A NEW POSSIBILITY OF LOW-Z GAS STRIPPER FOR HIGH-POWER URANIUM BEAM ACCELERATION AS ALTERNATIVE TO C FOIL

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Abstract

The RIKEN accelerator complex started feeding the next-generation exotic beam facility RIBF (RadioIsotope Beam Factory) with heavy ion beams from 2007 after its successful commissioning at the end of 2006. Many improvements carried out from 2007 to 2010 increased the intensity of various heavy ion beams. However, the available beam intensity, especially of uranium beams, is far below our goal of 1 pμA (6×10^{12} particle/s). In order to achieve it, upgrade programs are already in progress; the programs include the construction of a new 28-GHz superconducting ECR ion source and a new injector linac. However, the most serious problem of a charge stripper for uranium beams still remains unsolved, despite extensive R&D works. The equilibrium charge state in a gas stripper is considerably lower than that in a carbon foil due to the density effect of the latter. However, a gas stripper is free from the problems related to lifetime and thickness uniformity. These merits motivated us to develop a low-Z gas stripper to achieve a higher equilibrium charge state even in gases. We measured the electron-loss and electron-capture cross sections of U ion beams in He gas as a function of their charge state at 11, 14, and 15 MeV/u. The extracted equilibrium charge states from the cross point of the two lines of the cross sections were promisingly higher than those in N_2 gas by more than 10. We believe that the difficulty in the accumulation of about 1 mg/cm^2 of low-Z gases can be overcome by using a plasma window.

INTRODUCTION TO RI BEAM FACTORY

The RIKEN Nishina center for Accelerator-Based Science constructed the RIBF (RadioIsotope Beam Factory) [1] aiming to realize a next-generation facility that can provide the most intense RI beams, which is the highest in the world, at energies of several hundred MeV/nucleon over the entire range of atomic masses. The RIBF requires an accelerator complex that can accelerate ions over the entire range of masses and deliver 80-kW uranium beams at an energy of 345 MeV/nucleon. Figure 1 shows a bird's eye view of the RIBF. The left part is the old facility that was completed in 1990. Using the four-sector K540-MeV RRC (RIKEN Ring Cyclotron) [2] with the two injectors, RILAC (RIken Linear ACcelerator) [3] and the AVF cyclotron [4], many experiments were carried with RI beams of light ions because the RRC can accelerate relatively light

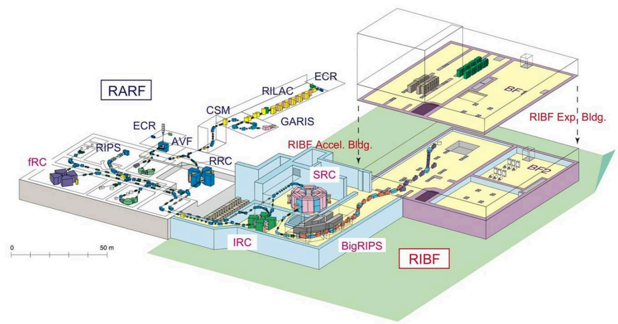

Figure 1: Bird's eye view of RI Beam Factory.

ions up to 100 MeV/u, which is the lower limit for RI beam production. In order to expand the mass range for RI beam production up to uranium, three ring cyclotrons, the fRC (fixed-frequency Ring Cyclotron) [5], IRC (Intermediate Ring Cyclotron) [6], and SRC (Superconducting Ring Cyclotron) [7], were designed and constructed as energy boosters for the RRC. The SRC is the first ring cyclotron in the world using superconducting sector magnets with the largest bending power.

The design and construction of the RIBF accelerators started from 1997, and the accelerator building was completed at the end of March 2003. In November 2005, we reached an important milestone: the superconducting sector magnets for the SRC were successfully excited at the maximum field level. The first beam was obtained on December 28, 2006 [8, 9]. Many improvements were carried out to increase the beam intensity and to commission new beam species to meet the requirements of different experiments. Table 1 shows a list of beams accelerated thus far. These beams were used in many nuclear experiments such as the discovery of 45 new isotopes [10] and the study of the halo structure and large deformation of extremely neutron rich Ne isotopes [11, 12]. Our goal is to achieve a beam intensity of 1 pμA for the entire atomic range. We reached the target intensity for He and O and about one fourth of the target intensity for Ca. However, the beam intensity of U beams is still very low, suggesting that we need to adopt drastic measures.

INCREASING INTENSITY OF URANIUM BEAM

From our operational experience, mentioned in the previous section, the key issues to be addressed for increasing

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Table 1: Accelerated Beams

Ion	Energy (MeV/u)	Intensity (pnA)	Date
pol-d	250	120	May 2009
^{4}He	320	1000	Oct 2009
^{14}N	250	80	May 2009
^{18}O	345	1000	Jun 2010
^{48}Ca	345	230	May 2010
^{86}Kr	345	30	Nov 2007
^{238}U	345	0.8	Dec 2009

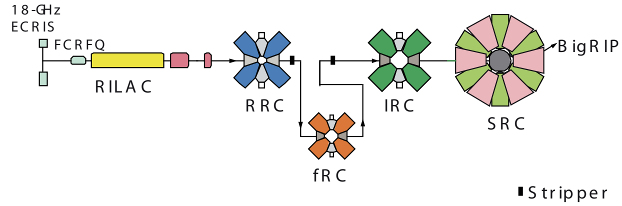

Figure 2: Acceleration scheme for uranium beams using two strippers.

the intensity of uranium ion beams can be clearly pointed out as follows. First, more beams are necessary from the ion source. Nakagawa et al. are currently developing a new 28-GHz superconducting ECR ion source, which is designed to have as large plasma volume of 1100 cm^3 [13, 14]. An important feature of this source is that its coil system is designed to obtain a flat magnetic field distribution in the central region, by exciting the solenoids independently. This ion source is expected to produce U^{35+} ions at an intensity of more than 15 pμA, which is necessary to obtain 1-pμA beams from the SRC. The coil was successfully excited to the designed level in October 2008. We started the testing of the ECR source from April 2009; we used the 18-GHz mode for this because we did not have a 28-GHz source then. The intensity of uranium beams reached 10 eμA, which is about five times that of the beams from the previously used ion sources. The ion source will be moved to the upstream of a new injector, mentioned in the next paragraph, and will be tested in the 28-GHz mode this year.

Next, a new injector is necessary to prevent emittance growth due to the space charge forces during the acceleration of ion beams from the new powerful ion source. The new injector is designed to efficiently accelerate ions with a mass-to-charge ratio of 7, aiming at heavy ions such as $^{84}Kr^{13+}$, $^{136}Xe^{20+}$, and $^{238}U^{35+}$, up to an energy of 680 keV/nucleon [15]. It mainly consists of an RFQ linac based on the four-rod structure and three DTLs (drift-tube linacs) based on a QWR (quarter-wavelength resonator). All the main components have already been installed, and the excitation test of all the tanks has been performed to start the beam commissioning from the middle of December 2010.

The last key issue is to develop a charge stripper with a long lifetime, which is still an open problem.

CHARGE STRIPPER PROBLEM FOR URANIUM ACCELERATION

Figure 2 shows the acceleration scheme for uranium beams using two strippers. The first stripper is located behind the RRC, with an energy of 11 MeV/u, and the second one is located behind the fRC, with an energy of 51 MeV/u. Carbon foils are used for both the strippers. The typical thicknesses of the foils for the first and second strippers are 300 μg/cm^2 and 17 mg/cm^2, respectively. The problem associated the first stripper is very serious. Carbon foils commercially available from ACF-Metals [16] are used for the first stripper. Their typical lifetime is about 12 h with 1 eμA. Carbon foils of the same thickness are being developed at RIKEN, the quality of which is getting closer to that of the commercially available ones [17]. There is no problem with the intensities available currently. However, it will be a serious problem in the future because the intensity of uranium beams will be increased by more than 100 times with the completion of the upgrade programs mentioned before, thereby requiring much stronger strippers. Therefore, intense R&D programs focusing on upgrading the first stripper have been initiated from 2008.

Firstly, we started conducting irradiation tests of a large foil on the rotating cylinder developed by Ryuto et al. [18] to expand the irradiation area, expecting to realize long lifetimes. We placed a foil with a diameter of 100 mm on the cylinder which can rotate in beam vacuum. The first sample tested two years ago broke quite as shortly as in about 15 min. We performed some tests to determine why the rotating foil broke so soon. We found that a very slowly (0.05 rpm) rotating foil can survive for more than 38 h with 1.7 eμA. However, we also found that beam intensity behind the stripper changes periodically and, hence, we could not tune the successive accelerator, suggesting that the uniformity of the foil is not sufficiently good. We might need a feedback system to compensate for the fluctuation in the foil thickness if we want to use it in real operations.

Next, we started to develop gas strippers. A gas stripper is free from lifetime related problems, although it has a lower equilibrium charge state than a carbon foil because of the density effect. We did not have data on the equilibrium charge state in N_2 gas, and no empirical formulas are available to predict it correctly. Therefore, we measured that at 11 MeV/u using a gas target system with a differential pumping system, which was formerly used for nuclear experiments [19]. The measured equilibrium charge state in N_2 was 56, which is far below that in a carbon foil, 71, suggesting that the gas stripper cannot be used for uranium because the acceptable charge state for the fRC is larger than 69.

LOW-Z GAS STRIPPER

The merits of a gas stripper are that it is free from lifetime related problems, and its thickness is completely uniform. Such merits motivated us to develop a gas stripper to achieve a higher charge state in gases. The first option is to increase the stripping energy because the equilibrium charge state generally increases as a function of the projectile energy. We measured the equilibrium charge states at 14 and 15 MeV/u using a N_2 gas stripper, described in the previous section; they were 61 and 62, respectively [20]. The extrapolation of the results suggests that the stripping energy should be increased to 22 MeV/u to obtain 69+ as a equilibrium charge state, which is the lowest acceptable charge state for the fRC. To realize this, we need an additional accelerator before the stripper and a decelerator behind the stripper or have to increase the injection radius of the fRC by more than 50 cm. Such extensive remodeling will cost more than \$10 million. The second option is changing the stripping material to a low-Z gas (He and H_2).

Background

The equilibrium charge state is determined by the competition between e-loss and e-capture processes of the ion. The capture cross sections depend strongly on the ion velocity V_p as compared to the target electrons. In particular, the e-capture phenomenon is highly suppressed because of the bad kinematical matching when the ion velocity significantly exceeds that of 1s electrons, V_{1s}, which are the fastest target electrons. Such suppression of e- capture is expected in the case of low-Z targets or high ion velocity, because V_{1s} is approximately expressed by Z/137, resulting in a higher equilibrium charge state. In fact, a substantial increase in the equilibrium charge state is observed in some experimental data on the equilibrium charge state or effective charge at intermediate energies in low-Z regions [21, 22, 23]. Table 2 summarizes the reaction conditions that show charge enhancement of the equilibrium charge state in low-Z region, along with the V_p/V_{1s} parameters from the references and the parameters for the reactions for which the cross section measurements were performed in He. These data show that charge enhancement can be achieved in low-Z regions. The table also lists the parameters for the reactions for which equilibrium charge states were measured in N_2; lower charge states are obtained due to the density effect.

Figure 3 shows e-loss and e-capture cross sections calculated by using the binary encounter model [24] and Schlachter's formula [25] as a function of the charge state for H_2, He, and N_2. The two lines for each case cross at the equilibrium charge state. They clearly show higher charge states in low-Z gases than in N_2 gas. There are no data on the equilibrium charge state of uranium in a low-Z gas in this energy region mainly because of the difficulty in accumulating low-Z gas without a window. For example, our gas stripper system, mentioned in the last section, can accumulate only 0.015 mg/cm^2 of He, which is not sufficient for U ions to reach their equilibrium at 11 MeV/u, while it can accumulate 1.3 mg/cm^2 of N_2. Hence, we measured the cross sections of loss and capture of 1s electron as a function of the charge state of uranium ions to extract the equilibrium charge from their cross point.

Table 2: Reactions for which enhancement of equilibrium charge is observed in low-Z target region. The definition of V_p/V_{1s} is given in the text. The lower part of the table lists the reactions for which equilibrium charge state measurements were carried out in this study and in references of [19, 20].

Reaction	Energy (MeV/u)	V_p/V_{1s}	Ref.
Ar + H_2	1.25	7.1	[21]
U + He	22	14.9	[22]
U + N_2	56	6.8	[23]
U + He	11	10.5	
U + He	14	11.9	
U + He	15	12.3	
U + N_2	11	3.0	
U + N_2	14	3.4	
U + N_2	15	3.5	

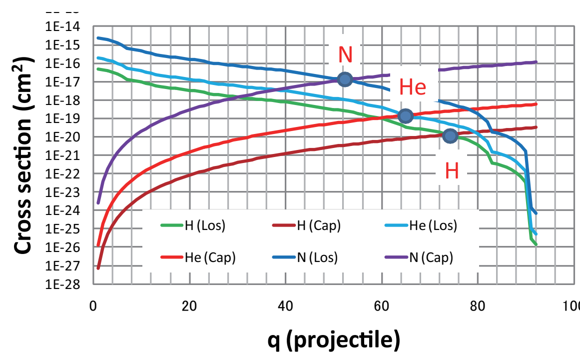

Figure 3: Simple estimation for cross sections of e-loss and e-capture in N_2, He, and H_2.

Experiment

The experiment was conducted at the RIBF using the RILAC and RRC. A schematic of the experimental setup is shown in Fig. 4. Beams of 11 MeV/u $^{238}U^{35+}$, 14 MeV/u $^{238}U^{41+}$, and 15 MeV/u $^{238}U^{41+}$ were extracted from the RRC. The incoming ions passed through a carbon foil located in front of a bending magnet, which was used to select the individual projectile charge state, Q_i. The thickness of the carbon foil was optimized so as to obtain the maximum intensity of the charge state. Each beam was directed through a windowless, differentially pumped He gas cell. After emerging from the gas cell, the beams passed through a second bending magnet into a FC (Faraday Cup) at point F41. The FC measured the intensity of the beam current of the charge state for e loss (Q_i + 1), e capture (Q_i - 1), and no reaction (Q_i). The pressure of the target He gas was monitored by using a Baratron pressure transducer, and the gas flow was regulated by means of an automated control valve and a flow controller. More details of the experimental setup are given in reference [19]. The cross section of e loss, σ_{loss}, and that of e capture, $\sigma_{capture}$, were obtained using the following equation:

$$\sigma_{loss} = \frac{1}{t}\frac{I(Q_i+1)}{\sum I(Q_m)} \quad (1)$$

$$\sigma_{capture} = \frac{1}{t}\frac{I(Q_i-1)}{\sum I(Q_m)} \quad (2)$$

where t is a gas thickness and $I(Q)$ is a beam intensity of ion charge Q at F41.

The intensity at F41 was normalized by the intensity measured by an FC located at the upstream of the gas cell to cancel the fluctuation in the beam intensity from the RRC. During the measurement, the cell pressure was 0.56 kPa. At this pressure, the thickness of the gas stripper was measured to be 13.27 ± 1.81 μg/cm^2, using α-rays from Am.

Figure 5 shows the measured cross section as a function of the the charge number of uranium ions at 11, 14, and 15 MeV/u. The absolute values of the cross sections shown in Fig. 5 have a deviation of 13.6%, although the relative values are accurate because the cross sections were extracted assuming the thickness to be the mean of the measurement values described above. The data show that the cross section of the e capture largely depends on the energy, while the e-loss cross section does not depend so much on the energy. Because the contribution of multiple electron transfer in He is very small [26], the cross point of the two lines gives a good approximation of the equilibrium charge state. The cross points are extracted to be 66, 73, and 75 at 11, 14, and 15 MeV/u, respectively. Table 3 lists the equilibrium charge state in He, N_2, and C. The equilibrium charge state in He is obviously larger than that in N_2 by more than 10 and is close to that in C.

Table 3: Equilibrium Charge State in He, N_2, and C at 11, 14 and 15 MeV/u. The data for N_2 and C were taken from reference [19, 20].

Material	Q_e@11 (MeV/u)	Q_e@14 (MeV/u)	Q_e@15 (MeV/u)
He	66	73	75
N_2	56	61	62
C	72	76	77

Gas Stripper with Plasma Windows

The measurement results show that a low-Z gas stripper can be realized for the higher charge state of uranium. However, the difficulty in the accumulation of low-Z gases still remains. As mentioned in the previous subsection, the existing gas stripper can accumulate only 0.015 mg/cm^2 (0.7 kPa) of He, while it can accumulate 1.3 mg/cm^2 of N_2.

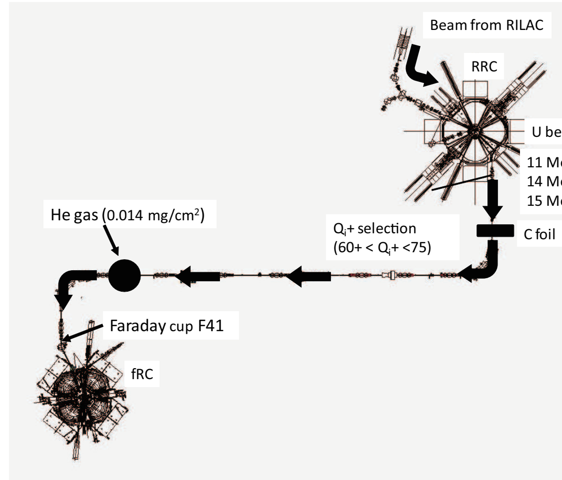

Figure 4: Schematic of experimental setup used for measurement of cross sections of e loss and e capture in RIBF beamlines.

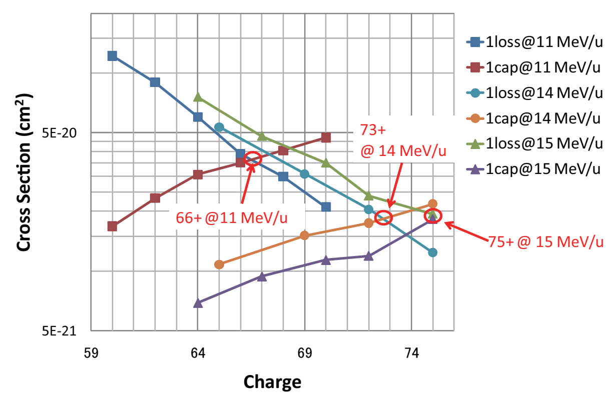

Figure 5: Measured cross section of e loss and e capture as a function of charge state of uranium ions at 11, 14, and 15 MeV/u in He gas. The cross sections were extracted assuming the thickness of the gas cell to be 13.27 μg/cm^2.

A simple estimation shows that about 1 mg/cm^2 of He or H_2 is necessary to achieve a higher charge state, suggesting the necessity of a new device to solve this problem. The plasma window invented by Hershcovitch in 1995 can be used for this [27]. The plasma window is a wall-stabilized plasma arc used as an interface between accelerator vacuum and pressurized targets. There is no solid material introduced into the beam and, therefore, the plasma window can transmit a charged particle beam with low loss. It mainly consists of 3 cathodes, an anode, and some cooling plates to cool the plasma arc, as shown in Fig. 6. The arc in the plasma window can generate a pressure difference between it's ends with a factor of 600. Hence, it can maintain the pressure inside of the gas cell while maintaining vacuum outside. Figure 7 shows a schematic of the low-Z gas stripper using two plasma windows, suggested by P. Thieberger from BNL at the workshop about charge

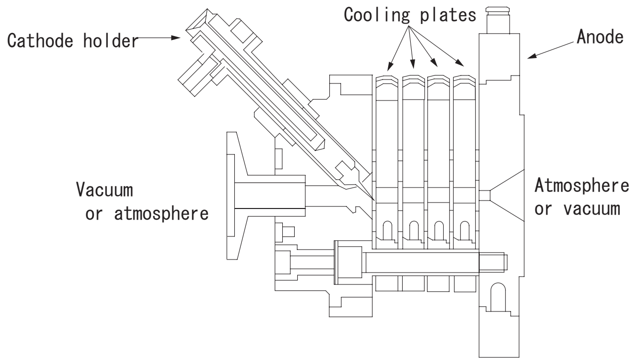

Figure 6: Schematic of plasma window.

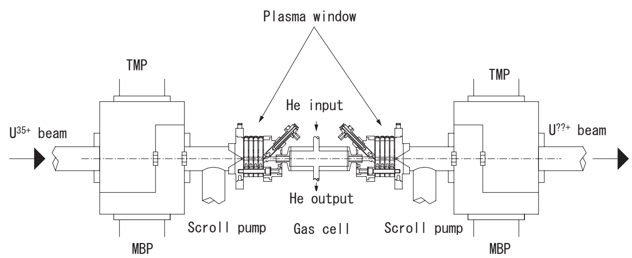

Figure 7: Conceptual sketch of low-Z gas stripper with two plasma windows.

stripper for FRIB in 2009 [28]. The low-Z gas is accumulated in the cell, which is sandwiched between the two plasma windows.

We are starting R&D programs to test of the plasma window in a test stand with help from Hershcovitch. As the first step, we will use Ar gas and window of diameter 2 mm in the test. We expect to obtain the first ignition by the end of March 2011. From 2011, we will study the performance of the plasma window with He or H_2 instead of Ar and with an extended diameter of 6 mm. From 2012, we will start fabricating the gas stripper with two plasma windows, as shown in Fig. 7, for off-line tests.

SUMMARY

The operation of the RIBF from 2007 to 2010 was very successful after the first beam was extracted. The new 28-GHz superconducting ECR ion source and the new injector are ready to be put into operation to increase the intensity of uranium beams. The stripper problem for uranium beams remains unsolved, despite carrying out extensive R&D work using rotating cylinder foils and a N_2 gas stripper. Recently, we found that a low-Z gas stripper would be a promising candidate for uranium beams. Measurement results showed that the equilibrium charge state in He is higher than that in N_2 by more than 10. We believe that the difficulty in the accumulation of low-Z gases can be overcome by using a plasma window.

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