Phase transitions in finite particle clusters in dusty plasmas

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The melting transition of finite dust clusters in a dusty plasma is studied experimentally. For that purpose, a system of a small number of charged microspheres is trapped in a discharge plasma and subsequently heated by laser manipulation to a liquid state. The fluid properties of the dust cluster such as the diffusion constant are measured from the particle trajectories using the instantaneous normal mode analysis. From that, the freezing temperature of the cluster is derived.

Finite systems ("clusters") of particles can undergo phase transitions similar to bulk matter. Upon heating, Lindemann-like fluctuations of the particles around their equilibrium position start to grow indicating a transition from a solid to a liquid "phase". On the contrary, thermodynamic properties (such as the specific heat) do not show a sharp transition for finite systems making it difficult to identify a distinct transition point. Further, the loss of order generally occurs in two steps, starting with a loss of orientational correlation, followed by a loss of radial order. Attempts have been made to assign criteria for the melting point from the particle configurations and their fluctuations [1, 2]. Here, we analyze the liquid phase of the system. A phase transition to the solid phase ("freezing") then is assigned to the point where the liquid properties are lost. Experimentally, charged microspheres trapped in a plasma discharge are a paradigm for the study of finite clusters as they can be realized in different geometries ranging from 1D linear chains to 3D spherical dust clouds [3, 4, 5, 6, 7]. Here, we will address the case of two-dimensional (2D) dust clusters.

The experiments have been performed in a dusty plasma where plastic microspheres are trapped in a gaseous discharge plasma. The plasma was ignited in argon at a gas pressure of 7 Pa using a radio-frequency discharge (f_{RF} = 13.56 MHz) at a power of 3 W. In this plasma, a small number N of microspheres was trapped to form two-dimensional finite dust clusters. The microspheres were 12.26 µm melamine-formaldehyde grains with a mass of m = 1.5 × 10^{-12} kg. The spheres attained a negative charge of Z ≈ 20000 elementary charges due to the continuous inflow of plasma electrons and ions. Vertically, the particles are trapped in a monolayer due to the strong confinement provided by gravity and electric fields in the space charge sheath. For horizontal confinement, the electrode has a very shallow spherical depression. The likewise curved equipotential planes trap the microspheres horizontally. The particle motion is recorded with high-resolution CCD-cameras at a frame rate of 60 frames per second.

To induce phase transitions, the dust clusters are heated by an in-plane four-axis laser system [8] where the laser beams randomly “kick” the microspheres on both horizontal axes in both directions by radiation pressure forces. The random process of laser-“kicks” is chosen in such a way that the obtained kinetic energies of the microspheres are isotropic with a nearly Maxwellian velocity distributions. Hence, the particles gain a temperature T in a true thermodynamic sense [8].

The dynamic properties of the dust clusters are determined by instantaneous normal mode analysis (INM) which allows to determine liquid transport properties such as the diffusion constant D [9, 10, 11]. In this INM analysis, the frequencies of the instantaneous normal modes are obtained from the eigenvalues of the dynamical matrix at any instant of time using the measured particle positions. The INM mode frequencies are either real or imaginary. Real values of belong to potential wells in which the individual particles can oscillate around their current equilibrium in the cage of the nearest neighbors. Imaginary values represent the potential hills that separate the minima. Now, especially these imaginary frequencies provides detailed information of the liquid behavior since the the thermal energy drives configurational transitions over these potential hills.
Here, we show the trajectories of a dust cluster with $N = 26$ particles in a dusty plasma that has been laser-heated to different temperatures up to 23,000 K (see Fig. 1). It is easily seen from the trajectories that the cluster shows only small excursions around the equilibrium positions at low temperatures indicating a solid state. At higher temperatures strong particle excursions are seen, even intershell transitions occur. This can be termed a liquid state.

Using INM, now the diffusion constant $D$ is determined for this cluster from the instantaneous normal modes [9, 10, 11]. The diffusion constant is found to increase almost linearly with temperature above a temperature threshold. This threshold might then be identified as the freezing temperature since here $D \to 0$, thereby assuming that in the solid regime the diffusion constant is much smaller than in the liquid. In doing so, the freezing temperature of the $N = 26$ cluster is obtained as $T \approx 2200$ K. For other clusters with different particle number decisively different melting temperatures are obtained reflecting the decisively different stability properties of the clusters [12].

In conclusion, our controlled laser-heating experiments together with the described analysis opens up new possibilities to study the fluid properties of charged-particle clusters. These now allow to address the solid-fluid phase transition from the fluid state and to determine the freezing point where the liquid properties are lost.

Fig. 1: a) Scheme of the experimental setup with the video camera and the laser manipulation system. b) Diffusion constant as a function of cluster temperature for a cluster with $N = 26$. Corresponding trajectories of the cluster particles over 250 s are also shown at three different temperatures.

References