PHYSICAL REVIEW A VOLUME 35, NUMBER 7 APRIL 1, 1987

Decrease and disappearance of the resonance contribution to the excitation cross section of ions in dense plasma

Takashi Fujimoto
Department of Engineering Science, Kyoto University, Kyoto 606, Japan

Takako Kato
Institute of Plasma Physics, Nagoya University, Nagoya 464, Japan

(Received 18 September 1986)

Taking the excitation $1s \rightarrow 2s$ of a hydrogenlike ion as an example, the authors have examined the effect of plasma electrons on the resonance contribution $1s \rightarrow 3pnl \rightarrow 2s$ to the excitation cross section, where $3pnl$ stands for the doubly excited ion produced by dielectronic capture of the $1s$ ion. They adopt an approximation method in which it is assumed that all the dielectronic capture into the doubly excited levels lying higher than a certain critical level is lost from the doubly excited levels through the ladderlike excitation "ionization." The part of the resonance cross section corresponding to these levels accordingly disappears. They follow the same procedure to obtain the effect on the resonance contributions from $1s \rightarrow 3snl \rightarrow 2s$ and $1s \rightarrow 3dnl \rightarrow 2s$. It is found that for the Ne^{9+} ion taken as an example the plasma electron effect is appreciable for densities higher than 10^{19} cm^{-3}.

I. INTRODUCTION

The importance of the resonance contribution to the excitation cross section has been recognized for more than ten years.[1] Resonances in the continuum states caused by the doubly excited Rydberg-series states contribute to the excitation cross section. A number of theoretical investigations have been carried out on various excitation cross sections. In all these studies the process is treated as an electron-ion two-body collision process. In what follows we consider an excitation cross section of a hydrogenlike ion for the purpose of illustration. In this example the resonance contribution may be interpreted as follows: Dielectronic capture into a doubly excited state $1s + e \rightarrow 3l'nl''$, followed by autoionization to the excited state $3l'nl'' \rightarrow 2l + e$, constitute an effective excitation $1s \rightarrow 2l$.

Suppose this ion is immersed in a plasma and is subjected to electron collisions. Then it is possible that the doubly excited ion $3l'nl''$ in the above example, suffers an electron collision before it autoionizes or decays radiatively. It is known[2,3] that the most probable inelastic electron collision on a singly excited Rydberg state nl'' is the excitation to the adjacent higher-lying level $(n+1)l'''$. It would be reasonable to assume that a similar excitation process that takes place in the present example $3l'nl''+e \rightarrow 3l'(n+1)l'''$ is the most probable inelastic collision process. The latter ion is further excited $3l'(n+1)l''' + e \rightarrow 3l'(n+2)l'''' + e \rightarrow \cdots$, and finally "ionized" $3l'ml^{(k)} + e \rightarrow 3l' + 2e$ $(m,k \gg 1)$. This series of processes may be called the ladderlike excitation-"ionization." As its consequence, the doubly excited ion $3l'nl''$ is lost before it autoionizes to produce the $2l$ ion. Therefore, it is expected that in a dense plasma the resonance contribution to the excitation cross section of $1s \rightarrow 2s$ may decrease and eventually disappear.

In recent papers,[4,5] the present authors proposed the dielectronic-capture—ladderlike-excitation mechanism: An example is $1s + e \rightarrow 2lnl'$, followed by $2lnl' + e \rightarrow 2l(n+1)l'' + e \rightarrow \cdots \rightarrow 2lml^{(k)} + e \rightarrow 2l + 2e$ $(m,k \gg 1)$. This mechanism results in an increase in the excitation rate coefficient of $1s \rightarrow 2l$. They carried out a collisional-radiative calculation on the system of a heliumlike ion with 60 doubly excited levels and the $1s$ and $2l$ hydrogenlike levels. They obtained an increase in the effective excitation rate coefficient for $1s \rightarrow 2l$ in dense plasmas as a function of electron density. In their study they have found that this increase in the rate coefficient is well approximated by an extrapolation of the excitation cross section below the threshold energy to a certain energy and integration over the Maxwellian distribution of electron velocities.[5] In the present paper we treat the decrease in the resonance cross section by the same approximation.

II. RESONANCE OF EXCITATION CROSS SECTION

A. Resonance excitation

Although the resonance contribution is small in the case of the excitation cross section of a hydrogenlike ion, we take as an example the excitation $1s \rightarrow 2s$ in this study for the purpose of illustration. In the present study we are not interested in a detailed structure of the excitation cross section. The objective of the following discussion is to examine the effect of plasma electrons on the excitation of the ion, or the variation of the excitation rate coefficient as a function of electron density. For that purpose, we may adopt the following crude approximation to the resonance contribution to the excitation cross section. Figure 1 shows the relevant schematic energy-level diagram; we take a series of processes of dielectronic capture

©1987 The American Physical Society

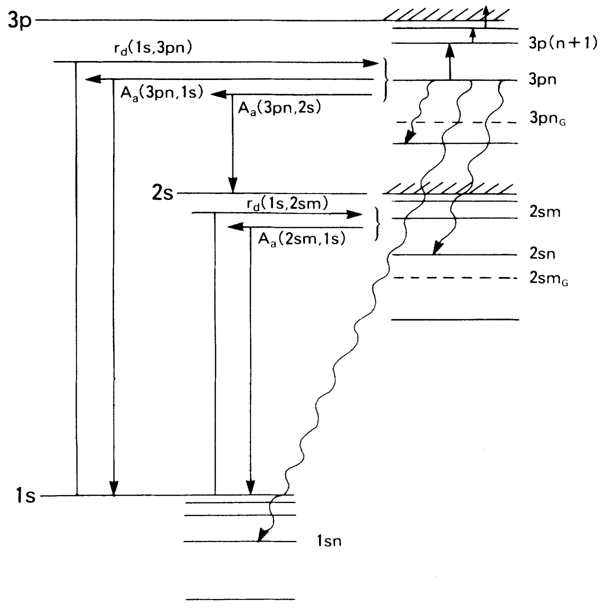

FIG. 1. Schematic energy-level diagram showing the dominant atomic processes of the doubly excited ions in the plasma. $3pn_G$ and $2sm_G$ are the critical level (the generalized Griem's critical level) between the higher-lying levels and the lower-lying ones. The doubly excited ions produced by dielectronic capture into the higher-lying levels undergo the ladderlike excitation-ionization by the plasma electrons.

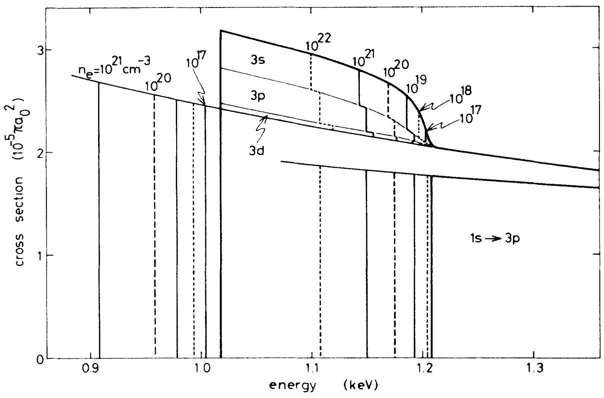

FIG. 2. The resonance contributions from the doubly excited levels to the excitation cross section $1s \rightarrow 2s$ of a hydrogenlike neon. The energy of the critical level is indicated with the thick lines, and the part of the resonance cross section at higher energies than the critical energy disappears. Instead, the excitation threshold of the excitation cross section $1s \rightarrow 3p$, which is also shown in this figure, is lowered to the critical level and the cross section is extrapolated to this energy. A similar procedure is adopted for the excitation cross section $1s \rightarrow 2s$ (Ref. 5). $T_e = 10^6$ K.

$1s + e \rightarrow 3pnl$ followed by autoionization $3pnl \rightarrow 2s + e$ as an example of the resonance contribution to $1s \rightarrow 2s$. Since we consider processes in a dense plasma later we assume that the collisional population mixing within the levels having the same principal quantum number n takes place so rapidly that the statistical population distribution is established among them. We use only n to designate the state of the running electron disregarding different l or the singlet and triplet systems in the L-S coupling scheme. This approximation is justified by the detailed collisional-radiative model calculation.[5]

First, we evaluate the resonance contribution $1s \rightarrow 3pn \rightarrow 2s$ in the limit of low density. We estimate the dielectronic capture rate coefficient $r_d(1s,3pn)$, or the autoionization probability $A_a(3pn,1s)$, on the basis of the threshold value of the excitation cross section $1s \rightarrow 3p$ in the infinite-z approximation by Golden *et al.*[6] The autoionization probability to the final state $A_a(3pn,2s)$ is estimated similarly. In estimating the branching ratio of $A_a(3pn,2s)$ leading to the excitation to $2s$ we include the stabilizing radiative decay $3pn \rightarrow 1sn$ and the decay $3pn \rightarrow 2sn$. These transition probabilities are given the values of the corresponding hydrogenlike transitions. We also include the radiative decay of the running electron $3pn \rightarrow 3pn'$ ($n' < n$). Its probability is given by the approximation for a hydrogenlike level n. By multiplying the cross section $1s \rightarrow 3p$ by the above branching ratio we obtain the excitation cross section $1s \rightarrow 3pn \rightarrow 2s$ as a function of energy; the result is understood to correspond to the averaged cross section over resonances. Figure 2 shows the result for Ne^{9+} taken as an example. In this figure also shown are the resonance contributions from $1s \rightarrow 3sn \rightarrow 2s$ and $1s \rightarrow 3dn \rightarrow 2s$; the contributions from the $3sn$ and $3dn$ have been calculated in a similar procedure. The decrease in the resonance cross section near the series limit is due to a decrease in the branching ratio of $A_a(3ln,2s)$ in comparison with the stabilizing radiative decay. This figure also includes the direct excitation cross sections $1s \rightarrow 2s$ and $1s \rightarrow 3p$, as given by Golden *et al.*

B. The effect of electron collisions

We consider the effect of the electron collisions on these cross sections. In Ref. 5 an approximation is proposed; that is, the doubly excited levels $2sm$ are grouped into the higher-lying levels and the lower-lying ones; the critical level between these two groups $2sm_G$ (the generalized Griem's critical level[2,3]) is defined such that the sum of the autoionization probability and the radiative decay probabilities from this level is equal to the total collisional depopulation rate from this level, the dominant contribution to it being the excitation $2sm + e \rightarrow 2s(m+1) + e$. It is justified (except in certain circumstances) to assume that the higher-lying levels than $2sm_G$ are in a flow of the ladderlike excitation-ionization so that all the dielectronic capture into these levels results in the excitation $1s \rightarrow 2s$, whereas the dielectronic capture into the lower-lying levels than $2sm_G$ is lost by autoionization or radiative decay and does not contribute to the excitation at all. Owing to the relationship between the excitation cross section $1s \rightarrow 2s$ and the autoionization probability $A_a(2sm,1s)$, we can approximate the above effect of dielectronic-capture ladderlike excitation-ionization by extrapolating the excitation cross section $1s \longrightarrow 2s$ down to the energy of the critical level $2sm_G$, and integrating it over the Maxwellian distribution of electron velocities.

In estimating the effect of electron collisions on the $3pn$ levels we adopt the similar approximation; we calculate the critical level $3pn_G$ by comparing the sum of the autoionization and radiative decay probabilities with the collisional depopulation rate as a function of electron density. We regard that the dielectronic capture into the higher-lying levels than $3pn_G$ is lost from the process of autoionization $3pn \longrightarrow 2s$ and that the part of the resonance contribution from these levels disappears resulting in a reduction in the excitation rate coefficient. In Fig. 2 we give the energy of the critical level; the principal quantum number n_G is 13.9, 8.3, 5.7, 4.3, and 3.3 for $n_e = 10^{18}$, 10^{19}, 10^{20}, 10^{21}, and 10^{22} cm^{-3}, respectively. We may approximate the reduction in the rate coefficient by dropping in the integration the higher-energy part of the resonance cross section $1s \longrightarrow 3pn \longrightarrow 2s$ than the critical energy. The similar upper limit is given to the other cross sections, and these are connected by thick lines. The value of n_G of the critical levels $3sn_G$ and $3dn_G$ can be known from that for $3pn_G$. The disappearance of the resonance cross sections is appreciable in dense plasmas of $n_e > 10^{19}$ cm^{-3}. This figure is for an example of electron temperature of 1×10^6 K, and the temperature dependence of the above effect is quite small. This is because the temperature dependence stems only from the excitation rate coefficient which is weakly temperature dependent. (See Fig. 3 of Ref. 5.)

As mentioned earlier,[5] the effect of inelastic electron collisions on the doubly excited ions $2sm$ that have been produced by the dielectronic capture is to increase the excitation rate coefficient $1s \longrightarrow 2s$, or effectively to extrapolate the excitation cross section to the critical doubly excited level. Thus the disappearance of the resonance cross section, e.g., of $1s \longrightarrow 3pn \longrightarrow 2s$, corresponds to the extrapolation of the excitation cross section $1s \longrightarrow 3p$ to the energy of the critical level $3pn_G$. In Fig. 2, the cross section is extrapolated below its threshold energy down to the critical energy. Also shown is the similar extrapolation of the cross section $1s \longrightarrow 2s$; this is taken from Ref. 5.

In this study the effect of ion collisions has been neglected. The ion collisions are effective in the excitation with a small energy difference, and they may contribute to the collisional depopulation in the present context. Therefore, the inclusion of these collisions would further lower the critical level than shown in Fig. 2.

It is noted that the lowering of the "ionization potential" takes place at much higher energy than that of the critical level; for example, at $n_e = 10^{22}$ cm^{-3} the lowering is about 18 eV, while the critical energy is about 1000 eV down from the original ionization limit. Therefore, the above treatment is little affected by the lowering. For the validity range of the present approximation see Ref. 5.

In the present example of the excitation cross section of a hydrogenlike ion, the contribution from the resonance to the excitation cross section is rather small; about 30% for $1s \longrightarrow 2s$ as seen in Fig. 2 and 15% for $1s \longrightarrow 2p$. In some cases the resonance contribution is quite important; sometimes it is larger than the direct or potential excitation cross section by an order. The above-mentioned plasma effect is also valid in such cases, resulting in a strong density dependence of the excitation rate coefficient.

---

[1] D. E. Osterbrock, J. Phys. B **3**, 149 (1970); A. R. G. Jackson, *ibid.* **6**, 2325 (1973); W. Eissner and M. J. Seaton, *ibid.* **7**, 2533 (1974); L. P. Presnyakov and A. M. Urnov, *ibid.* **8**, 1280 (1975).

[2] H. R. Griem, Phys. Rev. **131**, 1170 (1963).

[3] T. Fujimoto, J. Phys. Soc. Jpn. **47**, 273 (1979).

[4] T. Fujimoto and T. Kato, Phys. Rev. Lett. **48**, 1022 (1982).

[5] T. Fujimoto and T. Kato, Phys. Rev. A **32**, 1663 (1985).

[6] L. B. Golden, R. E. H. Clark, S. J. Goett, and D. H. Sampson, Astrophys. J. (Suppl.) **45**, 603 (1981).