the gas atom during acceleration from the gas cell to the skimmer. However, this does not occur in SPIG since the ions are extracted with no acceleration. We have obtained a mass spectrum of the ions in the off-line setup using a home-made quadrupole mass filter at the end of SPIG. The ions of mass number about 19, 37, 55 and 73 were detected as shown in Fig. 7. The ions produced in the gas cell by the discharge ion source are therefore thought to be associated with water molecules and their clusters. A solution to overcome this problem has been found by a Leuven group [14].

5. Summary

We have developed a SPIG-trap for the purpose of accumulating a continuous ion beam and extracting the accumulation as a bunch. The SPIG-trap was tested on-line using a 107 MeV oxygen beam from the GARIS. The overall efficiency in the 10 ms accumulation period was measured to be 10^{-5} including the loss in the energy degrader. The next step of our development is to use SPIG-trap to accumulate unstable nuclei from the on-line mass separator and to measure the absolute efficiency of such a system.

The trapping efficiency of SPIG-trap itself was about 10% for 10 ms accumulation, however, it could be increased by improving the vacuum and the configuration of trapping electrode.

Combined with a realistic overall efficiency of 1% in GARIS and Ion-guide system in the past GARIS-IGISOL experiment using radioactive products, we would conclude that the on-line laser spectroscopy experiments using GARIS, Ion-guide, and SPIG-trap is feasible.

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