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Experiments on Particle Interactions in 2D Dust Coulomb Clusters

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Complex plasmas consist of macroscopic charged particles, typically of micrometer size, immersed in a gaseous plasma. The particles acquire high negative charges of the order of ten thousand elementary charges by the continuous collection of plasma electrons and ions. The mutual electrostatic interaction between these highly charged microspheres by far exceeds their thermal energy under these conditions, they are strongly coupled.

The study of 2D finite Coulomb dust clusters offers a detailed insight into the dynamic properties of complex plasmas. These clusters consist of a small number of microspheres ($N = 1 \ldots 100$) trapped in the sheath of an rf discharge at low gas pressure [1, 2]. The particles are confined vertically in a strong potential well formed by gravity and the electric field thereby forcing the particles to form horizontally extended 2D systems. Horizontally (radially) they are confined in a shallow parabolic potential. The dynamical behavior of these systems is described in terms of their normal mode oscillations [3, 2, 4]. Due to the small numbers of particles involved experimental results can be compared to theory and simulations in every detail.

Here, measurements on the normal modes of different 2D finite clusters are presented. Normal modes oscillations of the dust clusters can either be excited by an active harmonic or pulse-like perturbation of the system or normal modes can be extracted from the thermal Brownian motion of the particles. The mode spectra of different clusters have been measured from such thermally excited Coulomb clusters. This technique, previously used in experiments by Nunomura et al. [5] on waves in “infinite” 2D plasma crystals, has been adapted here for finite clusters. It allows the simultaneous measurement of *all* the possible normal modes of finite clusters. From a comparison with calculated normal modes, the interaction between the microspheres has been derived in terms of the particle charge and the screening strength.

Two-dimensional finite clusters of N particles in a complex plasmas are characterized by

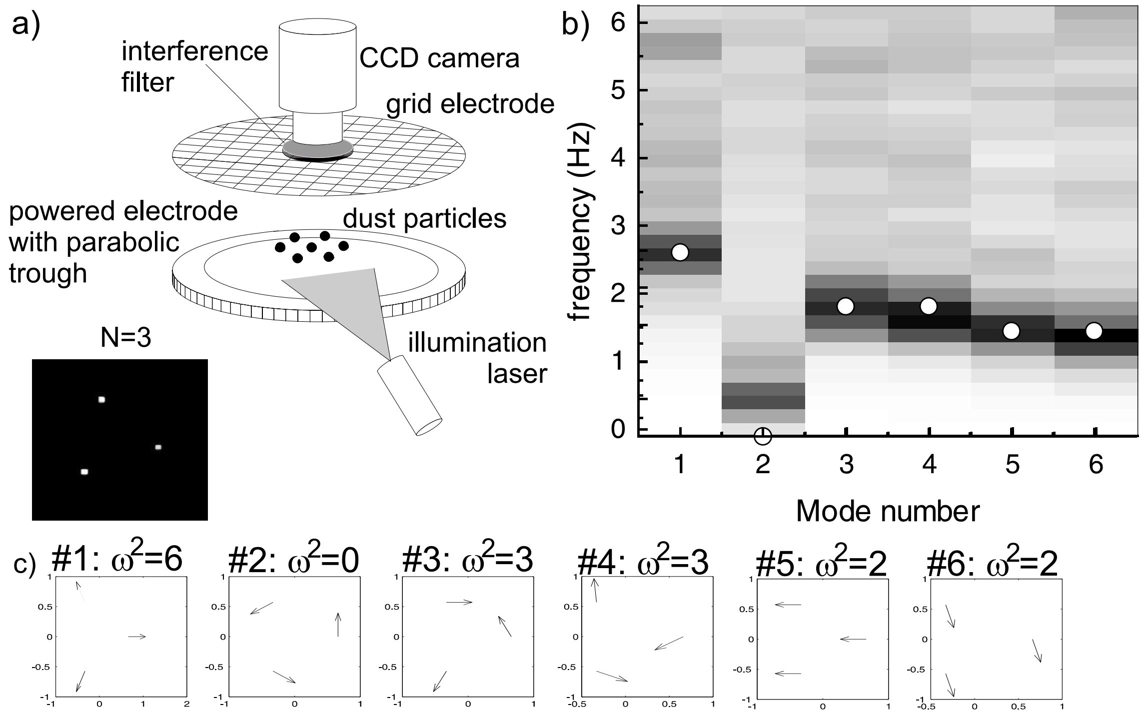

Figure 1: *a) Scheme of the experimental setup. The dust particles are illuminated by a sheet of laser light and the particle motion is recorded by a CCD camera from top. The insert shows a still image of the* $N = 3$ *cluster. b) Grey-scale plot of the power spectrum of the 6 modes of the 3 particle cluster. Superimposed (open circles) are the theoretical values of the eigenmode frequencies. c) Mode pattern of the 6 eigenmodes of the* $N = 3$ *cluster.*

the total energy E of the system

$$E = \frac{1}{2} m\omega_0^2 \sum_{i=1}^{N} r_i^2 + \frac{Z^2 e^2}{4\pi\varepsilon_0} \sum_{i>j}^{N} \frac{1}{r_{ij}} \exp\left(-\frac{r_{ij}}{\lambda_D}\right) \qquad (1)$$

which is the sum of the radial confining potential energy and the (screened) Coulomb interaction between the particles. Here, m denotes the mass of the particles and Z is their charge number. The strength of the horizontal confining potential is denoted by ω_0. In addition, $r_i = (x_i^2 + y_i^2)^{1/2}$ is the radial coordinate of the ith particle and $r_{ij} = |\vec{r}_i - \vec{r}_j|$ is the distance between particle i and j. The normal modes of the 2D clusters are then obtained from the dynamical matrix

$$E_{\alpha\beta,ij} = \frac{\partial^2 E}{\partial r_{\alpha,i} \partial r_{\beta,j}} \qquad (2)$$

with α and $\beta = x, y$ and i, j denoting the particle number. The normal mode frequencies ω_ℓ

of the $2N$ modes are the eigenvalues of the dynamical matrix and its eigenvectors describe the cluster oscillation mode pattern [3].

The experiments have been performed in a parallel plate rf discharge operated in argon at 13.56 MHz with gas pressures of 1.5 to 2 Pa and discharge powers between 3 and 40 W (see Fig. 1a). A few ($N = 3$ to 20) melamine-formaldehyde (MF) particles of 9.55 μm diameter are immersed into the plasma, trapped in the space charge sheath above the lower electrode by electric field forces and gravity, and are illuminated by a laser fan (at 690 nm, 40 mW). The particles form 2D finite Coulomb clusters above the lower electrode. The horizontal confinement for the particles is realized by a shallow circular parabolic trough in the electrode. The particle motion is viewed from top and from the side with video cameras and stored into the computer for further processing.

In the experiment, the particle motion was recorded for 1 minute (corresponding to 1500 frames at 25 frames per second). No excitation in any form was applied, only the thermal Brownian motion of the particles around their equilibrium positions $\vec{r}_i(t)$ was recorded. These thermal fluctuations were used to obtain the normal mode spectra in the following manner: First, the time series of the particle velocities $\vec{v}_i(t) = d\vec{r}_i(t)/dt$ projected onto the direction of the normal mode vectors was determined for each mode number $\ell = 1 \ldots 2N$, i.e. the quantity $f_\ell(t) = \sum_{i=1}^{N} \vec{v}_i(t) \cdot \vec{e}_{i,\ell}$ was calculated. Here, $\vec{e}_{i,\ell}$ is the eigenvector of particle i for mode number ℓ describing its oscillation amplitude and direction of oscillation. Thus, $f_\ell(t)$ is the contribution of the thermal fluctuations to mode number ℓ in the time domain. Finally, the normal mode spectra are obtained in form of the spectral power density $S_\ell(\omega) \propto |\int f_\ell(t) \exp(-i\omega t) dt|^2$.

The result of such a measurement is shown in Fig. 1b). There, the mode spectrum of a $N = 3$ cluster is shown for a discharge power of 9 W. The thermal fluctuations of the microspheres around their equilibrium are small, but they are nevertheless sufficient to determine the mode spectrum. The 6 eigenmodes of this clusters (see Fig. 1c) are the breathing mode ($\ell = 1$), rotation of the entire cluster ($\ell = 2$), a twofold degenerate “kink” mode ($\ell = 3,4$) and two sloshing modes in the confining potential well ($\ell = 5,6$).

In Fig. 1b, the measured mode spectrum is shown as a grey scale plot. Dark regions correspond to large power densities. For comparison, the calculated mode frequencies are also indicated by the circles. One can see the very good agreement between the measured power spectrum and the calculated mode frequencies. Thus, the measured spectrum very well reflects the expected values. The calculated mode frequencies contain the adjustable parameters ω_0 and κ. Best agreement with the measured spectrum is found in the range $\infty \geq \lambda_D \geq 600\ \mu$m and $\omega_0/(2\pi) = 1.3 \pm 0.2$ Hz resulting in a dust charge of $Z = 11\,000 \pm 1200$. These values are in excellent agreement with those obtained from excitation techniques [4].

Finally, the effective temperature of the cluster can be extracted from these data. It is seen from the intensities of the grey-scale plot that the different modes seem to have comparable power densities. Indeed, the stored energy $E_\ell = \int S_\ell(\omega) d\omega = 47$ meV is the same for each mode (within 5 % error). This energy corresponds to a temperature of the dust particles of $T = 540$ K which is slightly above room temperature. This means that the cluster modes are in thermal equilibrium and the principle of equipartition holds, here. These findings are substantiated by similar experiments on clusters with $N = 5, 7, 12, 16, 19$ and 20 particles.

In conclusion, the normal mode spectra of finite clusters have been determined from the thermal motion of the microspheres around their equilibrium positions. This technique, adapted for clusters from wave experiments of Nunomura et al. [5], allows to measure the energy stored in the modes and the corresponding mode frequencies of all modes of cluster. The cluster modes are in thermal equilibrium with a temperature close to room temperature. The particle interaction can be described by a screened Coulomb (Debye-Hückel) potential with a dust charge of $Z = 11\,000$.

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