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Electron-impact excitation of atoms in high-lying doubly excited states: Single-electron excitation between doubly excited states

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It is theoretically pointed out that, even between strongly correlated doubly excited states, there exist single-electron–type transitions for electron-impact excitation processes of He atoms in doubly excited states under the condition $\Delta L = 0$, where L is the total orbital angular momentum of the atom. The propensity rules found for the ${}^1P^o$-${}^1P^o$ and ${}^1D^e$-${}^1D^e$ double-excitation processes are also presented and discussed based on the rovibrational interpretation of the collective motion of two atomic electrons.

In our previous papers,[1,2] we theoretically investigated collisional properties of He atoms in high-lying doubly excited states in electron-impact excitation processes. We paid particular attention to correlation effects in collision dynamics. Therefore we focused on the theoretical studies of excitation processes between the intrashell doubly excited states in which correlated motion of two atomic electrons plays a decisive role, namely, the two electrons are forced to be involved in the transitions. Consequently, these excitation processes give rise to electron-pair excitations. In these studies,[1,2] we have employed the hyperspherical coordinate approach to calculate energy levels of the doubly excited states, to generate their wave functions,[3-5] and to evaluate Born cross sections for electron-impact excitation processes. We rely on the rovibrational interpretation of the collective motions of two atomic electrons.[6-8] For the ${}^1S^e$-${}^1S^e$, ${}^1S^e$-${}^1P^o$, and ${}^1S^e$-${}^1D^e$ electron-impact excitation processes, we have found that there exist some systematic trends in double-excitation processes. These trends can be summarized as a set of simple propensity rules in collision dynamics of He in the doubly excited states, particularly between the high-lying intrashell doubly excited states. These propensity rules indicate that a He atom in the high-lying intrashell doubly excited states behaves in collision dynamics quite similarly to a triatomic linear e—He^{2+}—e molecule except for the restriction arising from the Pauli exclusion principle for two atomic electrons.[2] (Hereafter, Ref. 2 will be referred to as I.) We have also confirmed that this set of propensity rules applies to the double-excitation processes from the ground state of He as long as the conditions $\Delta N \geq 1$ and $\Delta n \geq 1$ are satisfied.[9] Here N $(\leq n)$ is the principal quantum number of an inner (outer) electron.

The purpose of the present paper is to point out that, under a particular condition, i.e., with the total angular momentum of the He atom, L, unchanged in the excitation processes, there can exist single-electron–type transitions in which only one atomic electron participates between the strongly correlated doubly excited states. We also discuss a set of propensity rules found in double-electron-excitation processes in ${}^1P^o$-${}^1P^o$ and ${}^1D^e$-${}^1D^e$ transitions.

According to the same procedures employed in our previous work,[1,2] we have theoretically investigated the ${}^1S^e$-${}^1S^e$, ${}^1P^o$-${}^1P^o$, and ${}^1D^e$-${}^1D^e$ electron-impact excitation processes between the doubly excited states of He,

$$e + \mathrm{He}^{**}(i) \rightarrow e + \mathrm{He}^{**}(f) , \tag{1}$$

where i (f) denotes a set of the quantum numbers which specifies an initial (final) doubly excited state. We have assumed that the coupling of these doubly excited states to continua associated with the excited state of He$^+$ can be neglected and that the collisional excitation processes between the quasibound states are well defined as was shown in I.

In order to label the excited states, we employ the classification scheme $[N(K,T)^A n]^{2S+1}L^\pi$ proposed by Lin.[10] Here, K, T, and A are the so-called correlation quantum numbers. The quantum numbers K and T originate from the group-theoretical approach by Herrick[6] and describe angular correlation of the two electrons while the quantum number A $(=+,0,-)$ introduced by Lin[10] specifies radial correlation of the two atomic electrons. The state with $A=+$ has an antinode for $\alpha=\pi/4$ and that with $A=-$ has a node for $\alpha=\pi/4$. These states show a strongly correlated motion while the state with $A=0$ may be classified as the singly excited state. All these quantum numbers are approximate ones because the two-electron Schrödinger equation is only approximately separable into the collective motions of the two atomic electrons. Other quantum numbers L, S, and π are the conventional ones, i.e., total angular momentum, spin angular momentum, and parity of the atom. We also rely on the collective rovibrational interpretation of the energy levels of the doubly excited states.[7,8] It is quite useful to introduce the quantum numbers $v=N-K-1$ and $n_2=(v-T)/2$. The quantum number v corresponds to the doubly degenerate bending vibrational modes of the flexible e—He^{2+}—e linear molecule, while T is the projection of the total angular momentum to the mean molecular axis of the linear e—He^{2+}—e molecule and corresponds to the vibrational angular momentum of the triatomic linear molecule. The radial bending quantum number n_2 is the number of the nodes in the vibrational motion in θ_{12}, i.e., the angle between the radius vectors of the two electrons on the body-fixed frame. We employ this classification scheme as a language to describe collision dynamics involving the doubly excited states as was done in I.

To calculate the generalized oscillator strength, we have used the hyperspherical wave functions for the initial and final doubly excited states, as was done previously.[3-5] The hyperspherical wave functions used here are constructed in the same manner as was done in I. For the $^1S^e$ state wave functions are expanded over a set of 49 terms of basis functions. For $^1P^o$ and $^1D^e$ states, 64 and 95 terms have been used, respectively. We have evaluated the Born cross sections of the $^1S^e$-$^1S^e$, $^1P^o$-$^1P^o$ and $^1D^e$-$^1D^e$ excitation processes for the $N=3$, 4, and 5 manifolds as the initial states. We have only computed the Born cross sections with $\Delta N=0$ and 1 because there is a negligibly small overlap between the initial and final hyperradial wave functions for $\Delta N \geq 2$. The energy dependence of the Born cross sections shows a simple feature as shown in Fig. 1. Therefore we adopt the value of the Born cross sections at fixed energy as the measure of the likelihood of each excitation process. Here it should be noted that the Born approximation remains valid at 50 eV incident energy for the doubly excited states studied here because this incident energy is much larger than the excitation energies between the doubly excited states considered here.

Table I shows typical examples of the $^1S^e$-$^1S^e$ Born cross sections at 50 eV incident energy from the intrashell initial state and from the intershell initial states together with information on the change of the quantum numbers which occurs during the excitation processes. Here we change v instead of K and add the change of n_2. This enables us to understand the character of the transitions based on the rovibrational interpretation of the collective motion. The cross sections are listed according to the decreasing order of their magnitudes. From Table I(a), one immediately sees that the single-electron excitation process with $\Delta N=\Delta A=\Delta v=\Delta T=\Delta n_2=0$ and $\Delta n=1$ is most likely to take place. In this case we may interpret that only one electron in the intrashell orbit is excited into a higher outer orbital. Table I(b) also indicates that for the initial intershell $[3(2,0)^+4]^1S^e$ state there is anoth-

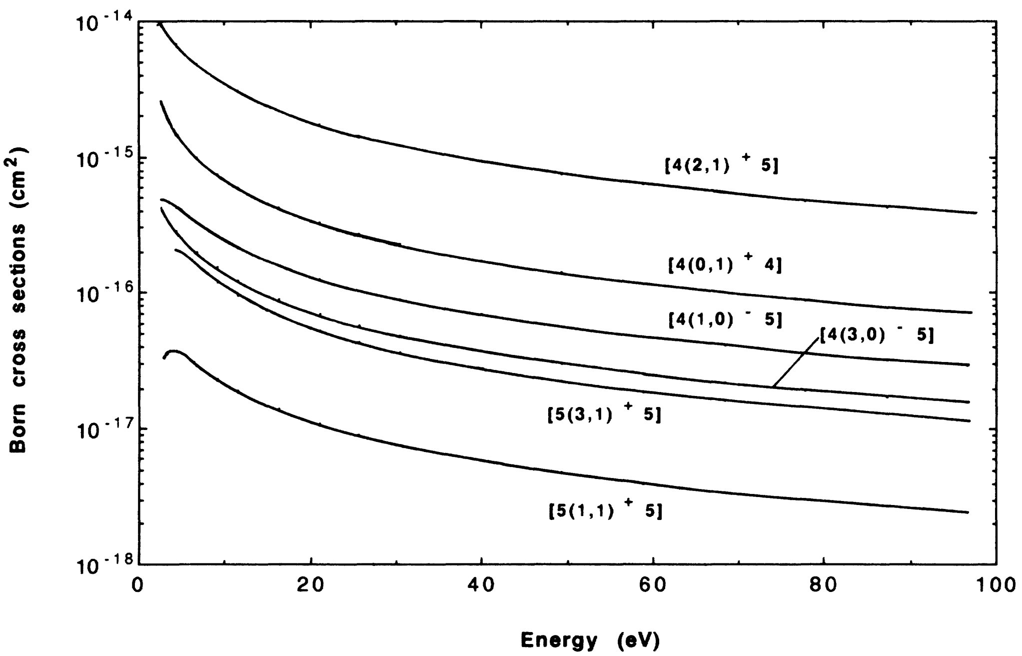

FIG. 1. Born cross sections for the $^1P^o$-$^1P^o$ excitation processes from the initial $[4(2,1)^+4]^1P^o$ state to the final $[4(K,T)^An]$ and $[5(K,T)^An]^1P^o$ states.

TABLE I. Born cross sections for the ${}^1S^e$-${}^1S^e$ excitation processes of He by electron impact at 50 eV incident energy, (a) $4(3,0)^+4 \rightarrow N(K,T)^An$, $N=4$ or 5, (b) $3(2,0)^+4 \rightarrow N(K,T)^An$, $N=3$ or 4, with the changes of the quantum numbers during excitation processes and the excitation energies for the transition in rydberg. The notation $[x]$ denotes 10^x.

Initial states $N(K,T)^An$	Final states $N(K,T)^An$	Born cross sections (cm^2)			Change of quantum numbers				
			ΔN	ΔA	Δv	ΔT	Δn_2	Δn	ΔE (Ry)
(a)									
$4(3,0)^+4$	$4(3,0)^+5$	7.1[−16]	0	0	0	0	0	1	0.0720
$4(3,0)^+4$	$5(4,0)^+5$	1.9[−17]	1	0	0	0	0	1	0.1426
$4(3,0)^+4$	$5(2,0)^+5$	1.3[−18]	1	0	2	0	1	1	0.1604
$4(3,0)^+4$	$5(0,0)^+5$	2.7[−19]	1	0	4	0	2	1	0.1789
$4(3,0)^+4$	$4(1,0)^+4$	3.6[−20]	0	0	2	0	1	0	0.0359
$4(3,0)^+4$	$5(-2,0)^+5$	3.0[−20]	1	0	6	0	3	1	0.2020
(b)									
$3(2,0)^+4$	$3(2,0)^+5$	6.5[−16]	0	0	0	0	0	1	0.0501
$3(2,0)^+4$	$4(3,0)^+4$	6.5[−17]	1	0	0	0	0	0	0.1551
$3(2,0)^+4$	$4(3,0)^+5$	1.9[−18]	1	0	0	0	0	1	0.2271
$3(2,0)^+4$	$3(0,0)^+4$	1.1[−18]	0	0	2	0	1	0	0.0425
$3(2,0)^+4$	$4(1,0)^+4$	5.5[−19]	1	0	2	0	1	0	0.1910
$3(2,0)^+4$	$4(1,0)^+5$	1.7[−19]	1	0	2	0	1	1	0.2513

TABLE II. Born cross sections for the ${}^1P^o$-${}^1P^o$ excitation processes of He by electron impact at 50 eV incident energy, (a) $4(2,1)^+4 \rightarrow N(K,T)^An$, $N=4$ or 5, (b) $4(3,0)^-4 \rightarrow N(K,T)^An$, $N=4$ or 5, (c) $3(1,1)^+4 \rightarrow N(K,T)^An$, $N=3$ or 4 with the changes of the quantum numbers during excitation processes and the excitation energies for the transition in rydberg. The notation $[x]$ denotes 10^x.

Initial states $N(K,T)^An$	Final states $N(K,T)^An$	Born cross sections (cm^2)			Change of the quantum numbers				
			ΔN	ΔA	Δv	ΔT	Δn_2	Δn	ΔE (Ry)
(a)									
$4(2,1)^+4$	$4(2,1)^+5$	7.5[−16]	0	0	0	0	0	1	0.0677
$4(2,1)^+4$	$4(0,1)^+4$	1.4[−16]	0	0	2	0	1	0	0.0431
$4(2,1)^+4$	$4(1,0)^-5$	5.6[−17]	0	X	1	−1	1	1	0.0762
$4(2,1)^+4$	$4(3,0)^-5$	3.0[−17]	0	X	−1	−1	0	1	0.0561
$4(2,1)^+4$	$5(3,1)^+5$	2.2[−17]	1	0	0	0	0	1	0.1366
$4(2,1)^+4$	$5(1,1)^+5$	4.7[−18]	1	0	2	0	1	1	0.1569
(b)									
$4(3,0)^-5$	$4(3,0)^-6$	1.2[−15]	0	0	0	0	0	1	0.0343
$4(3,0)^-5$	$4(2,1)^+5$	1.6[−16]	0	X	1	1	0	0	0.0115
$4(3,0)^-5$	$4(1,0)^-5$	1.2[−16]	0	0	2	0	1	0	0.0187
$4(3,0)^-5$	$5(3,1)^+5$	1.2[−16]	1	X	1	1	0	0	0.0805
$4(3,0)^-5$	$5(4,0)^-6$	7.7[−17]	1	0	0	0	0	1	0.1132
$4(3,0)^-5$	$4(0,1)^+5$	6.9[−18]	0	X	3	1	1	0	0.0372
$4(3,0)^-5$	$5(2,0)^-6$	4.4[−18]	1	0	2	0	1	1	0.1235
(c)									
$3(1,1)^+4$	$3(1,1)^+5$	7.5[−16]	0	0	0	0	0	1	0.0418
$3(1,1)^+4$	$3(0,0)^-4$	1.1[−16]	0	X	1	−1	1	0	0.0123
$3(1,1)^+4$	$3(-1,1)^+4$	8.4[−17]	0	0	2	0	1	0	0.0425
$3(1,1)^+4$	$3(2,0)^-5$	8.4[−17]	0	X	−1	−1	0	1	0.0308
$3(1,1)^+4$	$4(2,1)^+4$	6.4[−17]	1	0	0	0	0	0	0.1503
$3(1,1)^+4$	$3(0,0)^-5$	1.6[−17]	0	X	1	−1	1	1	0.0490
$3(1,1)^+4$	$4(0,1)^+4$	1.6[−17]	1	0	2	0	1	0	0.1929
$3(1,1)^+4$	$4(1,0)^-5$	5.8[−18]	1	X	1	−1	1	1	0.2252
$3(1,1)^+4$	$3(-2,0)^04$	3.8[−18]	0	X	3	−1	2	0	0.0512

er type of single-electron-excitation process with $\Delta N=1$ and $\Delta A=\Delta v=\Delta T=\Delta n_2=\Delta n=0$, though its cross section is much smaller than that for the single-electron excitation of the outer electron. Here only an inner electron is considered to be excited into the higher orbital. The next one has electron-pair excitation processes with $\Delta N=\Delta n=1$ and with all other quantum numbers unchanged, which we have already discussed in our previous paper.[1]

Figure 1 shows the $^1P^o$-$^1P^o$ excitation cross sections for the initial $[4(2,1)^+4]^1P^o$ states. Table II gives three typical examples of the $^1P^o$-$^1P^o$ Born cross sections at 50 eV incident energy from one intrashell initial state and two intershell initial states listed in a similar manner to Table I. In Tables II(a) and II(b), one sees again that the single-electron-excitation process with $\Delta N=\Delta A=\Delta v=\Delta T=\Delta n_2=0$ and $\Delta n=1$ is most likely to occur. Next, we show two types of double-electron-excitation processes, i.e., (i) $\Delta v=2$, $\Delta n_2=1$, and all other quantum numbers unchanged from the initial state with $A=+$ and (ii) $\Delta A\neq 0$, $\Delta v=1$, $\Delta T=1$ or -1, $\Delta n_2=0$ or 1, and all other quantum numbers unchanged from the initial state with $A=-$. In these excitation processes the doubly excited atoms are "vibrationally excited" and/or "rotationally excited (or deexcited)" along the molecular axis. Consequently two electrons show a strongly correlated motion. In Table II(c), a trend similar to Tables II(a) and II(b) can be seen except that there exists the single-electron excitation of the inner electron though its cross section is small in comparison with that of the single-electron excitation with $\Delta n=1$ and all other quantum numbers unchanged but comparable with that of the double-electron excitation.

Table III also gives three typical examples of the $^1D^e$-$^1D^e$ Born cross sections at 50 eV incident energy from one intrashell initial state and from two intershell initial states. Here one sees a systematic trend similar to those seen in Table II. Namely, the single-electron excitation with $\Delta n=1$ and with all other quantum numbers unchanged is most likely to occur. Then there are the

TABLE III. Born cross sections for the $^1D^e$-$^1D^e$ excitation processes of He by electron impact at 50 eV incident energy, (a) $3(2,0)^+3\rightarrow N(K,T)^An$, $N=3$ or 4, (b) $3(1,1)^-4\rightarrow N(K,T)^An$, $N=3$ or 4, (c) $3(2,0)^+4\rightarrow N(K,T)^An$, $N=3$ or 4 with the changes of the quantum numbers during the excitation processes and the excitation energies in rydberg. The notation [x] denotes 10^x.

Initial states $N(K,T)^An$	Final states $N(K,T)^An$	Born cross sections (cm^2)	Change of the quantum numbers						ΔE (Ry)
			ΔN	ΔA	Δv	ΔT	Δn_2	Δn	
				(a)					
$3(2,0)^+3$	$3(2,0)^+4$	2.7[−16]	0	0	0	0	0	1	0.1407
$3(2,0)^+3$	$3(0,0)^+3$	3.0[−17]	0	0	2	0	1	0	0.1262
$3(2,0)^+3$	$3(0,2)^+3$	1.9[−17]	0	0	2	2	0	0	0.0695
$3(2,0)^+3$	$3(1,1)^-4$	8.1[−18]	0	X	1	1	0	1	0.1477
$3(2,0)^+3$	$4(3,0)^+4$	7.3[−18]	1	0	0	0	0	1	0.2928
$3(2,0)^+3$	$3(-1,1)^04$	1.1[−18]	0	X	3	1	1	1	0.1935
$3(2,0)^+3$	$4(1,0)^+4$	9.7[−19]	1	0	2	0	1	1	0.3322
$3(2,0)^+3$	$4(1,2)^+4$	6.4[−19]	1	0	2	2	0	1	0.3167
				(b)					
$3(1,1)^-4$	$3(1,1)^-5$	6.3[−16]	0	0	0	0	0	1	0.0435
$3(1,1)^-4$	$3(0,2)^+4$	2.3[−16]	0	X	1	1	0	0	0.0256
$3(1,1)^-4$	$3(0,0)^+4$	5.8[−17]	0	X	1	−1	1	0	0.0410
$3(1,1)^-4$	$4(1,2)^+4$	2.8[−17]	1	X	1	1	0	0	0.1689
$3(1,1)^-4$	$4(2,1)^-5$	2.3[−17]	1	0	0	0	0	1	0.2195
$3(1,1)^-4$	$4(1,0)^+4$	1.3[−17]	1	X	1	−1	1	0	0.1845
$3(1,1)^-4$	$3(2,0)^+5$	8.8[−18]	0	X	−1	−1	0	1	0.0393
$3(1,1)^-4$	$3(-1,1)^04$	8.3[−18]	0	X	2	0	1	0	0.0458
				(c)					
$3(2,0)^+4$	$3(2,0)^+5$	7.6[−16]	0	0	0	0	0	1	0.0464
$3(2,0)^+4$	$4(3,0)^+4$	7.6[−17]	1	0	0	0	0	0	0.1522
$3(2,0)^+4$	$3(1,1)^-4$	2.8[−17]	0	X	1	1	0	0	0.0071
$3(2,0)^+4$	$3(0,0)^+4$	2.1[−17]	0	0	2	0	1	0	0.0481
$3(2,0)^+4$	$3(0,2)^+4$	1.4[−17]	0	0	2	2	0	0	0.0327
$3(2,0)^+4$	$3(-1,1)^04$	1.1[−17]	0	X	3	1	1	0	0.0529
$3(2,0)^+4$	$3(1,1)^-5$	1.1[−17]	0	X	1	1	0	1	0.0506
$3(2,0)^+4$	$4(1,0)^+4$	4.2[−18]	1	0	2	0	1	0	0.1915
$3(2,0)^+4$	$4(1,2)^+4$	3.5[−18]	1	0	2	2	0	0	0.1760

TABLE IV. Comparison of the cross sections for the single-electron-excitation processes with $\Delta L = 0$ and for the double-electron-excitation processes with $\Delta L = 1$ at 50 eV incident energy.

Initial states	Final states	σ (cm^2)	Change of quantum numbers[a]
$[4(3,0)^+4]^1S^e$	$[4(3,0)^+5]^1S^e$	7.1×10^{-16}	$\Delta L = 0$, $\Delta n = 1$
	$[4(2,1)^+4]^1P^o$	2.3×10^{-14}	$\Delta L = 1$, $\Delta v = \Delta T = 1$
$[4(1,0)^+4]^1S^e$	$[4(1,0)^+5]^1S^e$	5.5×10^{-16}	$\Delta L = 0$, $\Delta n = 1$
	$[4(0,1)^+4]^1P^o$	3.1×10^{-14}	$\Delta L = 1$, $\Delta v = \Delta T = 1$

[a] All other quantum numbers remain unchanged.

pair-excitation processes, which have the next largest cross sections. In Table III(c), there also exists the single-electron excitation of the inner electron with $\Delta N = 1$ and with all other quantum numbers unchanged whose cross section is small in comparison with that for the single-excitation process with $\Delta n = 1$ and is comparable with the cross sections for the double-electron excitation.

Here it should be noted that, only under the condition $\Delta L = 0$, can there exist the single-electron-excitation processes between the strongly correlated doubly excited states. In the excitation processes with $\Delta L \neq 0$, $\Delta n = 1$, and all other quantum numbers unchanged or with $\Delta L \neq 0$, $\Delta N = 1$ and all other quantum numbers unchanged, the doubly exicted atom as a "triatomic linear molecule" is rotationally excited. This inevitably requires the rotational collective motion of the two atomic electrons as a whole. Hence both of the two atomic electrons are forced to participate in the excitation processes. Figure 2 shows the $^1S^e$-$^1D^e$ excitation cross sections from the initial $[3(2,0)^+3]^1S^e$ state to some typical final states. For example, one sees that the $^1S^e$-$^1D^e$ cross section with $\Delta n = 1$ and with all other quantum numbers unchanged is comparable with those for other double-electron-excitation processes as is expected from the above arguments. Namely, this type of transition can be considered to be the double-electron-excitation process.

As we have already seen, the single-electron-excitation processes are most likely to occur under the condition $\Delta L = 0$. However, the cross sections for these processes σ_1 ($\Delta L = 0$) are still much smaller than the optically allowed cross sections for the double-electron-excitation processes σ_2 ($\Delta L = 1$) if one makes comparison among the excitation cross sections from the same initial N manifolds as shown in Table IV.

Now we turn our attention to the double-excitation

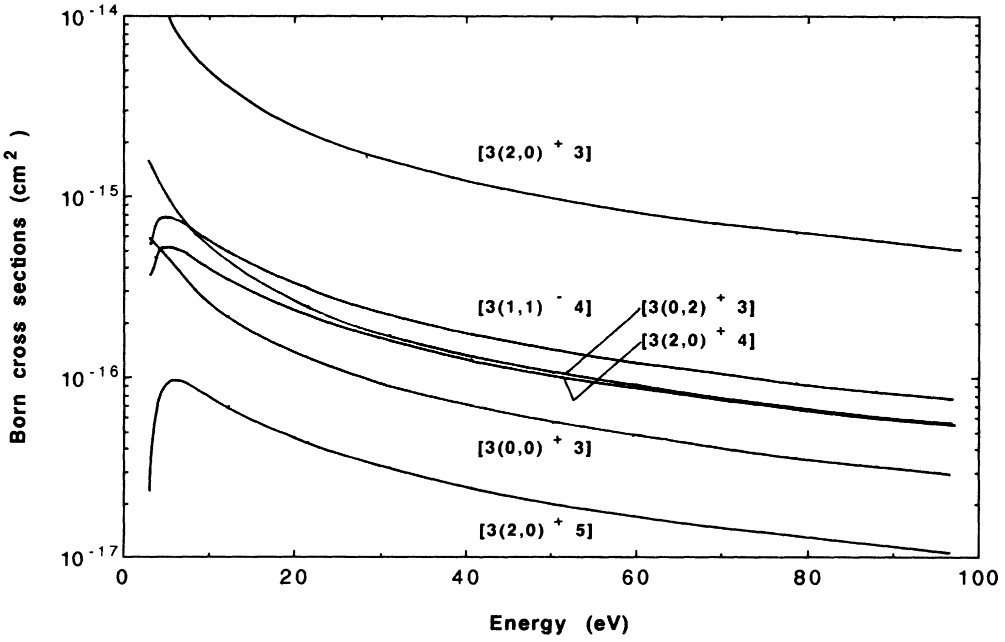

FIG. 2. Born cross sections for the $^1S^e$-$^1D^e$ excitation processes from the initial $[3(2,0)^+3]^1S^e$ state to the final $[3(K,T)^An]^1D^e$ states.

TABLE V. The propensity rules for the double-electron-excitation processes between the doubly excited states with $\Delta L=0$.

Excitation processes	Propensity rules	Interpretation based on the rovibrational model
$^1S^e$-$^1S^e$	$A=+;\Delta N=\Delta n=1$ $\Delta v=\Delta T=0$ $\Delta n_2=0$	Stretching
$^1P^o$-$^1P^o$ $^1D^e$-$^1D^e$	$A=+;\Delta N=\Delta n=0$ $\Delta A=0,\ \Delta v=2$ $\Delta T=0,$[a] $\Delta n_2=1$	Bending vibrational excitation
	$A=-;\Delta N=\Delta n=0$ $\Delta A\neq 0,\ \Delta v=1$ $\Delta T=1,\ \Delta n_2=0$ or $\Delta T=-1,\ \Delta n_2=1$	Change of radial correlation, bending vibrational excitation and rotational excitation around the molecular axis

[a] For the $^1D^e$-$^1D^e$ excitation, this process is almost comparable with the processes with $\Delta v=\Delta T=2$, $\Delta n_2=0$, and all other quantum numbers unchanged for the lowest vibrational state of each manifold with $N=3$ or 4.

processes, i.e., electron-pair excitation processes with $\Delta L=0$. As we have already seen, excitation of an electron pair, i.e., stretching of the linear e—He^{2+}—e molecule, is most likely to occur within the $^1S^e$-$^1S^e$ excitation processes. For the $^1P^o$-$^1P^o$ and $^1D^e$-$^1D^e$ excitation processes there are two types of excitation processes, i.e., (i) $\Delta A=0$, $\Delta v=2$, $\Delta T=0$, $\Delta n_2=1$ for the initial state with $A=+$ and (ii) $\Delta A\neq 0$, $\Delta v=1$, $\Delta T=1$ or -1, $\Delta n_2=0$ or 1 for the initial state with $A=-$ with all other quantum numbers unchanged. Namely, for the *P-P* and *D-D* double-excitation processes, rotational and/or vibrational modes are more likely to be excited than the stretching with $\Delta N=\Delta n=1$ of the doubly excited He as a linear triatomic molecule. This in sharp contrast with the systematic trend seen in the $^1S^e$-$^1S^e$ excitation processes. However, the behavior of the "vibrationally" excited initial states tends to deviate from the propensity rules obtained. This arises from the fact that the final states specified by these rules no longer exist because of the cutoff of the quantum numbers v (i.e., K) and T.

Table V summarizes the propensity rules, i.e., the systematic trend found in the double-excitation processes with $\Delta L=0$ including the $^1S^e$-$^1S^e$ case. For the $^1P^o$-$^1P^o$ and $^1D^e$-$^1D^e$ excitation, the isomorphism of the correlation patterns of the charge density plot between the initial and final states does not seem to explain the propensity rules. This is different from the case of the $^1S^e$-$^1S^e$ excitation. One possible reason may come from the fact that the vibrational and rotational excitation as a "linear molecule" within the same N manifold is more likely to occur than the stretching, i.e., hyperradial excitation with $\Delta N=1$ and $\Delta n=1$ from the energetic consideration. Another reason for this difference seems to arise from the momentum transfer from the relative motion between the incident electron and the atom, which is being investigated in more detail. It should be noted that the propensity rules obtained here and in our previous papers[1,2] also hold for excitation processes by charged particles other than electrons such as protons, multiply charged ions, for example, C^{6+}, in the energy regions where the Born approximation is valid.

In summary, we have theoretically found the following propensity rules for the excitation processes between the doubly excited states under the condition $\Delta L=0$. (i) The single-electron excitation with $\Delta n=1$ for the intrashell state with $N=n$ is most likely to occur. For the intershell states with $N<n$, the single-electron excitation for the inner electron also takes place though its cross section is much smaller than that for the outer-electron excitation, i.e., $\Delta n=1$ and all other quantum numbers unchanged and is comparable with that for the double-electron excitation. (ii) For the $^1P^o$-$^1P^o$ and $^1D^e$-$^1D^e$ double-electron-excitation processes, the rotational and vibrational modes as a "linear molecule" are more likely to be excited than the stretching mode. This is in sharp contrast with the findings for the $^1S^e$-$^1S^e$ excitation processes.

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