Available online at www.sciencedirect.com

ScienceDirect

MATTER AND RADIATION AT EXTREMES

Matter and Radiation at Extremes 1 (2016) 237–248

www.journals.elsevier.com/matter-and-radiation-at-extremes

Review article

Review of quantum collision dynamics in Debye plasmas

R.K. Janev [b], Songbin Zhang [a,*], Jianguo Wang [c]

[a] School of Physics and Information Technology, Shaanxi Normal University, Xi'an 710119, China
[b] Macedonian Academy of Sciences and Arts, P.O. Box 428, 1000 Skopje, Macedonia
[c] Key Laboratory of Computational Physics, Institute of Applied Physics and Computational Mathematics, P.O. Box 8009, Beijing 100088, China

Received 1 June 2016; revised 15 August 2016; accepted 16 August 2016
Available online 14 October 2016

Abstract

Hot, dense plasmas exhibit screened Coulomb interactions, resulting from the collective effects of correlated many-particle interactions. In the lowest particle correlation order (pair-wise correlations), the interaction between charged plasma particles reduces to the Debye–Hückel (Yukawa-type) potential, characterized by the Debye screening length. Due to the importance of Coulomb interaction screening in dense laboratory and astrophysical plasmas, hundreds of theoretical investigations have been carried out in the past few decades on the plasma screening effects on the electronic structure of atoms and their collision processes employing the Debye–Hückel screening model. The present article aims at providing a comprehensive review of the recent studies in atomic physics in Debye plasmas. Specifically, the work on atomic electronic structure, photon excitation and ionization, electron/positron impact excitation and ionization, and excitation, ionization and charge transfer of ion-atom/ion collisions will be reviewed.

PACS Codes: 32.80.-t; 32.70.-n; 34.70.-e; 34.80.-i; 52.20.-j

Keywords: Debye plasmas; Screened Coulomb potential; Atomic structure; Collision dynamics

1. Introduction

The study of Coulomb interaction screening in plasma environments is one of the major subjects in plasma physics [1–6]. The Coulomb interaction screening in plasma environments is a collective effect of correlated many-particle interactions [7–9]. It strongly affects the electronic structure (spectral) properties of atoms and properties of their collision processes with respect to those for isolated systems. Indeed, it has been observed experimentally in a number of laser-produced dense plasmas that the atomic spectral lines are significantly redshifted [10–14]. Note that the Debye–Hückel screening of Coulomb interaction between charged particles also appears in electrolytes, solid-state matter and many other physical systems (in nuclear physics it is known as Yukawa potential).

Extensive studies have been performed on the screening effects in classical hot, dense plasmas in the past decades (see examples in Refs. [7,8] and references therein). These studies have been motivated mainly by the researches in laser-produced plasmas, extreme ultraviolet (EUV) and X-ray laser developments, inertial confinement fusion and astrophysics (stellar atmospheres and interiors). The densities (n) and temperatures (T) in these plasmas span the ranges $n \sim 10^{15}$–10^{18} cm^{-3}, $T \sim 0.5$–5 eV for stellar atmospheres, $n \sim 10^{19}$–10^{21} cm^{-3}, $T \sim 50$–300 eV for laser-produced plasmas and $n \sim 10^{22}$–10^{26} cm^{-3}, $T \sim 0.5$–10 keV for inertial confinement fusion plasmas. In classical hot, dense plasmas, both Coulomb and thermal effects play important roles. The

* Corresponding author.
E-mail address: song-bin.zhang@snnu.edu.cn (S.B. Zhang).
Peer review under responsibility of Science and Technology Information Center, China Academy of Engineering Physics.

http://dx.doi.org/10.1016/j.mre.2016.10.002

relative importance of these two effects can be estimated by the so-called coupling parameter $\Gamma = \frac{\langle Z_i e\rangle^2}{R_i k_B T_e}$, where $\langle Z_i e\rangle$ is the average charge of ions in the plasma, $R_i = \left(\frac{3}{4\pi n_e}\right)^{1/3}$ is the average inter-ionic distance, k_B is the Boltzmann constant, T_e and n_e are the plasma electron temperature and density, respectively [4]. In the weakly coupled plasmas with relatively high temperatures and low densities, such as those created by laser irradiation of solids and existed in the inertial confinement fusion or the stellar interiors, the potential energy is relatively small compared to the kinetic energy, and long-range self-consistent interactions (described by the Poisson equation) dominate over short-range two-particle interactions (collisions) where $\Gamma \ll 1$. To the lowest particle correlation order (pair-wise correlations), the complete screened Coulomb potential in a more general way is given by [5,6,15—18].

$$V(r) = \begin{cases} -Ze^2\left(\dfrac{1}{r} - \dfrac{1}{D+D_A}\right), & r \le D_A \\ -Ze^2 \dfrac{D}{D+D_A}\dfrac{1}{r}\exp\left(-\dfrac{r-D_A}{D}\right), & r \ge D_A \end{cases}, \tag{1}$$

where Z is the nuclear charge, $D = \frac{(k_B T_e)^{1/2}}{(4\pi e^2 n_e)^{1/2}}$ and D_A are the screening length and the mean minimum radius of the ion sphere, respectively. D_A defines the ion sphere radius where the potential outside the ion sphere is screened by the plasmas, and $D_A < D$. In the limit when $D_A \to 0$, Eq. (1) reduces to the most often used Debye—Hückel (Yukawa-type) potential [7,8,19] as

$$V(r) = -\frac{Ze^2}{r}\exp\left(-\frac{r}{D}\right). \tag{2}$$

The Debye—Hückel representation of plasma-screened Coulomb interaction is appropriate for weakly coupled plasmas, $\Gamma \ll 1$, when the thermal effects dominate over the Coulomb ones. It is obvious from Eq. (2) that for $D \to \infty$, the Debye—Hückel potential approaches the Coulomb potential.

Alternatively, in strongly-coupled plasmas with relatively low temperature and high density ($\Gamma \ge 1$), the Coulomb effects are dominant (such as in the solid phase) and the ions are packed tightly together; each ion occupies an equal volume and is surrounded by a sphere of radius $R_Z = \left[\frac{3(Z-1)}{4\pi n_e}\right]^{1/3}$ (ion-sphere radius). Under these conditions, the plasma-screened Coulomb interaction is described by the ion sphere model potential, defined as [1,2,4,19].

$$V(r) = \begin{cases} -\dfrac{Ze^2}{r}\left[1 - \dfrac{r}{2R_Z}\left(3 - \dfrac{r^2}{R_Z^2}\right)\right], & r \le R_Z \\ 0, & r > R_Z \end{cases}. \tag{3}$$

Note that in the screened model Eq. (1) or Eq. (2), the thermal plasma effects dominate over the Coulomb effects, while in the potential Eq. (3) the opposite is true. Obviously they describe two different types of classical plasmas. Note that recently an analytical finite temperature ion sphere model was presented by Li et al. [20]. More information about the models of these plasmas can be found in Refs. [1,2,4,6,7,20]. It should be noted that recently a modified Debye—Hückel potential [21—24] has been proposed to describe the interaction screening in dense quantum plasmas, where the de Broglie wavelength of the charge carriers is comparable to or larger than the inter-particle distance and the plasma temperature is smaller than the Fermi temperature. Shukla and Eliasson [23] have shown that the effective potential of a test charge in a dense quantum plasma has the form of an exponential-cosine screened Coulomb potential as

$$V(r) = -\frac{Ze^2}{r}\exp\left(-k_q r\big/\sqrt{2}\right)\cos\left(k_q r\big/\sqrt{2}\right), \tag{4}$$

where $k_q = \left(\frac{4m^2\omega_p^2}{\hbar^2}\right)^{1/4}$ is the electron quantum wave number, m is the electron mass, and $\omega_p = \sqrt{4\pi n e^2/m}$ is the electron plasma frequency. Usually quantum plasmas are characterized by a very low temperature and a high number density. Such plasmas exist in metals, semiconductor devices, nanoscale structures (nanowires, quantum dots) and compact astrophysical objects (neutron stars, white dwarfs).

The above model potentials describe the interactions between the electron and the charged ion, while there are different arguments about whether a similar Coulomb screening between two atomic electrons should be applied [1,4,15]. Generally, three types of models are employed in Debye plasmas in this respect: The first one does not consider any screening [25],

$$V_{ee}(r_1, r_2) = \frac{e^2}{|\boldsymbol{r}_1 - \boldsymbol{r}_2|}, \tag{5}$$

where $\boldsymbol{r}_1$ and $\boldsymbol{r}_2$ are the electron coordinates. The second one considers only the screening on one electron coordinate [4],

$$V_{ee}(r_1, r_2) = \frac{e^2}{|\boldsymbol{r}_1 - \boldsymbol{r}_2|}\exp\left(-\frac{|\boldsymbol{r}_1|}{D}\right). \tag{6}$$

The third one considers the screening on both coordinates [1],

$$V_{ee}(r_1, r_2) = \frac{e^2}{|\boldsymbol{r}_1 - \boldsymbol{r}_2|}\exp\left(-\frac{|\boldsymbol{r}_1 - \boldsymbol{r}_2|}{D}\right). \tag{7}$$

In most of the recent works the last type of models is taken.

In the present review, we provide a comprehensive overview of the fundamental theoretical studies of atomic physics in Debye plasmas modeled with screened interactions (Eq. (2) and Eq. (7)) in the past decade; earlier comprehensive reviews of hot-dense plasmas can be found in Refs. [1,6—8]. In the sections below we summarize the work on atomic structure, photon collisions, electron collisions, positron collisions, and heavy particle collisions in a wide range of plasma screening conditions. Atomic units will be used in the remaining part of this article, unless explicitly indicated.

2. Atomic structure

In the nonrelativistic approximation, the radial Schrödinger equation for the hydrogenlike ion with nuclear charge Z in