New Excitation and Ionization Mechanism of Ions in Dense Plasmas: The Role of Autoionizing States

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It is shown that, in dense plasmas, dielectronic capture into doubly excited ionic states followed by the ladderlike excitation-ionization chain becomes important in the excitation-ionization process of ions. For the example of a hydrogenlike ion, its contribution to the excitation $1s \rightarrow 2s, 2p$ and also to the ionization has been evaluated by the method of the quasi steady-state solution to the rate equations. The increase is found to be substantial, i.e., by more than a factor of 2 for both the excitation and ionization rate coefficients.

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Recent developments of research on laser-produced plasmas show that, in the time development of the high-density plasma, highly ionized ions are produced much more rapidly than predicted from the conventional assumption[1] that ionization proceeds stepwise following the ionization chain starting from the neutral atom. For instance, the time-resolved x-ray streak picture[2] of aluminum and sodium spectra reveals that the hydrogenlike and heliumlike lines are emitted almost instantaneously without a delay from the laser pulse. In order to obtain full understanding of the ionization process, we should introduce a new ionization mechanism which would enhance the ionization rate coefficient for ions. In this Letter we propose an excitation-ionization mechanism that has been neglected so far and would be important whenever the plasma has a high electron density.

When the electron density n_e is very low, ionization of hydrogenlike ions, for example, is determined by the direct ionization due to electronic collisions, $1+e \rightarrow \text{ion}+2e$, where 1 stands for the ground level and e is the electron. (See Fig. 1.) With an increase in n_e the contribution from the ladderlike excitation-ionization mechanism becomes increasingly important[3]: This is the series of processes of excitation $1+e \rightarrow n+e$,

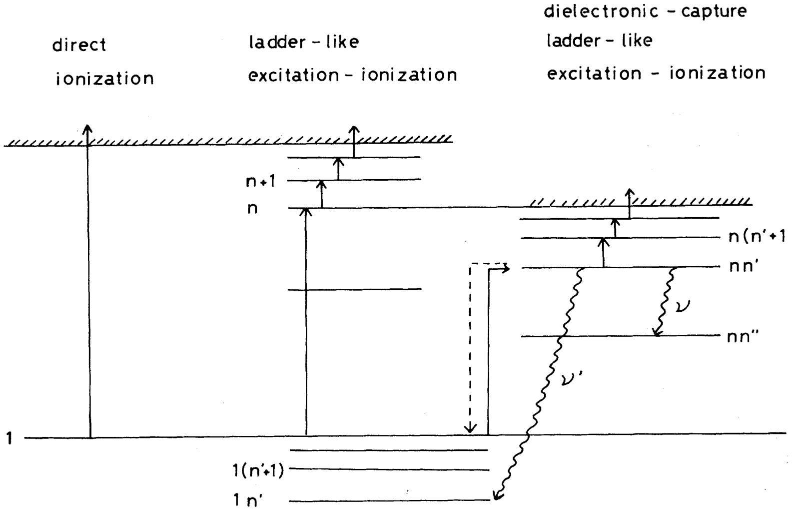

FIG. 1. Schematic energy level diagram of hydrogenlike and heliumlike ions. Transitions due to electronic collisions are denoted with solid arrows, radiative transitions with wavy arrows, and autoionization with a dotted arrow.

where n is the excited level with the principal quantum number n, followed by the ladderlike excitation, $n+e \rightarrow (n+1)+e \rightarrow (n+2)+e \rightarrow \ldots$, and finally by ionization, $(n+m)+e \rightarrow \text{ion}+2e$ ($m \gg 1$), as schematically illustrated in Fig. 1.[4] This process makes the net or collisional-radiative ionization rate coefficient S_{CR} increase with the increase in n_e.

An example is shown in Fig. 2 for the nuclear charge $z=10$, neon, as a function of n_e for the electron temperature of $T_e/z^2 = 3.6\times10^4$ K: This value approximately corresponds to the T_e at which the emission lines of the hydrogenlike neon have their maximum intensity in the low-density plasma. It is seen that S_{CR} begins to increase at about $n_e/z^7 \simeq 10^7$ cm^{-3}. This increase is interpreted as due to the lowering of the lower end of the excitation ladder in the system of excited levels. With the further increase in n_e, when the ladder reaches the first excited level $n=2$, the rate coefficient saturates; this takes place in Fig. 2 at $n_e/z^7 \simeq 10^{15}$ cm^{-3}. (Note that we are considering the high-temperature ionizing plasma of Ref. 3.) These features have been well established and understood in terms of the collisional-radiative model.[3]

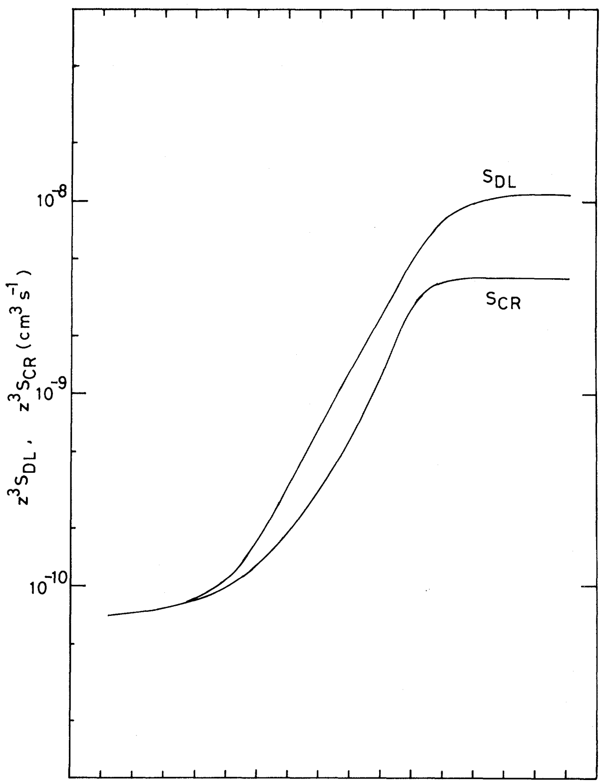

FIG. 2. Collisional radiative ionization rate coefficient S_{CR} and effective ionization rate coefficient S_{DL} that includes the contribution from dielectronic-capture–ladderlike excitation-ionization for Ne^{+9} ($z=10$) as a function of electron density n_e (cm^3) at $T_e/z^2 = 3.6\times10^4$ K.

We should note here that each excited state of ions, e.g., level n in Fig. 1, is the ionization limit of the Rydberg states, nn' ($n'>n$), of doubly excited ionic states of the adjacent lower ionization stage, heliumlike ion in this case. In the plasma these doubly excited states may be populated through dielectronic capture from the hydrogenlike ground state, $1+e \rightarrow nn'$ (Fig. 1). This state may, of course, autoionize, $nn' \rightarrow 1+e$, decay radiatively, $nn' \rightarrow nn'' + h\nu$ ($n''<n'$), or make a stabilizing transition, $nn' \rightarrow 1n' + h\nu'$ (Fig. 1). The last process is dielectronic recombination. However, when n_e is sufficiently high collisional process may become important.[5] For example, this state may be excited, $nn'+e \rightarrow n(n'+1)+e \rightarrow n(n'+2)+e \ldots$, before it autoionizes or decays radiatively, and it may finally be "ionized," $n(n'+m)+e \rightarrow n+2e$. This latter series of processes, dielectronic-capture–ladderlike (DL) excitation-ionization, is nothing more than the excitation $1+e \rightarrow n+e$ of the hydrogenlike ion. Thus, in considering excitation of the ion by electronic collisions in the plasma we should take into account this additional mechanism besides the direct excitation. In order to assess the importance of this new mechanism we make an evaluation of its contribution to the net or total excitation.

The method of the calculation is as follows; we take a hydrogenlike ion for the purpose of illustration. First, we consider the excitation $1s \rightarrow 2s$. The system of the doubly excited states $2sn'l\,^{2S+1}L$ is considered with sixty levels of $2 \leqslant n' \leqslant 20$, and rate coefficients for the collisional (excitation and deexcitation) and radiative transitions between these levels are approximated by those of the heliumlike ion states $1sn'l\,^{2S+1}L$ (Ref. 6); the $2s$ electron is assumed to act as a "spectator." Of course, ionization and recombination processes are included in a similar manner between the "ion" ($2s\,^2S$) and these levels.[7] We also include the collisional deexcitation from these states to singly excited states $1sn'l$. The dielectronic capture rate coefficient of each state with $n' \geqslant 3$ is evaluated from the threshold values of the partial excitation cross sections[8] for $1s+e \rightarrow 2s+e$ given by Burgess, Hummer, and Tully.[9] The autoionization probability is related to the dielectronic capture rate coefficient through the principle of detailed balance. For the states $2s2l$, the autoionization probability is taken from Boiko *et al.*[10] With these collisional and radiative rate coefficients the method of the quasi steady-state solution has been applied to the system of the coupled equations for $1s$, $2sn'l$, and $2s$. The effective excitation rate coefficient $C_{\mathrm{DL}}(1s \to 2s)$ has been evaluated so as to include the contribution from the excitation through these $2sn'l$ $(n' \geq 2)$ levels.[11] An example of the results is shown in Fig. 3 for the condition of Fig. 2.

A similar calculation has been carried out for $1s \to 2p$; in this case, necessary modifications have been made because the core is the p electron, and further, the stabilizing transition, $2pnl \to 1snl + h\nu'$, has been included. The result is also shown in Fig. 3. These curves show that the effective excitation rate coefficient increases in a high-density plasma. It should be noted that this increase in the excitation rate coefficient corresponds to a decrease in the dielectronic recombination.

The inclusion of the DL process into the excitation corresponds to the lowering of the threshold energy of the excitation cross section. This is analogous to the situation where the inclusion of the ladderlike excitation-ionization process approximately corresponds to the lowering of the ionization threshold for the direct ionization cross section. Therefore, both effects become more important for lower temperatures.

Next, the dielectronic-capture–ladderlike excitation-ionization process is incorporated into the calculation of the net ionization process, $1 \to$ ion, of the hydrogenlike ion. For this purpose the DL excitation-ionization rate coefficient should be evaluated for excitation to all of the excited states as well as for $1s \to 2s$ and $1s \to 2p$. For the DL excitation-ionization $1 \to n$ $(n \geq 3)$, we have considered only the doubly excited states nn' with $n' \geq n$ and have assumed that every electron captured dielectronically into nn' is eventually liberated into the "ion" n if n' is such that the collisional excitation probability from nn' is larger than the sum of the autoionization and radiative decay probabilities.[12] The autoionization probability for these levels has been given from Sampson and Parks,[13] and the DL excitation-ionization rate coefficient has been obtained. Then, the effective ionization rate coefficient S_{DL} has been evaluated by the conventional method of the quasi steady-state solution for the hydrogenic ion.[3] The result is shown in Fig. 2, which corresponds to $C_{\mathrm{DL}}(1s \to 2s, 2p)$ in Fig. 3. The difference between the present S_{DL} and conventional collisional-radiative ionization rate coefficient S_{CR} is significant: It is a factor of 2 for $10^{11} \lesssim n_e/z^7 \lesssim 10^{16}$ cm^{-3} and a factor of 3 for the higher densities.

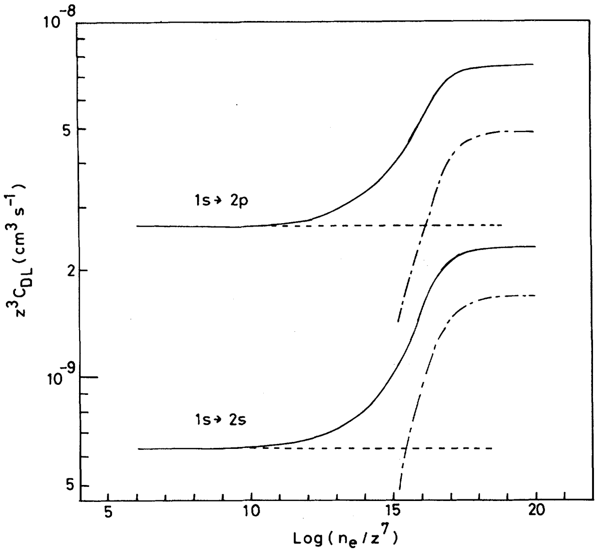

FIG. 3. Effective excitation rate coefficients C_{DL} (solid line) for the transitions $ls \to 2s$ and $1s \to 2p$ of Ne^{+9} $(z = 10)$ at temperature $T_e/z^2 = 3.6 \times 10^4$ K as a function of electron density n_e (cm^3). Dashed lines indicate the direct excitation rate coefficients and chained lines the dielectronic-capture–ladderlike excitation-ionization rate coefficients.

In this Letter we have pointed out the importance of the role played by the doubly excited states in the excitation and ionization processes of ions. We may further think about triply excited states, e.g., $2snn'$, quadruply excited states, and so forth. However, at the moment we do not have any clue to evaluate quantitatively their effects on the dynamics of excitation and ionization of ions. We only note here that the excitation and ionization processes involving multiply excited states may become more important for L- and M-shell ions than the K-shell ions as considered in this Letter.

The further details of the calculation and the validity range of the present mechanism will be discussed elsewhere.

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[1] For example, K. Nishihara, N. Miyanaga, Y. Ogaki, Y. Kato, K. Mima, and C. Yamanaka, in Proceedings of a Conference on Radiative Processes in Hot Plasmas,

Monterey, California, 17–20 November 1980, edited by Balazs Rosznyar and Abraham Szöki, J. Quantum Spectrosc. Radiat. Transfer, to be published.

[2] M. H. Key, C. L. S. Lewis, J. G. Lunney, A. Moore, J. M. Ward, and R. K. Thareja, Phys. Rev. Lett. 44, 1669 (1980).

[3] T. Fujimoto, J. Phys. Soc. Jpn. 47, 273 (1979). D. R. Bates, A. E. Kingston, and R. W. P. McWhirter, Proc. Roy. Soc. London 267, 297 (1962).

[4] The actual mechanism of the process is much more complicated, involving various processes (Ref. 3), and the following numerical calculation takes full account of these processes using the set of appropriate rate coefficients.

[5] V. L. Jacobs and M. Blaha, Phys. Rev. 21, 525 (1980); V. L. Bayanov *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. 24, 352 (1976) [JETP Lett. 24, 319 (1976)].

[6] T. Fujimoto, N. Yamaguchi, J. Mizui, T. Kato, and J. Fujita, J. Phys. D 14, 439 (1981); T. Fujimoto and T. Kato, Astrophys. J. 246, 994 (1981).

[7] The present approximation based on the $1s$-core He-like ion may not be highly accurate, especially for the $2s2l$ states. It has been found, however, that small changes in the individual rate coefficients involving these states make the curves in Figs. 2 and 3 shift slightly toward the lower or higher n_e direction.

[8] M. J. Seaton and P. J. Storey, *Atomic Processes and Applications* (North-Holland, Amsterdam, 1976), p. 133.

[9] A. Burgess, D. G. Hummer, and J. A. Tully, Philos. Trans. Roy. Soc. London, Ser. A 266, 225 (1970).

[10] V. A. Boiko, A. Ya. Faenov, S. A. Pikuz, and U. I. Safronova, Month. Not. Roy. Astron. Soc. 181, 107 (1977).

[11] In calculating the DL excitation-ionization rate coefficient we consider the situation where the population density of the "ion" $2\,^2S$ is set equal to zero. This corresponds to employing the ionizing plasma model when we calculate the collisional-radiative ionization rate coefficient, $S_{\rm CR}$.

[12] In a high-temperature ionizing plasma the most important collisional depopulation process from a level is the excitation to the adjacent higher-lying level; it is not the ionization or the deexcitation (Ref. 3). See also P. Mansbach and J. Keck, Phys. Rev. 181, 275 (1969).

[13] D. H. Sampson and A. D. Parks, Astrophys. J., Suppl. Ser. 263, 323 (1974).