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Electron Stripping Cross Sections for Light Impurity Ions in Colliding with Atomic Hydrogens Relevant to Fusion Research

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Abstract

Electron stripping (ionization) cross sections for impurity (carbon) ions with various charge states in collisions with atomic hydrogens have been surveyed. It has been found that these data are relatively limited both in collision energy and charge state and, in particular those necessary for high energy neutral beam injection (NBI) heating in fusion plasma research are scarce. Some relevant cross sections for carbon ions, C^{q+} (q=0-5) have been estimated, based upon the existing data, empirical behavior and electron impact ionization data.

[key words : electron stripping, carbon ion, atomic hydrogen]

I. Introduction

Recently a great deal of attention has been paid to the electron capture processes involving multiply charged impurity ions which are abundant in high temperature plasmas and a large volume of theoretical as well as experimental investigations have been performed and their data have been accumulated[1-5]. In particular, data for the most abundant impurity ions in plasmas such as carbon and oxygen ions have been carefully evaluated[6].
Generally speaking, the following electron capture process,

$$A^{q+} + B \rightarrow A^{(q-1)+}(nl) + B^{+}, \qquad (1)$$

where an electron is transferred into an excited state (nl) of ions A^{q+} from neutral atoms B, results in the emission of photons from ions, which in turn is found to be a significant energy loss from plasmas. Presently, this electron capture process is being used as a powerful plasma diagnostics tool (known as charge exchange recombination spectroscopy=CXRS[7] in plasma community) among many plasma-diagnostic techniques.
In addition to the radiation loss from plasmas due to electron capture into highly ionized ions, the electron capture process (1) would also induce the loss of neutral hydrogen beams, H, which are injected for heating plasmas :

$$A^{q+} + H \rightarrow A^{(q-1)+} + H^{+}, \qquad (1)'$$

thus resulting in a significant reduction of plasma heating efficiencies by neutral beam injection (NBI). This process (1)' as well as the electron capture process (1) have been reviewed by Hvelplund and Janev[8].
Data for this electron stripping (ionization) process from atomic hydrogen by common impurity ions such as C^{q+} and O^{q+} ion impact

have been already compiled by Janev et al.[9] and found to be represented using some empirical formula for various ion impact.[10,11]

On the other hand, the importance of the following electron stripping or loss processes of such impurity ions in plasmas has been almost neglected up to now :

$$A^{q+} + B \rightarrow A^{(q+1)+} + \Sigma B \qquad (2)$$

where Σ represents the summation over all possible target states including excitation as well as ionization.
The electron stripping processes of these (relatively slow moving) impurity ions through collisions with the injected high energy neutral hydrogen beams, similar to ionization processes by electron impact, are expected to increase sharply as the impact energy increases. As the plasma machines become large, the energy of neutral hydrogen beams for plasma heating have to increase, say up to 1 MeV/amu. Therefore, the electron stripping processes of impurity ions through collision with the injected neutral H beams are believed to play a significant role in plasmas and become important, in particular near the plasma edge region where impurity ions are in their relatively low ionization stages. This electron stripping of impurity ions, (2), results in increase of the effective charge of impurity ions which in turn would enhance radiation loss due to bremstrahlung of fast electrons in plasmas. It has been found that the cross sections for such electron stripping for impurity ions are scarce and available data are limited in ion energy and charge state of ions. In this report, in order to know the contribution of the electron stripping processes of carbon ions through collisions with the injected neutral hydrogen beams we try to survey, compile and estimate the cross sections for electron stripping of carbon impurity ions

with different charge states over the collision energy interested in neutral beam injection heating up to 1000 keV/amu.

II. Features and estimation of cross sections for electron stripping from ions

Because only a limited amount of data are available for electron stripping cross sections of impurity ions (for example, C^{q+}) by atomic hydrogen impact,

$$A^{q+} + H \rightarrow A^{(q+1)+} + \Sigma H, \qquad (3)$$

over the energy range of interest in plasma research, we have to rely upon some empirical behavior or some educated guess of the cross sections for electron stripping of the impurity ions in relation to electron impact ionization. In the following, some important features of the cross sections for electron stripping of ions under hydrogen atom collisions are pointed out :

1) Generally speaking, in electron stripping processes from an ion in collisions with a hydrogen atom, an electron which is going to be stripped interacts with an electron in atomic hydrogen as well as a proton, nucleus of atomic hydrogen. If the electron to be stripped from ion has an orbit larger than that of the electron in the ground state hydrogen (corresponding to the ionization potential of the ion lower than that of hydrogen atom), the interaction of electrons in ion with target hydrogen is dominated by that of the screened hydrogen atom and the contribution of the electron attached to hydrogen atom is small. That is the case for neutral and singly charged carbon ions C^{q+} (q = 0 and 1 : the corresponding ionization threshold energy = 11.3 and 24.4 eV, respectively). As the ionization of ions proceeds to higher charge state and the electron orbit becomes

comparable to that of hydrogen atoms, the situation seems to change (for C^{q+} ions with q = 2 and 3 : 47.9 and 64.5 eV, respectively). That is, the screening effects become less pronounced. Once all the outershell electrons are ionized and only the innershell electrons are left in ions, the orbit of electrons in ions shrinks and becomes smaller than that of hydrogen atom. Then, the electron in ion starts to interact with two independent particles, namely an electron and a proton in hydrogen atom. Thus the electron detachment from ion is caused by the interaction of two particles in hydrogen atoms. Thus the cross sections for electron stripping of C^{q+} (q = 4 and 5 : 392, 490 eV, respectively) ions are given as sum of those by two particles. It should be noted that the interference effect of ionization by proton and electron for carbon ions is relatively small in the present collision energy region.[12] This has already been demonstrated theoretically and experimentally.[12,13]

2) It has been already known that the ionization cross sections of atoms by proton impact become practically equal to those by electron impact with equivalent velocities at sufficiently high energies. This happens at the collision energy above 10-15 times the corresponding ionization threshold energy (E_i) of ions involved.[14] Indeed, the experimental data for $C^{+} \rightarrow C^{2+}$ process, where relatively reliable data are available over some collision energy, indicate such a trend, as will be seen later.

3) The ionization cross sections of ions of charge q with simple structures to charge q+1 by electron impact are known to be expressed through the following convenient analytical formula[15]:

$$\sigma_{q,q+1} = [1/\{E_i^2*(E/E_i)\}]*[a*\ln(E/E_i) + \Sigma b_j\{(E-E_i)/E\}^j]$$

where E represents the impact energy of the incident electrons and a and b_j are constants depending on particular ions. These constants which are best fitted to the observed data have been evaluated and given by Bell et al.[15] Their formula, based upon so-called Lotz empirical formula, indicates that the ionization cross sections are inversely proportional to the square of the electron ionization threshold energy E_i.
Maximum ionization cross sections of carbon ions with various charge states by electrons recommended by Bell et al. are shown in **Fig.1** as a function of the ionization threshold energy E_i.

4) The electron stripping cross sections from ions under heavy particle impact such as atomic hydrogen at high energy collisions are also known to be inversely proportional to the square of the ionization threshold energy (E_i) of ions, quite similar to the ionization by electron impact. In fact, as seen later, the observed data both for hydrogen atom impact and for electron impact show exactly such a behavior, when they are plotted as a function of the ionization threshold energy E_i, though absolute values are quite different at low energies ($< 10*E_i$) due to the mass difference between electron and proton.
The experimentally observed electron stripping cross sections by atomic hydrogen impact are also shown in Fig.1. Both electron and hydrogen impact data indeed show that maximum stripping or ionization cross sections are found to be varied as $E_i^{-1.8}$.

5) If not available, maximum cross sections for electron stripping and ionization of carbon ions with different charge state can be determined based upon the $E_i^{-1.8}$-dependence, which has been obtained as explained above (see 3 and 4).

6) As expected, the electron stripping cross sections by heavy

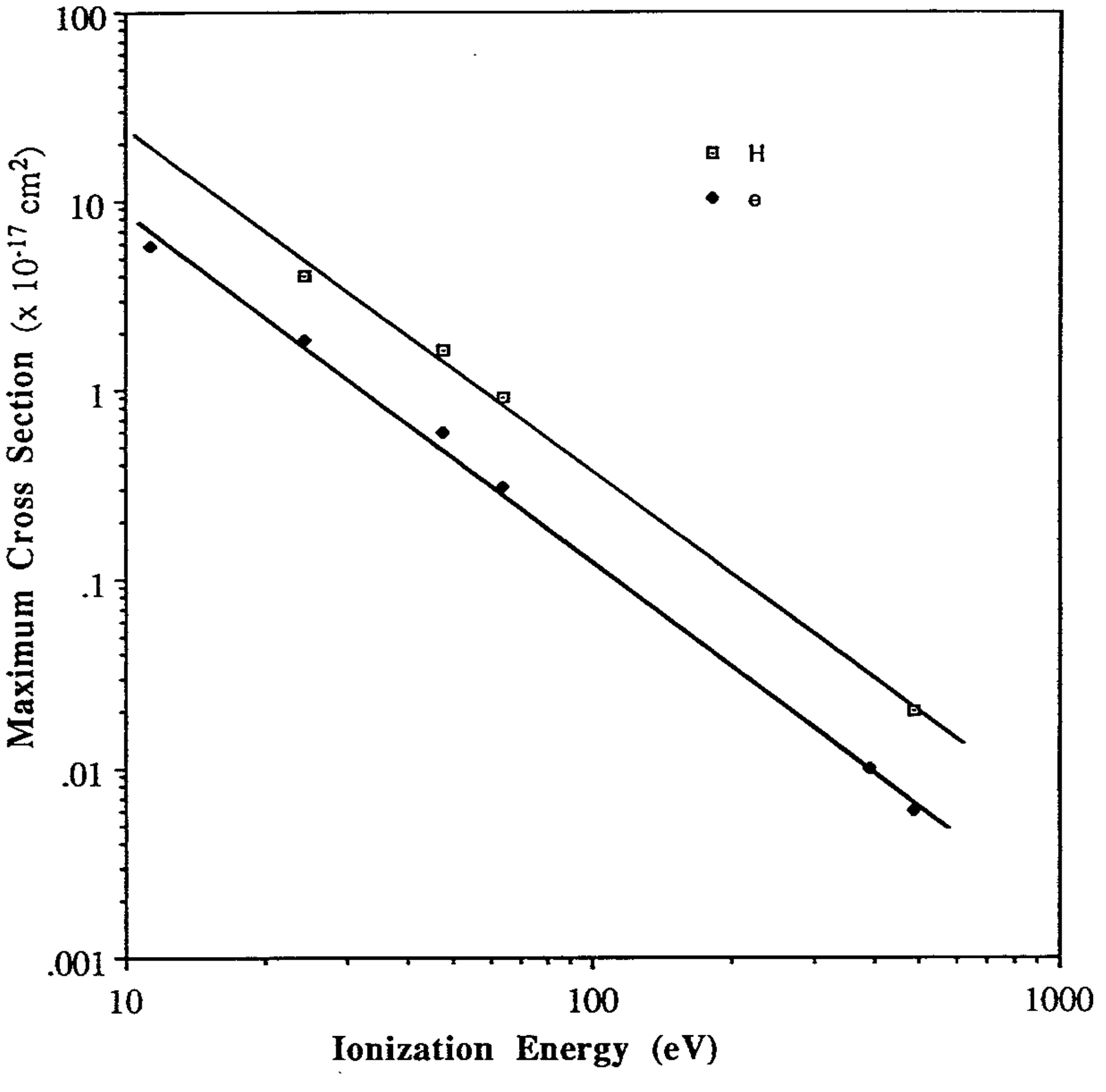

Fig.1 The observed maximum cross sections of carbon ions of various charges under hydrogen atom[16] (upper line) and electron[15)] (lower line) impact as a function of the ionization threshold energy

particle impact increase as the collision energy increases and reach maximum at around the energy where the particle velocity is nearly equal to that of electrons to be ionized, corresponding to the ionization threshold energy. This is in sharp contrast to those in electron impact where such maximum ionization cross sections are observed at around 2-3 times the ionization threshold energy. With further increase of the collision energy, they start to decrease relatively slowly and seem to have almost the same energy dependence in both heavy particle and electron impact.

On the other hand, the electron capture cross sections for multiply charged ions[9)] are roughly constant at energies up to 50-80 keV/amu and far larger than stripping cross sections but above 100 keV/amu they start to decrease quickly as the energy increases and the electron stripping processes begin to dominate the electron capture processes. For example, cross sections for these two processes become equal each other at 55, 105 and 270 keV/amu for carbon ions, C^{q+}, with q= 1, 2 and 3. For higher charge ions (q = 4 and 5), the stripping cross sections are estimated to be far smaller than the electron capture cross sections at the energy region of our interest.

7) The calculated collision energy dependence[12)] of electron stripping cross sections of various (hydrogenic) ions by hydrogen atoms above the collision energies where they become maximum seems to be practically the same for ions with different (nuclear) charge, though those at lower energies are somewhat different from each other. Thus we can use data available for C^+ ions to draw the energy dependence curves for carbon ions in various charge states at high energy region, as seen in the following figure.

III. Results and discussion

1) C^0 atoms : σ_{01}

$C + H \rightarrow C^+$

The cross sections for carbon atoms, C^0, by electron impact have been recommended by Bell et al.[15], meanwhile no data for electron stripping by H atoms are available. Thus we extrapolate the cross section using the energy dependence for C^{1+} ions (see the next section) which was adjusted to fit the electron impact data at the collision energy at around $15*E_i$. The final results are shown in **Fig.2** as a function of the collision energy, in comparing with electron impact ionization data.

2) C^+ ions : σ_{12}

$C^+ + H \rightarrow C^{2+}$

For this ion, relatively good quality of data are available over a limited collision energy range for hydrogen atom impact (Goffe et al.[16]). Thus extrapolation to high energy data based upon electron impact data (Bell et al.[15]) can be made nicely and reliably (see **Fig.3**). As expected, the extrapolated stripping cross sections indeed become roughly equal to the ionization cross sections by electron impact at around $10*E_i$. Also it would be interesting to compare those by hydrogen atom impact with those by proton impact data

$C^+ + H^+ \rightarrow C^{2+}$

by Neil et al.[17] and Hopkins et al.[18] Their proton impact data show that the electron stripping due to electron transfer into proton becomes dominant below 100 keV/amu, meanwhile those due to direct ionization begins to dominate at above 120 keV/amu.[17,18] The proton impact ionization cross sections are slightly larger than those in hydrogen atom impact. This can be understood to be due to the screening of a proton by an electron in hydrogen atom

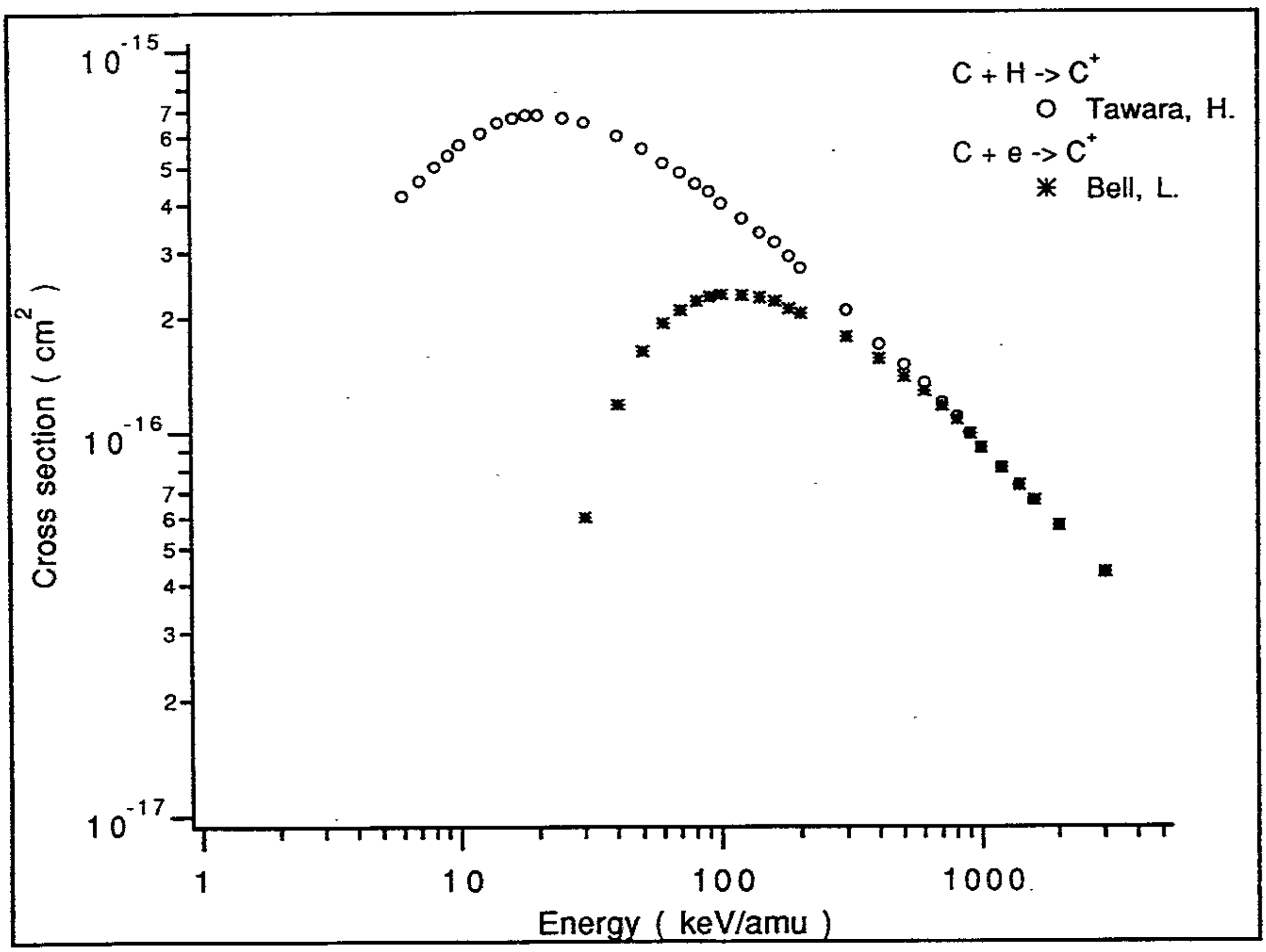

Fig.2 Electron stripping cross sections for C atoms under hydrogen atom and electron impact as a function of the collision energy

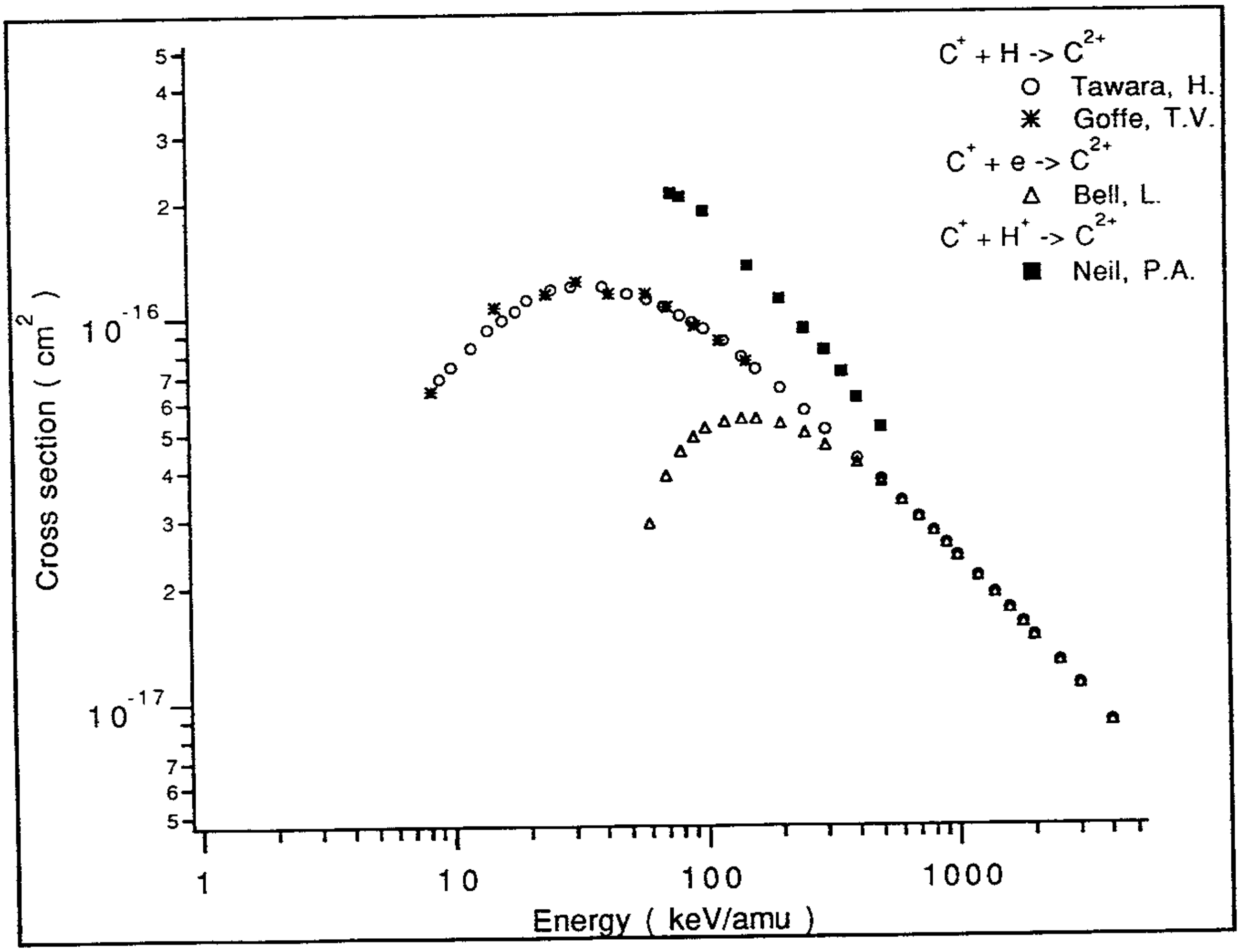

Fig.3 Electron stripping cross sections for C^+ ions under hydrogen atom and electron impact as a function of the collision energy

where the effective nuclear charge is smaller than that of proton. This screening effect by an additional electron in hydrogen atom becomes small at higher energies and the cross sections by atom at high energies tend to converge to those by proton impact as well as electron impact.
The recommended electron stripping data are shown in **Fig.3**.

3) C^{2+} ions : σ_{23}

$C^{2+} + H \rightarrow C^{3+}$

Only data by Goffe et al.[16] are available in hydrogen atom target up to the energy slightly above cross section maximum. If we use an extrapolation to high energies mentioned above, hydrogen atom impact data seem not to converge to but to be considerably larger than electron impact ionization data recommended by Bell et al.[15] Probably this is due to the fact that, when C^{2+} ions collide with hydrogen atoms, C^{2+} ions (which have two electrons in more tightly bound 2s orbit than 1s electron in the ground state hydrogen atom) interact with not a bare but slightly screened nucleus as well as an electron outside hydrogen nucleus (proton). Thus total electron stripping cross sections of ions should be sum of those by the screened nucleus and by an electron.
The extrapolated cross sections are based upon the same energy dependence as in C^{+} ions at high energies. As mentioned in the previous section, some contribution to the electron stripping of C^{2+} ions from ionization by electron impact becomes non-negligible which is clearly seen in **Fig.4** as a peak much broader than that for C^{+} ions.

4) C^{3+} ions : σ_{34}

$C^{3+} + H \rightarrow C^{4+}$

Data for hydrogen atoms by Goffe et al.[16] are limited in quantities and still far away from the converging energy region.

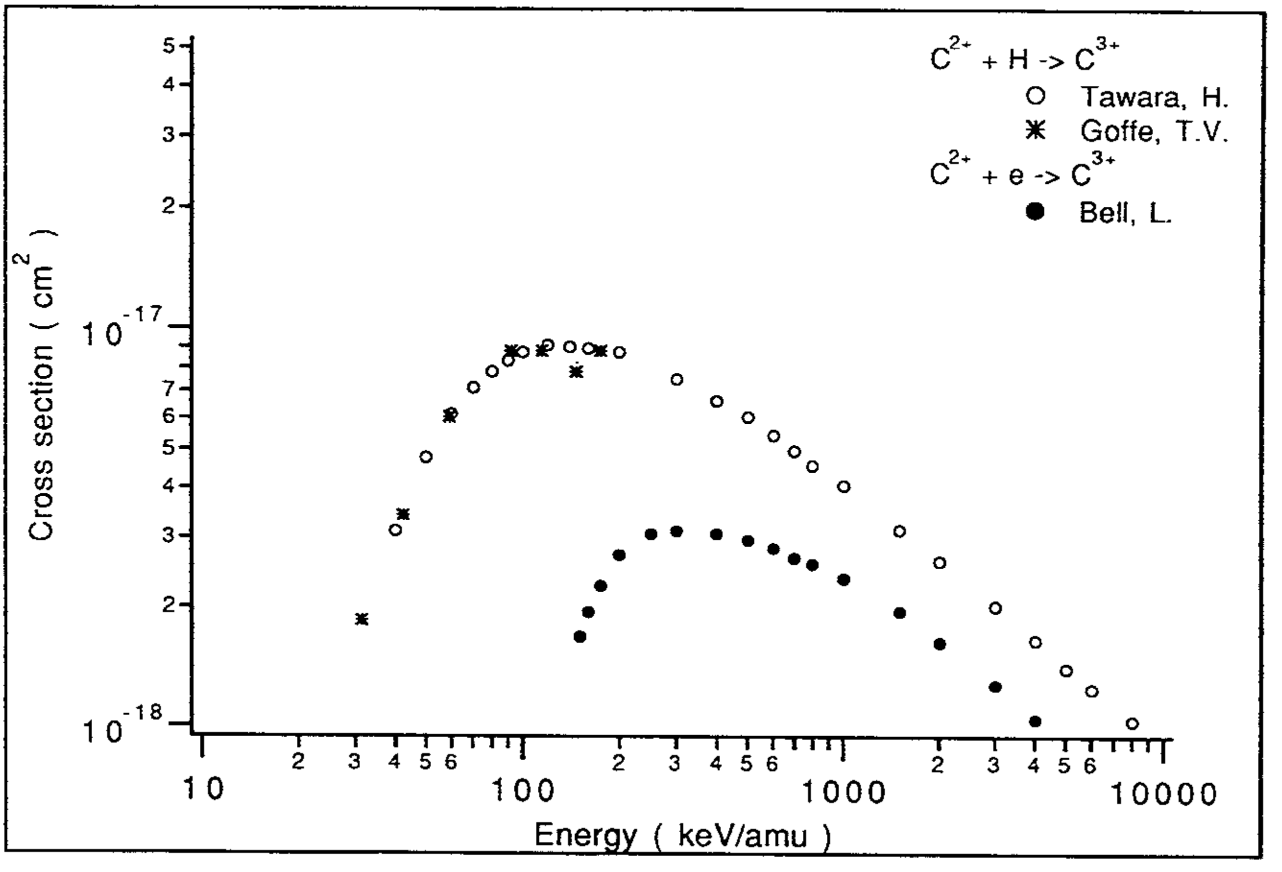

Fig.4 Electron stripping cross sections of C^{2+} ions under hydrogen atom and electron impact as a function of the collision energy

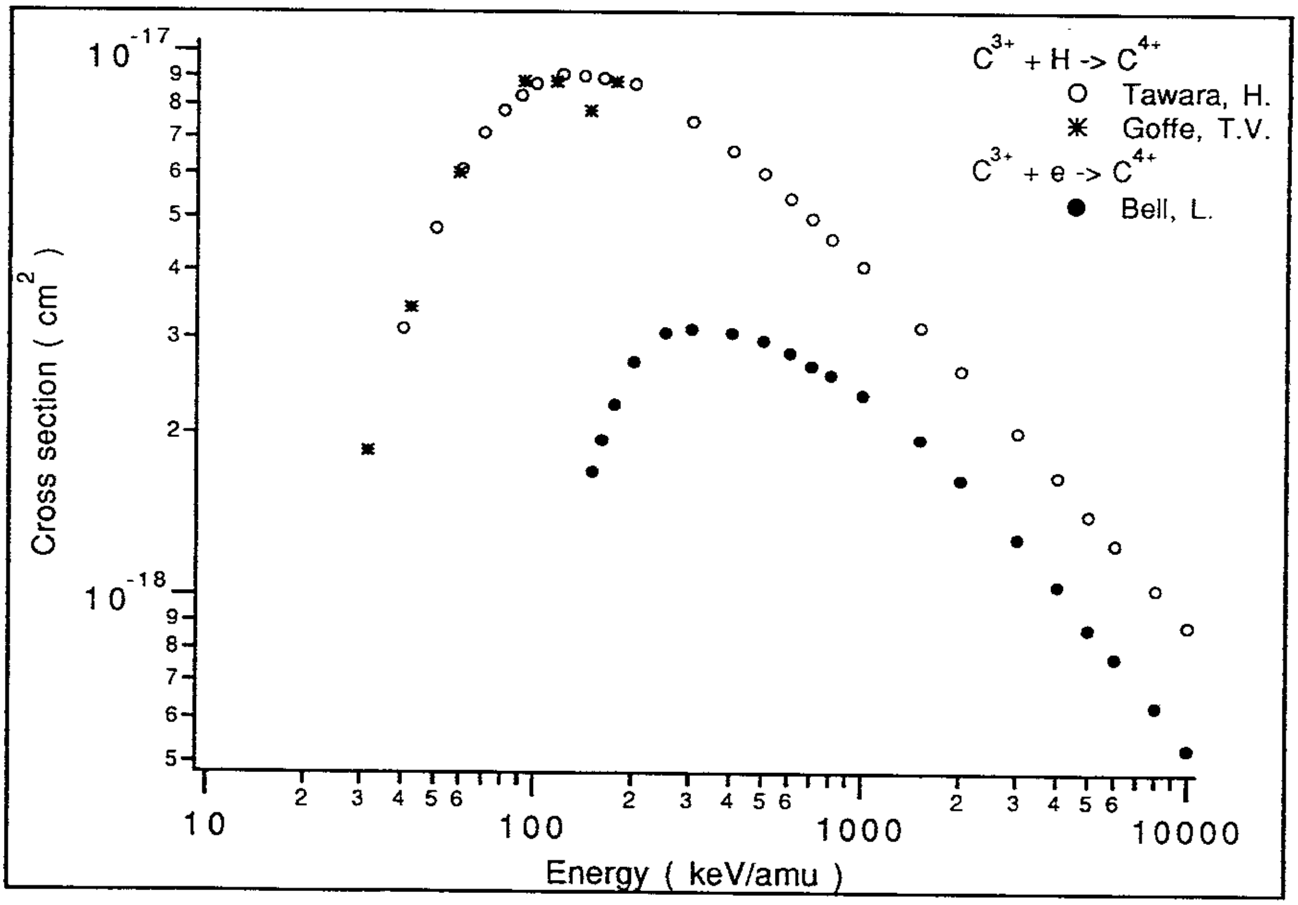

Fig.5 Electron stripping cross sections of C^{3+} ions under hydrogen atom and electron impact as a function of the collision energy

As in C^{2+} ion collisions, the extrapolated values at high collision energies seem to be slightly larger than those by electron impact at high energies recommended by Bell et al.[15] but smaller than twice those by electron impact due to slight screening by an electron. Here the contribution of electron impact ionization is clearly seen as a broad peak in cross section (**Fig.5**), as mentioned above. Indeed this feature has been observed in a recent experiment by Montenegro et al.[19] in H_2 target (instead of H target) who show the cross sections of electron stripping, divided by a factor of two due to H_2 targets at higher energies (200-300 keV/amu) are 15 % smaller than the present estimation.

5) C^{4+} ions : σ_{45}
$C^{4+} + H \to C^{5+}$

No data for hydrogen atom impact are available except for those for molecular hydrogen by Tonuma et al.[20] which are plotted after divided by two, assuming two independent hydrogen atoms in a hydrogen molecule. In C^{4+} ions, only two tightly bound electrons in 1s state are left. Then this ion feels almost two independent particles in hydrogen atom target (a proton and an electron) and thus the observed cross sections should be given as the sum of the cross sections by both particles. As mentioned above, at high energies, these two particles tend to have identical cross sections for electron stripping and thus the cross sections by hydrogen atoms could be taken as two times those of electron impact at highest energies, recommended by Bell et al.[15] (see **Fig.6**). It should be noted that experimental data by Tonuma et al. seem to be too small by 40 %, compared with those recommended here.

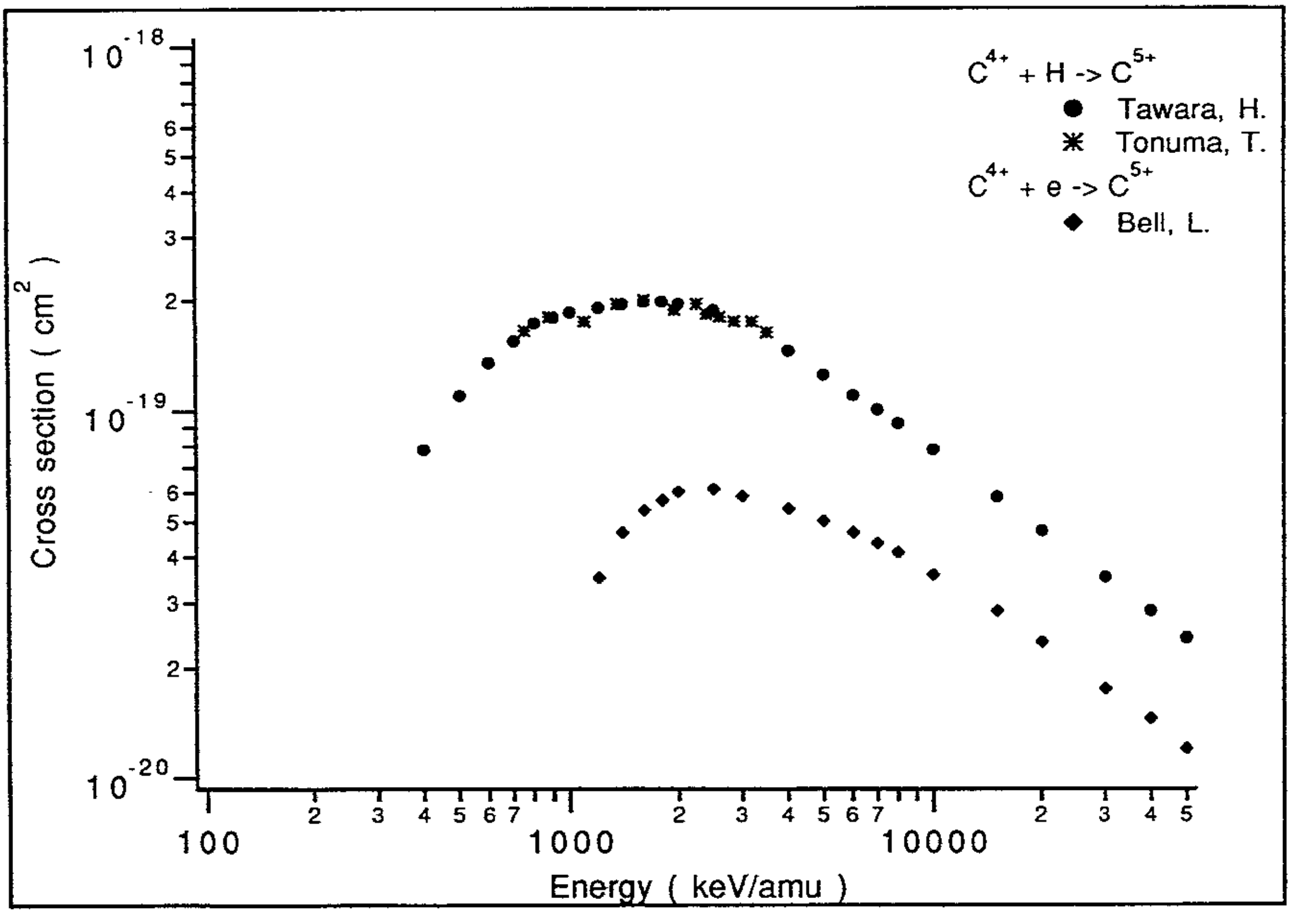

Fig.6 Electron stripping cross sections of C^{4+} ions under hydrogen atom and electron impact as a function of the collision energy

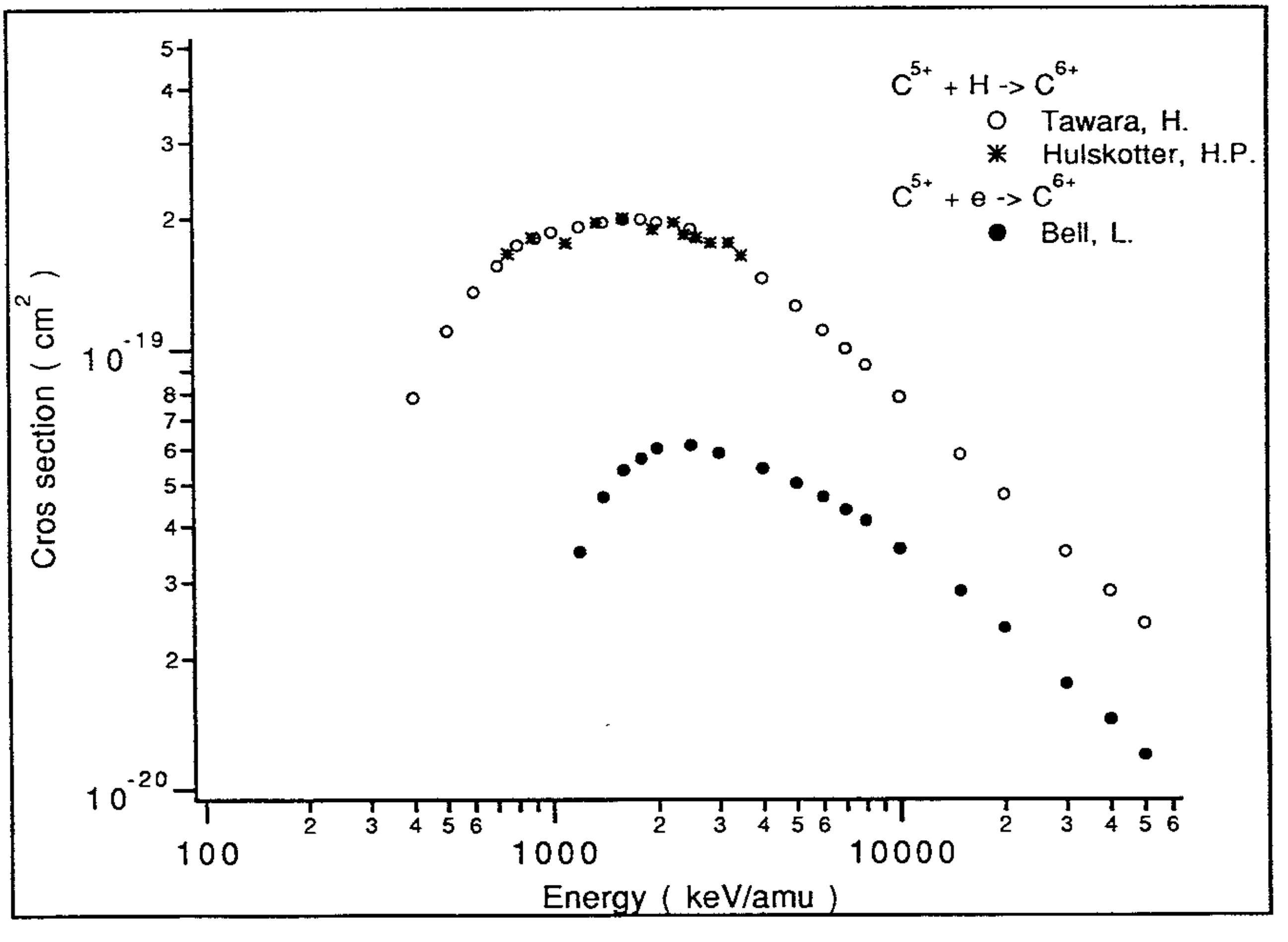

Fig.7 Electron stripping cross sections of C^{5+} ions under hydrogen atom and electron impact as a function of the collision energy

6) C^{5+} ions : σ_{56}

$C^{5+} + H \rightarrow C^{6+}$

Only data by Hülskötter et al.[13] for molecular hydrogen impact (instead of atomic hydrogen impact) are available at the collision energies where the electron stripping cross sections are close to maximum. These data could be assumed to be twice those for hydrogen atom at these high energies as shown in their theoretical calculation and thus plotted in **Fig.7**. Similar to C^{4+} ion collisions, hydrogen atom target could be considered to be two independent particles (a proton and an electron), both of which have practically identical cross sections at highest energies. In fact the cross sections thus determined at low energies seem to converge smoothly to twice those by electron impact ionization at high energies.

IV. Concluding remarks

High energy (100 - 1000 keV/amu) neutral beam injection (NBI) should result in the increased effective charge of plasmas by collisions of impurity ions with the injected neutral hydrogen beams, which, in turn, would enhance radiation loss through bremstrahlung by electrons in plasmas. In order to get information on this issue, we have estimated the electron stripping cross sections of carbon ions with different charge under atomic hydrogen collisions, based upon extrapolation of hydrogen impact data available over a limited collision energy range in combining with the well-established electron impact ionization data at high energy region. The estimated electron stripping data for carbon ions of all the charge states are summarized in **Fig.8**. As clearly seen in this figure, the cross sections for all ions show maximum at around the collision energy corresponding to the electron ionization threshold energy and then at higher collision energies they decrease with increasing

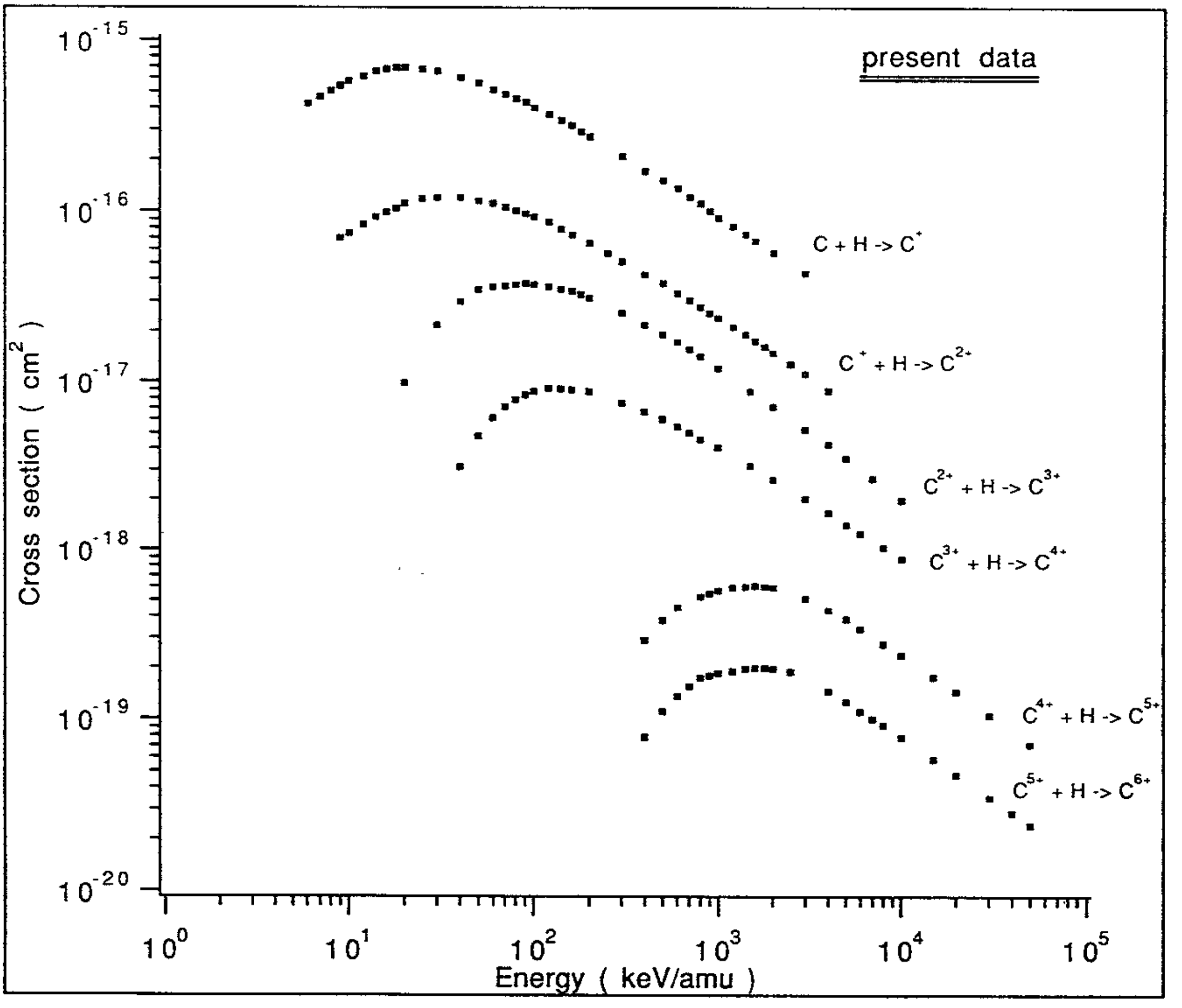

Fig.8 Estimated electron stripping cross sections for carbon ions of various charge under hydrogen atom impact as a function of the collision energy

the collision energy, its energy dependence being practically the same to electron impact ionization.
As shown in this report, the electron stripping cross sections of impurity ions in collisions with atomic hydrogen targets are still scarce. Indeed no data are available at all for the electron stripping of another typical impurity ions, O^{q+}, colliding with atomic hydrogens which is strongly related with the efficiencies of neutral beam injection heating system.

The double electron stripping cross sections of these ions are expected to be small, compared with single electron stripping cross sections described above. Therefore, we have not discussed them here.

Thus it would be urgently required to measure and calculate these electron stripping cross sections of the impurity ions, C^{q+} and O^{q+}, over a wide range of the collision energy.

Because of their scarcity of systematic investigations, we did not show any data for oxygen ions, O^{q+}. For information, we list in appendix some relevant references which include cross sections for electron stripping of the following processes :

$C^{q+} + H_2 \rightarrow C^{(q+1)+}$
$C^{q+} + He \rightarrow C^{(q+1)+}$
$O^{q+} + H \rightarrow O^{(q+1)+}$
$O^{q+} + H_2 \rightarrow O^{(q+1)+}$
$O^{q+} + He \rightarrow O^{(q+1)+}$.

It should also be pointed out that the electron stripping cross sections for oxygen ions could be estimated from those for carbon ions shown here (probably with the uncertainties of 50 - 100 %), by taking into account the fact that the cross sections are roughly proportional to the inverse square of the ionization threshold energy, except for those near the ionization threshold region.

Finally it should be pointed out that some empirical formulas have been proposed to calculate the electron stripping cross sections, with some success, for simple collision systems.[21-24)]

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Appendix

Here is a list of available data and references relevant to electron stripping processes involving C^{q+} and O^{q+} ions in collisions with H_2 and He collisions mentioned above. Note again that no investigation has been reported for O^{q+} + H collisions.

A1) $C^{q+} + H_2 \rightarrow C^{(q+1)+}$

Fogel et al. (1959)[a]	[σ_{01} : 2-5.5 keV/amu]
Goffe et al. (1979)[b]	[σ_{12} : 8-150 keV/amu ;
	σ_{23} : 18-210 keV/amu ;
	σ_{34} : 32-210 keV/amu]
Tonuma et al. (1973)[c]	[σ_{45} : 4.2-6.5 MeV/amu]
Hülstkötter et al. (1991)[d]	[σ_{56} : 0.7-3.5 MeV/amu]

A2) C^{q+} + He $\rightarrow C^{(q+1)+}$

Fogel et al. (1959)[a]	[σ_{01} : 2-5.5 keV/amu]
Nakai et al. (1991)[e]	[σ_{01} : 25-130 keV/amu]
Dmitriev et al. (1962)[f]	[σ_{34}, σ_{45} : 334 keV/amu]
Tonuma et al. (1973)[c]	[σ_{45} : 4.5-7.5 MeV/amu]
Hülskötter et al. (1991)[d]	[σ_{56} : 0.5-3.5 MeV/amu]

A3) $O^{q+} + H_2 \rightarrow O^{(q+1)+}$

Fogel et al. (1959)[a]	[σ_{01} : 1.5-4 keV/amu]
Olsen et al. (1974)[g]	[σ_{01} : 16-33 keV/amu ;
	σ_{12} : 6.5-32 keV/amu ;
	σ_{23} : 18-31 keV/amu]
Boman et al. (1989)[h]	[σ_{56}, σ_{67}, σ_{78} : 1.0 MeV/amu]
Tipping et al. (1988)[i]	[σ_{78} : 0.5-2.2 MeV/amu]

A4) $O^{q+} + He \rightarrow O^{(q+1)+}$

Fogel et al. (1959)[a]	[σ_{01} : 1.5-4 keV/amu]
Dmitriev et al. (1962)[f]	[σ_{23}, σ_{34}, σ_{45}, σ_{56}, σ_{67} : 0.33 MeV/amu]
Macdonald et al. (1971)[j]	[σ_{34} : 0.5-1.0 MeV/amu ; σ_{45} : 0.5-1.5 MeV/amu ; σ_{56} : 0.5-2.0 MeV/amu ; σ_{67} : 0.5-2.0 MeV/amu ; σ_{78} : 1.0-2.5 MeV/amu]
Dillingham et al. (1981)[k]	[σ_{78} : 0.55-2.5 MeV/amu]
Hippler et al. (1987)[l]	[σ_{67} : 1.0 MeV/amu ; σ_{78} : 1.0-2.0 MeV/amu]
Boman et al. (1989)[h]	[σ_{56}, σ_{67}, σ_{78} : 1.0 MeV/amu]

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