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Non-thermal renormalization shielding on the electron–atom collision in partially ionized generalized Lorentzian non-thermal plasmas

YOUNG-DAE JUNG[1] and WOO-PYO HONG[2]

[1]Department of Applied Physics, Hanyang University, Ansan, Kyunggi-Do 426–791, South Korea, and Department of Physics, Applied Physics, and Astronomy, Rensselaer Polytechnic Institute, 110 Eighth Street, Troy, NY 12180-3590, USA (ydjung@hanyang.ac.kr)
[2]Department of Electronics Engineering, Catholic University of Daegu, Hayang, Gyongsan, Gyungbuk 712-702, South Korea

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Abstract. The non-thermal renormalization shielding effects on the elastic electron–atom collision process are investigated in partially ionized generalized Lorentzian non-thermal plasmas. The eikonal analysis for the Hamilton–Jacobi solution and impact parameter method are employed to obtain the eikonal scattering phase shift and eikonal cross section as functions of the collision energy, Debye length, impact parameter, and spectral index of the Lorentzian plasma. It is found that the non-thermal renormalization shielding effect enhances the eikonal scattering phase shift as well as the eikonal collision cross section, especially for small impact parameter domains. It is also found that the non-thermal renormalization shielding effect on the eikonal scattering phase shift decreases with an increase of the impact parameter. In addition, it is found that the maximum position of the eikonal collision cross section has receded from the collision center with an increase of the non-thermal character of the plasma.

1. Introduction

The atomic collision process (Shevelko 1997; Shevelko and Tawara 1998; Beyer and Shevelko 2003; Smirnov 2003; Fujimoto 2004; Yoon et al. 2005) in plasmas has been a subject of special attention in many areas of physics, such as astrophysics, atomic physics, and plasma physics, since the electromagnetic radiation caused by collisional excitation is emitted from the plasma and the atomic collision cross section is quite sensitive to details of the collision structure and the correlation of plasma particles. In classical weakly coupled plasmas, the interaction potential between the charged particles has been described by the conventional Debye–Hückel potential obtained by the thermal Maxwellian distribution, since the average energy of interaction between plasma particles is usually smaller than the average kinetic energy of a particle (Ramazanov and Dzhumagulova 2002). In recent years, the investigation of physical characteristics of strongly coupled dense plasmas has received considerable attention since the strongly coupled plasmas have been found in various dense astrophysical and laboratory plasmas such as the interiors of the astrophysical compact objects, inertial confinement fusion plasmas, X-ray lithography, and modern nanodevices (Beyer and Shevelko 2003; Ramazanov and Turekhanova 2005; Ramazanov et al. 2005; Melose 2008; Shukla and Eliasson 2011). Very recently, the physical renormalization procedure (McComb 2004; Arkhipov et al. 2011) of particle interactions is proposed to acquire the generalized Poisson–Boltzmann equation for an effective interaction potential of two chosen plasma particles in the presence of a third particle in strongly coupled plasmas. It would be quite obvious that the screened effective interaction potential in these strongly coupled dense plasmas cannot be characterized by the standard Debye–Hückel method due to the collective non-ideal particle interactions (Baimbetov et al. 1995; Ramazanov and Dzhumagulova 2002). In addition, it has been found out that the non-Maxwellian distributions with depleted velocity tails are ubiquitous in numerous plasma environments due to the coupling of the external electromagnetic radiation field with the target plasma system (Hasegawa et al. 1985; Hasegawa and Sato 1989; Rubab and Murtaza 2006a, b). It is also found that the non-thermal plasma particles that escaped from the Maxwellian distribution would be represented quite well by the generalized Lorentzian kappa distribution function (Hasegawa et al. 1985; Hasegawa and Sato 1989). Hence, it can be expected that the atomic collisions and radiations in dense semi-classical non-thermal Lorentzian plasmas are quite different from those in classical thermal Maxwellian plasmas due to the non-thermal and non-ideal collective particle interactions. Thus, in this paper we investigate the non-thermal renormalization plasma shielding effect on the elastic electron–atom collision process in partially ionized dense

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non-thermal Lorentzian plasmas. The eikonal scattering phase shift and eikonal cross section for the elastic electron–atom collision are obtained as functions of the collision energy, Debye length, impact parameter, and spectral index of the plasma. In addition, the influence of the non-thermal renormalized plasma shielding on the eikonal collision cross section is also discussed.

In Sec. 2 we discuss the Hamilton–Jacobi solution and the eikonal method and also obtain the general expression of the semi-classical eikonal wave function. In Sec. 3 we discuss the generalized Lorentzian kappa distribution of non-thermal plasmas. In Sec. 4 we obtain the eikonal scattering phase shift and the eikonal cross section for the elastic electron–atom collisions in partially ionized Lorentzian non-thermal plasmas. In Sec. 5 the influence of the non-thermal renormalized plasma shielding on the eikonal scattering phase shift and the eikonal collision cross section is discussed. Finally, the conclusions are given in Sec. 6.

2. Hamilton–Jacobi solution and eikonal method

For electron collision with atomic system, the non-relativistic Schrödinger equation with the semi-classical eikonal wave function $\varphi_E(\mathbf{r}) \propto \exp[iS(\mathbf{r})/\hbar]$ leads to the following expression of the Hamilton–Jacobi equation for the action function $S(\mathbf{r})$ (Fröbrich and Lipperheide 1996):

$$\frac{1}{2\mu}[\nabla S(\mathbf{r})]^2 + V(\mathbf{r}) = E = \frac{\hbar^2 k^2}{2\mu}, \tag{1}$$

where $\hbar$ is the rationalized Planck constant, μ is the reduced mass of the collision system, $V(\mathbf{r})$ is the interaction potential, $E(=\mu v^2/2)$ is the collision energy, v is the collision velocity of the electron, and k is the wave number. Using the straight-line trajectory analysis in cylindrical coordinates, i.e. $\mathbf{r} = z\hat{\mathbf{n}} + \mathbf{b}$, the solution of the Hamilton–Jacobi equation for the action function can be obtained by

$$S(\mathbf{r}) \cong \hbar k_i z - \frac{\mu}{\hbar k_i}\int_{-\infty}^{z} dz'\, V(\mathbf{b}, z'), \tag{2}$$

where $\hat{n}$ is the unit vector normal to the momentum transfer $\Delta\mathbf{k}(\equiv \mathbf{k}_i - \mathbf{k}_f)$, $\mathbf{k}_i$ and $\mathbf{k}_f$ are, respectively, the incident and final wave vectors, and $\mathbf{b}$ is the impact parameter. Hence, the semi-classical eikonal wave function $\varphi_E(\mathbf{r})$ would be represented by

$$\varphi_E(\mathbf{r}) \cong \frac{1}{(2\pi)^{3/2}}\exp\left[ik_i z - \frac{i\mu}{\hbar^2 k_i}\int_{-\infty}^{z} dz'\, V(\mathbf{b}, z')\right]. \tag{3}$$

It has been known that the validity of the semi-classical eikonal analysis is known as $|V|/E < 1$ (Fröbrich and Lipperheide 1996), where $|V|$ is the strength of the interaction potential. The corresponding semi-classical eikonal scattering amplitude $F_E(\Delta\mathbf{k})$ is then obtained by the following integral representation:

$$F_E(\Delta\mathbf{k}) = -\frac{\mu}{2\pi\hbar^2}\int d^3\mathbf{r}\, V(\mathbf{r}) \times \exp\left[i\Delta\mathbf{k}\cdot\mathbf{r} - \frac{i\mu}{\hbar^2 k_i}\int_{-\infty}^{z} dz'\, V(\mathbf{b}, z')\right]. \tag{4}$$

Since the differential eikonal collision cross section is determined by the following relation, $d\sigma_E/d\Omega = |F_E(\Delta\mathbf{k})|^2$, the total elastic eikonal collision cross section (σ_E) would be then expressed by

$$\sigma_E(k) = \int d^2\mathbf{b}\,|\exp[i\eta_E(k,b)] - 1|^2, \tag{5}$$

where $d\Omega$ is the differential solid angle, $k(\equiv |\mathbf{k}_i| = |\mathbf{k}_f|)$ is the elastic scattering wave number, and $\eta_E(k,b)$ is the total eikonal scattering phase based on the series expansion technique (Metawei 2000):

$$\eta_E(k,b) = \sum_l \left(-\frac{\mu}{\hbar^2}\right)^{l+1}\frac{1}{(l+1)!}\frac{1}{k}\left(\frac{\partial}{\partial k}\frac{1}{k} - \frac{b}{k^2}\frac{\partial}{\partial b}\right)^l \times \int_{-\infty}^{\infty} dz'\, V^{l+1}(b, z'). \tag{6}$$

We then shall apply this semi-classical eikonal method to investigate the elastic electron–atom collision in generalized Lorentzian non-thermal plasmas, including the influence of the non-thermal renormalized plasma shielding.

3. Generalized Lorentzian distribution and effective potential

In numerous astrophysical and laboratory plasmas, it is shown that the main departures from the thermal Maxwellian distribution function would be expected due to the coupling with external disturbances. It has been also shown that the superthermal particles that escaped from the standard Maxwellian distribution would be described by the power-law form of the generalized Lorentzian kappa distribution $f_\kappa(v)$ (Hasegawa et al. 1985; Hasegawa and Sato 1989) in the following expression:

$$f_\kappa(v) = \left(\frac{m_e}{2\pi\kappa E_\kappa}\right)^{3/2}\frac{\Gamma(\kappa+1)}{\Gamma(\kappa-1/2)}\left(1 + \frac{m_e v^2}{2\kappa E_\kappa}\right)^{-\kappa-1}, \tag{7}$$

where $\kappa(>3/2)$ is the spectral index of the Lorentzian non-thermal plasma, m_e is the electron mass, $E_\kappa[= k_B T(\kappa - 3/2)/\kappa]$ is the characteristic energy, k_B is the Boltzmann constant, T is the plasma temperature, and $\Gamma(x)$ stands for the Euler-gamma function. In addition, it is shown that the external electromagnetic radiation field alters the conventional diffusion coefficient, since the non-Columbic diffusion coefficient (Hasegawa and Sato 1989)[16] would be produced by the radiation-induced field and is also proportional to the square of the

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velocity v of the plasma electron in non-thermal plasmas. Hence, the total diffusion coefficient (Hasegawa and Sato 1989) would be proportional to $(1 + \alpha v^2)$, where α is a constant related to the intensity of the electromagnetic radiation field. It is also interesting to note that the generalized Lorentzian velocity distribution function yields the standard Maxwellian distribution in the limiting case such as $\kappa \to \infty$ or in the absence of the external electromagnetic radiation field, $f_M(v) \propto e^{-m_e v^2/2k_B T}$ (Hasegawa et al. 1985), for all particle velocities. Moreover, the Lorentzian distribution function turns out to be a simple power-law distribution at high particle velocities such as $f_\kappa(v) \propto (m_e v^2/2\kappa E_\kappa)^{-(\kappa+1)}$. It has been also known that the hot solar coronal plasma contains the tail portion of the non-thermal Lorentzian electron velocity distribution with the spectral range $2.62 < \kappa < 3.15$ (Parks 2004). Hence, it has been found that the generalized Lorentzian distribution function covers quite wide range of particle velocity distributions from a simple inverse power-law form to a standard Maxwellian distribution function. Recently, the effective screening length λ_κ in Lorentzian non-thermal distribution plasmas (Rubab and Murtaza 2006b), i.e. the critical correlation length, has been obtained by the following relation, $\lambda_\kappa = \lambda_D \mu_\kappa$, where λ_D is the standard Debye length in Maxwellian distribution plasmas and the non-thermal parameter $\mu_\kappa \{\equiv [(\kappa - 3/2)/(\kappa - 1/2)]^{1/2}\}$ stands for the measure of the fraction of the superthermal population in the Lorentzian plasma distribution. Very recently, an excellent work of ABD (Arkhipov et al. 2011) has provided the quite useful analytic procedure of the renormalization method of plasma particle interactions to obtain the generalized Poisson–Boltzmann equation for an effective interaction potential of two chosen plasma particles in the presence of a third particle in partially ionized dense plasmas. Using this effective ABD potential model (Arkhipov et al. 2011) with the critical correlation length λ_κ of the generalized Lorentzian non-thermal plasma, the effective screening interaction potential $V_{\rm eff}(\mathbf{r})$ between the electron and the neutral hydrogen atom in highly ionized dense Lorentzian non-thermal plasmas ($n_n \ll n_e, n_p$), including influence of the non-thermal renormalization plasma shielding, is represented by

$$V_{eff}(\mathbf{r}) = -\frac{e^2}{(1 - a_0^2/4\lambda_\kappa^2)}\left(\frac{1}{a_0} + \frac{1}{r}\right)\exp(-2r/a_0) - \frac{e^2(a_0^2/4\lambda_\kappa^2)}{(1 - a_0^2/4\lambda_\kappa^2)^2 r}\exp(-2r/a_0) + \frac{e^2(a_0^2/4\lambda_\kappa^2)(2 - a_0^2/4\lambda_\kappa^2)}{(1 - a_0^2/4\lambda_\kappa^2) r}\exp(-r/\lambda_\kappa), \quad (8)$$

where n_n is the density of the neutral hydrogen atom, n_e is the electron density, n_p is the proton density, and $a_0 (= \hbar^2/m_e e^2)$ is the Bohr radius of the hydrogen atom.

4. Eikonal scattering phase shift and eikonal cross section

After some mathematical manipulations using (6) and (8), the first-order eikonal scattering phase shift $\eta_E(\bar{b}, \bar{E}, \kappa, \bar{\lambda}_D)$ for the elastic election–atom collision in partially ionized dense generalized Lorentzian non-thermal plasmas, including the influence of the non-thermal renormalization plasma shielding, is then found to be the following analytic expression:

$$\eta_E(\bar{b}, \bar{E}, \kappa, \bar{\lambda}_D) = \frac{2}{\sqrt{\bar{E}}}\left\{\frac{\bar{b}K_1(2\bar{b}) + K_0(2\bar{b})}{\left[1 - [(\kappa - 1/2)/4(\kappa - 3/2)\bar{\lambda}_D^2]\right]} + \frac{[(\kappa - 1/2)/4(\kappa - 3/2)\bar{\lambda}_D^2]K_0(2\bar{b})}{\left[1 - [(\kappa - 1/2)/4(\kappa - 3/2)\bar{\lambda}_D^2]\right]^2} - \frac{[(\kappa-1/2)/4(\kappa-3/2)\bar{\lambda}_D^2]\left[2-[(\kappa-1/2)/4(\kappa-3/2)\bar{\lambda}_D^2]\right]}{\left[1 - [(\kappa - 1/2)/4(\kappa - 3/2)\bar{\lambda}_D^2]\right]} \times K_0\left(\sqrt{\frac{(\kappa - 1/2)}{(\kappa - 3/2)}}\frac{\bar{b}}{\bar{\lambda}_D}\right)\right\}, \quad (9)$$

where $\bar{b} (\equiv b/a_0)$ is the scaled impact parameter, $\bar{E} (\equiv E/Ry)$ is the scaled collision energy, $Ry (= m_e e^4/2\hbar^2 \approx 13.6\,\text{eV})$ is the Rydberg constant, $\bar{\lambda}_D (\equiv \lambda_D/a_0)$ is the scaled standard Debye length, and $K_q(x)$ is the second kind modified Bessel function of order q. Then the scaled differential eikonal collision cross section $d\bar{\sigma}_E/d\bar{b} [\equiv (d\sigma_E/d\bar{b})/\pi a_0^2] = 2\bar{b}\,|\exp(i\eta_E) - 1|^2$ in units of πa_0^2 for the elastic electron–atom collision in partially ionized dense Lorentzian non-thermal plasmas, including the non-thermal renormalization plasma shielding effect, is found to be

$$d\bar{\sigma}_E/d\bar{b} = 2\bar{b}\left|\exp\left\{\frac{2}{\bar{E}^{1/2}}\left[\frac{1}{\left[1-[(\kappa-1/2)/4(\kappa-3/2)\bar{\lambda}_D^2]\right]} \times \left[\bar{b}K_1(2\bar{b}) + K_0(2\bar{b})\right] + \frac{[(\kappa - 1/2)/4(\kappa - 3/2)\bar{\lambda}_D^2]}{\left[1 - [(\kappa - 1/2)/4(\kappa - 3/2)\bar{\lambda}_D^2]\right]^2}K_0(2\bar{b}) - \frac{[(\kappa-1/2)/4(\kappa-3/2)\bar{\lambda}_D^2]\left[2-[(\kappa-1/2)/4(\kappa-3/2)\bar{\lambda}_D^2]\right]}{\left[1 - [(\kappa - 1/2)/4(\kappa - 3/2)\bar{\lambda}_D^2]\right]} \times K_0\left(\sqrt{\frac{(\kappa - 1/2)}{(\kappa - 3/2)}}\frac{\bar{b}}{\bar{\lambda}_D}\right)\right\} - 1\right|^2, \quad (10)$$

where the factor $(\kappa - 1/2)/4(\kappa - 3/2)\bar{\lambda}_D^2$ in the exponent represents the non-thermal renormalization plasma shielding effect due to the non-thermal and non-ideal collective plasma particle interactions in Lorentzian plasmas. Recently, the influence of the renormalization shielding (Hong and Jung 2012) on the elastic electron–atom collision process has been investigated in partially ionized thermal Maxwellian plasmas. However, the non-thermal renormalization shielding effect on the

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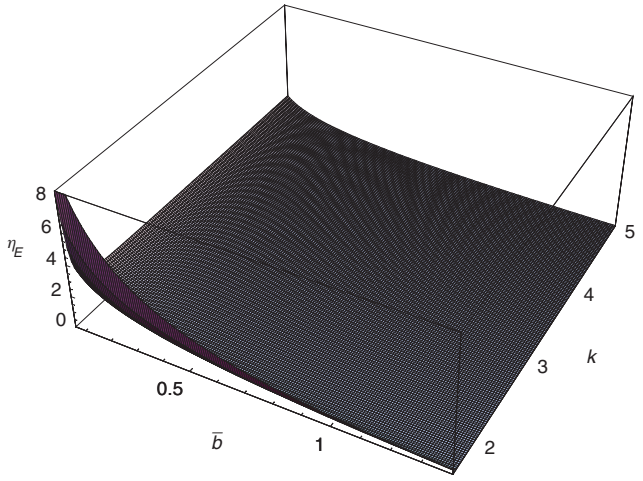


Figure 1. (Colour online) The eikonal scattering phase shift η_E for the elastic election–atom collision in partially ionized dense generalized Lorentzian non-thermal plasmas as a function of the scaled impact parameter $\bar{b}$ when $\bar{E} = 5$ and $\bar{\lambda}_D = 2$. The solid line represents the case of $\kappa = 1.7$. The dashed line represents the case of $\kappa = 1.8$. The dotted line represents the case of $\kappa = 1.9$.

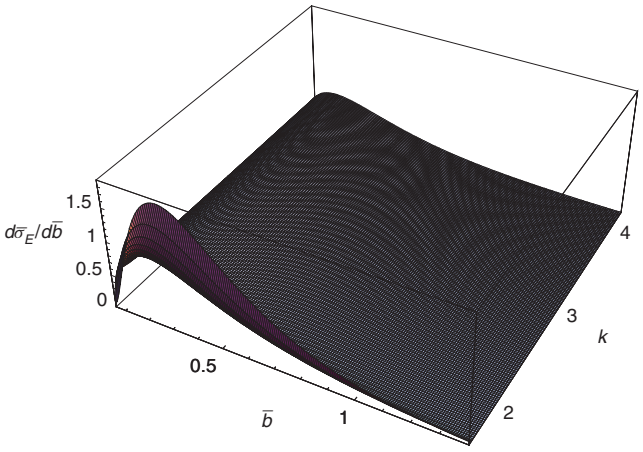


Figure 2. (Colour online) The scaled eikonal collision cross section $d\bar{\sigma}_E/d\bar{b}$ in units of πa_0^2 as a function of the scaled collision energy $\bar{E}$ when $\bar{b} = 0.5$ and $\bar{\lambda}_D = 2$. The solid line represents the case of $\kappa = 1.7$. The dashed line represents the case of $\kappa = 1.8$. The dotted line represents the case of $\kappa = 1.9$.

elastic collision cross section has not been explored as yet in generalized Lorentzian non-thermal plasmas. In weakly coupled classical plasmas discarding the influence of the non-thermal renormalization plasma shielding on the eikonal scattering phase shift, the scaled eikonal collision cross section would be represented by $d\bar{\sigma}'_E/d\bar{b} = 2\bar{b}\left|\exp[(2/\bar{E}^{1/2})(\bar{b}K_1(2\bar{b}) + K_0(2\bar{b}))] - 1\right|^2$ since the eikonal scattering phase shift is proportional to the factor $(2/\bar{E}^{1/2})[\bar{b}K_1(2\bar{b}) + K_0(2\bar{b})]$.

5. Non-thermal renormalized plasma shielding effect

In order to specifically investigate the non-thermal renormalized plasma shielding effects on the scattering phase shift and cross section for the elastic electron–atom collision process in partially ionized generalized Lorentzian non-thermal plasmas, we consider the collision energy with $\bar{E} > 1$ since the semi-classical eikonal analysis (Burke and Joachain 1995) is known to be valid for $v > \alpha_f c$, where $\alpha_f (= e^2/\hbar c \approx 1/137)$ is the fine structure constant and c is the speed of light. It would be then expected that the expression of the eikonal cross section [(10)] would be quite reliable to explore the electron–atom collision process for the collision energy with $\bar{E} > 1$, including the influence of the non-thermal renormalized plasma shielding in Lorentzian plasmas. Figure 1 represents the eikonal scattering phase shift η_E for the elastic election-atom collision in partially ionized dense generalized Lorentzian non–thermal plasmas as a function of the scaled impact parameter $\bar{b}$ for various values of the spectral index κ of the Lorentzian plasma. As shown in this figure, it is found that the eikonal scattering phase shift η_E decreases with an increase of the spectral index κ. It would be then expected that the eikonal scattering phase shifts for the elastic election–atom collisions in non-thermal plasmas are always greater than those in thermal Maxwellian plasmas due to the non-thermal character of the Lorentzian plasma. Hence, we have found that the non-thermal renormalization shielding effect strongly enhances the eikonal scattering phase shift η_E, especially for small impact parameters. It is also found that the influence of the non-thermal renormalization plasma shielding on the eikonal scattering phase shift η_E decreases with increasing impact parameter b. It would be then expected that the non-thermal character of the Lorentzian plasma couldn't be explored by the distant encounters in atomic collision and radiation processes. Figure 2 represents the scaled differential eikonal cross section $d\bar{\sigma}_E/d\bar{b}$ in units of πa_0^2 for the elastic electron–atom collision in partially ionized dense Lorentzian non-thermal plasmas as a function of the scaled collision energy $\bar{E}$ for various values of the spectral index κ. As seen, it is found that the eikonal collision cross section $d\bar{\sigma}_E/d\bar{b}$ decreases with an increase of the collision energy $\bar{E}$. It is also found that the eikonal collision cross section $d\bar{\sigma}_E/d\bar{b}$ decreases with increasing the spectral index κ. Hence, it would be then expected that the eikonal cross sections for the electron–atom collisions in non-thermal Lorentzian plasmas are always greater than those in thermal Maxwellian plasmas due to the non-thermal and non-ideal collective plasma interactions in generalized Lorentzian plasmas. We have found that the collision frequency in non-thermal Lorentzian plasmas is smaller than that in thermal Maxwellian plasmas due to the non-thermal property of the Lorentzian plasmas since the collision frequency is proportional to the electron–atom collision cross section. Moreover, we can expect that electric conductivity in non-thermal Lorentzian plasmas would be smaller than that in thermal Maxwellian plasmas

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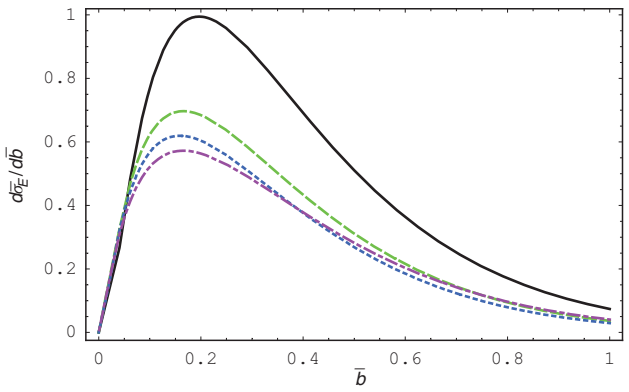


Figure 3. (Colour online) The scaled eikonal collision cross section $d\bar{\sigma}_E/d\bar{b}$ in units of πa_0^2 as a function of the scaled impact parameter $\bar{b}$ when $\bar{E} = 5$ and $\bar{\lambda}_D = 2$. The solid line represents the case of $\kappa = 1.7$. The dashed line represents the case of $\kappa = 1.8$. The dotted line represents the case of $\kappa = 1.9$. The dot-dashed line represents the thermal limit (i.e. $\kappa \to \infty$).

since the electric conductivity is inversely proportional to the electron–atom collision cross section. Figure 3 shows the scaled differential eikonal cross section $d\bar{\sigma}_E/d\bar{b}$ in units of πa_0^2 as a function of the scaled impact parameter $\bar{b}$ for various values of the spectral index κ. As shown in this figure, it is also found that the maximum position of the eikonal collision cross section has approached to the collision center in Lorentzian plasmas with an increase of the spectral index κ. Hence, it would be expected that the interaction domain for the electron–atom collision in non-thermal Lorentzian plasmas is greater than that in thermal Maxwellian plasmas.

6. Conclusions

In this work, we have proposed the influence of the non-thermal renormalization plasma shielding effects on the elastic electron–atom collision process in partially ionized generalized Lorentzian non-thermal plasmas. We employed the semi-classical eikonal method and impact parameter analysis to obtain the eikonal scattering phase shift and eikonal collision cross section as functions of the collision energy, Debye length, impact parameter, and spectral index of the plasma. In this work, we have found that the non-thermal renormalization plasma shielding effect enhances the eikonal scattering phase shift as well as the eikonal collision cross section, especially for small impact parameters, in Lorentzian non-thermal plasmas. Hence, we can expect that the eikonal scattering phase shifts for the elastic election–atom collisions in non-thermal plasmas are always greater than those in thermal Maxwellian plasmas due to the non-thermal character of the generalized Lorentzian plasma. We also found that the non-thermal renormalization plasma shielding effect on the eikonal scattering phase shift decreases with an increase of the impact parameter. In addition, we have found that the maximum position of the eikonal collision cross section has receded from the collision center in Lorentzian plasmas with an increase of the non-thermal character. We also found that the electric conductivity in non-thermal Lorentzian plasmas would be smaller than that in thermal Maxwellian plasmas since the electric conductivity is inversely proportional to the electron–atom collision cross section, and the collision frequency is proportional to the electron–atom collision cross section. We also found that the collision frequency in non-thermal Lorentzian plasmas is smaller than that in thermal Maxwellian plasmas since the collision frequency is proportional to the electron–atom collision cross section. We can also expect that the electric conductivity in non-thermal Lorentzian plasmas would be smaller than that in thermal Maxwellian plasmas due to the non-thermal properties of the Lorentzian plasma since the electric conductivity is inversely proportional to the electron–atom collision cross section. Hence, we have found that the non-thermal character of the generalized Lorentzian plasma extends the main interaction range for the elastic electron–atom collision in plasmas. Therefore, in this work we have found that the non-thermal renormalization plasma shielding effect plays a crucial role on the elastic electron–atom collision in partially ionized dense generalized Lorentzian non-thermal plasmas. These results would provide useful information on the non-thermal renormalization plasma shielding effect on the atomic collision and radiation process (Shevelko and Tawara 2012) in partially ionized dense non-thermal plasmas.

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