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Line-Emission Cross Sections for the Charge-exchange Reaction between Fully Stripped Carbon and Atomic Hydrogen in Tokamak Plasma

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Abstract

Line-emission cross sections of the charge-exchange reaction between fully stripped carbon and atomic hydrogen are measured in the energy range of 18-38 keV/amu in tokamak plasmas. The energy dependence of the emission cross sections for the transition of Δn= 8-7 and Δn= 7-6 and their ratios are compared with theoretical calculations.

Keywords: charge-exchange, l-mixing, fully stripped carbon ions, neutral beam, tokamak plasma.

The charge-exchange reaction between fully stripped carbon and atomic hydrogen becomes an important subject, since charge exchange spectroscopy (CXS) has been applied to measure ion temperature and the plasma rotation profile in magnetic confined plasmas [1]. Hydrogen or deuterium beam in the energy range of 30 - 100 keV, which is usually equipped to heat the plasma, is used also for CXS diagnostic. This technique also provides the fully stripped impurity radial profile and concentration with the use of the calculated charge exchange cross section [2]. Recently most measurements have been done with the use of the line of transition between high *n*-levels in the visible region taking advantage of the use of the optical fiber array to obtain multi-point simultaneous measurements [3]. Many theoretical calculations; molecular orbital (MO) calculation by Green et al. [4], the extended atomic orbital (AO) calculation of Fritsch and Lin [5,6], the unified atomic-molecular orbital (AO-MO) calculation of Kimura and Lin [7], the unitarized distorted-wave approximation (UDWA) of Ryufuku 8,9], and continuous energy state model of Koike [10], have been proposed. However most calculations [4,5,7] give the partial cross sections for the low *n*-levels below n=5, where X-ray or VUV emissions are produced. Few charge exchange cross sections for high *n*-level transitions above n=7 have been calculated and their values are quite different from each other[6,9,10].

Most experiment to measure the cross sections of charge exchange have been done with the ECR ion source [11-15], or pulsed-laser ion source [16], and therefore the energy range is limited to below 8 keV for these measurements. Measurements of relative cross sections between different *n*-levels have been done in tokamak plasma using heating beam with the high energy up to 50 keV [17]. Their results agree with the prediction by UDWA method [9] within 30%. In this paper, we present measurements of energy dependence of emission cross sections for Δn=7-6 and Δn=8-7 in the energy range of 18-38 keV/amu.

The measurements have been done using JIPP-TIIU tokamak device with the 18-38 keV hydrogen beam with the total input power of 0.4 MW. The major radius and minor radius of the plasma is 0.9 m and 0.23 m, respectively. The plasma is ohmically heated with the plasma current of 200 kA and with the toroidal field of 3 T. The central electron density for these measurements is 3.8 x $10^{13}/cm^3$, and the electron temperature is about 1 keV, which is high enough to produce fully stripped carbon. The radial profiles of the emission due to charge-exchange reaction between neutral hydrogen atoms and fully stripped carbon ions in the plasma are measured with multi-chord spectrograph with CCD detector which is absolutely calibrated. The spectral lines of CVI 3433.7 Å (Δn=7-6) and 5290.5 Å (Δn=8-7) are measured. These spectral lines are also produced by electron excitation and charge-exchange reactions with background slow neutral hydrogens in the plasma periphery as well as fast neutral hydrogens of the beam. In order to subtract this background emission at the plasma edge, two identical sets of viewing arrays, 17 spatial channels each, are installed in the tokamak. They are both viewing the plasma toroidally at the same radius and one is looking towards the source of charge exchange emission with fast neutral beam, and the other is looking at background light. The charge exchange emission due to fast neutral atoms of the beam is obtained by subtracting one from the other signal of these two sets of arrays. The Z_{eff} values are measured by visible bremsstrahlung with 8 channels to monitor the total amount of impurities. The fast neutral density profile for each energy component of the beam (E 60%, E/2 25%, E/3 15%) is calculated with Monte Carlo code, using the measured electron density and temperature profiles where E is the beam energy. Since the charge-exchange cross section drops sharply below 25 keV/amu, the contribution of E/2 and E/3 to the total charge-exchange reaction is at most 10%, which can be neglected. Then the charge exchange emission cross sections can be obtained from the line intensities, neutral density of the beam (E) of the order of 10^9 cm^{-3} and the amount of carbon impurity with the density of 10^{12} cm^{-3}. In order to determine the amount of carbon in the plasma, mixed gas of H_2 and CO_2 with the concentration of carbon of 2.5% of hydrogen atoms. is used for the measurements. Since the carbon impurity is sputtered from carbon limiters inside the tokamak, the carbon concentration in the plasma is considered to be higher than that of the mixed working gas. Therefore the absolute values of emission cross section is determined from the difference of intensity of two discharges; one is from pure hydrogen gas and the other is from hydrogen plus 2.5% CO_2 with similar electron density. In order to minimize the uncertainty due to the difference of recycling between hydrogen and carbon, we apply a strong gas puff during the measurements in the discharge.

The profiles of fully stripped carbon ion density of these discharges are similar to the electron density profile as shown in Fig.1, which support the assumption of flat distribution of the fraction of carbon impurity in the plasma. The beam energy is scanned from 18 to 38 keV with constant line-averaged electron density of 2.5 x 10^{13} cm^{-3}. The Z_{eff} values measured with visible bremsstrahlung stay constant as well as the electron density for this range of the energy of the neutral hydrogen atom. Since the contribution of oxygen to Z_{eff} is comparable to that of carbon, the absolute concentration of carbon can not be estimated from Z_{eff} measurements. Although the vacuum vessel wall has been titanium gettered to reduce oxygen influx, carbon recycling is considered to be different from hydrogen and/or oxygen. The absolute values of emission cross section by assuming 2.5% carbon concentration in the plasma is not accurate enough to be compared with those derived by various theories. Here we concentrate on the energy dependence of emission cross section of Δn=7-6 and Δn=8-7.

Figure 2 shows the emission cross section for the transition of 3433.7 Å (Δn=7-6) and 5290.5Å (Δn=8-7) as a function of beam energy, with the prediction of various theoretical models. The emission cross sections for hydrogen-like impurities are derived from partial cross sections as

$$\sigma_{em}(7\to6) = C_{cs}\ [\ 0.099\sigma(7s) + 0.010\sigma(7p) + 0.037\sigma(7d) + 0.102\sigma(7f) + 0.241\sigma(7g) + 0.511\sigma(7h) + \sigma(7i)\ ]$$

and

$$\sigma_{em}(8\to7) = C_{cs}\ [\ 0.073\sigma(8s) + 0.007\sigma(8p) + 0.025\sigma(8d) + 0.066\sigma(8f) + 0.148\sigma(8g) + 0.300\sigma(8h) + 0.563\sigma(8i) + \sigma(8j)\ ]$$

in the low density regions where the collisional processes are neglected. Here $\sigma(nl)$ is a partial cross section and C_{cs} is a correction due to the cascade from upper levels to n= 7 or 8. The coefficients attached to the partial cross section $\sigma(nl)$ are the branching ratios from the nl to the n-1 level through radiative decay. The cascade from upper levels, $\Sigma\sigma_{em}(n\to8)$ $(n > 8)$, is estimated with the assumption of $\sigma(n,l) \propto (2l+1)\,n^{-3}$, since theoretical partial cross sections above n= 8 are not available. The cascade correction factor C_{cs} is obtained to be 1.2 for $\sigma_{em}(7\to6)$ and $\sigma_{em}(8\to7)$. The theoretical emission cross sections by different theories are shown in Fig.2. The experimental data of FOM at the energy of 8.4 keV/amu taken from Ref 15 are shown. The energy dependence of the measured emission cross sections for Δn=7-6 and Δn=8-7 is stronger than theoretical calculations. Ryufuku's calculation gives similar emission cross section comparing to Fritsch's calculation in the range of 25 - 30 keV/amu, however, it shows much sharper drops of emission cross section than the measurements below 25keV/amu. Emission cross section calculated by Koike shows much smaller values than the other calculations and measurements in the energy range of 25 - 40 keV/amu both for Δn=7-6 and Δn=8-7 transitions. Emission cross sections calculated by Koike and Ryufuku are much smaller than the measured emission cross section reported from FOM.

The electron density in the range of $10^{13}/cm^3$ to $10^{14}/cm^3$ is the operational density in most tokamak plasma. In this region, *l*-mixing (the collisional excitation among the same *n*-levels) and excitation among different *n*-levels come to affect emission cross section for high-*n*-transition. Here we discuss the effect of *l*-mixing and excitation in the calculation of the emission cross section. The electron excitation among different *n*-levels increases the emission cross section at high *n*-levels such as *n* = 7 or 8[18], since the charge exchange cross section has the maximum at *n* = 4. The effect of electron excitation among different *n*-levels is negligible below the electron density of $10^{14}/cm^3$ when the *l*-mixing is much faster than the excitation. For example, the electron excitation increases emission cross section by 5% (Δn = 8-7, @25keV/amu) for Ryufuku's and Fritsch's *l*-distribution and 10% for Koike's *l*-distribution in the plasma with the electron density of 2.5 x $10^{13}/cm^3$. On the other hand, *l*-mixing becomes important even for the density of 10^{13} - $10^{14}/cm^3$, when Z_{eff} are high as in our experiments. The *l*-mixing is mainly caused by bulk ions and impurities since the energy gaps between different *l*-levels is small [1], whereas the excitation among different *n*-levels by electron excitation. The effect of l-mixing on emission cross section appears differently depending on the l-distributions of the cross section. The l-distributions are different among calculations as shown in Figure 3. For $n = 8$ levels, the partial cross section of the charge transfer have maximum values at $l = 2$ in Koike's, at $l = 3$ in Fritsch's, and at $l = 5$ in Ryufuku's calculation. In the limit of complete l-mixing, the emission cross section depends on the total cross section for each n-level as $\sigma_{em}(8 \rightarrow 7) = 0.158\,\sigma_8$ and $\sigma_{em}(7 \rightarrow 6) = 0.174\,\sigma_7$, since the l-distribution is re-distributed by l-mixing following the statistical weight. Figure 4 shows the calculated emission cross section for complete l-mixing with the experimental data. The emission cross sections decrease by up to factor of two by l-mixing for the l-distributions by Fritsch and Ryufuku although they increase for Koike's l-distributions. In the density region of l-mixing, the excitation among the different n-levels has also the effect. This effect depends on the ratios of the l-mixing rate to the excitation rate [18]. In the case of our experiment, l-mixing tate is larger than the excitation rate from the value $Z_{eff} = 4$.

The total charge exchange cross section has the maximum at $n = 4$ and decreases as $n^{-\alpha}$ where $\alpha > 3$ for $n > 5$. The ratio of emission cross section of $\Delta n = 7\text{-}6$ to $\Delta n = 8\text{-}7$ gives an estimation of α. Figure 5 shows the measured ratio of these two emission cross sections with estimate from each calculations. The experimental data of FOM and JET at the energy of 8.4 and 50 keV/amu are taken from Ref 15 and 17, respectively. Three calculations give similar ratio of emission cross section of Δn= 7-6 to Δn= 8-7, although they give quite different absolute values of emission cross section for Δn= 7-6 to Δn= 8-7. This is due to that these calculations have similar n-distribution but different l-distribution, since total cross sections of these calculations are quite similar. The error bar of the experimental data are too large to check the validity of different calculations. However they show that the value of α is in the range of $3 < \alpha < 9$, by taking l-distribution as $n^{-\alpha}\exp(-0.14(l-4)^2)$, which is not inconsistent with the calculations and the results from other measurements.

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Figure captions

Fig.1. Radial profile of density of fully stripped carbon estimated from the emission of Δn= 7-6 transition (3433.7Å) excited by the charge-exchange reaction for the energy of 24 keV/amu and the total current of 15A. Closed circles are profile for the discharge with hydrogen and CO_2 mixture gas (2.5% carbon) and open circles are with hydrogen gas.

Fig.2. Line-emission cross sections due to the charge-exchange reaction between fully stripped carbon and atomic hydrogen in the energy range of 18 - 38 keV/amu for (a) Δn=7-6 and (b) Δn= 8-7 transition. Lines are calculations by Ryufuku (R), Fritsch (F) and Koike (K), without taking into account the collisional processes.

Fig.3. The l-distribution calculated by Ryufuku (circles), Fritsch (squares) and Koike (triangles) for (a) Δn= 7-6 and (b) Δn=8-7 transition at the energy of 25 keV/amu .

Fig.4. Calculated line-emission cross sections [by Ryufuku (R), Fritsch (F) and Koike (K)] in the case of complete l- mixing for (a) Δn=7-6 and (b) Δn= 8-7 transitions in C^{5+}.

Fig.5. Ratio of charge-exchange C^{5+} emission cross section of Δn=7-6 transition to Δn= 8-7 transition in the energy range of 18 keV - 38 keV. Lines are ratios calculated by Ryufuku (R), Fritsch (F) and Koike (K).

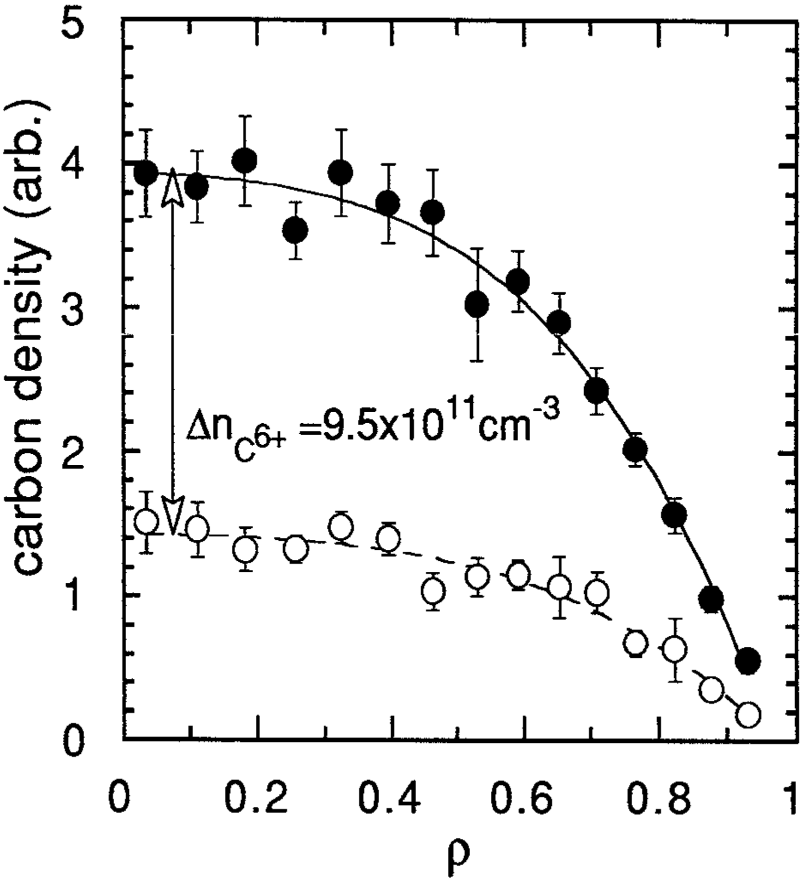
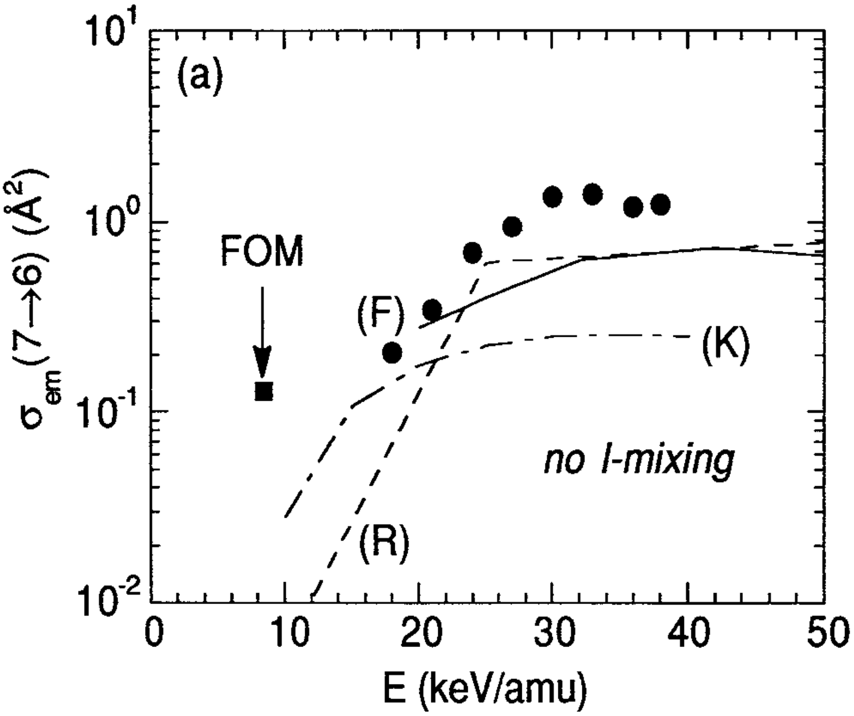


Figure 1 K.Ida and T.Kato



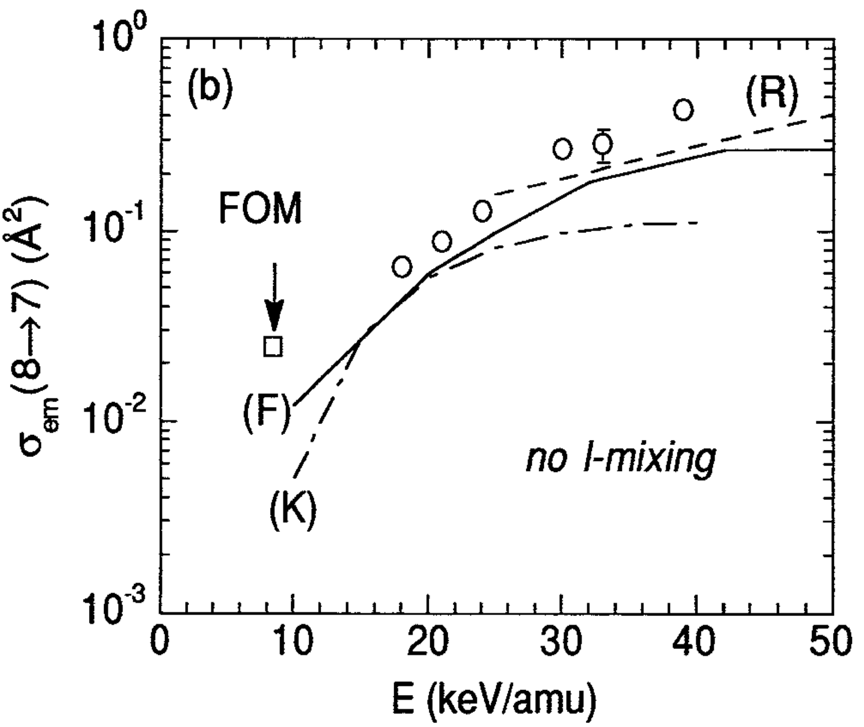


Figure 2 K.Ida and T.Kato

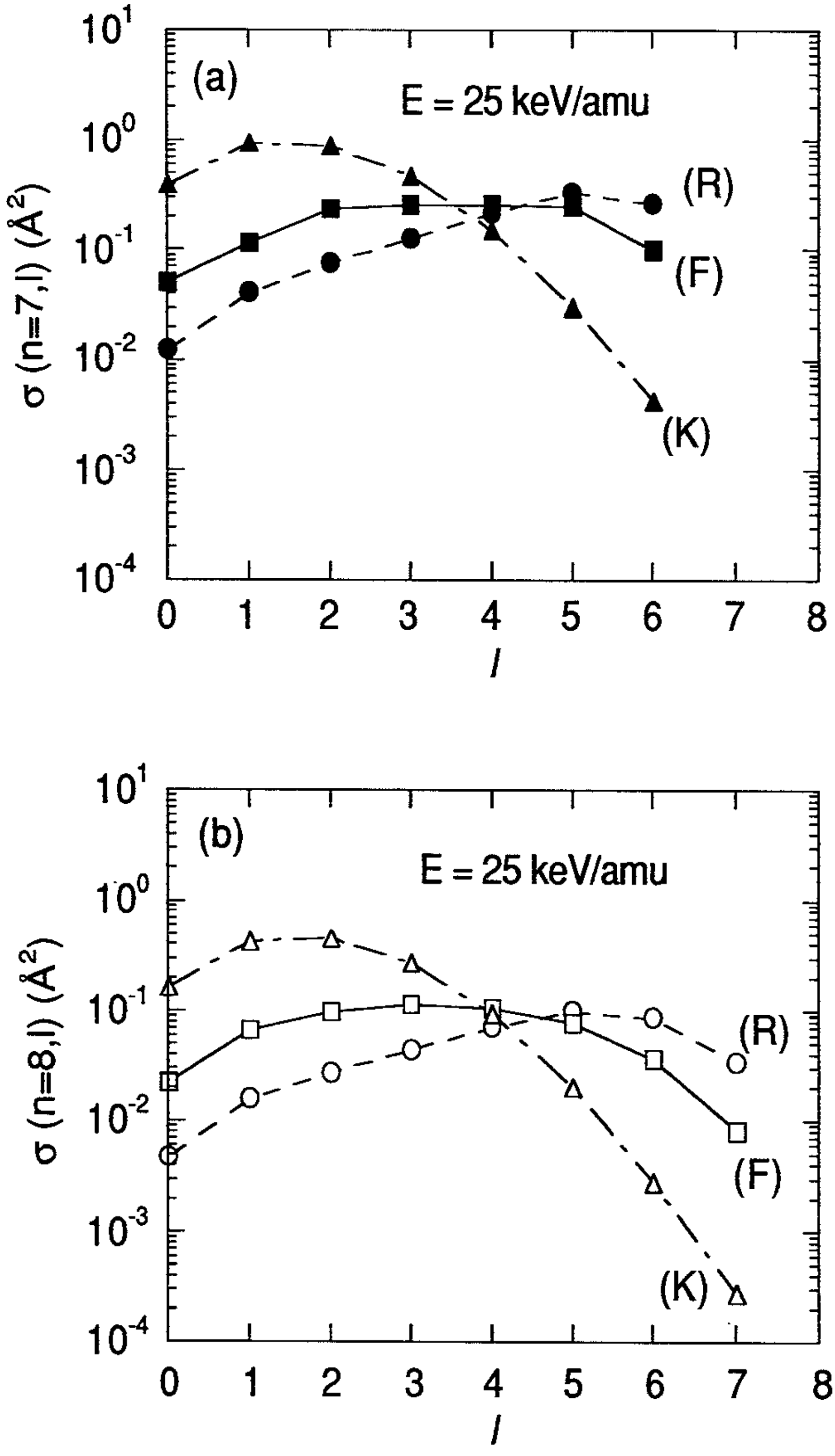
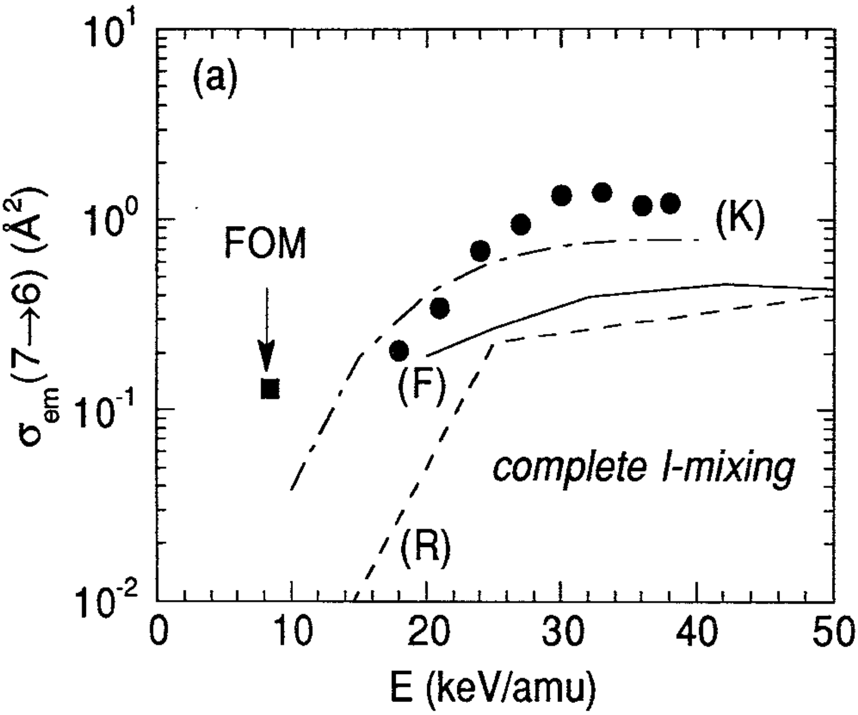


Figure 3 K.Ida and T.Kato



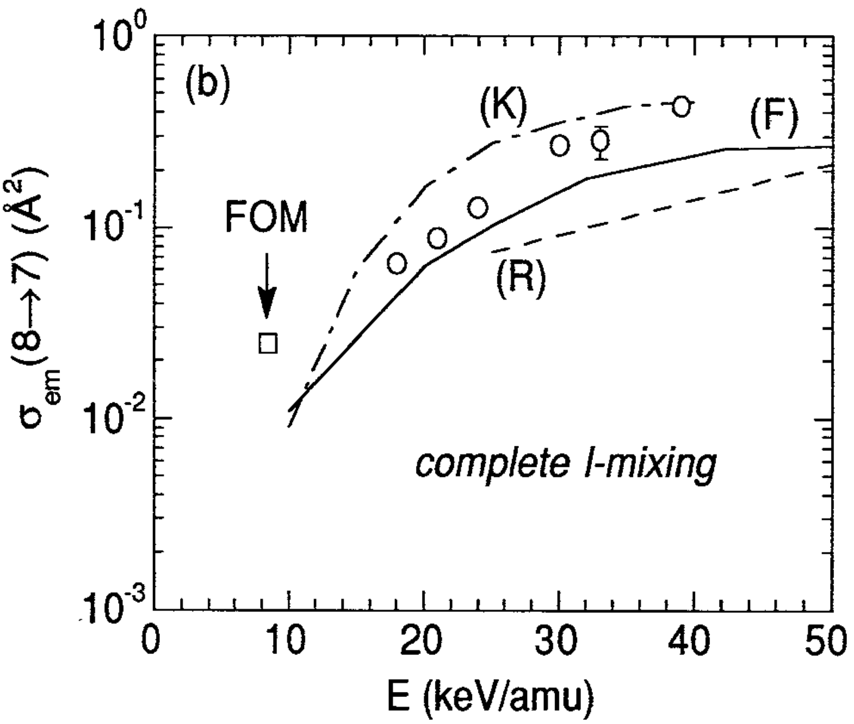


Figure 4 K.Ida and T.Kato

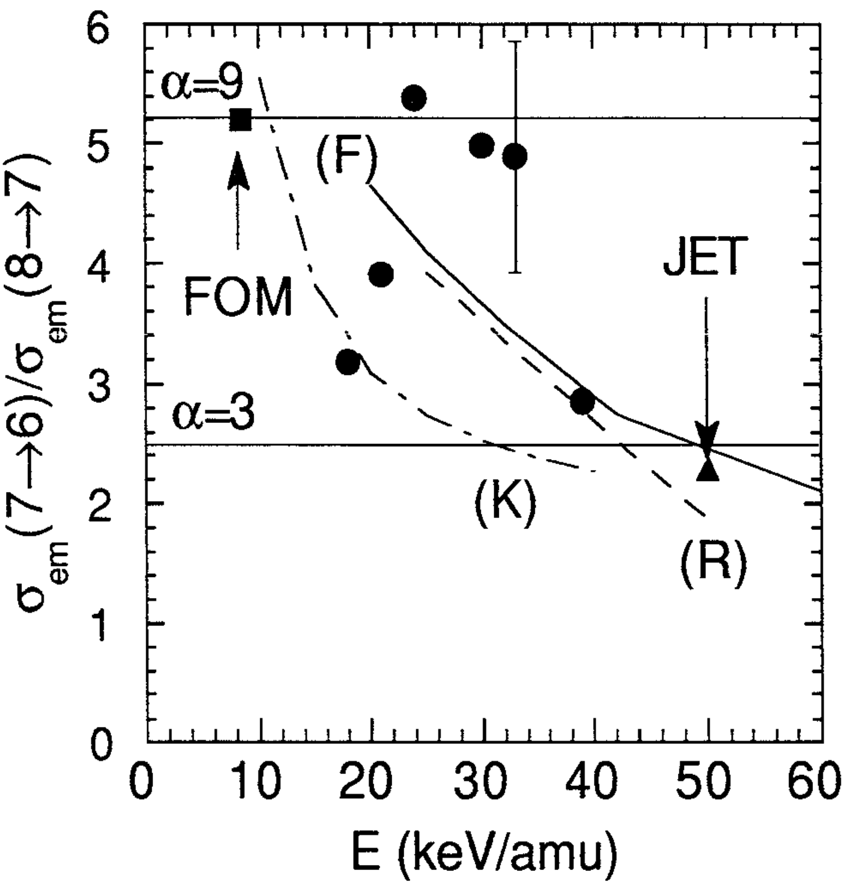


Figure 5

K.Ida and T.Kato

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