Recommended Cross Section Data for Carbon Ions and Atoms: Electron-impact Excitation, Ionization and Charge Exchange

Hiroya Suno and Takako Kato
National Institute for Fusion Science, Orosi-cho 322-6, Toki 509-5292, Japan
E-mail: e-mail: suno.hiroya@nifs.ac.jp

Abstract. Cross section data have been compiled for electron-impact excitation and ionization of carbon ions C\textsuperscript{\textit{n}+}, as well as charge-exchange process between carbon ions and hydrogen atoms. A large amount of theoretical and experimental cross section data have been collected from the literature, and we have critically assessed their accuracy. The recommended cross sections, the best values for use, are expressed in the form of simple analytical functions. These are also presented in graphical form.

Keywords: Electron-impact excitation, electron-impact ionization, charge exchange

1. Introduction
Electron-impact excitation and ionization of atomic carbon ions are important processes in plasma diagnostics and energy-loss calculations in fusion plasmas. Charge-exchange process of carbon ions with hydrogen atoms also provides a useful plasma diagnostics. In this report, we present a complete set of cross sections for these processes. As a basis for this cross section set we have used the available experimental and theoretical data from the literature and critically assessed their accuracy.

2. Electron-impact excitation
There exist numerous theoretical cross section data for electron-impact excitation of carbon ions. Previously, Itikawa et al. [1] compiled cross sections reported before 1985, assessed them for carbon ions (C\textsuperscript{+}-C\textsuperscript{5+}) as well as oxygen ions (O\textsuperscript{+}-O\textsuperscript{8+}), and fitted their recommended values to an analytical formula. Theoretical cross sections were reported by McDowell et al. [2], Aggarwal et al. [3], and Zou et al. [4] for C\textsuperscript{5+}. Fisher et al. [5] have also carried out cross section calculations. Callaway [6] have reported theoretical rate coefficient data. There also exist results on electron-impact excitation cross sections for the other ionic states. Except for optically allowed transitions, all electron-impact excitation cross sections are scattered, and it has been sometimes difficult to determine the recommended data. However, the close-coupling method and \textit{R}-matrix method provide more reliable results at lower collision energies, so can the distorted wave method and Coulomb-Born method at high energies. Our recommended cross sections are chosen following this criterion.
Electron-impact excitation cross sections $\sigma$ are expressed in terms of collision strengths $\Omega$. For the excitation from a state $i$ to $f$, the cross section is given by

$$\sigma_{if}[\pi a_0^2] = \frac{\Omega_{if}}{\omega_iE_e[Ry]} = \frac{1}{\omega_iV_{if}[eV]} \frac{\Omega_{if}}{X},$$

where $E_e$ is the energy of the incident electron, $\omega_i$ is the statistical weight of the initial state, $V_{if}$ is the excitation energy, and $\Omega_{if}$ is the collision strength. Here, the cross section is in units of $\pi a_0^2$, where $a_0$ is the Bohr radius and $X$ is the reduced electron energy defined by

$$X = E_e/V_{if}.$$

When the cross section and energy are given respectively in units of cm$^2$ and eV, we have

$$\sigma_{if}(\text{cm}^2) = 11.969 \times 10^{-16} \times \frac{\Omega_{if}}{\omega_iE_e[eV]} = 11.969 \times 10^{-16} \times \frac{\Omega_{if}}{\omega_iV_{if}[eV]X}.$$

With the Maxwellian distribution of electron velocity for temperature $T_e$, the rate coefficient is calculated by

$$R_{if}[\text{cm}^3\text{s}^{-1}] = \frac{8.010 \times 10^{-8}}{\omega_i\sqrt{T_e[eV]}} \int_1^{\infty} dX \Omega_{if}(X)e^{-yX},$$

where

$$y = V_{if}/T_e.$$

We have carefully chosen reliable electron-impact data from the above mentioned references. Once the recommended cross sections were determined, a fit was made, which facilitates their applications. Unless otherwise stated, we used the formula:

$$\Omega_{if}(X) = A + \frac{B}{X} + \frac{C}{X^2} + \frac{D}{X^3} + E\ln X,$$

where $A, B, C, D$ and $E$ are adjustable coefficients. The expression for the rate coefficient can be obtained analytically by using Eq.(4). For example, we have obtained $A = 2.446 \times 10^{-2}$, $B = -1.567 \times 10^{-2}$, $C = 1.010 \times 10^{-2}$, and $D = E = 0$ for the 1s$\rightarrow$2s transition of the C$^{5+}$ ion. The recommended collision strength and the original ones from the references are graphically shown in Fig. 1. The rate coefficients are shown in Fig. 2. In this work, we have treated 87 electron-impact excitation processes for C$^{5+}$-C$^{0+}$. These results will be published in Atomic Data and Nuclear Tables.

3. Electron-impact ionization

Electron-impact ionization of carbon ions has been extensively studied both experimentally and theoretically. Experimental measurements of C$^{n+}$ were carried out by Donets and Ovsyannikov [7] for ionic states $n = 1, 2, 3, 4$ and $5$, in the energy range above 0.1 keV. Cross sections were obtained semi-empirically by Pattard and Rost [8] for C$^{5+}$. Experimental measurements were also performed by Aichele et al. [9] for the same species. Theoretical calculation cross sections were also reported by Younger [10], Kao et al. [11], and Fang et al. [12].

The recommended cross section for electron-impact ionization is parametrized by the expression

$$\sigma[\text{cm}^2] = \frac{10^{-13}}{IE} \left\{ A_1 \ln(E/I) + \sum_{i=2}^{N} A_i \left( 1 - \frac{I}{E} \right)^{i-1} \right\},$$
where the collision energy $E$ and ionization potential $I$ are expressed in eV units and $A_i$ are fitting coefficients. The coefficient $A_1$ can be related to the continuum oscillator strength $df/d\epsilon$ by

$$A_1 = 8.39 \times 10^{-2} I[eV] \int_0^\infty \frac{1}{E + \epsilon} \frac{df}{d\epsilon} d\epsilon$$

(8)

where $\epsilon$ is the energy of ejected electrons. For example, we have obtained $I = 490.0$, $A_1 = 2.489 \times 10^{-1}$, $A_2 = 1.847 \times 10^{-1}$, $A_3 = 4.475 \times 10^{-2}$, $A_4 = -9.432 \times 10^{-2}$, and
where the collision energy $E$ is expressed in eV/amu units and $a_i$, $i = 1-14$ are fitting parameters. For example, we have found $a_1 = 2.301 \times 10^2$, $a_2 = 5.983 \times 10^3$, $a_3 = 3.117 \times 10^{-1}$, $a_4 = 1.300 \times 10^4$, $a_5 = 6.613 \times 10^{-1}$, $a_6 = 7.299 \times 10^4$, $a_7 = 4.985$, $a_8 = 2.100 \times 10^4$, $a_9 = 1.557$, $a_{10} = 3.355 \times 10^{-2}$, $a_{11} = 1.800 \times 10^5$, $a_{12} = -9.768 \times 10^{-2}$, $a_{13} = 4.500 \times 10^3$, and $a_{14} = 3.584$ for the $C^{6+}+H \rightarrow C^{5+}+H^+$ transition. The fitted cross section as well as the original cross sections for charge exchange processes are graphically shown in Fig. 4. In this work, we have treated 25 total and state-selective charge exchange processes in H+C\textsuperscript{m+} processes. These results were published in Ref. [20].
5. Summary
We have compiled and critically assessed the cross sections for electron-impact excitation and ionization of atomic carbon ions, as well as charge exchange in collisions between carbon ions and hydrogen atoms. The recommended cross sections are expressed in terms of simple analytic fit functions. These can immediately lead to applications in fusion science. In this paper, we have shown only examples of our results. All our results will be published in Atomic Data and Nuclear Data Tables.

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