Charge-state distribution measurements of ^{238}U and ^{136}Xe at 11 MeV/nucleon using gas charge stripper

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The charge-state distributions and equilibrium charge states of uranium (^{238}U) and xenon (^{136}Xe) ions at 11 MeV/nucleon were determined using a gas charge stripper. A differential pumping system facilitated the increase of the nitrogen gas thickness up to 1.3 mg/cm^2 , which is sufficient for the most probable charge state to attain equilibrium. The charge states of ^{238}U attain equilibrium at 56.0, 56.6, and 55.7 in N_2 , Ar, and CO_2 media with thicknesses of 125, 79, and $126 \mu\text{g/cm}^2$, respectively, while those of ^{136}Xe attain equilibrium at 40.5, 40.1, and 40.3 in N_2 , Ar, and CO_2 media with thicknesses of 163, 95, and $139 \mu\text{g/cm}^2$, respectively. The equilibrium charge states of ^{136}Xe are acceptable for acceleration by the subsequent cyclotron. The measured data of ^{238}U were used to devise an empirical formula for the prediction of the equilibrium charge state in gaseous media over the energy region of 0.01–60 MeV/nucleon. The equilibrium charge state of ^{136}Xe as predicted by the devised formula is in good agreement with the data.

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I. INTRODUCTION

One of the common goals of the so-called “next-generation” facilities such as RIKEN RI-beam factory (RIBF) [1], FAIR at GSI [2], and FRIB at MSU [3] is to provide high-intensity uranium beams with energies higher than 200 MeV/nucleon. Charge strippers are usually used for acceleration of heavy ions such as uranium at the output end of driver accelerators where the beam energy becomes $10 \sim 20 \text{ MeV/nucleon}$. The realization of stable and efficient acceleration strongly depends on the quality of charge strippers, and hence, any defects in the charge strippers in terms of lifetimes, charge states, material, and energy spread are considered to be critical issues at these facilities. In other words, charge strippers play an essential role in a heavy-ion accelerator complex.

Figure 1 shows a schematic diagram of acceleration at RIBF [4]. Heavy ions extracted from the RIKEN 18-GHz electron cyclotron resonance (ECR) ion source [5] are successively accelerated up to the final energy of 345 MeV/nucleon using the RIKEN heavy-ion linac (RILAC) [6], the RIKEN ring cyclotron (RRC) [7], a fixed-frequency ring cyclotron (fRC) [8], an intermediate-stage ring cyclotron (IRC) [9], and a superconducting ring cyclotron (SRC) [10].

Two charge stripper sections are placed downstream of the first two cyclotrons, the RRC and the fRC. The initial charge states of uranium (^{238}U) and xenon (^{136}Xe) ions extracted from the ECR ion source are $35+$ and $20+$, respectively. The ^{238}U and ^{136}Xe beams are accelerated up to 11 MeV/nucleon using the RILAC and the RRC and are

then transported to the first charge stripper located at the output end of the RRC. Since the lowest acceptable charge states of ^{238}U and ^{136}Xe for fRC acceleration are $71+$ and $41+$, respectively, carbon foils with a thickness of $300 \mu\text{g/cm}^2$ are used as the first charge stripper for enhancing the charge states of ^{238}U and ^{136}Xe up to $71+$ and $47+$, respectively. The second charge stripper is used to obtain U^{86+} and Xe^{52+} at the energy of 51 MeV/nucleon. The carbon foil thicknesses of the second charge stripper are 17 mg/cm^2 for ^{238}U and 20 mg/cm^2 for ^{136}Xe .

The charge states of heavy ions in solid materials have been intensively studied, and a number of data for uranium over the energy range of 0.01–1000 MeV/nucleon are available in Refs. [4,11–17]. In addition, the empirical formulas for predicting equilibrium charge states in solid materials have been improved. The predictions of the charge states of uranium using the formulas proposed by Baron [18], Leon [15], and Schiwietz [19] are accurate within the range of 72 ± 3 at 11 MeV/nucleon. The

FIG. 1. Acceleration scheme at RIBF. The ^{238}U or ^{136}Xe beams are accelerated by means of a linear accelerator and four cyclotrons. A pair of charge stripper sections is located downstream of the first and second cyclotrons, the RRC and the fRC, respectively.

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FIG. 2. The data of equilibrium charge state for uranium ions in (a) solid and (b) gaseous media. (a) Open circles represent data for solid materials [4,11–17]. Dashed, dotted, and dash-dotted curves represent the charge states for solid materials as predicted by the empirical formulas proposed by Leon [15], Baron [18], and Schiwietz [19], respectively. In the energy region of 40–1000 MeV/nucleon, the simulation results of GLOBAL [35] for carbon are represented by open triangles. The shaded area indicates the deviation of predicted values. (b) Solid circles represent data for gases [11,12,16,17]. Orange, green, blue, cyan, and magenta curves represent the charge states for gases as predicted by the empirical formulas proposed by Betz [28], Strehl [31], Sayer [30], Betz [29], and Schiwietz [19], respectively. The simulation results of GLOBAL for nitrogen are represented by solid triangles. The shaded area indicates the deviation of predicted values.

charge states predicted by these formulas are shown in Fig. 2(a) along with the data of uranium.

It should be noted that there are two serious problems with the first charge stripper made from carbon foils. One is its finite lifetime and the other is the energy spread owing to the nonuniformity of the foil thickness [20]. The carbon charge stripper has a lifetime of 10–12 h for ^{238}U beam irradiation with a beam intensity of 14 pA (0.5 W); this intensity is only one-hundredth of the desired beam intensity. An experiment involving ^{136}Xe beam irradiation for 6 h at an intensity of 1 pA (18 W) showed that the lifetime of carbon foils subjected to ^{136}Xe beam irradiation is longer than that of carbon foils subjected to ^{238}U beam irradiation. However, its lifetime is expected to drastically decrease when the irradiated beam intensity is increased by a hundred times using a newly developed ion source [21] and a new injector [22,23] in the near future.

It is believed that a charge stripper based on gaseous materials will function better as it would have a uniform thickness and will be able to withstand a high heat load. However, a gas charge stripper has a disadvantage: The charge state of ^{238}U becomes lower than $71+$ owing to the *density effect* [16,24–27]. In the case of gas charge strippers, excited projectiles have sufficient time between collisions to return to their ground states before subsequent collisions. Since the ionization cross section of projectiles in excited states is larger than that in ground states, the charge states obtained with a gas charge stripper are lower than those obtained with carbon foil strippers.

Moreover, it is difficult to predict the charge states obtained with a gas charge stripper, since the data of charge states in gaseous media are insufficient compared to those

in solid materials. The available data for a uranium beam in gases, plotted against the projectile energies in Fig. 2(b) [11,12,16,17], are mostly for energies below 0.1 MeV/nucleon and are, hence, of little importance at the desired energy of 11 MeV/nucleon. The empirical formulas for predicting charge states in gaseous media at the energy ~ 10 MeV/nucleon are proposed by Betz [28,29], Sayer [30], Strehl [31], and Schiwietz [19]; these predicted charge states are plotted in Fig. 2(b) along with the data of uranium. However, the equilibrium charge states for uranium at 11 MeV/nucleon as predicted by these formulas are as widely varying as 53, 66, 63, 59, and 64. All of the predicted values are obtained from extrapolation since these formulas were based on the data at energies less than 10 MeV/nucleon and included ions lighter than uranium.

In this study, we developed a windowless gas charge stripper whose thickness is sufficient for attaining equilibrium charge states and measured the charge-state distributions of ^{238}U and ^{136}Xe at 11 MeV/nucleon up to the equilibrium state. A new empirical formula for improving the accuracy of the prediction in the energy region of 0.01–60 MeV/nucleon has been obtained by a fit to the experimental data. We applied this new formula to predict the charge states of xenon and confirmed that the predicted values are in good agreement with the ^{136}Xe data.

II. GAS CHARGE STRIPPER SYSTEM

A. System overview

We have modified a windowless gas target [32] into a gas charge stripper system, as described below. Figure 3

FIG. 3. Schematic diagram of the gas charge stripper with its differential pumping system [32]. Gases are injected in the target cell (stage 1) located at the center. The length of the target cell is 14 cm. Other stages are also shown along with the pumping speeds of their respective attached pumps. The beam passes through four apertures (6 mm in diameter) to enter the target cell. The exits of the target cell and stage 2 are also 6-mm-diameter apertures. The exits of stage 3 and 4 are 8 and 10 mm diameter apertures, respectively.

shows the schematic diagram of this system along with its differential pumping system. The region in the target cell is defined as stage 1. The physical length of the target cell is 14 cm. The region outside the target cell is defined as stage 2. Similarly, the regions outside stages 2–4 are defined as stages 3–5, respectively. Stage 5 is divided into stages 5-1 and 5-2. The pressure at stages 1–5 is indicated by P_1 – P_5 , respectively. Since the gas charge stripper is operated along a beam line, the pressures P_2 – P_5 should fall as rapidly as possible while maintaining the pressure P_1 sufficiently high. Stages 6-1 and 6-2, which correspond to the beam line at the upstream and downstream of the stages 5-1 and 5-2, respectively, were newly added in order to maintain

the pressures at the beam line lower than the admissible value.

B. Offline pressure test

We performed an offline test to determine the achievable pressure in the target cell with nitrogen gas injection. The setup for this test is shown in Fig. 4. Figure 5 shows the results for pressures P_2 – P_5 and the pressures at the beam line plotted against P_1 . These results indicate that P_1 can be increased up to 7.7 kPa (1.3 mg/cm^2) while maintaining the beam line pressures lower than $4 \times 10^{-3} \text{ Pa}$, which is the allowable vacuum limit for beam lines.

FIG. 4. Overview of the gas charge stripper system for the offline test. The gas charge stripper chamber and two mechanical booster pumps (MBP1 and MBP2) are shown in the photograph.

FIG. 5. The pressure at each stage (P_2 – P_5) is plotted as a function of P_1 . Stage 5 has two separated areas, stage 5-1 and stage 5-2, which correspond to the areas upstream and downstream of stage 4, respectively. The pressures at stages 5-1 and 5-2 are denoted by P_{5-1} (blue) and P_{5-2} (green), respectively. The solid line indicates the limit for an interlock (4×10^{-3} Pa). The pressures at stages 6-1 and 6-2 are denoted by “beamline1” and “beamline2” and are maintained lower than the interlock limit if P_1 is lower than 7.7 kPa.

The most probable charge state attains equilibrium at a thickness of $500 \mu\text{g}/\text{cm}^2$ in the case of carbon foils [4]. With the assumption that the nitrogen gas thickness necessary for equilibrium is the same as the carbon foil thickness, we consider that a $1.3\text{-mg}/\text{cm}^2$ thick nitrogen gas stripper is sufficient for attaining equilibrium charge states.

C. Effective gas thickness measurement

In order to determine the effective thickness of the gas cell, the relationship between P_1 and the energy loss of low-energy alpha particles in the gas charge stripper was determined offline, using a ^{241}Am alpha source and a silicon detector (Canberra RF30*30–500EB) installed at the upstream and downstream of stage 4, respectively. Alpha particles with an energy of 5.486 MeV were emitted from ^{241}Am and detected with the silicon detector. Energy spectra of the alpha particles were obtained by means of a multichannel analyzer (Hoshin HE1442), and the peaks were fitted using Gaussian functions. The spectrum values in the case without gas injection are indicated by solid circles in Fig. 6(a). The peaks of the alpha particles passing through the gas medium shift to lower channels because the energy loss in the silicon detector is reduced owing to the energy loss in the gas. The spectra were obtained in the cases of N_2 , Ar, and CO_2 gas injections at different P_1 values. The typical spectra obtained with N_2 gas injection are shown in Fig. 6(a) as well. The energy loss was calculated from the difference between the central value of the peak in the case of no gas injection and that in the case of gas injection. The thickness of the gas medium was estimated by energy loss calculations using ATIMA [33]

FIG. 6. (a) Energy spectra of alpha particles after passing through the gas cell filled with N_2 gas at different pressures P_1 . The spectrum in the case of no gas injection is represented by solid circles. Asterisks, open circles, open triangles, open squares, and open diamonds represent the spectra with P_1 at 0.25, 0.52, 0.92, 2.02, and 4.58 kPa, respectively. (b) Gas thickness estimated from the energy loss measurement is plotted as a function of P_1 . The data for N_2 , Ar, and CO_2 gas injections are represented by solid circles, solid triangles, and solid squares, respectively. Fitting functions are represented by solid curves of cyan, red, and green for N_2 , Ar, and CO_2 gas injections, respectively.

installed in LISE++ [34]. The relationship between the gas medium thickness and the gas pressure P_1 is shown in Fig. 6(b). The data were fitted using linear functions. The thickness of the gas charge stripper was calculated from these functions.

III. EXPERIMENTS AND RESULTS

The experiments were performed at RIKEN Accelerator Research Facility. Figures 7 and 8 show the overview of the beam line and its detailed diagram, respectively. Uranium and xenon beams from the RILAC were accelerated up to 11 MeV/nucleon by the RRC. The beams were

FIG. 7. The beam line from the RRC to the fRC. The gas charge stripper is located upstream of the fRC.

transported to the gas charge stripper located upstream of the fRC. The incident beam intensities were measured using a Faraday cup (FC-D16) placed upstream of the gas charge stripper to be 300–500 enA (9–14 pA) and 500–600 enA (25–30 pA) for ^{238}U and ^{136}Xe , respectively. The spot size was about 6 mm in diameter, which was comparable to the aperture at the entrance of the gas charge stripper. The charge state was analyzed by dipole magnets DAD4 and DMD4. The magnetic field of these magnets was corrected by considering the energy loss in the gas. The intensities of the stripped beams were measured using a Faraday cup (FC-F41) at the downstream of DMD4.

FIG. 8. Schematic view of the gas charge stripper. The beam intensity upstream of the gas charge stripper was measured using a Faraday cup (FC-D16). Stripped beams were analyzed using a pair of dipole magnets DAD4 and DMD4. The beam intensity downstream of DAD4 and DMD4 was measured using a Faraday cup (FC-F41).

The fraction $F(q_i)$ of charge state q_i is defined as

$$F(q_i) = \frac{1}{N} \frac{I_{F41}/q_i}{I_{D16}/q_{ini}}, \quad (1)$$

where N , I_{F41} , I_{D16} , and q_{ini} denote a normalization constant, beam intensities measured at FC-F41 and FC-D16, and the charge state extracted from the ion source, respectively. In order to determine N , an unnormalized fraction $f(q_i) = (I_{F41}/q_i)/(I_{D16}/q_{ini})$ was first calculated. The data set of $f(q_i)$ is fitted by a Gaussian function. However, since the beam intensity measured using each Faraday cup includes its own offset value, the sum $\sum f(q_i)$ over all i does not equal unity. Therefore, the area of the fitted Gaussian function is calculated and introduced as a normalization constant N in order to make the sum of $F(q_i)$ unity. The set of $F(q_i)$ is then fitted by a Gaussian function again. The most probable charge states are defined as the central values obtained by the fitting procedure.

FIG. 9. Charge-state distributions of ^{238}U . The data of fractions calculated for (a) N_2 , (b) Ar , and (c) CO_2 are plotted. (a) The data for the N_2 gas medium with thicknesses of 48, 84, 150, 334, and $752 \mu\text{g}/\text{cm}^2$ are represented by asterisks, open triangles, open circles, open squares, and open diamonds, respectively. (b) The data for the Ar gas medium with thicknesses of 39, 106, 205, and $474 \mu\text{g}/\text{cm}^2$ are represented by open triangles, open circles, open squares, and open diamonds, respectively. (c) The data for the CO_2 gas medium with thicknesses of 32, 61, 122, 225, and $516 \mu\text{g}/\text{cm}^2$ are represented by asterisks, open triangles, open circles, open squares, and open diamonds, respectively.

TABLE I. The fitting parameters of ^{238}U charge-state distributions. The errors written here are arisen from fitting procedure.

Gas	Pressure (kPa)	Thickness ($\mu\text{g}/\text{cm}^2$)	Peak height	Center	σ
N_2	0.29	48 ± 3	0.137 ± 0.003	51.52 ± 0.07	2.92 ± 0.07
N_2	0.50	84 ± 3	0.139 ± 0.002	54.23 ± 0.05	2.87 ± 0.05
N_2	0.90	150 ± 3	0.158 ± 0.003	55.76 ± 0.05	2.53 ± 0.05
N_2	2.00	334 ± 4	0.159 ± 0.003	55.99 ± 0.06	2.51 ± 0.06
N_2	4.50	752 ± 6	0.161 ± 0.002	55.95 ± 0.04	2.47 ± 0.04
Ar	0.16	39 ± 5	0.0982 ± 0.0008	53.67 ± 0.04	4.08 ± 0.04
Ar	0.44	106 ± 5	0.128 ± 0.001	56.44 ± 0.04	3.10 ± 0.04
Ar	0.85	205 ± 5	0.129 ± 0.001	56.62 ± 0.03	3.08 ± 0.03
Ar	1.96	474 ± 7	0.126 ± 0.002	56.62 ± 0.05	3.17 ± 0.05
CO_2	0.12	32 ± 5	0.123 ± 0.002	48.79 ± 0.05	3.25 ± 0.06
CO_2	0.23	61 ± 5	0.126 ± 0.001	52.80 ± 0.04	3.16 ± 0.04
CO_2	0.46	122 ± 5	0.139 ± 0.001	55.02 ± 0.03	2.78 ± 0.03
CO_2	0.85	225 ± 5	0.140 ± 0.001	55.87 ± 0.02	2.86 ± 0.02
CO_2	1.95	516 ± 6	0.145 ± 0.002	55.68 ± 0.05	2.74 ± 0.05

A. ^{238}U charge-state distribution

The charge-state distributions of ^{238}U measured with N_2 , Ar, and CO_2 gases at the different pressures P_1 are shown in Fig. 9. All the fitted parameters are listed in Table I. It was found that the most probable charge states in the case of N_2 , Ar, and CO_2 attain equilibrium at 56.0, 56.6, and 55.7, respectively.

Figure 10 shows the most probable charge states plotted as a function of the gas thickness. The data were fitted by a function $f(t) = a - b \exp(-ct)$, where a , b , and c are fitting parameters. The equilibrium value of the most

probable charge state is denoted by a . Parameter b is related to the thickness required for equilibrium. Parameter c indicates the slope of the curve before equilibrium. The obtained parameters are listed in Table II. The thicknesses necessary for equilibrium, as calculated by $f(t)$, are 125, 79, and 126 $\mu\text{g}/\text{cm}^2$ for N_2 , Ar, and CO_2 , respectively. Here, the thickness required for equilibrium is defined as the thickness required for attaining 99% of the equilibrium charge state. The above-mentioned calculated values are considerably lesser than the carbon foil thickness ($\sim 500 \mu\text{g}/\text{cm}^2$).

B. ^{136}Xe charge-state distribution

The measured charge-state distributions of ^{136}Xe with N_2 , Ar, and CO_2 are shown in Fig. 11. The fitted parameters of ^{136}Xe are listed in Table III. It was found that the most probable charge states in the case of N_2 , Ar, and CO_2 attain equilibrium at 40.5, 40.1, and 40.3, respectively.

The most probable charge states are plotted as a function of the gas thickness in Fig. 12. The obtained parameters are listed in Table IV. The thicknesses necessary for equilibrium are 163, 95, and 139 $\mu\text{g}/\text{cm}^2$ for N_2 , Ar, and CO_2 , respectively.

FIG. 10. The most probable charge states of ^{238}U are plotted as a function of gas thickness. The data for N_2 , Ar, and CO_2 are represented by solid circles, solid triangles, and solid squares, respectively. Fitting functions are represented by solid curves. The error in thickness is because of the uncertainty of the fitting parameter obtained in Sec. II C and the fluctuation of pressure P_1 during the measurement.

TABLE II. The fitting parameters of $f(t)$ for ^{238}U are shown together with the thickness required for equilibrium. The equilibrium value of the most probable charge state is denoted by a . Parameter b is related to the thickness required for equilibrium. Parameter c indicates the slope of the curve before equilibrium.

Gas	a	b	c	Equilibrium thickness ($\mu\text{g}/\text{cm}^2$)
N_2	55.98	16.73	0.027	124.92
Ar	56.62	14.26	0.041	79.28
CO_2	55.85	16.36	0.027	125.83

FIG. 11. Charge-state distributions of ^{136}Xe . The data of fractions calculated for (a) N_2 , (b) Ar , and (c) CO_2 are plotted. (a) The data for the N_2 gas medium with thicknesses of 47, 85, 150, 336, and $752 \mu\text{g}/\text{cm}^2$ are represented by asterisks, open triangles, open circles, open squares, and open diamonds, respectively. (b) The data for the Ar gas medium with thicknesses of 27, 94, 196, and $462 \mu\text{g}/\text{cm}^2$ are represented by open triangles, open circles, open squares, and open diamonds, respectively. (c) The data for the CO_2 gas medium with thicknesses of 5, 11, 50, 111, 217, and $506 \mu\text{g}/\text{cm}^2$ are represented by crosses, asterisks, open triangles, open circles, open squares, and open diamonds, respectively. Solid lines are curves fitted using Gaussian functions.

FIG. 12. Most probable charge states of ^{136}Xe are plotted as a function of gas thickness. The data for N_2 , Ar , and CO_2 are represented by solid circles, solid triangles, and solid squares, respectively. Fitting functions are represented by solid curves. The error in thickness is because of the uncertainty of fitting parameter obtained in Sec. II C and the fluctuation of the pressure P_1 during the measurement.

and CO_2 , respectively. The equilibrium charge states of ^{136}Xe are acceptable for acceleration by the fRC.

IV. DISCUSSION

The measured data are plotted in Fig. 13 along with other data [11,12,16,17] and empirical formulas for gases. The data are fitted by a function of the following form [29]:

$$q_{\text{eq}} = Z \left[1 - C \exp \left\{ -A \left(\frac{v}{v_0} \right)^\delta Z^{-\gamma} \right\} \right], \quad (2)$$

TABLE III. The fitting parameters of ^{136}Xe charge-state distributions.

Gas	Pressure (kPa)	Thickness ($\mu\text{g}/\text{cm}^2$)	Peak height	Center	σ
N_2	0.28	47 ± 3	0.189 ± 0.006	35.74 ± 0.08	2.11 ± 0.08
N_2	0.28	47 ± 3	0.178 ± 0.003	36.10 ± 0.05	2.24 ± 0.05
N_2	0.51	85 ± 3	0.184 ± 0.003	38.48 ± 0.04	2.16 ± 0.04
N_2	0.90	150 ± 3	0.199 ± 0.003	40.07 ± 0.03	2.01 ± 0.03
N_2	2.01	336 ± 4	0.207 ± 0.003	40.59 ± 0.03	1.93 ± 0.03
N_2	4.50	752 ± 6	0.209 ± 0.003	40.51 ± 0.03	1.91 ± 0.03
Ar	0.11	27 ± 5	0.127 ± 0.002	34.62 ± 0.05	3.13 ± 0.05
Ar	0.39	94 ± 5	0.207 ± 0.003	39.67 ± 0.03	1.93 ± 0.04
Ar	0.81	196 ± 5	0.212 ± 0.003	40.05 ± 0.03	1.88 ± 0.03
Ar	1.91	462 ± 6	0.217 ± 0.004	40.10 ± 0.04	1.84 ± 0.04
CO_2	0.02	5 ± 3	0.179 ± 0.011	23.37 ± 0.16	2.23 ± 0.17
CO_2	0.04	11 ± 3	0.173 ± 0.004	28.15 ± 0.08	2.24 ± 0.10
CO_2	0.19	50 ± 5	0.184 ± 0.008	35.92 ± 0.11	2.16 ± 0.12
CO_2	0.42	111 ± 5	0.194 ± 0.005	39.06 ± 0.06	2.06 ± 0.07
CO_2	0.82	217 ± 5	0.207 ± 0.004	40.26 ± 0.05	1.93 ± 0.05
CO_2	1.91	506 ± 6	0.207 ± 0.002	40.30 ± 0.03	1.92 ± 0.03

TABLE IV. The fitting parameters of $f(t)$ and equilibrium thickness for ^{136}Xe . The notations are the same as those for Table II.

Gas	a	b	c	Equilibrium thickness ($\mu\text{g}/\text{cm}^2$)
N_2	40.56	12.14	0.021	162.75
Ar	40.08	15.09	0.038	94.85
CO_2	40.26	17.04	0.027	139.37

where q_{eq} , Z , v , and v_0 denote the equilibrium charge state, projectile atomic number, projectile velocity, and Bohr velocity of 2.188×10^8 cm/sec, respectively. C , A , δ , and γ are the fitting parameters of the function. The values of these fitting parameters are listed in Table V for the empirical formulas proposed in this work and other studies. The new empirical function is plotted in Fig. 13. The charge states of gases predicted by the various empirical formulas and other data are also plotted in this figure.

In order to test whether this formula can be applied to predict the equilibrium charge state of other ions, the measured equilibrium charge states of ^{136}Xe ion are plotted using this formula, as shown in Fig. 14. The formula seems to be applicable for xenon as well in the energy region of 0.004–11 MeV/nucleon.

V. SUMMARY AND CONCLUSIONS

We have obtained the data of ^{238}U and ^{136}Xe charge-state distribution at 11 MeV/nucleon using a gas charge

TABLE V. Values of the fitting parameters C , A , δ , and γ for the fitting function q_{eq} in this work and the empirical formulas proposed in Refs. [28–31].

C	A	δ	γ	Reference
1.01	0.042	1	0.70	Betz [28]
1.08	0.585	0.996	0.506	Sayer [30]
1	0.555	1.175	0.607	Betz [29]
1.045	1	1	0.65	Strehl [31]
1.01	1	0.990	0.676	This work

stripper. The most probable charge states of ^{238}U in N_2 , Ar, and CO_2 at equilibrium are 56.0, 56.6, and 55.7, respectively, while those of ^{136}Xe in the same conditions are 40.5, 40.1, and 40.3. The charge states of ^{136}Xe are acceptable for fRC acceleration. For ^{238}U , the N_2 , Ar, and CO_2 gas thicknesses required for the most probable charge states to attain equilibrium are 125, 79, and 126 $\mu\text{g}/\text{cm}^2$, respectively; for ^{136}Xe , the corresponding thicknesses are 163, 95, and 139 $\mu\text{g}/\text{cm}^2$, respectively. The Ar gas thickness required for the most probable charge states to attain equilibrium is less than the N_2 and CO_2 gas thicknesses required for the same. In addition, differences are observed between the equilibrium thicknesses for ^{238}U and ^{136}Xe ; the equilibrium thicknesses for ^{136}Xe are 1.1–1.3 times greater than those for ^{238}U . It has been found that the equilibrium charge states for uranium ions over the energy region of 0.01–60 MeV/nucleon can be predicted well by a function $q_{\text{eq}} = Z[1 - 1.01 \exp\{-(v/v_0)^{0.990} Z^{-0.676}\}]$. The value of the charge state predicted from this formula is also

FIG. 13. The data obtained at RIKEN are plotted by solid squares along with other available data for gases [11,12,16,17] shown in Fig. 2. The new fitting function $q_{\text{eq}} = Z[1 - 1.01 \exp\{-(v/v_0)^{0.990} Z^{-0.676}\}]$ is also indicated by a solid curve.

FIG. 14. The equilibrium charge states for xenon in gaseous media as predicted by the new fitting function is indicated by a solid curve. The data obtained from Refs. [12,36] are indicated by solid circles. The data obtained in this work is indicated by solid squares.

in good agreement with the measured equilibrium charge state of ^{136}Xe .

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