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STATISTICAL, NONLINEAR,
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Charge and Structures of Dust Particles in a Gas Discharge at Cryogenic Temperatures

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Abstract—A dusty plasma in a dc gas discharge is considered at low (cryogenic) temperatures of the gas. The formation of dusty plasma structures consisting of monodisperse poly(styrene) particles ($d = 5.44$ μm) in a dc glow discharge is experimentally investigated at cryogenic temperatures in the range from 4.2 to 77 K, and the results obtained are presented. The ion velocity distribution function and the charging of dust particles at cryogenic temperatures are calculated using the molecular dynamics method. The primary attention is focused on the correct inclusion of ion–atom collisions in the analysis. This is essential to the understanding of the main mechanisms of the experimentally observed increase in the density of dust particles with decreasing temperature of the gas in the discharge.

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1. INTRODUCTION

In recent years, plasma with macroparticles, or dusty plasma, has been the subject of extensive investigations [1]. Experiments have revealed various dusty plasma structures in which the observed ordering has been attributed to the Coulomb interaction. This work is devoted to the investigation of a dusty plasma in a dc gas discharge under the conditions where the walls of a gas-discharge tube are cooled to cryogenic temperatures. The experimental results have demonstrated that cooling of the walls of the gas-discharge tube to cryogenic temperatures leads to a radical change in the properties of the glow-discharge plasma.

The experiments performed with a glow-discharge plasma in helium at temperatures of atoms below 100 K have revealed that the specific features of this plasma become more pronounced with decreasing temperature [2]. At a temperature of 77 K in the range of low electric currents and weak reduced electric fields, the dependence of the electric current on the voltage is changed so that the field strength increases with an increase in the current. This portion of the current–voltage curve, which is referred to as the *H–T* transition, is inherent only in cryogenic plasmas. The *H–T* transition is accompanied by an increase in the intensity of the He_2^+ molecular bands, a change in the probe characteristics, and a variation in the character of the electric field inhomogeneity along the length of the positive column; more specifically, the electric filed is enhanced in the vicinity of the anode. This type of discharge was studied in a number of works [3, 4], in which it was established that the discharge under consideration is associated with the kinetic processes occurring with the participation of metastable states of helium. However, on the whole, the observed state of the cryogenic plasma has defied satisfactory explanation.

A decrease in the temperature of atoms leads to an increase in the fraction of three-body collisions and, as a consequence, can bring about a change in the molecular composition, i.e., the formation of molecular ions. Unfortunately, the kinetics of molecular ions in cryogenic discharges is still not clearly understood and too complicated to be studied by means of numerical simulations.

The mean free path of ions in experiments with a dusty plasma, as a rule, considerably exceeds the characteristic sizes of the problem (for example, the dust particle size and the screening length). Therefore, the use of the model of collisionless plasma is quite justified in the determination of many characteristics of macroparticles in the plasma. However, in recent studies [5–11], it has been noted that even rare collisions of ions can substantially change the characteristics of the screening and charging of dust particles. Since the ion–atom collision cross sections increase with a decrease in the collision energy, the decrease in the temperature of atoms leads to an enhancement of the influence of ion–atom collisions on many characteristics of the dusty plasma. In particular, this enhancement manifests itself in a drastic change in the ion velocity distribution, an increase in the ion current per dust particle, and a growth of the cloud of bound ions around the dust particle. Moreover, the collisions caused by the resonant charge exchange of ions with atoms of the parent gas can also affect the force of the interaction with the ion flow (there arises an effective reactive force accelerating the particle in the direction opposite to the flow) [11]. These collisions also lead to an additional repulsion of dust particles (there arise an effective recombination force) [11]. It is reasonable to begin the analysis of the influence of the decrease in the temperature of the neutral plasma component on the dusty plasma with the study of the influence on the characteristics of the gas discharge, such as the ion velocity distribution function and the spatial distributions of the field and the concentrations of electrons, ions, and atoms.

The first experiments with cooling of a gas-discharge dusty plasma to 77 K were performed by Fortov et al. [12]. These experiments revealed the possibility of forming considerably denser dust structures in the cryogenic plasma as compared to those observed in the discharge at room temperature. In [12], the authors put forward the assumption that the ion Debye length substantially decreases in the cryogenic plasma; furthermore, this phenomenon, in the authors' opinion, is the main factor responsible for the observed approach of dust particles to one another.

This paper reports on the results obtained from the experiments on the generation of dusty plasma structures in a dc glow discharge at cryogenic temperatures in the range from 4.2 to 77 K. The effect of cooling of the neutral component of the gas-discharge plasma on the increase in the density of dusty plasma structures was justified theoretically by analyzing the kinetics of ions in the cryogenic gas discharge. The dependences of the dust particle charge on the gas temperature and the density of the dusty plasma component were calculated using the molecular dynamics method.

2. RESULTS OF THE EXPERIMENTAL INVESTIGATIONS

The experiments were performed with a dc glow discharge generated in a vertical glass tube placed inside a cryostat designed in the form of a cylindrical system consisting of two glass Dewar vessels. The outer Dewar vessel served as a heat shield and was filled with liquid nitrogen. The glass discharge tube 1.2 cm in diameter with an interelectrode spacing of 40 cm was located in the inner Dewar vessel under the cover of the cryostat. The upper electrode was a hollow cylindrical anode through which dust particles were injected into the discharge. Dust particles were stored in a container with a perforated bottom and positioned above the anode. The discharge was generated in helium at pressures of the order of 1 Torr (hereafter, the density of the neutral component will be given in terms of a pressure at room temperature) and at discharge currents of the order of 0.1 mA.

The scheme of the experimental measurements was described in detail in our previous papers [13, 14], in which we also reported the results of the first experimental observations at temperatures of 77.0 and 4.2 K. An additional improvement used in the present work is the possibility of continuously varying and controlling the temperature conditions. The blowing of liquid-helium vapors through the inner Dewar vessel made it possible to controllably change the temperature of the walls of the gas-discharge tube in the range from 4.2 to 77.0 K. The temperature was controlled using a silicon sensor mounted on the outer surface of the wall of the gas-discharge tube near the region of the generation of dusty plasma structures. The temperature sensor was thermally insulated from the outer cooling medium and could measure the temperature of the discharge tube wall with an accuracy of no worse than 1–2 K.

The dusty plasma structures were formed with the use of monodisperse poly(styrene) spheres 5.44 ± 0.09 μm in diameter. In order to illuminate the dust particles, radiation from a diode-pumped solid-state laser with the wavelength $\lambda = 532$ nm was introduced into the cryostat through an optical fiber. The observations were performed through 1-cm-wide windows in the Dewar vessels with a CCD video camera at a rate of 25 frames per second. In order to generate stable striations over a wide range of parameters, the discharge was locally constricted with the use of an additional glass cylinder located in the lower part of the discharge tube. In the upper part, the cylinder narrowed to a capillary with an inner diameter of 0.1 cm. The results of the experiments demonstrated that, both in the discharge at room temperature and in the cryogenic discharge, the dusty plasma structures were formed in the stationary striations generated above the capillary. The observations were carried out in the first striation over the capillary.

In the experiments performed at room temperature, we observed the formation of anisotropic crystalline dust structures, which are typical of dc glow discharges and have a preferred direction along the axis of the discharge (see [15]). The dust particles in this case are ordered in the vertical direction, thus forming thread-like aggregates (dust chains) containing from two to ten particles. The number of chains can vary from several units to several tens, and the total number of particles usually does not exceed 10^2. Figure 1a shows a similar structure formed at the discharge current $i = 0.5$ mA and the gas pressure $p = 2$ Torr. The interparticle distance l_p for these parameters is equal to 500–750 μm [13, 14].

Upon changing over to cryogenic temperatures, both the pattern of the dust structure and the dynamics of dust particles in it become different. At a temperature of 77 K (Fig. 1b), we observed the formation of large-scale dusty plasma structures (with sizes of the order of 10^3 particles) made up of long chains (containing 15–20 particles). The interparticle distance in the chains amounted to 200–250 μm [13, 14]. This circumstance

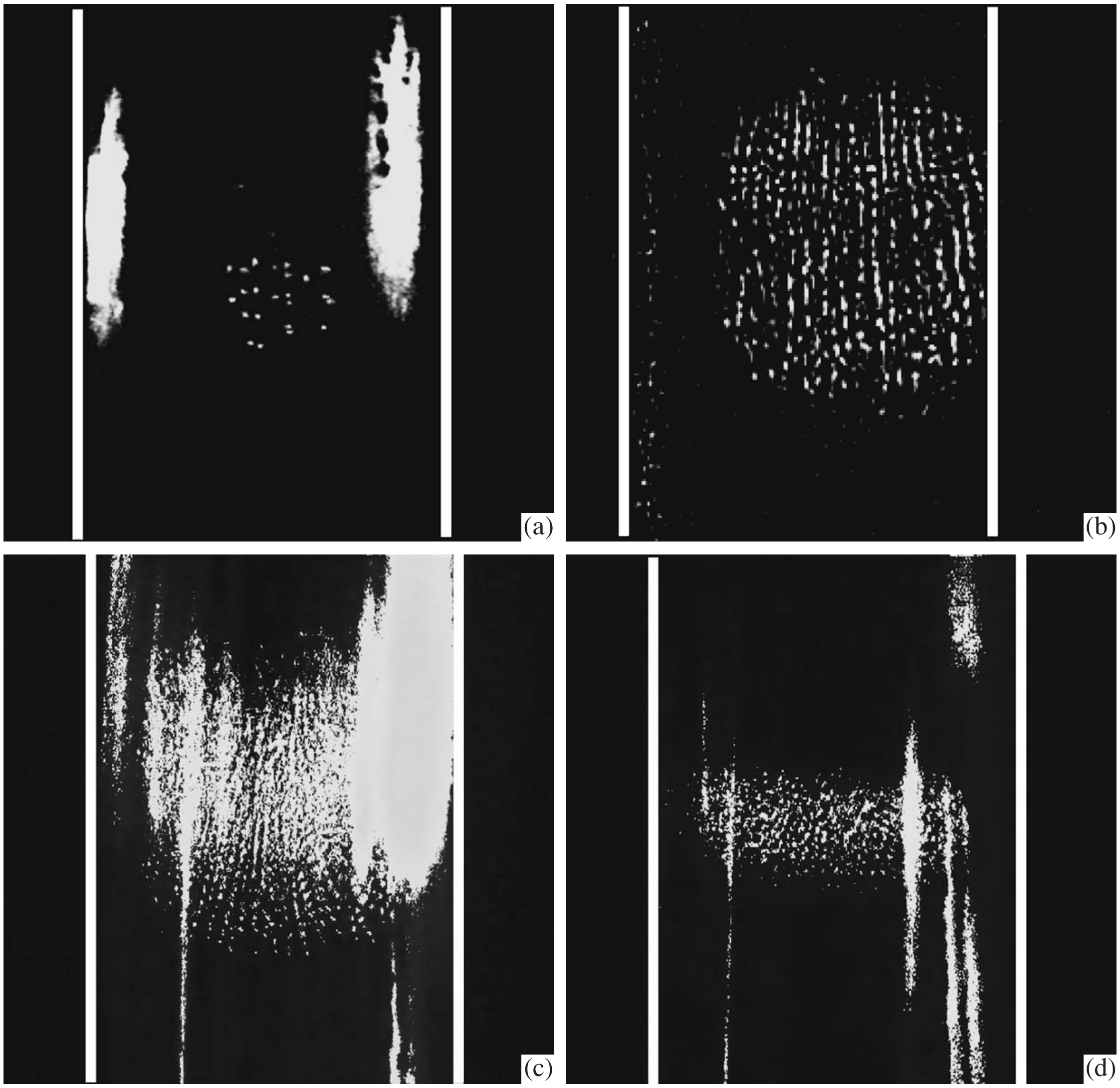

Fig. 1. Dusty plasma structures at cryogenic temperatures (side view): (a) room temperature, $i = 0.8$ mA, and $p = 2$ Torr; (b) 77 K, $i = 0.5$ mA, and $p = 2$ Torr; (c) 50 K, $i = 0.5$ mA, and $p = 5$ Torr; and (d) 25 K, $i = 0.2$ mA, and $p = 5$ Torr. Vertical straight lines indicate the boundaries of the observation region (the region width is approximately 4–6 mm). Spots and vertical bands are spurious reflections of laser radiation from the walls of the gas-discharge tube.

indicates that, compared to the density of dust structures at room temperature, the density of the dust structure at 77 K increases by at least one order of magnitude at the same values of the density of the neutral gas and the discharge current.

A further continuous cooling of the discharge is accompanied by a further decrease in the interparticle distances in the dust structure, a transformation of the pattern of the dust structure, and a change in the dynamics of dust particles in it. At temperatures in the range from 30 to 50 K (Fig. 1c), the interparticle distances decrease to 120–160 μm and the dust structure occupies the entire volume of the striation head. In this case, the dust structure consists of a complex aggregate involving regions of crystalline ordering and convective motions. The chain ordering of dust particles is retained only in the lower part of the structure, and the orientation of the chains is changed in such a way that the larger is the distance between the chain and the axis of the discharge, the greater is the tilt of the chain with respect to the vertical axis (the discharge axis). Upon cooling of the discharge, the interparticle distances decrease until the discharge becomes unstable. The development of discharge instabilities at the aforementioned discharge current prevents the confinement of dust particles in the discharge, and they are deposited on the bottom of the discharge tube. At temperatures below 30 K, the observations of particles were performed after the discharge current was decreased to 0.2 mA, when the discharge was stabilized. The structures formed under these conditions are characterized by a liquid-like behavior. Figure 1d displays the dust structure observed at a temperature of 25 K with a vortex motion, which is similar to dust vortices formed at room temperature [16, 17]. An increase in the density of the dusty plasma structures is observed until the helium is completely condensed in the Dewar vessel, i.e., when the cooling helium vapors transform into the liquid state (4.2 K). Note that, in this case, the conditions of observation of dust particles are substantially deteriorated (the measurement of interparticle distances is strongly complicated). The distances between the dust particles at a temperature of 4.2 K do not exceed 30 μm [13, 14].

Despite the large errors in the measurements due to the difficulties associated with the observation of dust structures through the windows of the cryostat and the difference in the densities of the neutral plasma component at different gas temperatures (5 Torr at temperatures of 4.2–50.0 K and 2 Torr at temperatures of 77 and 300 K), the experimental results obtained provide a qualitatively correct pattern of the variation in the density of the dusty plasma structures during cooling of the discharge to low (cryogenic) temperatures. The data presented in Fig. 2 demonstrate a strong nonlinear dependence of the interparticle distance l_p in the dusty plasma structures on the temperature T of neutral atoms. An analysis of the mechanisms of the phenomena under consideration should include a thorough examination of the transformation of the ion velocity distribution function at low temperatures of the gas atoms with the proper allowance made for the ion–atom collisions.

3. DEPENDENCE OF THE DUST PARTICLE CHARGE ON THE GAS TEMPERATURE AND THE DENSITY OF THE DUST COMPONENT

3.1. Dependence of the Characteristics of the Ion Flow on the Gas Temperature

A decrease in the gas temperature can lead to a considerable deviation of the ion velocity distribution function obtained at low temperatures of the gas atoms from an equilibrium distribution. In this respect, the determination of the ion velocity distribution function is one of the most important problems in an analysis of the experimental data on the properties of dust structures [11].

In order to evaluate the influence of ion collisions on the characteristics of the ion flow in a dc discharge in helium at cryogenic temperatures, we carried out the calculations by means of the Monte Carlo method. The results of these calculations have demonstrated that, under the conditions of the experiments performed, the effective temperature of ions varies insignificantly with a decrease in the temperature of the gas due to the heating of the ions in a strong electric field of the discharge. This implies that cooling of the neutral component of the gas discharge does not lead to a considerable cooling of the ions and the corresponding substantial decrease in the ion Debye length. Therefore, the experimentally observed decrease in the interparticle distance (see Fig. 1) cannot be explained by the decrease in the ion temperature.

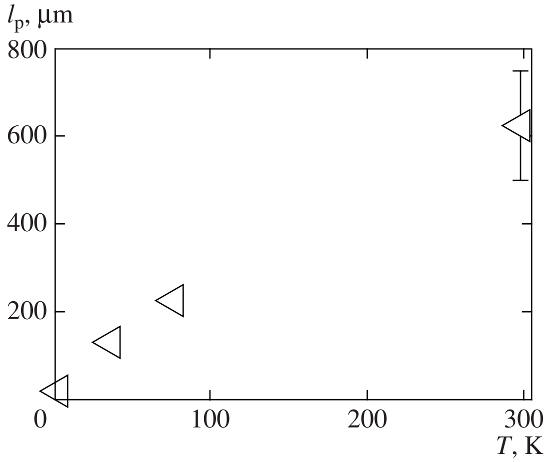

Fig. 2. Dependence of the interparticle distance l_p in the dusty plasma structures on the temperature of neutral atoms. Symbols indicate the interparticle distances in dust chains at room temperature, upon cooling of the gas-discharge tube walls with liquid nitrogen (77 K), upon cooling of the gas-discharge tube walls with liquid-helium vapors to temperatures of 25–50 K, and upon cooling of the gas-discharge tube walls with liquid helium (4.2 K).

The discharge in helium at low temperatures can be accompanied by the conversion of He^+ ions into He_2^+ and He_3^+ molecular ions [2]. We calculated the characteristics of the molecular-ion flow under the conditions of these experiments. According to the results of our calculations, the effective temperature of He_3^+ molecular ions considerably exceeds the gas temperature and, therefore, the He_3^+ molecular ions with a high probability should decay upon collisions with atoms. As a result, the discharge will not contain molecular ions in the presence of a strong electric field (of the order of 10 V/cm).

A change in the length of screening of the macroparticle charge in a dust crystal is an important consequence of the heating of ions in an electric field. The Debye length should be determined using not the temperature of atoms but the effective ion temperature $T_{eff} = (2/3)\langle\varepsilon\rangle$, which is governed by the thermal and directed motions of the ions. For the aforementioned plasma parameters, the effective temperature significantly exceeds the temperature of the atoms and, therefore, the heating of ions in the electric field cannot be ignored when determining the dust particle charge and the characteristic length of screening of the dust particle charge, as well as when calculating the forces of the interaction of dust particles with each other and with the ion flow. A detailed analysis of the distribution functions shows that, despite the large difference between the temperatures $T_\parallel$ and $T_\perp$ (see [11]), the distribution of the velocity magnitudes is adequately described by the Maxwellian function

$$\left(\frac{m}{2\pi T_{\mathrm{eff}}}\right)^{3/2}\exp\left(-\frac{mv^2}{2T_{\mathrm{eff}}}\right).$$

A considerable difference is observed only at high velocities. However, since the total number of ions in this range of the distribution function is small, the effective ion temperature T_{eff} can be used in the simulation for determining approximate macroscopic characteristics of the plasma.

A decrease in the temperature of the neutral plasma component also substantially affects the dust particle charge and the parameters of the charge screening in the discharge plasma.

3.2. Charging of a Dust Particle

Let us consider a stationary negatively charged sphere of radius a with the charge $Q = -eZ < 0$. It is assumed that the radius of the sphere, the screening length, and the charge-exchange mean free path of the ion satisfy the conditions

$$a \ll \lambda_{\mathrm{D}} \ll \lambda_{\mathrm{st}}, \tag{1}$$

while the temperatures of electrons, ions, and atoms satisfy the conditions

$$T_e \gg T_{\mathrm{i}} \approx T_{\mathrm{a}}. \tag{2}$$

The dust particle, as a rule, is charged so that the particle charge produces a considerable Coulomb barrier for electrons at which the time-averaged fluxes of ions and electrons at the particle surface are equal to each other. In the collisionless approximation, a part of the ions with a positive total energy are incident from infinity onto the surface of the dust particle. For these ions, the orbital-motion-limited (OML) approximation [1] is applicable fairly well. The ion flux incident on the dust particle surface in the framework of the orbital-motion-limited model coincides with the ion flux in the Langmuir and Mott–Smith model; that is,

$$J_{\mathrm{iOML}}(a) = \pi a^2 n_{\mathrm{i}0}\sqrt{\frac{8T_e}{\pi M}}\left(1 - \frac{e\varphi(a)}{T_{\mathrm{i}}}\right). \tag{3}$$

The electron flux incident on the dust particle is determined from the Boltzmann distribution:

$$J_e(a) = \pi a^2 n_{e0}\sqrt{\frac{8T_e}{\pi m}}e^{e\varphi(a)/T_e}. \tag{4}$$

When conditions (1) and (2) are satisfied, the surface potential of the dust particle can be written in the form $\varphi(a) \approx -eZ/a$. Hence, it follows from the equality of fluxes (3) and (4) that, at $n_{\mathrm{i}0} = n_{e0}$, the surface potential is predominantly determined by the electron temperature and has a characteristic value; that is,

$$e|\varphi(a)| \approx (2\text{–}4)T_e. \tag{5}$$

3.3. Collision Flux of Ions to a Dust Particle

A number of ions are incident on the surface of a dust particle due to the change in the trajectory after one or several collisions with atoms. Although collisions with atoms, as a rule, are highly improbable, this mechanism of particle charging (as a result of collisions) frequently turns out to be dominant [5–10]. When conditions (1) and (2) are satisfied, the screening characteristics substantially depend on the collisional relaxation even in the case where the collision frequency is infinitely low.

Now, we consider the recombination flux $J_{\mathrm{i\,rec}}$ of ions to a dust particle. The recombination flux is determined by the frequency of the above collisions in some volume V_0 in the vicinity of the particle after which the ion appears to be trapped by the potential field of the particle. In the course of further collisions, the trapped ion with a higher probability will lose the total energy and attain the surface of the dust particle. Therefore, we can assume with a high accuracy that the recombination flux $J_{\mathrm{i\,rec}}$ is determined by the number of ions trapped in a unit time. By assuming also that the volume V_0 is bounded by a sphere of radius $r_0 \gg a$, within which the potential varies according to the Coulomb law $\varphi(r) = -eZ/r$, we can estimate the radius r_0 from the equality of the potential energy in the field of the dust particle and the temperature of the atoms; that is,

$$r_0 = a\frac{e|\varphi(a)|}{T_{\mathrm{a}}}. \tag{6}$$

In a small volume ΔV (in the neighborhood of the point with the distance r from the center of the dust particle), the number of collisions in the time interval Δt is given by the formula $\Delta N_{\mathrm{st}}(r) = n_{\mathrm{i}}v\Delta V\Delta t/\lambda_{\mathrm{st}}$, where n_i is the density of free ions and v is their velocity. Assuming that $n_{\mathrm{i}}(r) \approx n_{\mathrm{i}0}$ and $v(r) \approx v_0$, where $v_0 = \sqrt{8T_{\mathrm{a}}/\pi M}$ is the thermal velocity of atoms, we obtain

$$J_{\mathrm{i\,rec}} = \int_a^{r_0}\frac{n_{\mathrm{i}}v}{\lambda_{\mathrm{st}}}4\pi r^2 dr \approx \frac{4\pi r_0^3 n_{\mathrm{i}0}v_0}{3\lambda_{\mathrm{st}}}. \tag{7}$$

The largest contribution to integral (7) is made by collisions that occur at large distances from the dust particle. Therefore, the estimate obtained from expression (7) is very approximate due to the inaccuracy in the determination of the trapping radius r_0 (see relationship (6)). It should be kept in mind that a number of factors (such as the screening effects, the presence of an external electric field, and the ion focusing) can substantially complicate the problem of determination of the volume V_0. For example, a strong screening can lead to the approximate equality $r_0 \approx \lambda_{\mathrm{D}}$.

3.4. Results of the Calculations of the Charging of a Dust Particle at Different Temperatures of Atoms

The influence of the temperature of the atoms on the dust particle charge can be illustrated using the results of the calculations of the charging of a dust particle in a helium plasma at room temperature and two cryogenic (liquid-nitrogen and liquid-helium) temperatures. All the calculations described below were performed by the particle-in-cell method. In these calculations, the electron temperature was assumed to be 3 eV at the ion density $n_i = 10^9$ cm^{-3} and the dust particle radius equal to 2.72 μm. For simplicity, we also consider the case of a stationary plasma in the absence of an external electric field and an ion drift.

First, we consider the case of a buffer gas at room temperature. For this case, we solve the problem of charging of a dust particle in a stationary two-temperature helium plasma consisting of singly charged ions with $z = 1$ at an ion temperature $T_\mathrm{i} = 0.025$ eV and a gas pressure of 1 Torr (the density of gas atoms $n_\mathrm{a} \approx 3.3 \times 10^{16}$ cm^{-3}). We take into account only one type of ion–atom collisions, i.e., the collisions caused by the resonant charge exchange of ions with atoms of the parent gas. The cross section of the resonant charge exchange of the helium ion with a stationary atom depends only weakly on the ion energy and can be approximated by the following function:

$$\sigma_\mathrm{res}(\varepsilon) = \sigma_\mathrm{res}(\varepsilon_0)[1 + a_0 \ln(\varepsilon_0/\varepsilon)]^2, \qquad (8)$$

where $\varepsilon_0 = 1$ eV, $a_0 \approx 0.0557$, and $\sigma_\mathrm{res}(\varepsilon_0) = \sigma_0 \approx 2.79 \times 10^{-15}$ cm^{-2} are the approximation constants [18].

The results of the calculations of the averaged charges and their fluctuations are presented in the table. Calculation no. 1 was carried out without regard for the ion–atom collisions. Calculation no. 2 was performed with allowance made for the ion–atom collisions with the resonant charge exchange. A comparison of the results of these two calculations demonstrates that the ion collisions even in the discharge at room temperature make an important contribution to the formation of the dust particle charge. Correspondingly, the cloud of bound ions responsible for the additional screening of the negative charge of the particle also has a substantial effect on the process (the influence of collisions and bound ions on the screening characteristics is considered in more detail in [9, 10]).

The results of the simulation of the charging of a dust particle in a cryogenic discharge at liquid-nitrogen and liquid-helium temperatures and a density of neutral atoms $n_\mathrm{a} \approx 1.6 \times 10^{17}$ cm^{-3} (5 Torr under normal conditions), which corresponds to the conditions of the performed experiments, are also given in the table (calculation nos. 3, 4).

Figure 3 presents the results of the calculations of the charging of a dust particle by the particle-in-cell method for three temperatures with allowance made for the ion–atom collisions (calculation nos. 2, 3, and 4).

Characteristics of an isolated dust particle in the absence of an external electric field at different temperatures of the gas

Calculation no.	1	2	3	4
T_a, K	293	293	77	4.2
$\lambda_\mathrm{st} = \lambda_\mathrm{st}(T_\mathrm{a})$, μm	∞	43	15	15
$\lambda_\mathrm{Di} = \lambda_\mathrm{D}(T_\mathrm{a})$, μm	37	37	21	4
$-Q/e$	6558	3071	2752	2009
$\Delta Q/e$	75	64	54	70

Note: The ion Debye length $\lambda_\mathrm{Di} = (T_\mathrm{a}/4\pi e^2 n_\mathrm{i})^{1/2}$, the mean free path of ions λ_st, the time-averaged particle charge, and the room-mean-square deviation of the time-averaged particle charge given in the table are calculated by the particle-in-cell method.

The results obtained have demonstrated that the gas temperature substantially affects the charge and screening of the particle. It should also be noted that a decrease in the gas temperature and a significant decrease in the charge (by a factor of approximately one and a half) are accompanied by a slight increase in the magnitude of the charge fluctuations. These data are in contradiction with the usually observed dependence of the fluctuation magnitude on the charge [10] and can be explained by the enhancement of the role played by the cloud of bound ions in the formation of the ion flux to the dust particles.

Therefore, the decrease in the dust particle charge due to the ion–atom collisions can be considered an important mechanism of the formation of dense dusty plasma structures at cryogenic temperatures. Moreover, the mutual effect of dust particles must be included in the analysis of the mechanisms responsible for the approach of particles to one another because of the increase in the density of the structures in cryogenic discharges. At cryogenic gas temperatures and in strong external electric fields, the collision flux of ions to finite orbits around the dust particles increases drastically and the charge of the cloud of trapped ions can reach 30–40% of the dust particle charge. This is accompanied by an enhancement of the screening of the negative charge of the dust particle and, consequently, by a decrease in the interparticle distance.

3.5. Dependence of the Charge of Dust Particles on Their Concentration in the Dusty Plasma Structure

Let us consider a model volume (a sphere in our case) containing a finite number of ions N_i. This situation corresponds to the case in which the plasma contains not a single dust particle but a sufficiently large number of dust particles $N_\mathrm{d} \gg 1$. In the case, the concentration of dust particles can be defined as $n_\mathrm{d} = N_\mathrm{d}/r_\mathrm{G}^3$, where $r_\mathrm{G} = 2r_\mathrm{N}$ is the distance from the nearest neighbor particle in the cubic lattice. The radius r_N of the spherical layer containing a dust particle of radius a

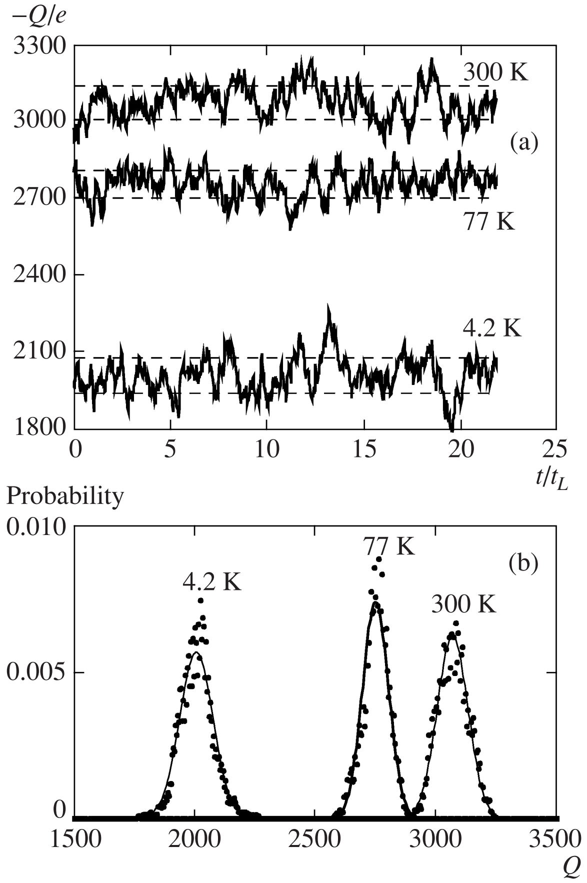

Fig. 3. (a) Time dependences of the dust particle charge (according to calculation nos. 2, 3, and 4 in the table). (b) Probability distributions of the dust particle charge according to the same calculations. Points represent the results of the simulation. Horizontal dashed lines in panel (a) indicate the variance of the mean value. Solid lines in panel (b) correspond to the Gaussian distributions with the mean value and the variance determined from the results of the simulation.

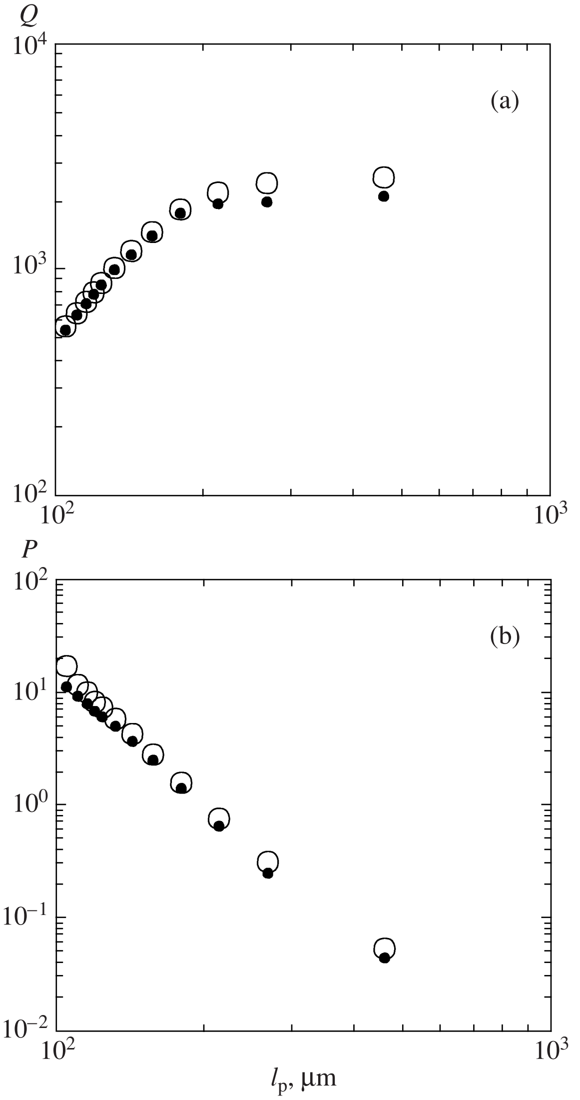

Fig. 4. Dependences of (a) the average charge of dust particles and (b) the Havnes parameter on the interparticle distance in the dusty plasma structure. The atomic density corresponds to the following pressures: (○) $p = 2$ Torr (300 K) for calculations at $T = 77$ K and (●) $p = 5$ Torr (300 K) for calculations at $T = 4.2$ K.

and a specified number of ions N_i is determined from the relationship

$$N_\mathrm{i} = \frac{4\pi}{3}(r_G^3 - a^2)n_\mathrm{i}.$$

The criterion for the mutual effect of dust particles on their charge is the Havnes parameter

$$P = n_\mathrm{d}|Q|/en_e, \tag{9}$$

which is equal to the ratio of the sum of charges at dust particles to the total charge of electrons in the plasma.

In order to investigate the mutual effect of dust particles on their charge in the cryogenic discharge, the charging of a dust particle was calculated by the particle-in-cell method for different numbers of ions in the computational cell. Qualitatively, this situation corresponds to different densities of dust particles (or to different distances from the nearest neighbor particle in the cubic lattice; here, $r_\mathrm{G} = 2(a^3 + 3N_\mathrm{i}/4\pi n_\mathrm{i})^{1/3}$ is the diameter of the spherical layer containing a dust particle and a specified number of ions). Figure 4 presents the results of the calculations of the average charge of dust particles and the Havnes parameter as functions of the interparticle distance in the dusty plasma structure. These data illustrate the mutual effect of charging of dust particles in the dust cloud at cryogenic temperatures. A comparison of the dependences shown in Figs. 4a and 4b demonstrates that the charge of dust particles in the dusty plasma structure drastically decreases at the Havnes parameter of the order of unity.

Therefore, the approach of dust particles to one another is accompanied by a decrease in their charge.

This facilitates the formation of dense dusty plasma structures at cryogenic temperatures. It should also be noted that, in the computational model, the boundary conditions for electrons correspond to the Maxwellian distribution of their energy at a specified temperature. Under the conditions where the majority of the electrons are localized on the dust particles, the calculated distribution function can differ from the Maxwellian distribution function because of the loss of electrons that are capable of overcoming the Coulomb barrier.

4. CONCLUSIONS

Thus, the results obtained in this study can be summarized as follows. The experimental investigation of the formation of dusty plasma structures in a dc glow discharge at temperatures in the range from 4.2 to 300 K revealed a strong dependence of the interparticle distance on the temperature of the gas-discharge tube wall.

The kinetic processes of interaction of dust particles with the plasma component at cryogenic temperatures were analyzed with the proper allowance for the ion–atom collisions. This analysis made it possible to determine the main mechanisms responsible for the observed increase in the density of dusty plasma structures: a decrease in the temperature of the walls of the gas-discharge tube leads to a decrease in the temperature of neutral atoms and, as a consequence, to an enhancement of the role played by the collisional effects, which, in turn, results in a decrease in the dust particle charge and an increase in the cloud of bound ions. Contrary to the expectations, the decrease in the effective temperature of ions turned out to be insufficient to decrease significantly the ion Debye length. Heating of the ions in the electric field of the discharge increases their effective temperature, which eventually becomes considerably higher than the temperature of the neutral plasma component.

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