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Experimental investigations of strongly coupled Coulomb systems of diamagnetic dust particles in a magnetic trap under microgravity conditions

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Abstract – A series of experiments on the modernized "Coulomb crystals" setup on board of the International Space Station (ISS) was performed. Formation of a cluster of charged and uncharged particles was observed. Excitation and damping of cluster oscillations, as well as its destruction in the high electric field were investigated. Charges of the particles were evaluated on the basis of their rate of expansion from the cluster. Some conclusions about the cluster structure have been presented.

Introduction. – The properties of strongly interacting spatially ordered structures consisting of micron-size charged particles have been studied in the framework of the experiment "Coulomb crystals" on board of the International Space Station (ISS) [1,2]. Unlike plasma-dust structures in gas discharges [3–5], used for this purpose before, our method allows to form stable three-dimensional structures of charged particles in non-ionized gas or in a vacuum. Therefore, screening of charged particles by plasma does not occur, and interactions between them are of purely Coulomb type, and not of the Debye type as in dusty plasmas. The main idea of the experiment was to hold charged particles by the forces different from the electrostatic ones causing interactions between them. In this experiment, a cusp magnetic trap for diamagnetic particles was used. We took graphite particles with a maximal diamagnetic susceptibility. The first experiments with magnetic confinement of charged Coulomb clusters of graphite particles were carried out in the ground-based conditions [6–8]. The obtained structures consisted of less than ten particles in the magnetic field of 10^4 G. To create a trap able to hold thousands of particles in the Earth's gravity field it is necessary to create a much more intensive magnetic field with higher gradients, which is a difficult technical task. As in the case of dusty plasma [9–12], the problem of creation of large structures of charged diamagnetic particles was solved by making experiments under microgravity conditions on board of spaceships. In the first ISS experiments under microgravity conditions the principal possibility of cluster formation was shown with the number of charged particles 10^3 in the fields 10^2 G with gradients 10^2 G/cm [1,2]. Estimations of such particle charges were made. When the magnetic field varied, clusters started to oscillate inside the trap. An analysis of the attenuation of oscillations enabled us to determine the diamagnetic susceptibility of graphite particles and one parameter of the magnetic system. Molecular dynamics is a powerful and convenient tool for the study of the different dynamical processes and properties of the many-particle systems. If one takes into account the influence of the

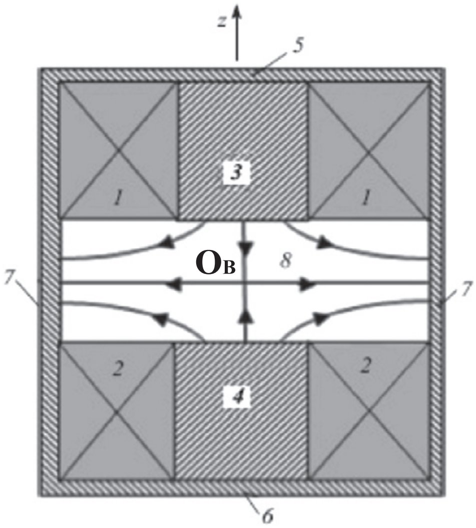

Fig. 1: Scheme of the experimental setup. 1, 2: solenoid coils; 3, 4: cores of the coils (steel); 5, 6: end-magnetic conductors (steel); 7: lateral magnetic conductors; 8: inner space of the replaceable container.

background gas, it is recommended to perform a computer simulation in the framework of the Langevin dynamics [13–17]. For the interpretation of the dynamics of the graphite particles in a rarified gas observed in cosmic experiments [1,2], a computer simulation of the system of charged particles in terms of the molecular dynamics was performed. It was shown that in the cusp magnetic field it is possible to form a cluster of charged particles in the shape of an oblate spheroid. In 2015, a new series of experiments on the modernized "Coulomb crystals" setup was performed by the cosmonaut Aidyn Aimbetov. The number of graphite particles for the formation of Coulomb structures was increased by an order of magnitude, the video surveillance system was improved and the possibility of particle charging to a higher potential was included. The formation of clusters of charged and uncharged particles, excitation and damping of cluster oscillations, as well as cluster destruction were observed.

Experimental setup. – Experimental setup is described in detail in [1,2], therefore, here we will briefly describe the main elements and changes in its structure. The setup consists of two electromagnet coils located on the same axis and separated by an interval of 6 cm (fig. 1). Currents within them flow in the opposite directions, so they create oppositely directed magnetic fields. The resulting cusp field has a zero point on the axis between the coils (O_B point).

Between the coils one of the replaceable containers is inserted, in the center of which a cylindrical glass ampoule with a diameter of 52 mm and a height of 40 mm is placed. Ampoules are filled with argon at atmospheric pressure and contain graphite particles. To charge the particles, the central wire electrode with a diameter of $2R_1 = 200\,\mu$m passes along the axis of the ampoule. An outer electrode of diameter 51 mm has a shape of a semi-circle and is placed near the cylindrical glass wall. The other half of the glass wall is free for making observations. In the experiments, we used graphite particles of sizes 100, 200, 300 and 400 μm, in an amount of about 3×10^4, in each container that is higher than the number of particles 2×10^3 in the first experiments [1,2]. It should be noted that both shape and dispersion of graphite particles are difficult to control, so each container undoubtedly contained particles of smaller sizes than the nominal one. The electric potential on the central electrode in containers with 100 and 400 μm particles can take values of 0, 6, 24 V. In containers with 200 and 300 μm particles the electrode potential was increased by a factor of 6.25, so its possible values are 0, 37.5, 75, 112.5 and 150 V, respectively.

In non-homogeneous magnetic field $\mathbf{B}$, any particle of mass m is subjected to the action of the effective force [18]

$$\mathbf{F}_B = (\chi m/2)\nabla(\mathbf{B}^2), \qquad (1)$$

where χ is the specific magnetic susceptibility of the particle material. For paramagnetic $\chi > 0$, for diamagnetic $\chi < 0$, so diamagnetic bodies are pushed into the local minimum —"the magnetic well" [19], in this setup— to the point O_B. Around it, in a radius of about 2 cm, *i.e.*, practically in the whole volume of the ampoule with graphite particles, the dependence of the field on the coordinates is linear with a good precision. At the maximum value of the current $i_{max} = 6.5$ in both the coils, the field gradient along the axis of the electromagnet is 400 G/cm; in the plane of the field symmetry passing through the point O_B the radial gradient is two times less than that and is equal to 200 G/cm, which is typical for the cusp trap. On the axis of symmetry z the magnetic field is directed along the axis and is well described in the linear approximation [1,2]

$$B_z = c(i_2 - i_1) - b(i_1 + i_2)z, \qquad (2)$$

where i_1 (i_2) is the current in the upper (lower) coil, the z-coordinate is measured from the point O_B at $i_1 = i_2$. When $i_1 \neq i_2$ point O_B (the bottom of the magnetic well) is displaced and its position is

$$z_0 = c(i_2 - i_1)/b(i_1 + i_2). \qquad (3)$$

The coefficient $b = 400/13\,\mathrm{G/(A\,cm)}$ is defined according to preliminary (on the ground) measurements, coefficient c is found in [1,2] using the observations of the behavior of an ensemble of particles in microgravity, $c = 115\,\mathrm{G/A}$. In the linear approximation, the radial component of the magnetic field is $B = (200/2i_{max})(i_1 + i_2)\,\mathrm{G}\rho$, where $\rho = (x^2 + y^2)^{1/2}$. The current in the windings of the electromagnet can take values of 0, 30, 50, 70 and 100% of the maximum. As mentioned above the voltage between the electrodes also varies discretely. It should be noted that due to certain structural features the ampoule was placed not absolutely symmetrically with respect to the electromagnet coils, so the point O_B at $i_1 = i_2$ is located slightly above the visual center of the ampoule, as shown in fig. 2(a).

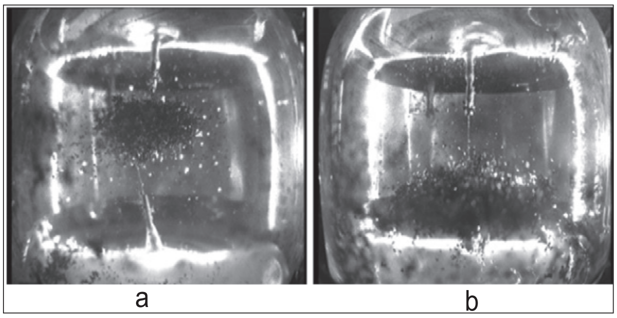

Fig. 2: Clusters of neutral (a) and charged (b) graphite particles in the cusp magnetic trap at $i_1 = 0.5i_{max}$ and $i_2 = 0.5i_{max}$ (a) or $i_2 = 0.3i_{max}$ (b). The thickness-to-diameter ratio is about 0.5 and 0.3, respectively.

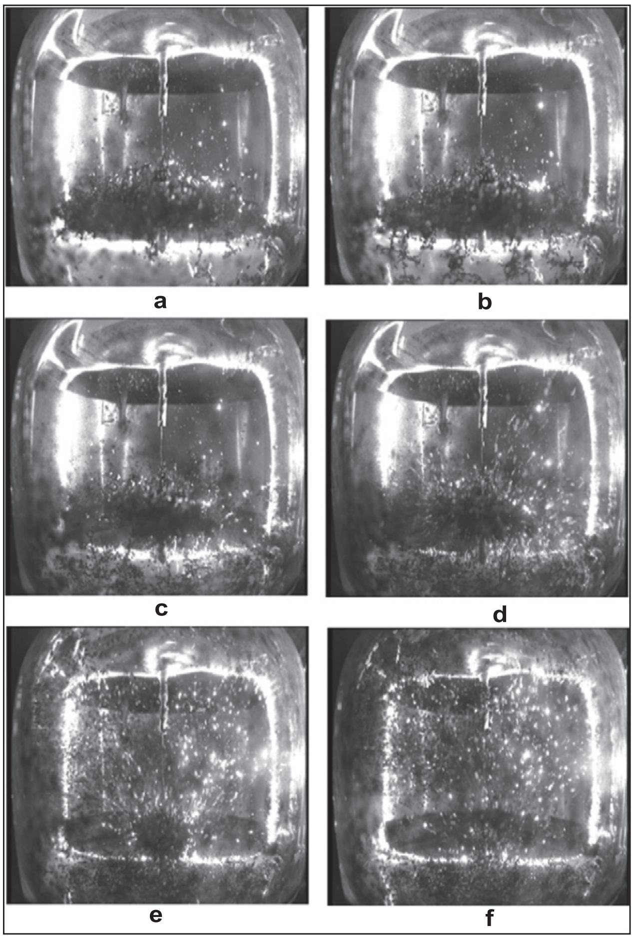

Fig. 3: Scattering of cluster particles caused by increasing potential on the central electrode: (a) 37.5 V, (b) 75 V, (c) 112.5 V, (d)–(f) 150 V.

Experiment. – During the present experiments clusters were formed by charged particles and also by neutral ones with their subsequent charging. Before the experiment, the graphite particles were mainly located on the walls of the ampoule. After shaking, they filled its volume and then, under the action of the magnetic field, moved into the magnetic well, forming a cluster. If the electrical potential had already been supplied to the central electrode, the particles would have obtained charges in contact with it, otherwise the cluster would have been formed from uncharged particles. The cluster's position on the z-axis depended on the ratio of the currents in the coils.

Figure 2 shows clusters formed by neutral and charged particles. In the first case, the ratio of thickness to diameter of the cluster is close to 0.5 (fig. 2(a)), in the second one to 0.3 (fig. 2(b)), which corresponds to the theoretical results for the uniform spheroid approximation in the cusp magnetic trap [1,2]. The position of the cluster is determined by the currents in the coils: $i_1 = i_2 = 0.5i_{max}$ in fig. 2(a), and $i_1 = 0.5i_{max}$ and $i_2 = 0.3i_{max}$ in fig. 2(b).

In this experiment cluster oscillations were excited in a different way from that in [1,2]. This enabled us to use a simpler method to determine the coefficient c in eqs. (2) and (3) and the specific magnetic susceptibility of graphite particles. The equilibrium position of the cluster depended on the ratio of currents in the coils of the electromagnet; its center of mass was placed at the point O_B determined by eq. (3). When the current in one of the coils changed, the point O_B shifted, and the cluster turned out to be in a non-equilibrium state, and its oscillations were excited around a new position of the point. When the oscillations damped, the coefficient c was determined by the displacement of the cluster with respect to its initial position. To determine the specific magnetic susceptibility χ of graphite, the oscillation frequency ω and the damping constant δ were measured.

The experiments [1,2] showed that the cluster practically did not react to any changes in the potential revision ϕ_0 on the central electrode from 0 to 24 V. In this experiment the potential ϕ_0 on the central electrode in the container with 300 μm particles was increased to a maximum value of 150 V at the currents in the electromagnet coils $i_1 = 0.5i_{max}$ and $i_2 = 0.3i_{max}$. The cluster was located close to the bottom plate, at a distance less than its thickness. The potential was increased from zero to 150 V in four steps, 37.5 V in each step, with a time interval between them of about 15 s. Gradual changes in the state of the cluster are shown in fig. 3. After the first step, a small number of particles left the lower surface of the cluster in the form of chains of particles stretching toward the bottom plate (fig. 3(a)). After switching on the second level (75 V), this process activated significantly (fig. 3(b)). Switching of the next level (112.5 V) resulted in a cascade growth of chains and a detectable loss of the cluster volume (near half) within 15 seconds (fig. 3(c)). Particles, both individually and in chains, left the cluster, moving not only in the direction of the bottom plate, but also in the direction of the side walls. At the maximal potential of 150 V we observed an intensive scattering of particles (fig. 3(d)), starting from the outer layers. It led to the complete disruption of the remainder of the cluster within 8 seconds (fig. 3(e), (f)). The velocities of the particles ranged from 1 to 4.5 cm/s. Scattering of particles was observed in all directions, but still chains moved mainly to the bottom plate (fig. 3(d), (e)), whereas individual particles moved in all directions. At the end of the scattering process one can observe the movement of the particles mainly to the bottom plate, where the magnetic field is weaker due to the fact that $i_1 > i_2$ (fig. 3(d), (e)). A significant part of the particles, reaching the outer electrode, recharged and returned to the center of the ampoule. Scattering of the cluster particles at growth of the ϕ_0 on the central electrode is explained by an increased charge of the particles and, hence, an excess of electrostatic repulsion forces over the confining ones.

From the comparison of the visual volume of the cluster with the total number of particles one can conclude that the average distance between the centers of particles is about 0.05 cm. Graphite particles may form fractal and filamentous (chain-like) structures [19], which were observed in the experiment during the cluster destruction. Apparently, the internal structure of the cluster is formed from the particles contacting with each other and forming conductive chains, as graphite is a conductive material. When the potential is applied to the central electrode, the charge flows to the outer particles through these chains. The particles, which accumulate sufficient charge, leave the cluster. After scattering of the outer-layer particles, the next layer is charged, and so on until the cluster disrupts. Stopping the downward movement is probably caused by the saturation of the closely located lower plate with charged particles.

Analytical estimations. –

The parameter c and the specific magnetic susceptibility. When the cluster is excited by the switching of the currents in the coils, the motion of its center of mass along the axis is described by the equation

$$\mathrm{d}^2 z/\mathrm{d}t^2 + 2\delta \mathrm{d}z/\mathrm{d}t = F_B/M, \tag{4}$$

where δ is the damping decrement, M is the mass of the cluster. From eqs. (1) and (2) for the magnetic force we obtain $F_B/M = \chi b[b(i_1+i_2)^2 z - c(i_2^2 - i_1^2)]$.

The initial position of the center of mass of a fixed cluster $z(0)$ is determined by the currents before switching. A solution of eq. (4) is

$$z(t) = z(0) + \left(z(0) + \frac{c}{b}\frac{i_1 - i_2}{i_1 + i_2}\right) \times \left\{\exp(-\delta t)\left[\cos(\omega t) + \frac{\delta}{\omega}\sin(\omega t)\right] - 1\right\}, \tag{5}$$

where

$$\omega = \sqrt{|\chi| b^2 (i_1+i_2)^2 - \delta^2}. \tag{6}$$

After the damping of the oscillations (formally at $t \to \infty$), the cluster's center of mass stops at the point z_0, defined by eq. (3) with currents after switching. Thus, by measuring the displacement of the cluster $z_0 - z(0)$, one can determine the constant c from (3), that is much simpler than the procedure described in [1,2]. By measuring the oscillation frequency ω and damping constant δ, we can find a specific magnetic susceptibility χ of the particle material from (6).

The cluster structure is not homogeneous, the particles are not distributed uniformly across the cluster, and it is slightly denser in the center than on the periphery. There are also some particles that levitate around the cluster (it is difficult to estimate their concentrations since we have only a two-dimensional pattern of the layer illuminated by the laser). As a result, it may turn out that it is necessary to take into account corrections to the gas viscosity due to these particles, which complicates the calculations of the damping coefficient of the cluster oscillations.

Increasing the current i_1 from $0.5i_{max}$ to $0.7i_{max}$ at constant current $i_2 = 0.5i_{max}$ we excited oscillations of cluster (consisting of 100 μm particles). After their damping we obtained the value of $z_0 = -0.65 \pm 0.02$ cm, which was used to determine the constant $c = 120 \pm 4$ G/A (the error is caused by the accuracy of the position of the cluster center of mass by the video). This value is in good agreement with the previously obtained one of 115 G/A [2] (or 117 G/A [1], in those papers the error was not given, however, it is not less than in this experiment and probably larger, as the method of determination of the constant c was more complicated). Using $\omega = 0.53\,\mathrm{s}^{-1}$ and damping constant $\delta = 0.07\,\mathrm{s}^{-1}$ we calculated the specific magnetic susceptibility of the particle material $\chi = 5 \times 10^{-6}\,\mathrm{cm}^3/\mathrm{g}$.

Oscillations of cluster consisting of $d = 200\,\mu$m particles were excited by an increase of the current i_2 from $0.5i_{max}$ to $0.7i_{max}$ (current $i_1 = 0.7i_{max}$ was not changed). By a shift of the cluster center from the position $z(0) = -0.66 \pm 0.02$ cm to $z_0 = 0$ we obtained the value of $c = 122 \pm 4$ G/A, which is also consistent with the above-mentioned results. In this experiment, the following values were found $\omega = 0.63\,\mathrm{s}^{-1}$, $\delta = 0.07$, which defined the specific magnetic susceptibility $\chi = 5,1 \times 10^{-6}\,\mathrm{cm}^3/\mathrm{g}$.

Video observations showed that as the cluster moved away from the equilibrium point along the axis of the container, it slightly rotated around its axis of symmetry at an angle not greater than 20 degrees. This result is explained by the fact that the center of mass of the cluster does not coincide with the zero point of the magnetic field. The non-homogeneous magnetic field acts on all diamagnetic particles with a force pushing them to the point O_B. As a result, a cluster with a non-homogeneous structure and non-perfect shape (an oblate spheroid) was formed, the center of mass of which did not coincide with the zero point of the magnetic field. This was caused by two reasons: firstly, cluster formation was accompanied by adhesion of particles and formation of fractal structures and, secondly, the particle flow was not homogeneous. Thus, the experiments on excitation of cluster oscillations confirm the fact that in a sufficiently large cluster with the number of particles of the order of 10^4 fractal structures are formed.

For $d = 300\,\mu$m particles cluster oscillations were excited by an increase of the current i_2 from $0.3i_{max}$ to $0.5i_{max}$ (current $i_1 = 0.3i_{max}$ was fixed). From the position of the cluster center $z_0 = -1.01 \pm 0.03$ cm we obtained the value of $c = 124 \pm 4$ G/A, which, within the error, is consistent with the above-mentioned value. In this experiment we could not determine ω and δ, as the cluster touched the bottom plate, which violated the periodicity of the oscillations and they quickly damped out. Therefore, the magnetic susceptibility was not determined either.

In these experiments, the oscillations of the cluster formed by $200\,\mu$m (and $100\,\mu$m) particles damped two times slower than in [1,2]. This can be explained by greater inertia of the cluster consisting of a large number of particles.

The distribution of charge on the surface of a conducting ellipsoid of revolution. For simplicity, we will assume that all particles are identical and have a spherical shape. Assuming that particles uniformly fill the volume of the conductive cluster, having a form of an oblate spheroid, we estimated the charge distribution on the surface, the total charge of any cluster and the charge per particle. The potential ϕ_0 and the surface charge density σ of the conducting ellipsoid with semi-axes a, b and c are defined by the equations [20]

$$\phi_0 = \int_0^\infty \frac{A\mathrm{d}s}{2\left[(a^2+s)(b^2+s)(c^2+s)\right]^{1/2}}, \qquad (7)$$

$$\sigma(x,y,z) = \frac{A}{4\pi abc\left(\frac{x^2}{a^4}+\frac{y^2}{b^4}+\frac{z^2}{c^4}\right)^{1/2}}, \qquad (8)$$

where A is a constant. In the case of an oblate spheroid ($b = a > c$) the integral (7) is taken in terms of elementary functions:

$$\phi_0 = \frac{A}{\sqrt{a^2-c^2}} \arccos\frac{c}{a}, \qquad (9)$$

And the surface charge density (8) can be represented as a function of one variable, for example, z, since radial $\rho = (x^2+y^2)^{1/2}$ and axial z coordinates are related by the equation for the ellipsoid of revolution $\rho^2/a^2 + z^2/c^2 = 1$. Eliminating the constant A in (8) and (9), we obtain

$$\sigma(z) = \frac{c\varphi_0}{4\pi a\left(\frac{c^4}{a^2-c^2}+z^2\right)^{1/2}\arccos(\frac{c}{a})}. \qquad (10)$$

In the case of uniform distribution of the particles in the cluster volume, the number of particles in its surface layer of thickness equal to their diameter d (if $d \ll c$) is $N_S = NSd/V$, where N is the total number of particles in the cluster, S is the area of its surface, $V = (4/3)\pi a^2 c$ is its volume. As a result, we find the charge of the particle in the surface layer of the cluster

$$q(z) = \sigma(z)\frac{S}{N_S} = \sigma(z)\frac{V}{Nd} = \frac{4\pi a^2 c}{3Nd}\sigma(z). \qquad (11)$$

On the edge of the cluster, in the region of maximal curvature of its surface ($z = 0, \rho = a$), we can obtain the particle charge substituting (10) into (11):

$$q(0) = \frac{\phi_0 a\sqrt{a^2-c^2}}{3Nd\arccos(c/a)}. \qquad (12)$$

In the region of minimal curvature ($z = c, \rho = 0$) the surface charge density (10) is a/c times lower and, therefore, the particle charge $q(c)$ is also a/c times smaller. The total charge of the oblate spheroid is

$$Q = \int_0^c 4\pi\rho\sqrt{1+\frac{\mathrm{d}\rho}{\mathrm{d}z}^2}\,\sigma(z)\mathrm{d}z = \phi_0\frac{\sqrt{a^2-c^2}}{\arccos(c/a)}. \qquad (13)$$

The comparison of (13) and (9) shows that in case of the spheroid the constant A has the meaning of its total charge.

In the cusp trap for the cluster of originally uncharged particles, $c = a/2$. After charging it at the potential ϕ_0 on the central electrode, the friction between contacting particles prevents changes in its form, and the ratio of c/a remains unchanged. In this case from (10), (12) and (13) we obtain, respectively,

$$\sigma(z) = \frac{3\sqrt{3}\phi_0}{4\pi^2\sqrt{a^2+12z^2}}, \quad q(0) = \frac{\sqrt{3}a^2\phi_0}{2\pi Nd}, \quad Q = \frac{3\sqrt{3}}{2\pi}a\phi_0. \qquad (14)$$

Estimation of the particle charge based on its velocity. Knowing the charge q and mass m_p of particles, one can estimate their scattering velocities in the final stage of cluster destruction, and compare with results of the video records. For $d = 300\,\mu$m particles the last gives 1–4.5 cm/s. The motion of particles in the magnetic trap after imposing the electric field $\mathbf{E}$ is described by the equation

$$m_p\frac{\mathrm{d}^2\mathbf{r}_k}{\mathrm{d}t^2} = \sum_l F(|\mathbf{r}_{kl}|)\frac{\mathbf{r}_{kl}}{|\mathbf{r}_{kl}|} + \mathbf{F}_{kB} + q\mathbf{E}(\mathbf{r}_k) + \mathbf{f}_k, \qquad (15)$$

where $\mathbf{r}_k$ is the radius vector of the particle k with respect to the origin of the coordinates (the point O_B at $i_1 = i_2$); $\mathbf{r}_{kl} = \mathbf{r}_k - \mathbf{r}_l$; $F(r) = q^2/r^2$ is the force of the Coulomb interaction between particles, $\mathbf{F}_{kB} = (\chi m_p/2)\nabla(\mathbf{B}^2(\mathbf{r}_k))$ is the power of the particle retention by the magnetic field. The electric field between the electrodes is assumed to be cylindrically symmetric, which is quite possible near the central electrode. In this case, the field intensity can be represented as $|\mathbf{E}(\mathbf{r}_k| = \phi_0/\rho_k\ln(R_2/R_1))$, where $\rho_k = \sqrt{x_k^2+y_k^2}$, R_1 and R_2 are radii of the central and outer electrodes, the direction of $\mathbf{E}(\mathbf{r}_k)$ coincides with the direction of the component of the vector $\mathbf{r}_k$ perpendicular to the z-axis. The friction force in the buffer gas is given by the Stokes formula [21] $f_k = -3\pi\eta d(\mathrm{d}\mathbf{r}_k/\mathrm{d}t)$, where η is the dynamic viscosity of the gas.

To estimate q we simplify eq. (15). Let us consider the motion of a particle in the x-y plane and replace the interaction with all particles by the interaction with the total cluster charge Q located in its center. As a result, we obtain the equation

$$m_p \frac{\mathrm{d}^2\rho}{\mathrm{d}t^2} = \frac{qQ}{\rho^2} - m_p|\chi|(B_p^{'})^2\rho + \frac{q\phi_0}{\rho\ln(R_2/R_1)} - 3\pi\eta d\frac{\mathrm{d}\rho}{\mathrm{d}t}, \tag{16}$$

where $B_\rho' = \mathrm{d}B_\rho/\mathrm{d}\rho = 200(i_1+i_2)/(2i_{max})\,\mathrm{G/cm}$.

Before the last stage of destruction (at $\phi_0 = 150\,\mathrm{V}$), when the cluster radius is $a = 0.9\,\mathrm{cm}$ and it has lost about half of its volume (fig. 3(b)), we assume that $N = 1.5 \times 10^4$. The graphite density is $2.1\,\mathrm{g/cm^3}$, and the particle diameter is $300\,\mu\mathrm{m}$, then its mass is $m_p = 3 \times 10^{-5}\,\mathrm{g}$. As was noted above the specific magnetic susceptibility of these particles could not be obtained, so we take the value $\chi = -5.1 \times 10^{-6}\,\mathrm{cm^3/g}$, which was found in this work for smaller particles ($d = 200\,\mu\mathrm{m}$); the same value χ was obtained in [2] for larger particles ($d = 400\,\mu\mathrm{m}$). The dynamic viscosity of argon under normal conditions is $\eta = 2.2 \times 10^{-4}$. The collapse of the cluster, as shown in fig. 3(d), (e), was observed at $i_1 = 0.5i_{max}$ and $i_2 = 0.3i_{max}$, so in a linear approximation the radial gradient of the magnetic field is $\mathrm{d}B_\rho/\mathrm{d}\rho = 0.4 \times 200\,\mathrm{G/cm}$. At $\phi_0 = 150\,\mathrm{V}$ in accordance with eq. (14) we obtain $Q = 8 \times 10^8 e$ and $q(0) = 5 \times 10^5 e$.

Substituting the described parameters into eq. (16), we solve it for initial conditions $\rho(0) = a, \mathrm{d}\rho/\mathrm{d}t|_0 = 0$ and find the time $t_p = 2.3\,\mathrm{s}$, during which the particle reaches the outer electrode, and its average velocity $v_\rho = (R_2 - a)/t_p = 0.71\,\mathrm{cm/s}$. This velocity is lower than the velocity of the slowest particles on the video record of the experiment, although comparable with them, and almost an order of magnitude lower than the velocity of the fastest particles. This situation may be explained by the fact that the particles are not identical, they are located on the surface of the cluster in different conditions, and the charge is unevenly distributed among them. The particles, which got higher charge, scatter first, and they are more visible in the video. An approximate dependence of the mean particle velocity v on its charge, obtained from the solution of eq. (16), is shown by the upper dashed curve in fig. 4. The maximum possible charge is $q_{max} = \phi_0 d/2 = 1.56 \times 10^7 e$, if the particle is charged, for example, directly at the central electrode. For these conditions $q_{max} = 1.56 \times 10^7 e$. The average velocity of the particle with the maximum charge is $v_{max} \approx 8\,\mathrm{cm/s}$, but particles with such velocities were not detected in the video. On the basis of this curve and the observed velocities of the particles it is possible to conclude that their charges are in the range $(1\text{–}6) \times 10^6 e$.

The lower dashed line in fig. 4 was also obtained from eq. (16) for the same particles, but at $\phi_0 = 75\,\mathrm{V}$. These estimates show that at the potential on the central electrode $\phi_0 = 75\,\mathrm{V}$ particles should scatter, although at lower velocities. However, this is not observed. This may be caused by autoadhesion of contacting graphite particles preventing their leaving from the cluster. Autoadhesion

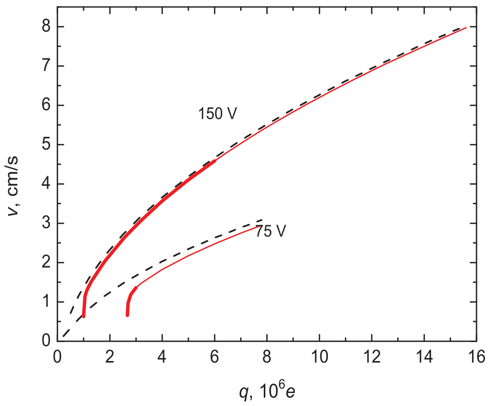

Fig. 4: (Colour online) Estimation of the $300\,\mu\mathrm{m}$ particle velocity as a function of its charge during cluster destruction. At the potential on the center electrode of 150 V (upper curves) and 75 V (lower curves), with (solid curves) and without (dashed curves) taking into account autoadhesion. The thick part of the solid curves corresponds to the realizable charge values.

is not taken into account by eqs. (15) and (16). This conclusion is confirmed by the experimental results in the ground-based conditions with a cluster consisting of a small number of particles [6–8]. In those experiments the formation of agglomerates of particles, which could not be separated by touching them with a special charged probe, was observed. As the probe potential increased, particles started to escape from the magnetic trap, either individually or as agglomerates. To some extent, it is an analogue of the separation of individual particles and filamentous complexes from the cluster, observed in this experiment. The formation of such filamentous complexes also confirms the importance of autoadhesion forces in the process of cluster evolution in the cusp magnetic trap.

To take into account this effect we add to the right side of eq. (15) an additional term, which retains particles with low velocities near the cluster and acts only at a distance of the order of the particle size d from it. As an approximate estimation we can write it in the following form:

$$-C\exp\left[-(\rho-a)^2/d^2\right], \tag{17}$$

where the coefficient C is chosen so that for $\phi_0 = 150\,\mathrm{V}$ particles with velocities $v < 1\,\mathrm{cm/s}$ unobserved in this experiment, *i.e.*, according to our estimation, with charges $q < 10^6 e$, were locked. For this purpose we set $C = 9\,\mathrm{cm/s^2}$. Then at $\phi_0 = 75\,\mathrm{V}$ particles with charges $q < 2.7 \times 10^6 e$ are locked. However, the term (16) practically does not affect the velocity of the particles with higher charges (solid curves in fig. 4). At $\phi_0 = 150\,\mathrm{V}$ the maximum observed velocities correspond to particle charges equal to $0.4q_{max}$; therefore, we show a part of the solid curves in fig. 4, corresponding to the realizable charge region, as thick. If we extrapolate this result to the case of $\phi_0 = 75\,\mathrm{V}$, then, taking into account the roughness of our estimates, it becomes clear that in this case there is no particles scattering from the cluster. There are no particles with charges higher than $q \approx 3 \times 10^6 e$, and particles with lower charges are locked due to autoadhesion.

Conclusion. – New experimental investigations of the behavior of Coulomb clusters of diamagnetic (graphite) particles in a cusp magnetic trap under microgravity conditions aboard ISS have been performed. Some results obtained in previous experiments are confirmed using simpler methods. The destruction of the cluster with the gradual increase in voltage at the center electrode of up to 150 V was observed. Estimations of the charges of the particles based on their observed velocities have been made. The interpretation of the obtained results is presented. It is shown that graphite particle autoadhesion can be important during cluster formation and destruction.

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