ESTIMATION OF CHARGE EXCHANGE CROSS SECTION FOR HEAVY IONS ACCELERATED IN THE JAERI AVF CYCLOTRON

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The charge exchange cross sections were estimated experimentally 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 reliable empirical formula for the charge exchange cross section.

1 Introduction

The charge exchange reactions which occur with high probabilities in ion-atom collision have been studied[1]-[4] 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.

We have already described some preliminary data such as pressure control, pressure distribution and attenuation of beam current in previous proceedings of this conference.[5]

2 Method of Estimation for Charge Exchange Cross Section

An intensity of ion beam 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.

We assume that I_{P1_n} is given as

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

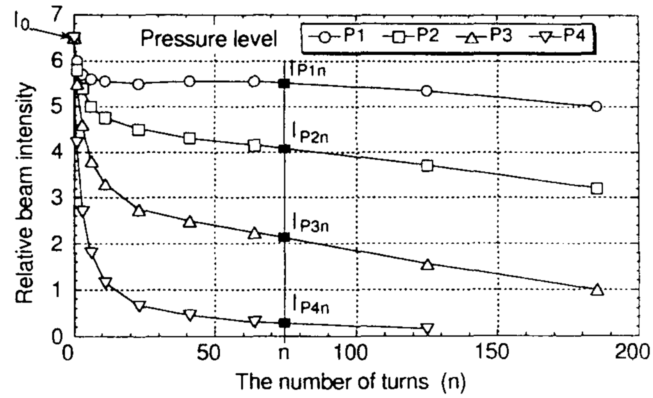

Fig. 1 Calculation model for beam intensities attenuated by gas feeding.

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

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

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

Where k is a constant, equal to $[6.023\times10^{23}/(22.4\times10^3)/(1\times10^5)\times273/(273+T)]$. 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}, R, is introduced because of elimination of the terms $f_a(n)$ and I_0.

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

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

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

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 the other pressure levels, another σ_n is also computed 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_i, is expressed generally based upon the motion of the ion in magnetic field.

$$r_i = \frac{\sqrt{E_i^2+2m_0E_i}}{0.2998\bullet Q\bullet B_0}\bullet\sqrt{1-\beta^2} \qquad (5)$$

Where, m_0 is rest mass of the ion in unit of MeV, E_i 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_i, 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.

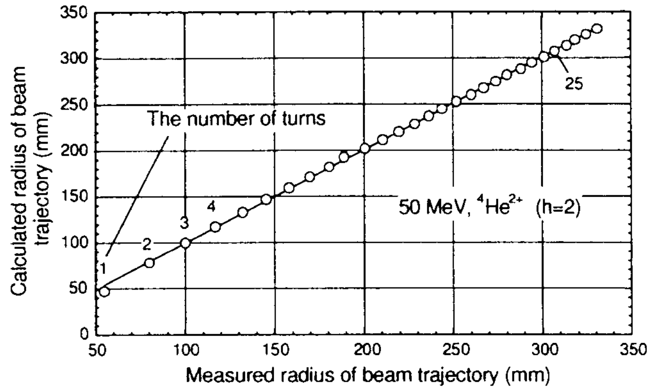

Fig. 2 Relationship between calculated and measured radii of the beam trajectory.

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 trustworthy estimation of the CECS. Nitrogen gas was selected as the feeding one from the viewpoint of practical effectiveness. Actually the pressure in the vacuum chamber was controlled only by flow rate regulation of nitrogen gas.

For the purpose of measuring the pressure distribution in the vacuum chamber, the head of the main probe was replaced with a vacuum gauge as illustrated in Fig. 3 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. The internal pressure distributions in the cyclotron are almost flattened independent of gas flow rate, they seem somewhat higher at the central region of the cyclotron.

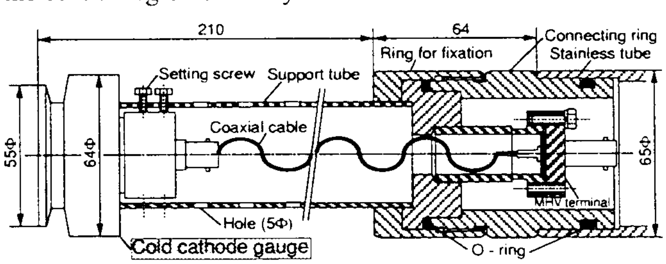

Fig. 3 A cold cathode gauge mounted the top of a main probe instead of an integral head.

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. 4, their inclinations of three straight lines are slightly different from 1.0 apart.

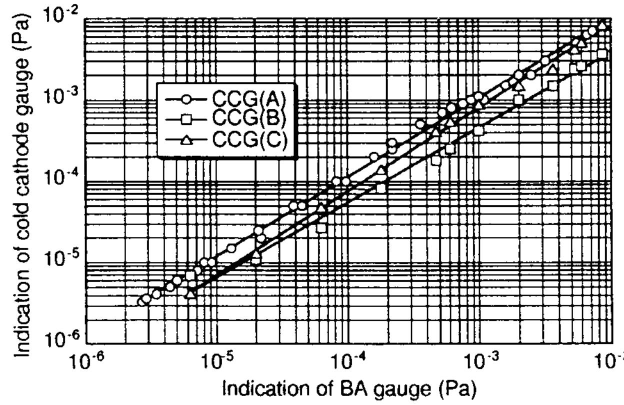

Fig. 4 Calibration lines for three cold cathode gauges (CCG) used in the experiment.

4 Beam Attenuation by Gas Feeding

Figures 5 and 6 show the beam intensities on the main probe when internal pressures by nitrogen gas feeding increase about two orders from the normal condition.

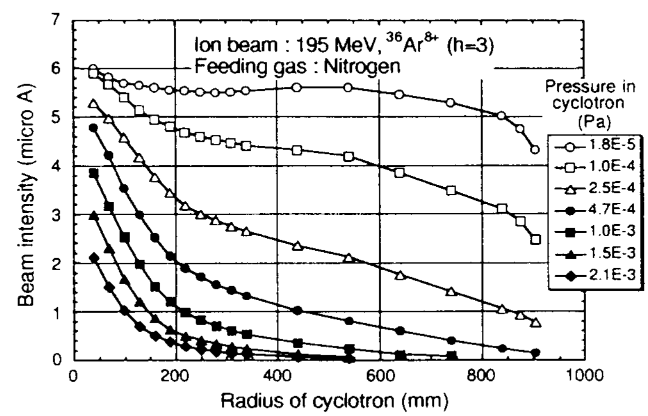

Fig. 5 The beam attenuation for 195 MeV, $^{36}Ar^{8+}$ ion by nitrogen gas feeding into the vacuum chamber.

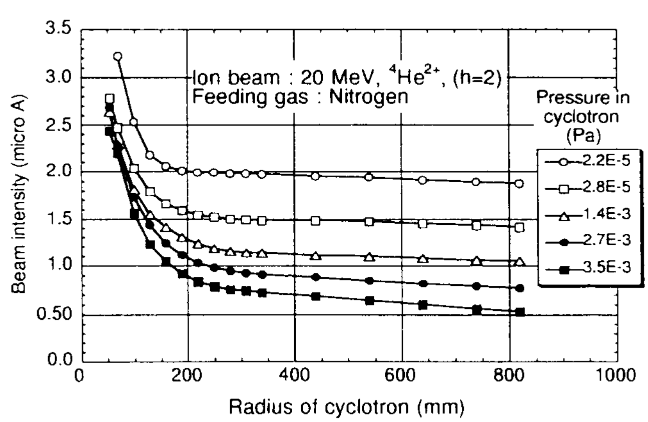

Fig. 6 The beam attenuation for 20 MeV, $^4He^{2+}$ ion by nitrogen gas feeding into the vacuum chamber.

Although the shape of beam attenuation for 195 MeV, $^{36}Ar^{8+}$ ion changes depending on the internal pressure, however one for 20 MeV, $^{4}He^{2+}$ ion dwindles with analogous pattern. These discrepancies among the shapes of beam attenuations can be compensated well in consequence of the computational procedure including the ratio of two beam intensities as described in formula (3). The beam intensities at 50 mm of the cyclotron radius are reduced because of the beam loss along the injection line where the pressure is made to rise on account of the contribution from the vacuum chamber.

5 Estimation of Charge Exchange Cross Section

As mentioned before, the beam loss along the perpendicular injection line needs to be taken into consideration carefully. The relative attenuation of the beam intensities along the injection line at several pressure levels is corrected surely using the exponential functions as shown in Fig. 7.

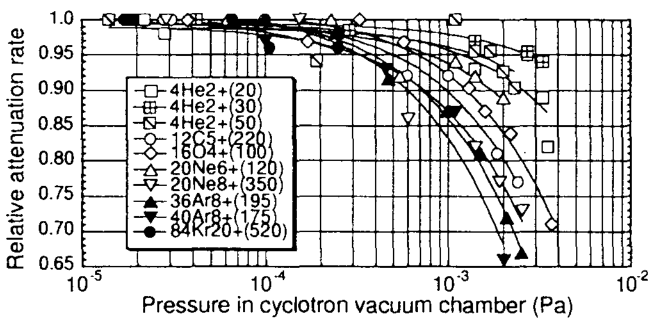

Fig. 7 Relative attenuation rate for various ions along the perpendicular injection line. The numbers in parentheses correspond to nominal energy of accelerated ions in unit of MeV.

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[6] and polynomial approximation. Furthermore, the computation of CECS is added to the calculation condition of $\sigma_n > \sigma_{n+1}$, since the individual CECS shows rather larger fluctuation at the range of β where the difference of beam intensities between two pressure levels becomes to be very small.

A comparison of CECS data computed by two manners is shown in Fig. 8. The CECS's estimated with polynomial approximation give certain values over the range of β wider than those by interpolating one.

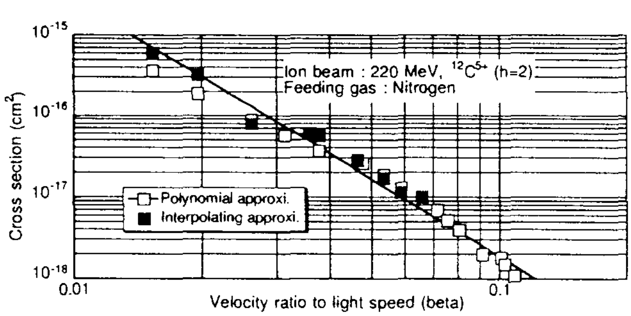

Fig. 8 Comparison between polynomial approximation and interpolating one.

Figure 9 summarizes the CECS's dealt with polynomial approximation for typical kinds of experimented ion beams. 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 ones.

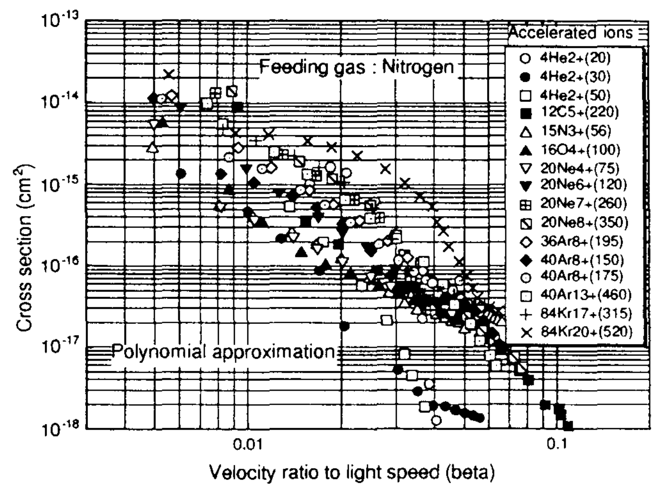

Fig. 9 Typical charge exchange cross sections estimated based on beam attenuation.

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. It is found out that σ for each ion can be expressed in the power form of $\sigma = a\,\beta^{-b}$ by means of the experimental result.

Both coefficients "a" and "b" are determined as a function of the ratio of ionization, Q_r which equals Q/Z, from two straight lines across in Fig. 10a and 10b without some $^{4}He^{2+}$ ions and 520 MeV, $^{84}Kr^{20+}$ one, because the CECS for each accelerated ion can be roughly approximated by exponential fitting. Where Z is atomic number of the ion.

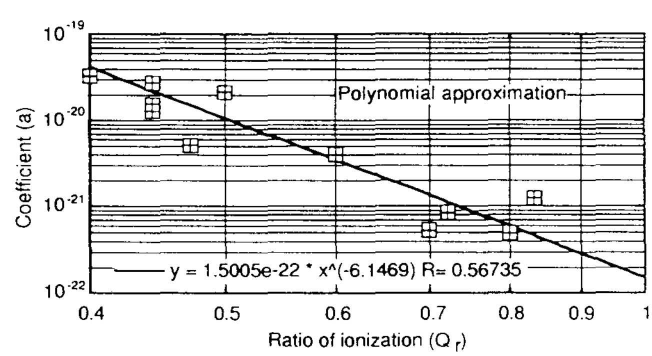

Fig. 10a Plotting of coefficient "a" to the ratio of ionization.

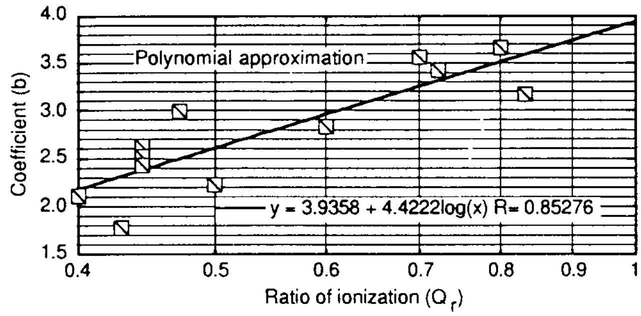

Fig. 10b Plotting of coefficient "b" to the ratio of ionization.

Finally, we derived a following comprehensive empirical formula which is given as a function of β and Q_r, within the range of β which is less than 0.1.

$$\sigma = 1.5\times10^{-22} \bullet Q_r^{-6.1} \bullet \beta^{-(3.9+4.4\bullet\log Q_r)} \qquad (6)$$

7 Comparison with Other Formulae

Some theoretical and semi-empirical formulae have been proposed so far as described in following formulae (7), (8) and (9) corresponding to references [7], [8] and [9], respectively.

$$\sigma = 2\pi a_0^2 (Z^{1/3} + Z_T^{1/3}) \bullet \left(\frac{v_0}{v}\right)^2 \qquad (7)$$

$$\sigma = \pi a_0^2 \left\{ Z_T^{2/3} Z^{4/3} Q^{-3} \left(\frac{v}{v_0}\right)^2 + Z_T^{1/3} Q^2 \left(\frac{v_0}{v}\right)^3 \right\} \qquad (8)$$

$$\sigma = 9\times10^{-19} Q^{-0.4} \beta^{-2} + 3\times10^{-28} Q^{2.5} \beta^{-7} \qquad (9)$$

Where a_0 is Bohr radius, Z_T is atomic number of the target medium, v and v_0 are velocities of the ion and an electron around 1s orbit in a hydrogen atom, respectively.

A comparison of these formulae and experimental result for $^{40}Ar^{8+}$ ion is shown in Fig. 11. The formula (7) theoretically suggested by Bohr is the most similar in shape to our formula among these formulae in case of this ion.

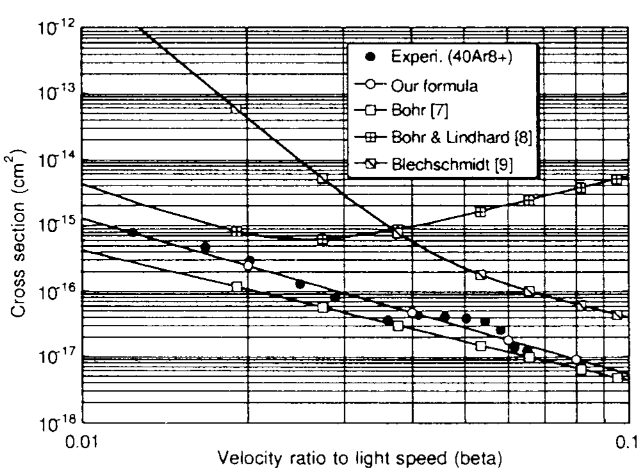

Fig. 11 Comparison of some formulae and an example of experimental result for $^{40}Ar^{8+}$ ion.

8 Beam Attenuation Through the Cyclotron

An example of beam attenuation through the cyclotron in case of pressure increase is shown in Fig. 12. At TS1 just downstream the cyclotron, as the pressure in the cyclotron rises up two orders, the beam intensity extracted from the cyclotron reduces about three orders.

In regard to the acceleration of relatively low energy ion such as 56 MeV, $^{15}N^{3+}$ ion which is a kind of cocktail beams with M/Q=5, we have to maintain the pressure in the cyclotron below 8 x 10^{-5} Pa from 2.5 x 10^{-5} Pa at original equilibrium pressure, if the beam loss through the cyclotron by charge exchange reaction needs to be restricted within 30 % which is equal to general transmission rate along an electrostatic deflector.

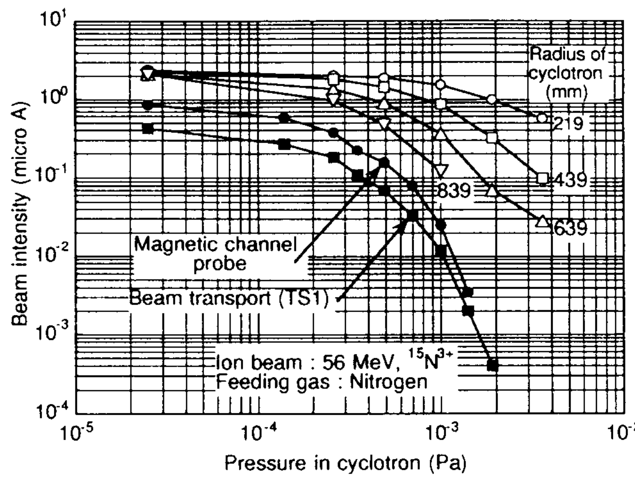

Fig. 12 An example of beam attenuation at several positions in the cyclotron and TS1 in the beam transport line just downstream one.

References

[1] H. D. Betz, *Rev. Mod. Phys.*, vol. 44, No.3, 465 (1972).

[2] C. L. Cocke, *Phys. Rev.* A, vol. 20, No.3, 749 (1979).

[3] P. D. Miller, *IEEE Trans. on Nucl. Sci.* vol. NS-26, No. 1, 1111 (1979).

[4] R. A. Gough and M. L. Mallory, *IEEE Trans. Nucl. Sci.*, NS-26, No. 2, 2384 (1979).

[5] Y. Nakamura, I. Ishibori, et al., *Proc. 14th Int. Conf. on Cyclo. and Their Applic.*, Cape Town, South Africa, 276 (1995).

[6] H. Akima, *Journal of the ACM*, vol. 17, 589 (1979).

[7] N. Bohr, *Kgl. Danske Viedenskab. Selskab, Mat.-Fys.* Medd. 18, No. 8 (1948).

[8] N. Bohr and J. Lindhard, *Kgl. Danske Viedenskab. Selskab, Mat.-Fys.* Medd. 28, No. 7 (1954).

[9] D. Blechschmidt and H.J. Halama, *Proc. HIF Workshop*, 136 (1977).