§16. Populating Mechanism in Dense Plasma for Doubly Excited States

Yamamoto, N. (Rikkyo Univ.),
Kato, T. (NIFS),
Fujimoto, T. (Kyoto Univ.)

We study effective rate coefficients using a collisional-radiative model (CRM) including doubly excited states. The effective rate coefficients in dense plasma were studied by Fujimoto and Kato [1]. They examined 1s-2s excitation / de-excitation using a CRM including doubly excited states 2*snl* as well as 1s-2p excitation / de-excitation including 2*pnl* states. They found an enhancement of the excitation and de-excitation rate coefficients with increasing electron density. We also found an enhancement due to different mechanism compared with their found mechanism [2]. In this paper, we present the populating mechanism of doubly excited states $2l'nl$ for effective 1s-2*l* excitation rate coefficients in dense plasma [3].

We constructed a new CRM including singly excited 1*snl* states and doubly excited $2l'nl$ and 3*dnl* states. Our model contains a total of 255 states; $1s^2$, 1s, 2*l*, and 3*l* states, 60 singly excited 1*snl* states, 118 doubly excited $2l'nl$, and 70 doubly excited $3l'nl$ states, where *n* is up to 20. The atomic processes considered in our model are excitation / de-excitation by electron impact, ionization / three-body recombination, radiative transitions, radiative recombination and auto-ionization / dielectronic capture. Atomic data used in our CRM for 1*snl* and $2l'nl$ states are the same as those described in ref.[1]. For $3l'nl$ states we calculated the data using HULLAC code [4].

Indirect contributions to effective 1s-2*l* excitation rate coefficients exceed direct excitation rate coefficient at $N_e \sim 10^{19}$ cm^{-3} for carbon ions (Z = 6) as shown in Fig.1. Indirect contributions through autoionization after dielectronic capture, 1s → $3l'nl$ → 2*l*, which is a resonance contribution, are important at low density. This resonance contribution decreases with increasing electron density at $N_e > 10^{21}$ cm^{-3}, as predicted in Ref.[5] by dielectronic capture ladder-like (DL) excitation-ionization process 1s → $3l'nl$ → $3l'n''l''$ → ... → $3l'$. With increasing density, indirect contributions through DL excitation-ionization, 1s → $2l'nl$ → $2l'n''l''$ → ...→ $2l'$ increase. At very high density (> 10^{21} cm^{-3}), indirect processes 1s → 1*snl* → $2l'nl$ → $2l'$ increase the effective rate coefficients proportionally to N_e [2]. We also found that for 2s-1s de-excitation, *l*-changing transitions, 2*snl*-2*pnl*, are important at intermediate densities.

Two population mechanisms are considered for doubly excited states at high density in ionizing phase (N_{1s} = 1). The first one is DL excitation-ionization, 1s → $2l'nl$ → $2l'$, where contributes to the increase in the effective excitation / de-excitation. The second one is indirect process 1s → 1*snl* → $2l'nl$ → $2l'$ where the excitation 1*snl* → $2l'nl$ process is important to produce the population densities of $2l'nl$ states. At high density, a population density for a high-*n* doubly excited state $q(2l'nl)$ can be written approximately using the method described in Ref.[6],

$$N_q \sim \frac{C_{q-1,q}}{C_{q,q+1}} N_{q-1} + \frac{C_{i,q}}{C_{q,q+1}} N_i . \quad (1)$$

The excitation rate coefficients are scaled as $C_{q-1,q} \propto (n-1)^7/n^3$, $C_{q,q+1} \propto n^7/(n+1)^3$. The excitation rate coefficents $C_{i,q}$ for $1snl$-$2l'nl$ do not depend on a principal quantum number *n*. We can derive $N_q / g_q \propto n^{-6}$ from the first term in eq.(1), as is shown in Ref.[6], where g_i is a statistical weight. The second term in eq.(1) corresponds to the second population mechanism, and $N_q / g_q \propto n^{-4}$ [3] is derived since $N_i \propto n^2$ in LTE. At very high density, the second process has a stronger effect than dose the first. So *n*-dependence of the population density per statistical weight changes from n^{-6} to n^{-4} at very high density as shown in Fig.2.

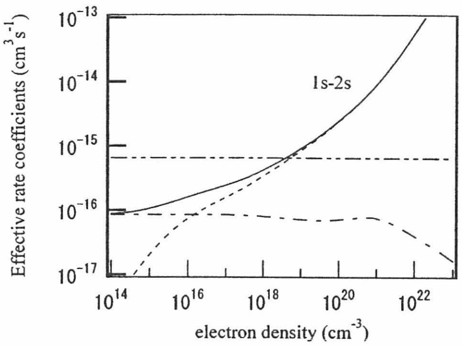

Fig.1. The effective 1s-2s excitation rate coefficients for Z = 6 at T_e = 3.5 × 10^5 K. Solid lines: indirect contribution including $2l'nl$ and $3l'nl$ states, dotted lines: without $3l'nl$ states, dot-dashed line: dielectronic capture resonances through $3l'nl$ states, dot-dot-dashed lines: direct 1s-2s.

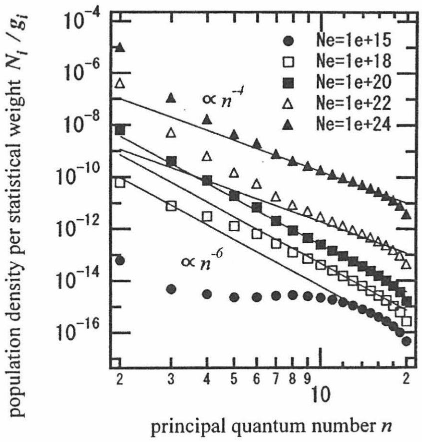

Fig.2 population density per statistical weight for doubly excited 2*snl* states for Z = 6 at T_e = 3.5x10^5 K.

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