Interaction potential of microparticles in a plasma: Role of collisions with plasma particles

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The interaction potential of two charged microparticles in a plasma is studied. Violation of the plasma equilibrium around the dust particles due to plasma-particle inelastic collisions results in three effects: long-range (non-Yukawa) electrostatic repulsion, attraction due to ion shadowing, and attraction or repulsion due to neutral shadowing (depending on the sign of the temperature difference between the particle surface and neutral gas). An analytical expression for the total potential is obtained and compared with previous theoretical results. The relative contribution of these effects is studied in two limiting cases—an isotropic bulk plasma and the plasma sheath region. The results obtained are compared with existing experimental results on pair particle interaction. The possibility of the so-called dust molecule formation is discussed.

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I. INTRODUCTION

A complex (dusty) plasma is an ionized gas containing small solid or liquid particles. The particles can grow in the plasma due to various processes, or they can be introduced into the plasma externally. Particles can acquire large electric charge due to electron and ion collection and sometimes due to electron emission [1]. In the absence of emission, the equilibrium charge of a particle is negative and is determined by the balance of the plasma fluxes on its surface. In accordance with the so-called orbit motion limited (OML) model, the dimensionless surface potential of a spherical particle in an isotropic plasma, $z=|Z_d|e^2/aT_e$ ($Z_d<0$ is the particle charge number, a is the particle radius, and T_e is the electron temperature), depends on two parameters only—the electron-to-ion temperature and mass ratios $\tau=T_e/T_i$ and $\mu=m_e/m_i$ (provided the electron and ion number densities are equal) [1,2]. The corresponding flux balance equation is $\exp(-z)=\sqrt{\mu/\tau}(1+z\tau)$. Figure 1 shows z for different gases and different values of the temperature ratio. Note that in a flowing plasma the particle charge is a rather complicated function of the plasma drift velocity [3].

The interaction potential between microparticles is one of the most interesting issues in the physics of complex plasmas. This question is not only of fundamental interest but is also important for interpretation of recent plasma crystal experiments [4–9]. An isotropic screened Coulomb (or Yukawa) potential $U(r)\propto\exp(-r/\lambda_D)/r$ is normally used in analogy with charged colloidal suspensions. For an isotropic plasma, the screening length is $\lambda_D=(\lambda_{De}^{-2}+\lambda_{Di}^{-2})^{-1/2}$, where $\lambda_{De(i)}=(4\pi e^2 n_{e(i)}/T_{e(i)})^{-1/2}$ is the electron (ion) Debye radius and $T_{e(i)}$ and $n_{e(i)}$ are the electron (ion) temperature and number density, respectively. The screened Coulomb potential is derived from the linearized Poisson equation assuming that electrons and ions have equilibrium (Boltzmann) distributions around the grain. This approach is reasonable for colloidal suspensions but generally is not correct for complex plasmas for the following reason: There exists continuous exchange of matter and/or energy between microparticles and the surrounding plasma, i.e., the particles play the role of a sink for a plasma—electrons and ions are absorbed on the particle surface (where they recombine). Therefore, plasma equilibrium is violated in the vicinity of a particle due to absorption, and the electrostatic potential at $r\gg\lambda_D$ is not of Yukawa type but has a different long-range asymptotic, $U(r)\propto r^{-2}$ [10]. Another consequence of the equilibrium violation is the existence of an attractive interaction between two particles proposed by Tsytovich *et al.* [2,11]: The anisotropy of the plasma flux striking one particle, due to plasma absorption by another particle, results in attraction between the particles. A similar mechanism of attraction (repulsion) is also possible because of neutral scattering, if the particle surface temperature is lower (higher) than the neutral gas temperature [12]. These forces are often referred to as the ''shadowing forces,'' and the corresponding ''shadowing'' pair potential has an r^{-1} dependence. Hence, at large distances the shadowing interaction might overcome the long-range electrostatic interaction ($\propto r^{-2}$). The effective lengths of the long-range electrostatic interaction as well as of the shadowing interaction are determined

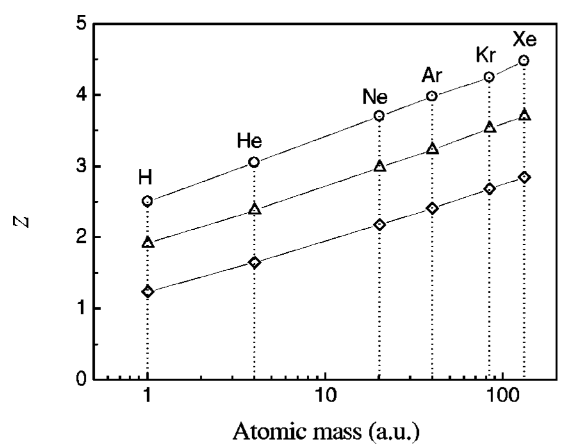

FIG. 1. Dimensionless surface potential of a microparticle, $z=e^2|Z_d|/aT_e$, versus the ion mass (gas type) for different values of the electron-to-ion temperature ratio $\tau=T_e/T_i$: 1 (○), 10 (△), and 10^2 (◇).

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by the spatial scale of the ion (neutral) Maxwellization—the mean free path of ion-neutral l_i (neutral-neutral l_n) collisions. At $r \gtrsim l_i$ ($r \gtrsim l_n$) the ion (neutral) distribution becomes isotropic and the shadow forces vanish. Typically, $l_i \sim l_n$ are much larger than λ_D.

Note that ground-based experiments are normally performed in the region of the plasma sheath, where a strong vertical electric force on the charged particle balances gravity and allows particle suspension. The ions in the sheath drift toward the electrode with a velocity much higher than their thermal velocity. This makes the interparticle interaction strongly anisotropic and can lead to the appearance of conelike vertical potential structures around the particles—the so-called wakes [13]. In addition, the particle polarization can be important in some cases [14]. However, in the (horizontal) direction, perpendicular to the ion flow, the particle potential was measured to be of the Yukawa type (at least at $r \lesssim 3\lambda_D$, with $\lambda_D \sim \lambda_{De}$) [15–17].

In this paper we focus on the interaction between micrograins, in particular, the effects caused by absorption (and/or scattering) of plasma particles. We investigate the dependence of the interaction potential on parameters of complex plasmas in the range typical for recent experiments. Contributions by the three effects discussed above are considered: long-range electrostatic interaction, attraction due to the shadowing effect associated with electrons and ions, and the shadowing effect associated with neutrals. We investigate the relative magnitude of these effects in two limiting cases—an isotropic bulk plasma and the plasma sheath—and show the range of the plasma parameters where the shadowing interaction can be important. The possibility of "dust molecule" formation is also discussed.

II. LONG-RANGE INTERACTION POTENTIAL

Usually the particle size is much smaller than the screening length, $a \ll \lambda_D$, and in turn λ_D is much smaller than the ion mean free path, $\lambda_D \ll l_i$ (these are also conditions when the OML theory is applicable). In the following we consider the pair interaction potential $U(r)$ in the range $\lambda_D \ll r \ll l_i$ for electrostatic, ion shadowing, and neutral shadowing forces.

A. Electrostatic potential

The approach proposed recently by Tsytovich *et al.* [2,11] to calculate the electrostatic potential around a spherical grain and the shadowing force between grains is based on the representation of the ion distribution function at a distance r from the particle in the form

$$f_i(\mathbf{v}) = \begin{cases} f_0(v), & \theta > \theta_* \\ 0, & \theta \leq \theta_*, \end{cases} \tag{1}$$

where $f_0(v)$ is a Maxwellian distribution function and θ is the angle between $\mathbf{v}$ and $\mathbf{r}$. The angle θ_* defines the solid angle in the velocity space where the ions (moving from the particle) are absent due to absorption. At large distances from the particle the angle θ_* is small and can be determined using the OML approach,

$$\sin^2\theta_* \simeq \frac{a^2}{r^2}\left(1 + \frac{2e|\phi_s|}{m_i v^2}\right), \tag{2}$$

where ϕ_s is the surface potential of a particle; for vacuum capacitance ($a \ll \lambda_D$) we have $|\phi_s| = |Z_d|e/a$. Then the electrostatic potential around the particle at large distances $r \gg a\sqrt{z\tau}$ and $r \gtrsim \lambda_D \ln(\lambda_D/a)$ can be written as [2,10,11]

$$\frac{e\phi(r)}{T_e} \simeq -\frac{1+2z\tau}{4(1+\tau)}\frac{a^2}{r^2}. \tag{3}$$

[Note that the dependence $\phi(r) \propto r^{-2}$ at large distances from the absorbing body in a plasma is well known from probe theories [10].] The potential energy of electrostatic interaction between two grains can then be written as

$$U_{el}(r) = Z_d e\phi(r). \tag{4}$$

B. Ion shadowing potential

Absorption of plasma on microparticles leads to a long-range attraction force: The absorption on one particle changes the plasma flux on the neighboring particle (making it anisotropic), and vice versa. This leads to an attractive drag force. (Note that electrons essentially do not contribute to this shadowing force, because their mass is much smaller than that of the ions.) The effective length of the ion shadowing interaction is determined by the mean free path of ions. The attractive force can be calculated as follows:

$$\mathbf{F}_i = m_i \int \mathbf{v} v \sigma_{id}(v) f_i(\mathbf{v}) d\mathbf{v}, \tag{5}$$

where σ_{id} represents the effective cross section of the ion-particle collisions. It consists of two parts: direct nonelastic collisions (ion collection by the particle surface) and elastic Coulomb scattering of ions in the particle field. Integrating with the OML collection cross section [2,11] and Coulomb scattering cross section [18] one gets the following result for the ion shadowing force:

$$F_i(r) = -\sqrt{\pi}(\chi_1 + \chi_2)\frac{n_i T_i a^4}{r^2}, \tag{6}$$

with

$$\chi_1 = 2\int_{y_1}^{\infty} (y^2 + z\tau)^2 \exp(-y^2) dy, \tag{7}$$

$$\chi_2 = z^2\tau^2 \int_{y_2}^{\infty} (1 + z\tau/y^2)\exp(-y^2)\ln\Lambda\, dy. \tag{8}$$

The lower limits of integration are

$$y_1 = a\sqrt{z\tau}/r, \tag{9}$$

$$y_2 = a\sqrt{z\tau}/\lambda_D, \tag{10}$$

and the argument of the logarithm in Eq. (8) is

$$\Lambda=\frac{4y^4\lambda_{\rm D}^2/a^2+z^2\tau^2}{(2y^2+z\tau)^2}. \tag{11}$$

The term χ_1 represents the contribution of the ion collection. The lower limit of integration in Eq. (7) represents the necessary condition $\sin\theta_*<1$. It implies that the approach (1) and (2) is valid (for the calculation of the ion shadowing) when the influence of y_1 is negligible in Eq. (7), i.e., when $y_1\ll 1$. This implies $r\gg a\sqrt{z\tau}$, and the resulting expression for χ_1 is

$$\chi_1\simeq\sqrt{\pi}(3/4+z\tau+z^2\tau^2). \tag{12}$$

[Note that the expression for the electrostatic potential (3) has the same limitation on r.] The term χ_2 represents elastic Coulomb scattering. In deriving Eq. (8) integration over the ion impact parameter was performed. The lower limit of integration was set equal to the maximum impact (collection) parameter for ion absorption, $b_{\rm c}(v)=a(1+2e|\phi_{\rm s}|/m_iv^2)^{1/2}$; for the upper limit the cutoff at $\lambda_{\rm D}$ was used. Then, after the final integration over the velocity distribution we get the limit (10). It is noteworthy that the lower limit of integration in Eq. (8) can never be set equal to zero, because $\Lambda<1$ [see Eq. (11)] and the Coulomb logarithm is negative for $0<y<y_2$.

Thus, the potential energy of interaction associated with the ion shadowing effect can be written finally as

$$U_i(r)=-\sqrt{\pi}(\chi_1+\chi_2)\frac{n_iT_ia^4}{r}. \tag{13}$$

The results obtained here differ from those in Refs. [2,19]: an additional factor $(1+z\tau/y^2)^{1/2}$ appears in the integral in Eq. (3.32) of Ref. [2] when calculating the shadowing force associated with direct ion bombardment (collection). Because of this factor the integral diverges logarithmically at $y\to 0$ (therefore, the integration starts from y_1 in [2]), and the resulting force is overestimated by $\sim\sqrt{z\tau}$. Lampe *et al.* [19] considered only the effect associated with ion collection. Their results [Eq. (A4)] are functionally identical to ours [Eq. (12) here]; the only difference is an additional numerical factor $3/(2\pi)$. We believe that this is due to a misprint in Ref. [19].

C. Neutral shadowing potential

The temperature of the particle surface is determined by the balance of various processes, such as radiative cooling, exchange of energy with neutral atoms and molecules, and recombination of electrons and ions on the surface. When the surface temperature is different from the temperature of the surrounding neutral gas there exists a net flux of energy and momentum between gas and particles. Hence, if two particles are located sufficiently close to each other (distance less than the mean free path of neutrals, $r\lesssim l_n$), an anisotropy in momentum fluxes on the particles will also exert a shadowing force between them as suggested by Tsytovich *et al.* [12]. Since l_n usually exceeds l_i, the kinetic approach can be used to calculate the neutral shadowing force at $r\ll l_i$. The result is [12]

$$F_n(r)=\frac{3\pi}{4}(\sqrt{T_{\rm s}/T_n}-1)\frac{n_nT_na^4}{r^2}, \tag{14}$$

where n_n and T_n are the neutral gas number density and temperature, respectively, and $T_{\rm s}$ is the particle surface temperature. If the surface temperature is smaller than the surrounding gas temperature the interaction is attractive; in the opposite case it is repulsive. Assuming $T_{\rm s}=T_n+\Delta T$ and $|\Delta T|\ll T_n$, the expression for the corresponding potential energy of interaction may be rewritten as

$$U_n(r)=\frac{3\pi}{8}\frac{n_n\Delta Ta^4}{r}. \tag{15}$$

Note that $U_n(r)$ and $U_i(r)$ have the same long-range scaling proportional to r^{-1}.

III. COMPARISON OF ION AND NEUTRAL SHADOWING

The ion shadowing is always attractive [see Eq. (13)], whereas the sign of the neutral shadowing (15) is determined by the difference of the particle surface temperature and the neutral gas temperature, ΔT. The value of ΔT depends on the competition of radiative cooling and plasma heating rate due to electron and ion recombination on the particle surface. For particular plasma parameters [20] the ratio $\Delta T/T$ was shown experimentally to be about $+0.2$, i.e., in this experiment the particle surface temperature was higher than the background gas temperature. A heat transfer model was proposed to interpret these results, but a few important parameters (such as particle emissivity and absorptivity) are only known within an order of magnitude.

It is useful to estimate the value of $|\Delta T|$ that is necessary for the neutral shadowing to exceed the ion shadowing. Since $U_{el}(r)\propto a^3/r^2$ and $U_i(r),U_n(r)\propto a^4/r$ [see Eqs. (3), (4), (13), and (15)], it is reasonable to consider the case of sufficiently large particles, when the shadowing interaction can be relatively strong compared to the electrostatic repulsion. Assuming $a\gtrsim\lambda_{\rm D}/\sqrt{z\tau}$ (note that typically $z\sim 1$–3, $\tau\sim 10^2$, and $\lambda_{\rm D}\simeq\lambda_{{\rm D}i}$), we have $y_2\gtrsim 1$ and thus the contribution from Coulomb elastic collisions to the ion shadowing effect can be neglected [see Eq. (8)]. Then from Eqs. (7), (12), (13), and (15) we get

$$|U_i(r)/U_n(r)|\simeq\frac{8}{3}\frac{n_iT_i}{n_nT_n}\frac{z^2\tau^2}{|\Delta T/T_n|}. \tag{16}$$

For $T_i\sim T_n$ the neutral shadowing dominates when

$$|\Delta T/T_n|\gtrsim\frac{8}{3}\alpha_iz^2\tau^2, \tag{17}$$

where $\alpha_i=n_i/n_n$ is the ionization fraction. In typical laboratory experiments the ionization fraction is very low, $\alpha_i\sim 10^{-6}$–10^{-7}. Therefore, neutral shadowing becomes more

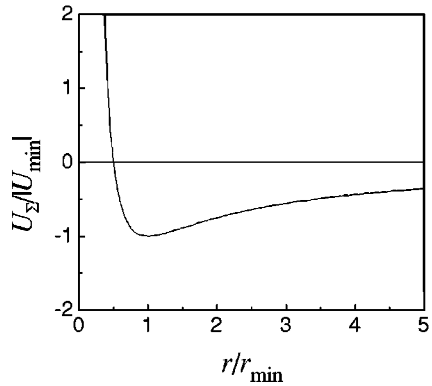

FIG. 2. Typical profile of potential energy U_Σ of the pair particle interaction including the shadowing attraction (normalized to the depth of the potential well $|U_{\max}|$), versus interparticle distance r (normalized to the position of the minimum $r_{\min}$). The interaction is attractive at large distances due to the shadowing interaction, $U_\Sigma \propto -r^{-1}$, and is repulsive at smaller distances due to electrostatic interaction, $U_\Sigma \propto r^{-2}$.

important than ion shadowing when the relative temperature difference is still quite small, $|\Delta T/T_n| \sim 3\times 10^{-3}$–$3\times 10^{-2}$. This shows that for the usual experimental conditions a temperature difference of a few degrees is sufficient for neutral shadowing to dominate.

IV. SHADOWING EFFECTS IN THE BULK PLASMA

In the bulk (isotropic) plasma the potential energy of a pair interaction is a combination of three effects: electrostatic repulsion and ion and neutral shadowing: $U_\Sigma(r) = U_{el}(r) + U_i(r) + U_n(r)$. For simplicity we restrict ourselves to consideration of two limiting cases: (i) $\Delta T = 0$ (ion shadowing dominates), and (ii) $\Delta T \neq 0$ with condition (17) satisfied (neutral shadowing dominates). In both cases the long-range interaction potential at $r \gg \lambda_{\mathrm{D}}$ can be written in the form

$$U_\Sigma(r) \simeq \frac{A}{r^2} + \frac{B}{r}. \tag{18}$$

(At smaller distances particles interact via a screened Coulomb potential with $\lambda_{\mathrm{D}} \simeq \lambda_{\mathrm{D}i}$.) Of most interest is the situation with $B<0$ [this is always satisfied in case (i), and is satisfied in case (ii) if $\Delta T<0$]. Then potential (18) exhibits attraction at large distances and repulsion at smaller distances. A typical profile of the resulting potential is shown in Fig. 2. The position of the potential minimum $r_{\min}$ (determined by the condition $\partial U_\Sigma/\partial r|_{r_{\min}}=0$) and the depth of the potential well $|U_{\min}| = |U(r_{\min})|$ can be directly related to the plasma parameters. From Eq. (18) we derive $r_{\min} = 2A/(-B)$ and $|U_{\min}| = B^2/4A$, where A is given by Eq. (4) and B by Eqs. (13) [case (i)] or (15) [case (ii)]. We can again substantially simplify the final results by considering sufficiently large particles, $a \gtrsim \lambda_{\mathrm{D}}/\sqrt{z\tau}$ (so that $\chi_2 \simeq 0$) and taking into account that $z\tau \gg 1$. Then the approximate expressions for A and B are

$$A \simeq \frac{1}{2} z|Z_d| T_e a^2, \tag{19}$$

$$B \simeq \begin{cases} -\pi z^2 \tau^2 n_i T_i a^4, & \text{case (i)} \\ \dfrac{3\pi}{8} n_n \Delta T a^4, & \text{case (ii)} \end{cases} \tag{20}$$

and the parameters of the potential well are

$$r_{\min} \simeq 4\frac{\lambda_{\mathrm{D}i}^2}{a},$$

$$|U_{\min}| \simeq \frac{1}{32} \frac{z\tau |Z_d| a^4}{\lambda_{\mathrm{D}i}^4} T_i, \quad \text{case (i)}, \tag{21}$$

$$r_{\min} \simeq \frac{8}{3\pi} \frac{z\tau T_n}{n_n |\Delta T| a^2},$$

$$|U_{\min}| \simeq \frac{9\pi^2}{128} \frac{(n_n a^3)^2}{z\tau |Z_d|} \frac{(\Delta T)^2}{T_n}, \quad \text{case (ii)}. \tag{22}$$

If $\Delta T>0$, then $U_\Sigma(r)$ is monotonic (repulsive) and expression (22) for $r_{\min}$ indicates the approximate distance where the repulsion due to neutral shadowing becomes stronger than electrostatic repulsion.

V. SHADOWING EFFECTS IN THE SHEATH REGION

In accordance with the experiments conducted so far [15,17] we restrict ourselves to the potential in the direction perpendicular to the ion flow. We also neglect effects of particle polarization [14] (which are more important for small distances and, e.g., particle agglomeration.)

In the sheath region ions are accelerated by a strong vertical electric field and their drift velocity is comparable to the ion acoustic velocity $c_s = \sqrt{T_e/m_i} \gg v_{T_i} = \sqrt{T_i/m_i}$. Therefore, ions do not participate very much in the screening of particle charge, and also the ion shadowing effect is weak. Consequently, the electrostatic interaction is then described in terms of a screened Coulomb potential with $\lambda_{\mathrm{D}} \sim \lambda_{\mathrm{D}e}$. The neutral shadowing potential is given by Eq. (15). If $\Delta T<0$ the neutral shadowing is attractive, and the parameters of the potential well are

$$r_{\min} \simeq \lambda_{\mathrm{D}e} \ln\left[\frac{Z_d^2 e^2}{n_n a^4 |\Delta T|}\right], \tag{23}$$

$$|U_{\min}| \sim \frac{n_n a^4}{\lambda_{\mathrm{D}e}} |\Delta T|.$$

For $\Delta T>0$, we get long-range repulsion. The distance at which the neutral shadowing dominates is determined by the approximate condition (23) for $r_{\min}$, as mentioned earlier.

Note that Eq. (15) for the neutral shadowing potential is valid for any $r \ll l_n$. Therefore we can evaluate the condition when the neutral shadowing (repulsive or attractive) dominates over the electrostatic interaction even at $r \lesssim \lambda_{\mathrm{D}e}$. For these distances, $U_{el}(r) \simeq e^2 Z_d^2/r$ and the condition is $|\Delta T| \gtrsim Z_d^2 e^2/(n_n a^4)$. This inequality is more easily satisfied for larger particles ($Z_d \propto a$ and thus the critical $|\Delta T|$ decreases with the particle size $\propto a^{-2}$). For instance, for $a \sim 10$ μm ($Z_d \sim 3\times 10^4$) and $n_n \sim 10^{15}$ cm^{-3} the necessary temperature difference is $|\Delta T| \gtrsim 3\times 10^{-2}$ eV, i.e., of the order of room temperature.

Recent ''collision'' experiments of Konopka *et al.* [17] show that experimental data on the horizontal particle interaction in the sheath can be fitted quite precisely to a screened Coulomb potential. Parameters of the experiments are $a = 4.5$ μm, $Z_d \simeq 1.5\times 10^4$, $T_n \simeq 3\times 10^{-2}$ eV, $n_n \simeq 7\times 10^{14}$ cm^{-3} ($p = 2.7$ Pa), and $\lambda_{\mathrm{D}e} \simeq 0.5$ mm. The potential was measured in the range $r \lesssim 3\lambda_{\mathrm{D}e}$. The result implies that neutral shadowing might be important only at $r \gtrsim 3\lambda_{\mathrm{D}e}$ for these conditions. Then the inequality $r_{\min} \gtrsim 3\lambda_{\mathrm{D}e}$ must be satisfied, i.e., the temperature difference should be sufficiently small. Using expression (23) for $r_{\min}$ we get $|\Delta T/T_n| \lesssim 0.3$ for this particular experiment, which seems to be reasonable.

VI. POSSIBLE FORMATION OF DUST MOLECULES

The existence of a long-range attraction, caused either by ion or neutral shadowing effects, makes the formation of a dust molecule possible (an association of two or more particles coupled by long-range attraction) [2]. Two necessary conditions are

$$|U_{\min}| \gtrsim T_d, \tag{24}$$

$$r_{\min} \lesssim \{l_i, l_n\}. \tag{25}$$

Condition (24) requires that the mean kinetic energy (temperature) of the particles T_d must be smaller than the depth of the potential well due to the shadowing effects. Since the effective range of the shadowing interaction is determined by the mean free path of ions l_i (when ion shadowing dominates) or neutrals, l_n (when neutral shadowing dominates), the minimum position of the potential well must satisfy condition (25) (otherwise, the potential well does not exist at all).

Massive micrograins are efficiently cooled by neutral gas. Therefore, it is usually assumed that the particle kinetic energy can be characterized by the neutral gas temperature $T_d \sim T_n \sim T_i$. However, there may also be ''anomalous'' particle heating (where the particle kinetic energy substantially exceeds the temperature of the neutrals and sometimes even the electron temperature), which was observed in many experiments in the plasma sheath [16,21,22]. Several theoretical interpretations of these observations have been proposed, e.g., energy supply by collective effects in the presence of supersonic ion flow [22–24], dependence of the particle charge on spatial coordinates [25], charge and plasma random fluctuations [26–28], etc. However, it is not yet clear if the anomalous heating exists only in strongly coupled systems, or if it works also for individual particles or pairs. Additional experimental and theoretical investigations are needed to study this phenomenon. It is also unknown if there are similar effects in the bulk plasma.

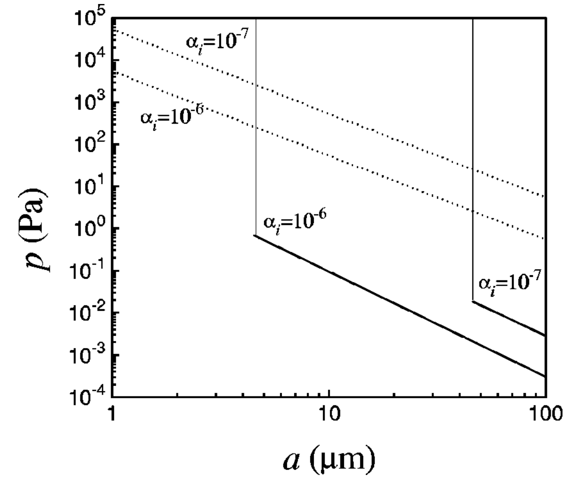

FIG. 3. Range of neutral gas (Ar) pressure p and microparticle radius a where dust molecule formation can be expected due to the ion shadowing effect. The results are presented for two values of the ionization fraction, $\alpha_i = 10^{-6}$ and $\alpha_i = 10^{-7}$. Other parameters: ratio of the electron-to-ion temperatures $\tau = 10^2$, dimensionless surface potential of a particle $z = 2.4$, and ion temperature $T_i = 3\times 10^{-2}$ eV. Vertical solid lines represent the condition $r_{\min} < l_i$ [Eq. (25)] while inclined solid lines denote the condition $|U_{\min}| > T_n$ [Eq. (24)]. For each value of α_i, dust molecule formation can be expected in the region to the right of the solid lines. The general limitation of the model applicability $a \ll \lambda_{\mathrm{D}i}$ (linear particle screening) is indicated by dotted lines.

With these uncertainties in mind, we use condition (24) with $T_d \sim T_n \sim T_i$ to investigate the possibility of dust molecule formation in the *bulk plasma*, and we treat it as a necessary condition rather than as a sufficient one. The parameters of the potential well, $|U_{\min}|$ and $r_{\min}$, are given by Eqs. (21) (ion shadowing) and (22) (neutral shadowing).

In order to obtain the plasma/particle parameter range where dust molecule formation is possible we introduce the ion (neutral) mean free path as $l_{i(n)}^{-1} \simeq \sigma_{in(nn)} n_n$. The following plasma parameters are used for the numerical results: Argon plasma with neutrals and ions at room temperature, $T_i = T_n \simeq 3\times 10^{-2}$ eV, electron-to-ion temperature ratio $\tau = 100$, $z \simeq 2.4$ (according to Fig. 1), and ion-neutral and neutral-neutral collision cross sections $\sigma_{in} \simeq 8\times 10^{-15}$ cm^2 and $\sigma_{nn} \simeq 4\times 10^{-15}$ cm^2, respectively.

The parameter range where one can expect formation of dust molecules due to ion shadowing (neutral shadowing is neglected) is shown in Fig. 3. The particle radius a and neutral gas pressure p are chosen as variable parameters while the value of the ionization fraction α_i is fixed (i.e., $n_i \propto p$). We present results for $\alpha_i = 10^{-6}$ and $\alpha_i = 10^{-7}$ which are typical for rf discharges. The vertical solid lines represent the condition $r_{\min} \lesssim l_i$ [Eq. (25)] which has the form $a > a_{\mathrm{cr}} \propto \alpha_i^{-1}$ ($a_{\mathrm{cr}} \simeq 5$ μm for $\alpha_i = 10^{-6}$ and $a_{\mathrm{cr}} \simeq 50$ μm for $\alpha_i = 10^{-7}$). The inclined solid lines represent the condition $|U_{\min}| \gtrsim T_d$ [Eq. (24)] rewritten in the form $p > \mathrm{const} \times \alpha_i^{-1} a^{-5/2}$ (where the value of the constant is determined by τ, z, and T_i). In the region to the right of the solid lines

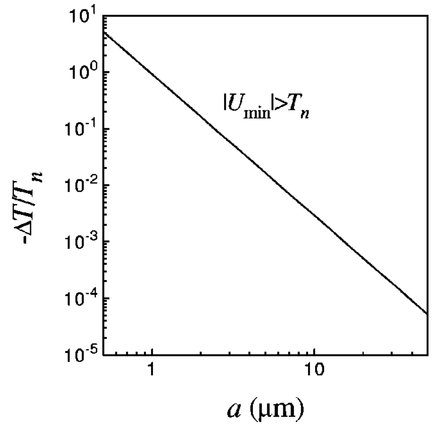

FIG. 4. Range of the temperature difference between the particle surface and the neutral gas (Ar), $\Delta T<0$, and the microparticle radius a where dust molecule formation can be expected due to the neutral shadowing effect. Other parameters: ratio of the electron-to-ion temperatures $\tau=10^2$, dimensionless surface potential of a particle $z=2.4$, and neutral gas temperature $T_n=3\times10^{-2}$ eV. The solid line shows the condition $|U_{\rm min}|>T_n$ [Eq. (24)] for a neutral gas pressure $p=5$ Pa. Dust molecule formation can be expected above this line, which scales as p^{-1}.

molecule formation might be expected. The dotted lines in Fig. 3 show the general limitation of the approach $a\ll\lambda_{\rm D}$ (linear particle screening), for each value of α_i. The condition $a\gtrsim\lambda_{\rm D}/\sqrt{z\tau}$, which allows us to neglect elastic ion scattering on the particles in the expression for the ion shadowing force, is well satisfied in the region where dust molecule formation can be expected (it is not shown here for clarity).

The parameter range where dust molecule formation is possible due to neutral shadowing is shown in Fig. 4. Here the difference of the particle surface temperature and the gas temperature, $\Delta T<0$, and the particle radius are chosen as variable parameters, and the neutral gas pressure is fixed ($p=5$ Pa). The solid line represents the condition $|U_{\rm min}|\gtrsim T_d$ [Eq. (24)] which in this case has the form $-\Delta T/T_n\gtrsim{\rm const}\times p^{-1}a^{-5/2}$ (the value of the constant is a function of τ, z, and T_i). The condition $r_{\rm min}\lesssim l_i$ [Eq. (25)] is not shown in Fig. 4 since it is much weaker in this range of a and ΔT (and it does not depend on p). Note that ΔT is not a fully independent parameter; its value can be dependent on many parameters like ion and neutral gas number densities, particle material properties, ion and neutral interaction properties with the particle surface, etc. Experimentally, it is not clear even if $\Delta T<0$ can be obtained in typical low-density gas discharge experiments. In accordance with condition (17) the neutral shadowing dominates over the ion shadowing when $|\Delta T/T_n|\gtrsim10^{-1}$ (for $\alpha_i=10^{-6}$) and $|\Delta T/T_n|\gtrsim10^{-2}$ (for $\alpha_i=10^{-7}$).

Our results show that in both cases (ion and neutral shadowing) rather large particles ($a\gtrsim10$ μm) are needed for dust molecule formation. In ground-based experiments, such particles cannot be levitated in isotropic plasmas (bulk or presheath regions of discharges), because the electric field is insufficient there to balance gravity. Perhaps this is one of the reason why associations of two (or more) particles in the absence of an external confinement have not been observed yet. Presumably, experiments under microgravity conditions will allow us to overcome this problem.

VII. SUMMARY

Long-range ($r\gg\lambda_{\rm D}$) interactions between small ($a\ll\lambda_{\rm D}$) charged particles in a plasma have been studied. Three effects were considered: long-range electrostatic repulsion caused by ion absorption on the particle surface, attraction due to ion shadowing, and neutral shadowing resulting in attraction or repulsion (depending on the sign of the temperature difference between the particle surface and neutral gas, ΔT). Analytical expressions for the resulting potential were obtained and compared with previous results.

Two situations were considered separately: (1) an isotropic bulk plasma where all three effects might be important and (2) the plasma sheath region where long-range electrostatic interaction as well as ion shadowing are absent. For both situations characteristics of the total interaction potential and the dependence of the effects on plasma/particle parameters were determined.

For the sheath region our model results were compared with recent measurements on the particle pair interaction. We showed that neutral shadowing is of minor importance for the plasma parameters used in these experiments. This is in agreement with the experimental results which revealed no noticeable deviation from the Coulomb screened potential up to distances of a few screening lengths [15,17].

For the bulk (isotropic) plasma the effects of ion and neutral shadowing were compared. It was shown that for typical gas discharge conditions a temperature difference ΔT of a few degrees is sufficient for the neutral shadowing to dominate over the ion shadowing. For an attractive shadowing interaction the conditions for possible dust molecule formation were studied, including experimental constraints and limitations. It was shown that relatively large particles ($a\gtrsim10$ μm) are needed to verify experimentally the possibility of such formation in the usual rf discharge conditions.

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