Influence of the Dynamic Quantum Shielding on the Transition Bremsstrahlung Spectrum and the Gaunt Factor in Strongly Coupled Semiclassical Plasmas

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This paper is dedicated to Professor Alfred Klemm, one of the pioneers in the field of isotope effects and molten salts and the founder of the Zeitschrift für Naturforschung, on the occasion of his 100th birthday.

The influence of the dynamic quantum shielding on the transition bremsstrahlung spectrum is investigated in strongly coupled semiclassical plasmas. The effective pseudopotential and the impact parameter analysis are employed to obtain the bremsstrahlung radiation cross section as a function of the de Broglie wavelength, Debye length, impact parameter, radiation photon energy, projectile energy, and thermal energy. The result shows that the dynamic screening effect enhances the transition bremsstrahlung radiation cross section. It is found that the maximum position of the transition bremsstrahlung process approaches to the center of the shielding cloud with increasing thermal energy. It is also found that the dynamic screening effect on the bremsstrahlung radiation cross section decreases with an increase of the quantum character of the semiclassical plasma. In addition, it is found that the peak radiation energy increases with an increase of the thermal energy. It is also found that the dynamic quantum screening effect enhances the bremsstrahlung Gaunt factor, especially for the soft-photon case.

Key words: Dynamic Quantum Screening; Transition Bremsstrahlung; Semiclassical Plasma.

The bremsstrahlung emission spectrum [1 – 7] due to the particle interactions in plasmas has received considerable attention since the bremsstrahlung process has played a crucial role in modern fields of plasma physics, such as plasma diagnostics, plasma discharges, and plasma spectroscopy. In addition to the bremsstrahlung emission by the electron–ion encounters, the transition bremsstrahlung process [3, 6] due to the polarization interaction between the plasma particle and the Debye shielding cloud in plasmas has been extensively investigated since this process has provided useful information on the physical properties of the screening structure and plasma parameters. The plasma described by the standard static Debye–Hückel potential has been known as the ideal or weakly coupled classical plasma since the average interaction energy between charged particles is smaller than the average kinetic energy of a plasma particle in plasmas [8, 9]. However, it is shown that the static interaction potential would not be reliable to explore the collision and radiation processes in plasmas when the velocity of the projectile is comparable to or smaller than the velocity of the plasma electron since the projectile electron would polarize the surrounding plasma shielding cloud due to the long-duration of the interaction [10]. In these circumstances, the dynamic description of the plasma electrons has to be taken into account in order to properly investigate the influence of the plasma shielding on the effective interaction potential in plasmas. In addition to the dynamic screen-

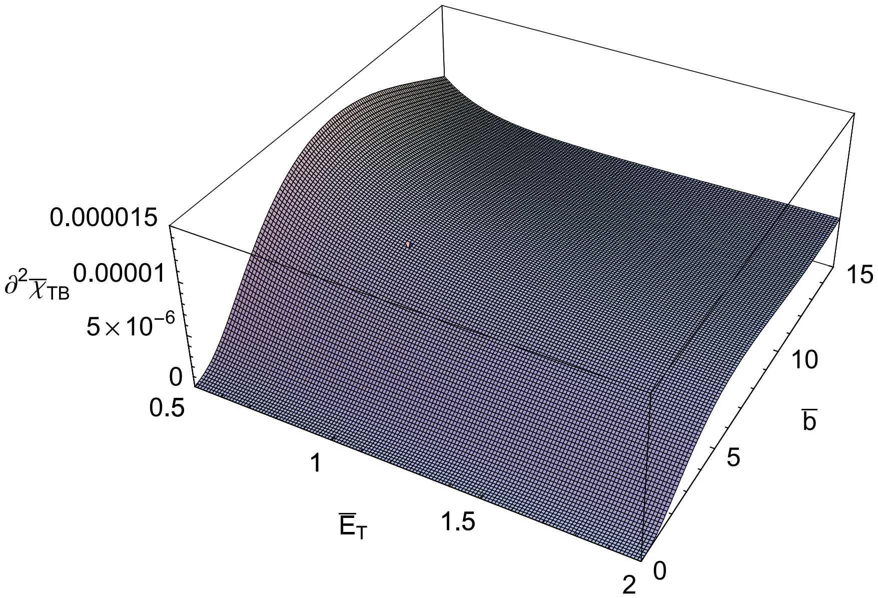

Fig. 1 (colour online). Scaled transition bremsstrahlung radiation cross section $\partial^2\bar{\chi}_{TB}$ in units of πa_0^2 in strongly coupled semiclassical plasmas as a function of the scaled thermal energy $\bar{E}_T$ and scaled impact parameter $\bar{b}$ when $\bar{E} = 0.9$, $\bar{\varepsilon} = 0.1$, $\bar{\lambda} = 1$, and $\bar{r}_D = 10$.

ing phenomenon, the multiparticle correlation effect caused by simultaneous many-particle interactions has to be taken into account with an increase of the plasma number density. Hence, the screened interaction potential in strongly coupled semiclassical plasmas would not be properly described by the conventional Debye–Hückel model due to the strong collective effect of nonideal particle interactions [11 – 14]. It would be then expected that the transition bremsstrahlung processes characterized by the dynamically screened effective potential in strongly coupled semiclassical plasmas would be considerably different from those by the static Debye–Hückel potential in weakly coupled classical plasmas due to the influence of the dynamic screening and nonideal collective interactions in semiclassical plasmas. Thus, in this paper, we investigate the dynamic quantum screening and nonideal collective effects on the transition bremsstrahlung process due to the polarization interaction between the electron and the polarized Debye shielding sphere in strongly coupled semiclassical plasmas. The impact parameter analysis and the effective pseudopotential are employed to obtain the bremsstrahlung radiation cross section for the transition bremsstrahlung process in semiclassical plasmas as a function of the electron de Broglie wavelength, Debye length, impact parameter, radiation photon energy, projectile energy, thermal energy, and other plasma parameters.

In the low-energy bremsstrahlung process, the classical expression of the bremsstrahlung radiation cross section [7] $\mathrm{d}\sigma_B(\omega)$ would be represented by

$$\mathrm{d}\sigma_B(\omega) = 2\pi \int \mathrm{d}b\, b\, \mathrm{d}P_\omega(b)\,, \tag{1}$$

where b is the impact parameter and $\mathrm{d}P_\omega(b)$ is the differential probability of emitting a bremsstrahlung photon of frequency ω within $\mathrm{d}\omega$. The photon emission probability $\mathrm{d}P_\omega(b)$ for a given impact parameter b would be obtained by the Larmor formula [15] for the instantaneous power emitted during the encounter of the projectile electron with the collision system such as

$$\mathrm{d}P_\omega(b) = \frac{8\pi e^2}{3\hbar m^2 c^3}\,|\mathbf{F}_\omega(b)|^2\,\frac{\mathrm{d}\omega}{\omega}\,, \tag{2}$$

where $\hbar$ is the rationalized Planck constant, m the electron mass, c the speed of light in vacuum, and $\mathbf{F}_\omega(b)$ the Fourier transform of the force for a given impact parameter associated with a radiation frequency ω:

$$\mathbf{F}_\omega(b) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \mathrm{d}t\,\mathbf{F}(\mathbf{r})\,\mathrm{e}^{\mathrm{i}\omega t}\,, \tag{3}$$

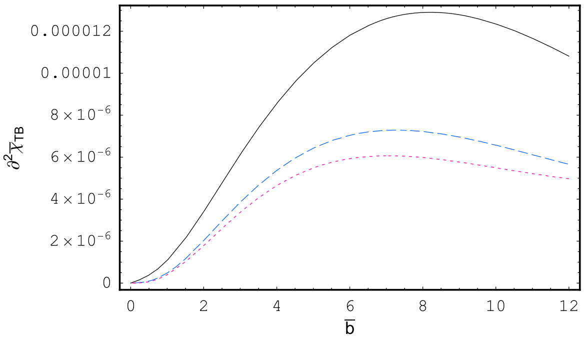

Fig. 2 (colour online). Scaled differential transition bremsstrahlung radiation cross section $\partial^2\bar{\chi}_{TB}$ as a function of the scaled impact parameter $\bar{b}$ when $\bar{E}=0.9$, $\bar{\varepsilon}=0.1$, $\bar{\lambda}=1$, and $\bar{r}_D=10$. The solid line represents the case of $\bar{E}_T=0.5$. The dashed line represents the case of $\bar{E}_T=1$. The dotted line represents the case of $\bar{E}_T=1.5$.

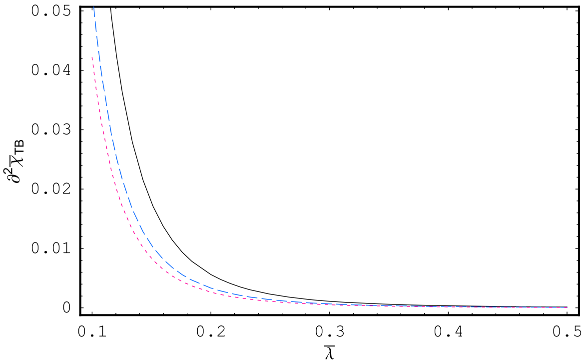

Fig. 3 (colour online). Scaled differential transition bremsstrahlung radiation cross section $\partial^2\bar{\chi}_{TB}$ as a function of the scaled de Broglie wavelength $\bar{\lambda}$ when $\bar{b}=5$, $\bar{E}=0.9$, $\bar{\varepsilon}=0.1$, and $\bar{r}_D=10$. The solid line represents the case of $\bar{E}_T=0.5$. The dashed line represents the case of $\bar{E}_T=1$. The dotted line represents the case of $\bar{E}_T=2$.

where $\mathbf{F}(\mathbf{r})$ is the force acting on the projectile electron by the collision system in plasmas. $\mathbf{r}(t)(=\mathbf{b}+\mathbf{v}t)$ is the trajectory of the projectile electron, v the velocity of the projectile electron, and $\mathbf{b}\cdot\mathbf{v}=0$. Then, the Fourier transform $\mathbf{F}_\omega(b)$ in the collision plane would be represented by

$$|\mathbf{F}_\omega(b)|^2=\left|\frac{\mathbf{v}\,[\mathbf{v}\cdot\mathbf{F}_\omega(b)]}{v^2}\right|^2+\left|\frac{[\mathbf{v}\times\mathbf{F}_\omega(b)]\times\mathbf{v}}{v^2}\right|^2, \quad (4)$$

where the Fourier transforms $\mathbf{v}(\mathbf{v}\cdot\mathbf{F}_\omega)/v^2[\equiv\mathbf{F}_{\|\omega}(b)]$ and $(\mathbf{v}\times\mathbf{F}_\omega)\times\mathbf{v}/v^2[\equiv\mathbf{F}_{\perp\omega}(b)]$ are the parallel and perpendicular components to the direction of the projectile electron, respectively.

Recently, the dynamic screening length [10] in nonideal plasmas has been obtained as a function of the velocity and temperature such as $r_0(v)[=r_D(1+v^2/v_T^2)^{1/2}]$, where r_D is the conventional Debye length, $v_T(=\sqrt{k_BT/m})$ is the electron thermal velocity, k_B the Boltzmann constant, and T the plasma temperature. The velocity dependence of the plasma shielding distance $r_0(v)$ would be readily understood since the dynamic plasma screening effect turns out to be the static plasma screening case, such as $r_0(v)\to r_D$, when the velocity of the projectile electron is smaller than the electron thermal velocity. In addition to the influence of the dynamic screening in plasmas, the effective pseudopotential [12] of the particle interactions in strongly coupled semiclassical plasmas taking into account the quantum-mechanical effect has been obtained on the basis of the dielectric response function technique. Hence, the effective dynamically screened potential $\varphi_{\text{eff}}(r,v)$ of the test charge q_0 in strongly coupled semiclassical plasmas based on the Ramazanov–Dzhumagulova method [12] with the dynamic screening length $r_0(v)$ would be represented by

$$\varphi_{\text{eff}}(\mathbf{r},v)=\frac{q_0}{\left[1-4\lambda^2/r_0^2(v)\right]^{1/2}}\cdot\left\{\frac{\exp[-A(\lambda,r_0(v))r]}{r}-\frac{\exp[-B(\lambda,r_0(v))r]}{r}\right\}, \quad (5)$$

where $\lambda(=\hbar/\sqrt{2\pi mk_BT})$ is the thermal electron de Broglie wavelength. The velocity dependent screening parameters are $A^2(\lambda,r_0(v))\equiv[1-\sqrt{1-4\lambda^2/r_0^2(v)}]/(2\lambda^2)$ and $B^2(\lambda,r_0(v))\equiv[1+\sqrt{1-4\lambda^2/r_0^2(v)}]/(2\lambda^2)$, respectively. It should be noted that the velocity dependent dynamic interaction potential $\varphi_{\text{eff}}(\mathbf{r},v)$ is valid for $(1+v^2/v_T^2)^{1/2}r_D/\lambda>2$. In these semiclassical plasmas, the electron number density $n(\mathbf{r},\lambda,v)$ within the Debye shielding sphere which contains the ion with nuclear charge Ze at the center and strongly coupled plasma electrons would be obtained by

$$n(\mathbf{r},\lambda,v)=\frac{Z}{4\pi r_0^2(v)\left[1-4\lambda^2/r_0^2(v)\right]^{1/2}}\cdot\left\{\frac{\exp[-A(\lambda,r_0(v))r]}{r}-\frac{\exp[-B(\lambda,r_0(v))r]}{r}\right\}. \quad (6)$$

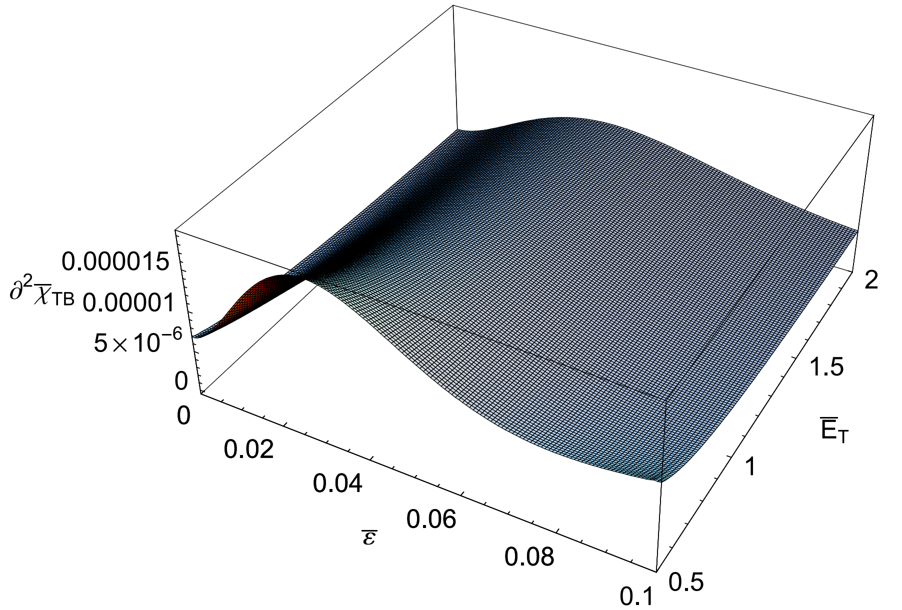

Fig. 4 (colour online). Scaled transition bremsstrahlung radiation cross section $\partial^2\bar{\chi}_{\mathrm{TB}}$ as a function of the scaled radiation photon energy $\bar{\varepsilon}$ and scaled thermal energy $\bar{E}_{\mathrm{T}}$ when $\bar{b}=5$, $\bar{E}=0.9$, $\bar{\lambda}=1$, and $\bar{r}_{\mathrm{D}}=10$.

Thus, the polarization force $\mathbf{F}_{\mathrm{pol}}(\mathbf{r},\lambda,v)$ acting on the projectile electron due to the polarized Debye shielding cloud in strongly coupled semiclassical plasmas is given by

$$\begin{aligned}\mathbf{F}_{\mathrm{pol}}(\mathbf{r},\lambda,v) &= -\frac{\partial}{\partial\mathbf{r}}\left[-\frac{e^2}{r^2}\int_{r'\le r}\mathrm{d}^3\mathbf{r}'r'n(\mathbf{r}',\lambda,v)\right] = \\ &-\frac{2Ze^2}{r_0^2(v)\sqrt{1-4\lambda^2/r_0^2(v)}}\frac{\mathbf{r}}{r^4}\left\{\frac{2}{A^3(\lambda,r_0(v))}\right. \\ &-\left(\frac{r^3}{2}+\frac{r^2}{A(\lambda,r_0(v))}+\frac{2r}{A^2(\lambda,r_0(v))}+\frac{2}{A^3(\lambda,r_0(v))}\right) \\ &\cdot\exp[-A(\lambda,r_0(v))r]-\left[\frac{2}{B^3(\lambda,r_0(v))}\right. \\ &-\left(\frac{r^3}{2}+\frac{r^2}{B(\lambda,r_0(v))}+\frac{2r}{B^2(\lambda,r_0(v))}+\frac{2}{B^3(\lambda,r_0(v))}\right) \\ &\left.\left.\cdot\exp[-B(\lambda,r_0(v))r]\right]\right\}.\end{aligned} \tag{7}$$

Hence, the differential transition bremsstrahlung cross section $\mathrm{d}\sigma_{\mathrm{TB}}(\omega)$ for the polarization interaction in strongly coupled semiclassical plasmas including the dynamic quantum screening and nonideal collective effects is found to be

$$\begin{aligned}\mathrm{d}\sigma_{\mathrm{TB}}(\omega) &= \frac{2^6}{3}\frac{\alpha^3a_0^2}{\bar{E}}\frac{\mathrm{d}\omega}{\omega}\int\mathrm{d}\bar{b}\bar{b} \\ &\cdot\left[\left|\bar{F}_{\perp\omega}(\bar{b},\bar{\lambda},\bar{r}_{\mathrm{D}},\bar{E},\bar{E}_{\mathrm{T}},\eta)\right|^2+\left|\bar{F}_{\parallel\omega}(\bar{b},\bar{\lambda},\bar{r}_{\mathrm{D}},\bar{E},\bar{E}_{\mathrm{T}},\eta)\right|^2\right],\end{aligned} \tag{8}$$

where $\alpha(=e^2/\hbar c\approx1/137)$ is the fine structure constant, $\bar{E}\equiv E/Z^2\mathrm{Ry}$, $E(=mv^2/2)$ is the kinetic energy of the projectile electron, and $\mathrm{Ry}(=me^4/2\hbar^2\approx13.6\,\mathrm{eV})$ is the Rydberg constant. The scaled parallel $\bar{F}_{\parallel\omega}(\bar{b},\bar{\lambda},\bar{r}_{\mathrm{D}},\bar{E},\bar{E}_{\mathrm{T}},\eta)$ and perpendicular $\bar{F}_{\perp\omega}(\bar{b},\bar{\lambda},\bar{r}_{\mathrm{D}},\bar{E},\bar{E}_{\mathrm{T}},\eta)$ Fourier coefficients of the polarization force are represented by the following forms:

$$\begin{aligned}\bar{F}_{\parallel\omega}(\bar{b},\bar{\lambda},\bar{r}_{\mathrm{D}},\bar{E},\bar{E}_{\mathrm{T}},\eta) &= -\left(\frac{\mathbf{v}\cdot\mathbf{F}_\omega}{v}\right)\left(\frac{\pi v a_Z}{2Ze^2}\right) \\ &= \mathrm{i}\int_0^\infty\mathrm{d}\tau\tau\sin(\eta\tau)\frac{J(\bar{r},\bar{\lambda},\bar{r}_{\mathrm{D}},\bar{E},\bar{E}_{\mathrm{T}})}{\bar{r}_0^2\bar{r}^4\sqrt{1-4\bar{\lambda}^2/\bar{r}_0^2}},\end{aligned} \tag{9}$$

$$\begin{aligned}\bar{F}_{\perp\omega}(\bar{b},\bar{\lambda},\bar{r}_{\mathrm{D}},\bar{E},\bar{E}_{\mathrm{T}},\eta) &= -\left(\frac{\mathbf{b}\cdot\mathbf{F}_\omega}{b}\right)\left(\frac{\pi v a_Z}{2Ze^2}\right) \\ &= \int_0^\infty\mathrm{d}\tau\bar{b}\cos(\eta\tau)\frac{J(\bar{r},\bar{\lambda},\bar{r}_{\mathrm{D}},\bar{E},\bar{E}_{\mathrm{T}})}{\bar{r}_0^2\bar{r}^4\sqrt{1-4\bar{\lambda}^2/\bar{r}_0^2}},\end{aligned} \tag{10}$$

where $\bar{b}(\equiv b/a_Z)$ is the scaled impact parameter, $a_Z(=a_0/Z)$ and $a_0(=\hbar^2/me^2)$ are the Bohr radii of the hydrogenic ion with nuclear charge Ze and of the hydrogen atom, respectively, $\eta \equiv \omega a_Z/v$, $\tau(\equiv vt/a_Z)$ and $\bar{E}_\mathrm{T}(\equiv k_\mathrm{B}T/2Z^2\mathrm{Ry})$ are the scaled time and the scaled thermal energy, respectively, $\bar{r}_0 \equiv \bar{r}_\mathrm{D}(1+\bar{E}/\bar{E}_\mathrm{T})^{1/2}$, and $\bar{r} \equiv r/a_Z[=(\bar{b}^2+\tau^2)^{1/2}]$. Here, the integrand function $J(\bar{r},\bar{\lambda},\bar{r}_\mathrm{D},\bar{E},\bar{E}_\mathrm{T})$ is given by

$$\begin{aligned} J(\bar{r},\bar{\lambda},\bar{r}_\mathrm{D},\bar{E},\bar{E}_\mathrm{T}) = &\left[\frac{2}{\bar{A}^3(\bar{\lambda},\bar{r}_0)} - \mathrm{e}^{-\bar{A}(\bar{\lambda},\bar{r}_0)\bar{r}} \right. \\ &\left.\cdot\left(\frac{\bar{r}^3}{2} + \frac{\bar{r}^2}{\bar{A}(\bar{\lambda},\bar{r}_0)} + \frac{2\bar{r}}{\bar{A}^2(\bar{\lambda},\bar{r}_0)} + \frac{2}{\bar{A}^3(\bar{\lambda},\bar{r}_0)}\right)\right] \\ &- \left[\frac{2}{\bar{B}^3(\bar{\lambda},\bar{r}_0)} - \mathrm{e}^{-\bar{B}(\bar{\lambda},\bar{r}_0)\bar{r}}\left(\frac{\bar{r}^3}{2} + \frac{\bar{r}^2}{\bar{B}(\bar{\lambda},\bar{r}_0)}\right.\right. \\ &\left.\left. + \frac{2\bar{r}}{\bar{B}^2(\bar{\lambda},\bar{r}_0)} + \frac{2}{\bar{B}^3(\bar{\lambda},\bar{r}_0)}\right)\right], \end{aligned} \tag{11}$$

where $\bar{\lambda}(\equiv \lambda/a_Z)$ and $\bar{r}_\mathrm{D}(\equiv r_\mathrm{D}/a_Z)$ are the scaled de Broglie wavelength and scaled Debye length, respectively, and the scaled screening functions are $\bar{A}(\bar{\lambda},\bar{r}_0)(\equiv Aa_Z) = [(1-\sqrt{1-4\bar{\lambda}^2/\bar{r}_0^2})/(2\bar{\lambda}^2)]^{1/2}$ and $\bar{B}(\bar{\lambda},\bar{r}_0)(\equiv Ba_Z) = [(1+\sqrt{1-4\bar{\lambda}^2/\bar{r}_0^2})/(2\bar{\lambda}^2)]^{1/2}$. Since the classical trajectory method is quite useful to investigate the low-energy bremsstrahlung process [2, 7], the expression of the transition bremsstrahlung cross section (8) would be reliable to explore the low-energy transition bremsstrahlung emission caused by the polarization interaction in strongly coupled semiclassical plasmas. It is shown that the continuum radiation spectrum due to the bremsstrahlung process would be investigated by the bremsstrahlung radiation cross section [16] defined as $\mathrm{d}\chi_\mathrm{B}/\mathrm{d}\bar{\varepsilon} \equiv \hbar\omega(\mathrm{d}\sigma_\mathrm{B}/\hbar\,\mathrm{d}\omega)$ because of the cancellation of the frequency factor $\mathrm{d}\omega/\omega$ in the photon emission probability, where $\bar{\varepsilon} \equiv \varepsilon/Z^2\mathrm{Ry}$ and $\varepsilon(=\hbar\omega)$ is the bremsstrahlung photon energy. Then, the scaled transition bremsstrahlung radiation cross section $\partial^2\bar{\chi}_\mathrm{TB}[\equiv(\mathrm{d}^2\chi_\mathrm{TB}/\mathrm{d}\bar{\varepsilon}\,\mathrm{d}\bar{b})/\pi a_0^2]$ in units of πa_0^2 due to the polarization interaction between the electron and the Debye shielding cloud in strongly coupled semiclassical plasmas is obtained by the following closed form:

$$\begin{aligned} \partial^2\bar{\chi}_\mathrm{TB}(\bar{b},\bar{\lambda},\bar{r}_\mathrm{D},\bar{E},\bar{E}_\mathrm{T}) = &\frac{2^6}{3\pi}\frac{\alpha^3}{\bar{E}}\bar{b} \\ &\cdot\left\{\left|\int_0^\infty \frac{\mathrm{d}\tau\tau}{\bar{r}_0^2\bar{r}^4\sqrt{1-4\bar{\lambda}^2/\bar{r}_0^2}}\sin\left(\frac{\bar{\varepsilon}\tau}{2\sqrt{\bar{E}}}\right)\times\left[\frac{2}{\bar{A}^3(\bar{\lambda},\bar{r}_0)}\right.\right.\right. \\ &- \mathrm{e}^{-\bar{A}(\bar{\lambda},\bar{r}_0)\bar{r}}\left(\frac{\bar{r}^3}{2} + \frac{\bar{r}^2}{\bar{A}(\bar{\lambda},\bar{r}_0)} + \frac{2\bar{r}}{\bar{A}^2(\bar{\lambda},\bar{r}_0)} + \frac{2}{\bar{A}^3(\bar{\lambda},\bar{r}_0)}\right) \\ &- \frac{2}{\bar{B}^3(\bar{\lambda},\bar{r}_0)} + \mathrm{e}^{-\bar{B}(\bar{\lambda},\bar{r}_0)\bar{r}}\left(\frac{\bar{r}^3}{2} + \frac{\bar{r}^2}{\bar{B}(\bar{\lambda},\bar{r}_0)} + \frac{2\bar{r}}{\bar{B}^2(\bar{\lambda},\bar{r}_0)}\right. \\ &\left.\left.\left. + \frac{2}{\bar{B}^3(\bar{\lambda},\bar{r}_0)}\right)\right]\right|^2 + \left|\int_0^\infty \frac{\mathrm{d}\tau\bar{b}}{\bar{r}_0^2\bar{r}^4\sqrt{1-4\bar{\lambda}^2/\bar{r}_0^2}}\right. \\ &\cdot\cos\left(\frac{\bar{\varepsilon}\tau}{2\sqrt{\bar{E}}}\right)\left[\frac{2}{\bar{A}^3(\bar{\lambda},\bar{r}_0)} - \mathrm{e}^{-\bar{A}(\bar{\lambda},\bar{r}_0)\bar{r}}\left(\frac{\bar{r}^3}{2}\right.\right. \\ &\left. + \frac{\bar{r}^2}{\bar{A}(\bar{\lambda},\bar{r}_0)} + \frac{2\bar{r}}{\bar{A}^2(\bar{\lambda},\bar{r}_0)} + \frac{2}{\bar{A}^3(\bar{\lambda},\bar{r}_0)}\right) - \frac{2}{\bar{B}^3(\bar{\lambda},\bar{r}_0)} \\ &+ \mathrm{e}^{-\bar{B}(\bar{\lambda},\bar{r}_0)\bar{r}}\left(\frac{\bar{r}^3}{2} + \frac{\bar{r}^2}{\bar{B}(\bar{\lambda},\bar{r}_0)} + \frac{2\bar{r}}{\bar{B}^2(\bar{\lambda},\bar{r}_0)}\right. \\ &\left.\left.\left.\left. + \frac{2}{\bar{B}^3(\bar{\lambda},\bar{r}_0)}\right)\right]\right|^2\right\}, \end{aligned} \tag{12}$$

since the bremsstrahlung parameter η in the nonrelativisitic limit would be represented by $\eta(\bar{\varepsilon},\bar{E}) = \bar{\varepsilon}/(2\bar{E}^{1/2})$. In a recent investigation [17], the collective effect on the transition bremsstrahlung process due to the polarization interaction between the electron and Debye shielding cloud has been investigated in nonideal plasmas. As it is seen in (12), the dynamic quantum screening and nonideal collective effects on the transition bremsstrahlung emission spectrum are included through the quantum and dynamic parameters $\bar{\lambda}$ and $\bar{r}_0[=\bar{r}_\mathrm{D}(1+\bar{E}/\bar{E}_\mathrm{T})^{1/2}]$. The integrated Gaunt factor over impact parameters is given by $G_\mathrm{FF} = \int_{b_\mathrm{min}}^{b_\mathrm{max}} \mathrm{d}b\,\partial^2\bar{\chi}_\mathrm{TB}$, where b_min is the minimum impact parameter and b_max is the maximum impact parameter since the free–free or bremsstrahlung Gaunt factor [18] G_FF is proportional to the bremsstrahlung radiation cross section. Then, the scaled integrated Gaunt factor $\bar{G}_\mathrm{FF}(\bar{E})$ is found to be

$$\begin{aligned} \bar{G}_\mathrm{FF}(\bar{E}) = &\int_{2\bar{E}^{-1}}^{\bar{r}_\mathrm{D}(1+\bar{E}/\bar{E}_\mathrm{T})^{1/2}} \mathrm{d}\bar{b}\frac{\bar{b}}{\bar{E}}\left\{\left|\int_0^\infty \frac{\mathrm{d}\tau\tau}{\bar{r}_0^2\bar{r}^4\sqrt{1-4\bar{\lambda}^2/\bar{r}_0^2}}\right.\right. \\ &\cdot\sin\left(\frac{\bar{\varepsilon}\tau}{2\sqrt{\bar{E}}}\right)\left[\frac{2}{\bar{A}^3(\bar{\lambda},\bar{r}_0)} - \mathrm{e}^{-\bar{A}(\bar{\lambda},\bar{r}_0)\bar{r}}\right. \\ &\cdot\left(\frac{\bar{r}^3}{2} + \frac{\bar{r}^2}{\bar{A}(\bar{\lambda},\bar{r}_0)} + \frac{2\bar{r}}{\bar{A}^2(\bar{\lambda},\bar{r}_0)} + \frac{2}{\bar{A}^3(\bar{\lambda},\bar{r}_0)}\right) \end{aligned}$$

$$
\begin{aligned}
&-\frac{2}{\bar{B}^3(\bar{\lambda},\bar{r}_0)} + \mathrm{e}^{-\bar{B}(\bar{\lambda},\bar{r}_0)\bar{r}}\left(\frac{\bar{r}^3}{2} + \frac{\bar{r}^2}{\bar{B}(\bar{\lambda},\bar{r}_0)} + \frac{2\bar{r}}{\bar{B}^2(\bar{\lambda},\bar{r}_0)}\right.\\
&\left.\left.+\frac{2}{\bar{B}^3(\bar{\lambda},\bar{r}_0)}\right)\right]\Bigg|^2 + \Bigg|\int_0^\infty \frac{\mathrm{d}\tau\bar{b}}{\bar{r}_0^2\bar{r}^4\sqrt{1-4\bar{\lambda}^2/\bar{r}_0^2}}\\
&\cdot\cos\left(\frac{\bar{\varepsilon}\tau}{2\sqrt{\bar{E}}}\right)\left[\frac{2}{\bar{A}^3(\bar{\lambda},\bar{r}_0)} - \mathrm{e}^{-\bar{A}(\bar{\lambda},\bar{r}_0)\bar{r}}\left(\frac{\bar{r}^3}{2}\right.\right. \qquad (13)\\
&\left.+\frac{\bar{r}^2}{\bar{A}(\bar{\lambda},\bar{r}_0)} + \frac{2\bar{r}}{\bar{A}^2(\bar{\lambda},\bar{r}_0)} + \frac{2}{\bar{A}^3(\bar{\lambda},\bar{r}_0)}\right) - \frac{2}{\bar{B}^3(\bar{\lambda},\bar{r}_0)}\\
&+\mathrm{e}^{-\bar{B}(\bar{\lambda},\bar{r}_0)\bar{r}}\left(\frac{\bar{r}^3}{2} + \frac{\bar{r}^2}{\bar{B}(\bar{\lambda},\bar{r}_0)} + \frac{2\bar{r}}{\bar{B}^2(\bar{\lambda},\bar{r}_0)}\right.\\
&\left.\left.+\frac{2}{\bar{B}^3(\bar{\lambda},\bar{r}_0)}\right)\right]\Bigg|^2\Bigg\},
\end{aligned}
$$

where the minimum impact parameter is given by the energy of the projectile electron, i. e., $b_{\min} = 2Ze^2/mv^2$, and the maximum impact parameters determined by the dynamic screening length, i. e., $b_{\max} = r_{\mathrm{D}}(1+\bar{E}/\bar{E}_{\mathrm{T}})^{1/2}$. Since the polarization interaction is expected to be significant for low-energy projectiles, and the classical expression of the bremsstrahlung cross section is suitable for $v < Z\alpha c$ [6], i. e., the velocity is small compared with the Coulomb unit, the transition bremsstrahlung radiation cross section $\partial^2\bar{\chi}_{\mathrm{TB}}$ of (12) is expected to be quite reliable for the investigation of the transition bremsstrahlung spectrum in strongly coupled semiclassical plasmas for the domain: $\bar{E} < 1$ and $\bar{\varepsilon} < \bar{E}$. Figure 1 represents the scaled transition bremsstrahlung radiation cross section $\partial^2\bar{\chi}_{\mathrm{TB}}$ in strongly coupled semiclassical plasmas as a function of the scaled thermal energy $\bar{E}_{\mathrm{T}}$ and scaled impact parameter $\bar{b}$. As it is seen, the transition bremsstrahlung radiation cross section decreases with an increase of the thermal energy. For example, it is found that the bremsstrahlung radiation cross section for $\bar{E}_{\mathrm{T}} = 1.5$ would be only 50% of the bremsstrahlung radiation cross section for $\bar{E}_{\mathrm{T}} = 0.5$. Hence, we have found that the dynamic plasma screening effect enhances the transition bremsstrahlung radiation cross section in strongly coupled semiclassical plasmas. It would be then expected that the transition bremsstrahlung radiation cross sections including the dynamic screening effects are always greater than those including the static screening effects. Figure 2 shows the scaled transition bremsstrahlung radiation cross section $\partial^2\bar{\chi}_{\mathrm{TB}}$ as a function of the scaled impact parameter $\bar{b}$ for various values of the thermal energy $\bar{E}_{\mathrm{T}}$. From this figure, we have found that the maximum position of the transition bremsstrahlung radiation cross section approaches to the center of the Debye shielding sphere, i. e., the collision center, with an increase of the thermal energy. Hence, it would be expected that the dynamic plasma screening effect enlarges the domain of the polarization interaction for the transition bremsstrahlung process. Figure 3 shows the transition bremsstrahlung radiation cross section $\partial^2\bar{\chi}_{\mathrm{TB}}$ as a function of the scaled electron de Broglie wavelength $\bar{\lambda}$ for various values of the thermal energy $\bar{E}_{\mathrm{T}}$. As we see in this figure, the dynamic screening effect on the transition bremsstrahlung radiation cross section decreases with an increase of the de Broglie wavelength. Hence, we have found that the quantum screening effect suppresses the influence of the dynamic screening on the transition bremsstrahlung process in strongly coupled semiclassical plasmas. It would be then expected that the dynamic screening effects on the transition bremsstrahlung cross sections in classical plasmas are always greater than those in dense semiclassical or quantum plasmas. Figure 4 represents the transition bremsstrahlung radiation cross section $\partial^2\bar{\chi}_{\mathrm{TB}}$ as a function of the scaled radiation photon energy $\bar{\varepsilon}$ and scaled thermal energy $\bar{E}_{\mathrm{T}}$. As shown in Figure 4, it is found that the peak bremsstrahlung energy increases with an increase of the thermal energy. Hence, we have found that the dynamic screening effect weakens the strength of the radiation photon energy in the transition bremsstrahlung process. Figure 5

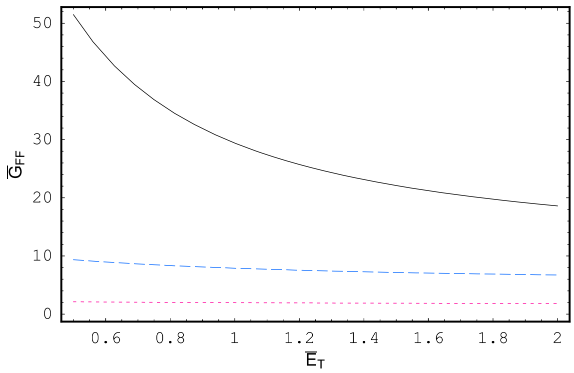

Fig. 5 (colour online). Scaled bremsstrahlung Gaunt factor $\bar{G}_{FF}$ for the transition bremsstrahlung process as a function of the scaled thermal energy $\bar{E}_T$ when $\bar{E} = 0.8$, $\bar{\varepsilon} = 0.1$, $\bar{\lambda} = 1$, and $\bar{r}_{\mathrm{D}} = 10$. The solid line represents the case of $\bar{\varepsilon} = 0.2$. The dashed line represents the case of $\bar{\varepsilon} = 0.4$. The dotted line represents the case of $\bar{\varepsilon} = 0.8$.

shows the scaled bremsstrahlung Gaunt factor $\bar{G}_{\mathrm{FF}}$ for the transition bremsstrahlung process as a function of the scaled thermal energy $\bar{E}_{\mathrm{T}}$ for various values of the radiation photon energy $\bar{\varepsilon}$. As shown, it is found that the dynamic quantum screening effect enhances the bremsstrahlung Gaunt factor in strongly coupled semiclassical plasmas. It is also found that the dynamic screening effect on the Gaunt factor is more significant for the soft-photon case of the transition bremsstrahlung process. From this work, we have found that the dynamic quantum screening and nonideal collective effects play significant roles in the transition bremsstrahlung process by the polarization interaction between the electron and the polarized Debye shielding sphere in strongly coupled semicalssical plasmas. These results would provide useful information on the collision and radiation processes associated with the projectile electron and the Debye plasma cloud in semicalssical plasmas including the influence of the collective interaction and dynamic screening.

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