STRUCTURES AND MOTIONS OF STRONGLY COUPLED DUSTY COULOMB CLUSTERS

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Abstract. The formation of quasi-2D Coulomb clusters of negatively charged dust particles with particle number N from 1 to a few hundred in a cylindrical plasma trap are demonstrated. The symmetry breaking due to the radial confining force leads to the formation of concentric shell structures, which suppresses radial excitations and prefers intershell angular vibrational and rotational excitations for small N. At large N, the triangular lattice for the infinite lattice is recovered in the inner part of the cluster. The radial confining force only forms few circular shells in the outer region. The vortex type excitation observed in our previous studies is recovered. The experimental results qualitatively agree well with the numerical results using simple models.

In a laboratory dusty plasma system, the suspended micrometer sized dust particles can be charged up to 10^4 electrons due to the higher electron transport rate than ion. It turns the system into a strongly coupled Coulomb system even at room temperature. Large volume crystal (with sub mm lattice constant) and liquids exhibiting interesting structures and motions have been demonstrated experimentally [1-3]. The proper spatial and temporal scales of the system allow direct optical monitoring of the microscopic phenomena. With this convenient system, it is nature to raise the interesting issues: (1) Is it possible to stably confine clusters consisting of small number N of dust particles? (2) How do these *classical-atom* like clusters behave?

The strongly coupled Coulomb cluster (SCCC) with a small N is a mesoscopic nonlinear system with finite degrees of freedom, which exhibits rich microscopic structures and nonlinear collective excitation under thermal fluctuations. The classical atom proposed by J.J. Thomson with electrons embedded in a uniform neutralizing background (equivalent to a parabolic confining potential), electrons in quantum dots, flux lines in the superfluids, superconductors and magneto-plasmas all share some common features as the 2D SCCC [4-8]. Basically, for an infinite N system, the structure of the Wigner crystal is mainly determined by the mutual repulsion which leads to the uniform triangular lattice. The central confining force and the finite boundary at small N breaks the symmetry and leads to the competition between the shell structures and the triangular lattice. Under the structure with special symmetry, the collective excitation are also nonuniform and anisotropic. The concentric shell structures and the normal mode excitations have been predicted by Monte Carlo simulations [5-7].

A cylindrical rf glow discharge system with a 9 cm diameter and 4.5 cm height for our previous large volume dust crystal experiment is modified for this experiment [1]. The weakly ionized glow discharge is generated in Ar at a few hundred mtorr pressure and low rf power (< 0.5 W) using a 14 MHz rf power system. Polystyrene particles with 0.005 mm diameter are used as dust particles. Instead of the large radius groove for our previous experiment, a concentric hollow cylinder with 3 cm diameter and 1.5 cm height is put on the bottom electrode to confine dust particles. The larger electron mobility than ion makes the plasma float positively to the electrodes to balance their loss rates. Under very low rf power, a small region with uniform plasma density and a few mm diameter appears in the center. It is surrounded by the thick dark space (double layer) supporting outward radial space charge field adjacent to the glass wall. Adding dust particles into the discharge sucks part of the electrons and leaves a ion rich background. Particles can then be trapped and form a cluster in the center uniform region. The strong vertical ion flow generates dipole interactions and aligns particles vertically. Namely, the system is quasi-2D. Particle mainly move in the horizontal plane and their trajectories can be long term monitored using an optical microscope with small optical depth and connected to a CCD camera. Unlike other ion traps operated at a few mK temperature and require complicated photo counting detection [9], this study in the plasma trap give the first systematic experimental supports for the theoretical predication of the behavior of 2D SCCC.

Figure 1 shows a few typical configurations observed in our experiment at different N. Basically, as predicted by theories, the radial confining force tend to bend the triangular lattice to form concentric shell structures. However, from the coarse grain scale, the configuration tends to be space charge free to minimize the electrostatic energy. The best way is forming triangular type lattice in the inner core with uniform interparticle spacing, i.e. pushing the nonuniform space charge around the cluster boundary. Therefore, although concentric shells can be drawn, the particles in the inner part sit close to the triangular lattice site by forming single point, dumbbell, triangle, and diamond structures in the center shell. Only the outmost shell is circular. For example, the second shell of the (2,8) or (2,8,13) structure is elliptical instead of circular. We also carried out a Molecular Dynamics simulation with small linear damping and adjustable temperature, for a parabolic confining field and Yukawa type repulsion. It shows that the generic packing behaviors are very similar over a wide range of Debye length, as long as the Debye length is greater than 1 lattice constant. For the very short Debye length, the total cluster size is reduced. The structure is more similar to what obtained from a hard sphere system. The system is highly incompressible and likes to have less elongated shape to reduce confining potential by squeezing particles into the center part to form a less elongated center part. Our experimental results agree very well with those obtained from the simulation of the bare Coulomb repulsion. It indicates that the range of repulsion in our system is not very hard core type. The formation of pentagon inner shell is also another evidence of the soft repulsion. The contribution from the dipole or the adjacent particles along the chain might compensate part of the Debye screening.

The strong radial locking due to the formation of shell structures suppresses the radial excitation. The intershell radial hopping is not observed. The system prefers the intershell angular vibrational and rotational excitations at finite temperature. As N increases to larger than 50, the circular shells can only be identified in the outmost region of the cluster. The center part recovers to the triangular lattice with thermal defects as an infinite N system. The intrinsic defects could also move into the boundary between the shell and triangular structures. The excitation also recovers to the vortex type excitation observed in the large volume system.

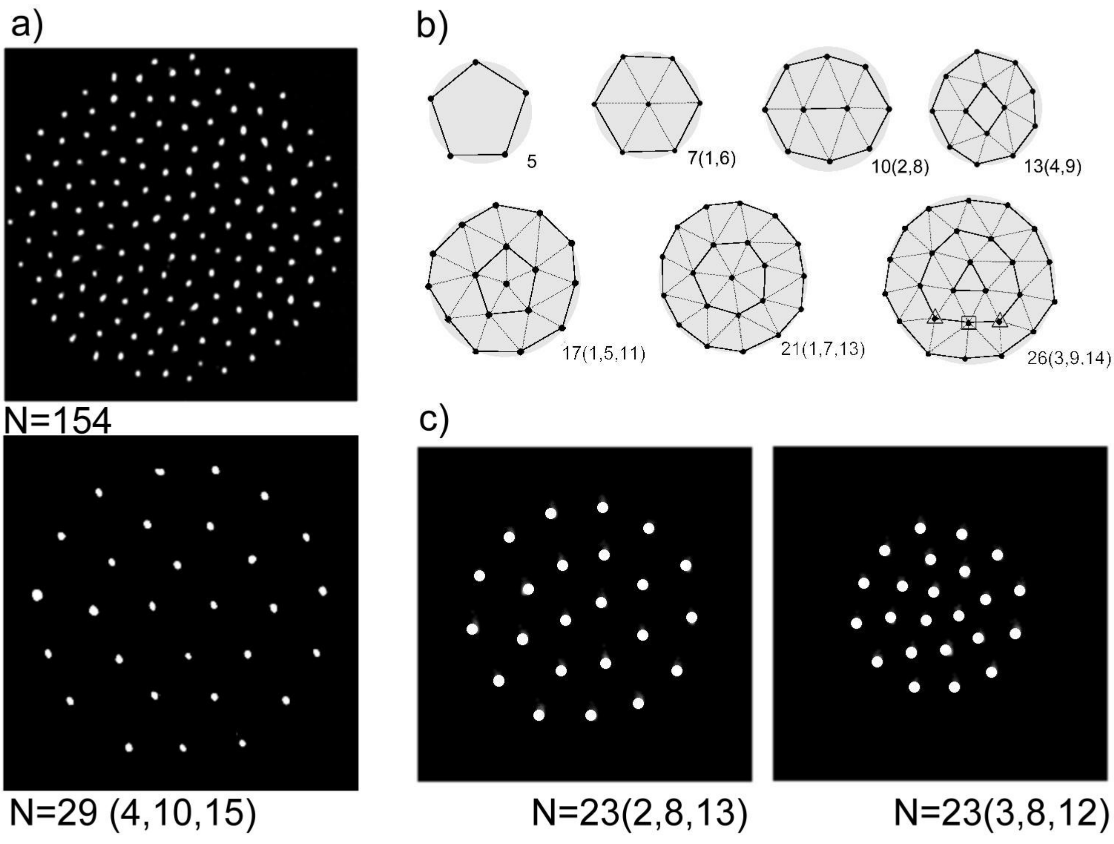
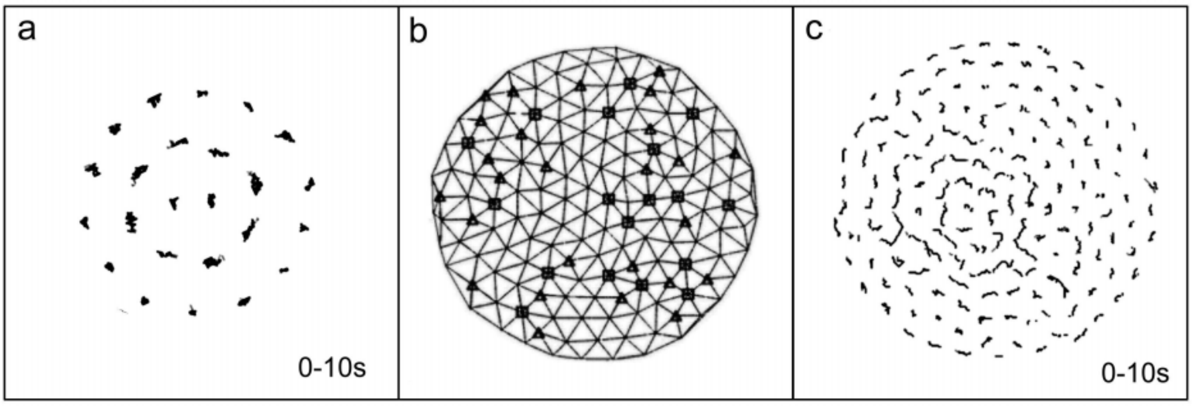


Fig. 1. a) The typical microimages with large and small N from our experiment. b) The stable triangulated configurations obtained from our experimental images. The scales are not exactly the same. The mean interparticle distance is about 0.6 mm. c) The typical ground state configurations from the MD simulation using bare Coulomb interaction. Making the Debye length too short will turn the (2,8,13) structure into the (3,8,12) structure which has less elongated shape.



Fig, 2. a) The trajectories showing the angular excitation dominated motion for the (2,8,14) state. b) The triangulated structure of the N = 155 state. c) The trajectories showing the vortex excitation dominated motion.

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