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Orientation Phenomena for Electron-Ion Collisional s-p Excitation in Semiclassical Strongly Coupled Plasmas

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Abstract

The orientation phenomena for the 1s $\longrightarrow$ $2p_{\pm}$ collisional excitations in strongly coupled semiclassical plasmas are investigated. The angular momentum orientation parameter $L_{\perp}$ is determined for various Debye length, thermal de Broglie wave length, and collision energy. It is found that the 1s $\longrightarrow$ $2p_{-}$ transitions are strongly favored in all impact parameter regions. The $2p_{-}$ preference increases with decreasing the thermal de Broglie wave length and decreases with increasing the collision energy. It is also found that the orientation parameters have minima which correspond to the complete 1s $\longrightarrow$ $2p_{-}$ transition since the 1s $\longrightarrow$ $2p_{+}$ transition probability is quite small for small impact parameters.

Keywords:

atomic collision in plasam, orientation phenomena

1. Introduction

The orientation and alignment parameters in atomic collisions [1-5] have been actively studied since these phenomena provide detailed information on the mechanism of collisional excitations of target atoms or ions. The electron collisions with ions in nonideal plasmas have received much attention due to many applications using the radiation spectra from the excited ions. The orientation phenomena in plasmas could provide detailed information on plasma parameters. Thus we investigate the plasma screening and quantum effects on the orientation parameter for direct s – p excitations in electron-hydrogenic ion collisions in strongly coupled semiclassical plasmas. In strongly coupled plasma systems, the screening and quantum-mechanical effects play important roles in studies of thermodynamic and kinetic properties of plasmas. Recently, a description of the strongly coupled semiclassical plasmas is provided by the analytic form of the pseudopotential model [6-9] taking into account both the quantum effect and also the plasma screening effect is obtained for the interaction potential in strongly coupled semiclassical plasmas. In this work, we use the first-order semiclassical straight-line trajectory analysis [10,11] for the motion of the projectile electron in order to obtain the orientation parameter ($L_{\perp}$) for the direct s – p excitations as a function of the impact parameter, collision energy, and plasma parameters. Without plasma screening and quantum effects, it has been known that the probability of populating a p_{-1} state tends to dominate over the probability of populating a p_{+1} state in planar collisions due to the propensity rule [2,12]. The angular momentum orientation parameter in strongly coupled semiclassical plasmas is determined for various scaled Debye length and thermal de Broglie wave length.

2. Excitation processes

From the first-order semiclassical analysis, the total excitation cross section from an unperturbed atomic state $|n>$ [$\equiv \Psi_{nlm}(\boldsymbol{r})$] to an excited state $|n'>$ [$\equiv \Psi_{n'l'm'}(\boldsymbol{r})$] is given by [10]

$$\sigma_{n',n} = \int d^2\boldsymbol{b}|T_{n',n}(b)|^2, \tag{1}$$

where b is the impact parameter and $T_{n',n}(b)$ is the transition amplitude:

$$T_{n',n}(b) = -\frac{i}{\hbar}\int_{-\infty}^{\infty} dt e^{i\omega_{n',n}t} < n'|V|n >, \tag{2}$$

where $\omega_{n',n} \equiv (E_{n'} - E_n)/\hbar$, and E_n and $E_{n'}$ are the energy eigenvalues for the eigenstates n and n', respectively, and V is the interaction potential. In strongly coupled plasma systems, the collective screening and quantum effects play important roles in the studies of thermodynamic and kinetic properties of plasmas. Recently, the analytic form of the effective temperature-dependent pseudopotential [9] was obtained as a result

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of the correlation between the Boltzmann factor and the quantum-mechanical Slater sum. Using the pseudopotential model, the interaction potential between the electron and the hydrogenic target ion with nuclear charge Z in strongly coupled semiclassical plasmas can be represented in the following form:

$$V(\boldsymbol{r},\boldsymbol{R}) = -\frac{Ze^2}{\sqrt{1-4\lambda_{ie}^2/\Lambda^2}}\left(\frac{e^{-AR}}{R}-\frac{e^{-BR}}{R}\right) + \frac{e^2}{\sqrt{1-4\lambda_{ee}^2/\Lambda^2}}\left(\frac{e^{-A'|\boldsymbol{r}-\mathrm{R}|}}{|\boldsymbol{r}-\boldsymbol{R}|}-\frac{e^{-B'|\boldsymbol{r}-\boldsymbol{R}|}}{|\boldsymbol{r}-\boldsymbol{R}|}\right), \tag{3}$$

where $\boldsymbol{r}$ and $\boldsymbol{R}$ are position vectors of the bound electron and the projectile electron, respectively,

$$A=\sqrt{\frac{1-\sqrt{1-4\lambda_{ie}^2/\Lambda^2}}{2\lambda_{ie}^2}},\ B=\sqrt{\frac{1+\sqrt{1-4\lambda_{ie}^2/\Lambda^2}}{2\lambda_{ie}^2}},$$

$$A^{'}=\sqrt{\frac{1-\sqrt{1-4\lambda_{ee}^2/\Lambda^2}}{2\lambda_{ee}^2}},\ B^{'}=\sqrt{\frac{1+\sqrt{1-4\lambda_{ee}^2/\Lambda^2}}{2\lambda_{ee}^2}},$$

$\lambda_{ie}(=\hbar/\sqrt{2\pi\mu_{ie}k_BT})$ and $\lambda_{ee}(=\hbar/\sqrt{2\pi\mu_{ee}k_BT})$ are the thermal de Broglie wave lengths of the electron-ion pair and the electron-electron pair, μ_{ie} and μ_{ee} is the reduced mass of the electron-ion system and electron-electron system, k_B is the Boltzmann constant, T is the plasma temperature, and Λ is the Debye length. It is shown that the pseudopotential form is valid for $\lambda < \Lambda/2$, i.e., the region of weakly degenerate plasmas. When the quantum effect is absent, i.e., $\lambda \to 0$, the pseudopotential goes over into the Debye-Hückel interaction potential $V_{DH} \to (-Ze^2/r)e^{-r/\Lambda}$. In addition, when the screening and quantum effects are absent, i.e., $\Lambda \to \infty, \lambda \to 0$, this pseudopotential leads to the pure Coulomb potential $V_C \to (-Ze^2/r)$.

For inelastic collisions ($n' \neq n$), the electron-nucleus interaction term gives noncontribution to the transition amplitude due to orthogonality of the initial and final states of the target system. For the $1s \to 2p_{\pm1}$ excitations, the transition matrix elements $\widetilde{V}^{\alpha}_{2p_{\pm1},1s}$ become

$$\widetilde{V}^{\alpha}_{2p_{\pm1},1s} \equiv \int d^3\boldsymbol{r}\Psi_{2p_{\pm1}}(\boldsymbol{r})\frac{e^{-\alpha|\boldsymbol{r}-\boldsymbol{R}|}}{|\boldsymbol{r}-\boldsymbol{R}|}\Psi_{1s}(\boldsymbol{r}). \tag{4}$$

Since the nonspherical electron-electron interaction term in Eq. (3) has a form of the modified Helmholtz operator Green's function, it can be expanded, using the addition theorem with the spherical harmonics [13]. After some algebra, the total $1s \to 2p_{\pm1}$ transition matrix elements are obtained as

$$< 2p_{\pm}|V(\boldsymbol{r},\boldsymbol{R})|1s > = \frac{4\sqrt{6}}{a_Z}\frac{Y^*_{1\pm1}(\hat{R})}{\bar{R}^2} \frac{e^2}{\sqrt{1-4\bar{\lambda}_{ee}^2a_\Lambda^2}}\times\left[\frac{1}{(\frac{9}{4}-\bar{A}'^2)^3}\times\left[(\bar{A}'\bar{R}+1)e^{-\bar{A}\bar{R}}-e^{-\frac{3}{2}\bar{R}}\left(1+\frac{3}{2}\bar{R}\right)\right] - \frac{1}{\left(\frac{9}{4}-\bar{B}'^2\right)^3}\times\left[(\bar{B}'\bar{R}+1)e^{-\bar{B}'\bar{R}}-e^{-\frac{3}{2}\bar{R}}\left(1+\frac{3}{2}\bar{R}\right)\right]\right], \tag{5}$$

where $a_\Lambda(\equiv a_Z/\Lambda)$ is the scaled Debye length, $a_Z(=\hbar^2/Zme^2)$ is the Bohr radius of the hydrogenic ion with nuclear charge Z, $\bar{\lambda}_{ee}(=\lambda_{ee}/a_Z)$ is the scaled thermal de Broglie wave length, $\bar{A}'^2 \equiv \frac{1-\sqrt{1-4\bar{\lambda}_{ee}^2a_\Lambda^2}}{2\bar{\lambda}_{ee}^2}$, $\bar{B}'^2 \equiv \frac{1+\sqrt{1-4\bar{\lambda}_{ee}^2a_\Lambda^2}}{2\bar{\lambda}_{ee}^2}$, and $\bar{b}(=b/a_Z)$ is the scaled impact parameter. In order to describe the projectile motion, we assume that the projectile electron is moving on the straight-line trajectory in the so-called natural coordinate frame in which the axis of quantization z is chosen perpendicular to the collision plane. Then, the position of the projectile electron can be written as a function of time t and the impact parameter b,

$$\boldsymbol{R}(t) = b\hat{y} + vt\hat{z}, \tag{6}$$

where v is the collision velocity and $t = 0$ is arbitrary, chosen as the instant at which the projectile makes its closest approach to the target ions. Under these circumstances, in $1s \to 2p$ excitations, the conservation law prohibits the $1s \to 2p_0(m = 0)$ transition; only $m = \pm1$ substates $2p_{\pm1}$) of the 2p level are possible. In this natural coordinate frame, the spherical harmonics $Y^*_{1\pm1}(\hat{R})$ become

$$Y^*_{1\pm1}(\hat{R}) = \mp\sqrt{\frac{3}{8\pi}}\frac{\bar{v}t \mp i\bar{b}}{\bar{R}}, \tag{7}$$

where $\bar{R} \equiv R/a_Z$ and $\bar{v}(=v/a_Z)$ is the scaled projectile velocity. Then, the $T_{2p_{\pm1},1s}$ transition amplitudes are found to be

$$T\pm(\bar{b},\bar{\lambda}_{ee},a_\Lambda,\bar{E}) = \mp\frac{12}{\hbar v}\frac{e^2}{\sqrt{1-4\bar{\lambda}_{ee}^2a_\Lambda^2}} \left[\int_0^\infty d\tau\frac{(\tau\sin\beta\tau \mp \bar{b}\cos\beta\tau)}{(\tau^2+\bar{b}^2)^{3/2}}\frac{1}{\left(\frac{9}{4}\bar{A}'^2\right)^3}\times\left[\left(\bar{A}'\sqrt{(\tau^2+\bar{b}^2)}+1\right)e^{-\bar{A}'\sqrt{(\tau^2+\bar{b}^2)}} - e^{-\frac{3}{2}\sqrt{(\tau^2+\bar{b}^2)}}\left(1+\frac{3}{2}\sqrt{(\tau^2+\bar{b}^2)}\right)\right] - \int_0^\infty d\tau\frac{(\tau\sin\beta\tau \mp \bar{b}\cos\beta\tau)}{(\tau^2+\bar{b}^2)^{3/2}}\frac{1}{\left(\frac{9}{4}-\bar{B}'^2\right)^3}\right.$$

$$\times \left[\left(\bar{B}' \sqrt{(\tau^2 + \bar{b}^2)} + 1 \right) e^{-\bar{B}' \sqrt{(\tau^2+\bar{b}^2)}} - e^{-\frac{3}{2} \sqrt{(\tau^2+\bar{b}^2)}} \left(1 + \frac{3}{2} \sqrt{(\tau^2 + \bar{b}^2)} \right) \right] \Bigg], \quad (8)$$

where $\tau(\equiv \bar{v}t)$ and $\bar{E}(\equiv mv^2/2Z^2Ry)$ is the dimensionless time and the projectile energy , $\beta(\equiv \frac{\omega_{\pm}a_Z}{v}) = \frac{3}{8\sqrt{\bar{E}}}$.

3. Orientation phenomena

The orientation parameter [2,12] is represented as

$$L_{\perp}(\bar{b}, \bar{\lambda}_{ee}, a_{\Lambda}, \bar{E}) = \frac{|T_{+}(\bar{b}, \bar{\lambda}_{ee}, a_{\Lambda}, \bar{E})|^2 - |T_{-}(\bar{b}, \bar{\lambda}_{ee}, a_{\Lambda}, \bar{E})|^2}{|T_{+}(\bar{b}, \bar{\lambda}_{ee}, a_{\Lambda}, \bar{E})|^2 + |T_{-}(\bar{b}, \bar{\lambda}_{ee}, a_{\Lambda}, \bar{E})|^2}. \quad (9)$$

This quantity $L_{\perp}(\bar{b}, \bar{\lambda}_{ee}, a_{\Lambda}, \bar{E})$ is a measure of the expectation value of the transferred orbital angular momentum to the bound electron in the target ion due to the direct $1s \to 2p_{\pm 1}$ excitations. Since the line intensity ratios are directly related to the $1s \to 2p_{\pm 1}$ excitations rates, the orientation parameter is connected to the relative number of coincidences for RHC (right-hand circularly polarized light) and LHC (left-hand circularly polarized light) photon emitting due to the de-excitation to the ground state since the degree of linear polarization [12] P_l is related to $L_{\perp}$. Figures 1 and 2 show the orientation parameters for the $1s \to 2p_{\pm 1}$ excitations as functions of the scaled impact parameter for various values of the Debye length and thermal de Broglie wave length. As we see in these figures, $L_{\perp} < 0$ for both the high and low projectile energies in all impact parameter regions, i.e., the probability of populating the $2p_{-1}$ state dominates the probability of the populating the $2p_{+1}$ state in planar collisions, due to the propensity rule. It is found that the $1s \longrightarrow 2p_{-}$ transitions are strongly favored in all impact parameter regions and the $2p_{-1}$ preference increases with decreasing the thermal de Broglie wave length. The quantum and screening effects on the orientation parameter increase with increasing the projectile energy. It is also found that the $s \to p_{-1}$ preference is appreciably reduced as the projectile energy increases. However, it should be noted that the quantum and screening effects increase with increasing the collision energy. For small impact parameters, the orientation parameters have minima which correspond to the complete $1s \to 2p_{-1}$ transitions since the $1s \to 2p_{+1}$ transition probabilities are found to be quite small for $\bar{b} < 1$.

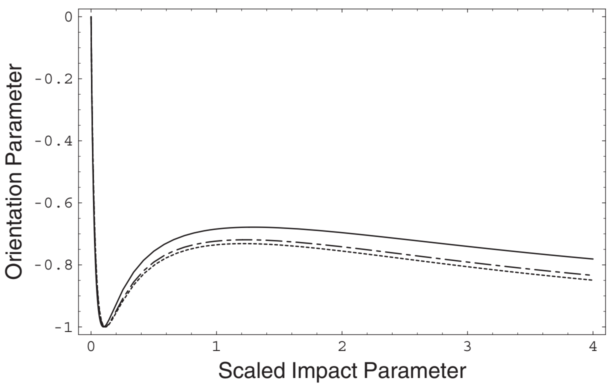

Fig. 1 The orientation parameter $L_{\perp}(\bar{b}, \bar{\lambda}_{ee}, a_{\Lambda}, \bar{E})$ for the direct $s \to p_{\pm 1}$ excitations when $\bar{E} = 9$. The solid line represents the orientation parameters for $\bar{\lambda}_{ee} = 0.1$ and $a_{\Lambda} = 0.1$. The dash-dotted line represents the orientation parameters for $\bar{\lambda}_{ee} = 0.05$ and $a_{\Lambda} = 0.05$. The dotted line represents the orientation parameters for $\bar{\lambda}_{ee} = 0.025$ and $a_{\Lambda} = 0.025$.

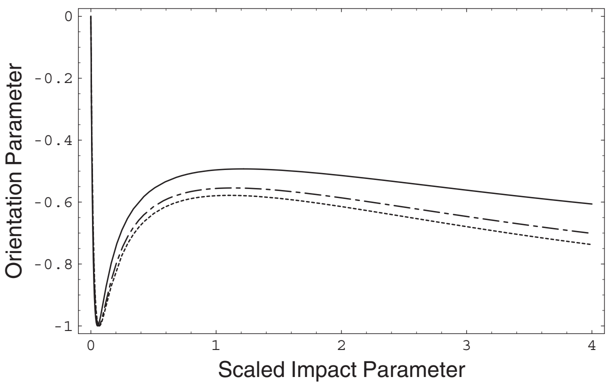

Fig. 2 The orientation parameter $L_{\perp}(\bar{b}, \bar{\lambda}_{ee}, a_{\Lambda}, \bar{E})$ for the direct $s \to p_{\pm 1}$ excitations when $E = 25$. The solid line represents the orientation parameters for $\bar{\lambda}_{ee} = 0.1$ and $a_{\Lambda} = 0.1$. The dash-dotted line represents the orientation parameters for $\bar{\lambda}_{ee} = 0.05$ and $a_{\Lambda} = 0.05$. The dotted line represents the orientation parameters for $\bar{\lambda}_{ee} = 0.025$ and $a_{\Lambda} = 0.025$.

4. Conclusion

The orientation phenomena for the $1s \longrightarrow 2p_{\pm}$ collisional excitations in strongly coupled semiclassical plasmas are investigated. The angular momentum orientation parameter $L_{\perp}$ is determined for various Debye length, thermal de Broglie wave length, and collision energy. The result show that the probability of populating the $2p_{-1}$ state dominates the probability of the populating the $2p_{+1}$ state in planar collisions, due to the propensity rule. It is found that the $1s \longrightarrow 2p_{-}$ transitions are strongly favored in all impact parameter regions and the $2p_{-1}$ preference increases with decreasing the thermal de Broglie wave length. The quantum and screening effects on the orientation parameter increase with increasing the projectile energy. It is also found that the $s \to p_{-1}$ preference is appreciably reduced as the projectile energy increases. However, it should be noted that the quantum and screening effects increase with increasing the collision energy. For small impact parameters, the orientation parameters have minima which correspond to the complete $1s \rightarrow 2p_{-1}$ transitions since the $1s \rightarrow 2p_{+1}$ transition probabilities are found to be quite small for $\bar{b} < 1$. Since the orientation parameter is obtained by the transition amplitudes including the close-encounter effects, i.e., without using the dipole approximation, the results for small impact parameter domain would be quite reliable. These results provide useful information on the orientation phenomena for $s-p$ excitations in strongly coupled semicalssical plasmas.

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