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Microfield distribution in semiclassical plasma

Abstract. In this article the calculation and analysis of the plasma microfield distribution function of non-ideal dense plasma are presented. Plasma particles interact via the effective potential which takes into account of the quantum effect of diffraction and the screening effect. Method of Iglesias was used for calculation of the microfield distribution function of the ionic component. The advantage of this method is that the distribution function is exactly expressed in terms of a two-body function and does not require knowledge of many-body functions, this fact significantly simplifies the problem. Results were compared with the results obtained on the basis of other models. The discussion and conclusion are presented.
Keywords: Microfield distribution function, plasma microfield.

Introduction

In a real plasma processes are continuously occurring which affects plasma properties and its composition. These are ionization, dissociation processes, excitation of bound electrons in atoms [1]. In turn, plasma environment very strongly affects the processes occurring in it. The fact is that in a sufficiently small volume of plasma $V < l_s^3$, where l_s is a characteristic screening radius, at distances $r < l_s$ distribution of charged particles in the system is not homogeneous. Therefore, although the plasma is electrically neutral as a whole, at sufficiently small distances an electric field shows its action, which greatly affects many plasma properties (the kinetic coefficients and thermodynamic properties, radiation, etc.) [2].

The internal microscopic field exerts a strong effect on the spectral lines shape, causing the phenomenon of Stark broadening, which attracts much attention because of the wide practical application.

Microfield distribution function in strongly coupled plasmas

It should be noted that the microfield is variable for a given density of charged particles due to density fluctuations. The motion of charged particles perturbing atom leads to the distribution of the microfield in a plasma. The main characteristic of the internal plasma microfield is its distribution function, which determines the probability of finding an electric field at a point located at $\vec{r}_0$.

The microfield distribution was first calculated by Holtsmark [3], who neglected correlation phenomena, so that subsequent research focused on taking into account correlations between the particles. Holtsmark's results are valid for high-density plasma.

Ecker and Muller [4] were the first to include correlations for the low-frequency ionic components of the electric field. The authors used a model of uncorrelated distribution of screened ions. According to this approximation, the effective fields are defined by the expression

$$\vec{E} = \frac{e}{r^3}\vec{r}(1 + r / r_D)e^{-r/r_D} \qquad (1)$$

In the early '80s Morita noticed that the problem of microfield distribution is formally similar to the problem of determining chemical potential. This allowed Iglesias [5] to reduce the microfield problem to finding the radial distribution functions (RDF) of some fictitious system with complex potential energy of interaction. This made a basis for development of the integral equations method to study the problem of plasma microfield distribution.

In this paper we use a method for calculating the distribution function of the ionic microfield component *P(E)* proposed by Iglesias [6]. The advantage of this method is that the distribution function is exactly expressed in terms of

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a two-body function and does not require knowledge of many-body functions. We consider OCP model, i.e. a fully ionized plasma, in which electron component forms a homogeneous neutralizing background with N positively charged particles. The microfield distribution $W(\vec{E})$ is defined as the probability of finding an electric field $\vec{E}$ at a singly charged point located at $\vec{r}_0$. It's generally expressed in terms of the probability density $P_{N+1}(\vec{r}_0, \vec{r}_1, ..., \vec{r}_N)$ of finding a particular configuration of $N+1$ particles:

$$W(\vec{E}) = \int \dots \int \delta(\vec{E} - \sum_{i=1}^{N} \vec{E}_i) P_{N+1}(\vec{r}_0, \dots, \vec{r}_N) d\vec{r}_0 d\vec{r}_1 \dots d\vec{r}_N \,, \qquad (2)$$

where $\vec{E}_i$ – is the electric field, creating by *i*-th particle at $\vec{r}_0$ of radiating particle.

Assuming that our system is isotropic we may rewrite Eq. (2) as:

$$P(E) = \frac{2E}{\pi} \int_0^\infty lT(l) \sin(El) dl \,, \qquad (3)$$

The main result obtained in [6], is an equation that relates the Fourier transform of the microfield distribution function *T(l)* with a total pair correlation function $h(\vec{r};\lambda)$.

$$\ln T(l) = n \int_0^l d\lambda \int_0^\infty d\vec{r} \, \frac{iql\vec{r}}{r^3} h(\vec{r};\lambda) \,, \qquad (4)$$

where l is a unit vector in the direction of $\vec{l}$, λ is a magnitude of the vector $\vec{l}$, q is a charge of ions, immersed in a neutralizing electron background. The next step is a definition of $h(\vec{r};\lambda)$. The simplest approximation suitable for a Coulomb system is the Debye-Hückel theory. In this approximation we have

$$h(\vec{r};\lambda) \approx \exp\{-\beta[1 - \frac{i\lambda\vec{l}}{q\beta}\vec{\nabla}_0]\Phi(r)\} - 1 \,. \qquad (5)$$

In [7] with the help of linear response method an effective potential was obtained which is used in this paper. It takes into account both the diffraction effects at short distances and also screening field effects at large distance.

$$\Phi_{\alpha e}(r) = \frac{Z_\alpha e^2}{\sqrt{1 - 4\lambda_{\alpha e}^2 / r_D^2}} \left(\frac{e^{-Br}}{r} - \frac{e^{-Ar}}{r} \right), \qquad (6)$$

where

$$A^2 = \frac{1}{2\lambda^2}\left(1 + \sqrt{1 - 4\lambda_{\alpha e}^2 / r_D^2}\right); \; B^2 = \frac{1}{2\lambda^2}\left(1 - \sqrt{1 - 4\lambda_{\alpha e}^2 / r_D^2}\right)$$

The coupling parameter is

$$\Gamma = \beta e^2 / r_0 \,,$$

the Debye length is $r_D = \left(4\pi n e^2 \beta\right)^{1/2}$, $\beta = \left(k_B T\right)^{-1}$, average interparticle distance r_0, and

$$\frac{4}{3}\pi r_0^3 n = 1 \,.$$

Instead of $\Phi(\vec{r})$ in Eq. (5) we used the reduced form of pseudopotential (6):

$$-\beta\Phi(r) = -\frac{\Gamma}{R}\frac{1}{\sqrt{1-24\Gamma^2/\pi r_s}}\left(e^{-BR} - e^{-AR}\right), \tag{7}$$

where

$$A^2 = \frac{\pi r_s}{4\Gamma}\left(1+\sqrt{1-24\Gamma^2/\pi r_s}\right);\ B^2 = \frac{\pi r_s}{4\Gamma}\left(1-\sqrt{1-24\Gamma^2/\pi r_s}\right).$$

In order to solve Eq. (3) numerically it's better to use the dimensionless parameter:

$$E^* = \frac{E}{E_0},\ \text{где}\ \ E_0 = \frac{q}{r_0^2}, \tag{8}$$

and to introduce $l^* = E_0 l$. Thus we obtain formula to calculate the distribution of electric field E^*

$$P(E^*) = \frac{2E^*}{\pi}\int_0^\infty dl^* l^* T(l^*)\sin(E^* l^*). \tag{9}$$

Substitution of Eq. (5) into Eq. (4) yields

$$\ln T(l) = 3\int_0^\infty dR \cdot \exp\left\{\frac{\Gamma}{R}\frac{1}{\sqrt{1-\chi}}\left(e^{-AR} - e^{-BR}\right)\right\}$$

$$\times \frac{R^2}{e^{-BR}\left(1+BR\right) - e^{-AR}\left(1+AR\right)} \cdot \left\{\frac{\sin lb(R)}{lb(R)} - 1\right\}, \tag{10}$$

where $\chi = 6\Gamma^2/\pi r_s$, $lb(R) = \frac{lq}{r_0^2}\left(\frac{e^{-BR}(1+BR) - e^{-AR}(1+AR)}{R^2}\right)$, $R = r/r_0$.

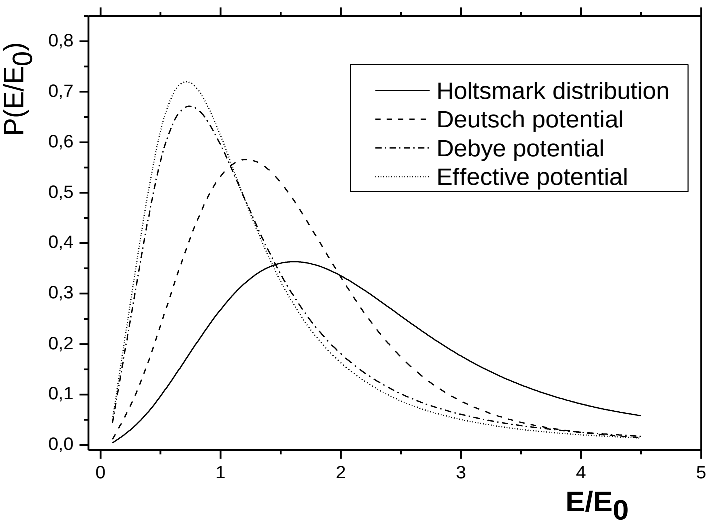

Figure 1 – A comparison of $P(E/E_0)$ curves for $\Gamma = 0{,}5$. Solid line - the distribution of Holtsmark; dash-dotted line - the results obtained in this work; dashed line - the results of Iglesias; dashed line - distribution obtained on the basis of Deutsch potential.

The one-dimensional integration over R and the sine transform in Eq.(3), in which $T(l)$ is defined by (4), were done numerically. The results are presented in Figs. 1 and 2.

In Fig. 1 we have a $P(E/E_0)$ plot for the value of Γ=0,5, where we compare our results with the those of Holtsmark [3] and Iglesias [6]. It also shows the distribution of microfield, obtained on the basis of Deutsch potential, taking into account the effects of diffraction of particles.

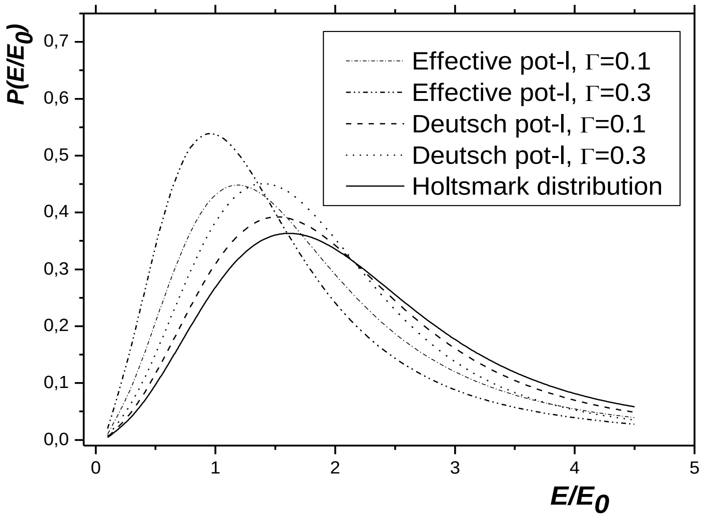

Figure 2 – A comparison of $P(E/E_0)$ curves for Γ = 0,1 and Γ = 0,3. Solid line - the distribution of Holtsmark; dashed line - distribution obtained on the basis of Deutsch potential (Γ = 0,1); dashed line - distribution obtained on the basis of Deutsch potential (Γ = 0,3); dash-dotted line - the results obtained on the basis of effective potential (Γ = 0,1); bar with a double dotted line - the results obtained on the basis of the effective potential (Γ = 0,3).

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