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Polarization bremsstrahlung process in quantum plasmas including electron-exchange and shielding effects

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ABSTRACT

The electron-exchange and quantum shielding effects on the polarization bremsstrahlung spectrum due to the electron-shielding sphere encounters are investigated in quantum plasmas. From this work, it is found that the electron-exchange effect strongly suppresses the polarization bremsstrahlung radiation cross section. Additionally, it is found that the polarization bremsstrahlung radiation cross section increases with increasing plasmon energy and, however, decreases with increasing Fermi energy. The variation of the influence of electron-exchange and quantum shielding on the polarization bremsstrahlung spectrum is also discussed.

The continuum radiation spectra due to the bremsstrahlung process [1–13] have been widely used as the main plasma diagnostic process since the continuum UV and X-ray emissions caused by the projectile–target encounters has provided useful information on various plasma parameters in astrophysical and laboratory plasmas. It has been known that the bremsstrahlung mechanism would be mainly classified as the ordinary bremsstrahlung radiation known as the static electron–ion bremsstrahlung process and the polarization bremsstrahlung radiation caused by the interaction between the projectile electron and the polarized target system [13]. The conventional electron–ion bremsstrahlung radiation process has been extensively investigated in various plasma states by using the screened interaction potentials so-called the Debye–Hückel model for weakly coupled plasmas and the ion-sphere model for strongly coupled plasmas [14]. Recently, aside from the conventional electron–ion bremsstrahlung process, the polarization bremsstrahlung process caused by the interaction between the plasma particle and polarized shielding sphere in plasmas has been extensively investigated since the polarization bremsstrahlung can generate the continuum radiation spectrum in wide spatial radiation domains [11,13,15]. It would be then expected that the low-energy projectile would be more actively involved in the polarization bremsstrahlung process since the polarization bremsstrahlung radiation is known to be produced by the electron-polarized target encounter. Recent years, there has been of a considerable interest in investigating and also searching unique physical characteristics and properties of low-temperature and high-density quantum plasmas since the quantum plasmas have been found in various nano-scale objects in modern sciences and technologies such as nano-wires, quantum dot, semiconductor devices, and also laser produced dense plasmas [16–28]. In these dense quantum plasmas, as we can expect, the screened interaction potential would be quite different from the ordinary Debye–Hückel model in weakly coupled plasmas due to the nonideal multiparticle correlation and quantum-mechanical characters such as the Bohm potential and quantum statistical pressure effects [20]. Very recently, Shukla and Eliasson [27] have shown that the electron-exchange effect caused by the electron 1/2-spin in degenerate quantum plasmas plays a crucial role in the formation of the electric potential and dielectric function. Hence, it has been shown that the screened interaction potential including the fermionic character of plasma electrons in degenerate quantum plasmas is different from the standard Thomas–Fermi screened interaction potential [27] in the form: $V_{TF}(r) \propto e^{-k_s r}/r$, where k_s represents the Thomas–Fermi (TF) screening wave number. Hence, we can expect that the polarization bremsstrahlung emission due to the electron-polarized shielding sphere encounters including the influence of electron-exchange and quantum shielding in degenerate quantum plasmas would be different from that in conventional quantum plasmas represented by the Thomas–Fermi screening length k_s^{-1}. However, the polarization bremsstrahlung process including the electron-exchange and quantum shielding effects in degenerate quantum plasmas has not been investigated as yet. This polarization bremsstrahlung process would be completely different

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from the ordinary electron–electron bremsstrahlung radiation since the nonrelativistic electron–electron bremsstrahlung process cannot produce the dipole radiation since the electron–electron two body system has zero dipole moment [12]. On the other hand, the electron polarization bremsstrahlung radiation has been known to be caused by the polarization interaction between the projectile electron and Debye shielding sphere in plasmas. Thus, in this paper we investigate the influence of electron-exchange and quantum shielding on the polarization bremsstrahlung radiation spectrum in degenerate quantum plasmas. In this work, the effective screened potential and the impact-parameter analysis [12] are applied to obtain the polarization bremsstrahlung radiation cross section as a function of the impact parameter, electron-exchange parameter, Fermi energy, photon energy, plasmon energy, and projectile energy. The variation of the electron-exchange and quantum shielding effects on the polarization bremsstrahlung spectrum is also discussed.

For the low-energy bremsstrahlung process such as the continuum radiation in low-temperature plasmas, the differential bremsstrahlung cross section [12] $d\sigma_{br}$ for producing a photon of frequency between ω and $\omega + d\omega$ would be represented by the impact parameter method as follows:

$$d\sigma_{br} = \int d^2\boldsymbol{\rho}\, dw_\omega(\rho), \tag{1}$$

where $\boldsymbol{\rho}$ is the impact parameter vector from the center of the target system and $dw_\omega(\rho)$ is the differential probability of emitting a photon within frequency $d\omega$ for a given impact parameter ρ. For the instantaneous power emitted due to the electron–target encounters, the probability of photon emission $dw_\omega(\rho)$ $[= (8\pi e^2/3m^2c^3\hbar)|\mathbf{F}_\omega(\rho)|^2 d\omega/\omega]$ can be obtained by the Larmor formula [12,14], where $\hbar$ is the rationalized Planck constant, e is the elementary electric charge, m is the electron mass, c is the speed of the light in vacuum, $\mathbf{F}_\omega(\rho)$ $[= (2\pi)^{-1}\int_{-\infty}^{\infty} dt\mathbf{F}(t)e^{i\omega t}]$ is the Fourier transform of the force $\mathbf{F}(t)$ acting on the projectile electron due to the polarized shielding sphere. The absolute value of the Fourier transform $|\mathbf{F}_\omega(\rho)|$ would be decomposed into the parallel $\mathbf{F}_{\parallel\omega}$ and perpendicular $\mathbf{F}_{\perp\omega}$ Fourier components with respect to the direction of the projectile velocity $\mathbf{v}$ such as

$$\begin{aligned}\left|\mathbf{F}_\omega(\rho)\right|^2 &= \left|\hat{\mathbf{v}}(\hat{\mathbf{v}}\cdot\mathbf{F}_\omega)\right|^2 + \left|\hat{\mathbf{v}}\times(\hat{\mathbf{v}}\times\mathbf{F}_\omega)\right|^2\\ &= \left|\mathbf{F}_{\parallel\omega}(\rho)\right|^2 + \left|\mathbf{F}_{\perp\omega}(\rho)\right|^2,\end{aligned} \tag{2}$$

where $\hat{\mathbf{v}}$ $(= \mathbf{v}/v)$ is the unit velocity vector.

Very recently, Shukla and Eliasson (SE) [27] have obtained an extremely useful form of the effective electrostatic potential $\phi_{SE}(r)$ $[= (Ze/2\pi^2)\int d^3\mathbf{k}e^{i\mathbf{k}\cdot\mathbf{r}}/(k^2\varepsilon_{SE}(k))]$ of an ion with change Ze in degenerate quantum plasmas using the Shukla–Eliasson plasma dielectric function $\varepsilon_{SE}(k)$ $\{= [1 + [(k^2/k_s^2) + \alpha k^4/k_s^4]/[1 + (k^2/k_s^2) + \alpha k^4/k_s^4]]^{-1}\}$ including the influence of electron-exchange correction and quantum shielding with quasistationary density perturbations when the plasmon energy E_P $(= \hbar\omega_P)$ is smaller or comparable to the Fermi energy E_F $(= mv_F^2/2)$, where k_s $[= \omega_p/(v_F^2/3 + v_{ex}^2)^{1/2}]$ represents the inverse effective Thomas–Fermi screening length, ω_P is the electron plasma frequency, v_F is the electron Fermi velocity, v_{ex} is the electron-exchange velocity associated with the electron-exchange effect, and α $[= \hbar\omega_p^2/4m^2(v_F^2/3 + v_{ex}^2)^2]$ is the quantum recoil parameter. Using the effective electric potential model [27,28], the Shukla–Eliasson effective interaction potential $V_{SE}(r)$ between the projectile electron and target ion with nuclear charge Ze in degenerate quantum plasmas is then found to be

$$\begin{aligned}V_{SE}(r,\alpha) = -\frac{Ze^2}{2r}\big\{&\big[1+\xi(\alpha)\big]\exp\big[-k_+(\alpha)r\big]\\ &+\big[1-\xi(\alpha)\big]\exp\big[-k_-(\alpha)r\big]\big\},\end{aligned} \tag{3}$$

where $\xi(\alpha) \equiv (1-4\alpha)^{-1/2}$ and the effective inverse screening lengths $k_\pm(\alpha)$ are given by $k_\pm(\alpha) \equiv k_s[1 \mp (1-4\alpha)^{1/2}]^{1/2}/(2\alpha)^{1/2}$. It can be readily shown that, when the quantum recoil is quite small, i.e., in the limit $\alpha \to 0$, the Shukla–Eliasson effective interaction potential $V_{SE}(r)$ turns out to be the standard Thomas–Fermi screened Coulomb potential such as $V_{SE}(r) \to V_{TF}(r) = -(Ze^2/r)e^{-k_s r}$ since $k_+ \to k_s$ and $k_- \to \infty$ as $\alpha \to 0$. Using the Shukla–Eliasson effective interaction potential, the polarization force $\mathbf{F}_{pol}(\mathbf{r})$ acting on the projectile electron due to the polarized shielding sphere in degenerate quantum plasmas is then found to be

$$\begin{aligned}&\mathbf{F}_{pol}(\mathbf{r})\\ &\quad= -\nabla\Bigg[-\frac{Ze^2}{r^2}\int_{r'\le r} d^3\mathbf{r}'\, r'\frac{1}{4\pi r_s^2}\frac{1}{2r}\\ &\qquad\times\big((1+\xi)e^{-k_+r} + (1-\xi)e^{-k_-r}\big)\Bigg]\\ &\quad= -\frac{Zk_+^2e^2\mathbf{r}}{r^4}\Bigg\{(1+\xi)\Bigg[\frac{2}{k_+^3} - \Bigg(\frac{2}{k_+^3} + \frac{2r}{k_+^2} + \frac{r^2}{k_+} + \frac{r^3}{2}\Bigg)e^{-k_+r}\Bigg]\\ &\qquad+(1-\xi)\Bigg[\frac{2}{k_-^3} - \Bigg(\frac{2}{k_-^3} + \frac{2r}{k_-^2} + \frac{r^2}{k_-} + \frac{r^3}{2}\Bigg)e^{-k_-r}\Bigg]\Bigg\},\end{aligned} \tag{4}$$

since the electron number density $n_e(r')$ within the shielding cloud which contains the ion with nuclear charge Ze and plasma electrons would be represented by $n_e(r) = (Z/4\pi r_s^2)(1/2r)[(1+\xi)e^{-k_+r} + (1-\xi)e^{-k_-r}]$ in quantum plasmas, where the position vector is given by $\mathbf{r} = \mathbf{v}t + \boldsymbol{\rho}$ with the condition $\mathbf{v}\cdot\boldsymbol{\rho} = 0$, the effective shielding distance is determined by $r_s = \max\{1/k_+, 1/k_-\}$, and "max" is the larger of $1/k_+$ and $1/k_-$. The scaled perpendicular Fourier coefficient $\bar{F}_{\perp\omega}$ $[\equiv -(\pi/2)(\hat{\boldsymbol{\rho}}\cdot\mathbf{F}_\omega)(va_Z/Ze^2)]$ and parallel Fourier coefficient $\bar{F}_{\parallel\omega}$ $[\equiv -(\pi/2)(\hat{\mathbf{v}}\cdot\mathbf{F}_\omega)(va_Z/Ze^2)]$ of the polarization force would be then represented by

$$\begin{aligned}&\bar{F}_{\perp\omega}(\bar{\rho},\bar{k}_+,\bar{k}_-)\\ &\quad= \int_0^\infty d\tau\,\frac{\bar{\rho}\bar{k}_+^2\cos(\eta\tau)}{2\bar{r}^4}\\ &\qquad\times\Bigg\{(1+\xi)\Bigg[\frac{2}{\bar{k}_+^3} - \Bigg(\frac{2}{\bar{k}_+^3} + \frac{2\bar{r}}{\bar{k}_+^2} + \frac{\bar{r}^2}{\bar{k}_+} + \frac{\bar{r}^3}{2}\Bigg)e^{-\bar{k}_+\bar{r}}\Bigg]\\ &\qquad+(1-\xi)\Bigg[\frac{2}{\bar{k}_-^3} - \Bigg(\frac{2}{\bar{k}_-^3} + \frac{2\bar{r}}{\bar{k}_-^2} + \frac{\bar{r}^2}{\bar{k}_-} + \frac{\bar{r}^3}{2}\Bigg)e^{-\bar{k}_-\bar{r}}\Bigg]\Bigg\},\end{aligned} \tag{5}$$

$$\begin{aligned}&\bar{F}_{\parallel\omega}(\bar{\rho},\bar{k}_+,\bar{k}_-)\\ &\quad= i\int_0^\infty d\tau\,\frac{\tau\bar{k}_+^2\sin(\eta\tau)}{2\bar{r}^4}\\ &\qquad\times\Bigg\{(1+\xi)\Bigg[\frac{2}{\bar{k}_+^3} - \Bigg(\frac{2}{\bar{k}_+^3} + \frac{2\bar{r}}{\bar{k}_+^2} + \frac{\bar{r}^2}{\bar{k}_+} + \frac{\bar{r}^3}{2}\Bigg)e^{-\bar{k}_+\bar{r}}\Bigg]\\ &\qquad+(1-\xi)\Bigg[\frac{2}{\bar{k}_-^3} - \Bigg(\frac{2}{\bar{k}_-^3} + \frac{2\bar{r}}{\bar{k}_-^2} + \frac{\bar{r}^2}{\bar{k}_-} + \frac{\bar{r}^3}{2}\Bigg)e^{-\bar{k}_-\bar{r}}\Bigg]\Bigg\},\end{aligned} \tag{6}$$

where $\hat{\boldsymbol{\rho}}$ $(= \boldsymbol{\rho}/\rho)$ is the unit impact parameter vector, a_Z $(= a_0/Z)$ is the first Bohr radius of the hydrogenic ion with nuclear charge Ze, a_0 $(= \hbar^2/me^2)$ is the first Bohr radius of the hydrogen atom, $\bar{\rho}$ $(\equiv \rho/a_Z)$ is the scaled impact parameter, τ $(\equiv vt/a_Z)$ is the scaled time, η $(\equiv \omega a_Z)$ is the characteristic bremsstrahlung emission parameter, $\bar{r}$ $(\equiv r/a_Z)$ is the scaled distance, and $\bar{k}_\pm$ $(\equiv k_\pm a_Z)$ are the scaled screening lengths in quantum plasmas. Hence, the

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