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Order Phenomena of 3D Yukawa-Balls

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Dusty plasmas are ideal systems to study the dynamics of crystalline charged particle systems since the spatial and temporal scales are perfectly suited for direct observation by video cameras [1, 2]. The particles immersed in a plasma environment become highly negatively charged due to the continuous inflow of plasma electrons and ions. Recently it has become possible to trap ball-shaped three-dimensional dust clusters called Yukawa balls [3, 4]. The Yukawa balls that consist of several concentric shells provide a detailed insight into their structure and dynamic properties. Dust clouds build ordered states when the coupling parameter $\Gamma = Z^2e^2/4\pi\varepsilon_0 bk_BT$ reaches a value of 180 for infinite systems (Z charge number, b interparticle separation). Highly-charged microparticles (Z=2000) trapped in a plasma envirionment are strongly coupled at large interparticle distances $(b \approx 500\ \mu m)$ and room temperature (T=300 K). It has to be taken into consideration that highly charged particles interact by a shielded Debye-Hueckel potential in contrast to ion crystals which interact by a pure Coulomb potential.

For the investigation of the full three-dimensional structural and dynamical properties of Yukawa balls we have developed a system of three high-speed video-cameras that are arranged perpendicular to each other (Fig. 1). This setup allows the determination of all particle positions simultaneously and with high spatial and temporal resolution.

In this contribution results from long-time investigations of Yukawa balls are presented with particular interest to the motion of particles on shells and transitions of particles between shells. Clusters with fixed particle number are known to usually posses metastable states with energies higher than the ground state. The different metastable configurations are investigated with respect to their structure the frequency of occurrence. The experiments have been performed in a capacitively coupled rf-discharge at 13.56 MHz in argon at

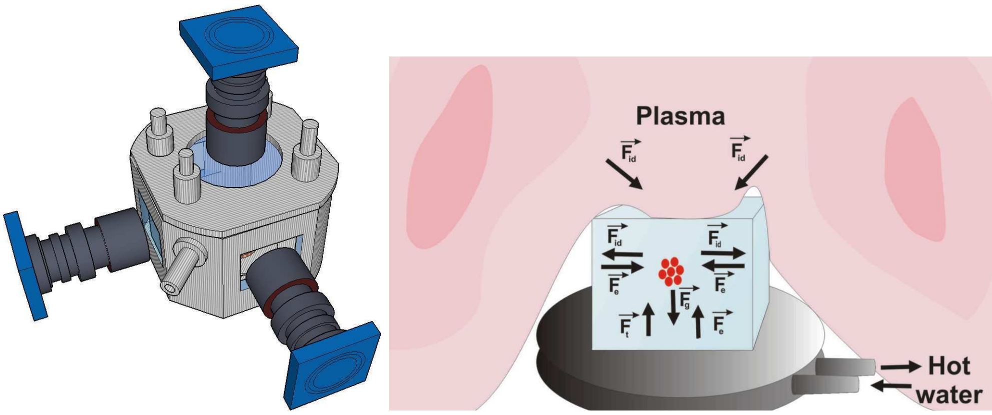

Figure 1: Left: Stereoscopic setup of three synchronized high-speed cameras. The particle cloud is illuminated (not shown) by an expanded laser beam (532 nm, 0.6 W). Right: Trapping schema of Yukawa balls. (See text for details)

a gas pressure of 90 Pa and a discharge power of 7.5 W. The horizontal confinement of the monodisperse plastic spheres of 3.46 μm diameter is provided by a cubic glass tube placed on the lower electrode, see Fig 1 (right). The vertical position where the particles are trapped is defined by the electric field of the electrode and the applied upward thermophoretic force that partially compensates gravity by a combined action [3, 5].

The occurrence of transitions between shells in Yukawa balls is investigated by recordings at a low frame rate of 4 fps. This enables long-time experiments that allow a reliable tracking of individual particles. An example of a cluster with N=31 particles is shown in Fig. 2 (left). The cluster of N = 31 particles is well suited to investigate different configurations in view of structure and probability of appearance because the particle number is well separated from magic configurations (N = 12 and N = 57). Apart from the imperfections of particle detection is seen that the occupation number of the outer shell temporarily decreases while the particle number of the inner shell increases. This transition is furthermore illustrated in the cylindrical coordinates ρ-z. It is seen that the configuration of the cluster changes from (4,27) to (5,26). Thus, here a self-excited transition from the ground state (4,27) to the metastable configuration (5,26) is observed. To intentionally generate different configurations of a cluster the following procedure is applied. The confinement of the trapped Yukawa ball is very sensitive to the discharge parameters and can therefore be destroyed by a well adjusted variation of the parameters without losing the particles. When the plasma is restored to its former

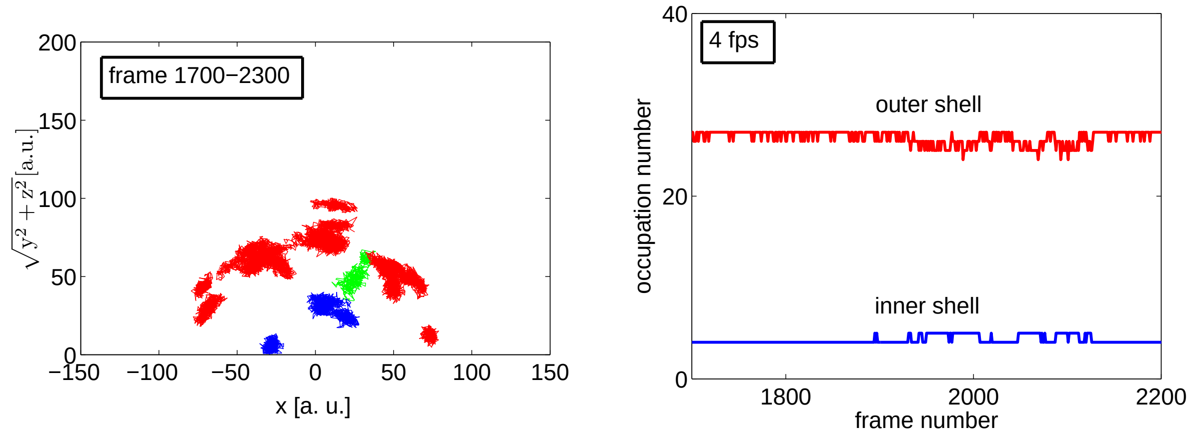

Figure 2: Transition of a single particle between shells in Yukawa balls. Left: particle trajectories in a $\rho = \sqrt{y^2 + z^2}$ vs. x plot. Right: Occupation number of inner and outer shell versus time: The structure of the crystal with N=31 particles changes from (4,27) to (5,26).

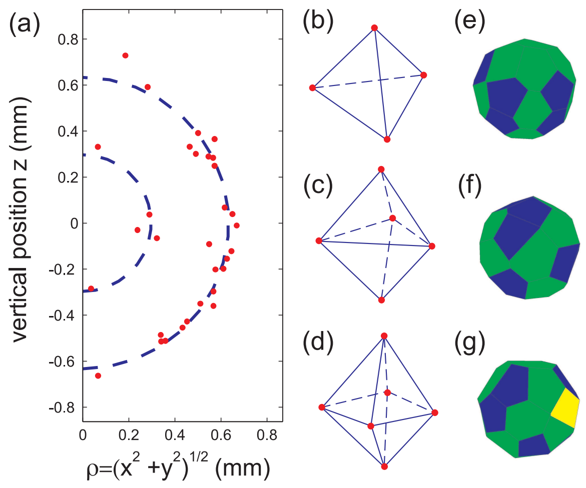

Figure 3: Structure of metastable configurations of the $N = 31$ cluster. (a) Particle positions in cylindrical coordinates in the ρ-z plane. The red dots are the average particle positions of a (5,26) configuration. The dashed lines indicate the shell radii (R_i and R_o). (b-d) show the average structure of the inner shell. The particle arrangement is shown for clusters with $N_i = 4$ (b), $N_i = 5$ (c), and $N_i = 6$ (d) particles. (e-g) Voronoi analysis of the corresponding outer shell for $N_o = 27$ (e), $N_0 = 26$ (f), and $N_o = 25$ (e) particles. Pentagons are blue and hexagons are green. All plots show experimental results.

conditions the dust cloud rearranges without any memory to its former configuration. Fig. 3 shows different configurations of a N = 31 cluster. All clusters are found to consist of two shells, but the shell population differs among these clusters. Clusters with $N_i = 4, 5$ and 6 particles on the inner shell are observed. The particle arrangement of the inner shell is given in Fig. 3b-d. The observed structures are in perfect agreement with those expected from geometric considerations, namely a tetrahedron for $N_i = 4$ a double tetrahedron for $N_i = 5$ and a bipyramid for $N_i = 6$. As shown by the Voronoi cells in Fig. 3e-g, the particles on the outer shell arrange in an organized pattern of hexagons and pentagons as required for a hexagonal lattice bent onto a sphere. Hence, well defined crystalline clusters of different (metastable) states (4,27), (5,26) and (6,25) have been reliably produced in the experiment.

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