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Investigation of the Interaction Potential and Thermodynamic Functions of Dusty Plasma by Measured Correlation Functions

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Dusty plasma is a quasi-neutral assembly of ions, electrons, and charged micro-particles. A great deal of effort has been devoted in recent years to study dusty gas-discharge plasma. This fact is primarily associated with the fact that dust particles interacting with one another may form ordered structures similar to liquid or solid. Studying the physical properties of such strongly interacting systems is of interest, on the one hand, from the standpoint of fundamental physics and, on the other hand, for various applications.

In this paper we report the first results of investigation of the compressibility factor, compressibility, the internal energy of dusty plasma and the interaction potential of dust particles that based on the integral equations approach and experimentally obtained pair correlation functions of ordered dust particles' structures. We carried out measurements of binary correlation functions of plasma-dust structures formed in the electrode layer of a capacitive radio-frequency (RF) discharge. Two plate electrodes are placed in a vacuum chamber. The lower, grounded, electrode is a metal disk of diameter d = 19 cm. The upper electrode located at height H = 5 cm above the lower one has the form of a ring with outside diameter d_{out} = 19 cm and inside diameter d_{in} = 5 cm. During the experiment, the vacuum chamber was filled with argon at pressure P_g = 5 mbar and P_g = 16 mbar, the voltage from a radio-frequency oscillator with a frequency of 13.56 MHz was applied to the electrodes, and a glow discharge was ignited between the electrodes in the argon atmosphere. Monodisperse dust particles 5.51 mkm in diameter were dropped into the discharge from a special container.

For visualization, the resultant structure was illuminated by a ribbon beam of a He-Ne laser (λ = 633 nm). In this case, the laser beam was the so-called "laser sheet" 2.5 cm wide with a characteristic thickness in the waist region of 200 μm. As a result, the horizontal cross section of the dust formation was accessible to observation. The position of dust particles was registered by a video camera (see Fig. 1).

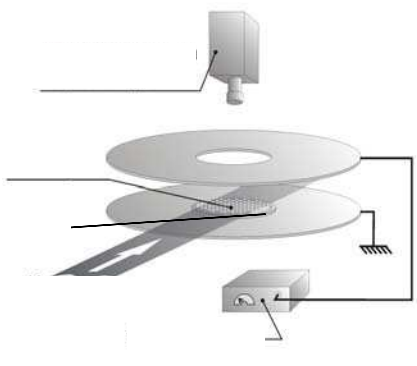

Fig. 1. Experimental setup.

We find interaction potential between spherical dusty particles using the preceding measured correlation functions. The problem of determining the potential by the known correlation function $g(r)$ is solved by using integral equations of the fluid theory. Here r is a distance from the central point of spherical particle to the point to be considered. The basic relation defining the potential $U(r)$ is

$$U(r) = T_d \times \left[\omega(\gamma) - \ln g(r) \right], \tag{1}$$

where T_d is the temperature of dust system. The function ω in formula (1) depends on the nction γ defined as

$$\gamma(r) = h(r) - c(r) + B(r). \tag{2}$$

Equation (2) includes the difference between the direct correlation function $c(r)$ and function $h(r) = g(r) - 1$; $B(r)$ is a bridge functional representing infinite series of irreducible diagrams. It is impossible to sum infinite series of bridge functional, and the objective of theory is to search for adequate and physically valid approximations of bridge functional. The transition to approximate equations is based on the replacement of nonlocal bridge functional *B(r)* by local bridge function $B(h(r))$ or $B(\gamma(r))$, $B(\omega(r))$.

In the hypernetted-chain approximation (HNC), which is most frequently used compared to other approximations, the bridge functional is zero, and the closure is

$$\omega(r) = \gamma(r) \tag{3}$$

Another local equation, that of Percus–Yevick (PY equation), is also extensively employed,

$$e^{\omega} = 1 + \gamma(r). \tag{4}$$

The Martynov–Sarkisov closure has the form

$$\omega = \gamma(r) + a\omega^2, \tag{5}$$

where a is some constant.

We can use the Ornstein–Zernike equation to represent the function γ in the form

$$\gamma(r) = \frac{4\pi n_d}{(2\pi)^3} \int_0^\infty k^2 dk \frac{\sin(kr)}{kr} \frac{\tilde{h}(k)^2}{1 + n_d \tilde{h}(k)}. \tag{6}$$

In Eq. (6), n_d is the concentration of dust particles. The function $\tilde{h}(k)$ is the Fourier transform of $h(r)$,

$$\tilde{h}(k) = 4\pi \int_0^\infty r^2 dr \left[g(r) - 1 \right] \frac{\sin(kr)}{kr}. \tag{7}$$

Two measured correlation functions were selected for the calculation of the potential parameters. We approximated the potential energy, which was found using the measured correlation functions, by the expression for screened Coulomb potential of arbitrary charge and screening radius,

$$W\left(Z,\lambda_d\right)=\frac{\left(Ze\right)^2}{r}exp(-r/\lambda_d). \qquad (8)$$

The parameters Z (charge of the particle) and λ_d (screening radius) are found from the condition of best correspondence of the functions of U and W. The potential U was calculated by formulas (1)–(7). In Fig. 2a one can see the first correlation function and in Fig. 2b – the potential calculated for it. In Fig. 3a one can see the first correlation function and in Fig. 3b – the potential calculated for it.

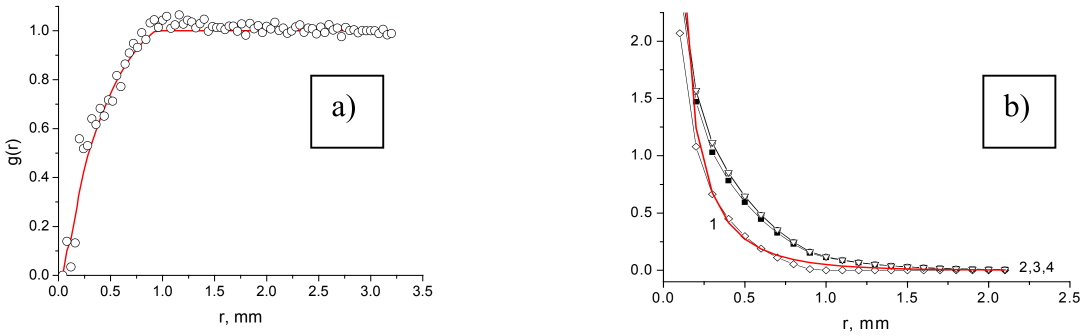

Fig. 2. a) Correlation function at $n_d = 2000$ cm^{-3}, b) Lines with symbols: (1 - ◊) $U(r) = -T_d \ln g(r)$, (2 - ■) PY, (3 - ○) HNC, (4 - ∇) MS. Solid line without symbols indicates the screened potential with **Z** = 3000 and $\boldsymbol{\lambda_d}$= 0.4 mm.

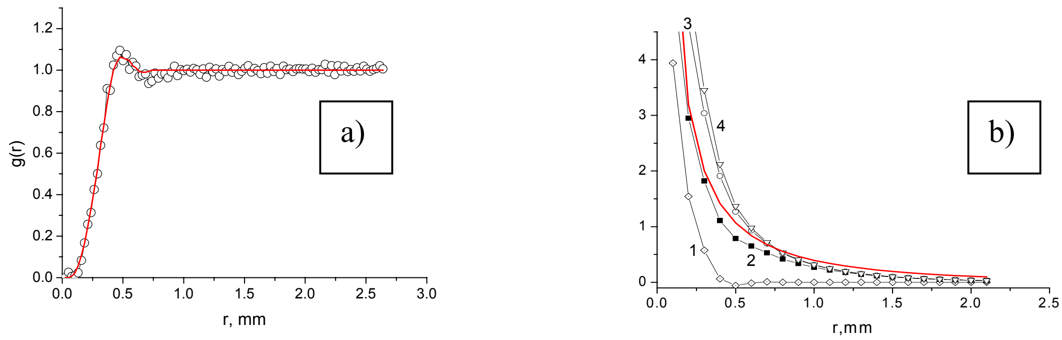

Fig. 3. a) Correlation function at $n_d = 10000$ cm^{-3}, b) Lines with symbols: (1 - ◊) $U(r) = -T_d \ln g(r)$, (2 - ■) PY, (3 - ○) HNC, (4 - ∇) MS. Solid line without symbols indicates the screened potential with **Z** = 3500 and $\boldsymbol{\lambda_d}$= 0.5 mm.

We assume that a subsystem of dust particles is in the state of local thermodynamic equilibrium at temperature T_d. In this case we can use the measured correlation functions and the obtained potential to find some thermodynamic parameters of such a system of dust particles, first of all, the partial pressure of the dust component P_d. We apply the known formula from to write

$$P_d = n_d T_d - \frac{4\pi n_d^2}{6}\int_0^\infty r^3 \frac{dW}{dr} g(r)\, dr\ . \tag{9}$$

The reduced isothermal compressibility has the form

$$\chi_d = T_d \left(\frac{\partial n_d}{\partial P_d}\right)_T = 1 + 4\pi n_d \int_0^\infty h(r) r^2 dr\ . \tag{10}$$

The total energy of a dust particle is defined as

$$E = 3T_d / 2 + 2\pi n_d \int_0^\infty r^2 W(r) g(r, T_d)\, dr\ . \tag{11}$$

Equation (11) is used to determine the coupling parameter of dusty plasma system in terms of the correlation function,

$$\Gamma_1 = \frac{4\pi n_d}{3T_d}\int_0^\infty W(r) g(r) r^2 dr\ . \tag{12}$$

For both correlation functions the values of calculated thermodynamic parameters: compressibility factor $P_d/(n_d T_d)$, coupling parameter Γ_1, and isothermal compressibility χ_d for the dust system are given in the table 1.

№ п/п	**n_d, cm^{-3}**	**P_g, mbar**	**R_d, µm**	**T_d, eV**	**λ_d, mm**	**Z**	**Γ**	**$P_d/(n_d T_d)$**	**Γ_1**	**χ_d**
1	1840	5	5.5	~ 35	~ 0.5	3000	0.4	3	1.2	0.8
2	10710	16	5.5	~ 18	~ 0.4	3500	2	20	17	0.18

Table 1. Main parameters were obtained in this work. n_d – concentration of dust particles, **P_g** - argon pressure in vacuum chamber, **R_d** – radius of dust particle, **T_d** – temperature of dust component, **λ_d** – screening radius, **Z** – charge of dust particle, **Γ** – coupling parameter of dusty plasma system $\Gamma = (Ze)^2 n_d^{1/3}/T_d$, **$\Gamma_1$** – coupling parameter of dusty plasma system calculated in terms of correlation function $\Gamma_1 = \frac{4\pi n_d}{3T_d}\int_0^\infty W(r) g(r) r^2 dr$, **$P_d/(n_d T_d)$** – compressibility factor, **χ_d** – isothermal compressibility.

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