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Wannier threshold law for two-electron escape in dense high-temperature plasmas

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Abstract

The quantum-mechanical and plasma screening effects on the Wannier ionization threshold law for the two-electron escape into the continuum is investigated in dense high-temperature plasmas. An effective pseudopotential model is applied to describe particle interactions in dense high-temperature plasmas. The screened renormalized electron charge is obtained as a function of the thermal de Broglie wavelength, Debye length, and charge of the residual ion. The screened threshold exponent of the double ionization cross section is also obtained by using the effective screened charge $Z_{\rm eff}$. It is found that the quantum-mechanical effect increases the renormalized electron charge, especially, in the short distance region. It is also found that the screened Wannier exponent increases due to the quantum-mechanical effect, especially, when the de Broglie wavelength is comparable to the Bohr radius. In dense high-temperature plasmas, the quantum-mechanical effect is found to be more significant than the plasma screening effect.
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The atomic ionization process [1–7] is a subject of a special attention in many areas of physics such as astrophysics, atomic physics, chemical physics, and plasma physics since this process is extremely sensitive to the details of atomic structure and the correlation effects between atomic electrons. Especially, the double ionization process [8–10] has received considerable attention in order to investigate the long range electron–electron correlation since the universal threshold law [11] for the two-electron escape was obtained by using the classical treatments. Recently, atomic processes in plasmas [12,13] have been of great interest since collision and radiation processes are known to be quite useful for plasma diagnostics. The plasmas described by the Debye–Hückel model

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are called ideal plasmas since the average energy of interaction between particles is small compared to the average kinetic energy of a particle [14]. Recently, the importance of study of various properties of dense plasmas such the interiors of the astrophysical compact objects has considerably increased. This is a result of common interest in investigations of astrophysical plasmas such as the interiors of the compact objects such as white dwarfs and neutron stars, which are the products of the final stages of stellar evolution. The density of charged particles in such astrophysical compact objects is about 10^{19}–10^{26} cm^{-3} and the temperature is about 10^5–10^7 K. It is quite obvious that the properties of matter existing under such dense plasmas differ radically from the properties of a classical plasma. In dense high-temperature plasmas, the interaction potential is known to be different from the Debye–Hückel type because of strong collective effects and quantum-mechanical effects of diffraction and symmetry on a level with plasma polarization effects [15–17]. Then, the two-electron escape into the continuum in dense high-temperature plasmas is different from that in a classical plasma. Thus, in this Letter we investigate quantum-mechanical and plasma screening effects on the Wannier ionization threshold law for the double electron escape into the continuum in dense high-temperature plasmas by using the classical treatments with the screened effective charge since the theoretical atomic spectroscopy is essential in the study of plasma parameters. An effective pseudopotential model taking into account both quantum-mechanical effects and plasma screening effects is applied to describe the electron–electron and electron–residual-ion interaction potentials in semiclassical dense high-temperature plasmas. The screened renormalized electron charge due to the quantum-mechanical and plasma screening effects is obtained as a function of the thermal de Broglie wavelength, Debye length, and charge of the residual ion. The screened threshold exponent of the double ionization cross section is also discussed by using the effective charge analogy.

Recently, an integro-differential equation for the effective potential of the particle interaction of semiclassical plasmas taking into account both quantum-mechanical effects of diffraction and symmetry and plasma screening effects was obtained on the basis of a sequential solution of the chain of Bogolyubov equations [18,19] for the equilibrium distribution functions of particles in dense high-temperature plasmas and an analytic expression for the pseudopotential [16] of the particle interaction was also obtained. Using the pseudopotential model suggested by Arkhipov et al. [16] taking into account quantum-mechanical effects and plasma screening effects, the potential $V_{\alpha\text{–}\beta}(r)$ of plasma particle interaction in dense high-temperature plasmas for small de Broglie wavelengths can be represented by

$$V_{\alpha\text{–}\beta}(r) = \frac{e_\alpha e_\beta}{r}\left(e^{-r/r_{\mathrm{D}}} - e^{-r/\lambda_{\alpha\beta}}\right) + \delta_{\alpha e}\delta_{\beta e} k_B T(\ln 2) e^{-r^2/(\lambda_{ee}^2 \pi \ln 2)}, \tag{1}$$

where e_α is the electric charge of the particle α, r_{D} is the Debye length, $\lambda_{\alpha\beta} = \hbar/(2\pi\mu_{\alpha\beta}k_B T)^{1/2}$ is the thermal de Broglie wavelength of the interacting pair α–β, $\mu_{\alpha\beta} = m_\alpha m_\beta/(m_\alpha + m_\beta)$ is the reduced mass, m_α is the mass of the particle α, $\delta_{\alpha e}$ is the Kronecker delta, k_B is the Boltzmann constant, and T is the plasma temperature. In the absence of the quantum-mechanical effects ($\lambda_{\alpha\beta}, \lambda_{ee} \to 0$), it can be found that the pseudopotential $V_{\alpha\text{–}\beta}(r)$ goes over into the classical Debye–Hückel potential $V_{\mathrm{DH}}(r) \to (e_\alpha e_\beta/r)e^{-r/r_{\mathrm{D}}}$. In dense high-temperature plasmas, the classical equation of the motion for the two electrons $(\mathbf{r}_1, \mathbf{r}_2)$ in the field of the residual ion would be obtained by the force $\mathbf{F}(\mathbf{r}_a)$ on the electron at $\mathbf{r}_a$:

$$\mathbf{F}(\mathbf{r}_a) = -\left[\frac{\partial}{\partial \mathbf{r}_a} V_{e\text{–}i}(r_a) + \frac{\partial}{\partial \mathbf{r}_a} V_{e\text{–}e}\big(|\mathbf{r}_a - \mathbf{r}_b|\big)\right], \tag{2}$$

where $(a, b) = (1, 2)$ or $(a, b) = (2, 1)$, $V_{e\text{–}i}(r_a)$ and $V_{e\text{–}e}(|\mathbf{r}_a - \mathbf{r}_b|)$ are, respectively, the electron–ion and electron–electron interaction potentials:

$$V_{e\text{–}i}(r_a) = -\frac{Ze^2}{r_a}\left(e^{-r_a/r_{\mathrm{D}}} - e^{-r_a/\lambda_{ei}}\right), \tag{3}$$

here, Z is the charge of the residual ion,

$$V_{e\text{–}e}\big(|\mathbf{r}_a - \mathbf{r}_b|\big) = \frac{e^2}{|\mathbf{r}_a - \mathbf{r}_b|}\left(e^{-|\mathbf{r}_a - \mathbf{r}_b|/r_{\mathrm{D}}} - e^{-|\mathbf{r}_a - \mathbf{r}_b|/\lambda_{ee}}\right) + \delta_{ee}\delta_{ee} k_B T(\ln 2) e^{-|\mathbf{r}_a - \mathbf{r}_b|^2/(\lambda_{ee}^2 \pi \ln 2)}. \tag{4}$$

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