# Database for Dielectronic Recombination Rate Coefficients to the Excited States of the Carbon Atom and Ions

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## 1 Introduction

Dielectronic recombination processes for L-shell ions are important in plasmas such as the solar corona and divertor plasma for plasma diagnostics. We have calculated the dielectronic recombination rate coefficients to the excited states (n = 2 - 6) of L-shell carbon atom and ions (C I - C IV). These data are necessary to calculate the population density of excited states of each ion as well as for total recombination rate coefficients. Atomic data (energy levels, transition probabilities, autoionization rates) are calculated by the Cowan code and AUTOLSJ methods [1].

Scaling methods are used for highly excited states because the contribution of the highly excited states up to more than n = 100 is not negligible. We present the dielectronic recombination rate coefficients to the excited states by a parameter fit to an analytical formula. Density effects on the effective recombination rate coefficients are discussed.

## 2 Method

Dielectronic recombination rate coefficients $\alpha_d$ to the excited states *nl* [LS] of an ion $X^{(z-l)+}$ from an initial state $\alpha_0$ of a recombining ion $X^{z+}$ are calculated by

$$\alpha_d(nl\,[LS]\,|\,\alpha_0) = (h^2/2\pi\, mkT_e)^{3/2} \sum_\gamma \sum_J (\, g_{z-1}(\gamma[L'S'J'])/2g_z(l)\,) \\ \times (A_a(\gamma\,[L'S'J'], \alpha_0)\, A_r(\gamma\,[L'S'J'], nl[LSJ]) / (\sum A_a + \sum A_r) \exp(-E_s/kT_e) \qquad (1)$$

for the process as follows,

$$X^{Z+}(\alpha_0) + e \rightarrow X^{(Z-l)} + {}^{**}(\gamma) \rightarrow X^{(Z-1)+}(nl\,[LS]\,) + h\nu \qquad (2)$$

where $\gamma$ is the autoionizing state, *nl* the bound states, $A_a$ the autoionization rate, $A_r$ radiative transition probability, $E_s$ the energy of the state $\gamma$ relative to the initial state $\alpha_0$ which we assumed to be the ground state of a recombining ion. The values for $A_a$, $A_r$, and $E_s$ are calculated for fine structure levels with n = 1 – 6 [1-4] and the rate coefficients are summed into LS levels by Eq. (l).

## 3 Fit Parameters for the Rate Coefficients $\alpha_d$(nl [LS])

We have fitted the rate coefficients to each excited state by a fitting formula as follows,

$$\alpha_d \,(\mathrm{nl\ [LS]}\ |\alpha_0) = \Sigma i A_i \exp\{-(E_i / T_e)\}\ T_e^{-3/2}\ \ \mathrm{cm^3 s^{-1}} \tag{3}$$

where $E_i$ and $T_e$ are in eV. An example of these parameters is given in Table 1. The data for C I - C III are available upon request (takako@nifs.acjp).

## 4 nl-Dependence of $\alpha_d$

The rate coefficients have large values even if the principal quantum number is above n = 100, and their contribution is not negligible for the total recombination rate and for the population density in a recombining plasma. We obtained the values for n > 6 by using scaling formulae [1] of $A_r$ (2pnl, 2snl) = $A_r$ (2p6l, 2s6l) and $A_a$ (2pnl) = $(6/n)^3$ $A_a$(2p6l) for each LSJ level and summed up with LSJ after scaling. In Fig.1, we show the distribution of $\alpha_d$(nl) of C I as an example.

## 5 Total Recombination Rate Coefficients and the Density Effect

In order to obtain the total recombination rate coefficients we summed the rates up to n = 500. However, a real plasma has a finite electron density, and the collisional effects for such high n cannot be neglected. For example, the thermal limit is estimated to be n ~ 15 for a plasma of $T_e$ = 30 eV and $n_e$ = $10^8$ $\mathrm{cm^{-3}}$. Therefore, it is necessary to include the density effect when the recombination rate coefficients are used to obtain the ion abundances in plasmas. We define the effective recombination rate coefficient as follows,

$$\alpha_{\mathrm{eff}} \equiv \Sigma_i \,(A_{i1} / n_e + C_{i1})\ n(i) + \alpha_t(1)\ n_e + \alpha_r(1) + \alpha_d(1) \tag{4}$$

where $\alpha_t(1)$ and $\alpha_r(1)$ indicate the three body and radiative recombination rate coefficients to the ground state, respectively and $C_{i1}$ is the collisional de-excitation rate coefficient from the level i to the ground state. The $\alpha_{\mathrm{eff}}$ for the various electron densities as a function of electron temperature are shown in Fig. 2. However, in order to obtain $\alpha_{\mathrm{eff}}$, we should consider collisional and microfield l-mixing in autoionizing levels which are not included in our calculation. Further investigations are required for these processes.

## References

[1] J. Dubau, T. Kato, U. I. Safronova, these proceedings (1997)

[2] U. I. Safronova and T. Kato, *Physica Scripta* **53**, 461-472 (1996)

[3] T. Kato, U. I. Safronova and M. Ohira, *Physica Scripta* **55**, 185 -199 (1997)

[4] U. Safronova, T. Kato and M. Ohira, NIFS-DATA-37 (1996), *J. Quant. Spectrosc. Radiat. Transfer* **58**, 193 (1997)

Table 1: Fitting parameters by formula Eq. (3) for $\alpha_d(k)$ of C I.

| Excited state | | $A_1(cm^3s^{-1})$ | $E_1$(eV) | $A_2(cm^3s^{-1})$ | $E_2$(eV) |
|---|---|---|---|---|---|
| $2s^2$ $2p^2$ | $^3P$ | 1.051E-13 | 1.723E+00 | 1.088E-12 | 3.887E+00 |
| $2s^22p^2$ | 1D | 6.402E-13 | 2.310E+00 | 5.551E-13 | 4.706E+00 |
| 2s22p2 | 1 S | 1.276E-13 | 3.522E+00 | 1.263E-14 | 1.247E+01 |
| | | | | | |
| $2s2p^3$ | $^5S$ | 1.177E-13 | 3.664E+00 | 3.820E-14 | 1.017E+00 |
| $2s2p^3$ | $^3D$ | 5.296E-13 | 4.615E+00 | 3.368E-14 | 1.588E+00 |
| $2s2p^3$ | $^3P$ | 7.903E-13 | 7.606E+00 | 4.663E-14 | 2.488E+00 |
| | | | | | |
| $2s^22p^3s$ | $^3P$ | 4.716E-13 | 6.671 E+00 | 4.671E-15 | 1.584E+00 |
| $2s^22p3s$ | $^1P$ | 4.263E-13 | 9.887E+00 | 2.828E-14 | 5.982E+00 |
| $2s^22p3p$ | $^1P$ | 4.525E-16 | 2.323E+00 | 5.378E-14 | 8.250E+00 |
| $2s^22p3p$ | $^3D$ | 3.551E-16 | 2.820E+00 | 5.530E-13 | 1.015E+01 |
| $2s^22p3p$ | $^3S$ | 8.293E-17 | 2.835E+00 | 1.130E-13 | 9.877E+00 |
| $2s^22p3p$ | $^3P$ | 2.585E-13 | 9.126E+00 | 2.995E-14 | 3.057E+00 |
| $2s^22p3p$ | $^1D$ | 1.394E-13 | 7.211E+00 | 7.422E-17 | 2.311E+00 |
| $2s^22p3p$ | $^1S$ | 1.917E-14 | 9.648E+00 | 3.491E-17 | 3.532E+00 |
| $2s^22p3d$ | $^3P$ | 7.198E-13 | 7.971E+00 | 2.832E-14 | 2.385E+00 |
| $2s^22p3d$ | $^1D$ | 2.822E-13 | 1.195E+01 | 3.188E-14 | 7.500E+00 |
| $2s^22p3d$ | $^3F$ | 3.012E-12 | 1.177E+01 | 3.278E-13 | 7.593E+00 |
| $2s^22p3d$ | $^3D$ | 1.420E-12 | 1.016E+01 | 9.464E-15 | 2.468E+00 |
| $2s^22p3d$ | $^1P$ | 2.759E-13 | 1.118E+01 | 2.014E-15 | 4.325E+00 |
| $2s^22p3d$ | $^1F$ | 8.183E-13 | 1.135E+01 | 2.966E-14 | 6.126E+00 |
| | | | | | |
| $2s^22p4s$ | $^3P$ | 6.280E-13 | 9.549E+00 | 9.864E-16 | 1.608E+00 |
| $2s^22p4s$ | $^1D$ | 3.266E-13 | 1.189E+01 | 1.628E-14 | 7.139E+00 |
| $2s^22p4p$ | $^1P$ | 5.684E-14 | 9.861 E+00 | 2.220E-16 | 2.426E+00 |
| $2s^22p4p$ | $^3D$ | 7.955E-13 | 1.180E+01 | 7.628E-16 | 2.862E+00 |
| $2s^22p4p$ | $^3S$ | 1.508E-13 | 1.142E+01 | 2.162E-16 | 2.875E+00 |
| $2s^22p4p$ | $^3p$ | 3.271E-13 | 1.140E+01 | 1.060E-14 | 3.154E+00 |
| $2s^22p4p$ | $^1D$ | 1.826E-13 | 8.673E+00 | 4.409E-16 | 2.944E+00 |
| $2s^22p4p$ | $^1S$ | 2.975E-14 | 1.080E+01 | 2.291E-16 | 3.524E+00 |
| $2s^22p4d$ | $^1D$ | 4.912E-13 | 1.241E+01 | 1.285E-14 | 7.266E+00 |
| $2s^22p4d$ | $^3F$ | 3.024E-12 | 1.123E+01 | 2.781E-15 | 3.138E+00 |
| | | | | | |
| Sum (n=7-500) | | 1.006E-09 | 1.189E+01 | 1.378E-11 | 6.406E+00 |

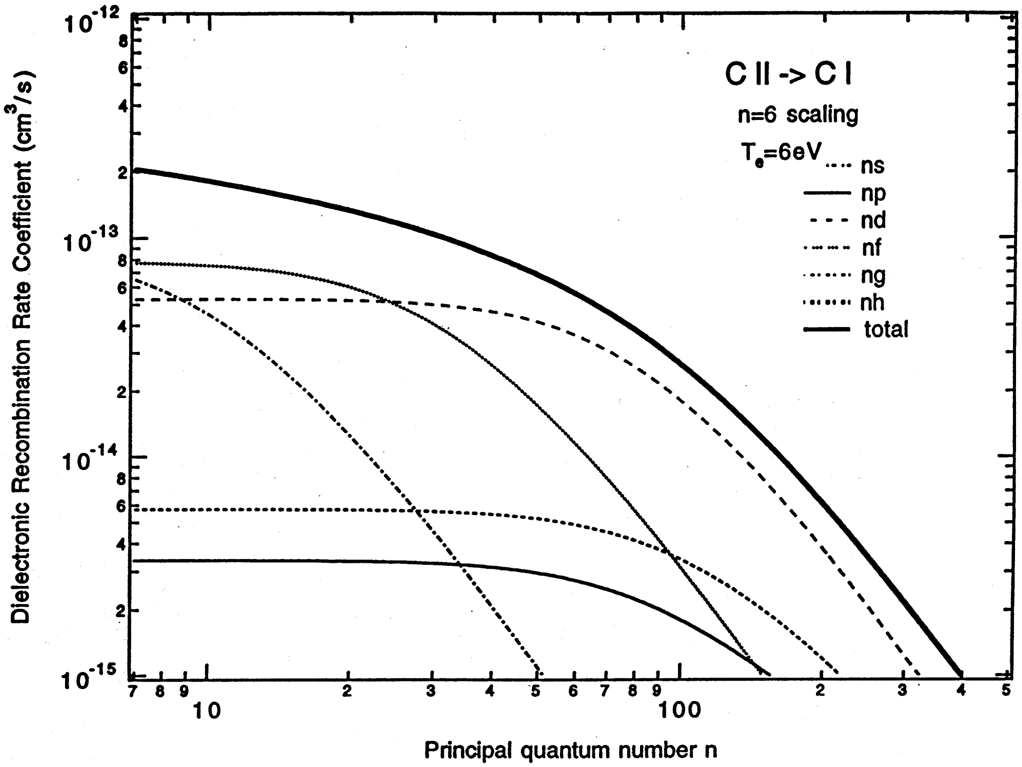

Figure 1: The dielectronic recombination rate coefficients to n-l states from C II to C I.

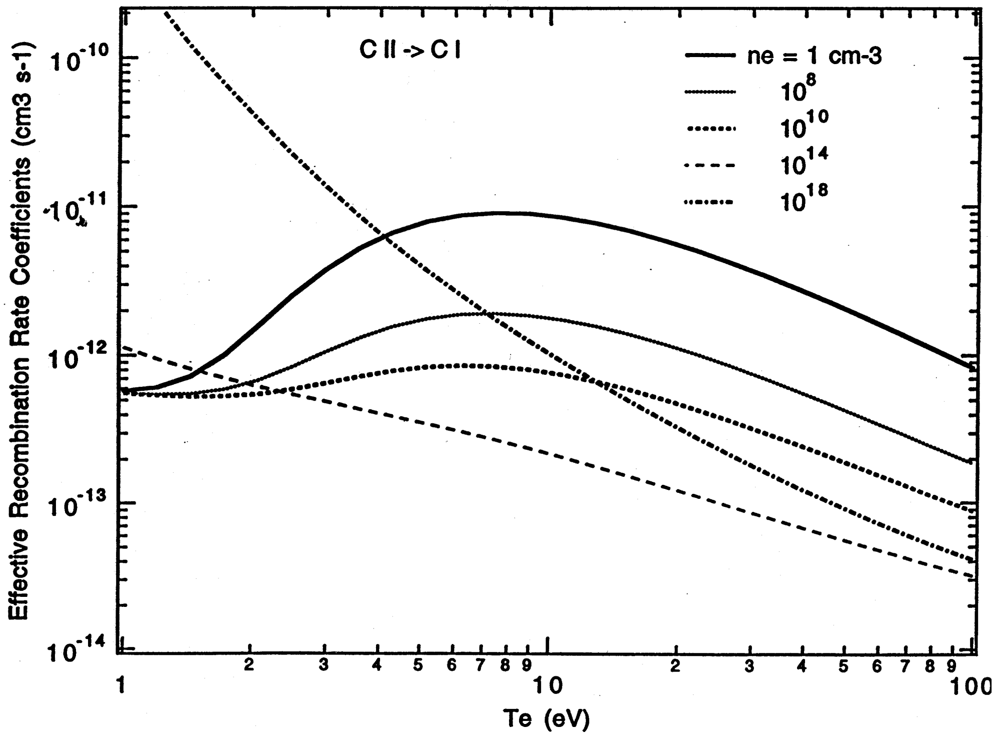

Figure 2: The effective recombination rate coefficients from C II to C I.