Dynamic Screening Effects on Collisional Orientation Phenomena in Nonideal Plasmas

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Dynamic screening effects on orientation phenomena of 1s $\rightarrow$ 2p$_{\pm 1}$ excitations in nonideal plasmas are investigated. A semiclassical method is employed to describe the motion of the projectile electron in order to investigate the variation of the orientation parameter as a function of the impact parameter, projectile energy, thermal energy, and Debye length. The result shows that the preference for the 1s $\rightarrow$ 2p$_{-1}$ transition significantly decreases with increasing projectile energy. It is found that the dynamic screening effect increases with increasing impact parameter and also with increasing projectile energy. It is also found that the 1s $\rightarrow$ 2p$_{-1}$ preference decreases with increasing thermal energy.

Key words: Dynamic Screening; Collisional Orientation.

The electron-ion collision process [1 – 4] has been of great interest since this process has been widely used in many areas of physics, such as astrophysics, atmospheric physics, atomic physics, collision physics, molecular physics, and plasma physics. A recent experimental investigation shows the possibility of the detection of radiative transitions from the p$_{\pm 1}$ ($m = \pm 1$) excited states to the ground state [5]. The atomic orientation phenomena have been investigated, since these phenomena provide detailed information on the mechanism of the collisional excitations of the target system [6 – 8]. Recently, the plasma diagnostics using various atomic collision processes [9 – 12] in plasmas have paved new ways to investigate plasma parameters. The plasma described by the Debye-Hückel potential is classified as the ideal plasma, since the average interaction energy between charged particles is smaller than the average kinetic energy of a particle [13]. However, the correlation effects caused by simultaneous interaction of many charged particles have to be taken into account if the plasma density increases. Then, the interaction potential would not be represented by the ordinary Debye model due to the strong collective effects of nonideal particle interactions [14 – 16]. In addition, for electron-ion collisions in plasmas, the static Debye screening formula would not be reliable when the velocity of the plasma electron is comparable to or smaller than the velocity of the projectile electron, since the projectile polarizes the surrounding plasma electrons. Under these circumstances, the dynamic motion of the plasma electrons has to be taken into account in order to properly investigate the plasma screening effects on the collision process in plasmas. Then, the electron-ion collisional excitation process in nonideal plasmas would be different from those described by the static Debye-Hückel interaction potential. Thus, in this paper we investigate the dynamic plasma screening effects on the orientation phenomena in the electron-ion collisional excitation processes in nonideal plasmas. The modified Debye-Hückel form of the effective interaction potential [16], taking into account the dynamic screening, is applied to represent electron-ion interactions in nonideal plasmas. The semiclassical method [17] is employed to investigate the orientation parameter for the direct 1s $\rightarrow$ 2p$_{\pm 1}$ excitations as a function of the impact parameter, projectile energy, thermal energy, and Debye length.

In the first-order semiclassical approximation, the excitation cross-section [17] from an unperturbed atomic state $|n\rangle[\equiv \Psi_{nlm}(\mathbf{r})]$ to an excited state $|n'\rangle[\equiv \Psi_{n'l'm'}(\mathbf{r})]$ is given by

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

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

$$T_{n'n} = -\frac{\mathrm{i}}{\hbar}\int_{-\infty}^{\infty} \mathrm{d}t\, \mathrm{e}^{\mathrm{i}\omega_{n',n}t}\langle n'|H_{\text{int}}|n\rangle, \tag{2}$$

where $\omega_{n',n} = (E_{n'} - E_n)/\hbar$, $E_{n'}$ and E_n are the energies of the atomic states $|n'\rangle$ and $|n\rangle$, respectively, and H_{int} is the interaction Hamiltonian between the projectile and the target system. The semiclassical method has a strong appeal in aiding the physical intuition and is mathematically more tractable than fully quantum mechanical treatments. The semiclassical straight-line trajectory approximation is known to be valid for high collision energies [18, 19]. It is known that the semiclassical cross-section is identical with the quantum mechanical Born cross-section with a finite cutoff in the momentum transfer [19]. Since the impact parameter is conjugate to the momentum transfer, the dependence of the transition probability on the impact parameter in the semiclassical method contains the same physics seen in the dependence of the generalized oscillator strength on the momentum transfer in the Born approximation [20]. A detailed discussion of the generalized oscillator strength in the first-order plane-wave Born approximation has been given by Iwai, Shimamura, and Watanabe [21].

Recently, the simple analytic form [16] of the modified Debye potential including the dynamic screening effects in nonideal plasmas has been obtained by an approach based on the dynamically screened ladder approximation. Using this effective potential model, the dynamic interaction Hamiltonian between the projectile electron and the hydrogenic target ion with nuclear charge Ze is given by

$$\begin{aligned} H_{\text{int}}(\mathbf{r}',\mathbf{r},v) = &-\frac{Ze^2}{r'}\exp[-r'/r_0(v)] \\ &+\frac{e^2}{|\mathbf{r}'-\mathbf{r}|}\exp[-|\mathbf{r}'-\mathbf{r}|/r_0(v)], \end{aligned} \tag{3}$$

where $\mathbf{r}'$ and $\mathbf{r}$ are, respectively, the positions of the projectile electron and the bound electron of the target ion, $r_0(v)$ $[= r_{\text{D}}(1+v^2/v_{\text{th}}^2)^{1/2}]$ is the modified screening length, r_{D} the Debye length, v the velocity of the projectile electron, v_{th} $(= \sqrt{k_{\text{B}}T/m})$ the thermal velocity, k_{B} the Boltzmann constant, T the plasma temperature, and m the electron mass. The idea of this effective screening length was obtained to produce the correct asymptotic results for the stopping power by Zwicknagel, Toepffer, and Reinhard [22]. The velocity dependence of the plasma screening length in (3) would be understood when the projectile velocity is smaller than the electron thermal velocity, since the dynamic plasma screening turns out to be the static plasma screening, i. e., $r_0(v) \to r_{\text{D}}$. However, when the projectile velocity is greater than the thermal velocity, the interaction potential is almost unshielded, i. e., the dynamic screening length is greater than the Debye length. In the absence of the dynamic screening, the interaction Hamiltonian goes over into the nonspherical Debye-Hückel form $[H_{\text{DH}} \to -(Ze^2/r')\mathrm{e}^{-r'/r_{\text{D}}} + (\mathrm{e}^2/|\mathbf{r}'-\mathbf{r}|)\mathrm{e}^{-|\mathbf{r}'-\mathbf{r}|/r_{\text{D}}}]$ with the static screening length r_{D}.

For inelastic atomic collisions, the electron-nucleus interaction term in (3) does not contribute to the Hamiltonian matrix elements $H_{n',n}$ due to orthogonality of the initial and final states of the target system, i. e., $\langle n'|n\rangle = \delta_{n'n}\delta_{l'l}\delta_{m'm}$. Using the addition theorem with the spherical harmonics Y_{lm}, the modified Helmholtz operator Green's function [23] would be expressed as

$$\begin{aligned} &\frac{\exp[-|\mathbf{r}'-\mathbf{r}|/r_0(v)]}{|\mathbf{r}'-\mathbf{r}|/r_0(v)} = \\ &4\pi\sum_{l=0}^{\infty}\sum_{m=-l}^{l} i_l(r_</r_0(v))k_l(r_>/r_0(v))Y_{lm}(\hat{r})Y_{lm}^*(\hat{r}'), \end{aligned} \tag{4}$$

where i_l and k_l are spherical modified Bessel functions and $r_<$ $(r_>)$ is the smaller (larger) of r and r'. Here, we assume that the projectile electron is moving on a straight-line trajectory in the natural coordinate frame [6], in which the axis of the quantization z is chosen perpendicular to the collision plane. Then, the position of the projectile electron can be expressed as a function of time t and the impact parameter b, i. e., $\mathbf{r}'(t) = vt\hat{x} + b\hat{y}$. After some manipulations using the hydrogenic wave functions [17], the Hamiltonian matrix elements $H_{2\text{p}_{\pm1},1\text{s}}$ for the direct $1\text{s} \to 2\text{p}_{\pm1}$ excitations are found to be

$$\begin{aligned} H_{2\text{p}_{\pm1},1\text{s}} &\equiv \langle 2\text{p}_{\pm1}|H_{\text{int}}(\mathbf{r}',\mathbf{r},\bar{E})|1\text{s}\rangle \\ &= \mp\frac{(6e^2/a_Z)}{[9/4-a_{\text{D}}(\bar{E})]^3}\frac{\bar{v}t\mp \mathrm{i}\bar{b}}{\bar{r}'(\bar{v},\bar{b})}\left\{\left(\frac{1}{\bar{r}'(\bar{v},\bar{b})}+\frac{a_{\text{D}}(\bar{E})}{\bar{r}'(\bar{v},\bar{b})}\right)\mathrm{e}^{-a_{\text{D}}(\bar{E})\bar{r}'(\bar{v},\bar{b})}\right. \\ &\left.-\left[\frac{1}{\bar{r}'(\bar{v},\bar{b})}+\frac{3}{2\bar{r}'(\bar{v},\bar{b})}+\frac{9}{8}-\frac{a_{\text{D}}^2(\bar{E})}{2}+\left(\frac{27}{64}-\frac{8a_{\text{D}}^2(\bar{E})}{3}+\frac{a_{\text{D}}^4(\bar{E})}{12}\right)\bar{r}'(\bar{v},\bar{b})\right]\mathrm{e}^{-3\bar{r}'(\bar{v},\bar{b})/2}\right\}, \end{aligned} \tag{5}$$

where $\bar{E}$ ($\equiv mv^2/2Z^2Ry$) is the scaled projectile energy, Ry ($= me^4/2\hbar^2 \approx 13.6$ eV) is the Rydberg constant, a_Z ($= a_0/Z$) is the Bohr radius of the hydrogen ion with nuclear charge Ze, a_0 ($= \hbar^2/me^2$) is the Bohr radius of the hydrogen atom, $a_{\rm D}(\bar{E})[\equiv a_Z/r_0(v)] = a_{\rm D}(1+\bar{E}/\bar{E}_{\rm th})^{-1/2}$, $a_{\rm D}$ ($\equiv a_Z/r_{\rm D}$) is the scaled reciprocal Debye length, $\bar{E}_{\rm th}$ ($\equiv k_{\rm B}T/2Z^2Ry$) is the scaled thermal energy, $\bar{v} \equiv v/a_Z$, $\bar{b}$ ($\equiv b/a_Z$) is the scaled impact parameter, and $\bar{r}'(\bar{v},\bar{b})(\equiv r'/a_Z) = [(\bar{v}t)^2+\bar{b}^2]^{1/2}$. The investigation of various physical properties of the collision cross-section is essential in theoretical atomic spectroscopy, since one of the most important parameters in collision physics is the cross-section. The scaled $1\text{s} \rightarrow 2\text{p}_{\pm1}$ excitation cross-sections for the electron-ion collisions in a nonideal plasmas, including the dynamic screening in units of πa_0^2, are obtained as

$$Z^4\sigma_{\pm1}/\pi a_0^2 = \int \bar{b}\,{\rm d}\bar{b}\,|\bar{T}_{\pm1}(\bar{b},\bar{E},\bar{E}_{\rm th},a_{\rm D})|^2, \quad (6)$$

where the scaled transition probabilities $\bar{T}_{\pm1}$ are found to be

$$\begin{aligned}|\bar{T}_{\pm1}(\bar{b},\bar{E},\bar{E}_{\rm th},a_{\rm D})|^2 = {} & \frac{(2^{17}/3^{10})}{\bar{E}[9/4-a_{\rm D}^2(1+\bar{E}/\bar{E}_{\rm th})^{-1}]^6}\left|\int_0^\infty {\rm d}\tau\left[\tau\sin\left(\frac{3\tau}{8\bar{E}^{1/2}}\right)\mp\bar{b}\cos\left(\frac{3\tau}{8\bar{b}^{1/2}}\right)\right]\right.\\ & \cdot\left\{\left(\frac{1}{(\tau^2+\bar{b}^2)^{3/2}}+\frac{a_{\rm D}(1+\bar{E}/\bar{E}_{\rm th})^{-1/2}}{(\tau^2+\bar{b}^2)}\right)\exp\left[-a_{\rm D}(1+\bar{E}/\bar{E}_{\rm th})^{-1/2}(\tau^2+\bar{b}^2)^{1/2}\right]\right.\\ & -\left[\frac{1}{(\tau^2+\bar{b}^2)^{3/2}}+\frac{3}{2(\tau^2+\bar{b}^2)}+\left(\frac{9}{8}-\frac{a_{\rm D}^2(1+\bar{E}/\bar{E}_{\rm th})^{-1}}{2}\right)\frac{1}{(\tau^2+\bar{b}^2)^{1/2}}\right.\\ & \left.\left.\left.+\left(\frac{27}{64}-\frac{8a_{\rm D}^2(1+\bar{E}/\bar{E}_{\rm th})^{-1}}{3}+\frac{a_{\rm D}^4(1+\bar{E}/\bar{E}_{\rm th})^{-2}}{12}\right)\right]\exp\left[-3(\tau^2+\bar{b}^2)^{3/2}/2\right]\right\}\right|^2,\end{aligned} \quad (7)$$

where τ ($\equiv \bar{v}t$) is the dimensionless time. In the natural frame, the orientation parameter for the $1\text{s} \rightarrow 2\text{p}_{\pm1}$ excitations is defined as

$$\begin{aligned}& L_\perp(\bar{b},\bar{E},\bar{E}_{\rm th},a_{\rm D}) = \\ & \frac{|\bar{T}_{+1}(\bar{b},\bar{E},\bar{E}_{\rm th},a_{\rm D})|^2-|\bar{T}_{-1}(\bar{b},\bar{E},\bar{E}_{\rm th},a_{\rm D})|^2}{|\bar{T}_{+1}(\bar{b},\bar{E},\bar{E}_{\rm th},a_{\rm D})|^2+|\bar{T}_{-1}(\bar{b},\bar{E},\bar{E}_{\rm th},a_{\rm D})|^2} \\ & \equiv w_{+1}-w_{-1},\end{aligned} \quad (8)$$

where $|\bar{T}_{+1}|^2$ and $|\bar{T}_{-1}|^2$ are the scaled transition probabilities for the $1\text{s} \rightarrow 2\text{p}_{+1}$ and $1\text{s} \rightarrow 2\text{p}_{-1}$ excitations, respectively, and $w_{\pm1}$ $[\equiv (\pi a_0^2\bar{b}/Z^4)|\bar{T}_{\pm1}|^2/\sum_{i=\pm1}{\rm d}\sigma_i/{\rm d}\bar{b}]$ are weighting factors with $\sum_{i=\pm1} w_i = 1$. The orientation parameter $L_\perp$ is the measure of the expectation value of the angular momentum transfer to the bound electron in the target ion due to the direct $1\text{s} \rightarrow 2\text{p}_{\pm1}$ collisional excitations. In addition, the orientation parameter is related to the number of coincidences for the right-hand circularly polarized (RCP) photons and the left-hand circularly polarized (LCP) photons emitting due to the radiative decay from the 2p_{+1} and 2p_{-1} excited states to the ground state, since the line intensity ratios are directly related to the excitation rates. There have been experimental evidences [5, 8] for detecting the relative number of coincidences for RCP and LCP photons due to atom-ion collisional excitations. It is known that the spectroscopic investigations of the radiation emitted from various plasmas have contributed to establishing quantum mechanics [24]. In the future, we may detect and resolve the relative number of RCP and LCP photons due to the $1\text{s} \rightarrow 2\text{p}_{\pm1}$ electron-ion excitation in nonideal plasmas, since the temperature dependence of the ratio of RCP to LCP photons including the dynamic screening is expected to be very different from the no screening and static screening cases. Therefore it would be expected that the orientation parameter atomic collisions in plasmas can be used as a tool for plasma diagnostics, since the temperature and density dependence of the relative number of coincidences for RCP and LCP photons is determined by the dynamically screened orientation parameter $L_\perp(\bar{b},\bar{E},\bar{E}_{\rm th},a_{\rm D})$.

In order to adequately investigate the dynamic plasma screening effects on the orientation parameter for the direct $1\text{s} \rightarrow 2\text{p}_{\pm1}$ electron-ion excitations in nonideal plasmas we choose $\bar{E} > 7$, since the semi-classical straight-line trajectory analysis is known to be valid for high projectile energies [18, 19]. The dynamically screened interaction would be important in dense laboratory and dense astrophysical plasmas. In these circumstances, the ranges of the electron number density and temperatures are known to be around $10^{20}-10^{23}$ cm^{-3} and 10^6-10^8 K, respectively, and

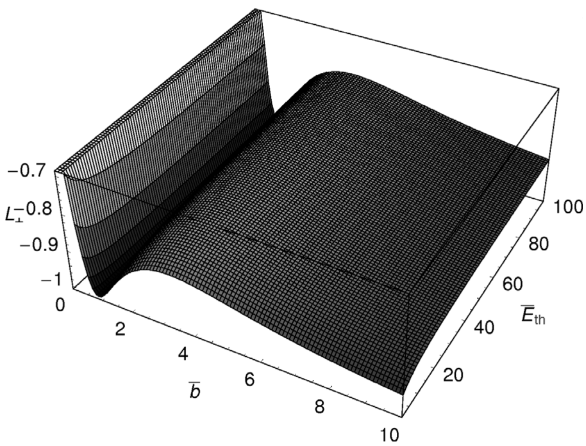

Fig. 1. Surface plot of the orientation parameter ($L_\perp$) as a function of the scaled impact parameter ($\bar{b}$) and the scaled thermal energy ($\bar{E}_{\rm th}$), when $\bar{E} = 10$ and $a_{\rm D} = 0.1$.

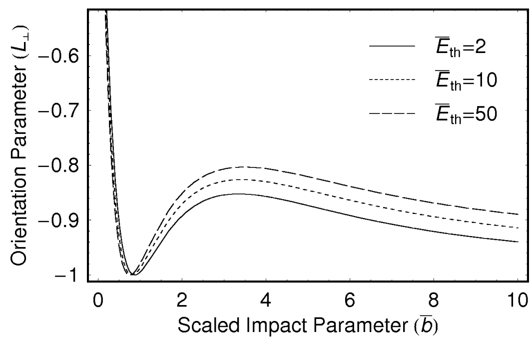

Fig. 2. The orientation parameter ($L_\perp$) as a function of the scaled impact parameter ($\bar{b}$), when $\bar{E} = 10$ and $a_{\rm D} = 0.1$. The solid line is the case of $\bar{E}_{\rm th} = 2$, i. e., $\gamma(= a_{\rm D}/Z\bar{E}_{\rm th}) = 0.05$ for $Z = 1$. The dotted line is the case of $\bar{E}_{\rm th} = 10$ and $\gamma = 0.01$. The dashed line is the case of $\bar{E}_{\rm th} = 50$ and $\gamma = 0.002$.

then the Debye length $r_{\rm D}$ is known to be greater than the Bohr radius, so that the range of the nonideal coupling plasma parameter $\gamma\ (= e^2/r_{\rm D}k_{\rm B}T)$ would be $\gamma \leq 1$. Figure 1 shows the surface plot of the orientation parameter $L_\perp$ as a function of the scaled impact parameter ($\bar{b}$) and scaled thermal energy ($\bar{E}_{\rm th}$). It is found that the probability of populating the $2p_{-1}$ excited state dominates the probability of populating the $2p_{+1}$ excited state in planar collisions due to a propensity rule. The minimum phenomena [25], which correspond to the complete $1s \rightarrow 2p_{-1}$ excitations, are also found in small parameter domains in nonideal plasmas including the dynamic screening. These minimum phenomena are quite similar to the Cooper zeros [26] in the photoabsorption process. Figure 2 represents the orientation parameter as a function of the scaled impact parameter for various values of the thermal energy. It is interesting to note that the preference for the $1s \rightarrow 2p_{-1}$ transition significantly decreases with increasing thermal energy for a given projectile energy. Figure 3 shows the orientation parameter for various values of the projectile energy. It should be noted that the preference for the $1s \rightarrow 2p_{-1}$ transition decreases with increasing projectile energy for a given thermal energy. In addition, Fig. 4 shows the surface plot of the ratio of the orientation parameter including the dynamic screening to that including the static screening as a function of the impact parameter and projectile energy. It is also found that the dynamic plasma screening effect on the orientation parameter increases with increasing impact parameter, i. e., distant collisions. In

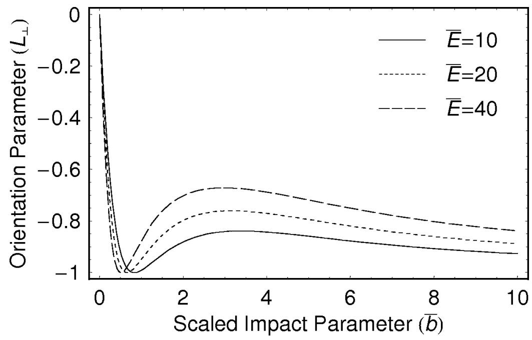

Fig. 3. The orientation parameter ($L_\perp$) as a function of the scaled impact parameter ($\bar{b}$), when $\bar{E}_{\rm th} = 5$, $a_{\rm D} = 0.1$, and $\gamma(= a_{\rm D}/Z\bar{E}_{\rm th}) = 0.02$ for $Z = 1$. The solid line is the case of $\bar{E} = 10$, the dotted line is the case of $\bar{E} = 20$, and the dashed line is the case of $\bar{E} = 40$.

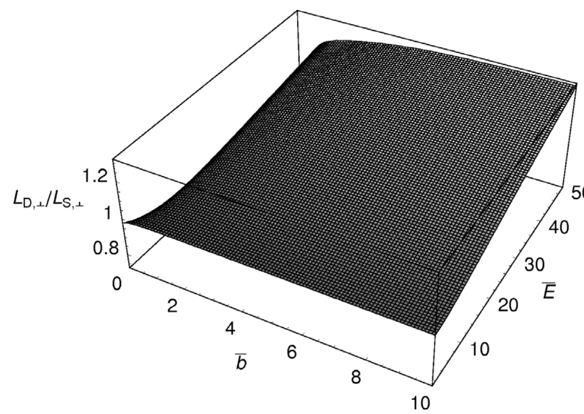

Fig. 4. Surface plot of the ratio ($L_{{\rm D},\perp}/L_{{\rm S},\perp}$) of the orientation parameter including the dynamic screening to that including the static screening as a function of the impact parameter ($\bar{b}$) and projectile energy ($\bar{E}$), when $\bar{E}_{\rm th} = 10$, $a_{\rm D} = 0.1$, and $\gamma(= a_{\rm D}/Z\bar{E}_{\rm th}) = 0.01$ for $Z = 1$.

addition, the dynamic screening effect is found to increase with increasing projectile energy.

These results provide useful information concerning the dynamic plasma screening effects on the atomic excitation processes in nonideal plasmas.

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