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Landau retardation on the occurrence scattering time in quantum electron–hole plasmas

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ABSTRACT

The Landau damping effects on the occurrence scattering time in electron collisions are investigated in a quantum plasma composed of electrons and holes. The Shukla–Stenflo–Bingham effective potential model is employed to obtain the occurrence scattering time in a quantum electron–hole plasma. The result shows that the influence of Landau damping produces the imaginary term in the scattering amplitude. It is then found that the Landau damping generates the retardation effect on the occurrence scattering time. It is found that the occurrence scattering time increases in forward scattering domains and decreases in backward scattering domains with an increase of the Landau parameter. It is also found that the occurrence scattering time decreases with increasing collision energy. In addition, it is found that the quantum shielding effect enhances the occurrence scattering time in the forward scattering and, however, suppresses the occurrence scattering time in the backward scattering.

The atomic collision process [1–7] is known to be one of the most important processes in plasmas and has been extensively investigated as a plasma diagnostic tool for determining plasma parameters in various astrophysical and laboratory plasmas. It is also shown that the electron–electron collisions make contributions to the collective effects on the electron–ion bremsstrahlung spectrum and also to the Lorentzian conductivity in plasmas [8,9]. The screened Debye–Hückel interaction model [10] has been widely used to investigate various atomic processes in weakly coupled classical plasmas since the Yukawa-type Debye–Hückel potential corresponds to the pair correlation approximation in low-density plasmas. However, it has been shown that the quantum–mechanical and multiparticle correlation effects due to the simultaneous interaction of many particles have to be taken into account to represent the plasma shielding phenomena in dense plasmas [11–14]. In recent years, there has been a considerable interest in the physical characteristic and properties of semiclassical and quantum plasmas since dense plasmas are ubiquitous and have been also found in various modern nano-scale objects such as nano-wires, quantum dot, semiconductor devices, laser produced dense plasmas as well as dense plasmas in astrophysical compact objects [15–24]. An effective interaction potential model has been obtained by Shukla, Stenflo, and Bingham [14] using the plasma dielectric function including the Debye shielding term and the additional far-field term due to the Landau damping effect in a quantum plasma composed of electrons and holes. Hence, the electron–electron collisions in quantum electron–hole plasmas would be quite different from those in conventional classical plasmas. It has been known that the time-dependence [25–27] in atomic and nuclear collisions reveals significant aspects of scattering mechanisms. It has been also shown that the physical property known as the occurrence scattering time [26,27] represents the time of emergence of the incident wave packet during atomic collisions and also characterizes quantum collision processes. The physical characteristics of the occurrence scattering time have been investigated in various plasmas since the angular-dependence of the occurrence scattering time in plasmas provides useful information on the scattering mechanisms as well as the physical properties of the plasma since the occurrence scattering time advance or delay would be expected to reveal for charged particle collisions [28–30]. Thus, in this Letter, we investigate the Landau damping effects on the occurrence scattering time in electron–electron collisions in a quantum plasma composed of electrons and holes. The first-order Born method is employed to obtain the occurrence scattering time by using the Shukla–Stenflo–Bingham effective potential [14] in electron–hole plasmas.

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It has been shown that the scattering amplitude obtained by the Born approximation [31,32] provides the accurate qualitative description of scattering cross sections for collisions with the condition: $|V|R/\hbar v < 1$, where $|V|$ is the typical strength of the interaction potential, R is the range of the potential, $\hbar$ is the rationalized Planck constant, and v is the collision velocity, since the solution of the Schrödinger equation and the scattering cross section would be represented by the scattering amplitude $f(\mathbf{k}_i, \mathbf{k}_f)$. Hence, the scattering amplitude $f(\mathbf{k}_i, \mathbf{k}_f)$ in the first-order Born analysis is represented as the Fourier transform of the interaction potential $V_{\rm int}(\mathbf{r})$ such as

$$f(\mathbf{k}_i, \mathbf{k}_f) = -\frac{\mu}{2\pi\hbar^2}\int d^3\mathbf{r}\exp\big[i(\mathbf{k}_i - \mathbf{k}_f)\cdot\mathbf{r}\big]V_{\rm int}(\mathbf{r}), \tag{1}$$

where $\mathbf{k}_i$ and $\mathbf{k}_f$ are, respectively, the incident and scattered wave vectors, and μ is the reduced mass of the collision system. Recently, a quite useful analytic form of the effective screened electric potential [14] of the projectile electron in a quantum plasma composed of electrons and holes has been obtained by the plasma dielectric function $D(\omega, q)$, where ω is the frequency and q is the wave number. Using the Shukla–Stenflo–Bingham (SSB) effective potential model [14], the electron–electron interaction potential $V_{SSB}(\mathbf{r})$ for $v < v_{tj}$ in quantum electron–hole plasmas would be represented by

$$V_{SSB}(\mathbf{r}) = \frac{e^2}{r}\exp(-r/\lambda_q) + \frac{e^2\alpha v}{r^3}\cos\theta, \tag{2}$$

where v_{tj} $[= (2E_{Fj}/m_j)^{1/2}]$ is the Fermi thermal speed of the particle species j (electron: $j = e$, hole: $j = h$), E_{Fj} $[= (\hbar^2/2m_j)\times(3\pi^2 n_j)^{2/3}]$ is the Fermi energy, m_j is the mass of the particle, n_j is the equilibrium number density, λ_q $(= \sum_{j=e,h}\lambda_j^{-2})^{-1/2}$ is the effective Debye length, $\lambda_j = K_{Fj}^{-1}$, K_{Fj} $(= \sqrt{3}\omega_{pj}/v_{tj})$ is the Fermi–Thomas screening wave number, ω_{pj} $[= (4\pi n_j e^2/m_j)^{1/2}]$ is the plasma frequency, the parameter α related to the Landau damping is defined as $\alpha \equiv \lambda_q^4\sum_{j=e,h}\lambda_j^{-2}v_{tj}^{-1}$, and θ is the angle between the position vector $\mathbf{r}$ and the velocity $\mathbf{v}$. As shown in Eq. (2), the Shukla–Stenflo–Bingham effective interaction potential [14] encompasses the far-field term caused by the influence of Landau damping [33], i.e., the singular points in the imaginary part of the inverse of the plasma dielectric function $1/D(\omega, q)$, apart from the standard screened Debye shielding term $(e^2/r)\exp(-r/\lambda_q)$. After some mathematical manipulations, the scattering amplitude $f(\bar{k}_i, \bar{k}_f, \varphi)$ $[= |f(\bar{k}_i, \bar{k}_f, \varphi)|\exp[i\eta(\bar{k}_i, \bar{k}_f, \varphi)]]$ for the electron–electron scattering in a quantum plasma is then found to be

$$\begin{aligned} f(\bar{k}_i, \bar{k}_f, \varphi) &= \frac{2a_0}{\bar{Q}^2 + \bar{\lambda}_q^{-2}}\Bigg[1 + i\frac{\sqrt{2}\pi}{4}\bar{k}\frac{\bar{\lambda}_q^4}{a_0^2}\sum_{j=e,h}\bar{\lambda}_j^{-2}(v_0/v_{ts}) \\ &\qquad \times\big(\bar{Q}^2 + \bar{\lambda}_q^{-2}\big)\Bigg] \\ &= \frac{2a_0}{\bar{k}_i^2 + \bar{k}_f^2 - 2\bar{k}_i\bar{k}_f\cos\varphi + \bar{\lambda}_q^{-2}}\Bigg[1 + i\frac{\sqrt{2}\pi}{4}\bar{k}_i \\ &\qquad \times\frac{\bar{\lambda}_q^4}{a_0^2}\sum_{j=e,h}\bar{\lambda}_j^{-2}(v_0/v_{ts}) \\ &\qquad \times\big(\bar{k}_i^2 + \bar{k}_f^2 - 2\bar{k}_i\bar{k}_f\cos\varphi + \bar{\lambda}_q^{-2}\big)\Bigg] \\ &= f_R(\bar{k}_i, \bar{k}_f, \varphi) + if_I(\bar{k}_i, \bar{k}_f, \varphi), \end{aligned} \tag{3}$$

where $\bar{k}_i$ $(\equiv k_i a_0)$ and $\bar{k}_f$ $(\equiv k_f a_0)$ are the scaled initial and final wave numbers, a_0 $(= \hbar^2/m_e e^2)$ is the first Bohr radius of the hydrogen atom, m_e is the mass of the electron, $|f(\bar{k}_i, \bar{k}_f, \varphi)|$ is the absolute value of the scattering amplitude, $\eta(\bar{k}_i, \bar{k}_f, \varphi)$ is the argument of the scattering amplitude, φ is the angle between $\mathbf{k}_i$ and $\mathbf{k}_f$, i.e., the scattering angle measured in the center of mass system, $\bar{\lambda}_q$ $(\equiv \lambda_q/a_0)$ is the scaled effective Debye length, $\bar{\lambda}_j \equiv \lambda_j/a_0$, v_0 $(= \alpha_f c)$ is the Bohr velocity, α_f $(= e^2/\hbar c \approx 1/137)$ is the fine structure constant, c is the speed of the light, and $\bar{Q} \equiv Q(k_i, k_f, \varphi)a_0$. Here, $Q(k_i, k_f, \varphi)$ $[= (k_i^2 + k_f^2 - 2k_i k_f\cos\varphi)^{1/2}]$ is the momentum transfer, $f_R(\bar{k}_i, \bar{k}_f, \varphi)$ and $f_I(\bar{k}_i, \bar{k}_f, \varphi)$ are the real and imaginary parts of the scattering amplitude, respectively. It is shown that the scattering amplitude is essential to investigate the physical characteristics of the collision dynamics as well as the physical properties of the collision system [25]. For elastic collisions, i.e., $k_i = k_f$ $(\equiv k)$, the occurrence scattering time [26,27] τ would be represented by the first-derivative of the argument η of the scattering amplitude with respect to the initial wave number k_i:

$$\tau(k, \varphi) = \frac{\mu}{k_i\hbar}\left(\frac{\partial\eta}{\partial k_i}\right)\Bigg|_{k_i = k_f = k}, \tag{4}$$

when the collision center of the free wave packet is assumed to be reached the origin $\mathbf{r} = 0$ at $t = 0$. For elastic electron–electron collisions, the real and imaginary parts of the scattering amplitude and the partial derivative of the scattering amplitude in quantum electron–hole plasmas are, respectively, found to be

$$f_R(\bar{k}_i, \bar{k}_f, \varphi)|_{\bar{k}_i = \bar{k}_f = \bar{k}} = f_R(\bar{E}, \varphi) = \frac{2a_0}{2\bar{E}\sin^2(\varphi/2) + \bar{\lambda}_q^{-2}}, \tag{5}$$

$$f_I(\bar{k}_i, \bar{k}_f, \varphi)|_{\bar{k}_i = \bar{k}_f = \bar{k}} = f_I(\bar{E}, \varphi) = \frac{\pi a_0}{2}\bar{\alpha}\bar{E}^{1/2}, \tag{6}$$

$$\frac{\partial}{\partial\bar{k}}f_R(\bar{k}_i, \bar{k}_f, \varphi)\Bigg|_{\bar{k}_i = \bar{k}_f = \bar{k}} = -\frac{2a_0\sin\varphi}{[2\bar{E}\sin^2(\varphi/2) + \bar{\lambda}_q^{-2}]^2}, \tag{7}$$

and

$$\frac{\partial}{\partial\bar{k}}f_I(\bar{k}_i, \bar{k}_f, \varphi)\Bigg|_{\bar{k}_i = \bar{k}_f = \bar{k}} = \frac{\pi a_0}{\sqrt{2}}\bar{\alpha}, \tag{8}$$

since $Q(\bar{k}_i, \bar{k}_f, \varphi)|_{\bar{k}_i = \bar{k}_f = \bar{k}} = 2\sqrt{\bar{E}}\sin(\varphi/2)$, where $\bar{k} \equiv ka_0$, $\bar{E}$ $(\equiv E/Ry = 2\bar{k}^2)$ is the scaled collision energy, E $(= \mu v^2/2)$ is the collision energy, Ry $(= m_e e^4/2\hbar^2 \approx 13.6$ eV) is the Rydberg constant, and $\bar{\alpha} \equiv v_0\alpha/a_0^2$. The scaled occurrence scattering time $\bar{\tau}(\bar{k}, \varphi)$ $(\equiv \tau v/a_0)$ for the elastic collision is then given by

$$\begin{aligned} \bar{\tau}(\bar{k}, \varphi) &= \frac{1}{f_R^2(\bar{k}_i, \bar{k}_f, \varphi) + f_I^2(\bar{k}_i, \bar{k}_f, \varphi)} \\ &\quad \times\Bigg(f_R(\bar{k}_i, \bar{k}_f, \varphi)\frac{\partial f_I(\bar{k}_i, \bar{k}_f, \varphi)}{\partial\bar{k}_i} \\ &\quad - f_I(\bar{k}_i, \bar{k}_f, \varphi)\frac{\partial f_R(\bar{k}_i, \bar{k}_f, \varphi)}{\partial\bar{k}_i}\Bigg)\Bigg|_{\bar{k}_i = \bar{k}_f = \bar{k}}. \end{aligned} \tag{9}$$

From Eq. (3), we have found that the influence of Landau damping on the electron–electron collision process in electron–hole plasmas generates the imaginary part $f_I(\bar{k}_i, \bar{k}_f, \varphi)$ of the scattering amplitude. If we neglect the Landau damping effects, the scattering amplitude becomes a real function so that the occurrence scattering time turns out to be zero. It is interesting to note that the imaginary part $f_I(\bar{k}_i, \bar{k}_f, \varphi)$ causes the time advance or delay on the occurrence scattering time. After some algebra, the Landau retardation effect on the scaled occurrence scattering time $\bar{\tau}_{LR}(\bar{E}, \bar{\lambda}_q, \bar{\alpha}, \varphi)$ for the electron–electron collision is found to be the following form: