Article Type

Structure of a Coulomb cluster in the cusp magnetic trap under microgravity conditions

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Summary

The results of the experiment on the formation of a cluster in a cusp magnetic trap under microgravity conditions and its destruction at a gradual increase of its electric potential are discussed. It is shown that if a cluster is formed from initially uncharged particles, then the autoadhesion forces exert an important influence on its shape, structure and subsequent decay. The structure of the cluster is discussed and shown that it is formed by filamentary fragments.

Keywords: Coulomb systems, cusp magnetic trap, diamagnetic particle, cluster structure

1 Introduction

The main idea of the experiment "Coulomb crystal" aboard the International Space Station (ISS) [1–4] is formation, confinement and investigation of stable structures of charged particles in non-ionized medium at room temperature. This is an alternative of plasma-dust structures in gas discharges usually used for the study of Coulomb structures [5–7]. In our experiment a cusp magnetic trap for diamagnetic graphite particles is used. In non-homogeneous magnetic field B, any particle of mass is subjected to the action of the effective force [8]

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

where χ is the specific magnetic susceptibility of the particle material. For diamagnetic $\chi < 0$, so diamagnetic bodies are pushed into the local minimum – "the magnetic well" [9]. We use graphite particles because of maximum magnetic susceptibility of graphite, despite its strong anisotropy. For poly-crystalline graphite, the average value is $\chi = -(2.3 - 3) \times 10^{-6}\ cm^3$/g, however, for small particles it can differ from this value because of anisotropy. The first experiments with magnetic confinement of charged graphite particles were carried out in the ground-based conditions [10–12]. However, obtained clusters consisted of fewer than ten particles in the magnetic field $B \approx 10^4$ G with $\nabla B \approx 10^5$ G/cm . On the next step, to create Coulomb clusters containing thousands particles we have used the cusp magnetic trap aboard ISS under microgravity conditions [1, 2]. In this case, the fields $B \approx 10^2$ G with $\nabla B \approx 10^2$ G/cm were enough. The graphite particles were charged by contact with the electrode under potential 24 V, and then the magnetic field was switched on. In recent experiments [3, 4], the cluster was created from uncharged particles, then an electric potential was applied to the electrode and the cluster was charged. At the electric potential 150 V we observed the particles scattering and cluster destruction [3]. In the following experiment [4] the potential was increased from zero to 150 V in four steps, 37.5 V in each step, with a time interval of about 15 s. So we have observed details and peculiar properties of the cluster destruction. In this paper, based on these observations and estimations of the particle charges and their interaction forces at different steps of the electric potential increasing, we draw some conclusions about the structure of the cluster.

2 Experiment

We present here only main features of the experimental setup "Coulomb crystal" that are necessary for understanding the experimental results. It is described in details in [1, 2]. A cusp magnetic field is produced by two electromagnet coils located on the same axis with currents circulated in opposite directions. They are separated by an interval of 6 cm. Sketch of the setup is presented in Fig. 1. The resulting cusp magnetic field has a zero point O_B (magnetic well) on the symmetry axis between the coils. If the currents in both of the coils are identical, the point O_B is placed in the center between the coils as shown in Fig. 1.

In this region, a sealed cylindrical glass cell with a diameter of 52 mm and a height of 40 mm is placed. It is field with argon at atmospheric pressure and contains graphite particles. In the area inside the cell around O_B of radius no less than 2 cm, the magnetic field has a linear dependence on the coordinates with a good accuracy (within a few percent). In the direction of the symmetry axis $|dB/dZ| = 400(i_1 + i_2)/2i_m$ G/cm where i_1 and i_2 are the currents in both of the coils and $i_m = 6.5$ A is the maximum current in them. In the symmetry plain passing through the point O_B the radial component ($\rho^2 = x^2 + y^2$) of the field is two times less, $dB_\rho/d\rho = 200(i_1 + i_2)/2i_m$ G/cm which is typical for the cusp trap. Therefore, the effective force (1) of the cusp magnet trap has a linear dependence on the coordinates. The current in the coils can take values of 0, 30, 50, 70 and 100 % of the maximum i_m. Charging of the

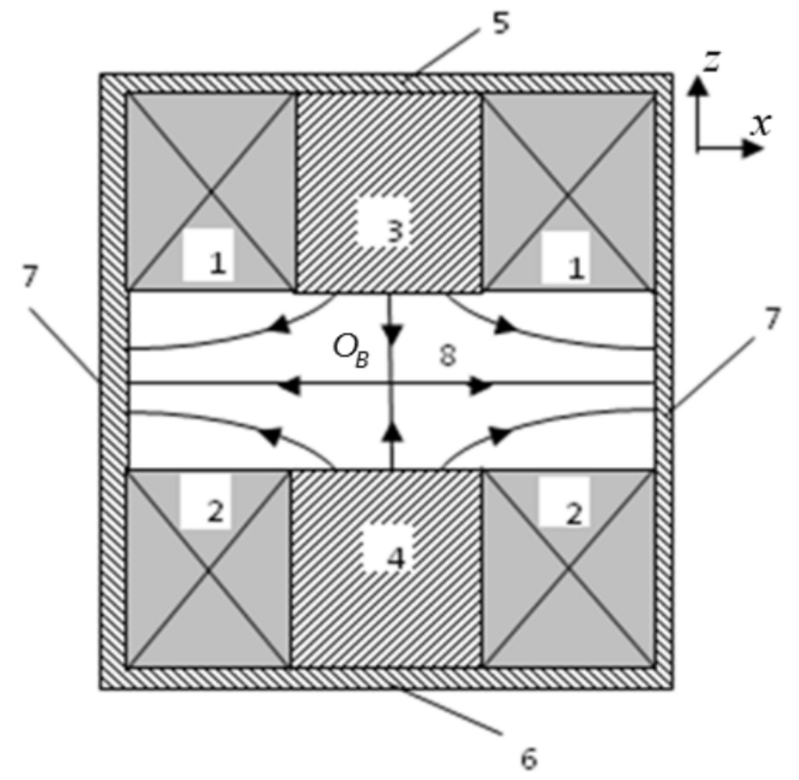

Figure 1: Sketch of the experimental setup creating a cusp magnetic trap. 1 and 2, solenoid coils; 3 and 4, cores of the coils (steel); 5 and 6, end magnetic conductors (steel); 7, side magnetic conductors; 8, working region is the magnetic trap. The case of identical currents in the coils $i_1 = i_2$ is shown; point O_B is the magnetic well, $\mathbf{B}(O_B) = 0$. The arrows indicate the direction of the magnetic field lines.

particles was carried out in contact with the wire electrode of diameter $2R_1 = 200\ \mu m$ passing along the cell axis. An outer grounded semicircular electrode of diameter $2R_2 = 51$ mm was placed near the cylindrical glass wall. The other half of the wall was free for observations. In the present paper we discuss results of the experiment [4] with about 30 thousand particles of size 300 μm in the glass cell. However, we should note that both the shape and size of graphite particles are difficult to control, therefore this size is approximate.

After shaking, the particles initially located on the glass walls filled the cell volume. Then the magnetic field was switched and under action of the cusp trap forces a cluster of uncharged particles was created in the form similar an oblate spheroid. Initial view and position of the cluster is presented in Fig. 2. Its thickness $2c$ along the symmetry axis z is about 1.2 cm and diameter $2a$ in the plane $x - y$ is about 2.4 cm. The relation $c/a = 1/2$ corresponds to the inverse ratio between the axial and radial components of the cusp trap force and is in agreement with the theoretical result in the approximation of continuous medium [2].

The position of the cluster on the z-axis depends on the relation between the currents in the coils. In the experiment under consideration, $i_1 = 0.5i_m$ and $i_2 = 0.3i_m$, so the cluster position is closer to the lower coil (bottom plate in the cell) that is seen in fig, 2.

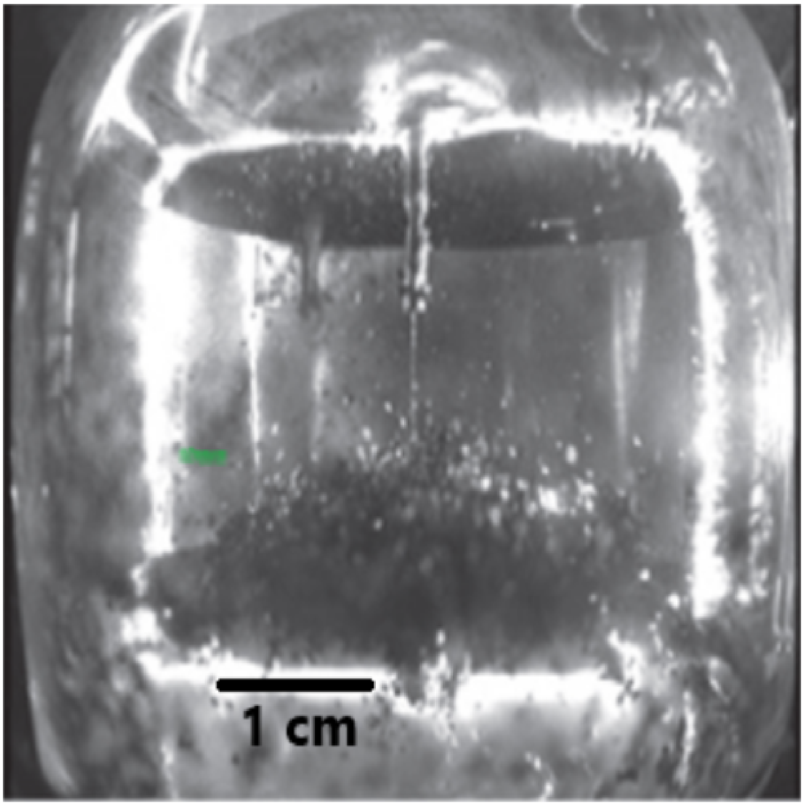

Figure 2: Initial position and shape of the cluster consisting of near 30000 initially uncharged graphite particles in the cusp magnetic trap at $i_1 = 0.5i_m$ and $i_2 = 0.3i_m$.

A potential was applied to the central electrode gradually increasing from zero to $\phi = 150$ V in four steps, 37.5 V in each step, with a time interval of about 15 s between them. During the whole experiment, a video was recorded. On the first step only a few filamentous complexes of particles leave the lower surface of the cluster and go to the bottom plate. It is known that graphite particles may form fractal and filamentous (chain-like) structures [13]. After switching on the second level ($\phi = 75$) V, this process significantly intensified. However, the decrease in cluster size is still imperceptible. On the next potential level ($\phi = 112.5$) V we see a cascade growth of the number of particle chains leaving the cluster and moving mainly to the bottom plate, although some of them move toward the side walls. At this stage, we can also observe small number of individual particles leaving the cluster with velocities $0.3 - 1$ cm/s. On the third step, the cluster loses about half its volume within 15 s. When the maximal potential of the central electrode ($\phi = 150$) V is switching on, we have observed an intensive scattering of individual graphite particles from the outer layer of the cluster in all directions similar "Coulomb explosion", however some particle chains moved mainly down. As the outer layer of particles decayed, the particles of the next layer are scattered, and so on until the cluster is destroyed completely within 8 s. The velocities of the scattered individual particles were from 1 to 4.5 cm/s. The wide range of the particle velocities indicates the considerable difference in particle charges. At the end of the scattering process there was no downward movement of particles to the bottom plate. Most particles move upward at an angle of $30 - 50°$ to the axis. This can be explained by the fact that many equally charged particles settled on the lower plate. Photos of the cluster in the cusp magnetic trap at different stages of its destruction are presented in our paper [4].

3 Estimations and discussion

On the base of the obtained experimental results we can draw some conclusions about the cluster structure. Its initial volume is about 3.5 cm^3, number of particle $N \approx 3 \times 10^4$, their size $d \approx 300\ \mu m$. The form of graphite particles is evidently irregular. However for estimations, we can assume that they are spherical with volume 10^{-5} cm^3. Therefore, the particles occupy only less than 10% by the cluster volume, i.e. the cluster structure is rather loose. Nevertheless, the cluster is a conductive structure, at least in the direction from the symmetry axis to the surface, i.e. between the central wire electrode and the cluster surface, since the cluster charge is distributed over its surface. The surface location of the cluster charge follows from the features of its destruction, namely the scattering of particles from the outer layer. In the case of the volume charge distribution the cluster destruction occurs with its volume increasing, bloating.

Assuming that the cluster is a conductive body in the form of an oblate spheroid under the potential of the central electrode ϕ, we estimate its total charge Q and surface charge density σ. Equation of an oblate spheroid surface is

$$\rho^2/a^2 + z^2/c^2 = 1, \tag{2}$$

where $\rho^2 = (x^2+y^2)$ and $a > c$. The potential ϕ, charge Q and the surface charge density σ are related by equations [14].

$$Q = \phi \frac{\sqrt{a^2 - c^2}}{\arccos(c/a)}, \tag{3}$$

$$\sigma(\rho, z) = \frac{Q}{4\pi a^2 c(\rho^2/a^4 + z^2/c^4)^{1/2}}. \tag{4}$$

Inserting Eq. (3) into Eq. (4) and excluding z by means of Eq. (2), we obtain the equation

$$\sigma(\rho) = \frac{\phi}{4\pi\left(\frac{a^4}{a^2-c^2} - \rho^2\right)^{1/2} \arccos(\frac{c}{a})}, \tag{5}$$

from which follows that the charge density is maximal at the cluster edge $\rho = a$. For estimations we do not take into account the distortion of $\sigma(\rho)$ at $\rho << a$ because of the electric field between the electrodes $E_e = \phi/\rho \ln(R_2/R_1)$. For $\rho \approx a$ its influence is small since the cluster field $E_c = 4\pi\sigma(\rho) >> E_e$.

In our case $c = a/2$ and from Eqs. (3) and (5) we have

$$Q = \frac{3^{3/2}}{2\pi} a\phi, \tag{6}$$

$$\sigma(\rho) = \frac{3^{3/2}\phi}{4\pi^2(4a^2 - 3\rho^2)^{1/2}}. \tag{7}$$

On the first step of the potential increasing ($\phi = 37.5$) V the cluster size is initial, $a = 1.2$ cm and $N = 30000$. Then we have $Q = 2.6 \times 10^8 e$, where e is the elementary charge. On the second step ($\phi = 75$) V the cluster destruction is still imperceptible and we can put the same values of a, so $Q = 5.2 \times 10^8 e$. At the third stage ($\phi = 112.5$) V, the cluster loses up to half of the particles in 15 s. For estimations we take average for this time value $a = 1.1$ cm , then $Q = 7.1 \times 10^8 e$. At the beginning of the fourth stage ($\phi = 150$) V, during which the cluster is completely destroyed, we put $a = 0.9$ cm, then we have $Q = 7.8 \times 10^8 e$.

Until the beginning of the fourth stage, the proportion between the linear dimensions of the cluster $a/c = 2$ is approximately preserved. However, during the intensive destruction it decreases and in the end of the decay $a/c \approx 1$. Such uneven destruction can be explained by more intensive leaving of the particles from the edge of the cluster ($\rho \approx a$), where the surface charge density (7) is maximal. The charge of the scattered particles can be estimated from their velocities obtained from the experiment. The motion of particles in the cusp magnetic trap is described by the equation

$$m_p \frac{d^2\mathbf{r}_p}{dt^2} = \sum_l F(|\mathbf{r}_{pk}|)\frac{\mathbf{r}_{pk}}{|\mathbf{r}_{pk}|} + \mathbf{F}_{Bp} + q_p\mathbf{E}_e(\mathbf{r}_p) + \mathbf{f}_p + \mathbf{F}_a, \tag{8}$$

where m_p and $\mathbf{r}_p$ are the mass and radius vector of the particle p, $\mathbf{r}_{pk} = \mathbf{r}_p - \mathbf{r}_k$, $F(r) = q_p q_k / r^2$ is the force of the Coulomb interaction between particles p and k, $\mathbf{F}_{Bp} = (\chi m_p/2)\nabla(\mathbf{B}^2(\mathbf{r}_p))$ is the force (1) of particle retention by the magnetic field. For simplicity the electric field between the electrodes near the central electrode is assumed to be cylindrically symmetric, then $|\mathbf{E}_e(\mathbf{r}_p)| = \phi/(\rho_p \ln(R_2/R_1))$ and the direction of $\mathbf{E}_e(\mathbf{r}_p)$ coincides with the direction of the component of the vector $\mathbf{r}_p$ normal to the z axis. The friction force in the buffer gas is given by the Stoke's law $f_p = -3\pi\eta d(d\mathbf{r}_p/dt)$ [15], where η is the dynamic viscosity of the gas. The last term $\mathbf{F}_a$ in Eq. (7) is the autoadhesion force between contacting graphite particles. This force acts at very short distances $s << d$.

We simplify Eq. (8) for estimation of the particle charge. Let us consider the separation of particles from the cluster at its edge ($z = 0, \rho = a$) and their motion in $x - y$ plane. Then we replace the interaction with all particles by the interaction with the total cluster charge Q located in its center. We approximate the autoadhesion force by an exponential dependence. As a result, we obtain the equation

$$m\frac{d^2\rho}{dt^2} = \frac{qQ}{\rho^2} - m|\chi|(B_p^{'})^2\rho + \frac{q\phi}{\rho\ln(R_2/R_1)} - 3\pi\eta d\frac{d\rho}{dt} - f_a \exp(\frac{-(\rho-a)^2}{s^2}). \quad (9)$$

The autoadhesion force f_a can be estimated on the base of the results of our experiments with graphite particles carried out in the ground-based conditions [10–12]. In that experiments charged particles separated if their potential was more than 30 V. But the electrostatic force of interaction between two contacting spherical particles under potential ϕ is $\phi^2/16$. Thus we can estimate the autoadhesion force between graphite particles as $f_a \approx 6 \times 10^{-9}$ N. With the density of graphite 2.1 g/cm^3 the particle mass $m \cong 3 \times 10^{-5}$ g, for the specific magnetic susceptibility we take the value $\chi = -5.1 \times 10^{-6}$ cm^3/g [4], the dynamic viscosity of argon under normal conditions is $\eta = 2.2 \times 10^{-4}$ g/(cm s).

We solve Eq. (9) with initial conditions $\rho(0) = a$ and $d\rho/dt\,|_0 = 0$ by setting corresponding values of ϕ, Q and a and specifying different values of the particle charge q. From the solution we get the dependence $\rho(t)$, the time t_p during which the particle reaches the outer electrode and its average velocity $\nu = (R_2 - a)/t_p$ depending on q. Results for $\phi = 75$, 112.5 and 150 V are presented in Fig. 3.

Calculations are performed for $q < q_{max} = \phi d/2$. Maximum value q_{max} corresponds to the particle charging directly from the central wire electrode without subsequent collisions with other particles that is practically impossible. Indeed, the particle velocities registered in the experiment, which given by the thick red part of the curves, correspond to much smaller charges. Vertical parts of the curves correspond to the minimum charges of particles that can be detached from the cluster. The particles with smaller charges are held by autoadhesion forces. For last stage ($\phi = 150$) V we give two curves in Fig .3 corresponding to the beginning ($a = 0.9$ cm) and the middle ($a = 0.6$ cm) of the

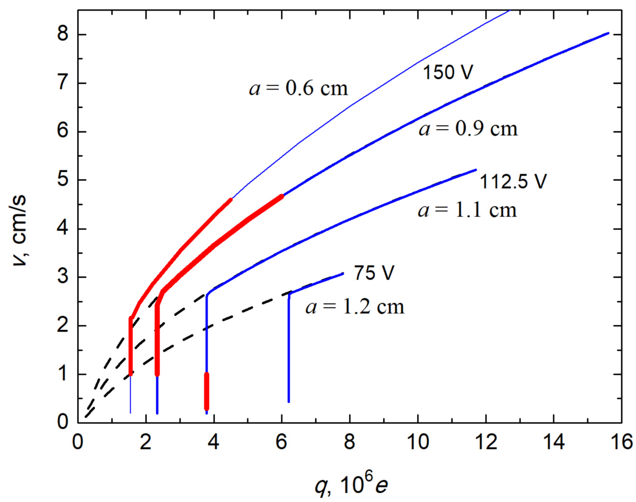

Figure 3: Dependence of the particle velocity on its charge at the cluster potential $\chi = 75, 112.5$, and 150 V (relative to the grounded electrode); two curves for 150 V correspond to the beginning of the cluster decay into individual particles ($a = 0.9$ cm) and after approximately 4 s ($a = 0.6$ cm).Thick red part of the curves corresponds to the range of observed velocities. Dashed curves correspond to the calculation without taking into account the autoadhesion forces.

cluster decay into individual particles. The relative position of these curves shows that as the cluster size decreases particles with smaller charges are detached from it. Indeed, for the first term on the right-hand side of Eq. (9), which is responsible for the Coulomb decay of the cluster, we have $qQ/a^2 \approx q/a$ according to Eq. (6). In the experiment we also observed some decrease in particle velocities during the 4th stage. In order to show the role of the autoadhesion forces we present by dashed curves the results of the calculations without the last term in Eq. (9). It is seen that they affect only the minimum charge of particles that can come off, but do not affect the velocity of particles with more charges (solid and dashed curves coincide). The destruction of the cluster begins with the detachment of filamentous fragments since their total charge may be sufficient to overcome the autoadhesion forces.

We can make some conclusions about the cluster structure. The cluster was formed by uncharged particles, so they could come into contact with each other and autoadhesion forces arose. These forces are strong enough to the cluster shape does not change after the electric field is turned on and the cluster is charged. This means that the auto-adhesion counteract the Coulomb repulsion to a greater extent than the magnetic confinement. If the charged particles were separated and held only by magnetic forces, the cluster would become more oblate; for the cluster of charged particles in a cusp trap $c/a = 0.3$ [2]. But the particles do not form a dense structure; they occupy only $1/10$ of the cluster volume. Apparently, the cluster consists of filamentary formations, which we see at the beginning of its destruction. The rupture occurs in places of the weakest autoadhesion. Since the graphite particles are irregular in shape, the autoadhesion forces have a considerable spread in magnitude. When there is a breakdown of the cluster into individual particles (on the fourth stage at $\phi = 150$ V), a significant scatter of their velocities is observed. This means a significant scatter of their charges, which can be associated with two reasons: some scatter in the size of the particles and an inhomogeneous charge distribution on the cluster surface. The latter can mean that the surface is inhomogeneous and its conductivity is not good enough. Thus, we can assume that the basic direction of the filamentary formations is from the axis of the cluster to its surface, which provides good conductivity between the central electrode and the surface, whereas the surface is not whole, entire and homogeneous, and its conductivity is not good.

4 Conclusions

We carried out a detailed analysis of the results of recent experiments [4] with a cusp magnetic trap for the diamagnetic (graphite) particles aboard the ISS (the "Coulomb crystal" experiment). By the features of the observed fragments of the cluster in the trap when it is destroyed as a result of a gradual increase in its electric potential and by the data of the corresponding calculations, we conclude following: (1) autoadhesion plays an important role in the formation of the cluster structure and its destruction; (2) the cluster charge is concentrated on its surface; (3) the cluster structure is formed mainly by filamentary fragments occupying about 10 % of the cluster volume and extended mainly from the symmetry axis to the surface.

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