Effect of electrostatic plasma oscillations on the kinetic energy of a charged macroparticle

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The stochastic energy acquired by an isolated charged macroparticle ("dust" particle) due to electrostatic fluctuations of a weakly ionized plasma is investigated. Analytic relations are derived and numerical modeling of the problem for the conditions close to those of typical laboratory experiments in a complex dusty plasma is done. The study demonstrates that the kinetic energy of a dust particle, induced by the considered effect, can significantly exceed the temperature of the background gas. The most important contribution to the energy acquired by the macroparticle is due to the ion plasma component. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2167311]

I. INTRODUCTION

A dusty plasma is an ionized gas containing charged solid macroscopic (comparing to the sizes of atoms and molecules) particles (dust grains), typically of a micrometer size. This type of plasma is ubiquitous in nature (in space, such as in interstellar and interplanetary medium, in molecular dust clouds, in planetary atmospheres, and in the upper layers of the Earth's atmosphere) and often appears in a number of technological processes (such as in fuel burning, in plasma etching and deposition, and in nanotechnology).[1,2] The charged solid particles change the properties of ambient plasmas dramatically.[3] Complex plasmas behave unusually and tend to structure themselves; remarkably, the basic physics behind numerous self-organization phenomena ranging from nanotechnology to astrophysics is often the same and related to fundamental properties of complex plasmas as open dissipative systems.[2] Open systems need sources of energy to sustain themselves and they are self-organizing in order to adapt to (changing) conditions. The complex plasma exhibits a wealth of self-organization phenomena and appears as a good model to study various physical phenomena in systems of interacting particles that attract widespread interest in the physics of nonideal plasmas as well as in other areas such as plasma chemistry, physics, and chemistry of the Earth's atmosphere, astrophysics, and space physics.[1–3] Due to the openness of the complex plasma systems and because of intensive interactions with other plasma components, the behavior of macroparticles often reveals unusual counterintuitive phenomena, such as unexpectedly high values of the kinetic energy of the dust grains that characterizes the energy of their chaotic "thermal" energy and is neither in equilibrium with the surface temperature of the grains themselves nor with the kinetic temperature of the background (such as a weakly ionized gas).

The majority of experimental studies of complex dusty plasmas are done in a weakly ionized plasma of a gas discharge with the pressure P of the neutral (typically, noble) gas component within the range from 0.03 to 3 Torr when dissipation due to collisions with the gas atoms/molecules is significant.[4–7] Dust particles in a gas-discharge plasma are charged, mainly by plasma electron and ion currents; the net charge in this case can be significant, of order $10^2 - 10^4 e$, where e is the elementary charge.[8–12] These highly charged particles effectively interact with each other as well as with the background plasma and the electric fields. It was observed that the kinetic temperature of dust particles can significantly exceed not only their surface temperature [that itself can exceed the room temperature of the neutral gas background by more than 100 K (Ref. 13)] but also the kinetic temperature of the electron component (the latter is usually of 1–5 eV).[14–16] Possible reasons for these anomalously high dust kinetic temperatures include the space-time fluctuations of the dusty plasma parameters[15–20] (e.g., the macroparticle charges) as well as development of various plasma-dust instabilities in the electric fields of the gas-discharge chambers.[21–25]

In this paper, we consider the effect of electrostatic oscillations of a quasiequilibrium plasma on the kinetic temperature of an isolated dust particle. These oscillations appear as a consequence of the space separation of the plasma charges because of their thermal motions and lead to the time fluctuations of the plasma electric field $E(t)$, with the mean average $\langle E(t)^2\rangle \propto T_{\rm pl}$, where $T_{\rm pl}$ is the plasma temperature. The main physics of the influence of the electrostatic plasma oscillations on the kinetic energy of dust particles is that the electric field fluctuations induced by the stochastic motions of the electron/ion plasma component lead, in their turn, to fluctuations of the electric forces, $\sim F_E(t)=eZE(t)$, acting on the macroparticles (where $-eZ$ is the particle charge). This causes extra chaotic movements (in addition to the Brownian motion of the macroparticle due to its collisions with the neutral gas atoms) with the kinetic energy $T_{kd}\propto\langle Z^2E(t)^2\rangle$, which is nonzero even in the case when the stochastic charge fluctuations (because of the discrete character of charging plasma currents) are ignored, $Z(t)=\text{const}$.

II. ELECTROSTATIC PLASMA OSCILLATIONS AND THE KINETIC ENERGY OF A MACROPARTICLE

Consider electrostatic oscillations of an unmagnetized plasma due to its thermal fluctuations in the two limiting cases: (1) for Langmuir oscillations of electrons on the background of stationary ions, and (2) for electrostatic oscillations (with no dispersion) of the number density of cold single-charged ions on the adiabatic electron background (with the thermal electron motions). The last case takes place when the electron temperature significantly exceed the ion temperature, $T_e \gg T_i$. The field appearing because of the charge separation due to the thermal motion of plasma electrons and ions is determined by the Poisson equation

$$\nabla\cdot\mathbf{E} = -4\pi e(n_e - n_i), \tag{1}$$

where $n_{e(i)}$ is the electron (ion) number density and the (space) charge density, $q=e(n_i-n_e)$, according to the quasineutrality condition, is determined by the charge density of the perturbed component. For the cases analyzed here, the condition of the conservation of the electric charge is determined by the continuity equation for the considered perturbed plasma component,

$$\frac{\partial n_{e(i)}}{\partial t} = -\nabla\cdot(n_{e(i)}\mathbf{v}_{e(i)}), \tag{2}$$

where $\mathbf{v}_{e(i)}$ is the electron(ion) velocity. We perform the analysis of the motions of the considered plasma particles (electrons/ions) taking into account various processes leading to the establishing equilibrium temperature $T_{e(i)}$ such as their collisions with the neutral gas atoms (and other dissipative processes leading to the damping of the oscillations) described by the electron (ion) friction forces, $-\nu_e m_e\mathbf{v}_e$ and $-\nu_i m_i\mathbf{v}_i$, where $\nu_{e(i)}$ and $m_{e(i)}$ are the friction coefficient and the mass of plasma electrons (ions), and the stochastic forces $\widetilde{F}_e$ and $\widetilde{F}_i$ describing the random pushes of the neutral gas atoms as well as other possible stochastic processes. We have

$$\frac{\mathrm{d}m_e\mathbf{v}_e}{\mathrm{d}t} = -\nu_e m_e\mathbf{v}_e - e\mathbf{E} + \widetilde{\mathbf{F}}_e \tag{3a}$$

and

$$\frac{\mathrm{d}m_i\mathbf{v}_i}{\mathrm{d}t} = -\nu_i m_i\mathbf{v}_i + e\mathbf{E} + \widetilde{\mathbf{F}}_i. \tag{3b}$$

For the conditions of the local equilibrium of the considered dusty plasma system, the mean value of the stochastic force $\langle\widetilde{\mathbf{F}}_{e(i)}\rangle=0$, and the correlation function given by $\langle\widetilde{\mathbf{F}}_{e(i)}\times(0)\cdot\widetilde{\mathbf{F}}_{e(i)}(t)\rangle=6T_{e(i)}m_{e(i)}\ \nu_{e(i)}\delta(t)$ (Refs. 26 and 27) describes the δ-correlated Gaussian process (the angle brackets stand for the time average). Equations (3a) and (3b) are the Langevin equations with the forces $\mathbf{F}_{i(e)}=(\pm e\mathbf{E})$ uncorrelated with the stochastic forces, i.e., $\langle\widetilde{\mathbf{F}}_{e(i)}(t)\mathbf{F}_{i(e)}(t)\rangle=0$.

In a weakly ionized plasma, where collisions between plasma particles and the collisionless dissipation can be ignored, the introduced friction factors characterize mostly the effective friction frequency of the plasma particles with the neutral gas atoms/molecules ($\nu_e\cong\nu_{en}$ and $\nu_i\cong\nu_{in}$).[28] These collisions can lead to significant damping of plasma collective waves. We stress here that most of the plasma oscillations that appear as solutions in hydrodynamic approximation for the equations of motion of the plasma components cannot be realized in a weakly ionized plasma without additional energy sources compensating the dissipative losses of the kinetic energy of plasma particles.[29,30]

Solution of Eqs. (1), (2), and (3a) [or (3b), in the respective case] by assuming that the perturbations are small (linear approximation) give for the fluctuations of the plasma electric field $\mathbf{E}=\mathbf{E}(t)$ the following equation:

$$\frac{\mathrm{d}^2\mathbf{E}}{\mathrm{d}t^2} = -\nu_{pn}\frac{\mathrm{d}\mathbf{E}}{\mathrm{d}t} - \omega_p^2\mathbf{E} + \frac{4\pi e n_p\widetilde{F}_p}{m_p}, \tag{4}$$

where $\omega_p^2=4\pi e^2 n_p/m_p$ is the squared plasma frequency. In the first case of the high-frequency Langmuir oscillations, the field fluctuations are fully determined by the parameters of the electron plasma component ($\nu_{pn}=\nu_{en}$, $m_p=m_e$, $n_p=n_e$, $\widetilde{F}_p=\widetilde{F}_e$). In the second case (of the ions on the electron background) the electric field lower-frequency fluctuations are mostly determined by the ion characteristics ($\nu_{pn}=\nu_{in}$, $m_p=m_i$, $n_p=n_i$, $\widetilde{F}_p=\widetilde{F}_i$). It is not difficult to demonstrate that the distribution of the fluctuations $\mathbf{E}(t)$ follows the normal distribution law with the dispersion $\langle E^2\rangle=\langle\mathbf{E}(t)^2\rangle$. The value of the mean quadratic $\langle\mathbf{E}^2\rangle$ can be found by multiplying Eq. (4) by $\mathbf{E}$, with subsequent averaging. After some algebra, taking into account that in the stationary state $\mathrm{d}^2\langle\mathbf{E}^2\rangle/\mathrm{d}t^2=\mathrm{d}\langle\mathbf{E}^2\rangle/\mathrm{d}t=0$, $\langle(\partial\mathbf{E}/\partial t)^2\rangle=(n_p\mathbf{V}_p)^2$, $\langle V_p^2\rangle=3T_p/m_p$, where $\mathbf{V}_p=\mathbf{V}_{e(i)}$ and $T_p=T_{e(i)}$, we obtain

$$e^2\langle E^2\rangle = 3\omega_p^2 m_p T_p. \tag{5}$$

The equation of motion of a dust particle (macroparticle) with the mass M and the charge eZ in the fluctuating plasma field $\mathbf{E}(t)$ is given by

$$\frac{\mathrm{d}\mathbf{V}}{\mathrm{d}t} = -\nu_{\mathrm{fr}}\mathbf{V} + \frac{eZ}{M}\mathbf{E}, \tag{6}$$

where $\mathbf{V}$ is the velocity of the dust particle, ν_{fr} is the effective friction of the particle with the ambient plasma, and the Langevin forces acting on the dust particle from the neutral gas atoms are omitted for simplicity. By assuming that the macroparticle does not affect the thermal plasma fluctuations, its kinetic temperature $T_d=M\langle V^2\rangle/3$ can be found from Eqs. (4)–(6). It is given by

$$T_d = \frac{Z^2 m_p \omega_p^2 T_p(\nu_{\rm fr}+\nu_{pn})}{M\nu_{\rm fr}[\nu_{\rm fr}(\nu_{\rm fr}+\nu_{pn})+\omega_p^2]}. \quad (7)$$

When $\nu_{pn} \gg \nu_{\rm fr}$ and $\omega_p \gg \nu_{\rm fr}$, this equation can be written in the simpler form:

$$T_d = \frac{Z^2 m_p T_p \nu_{pn}}{M\nu_{\rm fr}}, \quad (8)$$

where $T_p m_p \nu_{pn} = T_{e(i)} m_{e(i)} \nu_{e(i)n}$ depending on the type of electrostatic plasma oscillations.

The dust temperature estimated using Eq. (8) can be also obtained from another approach proposed in Ref. 18. In that approach, which was for one degree of freedom, electric field fluctuations $\delta E = \delta E(t)$ with a correlation time τ_c relation result in a dust temperature $T_d \approx Z^2 e^2 \tau_c \langle \delta E^2 \rangle / (M\nu_{\rm fr})$. This is comparable to the prediction of Eq. (8), taking into account that the value of τ_c corresponding to a relaxation time of the space-charge density is $\tau_c \approx \nu_{\rm fr}/\omega_p^2$,[28] and that $e^2\langle \delta E^2 \rangle = \omega_p^2 m_p T_p$ [see Eq. (5)].

Recall that in the numerical simulation runs we can easily establish which plasma component (electron or ion) mostly affects the energy gaining by the macroparticle. To establish that, it is sufficient to consider a particle, levitating in a trap (such as the electrostatic trap with the electric field gradient α). For simplicity, we assume that the electric field of the trap does not affect the plasma particles (electrons and ions). This allows us to determine the eigenfrequency ω_p of the oscillations by analyzing the resonance curve. Indeed, the one-dimensional equation of motion in the field of this electrostatic trap can be written as

$$\frac{d^2x}{dt^2} = -\nu_{\rm fr}\frac{dx}{dt} - \frac{eZ\alpha}{M}x + \frac{eZ}{M}E_x. \quad (9)$$

The solution of Eqs. (4), (5), and (9) gives the kinetic energy of the macroparticle

$$T_d(\gamma) = \frac{Z^2 m_p T_p(\nu_{\rm fr}+\nu_{pn})}{M\nu_{\rm fr}\{(\gamma-1)[\gamma-1+\nu_{pn}(\nu_{\rm fr}+\nu_{pn})/\omega_p^2]+(\nu_{\rm fr}+\nu_{pn})^2/\omega_p^2\}}, \quad (10)$$

where $\gamma = (eZ\alpha/M)/\omega_p^2$. Equation (10) shows the possibility of the resonant heating of the macroparticle when $\gamma \to 1$ and $(\nu_p+\nu_{\rm fr})^2 < \omega_p^2$, and can be used to determine the characteristic frequency ω_p of the fluctuations of the electrostatic plasma field in the numerical simulation. The method suggested here for determining the characteristic frequency ω_p cannot be used for real laboratory experiments because of the extreme disparity of frequencies. The value of $\omega_p \sim 1-10^2$ MHz is orders of magnitude higher than the characteristic resonance frequencies of dust particles, such as the dust plasma frequency for disordered dusty plasmas, the Einstein frequency for a plasma crystal, and/or the resonant frequency for a single dust particle trapped in a millimeter-sized potential well in either the vertical or horizontal directions. (The resonant frequency $\{eZ\alpha/M\}^{1/2}$ is $\sim$10–100 Hz in typical experiments). Finally, we note that when $\gamma \ll 1$, Eq. (10) transforms into Eq. (7).

III. NUMERICAL SIMULATIONS

Simulation runs were done for the conditions close to those of a typical laboratory experiment in a gas-discharge dusty plasma where the plasma is weakly ionized and $T_i/T_e \ll 1$. A macroparticle with mass M, radius R, and fixed charge $Q = -eZ$ was confined in the center of the cubic simulation box with length $2L$ by the linear electrostatic field with gradient $\alpha = 4\pi en$, where n is the average number density of the plasma, $n = N_e/(2L)^3 = N_i/(2L)^3$, and $N_e = N_i$ is the number of electrons/ions in the simulation cell. The field of the trap did not affect the plasma electrons and ions. The macroparticle's equation of motion (9) was solved for the three degrees of freedom, and the field $\mathbf{E} = (E_x, E_y, E_z)$ was determined taking into account the effect of plasma electrons and ions. For the latter (i.e., for the plasma electrons and ions), the Langevin equations of motion were solved taking into account the electric field of the charge macroparticle acting on plasma particles as well as the plasma particle interactions (electron-electron, electron-ion, and ion-ion). The plasma particles that appeared beyond the simulation box as well as those absorbed by the macroparticle were substituted at a random position with a random velocity corresponding to their kinetic temperature.

We have considered argon as a neutral gas, with gas pressure $P = 0.3; 1; 3$, 10 Torr. The effective collision frequencies v_{in} (v_{en}) of the ions (electrons) with the neutral gas atoms were proportional to P and were taken as $v_{in} = 8 \times 10^6$ s^{-1} ($v_{en} = 5.3 \times 10^9$ s^{-1}) for $P = 1$ Torr. Simulations were done for $|Z| = 10; 100; 1000$, $R = 0.1$, 0.3, 1, 3 μm, $T_i/T_e = 0.01-0.1$, $\nu_{\rm fr} = \nu_{in}/100$, and $M = (100-10\,000)m_i$. The physical scale of the (cubic) simulation box was changed from $\sim 1.5\lambda_{Di}$ to $\sim 15\lambda_{Di}$ by varying the number of plasma particles $N = 15\,000-150\,000$; their number density was $n \sim 10^9-10^{12}$ cm^{-3} and the ion temperature was $T_i = 30-300$ K. [Here $\lambda_{Di} = (T_i/4\pi e^2 n_i)^{1/2}$ is the ion Debye length.] The time step of the integration was taken as $\Delta t = [50 \times \max(v_{en}, \omega_e)]^{-1}$. The simulation was done until the macroparticle's kinetic temperature achieves a stationary value; typically, the run time was $\sim 5-10/\nu_{\rm fr}$.

We note that the time necessary to achieve a stationary temperature (the "heating" time) is determined by the macroparticle's mobility $\propto Z/(M\nu_{\rm fr})$. Since the mobility of particles with the parameters close to those in real dusty plasma experiments is a few orders of magnitude less, the choice of these parameters significantly increases the simulation time. By keeping other parameters of the simulations unchanged, the increase of the particle mass from $100m_i$ to $1000m_i$ has lead to the corresponding (proportional) decrease of the acquired (by the particle) temperature. Thus we can assume that a further increase of the particle mass does not affect the simulation results. Nevertheless, the real macroparticle sizes that (together with the particle charge) determine the cross section of absorption of plasma particles can affect the simulation results. To check this hypothesis, we have done numerical simulations for various macroparticle sizes under conditions $R \ll \lambda_{Di}$ and $R \ll n^{-1/3}$. The simulations have demonstrated that in this case the temperature T^{cal} determined in the simulation runs was not depending on the macroparticle's radius R.

The shorter simulation run time can be also achieved by decreasing the number of plasma particles N, e.g., by decreasing the plasma number density, as well as by decreasing the ion temperature. On the other hand, the use of nontypical (for common laboratory experiments) temperatures and number densities allows us to investigate the effects of these parameters on the simulation results. For example, results of our simulations demonstrated that the decrease of the ion temperature leads to the proportional decrease of the kinetic energy acquired by a macroparticle.

Here, we would like to remark on the modeling conditions for the problem. A self-consistent solution of the problem (e.g., taking into account the actual size of the macroparticle as well as its charging) does not impose an additional numerical difficulty, but it needs a significantly longer simulation time. Our choice of a fixed charge $Z(t)=\mathrm{const}$ of the macroparticle is made with the aim to avoid the effect of the charge fluctuations and elucidate the effect of the electrostatic plasma field fluctuations on the acquired kinetic energy T_d. Since the macroparticle is placed in the electrostatic field of the trap, its displacement Δr relative to the center of the cell causes the additional stochastic force $F_{\mathrm{st}} \propto Z(t)\alpha\Delta r$ that in turn can lead to an increase of the macroparticle's kinetic temperature.[18–20] The placement of the macroparticle in the electrostatic trap was done for two reasons: first, to determine the eigenfrequency of the oscillations of the plasma that is around the macroparticle and, second, to keep the macroparticle in the center of the simulation box during the simulation runs since without the trap the macroparticle, because of the acquiring kinetic thermal energy, leaves the simulation region quite fast.

To determine the plasma eigenfrequency ω_p in the numerical simulation, we varied the values of $Z\alpha/M$ and ν_{in} (see Fig. 1). As a result, we have obtained that $\omega_p^2 \approx 8\pi e^2 n/(3m_i)$. When $\gamma \ll 1$, the temperature T^{cal} acquired by the macroparticle depends on the ratio L/λ_{Di} and changes proportionally to $T^{\mathrm{app}}=T_d$ given by Eq. (8), with the parameters of the ion plasma component, i.e.,

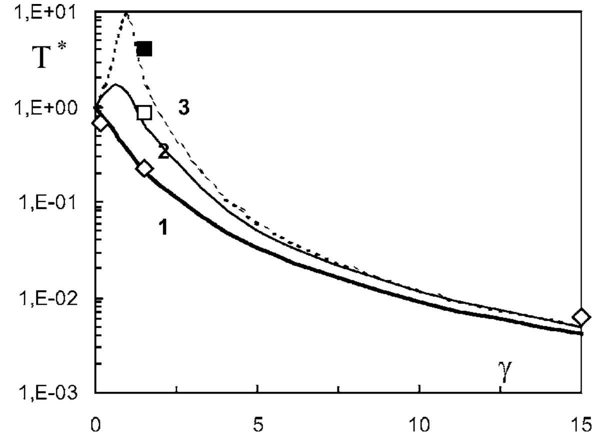

FIG. 1. The dependence of the relative macroparticle's temperature $T^* = T_d(\gamma)/T_d(0)$ on the parameter $\gamma = 1.5(eZ\alpha/M)/\omega_i^2$ for various values of ν_{in}^2/ω_i^2: **1** (◇) 1.92; **2** (□) 0.48; **3** (■) 0.077. The lines correspond to the values of T^* obtained from Eqs. (7) and (10) the figures represent the results of the simulation.

$$T^{\mathrm{app}} = \frac{Z^2 m_i T_i \nu_{in}}{M \nu_{\mathrm{fr}}}. \qquad (11)$$

With the increase of $\beta = L/\lambda_{Di}$, the numerically determined value T^{cal} increases and for $\beta > 10$ approaches T^{app} (i.e., $T^{\mathrm{cal}} \to T^{\mathrm{app}}$). The illustration of the time evolution of the heating of the macroparticle in the simulation cell is presented in Fig. 2 for $L/\lambda_{Di} \approx 15$ and various other parameters.

Thus the dust macroparticle in a plasma can acquire an additional thermal energy that is the stochastic kinetic energy T_d. The value of T_d is determined by the fluctuations of the electric field caused by the thermal motion of plasma ions. If to consider the conditions of typical laboratory experiments in a gas-discharge plasma (such as argon discharge) and write the coefficient for the friction of the macroparticle in the free-molecular approximation [ν_{fr} (s^{-1}) ≈ 1040 P (Torr)/R (μm) ρ (g cm^{-3}), where ρ is the mass density of dust particles][30] and the macroparticle's charge in the orbit-motion-limited (OML) approximation [Z

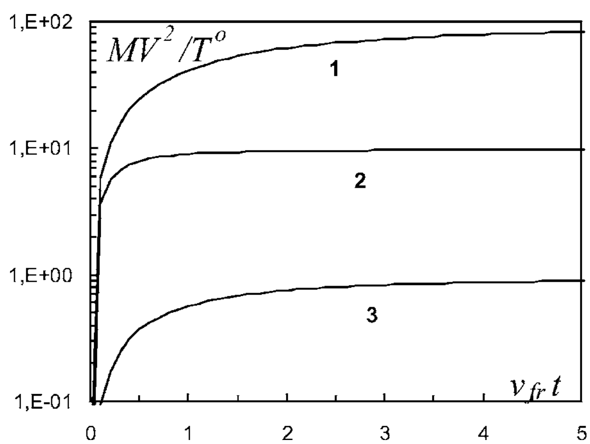

FIG. 2. The dependence of the ratio of MV^2 to the value $T^0 = 300\ T_i$ on time (in the units of the inverse friction time $\nu_{\mathrm{fr}} t$) for (1) $M = 10^4 m_i$, $Z = 10^3$, (2) $M = 10^3 m_i$, $Z = 10^2$, (3) $M = 10^2 m_i$, $Z = 10$. Here, $V^2 = \langle V_x^2 + V_y^2 + V_z^2 \rangle$ is the macroparticle's velocity averaged over the simulation run time t.

$\approx|2100R\ (\mu\text{m})\ T_e\ (\text{eV})|]$,[31,32] then, taking into account $v_{in}\ (\text{s}^{-1})=8\times10^6\ P$ (Torr), the acquired kinetic temperature can be estimated as

$$T^{\text{app}}\approx 0.5[T_e(\text{eV})]^2T_i. \tag{12}$$

Thus for the approximations used, the value of T^{app} does not depend either on the macroparticle's mass or the neutral gas pressure. For the electron temperature of $\sim$3–5 eV and the room ion temperature of $\sim$0.026 eV, the kinetic energy of the macroparticle can achieve $\sim$0.14–0.34 eV due to the electrostatic fluctuations of the ambient plasma; this is approximately one order of magnitude higher than the room temperature T_r of the plasma ions/neutral gas atoms.

We note that for the conditions of a typical laboratory experiment with a dusty plasma, collisions of plasma ions with the neutral gas atoms can significantly decrease the charge on a macroparticle (by as much as an order of magnitude) as compared to that determined by OML.[33] Since $T^{\text{app}}\propto Z^2$, this in turn can lead to significant decrease of the kinetic energy acquired ($T^{\text{app}}\ll T_r$). We also note that the estimates presented here are for a weakly ionized plasma, where the primary energy loss for charged particle motion is due to friction on gas neutrals. For noble gases this takes place only if the ionization factor is significantly below 1%.[28]

IV. CONCLUSIONS

To conclude, we have presented here the analytic relations for the stochastic energy that is acquired by an isolated solid macroparticle in a weakly ionized plasma because of the thermal electrostatic plasma fluctuations. The fluctuations can be related to the Langmuir plasma mode as well as to the electrostatic (cold) ion mode. The derived expressions allowed us to estimate the minimum value of the kinetic temperature of the macroparticle in a quasiequilibrium plasma for the conditions where there are no plasma-dust instabilities and no propagated plasma waves.

Numerical simulations have demonstrated that for the quasiequilibrium conditions of laboratory experiments in a gas-discharge complex plasma (when, in particular, $T_i/T_e\ll 1$), the most significant contribution to the energy acquired by the macroparticle comes from the plasma fluctuations associated with the ion component. The kinetic temperature of the macroparticle acquired in this way can significantly exceed the room temperature of the background gas/plasma ions. Thus the considered phenomenon is the source (which can be auxiliary to other possible mechanisms such as the stochastic fluctuations of the dust particle charges) of the dust particle "heating" that can significantly affect the kinetic temperature of macroparticles as well as the development of various plasma-dust instabilities in a laboratory plasma.

Although the simulations were done for an isolated particle, these results also can be useful for the analysis of extended plasma-dust structures (consisting of many macroparticles) if the mean interparticle distance significantly exceeds the ion Debye length. We note that this is the case for most of the laboratory experiments.

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