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Heating and Phonon Spectra of 2D and 3D Finite Dust Clusters

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Dusty plasmas are ideal systems to study the dynamics of crystalline, fluid and gas-like charged particle systems since the spatial and temporal scales are perfectly suited for direct observation by video cameras. The particles are highly negatively charged due to the continuous inflow of plasma electrons and ions. Micrometer-sized particles usually attain charge numbers Z of the order of 10 000. Due to these high charges the dust particles arrange in ordered Coulomb lattices. Finite dust clusters consist of a small number of dust particles N immersed in a gaseous plasma environment. Dust clusters in two dimensions (2D) are formed by trapping the dust particles in the sheath above a bowl-shaped electrode. Vertically the particles are strongly confined due to the balance of electric field force and gravity. A much weaker horizontal confinement is provided by the distorted equipotential lines of the curved electrode. 2D clusters arrange in concentric rings (see e.g. [1, 2]). In contrast, the formation of spherical 3D clusters is achieved by special discharge configurations and support by thermophoretic forces [3]. 3D clusters arrange in “onion-shells”.

In this paper, we will focus on the dynamics of 2D clusters under a phase transition from the solid to the liquid state. Phase transitions can be driven by reducing the gas pressure in multi-layer dust systems [4, 5]. This is due to an oscillatory instability of the lower layer particles which is excited by the ion streaming motion in the sheath [6]. The oscillations heat the dust particles which leads to the melting of the ordered dust system. Here, the full dynamical properties of a dust cluster with $N = 42$ particles is determined during the phase transition. The dynamics are derived in form of the mode spectrum of the $2N$ cluster modes. To pinpoint the melting transition to the instability of the lower layer particles a dust cluster with only a single lower layer particle was prepared (see Fig. 1). The dynamic properties of the cluster were directly obtained from the thermal motion of the upper layer particles during

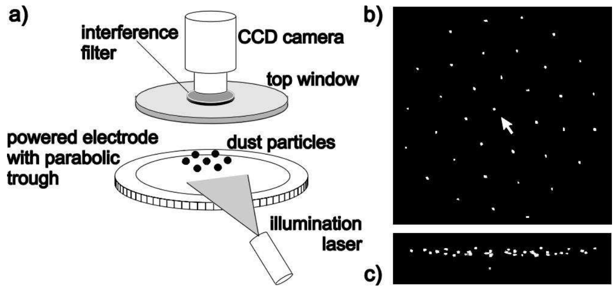

Figure 1: *a) Scheme of the experimental setup, b,c) Snapshots of a cluster with* $N = 36$ *upper particles and a single lower particle. b) top view. The arrow indicates the particle under which the lower particle is located. c) side view. The side view camera is slightly tilted with respect to the cluster plane, so the upper layer appears as an elliptical disc.*

the phase transition. This technique is described in detail in Ref. [2]. The analyzed video sequences cover 41 s at a frame rate of 50 frames per second.

Figure 2 shows the dynamical properties of the cluster during the phase transition for 3 representative gas pressures of 12 Pa, 11 Pa and 6 Pa. There the cluster changes from the solid state (at 12 Pa) to an intermediate state (at 11 Pa) and, finally, to the liquid state (at 6 Pa). From the particle trajectories (Fig. 2a) at 12 and 11 Pa the cluster is seen to be well ordered whereas at 6 Pa many changes in equilibrium positions can be identified. In the intermediate state the particles are found to exhibit an oscillatory motion which are notable from the circular particle trajectories, especially for that central particle under which the lower particle is located (see arrow).

Fig. 2b) shows the mode spectra obtained from the thermal motion of the particles together with the theoretical mode frequencies. In the solid state at 12 Pa the mode spectrum closely follows the expected mode frequencies. In the intermediate state at 11 Pa the situation is drastically different. From the intense horizontal band a dominating oscillatory motion at a frequency of about 4 Hz is observable. This is exactly the frequency of the unstable oscillation of the lower particle that sets in at exactly this gas pressure. It is somewhat surprising that the single lower particle dominates all modes of the cluster. The second harmonic of the unstable oscillations at 8 Hz is also detectable. A closer inspection of the modes reveals that the expected mode structure of the solid state is also faintly visible in the spectrum. In contrast, in the liquid state at 6 Pa the spectrum is broad for all modes and does not at all resemble the mode spectrum of the solid state.

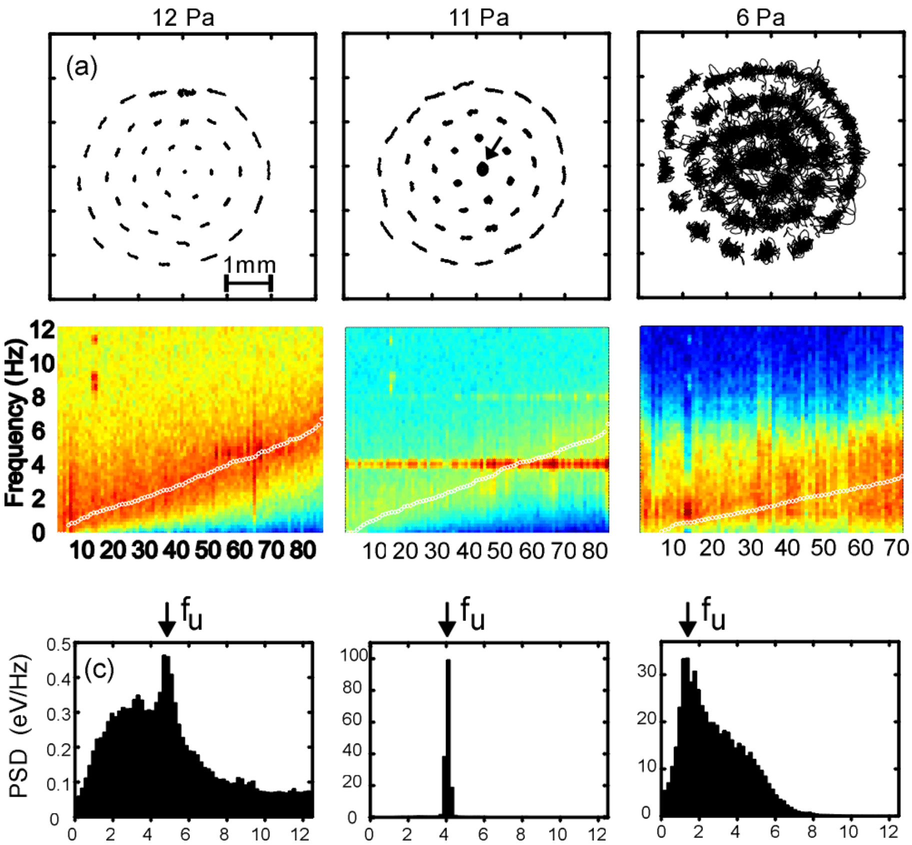

Figure 2: *Melting transition of the dust cluster with decreasing gas pressure. (a) Trajectories of the cluster particles (b) Color-coded power spectra of the normal mode oscillations of the cluster. Red colors correspond to higher power density. The theoretical mode frequencies for a solid state are also indicated as the white symbols. (c) Power spectral density (PSD) integrated over all mode numbers. Note the drastically different scales of the vertical axes.*

The dynamic behavior is even more clearly seen in the mode-integrated spectra (Fig. 2c). For the solid state, the spectrum is broad as expected. However, also a peak structure is observed at about $f_u = 5$ Hz. This peak is a sign of the oscillatory instability which is not observable in the trajectories. The instability already manifests in the spectrum although it is still beyond the threshold and is not excited at this pressure. In the intermediate state, however, only the dominant unstable oscillation ($f_u = 4$ Hz) can be identified. In the liquid state, the spectrum is broad again, but at a much higher absolute level. In addition, the peak of the instability ($f_u = 1.5$ Hz) is still clearly visible. The change in the frequency of the instability is associated with an increase of the interparticle distance and the corresponding change of the plasma frequency $2\pi f_{\rm pd} = (Z^2e^2/4\pi\varepsilon_0 ma^3)^{1/2}$.

The change of the dynamics is accompanied by a change of the global parameters that describe the dust system, namely dust temperature T_d and the Lindemann order parameter δ. The dust temperature suddenly increases from about $T_d = 0.1$ eV at 12 Pa to $T_d = 1$ eV at 11 Pa and even further to 5 eV at 6 Pa. The onset of the instability thus effectively heats the dust system. The Lindemann parameter δ that describes the root-mean-square excursions of the particle from the equilibrium positions stays at a very low level down to gas pressures of 8 Pa. This indicates strong order. Below 8 Pa, δ suddenly jumps to large values which is a clear sign of melting [7].

Concluding, three different phases of the dust cluster have been identified. At high gas pressures, the cluster is in a solid state with high order, low dust temperature and a solid-like mode spectrum. In the intermediate phase, the cluster is dominated by the unstable oscillations. The particles are heated, but the system is still in an ordered state. Thus, this state can be characterized as a hot, oscillating crystal. At low gas pressures the cluster goes to the liquid phase with even hotter instability-heated particles, low order and a broad mode spectrum. The analysis of the cluster dynamics thus demonstrates that the heating can be definitely attributed to the heating by the oscillatory instability of the lower layer particle.

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