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Levitation and agglomeration of magnetic grains in a complex (dusty) plasma with magnetic field

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Abstract. Interaction of magnetic particles with each other and with a magnetic field was studied experimentally in a complex plasma. Monodisperse plastic microspheres with magnetic filler were suspended in an rf symmetrically driven discharge to form a multilayer dust cloud. The magnetic field induced a magnetic moment in the grains. The particles were pulled upward in the direction of the magnetic field gradient and their levitation height increased. This was used as a new diagnostic method to calculate the particle charge and the thickness of the plasma sheath. It was demonstrated that the particle weight can be compensated for. Some particles formed agglomerates due to magnetic attraction between the grains. Analysis of the particle interaction forces showed that at intermediate magnetic fields (used in the experiment) the particles can agglomerate only if their kinetic energy is high enough to overcome the barrier in the interaction potential. The possibility of magnetically induced formation of a plasma crystal was discussed.

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1. Introduction

A typical complex (dusty) plasma consists of a plasma with immersed micron-sized particles [1, 2, 3, 4]. The particles acquire an electric charge and interact with each other electrostatically. They can levitate in electric fields e.g. the sheath of a plasma and form a cloud of mutually repelling particles. This cloud can be in different phase states: gaseous, liquid and solid [1, 5, 6]. It can sustain waves [7, 8], solitons [9] and Mach cones [10]. Since microparticles can be easily observed with a normal video camera, a complex plasma can be used as a model system to study phase transitions, wave propagation, and transport phenomena at a kinetic level [1, 11].

Complex plasmas are in some ways analogous to colloidal suspensions; in the latter the plasma is substituted with a fluid electrolyte. Compared to colloids, complex plasmas have much lower damping due to the neutral gas drag, which is a few orders of magnitude lower than the fluid drag. Lower damping can be an advantage, because it makes it possible to observe undamped wave modes and fast processes. Also, equilibration of the complex plasma takes seconds or minutes instead of days for colloids.

Lower damping can also be a disadvantage, the associated lower buoyancy makes complex plasmas more sensitive to the force of gravity. Equilibrated particles levitate in striations or in the plasma sheath where the electric field is strong enough to support them. Hence in ground-based experiments complex plasmas often form either a monolayer or a cloud with a few layers, i.e. two-dimensional or quasi-two-dimensional systems. Three-dimensional clouds can be obtained either with submicron-sized particles (which is not always desirable), under microgravity conditions [12], or if another force compensates for gravity. The thermophoretic force was used for this purpose in [13]. Here we propose to use a magnetic force to support magnetic particles and compensate gravity.

Magnetic particles were used earlier in colloids to study ordering phenomena (i.e. crystal formation and particle aggregation) [14], phase transitions [15], optical and magnetic properties [16, 17]. In this paper we investigate levitation and agglomeration of magnetic particles in a complex plasma under the influence of an inhomogeneous magnetic field.

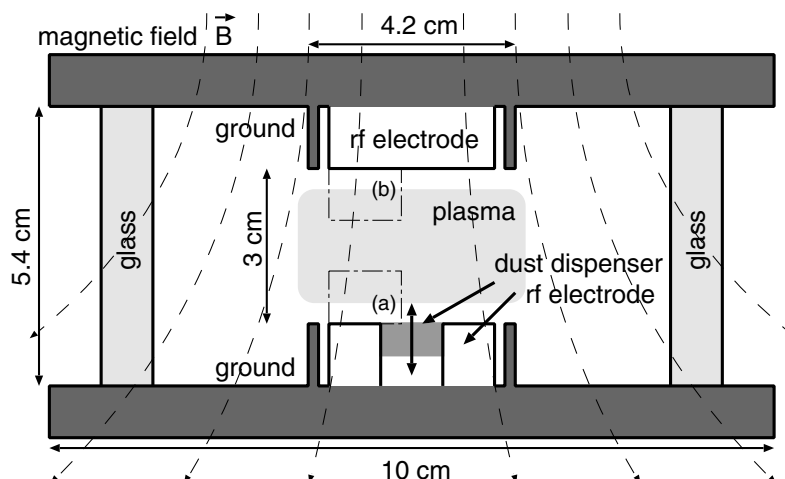


Figure 1. Side view of the experimental setup. The plasma was created by a capacitively coupled rf discharge between symmetrically driven parallel plate electrodes. Particles were levitated in the sheath region of the lower or upper electrode. The video camera viewed one of the two areas: (a) lower, for the lower sheath; (b) upper, for the upper sheath.

2. Experimental setup and observations

The experiments were performed in a capacitively-coupled radio-frequency discharge (figure 1). The discharge chamber was grounded and had two parallel plate electrodes, 4.2 cm in diameter, separated by 3 cm. They were symmetrically driven with a peak-to-peak voltage of 90 V. An argon gas pressure was maintained at 46 Pa.

A magnetic field (figure 2) was created by magnetic coils coaxial with the chamber. The distance between the lower edge of the coils and the lower electrode was 28 cm. The coils were powered with a current of up to 1.6 kA, yielding a magnetic field of up to 0.13 T in the middle of the chamber. The field gradient ($\approx 5 \text{ T m}^{-1}$) pointed up, exerting a levitating force on paramagnetic particles which had magnetic permeability $\mu = 4$.

We used plastic microspheres 4.5 μm in diameter (Dynobeads M-450 Epoxy) with an even dispersion of magnetic material (gamma Fe_2O_3 and Fe_3O_4) throughout the bead. The particles contained 20% iron and were super-paramagnetic i.e. they exhibited magnetic properties when placed within a magnetic field, but had no residual magnetism when removed from the magnetic field (as described on the company's web site). The particle mass density was 1500 kg m^{-3} .

When the particles were injected into the discharge in the absence of the magnetic field, they charged up and levitated as a multi-layer structure (figure 3(a)) in the plasma sheath electric field at the lower electrode. When the magnetic field was applied (figure 3(b)), some particles formed agglomerates, which were suspended below the main cloud. The main cloud levitated slightly higher than in the absence of the field. When we increased the magnetic field, the grains jumped into the upper sheath of the discharge (figure 3(c)). In this case the agglomerates moved above the main cloud.

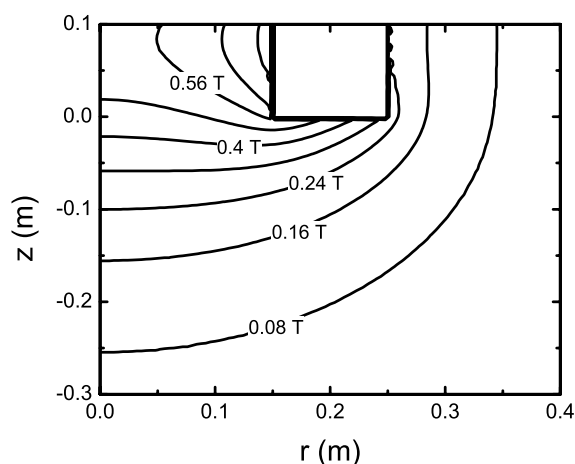


Figure 2. Magnetic field configuration at the current of 1 kA. The field is rotationally symmetric around the axis at $r = 0$ and coaxial with the chamber. The lower electrode of the chamber was positioned below the magnetic coils at -0.28 m. The coils created an inhomogeneous field with the gradient pointing upward. This applied a levitating force to the magnetic particles.

3. Discussion

3.1. Forces on the grains

In order to interpret the experimental results let us review the forces acting on the particles. The gravitational force is present in all ground-based experiments

$$F_g = m_p g = (4/3)r_p^3 \pi \rho_p g, \quad (1)$$

where m_p , r_p , and ρ_p are the mass, the radius, and the mass density of the particles respectively; g is the free-fall acceleration. This force scales as r_p^3 and does not depend on the particle height above the electrode. Gravity pushes particles larger than $1\text{--}2 \mu\text{m}$ down into the sheath making it difficult to create three-dimensional clouds. This makes it almost impossible to levitate large ($100\text{--}200 \mu\text{m}$) grains.

The electrostatic force is often used to levitate and confine the particles

$$F_e = QE, \quad (2)$$

where Q is the particle charge and E is the electric field. In first approximation the charge can be determined from the orbit-limited (OML) model $Q = 4\pi\epsilon_0 r_p \phi_p$, where ϵ_0 is the dielectric permittivity of vacuum and ϕ_p is the floating potential. This model is valid if the Debye length $\lambda_D \gg r_p$, which is a reasonable assumption for many laboratory experiments with micron-sized particles. The floating potential depends on the kind of gas and the electron temperature and is constant in the bulk of the discharge. In this case F_e scales as r_p . The electric field (and hence the electrostatic force) is high deep in the plasma sheath ($30\text{--}300 \text{ V cm}^{-1}$) and small in the bulk plasma (a few V cm^{-1}). Micron-sized particles normally levitate in the plasma sheath under gravity conditions.

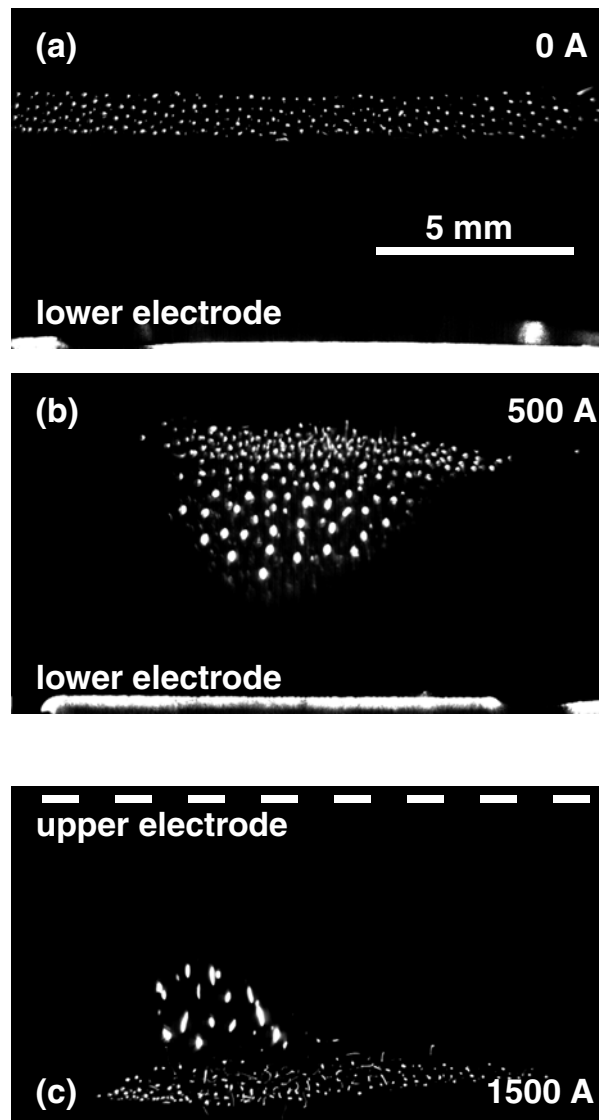


Figure 3. Particles levitated in the plasma. The current in the magnetic coils is indicated on the right. (a) Without the magnetic field. Particles form a multilayer cloud in the lower plasma sheath (lower viewing area). (b) Magnetic field of 0.04 T. Some particles agglomerate and levitate in the lower sheath below the main cloud (lower viewing area). The main cloud is compressed and slightly shifted upwards. (c) Magnetic field of 0.12 T. The cloud is levitated in the upper sheath (upper viewing area). The larger agglomerated particles levitate above the main cloud. Gravity can be compensated by the magnetic force.

The electric field in the plasma sheath polarizes the particles. The induced polarization is

$$\mathbf{p} = 4\pi\epsilon_0 r_p^3 \frac{(\epsilon - 1)}{(\epsilon + 2)} \mathbf{E}, \quad (3)$$

where ϵ is the dielectric permittivity of the grains. Since the electric field is not homogeneous

in the sheath it exerts a polarization force on the particles

$$\mathbf{F}_{pol} = -\mathbf{p}\nabla\mathbf{E}. \quad (4)$$

However this force is smaller than the gravitational force by six orders of magnitude and we can safely neglect it in our experiment.

If the particles have magnetic properties, they get magnetized in the external magnetic field and acquire a magnetic moment

$$\mathbf{m} = \frac{4\pi r_p^3 (\mu - 1)}{\mu_0 (\mu + 2)} \mathbf{B}, \quad (5)$$

where μ is the magnetic permeability of the particles, μ_0 is the magnetic permeability of vacuum, \mathbf{B} is the magnetic field. They are affected by a magnetic force if the magnetic field is inhomogeneous [18, 19]

$$\mathbf{F}_m = (\mathbf{m} \cdot \nabla)\mathbf{B}. \quad (6)$$

It is significant that this force scales as r_p^3 and therefore can exactly compensate for gravity even for non-monodisperse particles, provided that they have the same magnetic susceptibility.

The magnetic dipole is normally affected by a torque which turns it in the direction of the magnetic field. However, in our experiments, the magnetic dipole is induced and always aligned with the field, therefore the torque is zero.

In addition to these forces, grains are affected by the ion drag, thermophoretic and neutral drag forces which all scale as r_p^2 . The ion drag force results from streaming ions. It can be responsible for the cloud instability and the void formation [20]. The thermophoretic force arises if temperature gradients are present. The neutral drag force is due to collisions with neutral atoms. It damps the waves and instabilities.

3.2. Grain–grain interaction

In a strongly coupled complex plasma, the charged and magnetized particles are located a relatively small distance apart. Thus they can interact not only with the external fields but also with each other.

Grains with the same charge sign repel one another electrostatically. They are immersed in a plasma which shields the electric charges over a characteristic distance. The resulting interaction potential is of Yukawa type. The resulting repulsive force is

$$F_{el} = -\frac{Q^2}{4\pi\epsilon_0} \frac{\exp(-r/\lambda_D)}{r^2} \left(1 + \frac{r}{\lambda_D}\right) \quad (7)$$

where r is the distance between the particles and λ_D is the screening (Debye) length.

The induced magnetic dipoles interact with each other via a dipole magnetic force. The magnetic interaction potential is $U_{mag} = -\mathbf{m} \cdot \mathbf{B}$ [18, 19]. Substituting the expression for the field produced by a magnetic dipole gives the interaction potential of two magnetic dipoles [21]

$$U_{mag} = \frac{\mu_0}{4\pi} \left[\frac{\mathbf{m}_1 \cdot \mathbf{m}_2}{r^3} - \frac{3(\mathbf{m}_1 \cdot \mathbf{r})(\mathbf{m}_2 \cdot \mathbf{r})}{r^5} \right], \quad (8)$$

where \mathbf{r} is the radius-vector between the grains, subscript 1 or 2 denotes different particles. This potential will exert forces and torques on the dipoles. We do not consider the torques since the dipoles are aligned with the external magnetic field, which is assumed to be much stronger than the field of other dipoles.

In our experiment all the dipole moments are parallel and have equal magnitude. The magnetic interaction force of identical dipoles ($\mathbf{m}_1 = \mathbf{m}_2 = \mathbf{m}$) can be calculated by a straightforward procedure

$$\mathbf{F}_{mag} = -\nabla U_{mag} = \frac{\mu_0}{4\pi} \frac{3m^2}{r^4} [-\mathbf{n}_r (5 \cos^2 \theta - 1) + 2\mathbf{n}_m \cos \theta], \quad (9)$$

where \mathbf{n}_m and \mathbf{n}_r are the unit vectors in the direction of the magnetic moment and the radius vector \mathbf{r} between the particles ($\mathbf{m} = m\mathbf{n}_m$, $\mathbf{r} = r\mathbf{n}_r$); θ is the angle between \mathbf{n}_m and \mathbf{n}_r .

If the particles levitate in the same plane with their magnetic moments perpendicular to this plane ($\theta = \pi/2$), the interaction force is repulsive

$$F_{rep} = \frac{\mu_0}{4\pi} \frac{3m^2}{r^4}. \quad (10)$$

If the grains are arranged in a line along the same axis as their magnetic moments ($\theta = 0$), the interaction force is attractive

$$F_{attr} = -\frac{\mu_0}{4\pi} \frac{6m^2}{r^4}. \quad (11)$$

3.3. Levitation of the particles

In ground-based experiments without a magnetic field, the levitation condition will be mostly determined by gravity and the electrostatic force. Since the particle mass scales as r_p^3 and the charge as r_p , gravity will have a different effect on particles of different size. Smaller particles will have larger charge-to-mass ratio and therefore can be easily levitated even in small electric fields such as those present in the bulk plasma. Submicron-sized grains grown in a sputtering discharge easily form three-dimensional clouds in the bulk plasma [20].

Micron-sized grains require a larger electric field to levitate and therefore can only be suspended in the plasma sheath, where the electric field is strong enough. This case is shown in figure 3(a), where the particles levitate 5.7 mm above the lower electrode. The magnetic force changes the force balance and lifts the main cloud of single particles to a height of 6.4 mm (figure 3(b)). We can use this measurement to calculate the particle charge and the sheath thickness.

In a parabolic sheath approximation the sheath electric field is

$$E(z) = 2 \frac{\phi_0}{\lambda_s} \left(1 - \frac{z}{\lambda_s}\right), \quad (12)$$

where ϕ_0 is the potential drop in the sheath ($\phi_0 = 20$ V in the experiment), λ_s is the sheath thickness, and z is the particle height above the electrode. Substituting the measured values into the force balance equations with and without the magnetic field, and assuming that the particle charge does not change, we obtain

$$2 \frac{Q\phi_0}{\lambda_s} \left(1 - \frac{z_1}{\lambda_s}\right) = m_p g, \quad (13)$$

$$2 \frac{Q\phi_0}{\lambda_s} \left(1 - \frac{z_2}{\lambda_s}\right) + \frac{4\pi}{\mu_0} \frac{(\mu - 1)}{(\mu + 2)} r_p^3 B \nabla B = m_p g, \quad (14)$$

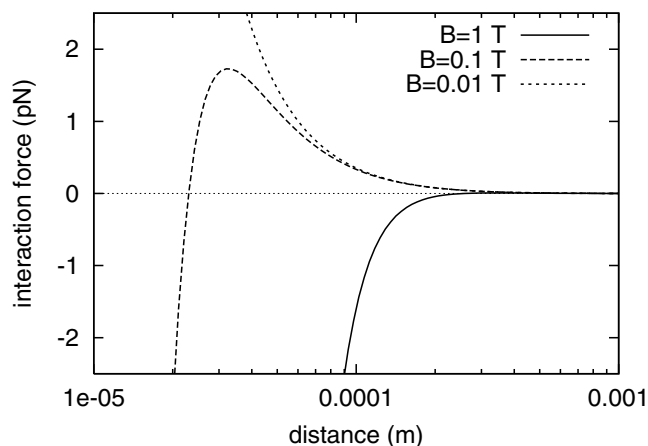


Figure 4. Calculated interaction force between the grains ($Q = 4000e$, $\mu = 4$) as a function of distance. The force is attractive at high magnetic fields ($B = 1$ T), changes sign at intermediate fields ($B = 0.1$ T), and is repulsive at low fields ($B = 0.01$ T).

where z_1 and z_2 are the particle heights without and with the magnetic field respectively. Solving these equations we obtain the sheath thickness and the grain charge

$$\lambda_s = z_1 + \frac{4\pi (\mu - 1)}{\mu_0 (\mu + 2)} \frac{m_p g}{r_p^3 B \nabla B} (z_2 - z_1), \quad (15)$$

$$Q = \frac{m_p g}{2\phi_0} \frac{\lambda_s}{(1 - z_1/\lambda_s)}. \quad (16)$$

For our experimental conditions we have $\lambda_s = 7$ mm and $Q = 4000e$. This procedure can be used for diagnostic purposes.

When the magnetic field is increased further, the particles move out of the lower sheath region into the bulk plasma and then jump into the upper sheath figure 3(c). They do not stay in the bulk plasma. This shows that gravity can be compensated for by the magnetic force.

With the magnetic field present (figure 3(b, c)), both single and agglomerated particles coexist and levitate at different heights. As mentioned above, this is due to the different charge to mass ratio, which is higher for smaller particles. If the magnetic field is weak and gravity is stronger than the magnetic force (figure 3(b)) the particles are confined in the lower sheath. The agglomerates are less affected by the electrostatic force and therefore levitate below the single grains, deeper in the sheath where the electric field is stronger and can support them. In case of a strong magnetic field (figure 3(c)) the magnetic force prevails over gravity and takes its role in pushing the agglomerates deeper into the upper sheath, while single grains remain closer to the bulk plasma in the region of a weaker electric field.

3.4. Agglomeration of the grains

If the attractive magnetic force between the particles exceeds the electrostatic repulsion, it can cause formation of agglomerates. The attractive force is highest if the particles levitate along the magnetic field lines. The induced dipoles are then aligned with opposite poles facing each other. Figure 4 shows the sum of the electrostatic (7) and magnetic dipole (9) forces between

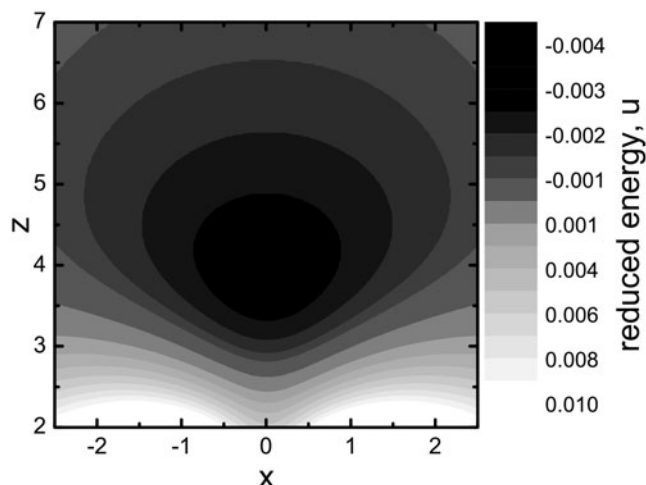


Figure 5. Interaction energy of two charged and magnetized particles as a function of their relative position, normalized by the Debye length. The particles are aligned vertically along the magnetic field, their induced magnetic moments are also vertical. There is a weak potential well which can in principle lead to the formation of linear chains of particles along the magnetic field, with particle separation of about $4\lambda_D$.

two particles at different magnetic fields. At distances greater than the particle size, this force is attractive at high magnetic fields ($B = 1$ T), changes its sign at intermediate fields ($B = 0.1$ T), and is repulsive at low fields ($B=0.01$ T). Thus the particles always agglomerate at high B , and always stay apart at low B .

At intermediate B , the force between the particles is attractive at small (and very large) distances and repulsive at intermediate distances, forming a barrier. The particles agglomerate only if they can penetrate through this barrier, for example due to the thermal motion. In the experiment (figure 3(b, c)) we observe both agglomerated and single particles which implies that particle thermal motion was significant.

3.5. Magnetically induced crystallization

In the case of intermediate magnetic fields described above, the particles repel each other at intermediate distances because the electrostatic force is stronger. However at larger distances, the magnetic force always prevails, since it decays as $1/r^4$, while the electrostatic force is screened and proportional to e^{-r/λ_D} . This forms a well in the interaction potential of two grains (figure 5). The well is placed at distances larger than the repulsive barrier described above. Sufficiently ‘cold’ interacting particles can be confined in this well at a distance of about $4\lambda_D$ and can thus form particle chains in the direction of the magnetic field. In order to actually induce crystallization, the particle kinetic energy should be much lower than the depth of the well. However, the depth of this well is less than a few per cent of the electrostatic potential of two particles at a distance of λ_D , too shallow to be visible in figure 4.

4. Conclusion

A complex plasma with magnetic particles was produced and investigated experimentally. The grains were charged by the plasma and had magnetic dipole moments induced by the external magnetic field. We studied the interaction of the particles with the external magnetic field and with each other by observing their levitation and agglomeration.

It was found that the levitation height of the grains increased when the magnetic field was switched on, as a consequence of the force exerted by the field gradient. From the increased levitation height it was possible to calculate the particle charge and the plasma sheath thickness (providing a new charge diagnostics method).

A stronger magnetic field drove the grains into the upper sheath, demonstrating that gravity can be compensated for magnetically.

It was further shown that the particles can form agglomerates due to magnetic attraction. We calculated that the grain–grain interaction potential forms a barrier at the magnetic field strength used in the experiment. The particles had high enough kinetic energy, however, to overcome this barrier. This explained the coexistence of single particles and agglomerates.

It was calculated that the magnetic attraction can give rise to a one-dimensional crystal structure in the direction of the magnetic field (the magnetic attraction is long range and the electrostatic repulsion is short range). Therefore a well in the particle interaction potential can be formed under certain conditions. Since this well is very shallow, the particles need to have very small kinetic energy in order to lead to confinement and crystal formation. Cryogenic magnetic systems may be able to provide the desired conditions for this new type of ‘electromagnetic plasma crystal’.

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