Estimation of Charge Exchange Cross Section for Multiply Charged Ions Accelerated in the JAERI AVF Cyclotron

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Abstract

An estimation of charge exchange cross section was experimented with the JAERI AVF cyclotron. The beam loss of accelerating ions was made to occur intentionally by gas feeding into the vacuum chamber of the cyclotron. The charge exchange cross sections for various heavy ions were calculated based on the attenuation of beam intensity on the main probe. These cross sections largely decrease with increase the energy of the accelerating ions. Furthermore, we also tried to get a preliminary empirical formula.

1 Introduction

The charge exchange reactions which occur with high probabilities in ion-atom collision have been studied [1]-[3] from a standpoint of theoretical and experimental situations since the 1960s. A charge exchange cross section (CECS) for heavy ions is one of the important data to design the vacuum requirement for accelerator as an AVF cyclotron, it may bring a serious beam reduction in the initial acceleration process especially. However, reliable experimental data and comprehensive empirical formulae for many kinds of ions almost have been not reported so far.

In general, it has been well known that the CECS strongly depends on energy and charge state of the ion beam. Therefore, the AVF cyclotron is very convenient machine to investigate the energy dependence on the CECS because the energy of the ion increases gradually with increase of a radius of the cyclotron. In consideration of this advantage, we experimented to get the CECS which is estimated from an attenuation of beam intensity by aggressive gas feeding into the vacuum chamber of the JAERI AVF cyclotron.

2 Method of Estimation for Charge Exchange Cross Section

General shape of ion beam intensity observed on a main probe, in case of the increase of feeding gas quantity into the vacuum chamber of the cyclotron, will be varied as shown in Fig. 1. The vertical and horizontal axes indicate the beam intensity and the number of turns of ion beam.

First, four values of beam intensity, when the position of the ion is n-th turn and where their pressures are P_1, P_2, P_3 and P_4, are put as I_{P1n}, I_{P2n}, I_{P3n} and I_{P4n}, respectively. The attenuation of the beam intensity along the radius of the cyclotron is thought that it can be expressed by the product of two functions. One of two, $f_a(n)$, is the effect related to original acceleration process, independents of pressure in the cyclotron. The other, $f_c(n)$, shows the attenuation term induced by the charge exchange reaction.

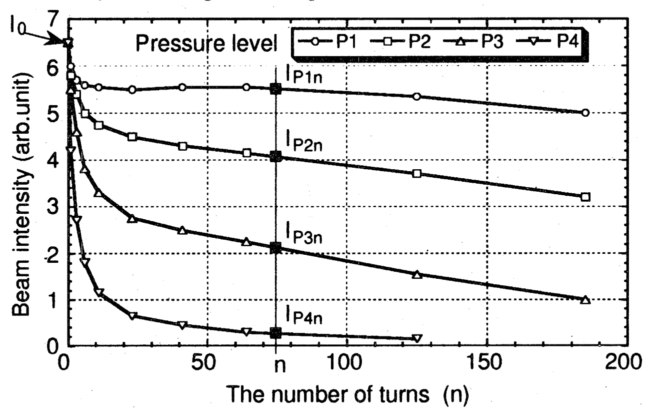

Fig. 1 A calculation model for attenuated beam intensities by gas feeding.

We assume that I_{P1_n} is given as

$$I_{P1n} = I_0 \bullet f_a(n) \bullet f_{1c}(n). \tag{1}$$

In addition, $f_{1c}(n)$ for I_{P1n} is written by next formula.

$$f_{1c}(n) = e^{-k\bullet P_1\bullet \sigma_1 \bullet X_1} \bullet e^{-k\bullet P_1\bullet \sigma_2 \bullet X_2} \bullet \text{------} \bullet e^{-k\bullet P_1\bullet \sigma_n \bullet X_n}$$

$$= e^{-k\bullet P_1 \bullet \left\{ \sum_{i=1}^{n} (\sigma_i \bullet X_i) \right\}} \tag{2}$$

Where k is a constant, equal to $[6.023\times10^{23}/(22.4\times10^{3})/(1\mathrm{x}10^{5})\times273/(273+T)]$. T is temperature in the vacuum chamber. The values of P_1, σ_i and X_i correspond to the pressure in the vacuum chamber (Pa), the cross section of charge exchange reaction (cm^2) and the traveling distance of ion (cm), respectively. Then, the ratio of I_{P1n} and I_{P2n} is introduced because of the elimination of the terms $f_a(n)$ and I_0.

$$I_{P1n}/I_{P2n} = e^{-k\bullet(P_1-P_2)\bullet \left\{ \sum_{i=1}^{n} (\sigma_i \bullet X_i) \right\}} \tag{3}$$

Finally, the value of σ_n which should be obtained is derived from a following formula.

$$\sigma_n = \frac{1}{X_n} \bullet \left[\frac{1}{-k\bullet(P_1-P_2)} \bullet \ln\left(I_{P1n}/I_{P2n} \right) - \left\{ \sum_{i=1}^{n-1} (\sigma_i \bullet X_i) \right\} \right] \tag{4}$$

The value of σ_n can be calculated in turn, if the ratio of two intensities of I_{P1n} and I_{P2n}, the summation of the product of σ_i and X_i are given. In case of other pressure levels, another σ_n can be also calculated in combination with their beam intensities, for instance, I_{P1n} and I_{P3n} or I_{P1n} and I_{P4n}.

On the other hand, the average orbit radius of accelerating ion in the cyclotron, r_n, is expressed generally based upon the motion of the ion in magnetic field.

$$r_n = \frac{\sqrt{E_n^{\,2} + 2m_0 E_n}}{0.2998 \bullet Q \bullet B_0} \bullet \sqrt{1-\beta^2} \qquad (5)$$

Where, m_0 is the rest mass of ion in unit of MeV, E_n kinetic energy (MeV), Q charge state, B_0 base magnetic field (kG) and β the ratio of ion velocity to light speed.

In order to confirm the certainty of r_n, the beam turn pattern detected by differential head of the main probe was analyzed. An example of the relationship between calculated and measured radii of the beam trajectory is shown in Fig. 2. A linear relation is kept completely within the radius of 330 mm with the exception of first turn.

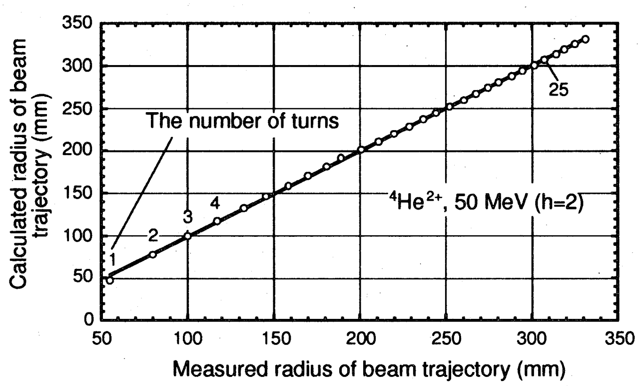

Fig. 2 A relationship between calculated and measured radii of the beam trajectory.

3 Pressure Control, Distribution and Calibration

Pressure control in the vacuum chamber, measurement of pressure distribution along the radius and calibration for a vacuum gauge have to be carried out for estimation of the CECS.

A block diagram for pressure control is shown in Fig. 3. Nitrogen gas was selected as the feeding one from the viewpoint of practical effectiveness. The gas feeding line constituted of copper pipe through two valves and a mass flow meter was connected to the side of the vacuum chamber. Actually the pressure in the vacuum chamber was controlled only by flow rate regulation of nitrogen gas.

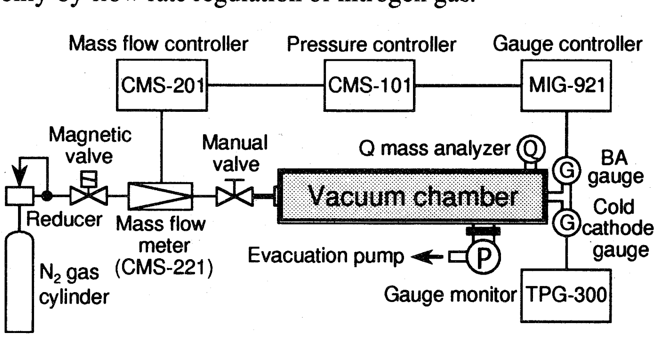

Fig. 3 A block diagram for pressure control in the vacuum chamber of the cyclotron.

For the purpose of measuring the pressure distribution in the vacuum chamber, the head of the main probe was replaced with a vacuum gauge so that the radial distribution can be got easily without vacuum break. A cold cathode gauge (IKR-20, Balzers) built-in a permanent magnet was chosen owing to the apprehension for residual field from the main magnet. Figure 4 shows the pressure distributions along the cyclotron radius as a function of gas flow rate. Although the internal pressure distributions in the cyclotron are roughly flattened independent of gas flow rate, they seem somewhat higher at the central region of the cyclotron.

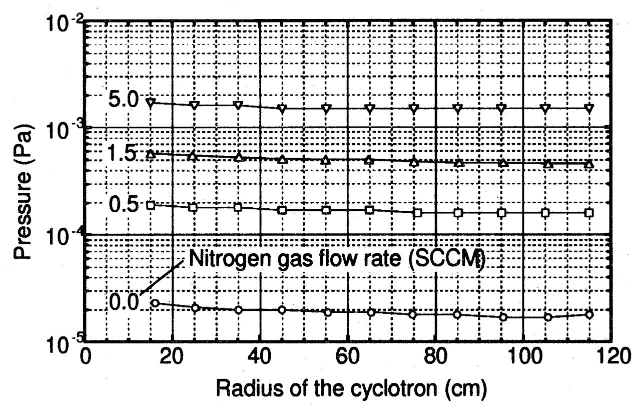

Fig. 4 Pressure distributions along the radius of the cyclotron .

To obtain the absolute values of the CECS, a calibration of the cold cathode gauge was performed in comparison with a nude BA gauge. A clear linear relation is observed along both logarithmic axes in Fig. 5, its inclination of straight line is slightly different from 1.0 apart.

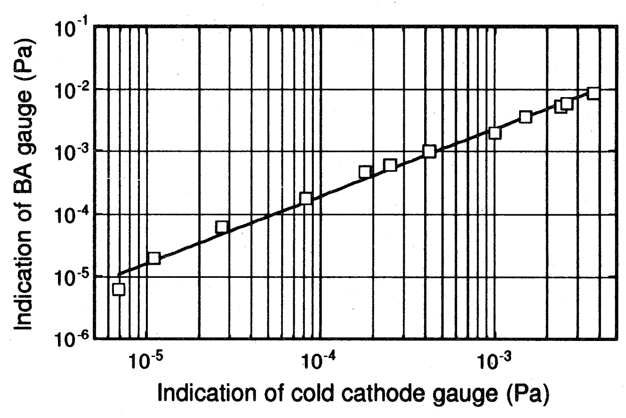

Fig. 5 A calibration line for cold cathode gauge used in experiment.

4 Beam Attenuation by Gas Feeding

Figures 6 and 7 show the beam intensities on the main probe when internal pressures by nitrogen gas feeding increase up to about two orders from the normal condition. The beam intensities at 50 mm of the cyclotron radius are reduced because of the beam loss along a perpendicular injection line where the pressure is made to rise on account of the contribution from the vacuum chamber.

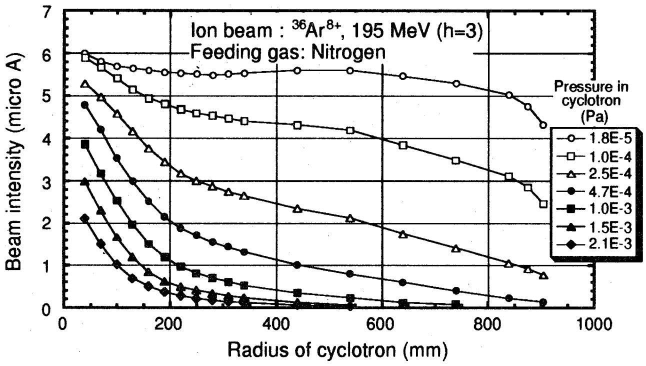

Fig. 6 The beam attenuation for $^{36}Ar^{8+}$, 195 MeV ion by nitrogen gas feeding into the vacuum chamber.

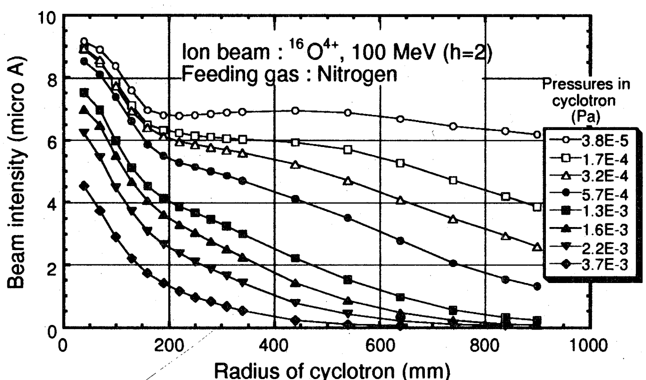

Fig. 7 The beam attenuation for $^{16}O^{4+}$, 100 MeV ion by nitrogen gas feeding into the vacuum chamber.

5 Estimation of Charge Exchange Cross Section

As mentioned before, the beam loss in the injection line needs to be considered carefully. The relative attenuation of the beam intensity at several pressure levels can be corrected surely by the exponential functions as shown in Fig. 8.

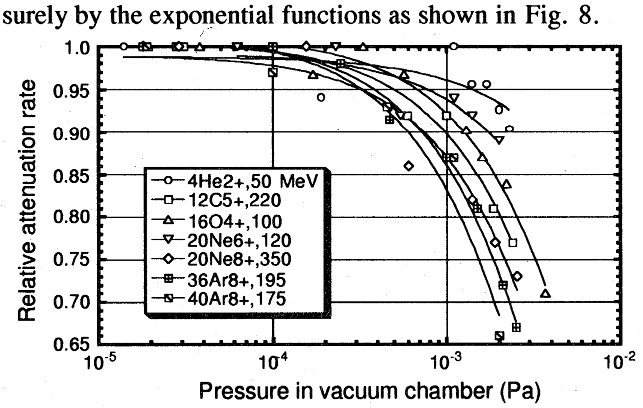

Fig. 8 The beam attenuation for various ions in the injection line.

A FORTRAN program for estimation of the CECS was made newly by ourselves. The values of the CECS are calculated with double precision by two manners of interpolation using Akima's method[4] and polynomial approximation .

Figure 9 summarizes the CECS for typical kinds of ion beams computed by polynomial approximation. Although a little big variations appear in a lot of data points, whole tendency shows that the CECS's for various ions decrease with increase of the ion velocity. Furthermore, the CECS's for highly charged ions are relatively larger than that of lowly charged one.

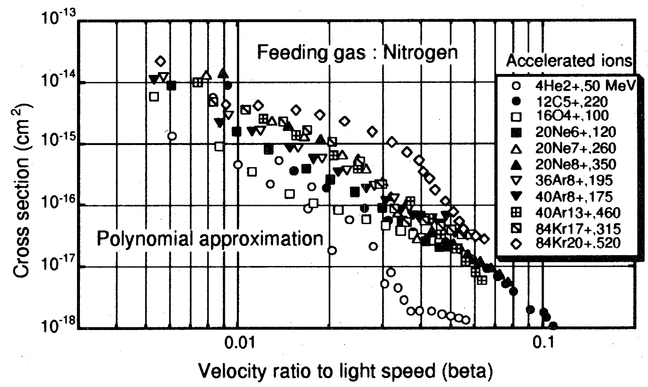

Fig. 9 Typical charge exchange cross sections estimated based on beam attenuation.

6 Derivation of Empirical Formula

We tried to get a reliable empirical formula which is available over the range of ion energy and charge state as wide as possible based on above data. As a result, we derived a following preliminary formula which is given as a function of β and the rate of ionization, Q_r, within the range of β which is less than 0.1.

$$\sigma = 1.5\times10^{-22}\bullet Q_r{}^{-6.2}\bullet \beta^{-(3.9+4.3\bullet\log Q_r)} \qquad (6)$$

Where Q_r equals Q/Q_0, and Q_0 is charge state at full-strip condition of the ion.

7 Further plan

So far, experimental data making use of cyclotrons, some theoretical and semi-empirical formulae have been already presented [5]-[8]. We are planning to acquire more excellent empirical formula and reliable experimental data in future.

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