Empirical Rule for Phase Transitions in Dusty Plasma Crystals

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Introduction

- Dusty plasma is consisted of neutral gas, ions, electrons, and micron-size particles that have a negative charge.
- Under certain conditions, dust immersed in plasma form stable structures similar to the liquid or the solid.
- There are two known empirical rules for fluid-solid first-order phase transition.
  - The first rule is the Lindemann criterion, which determines the ratio of the mean-square displacement and the interparticle distance at the melting line of the solid as a value close to 0.15.
  - The second rule, the Hansen criterion, determines the first maximum of the liquid structure factor as a value less than 2.85.
Here we report the experimental observation of phase transition in a plasma crystal consisting of several layer of dust particle tapped in sheath region of a planar rf discharge. The phase transition was produced by power and pressure variation. The melting point was determinates by analysis of 2-D pair correlation function. The phase diagram in pressure-power plots shows that the phase transition in monolayer and multilayer crystal are different. In the monolaeyr case the melting can be initiated by raising rf power or by reducing the gas pressure. In case of multilayer structure the phase state dependence on discharge power is non monotonic and frozen due to decreased power structure can be melted again if power continue decreasing.

The experiments were carried out in a 40-cm inner diameter cylindrical stainless steel vacuum vessel with many ports for diagnostic access. The chamber height is 30 cm. We use an aluminium disk as the powered electrode and a stainless steel disk with hole as the grounded electrode. The diameters of electrodes are of 10 cm, the inner hole of the grounded disk is a 5 cm. The powered electrode is placed below the grounded, which can be moved vertically. In our experiments the disks is centred the axis of system and the distance between the electrodes is 30 mm. Both electrodes are connected to electrical feedthroughs. Argon plasmas are generated at pressures in the range 10 - 100 mTorr by applying a 15 MHz signal to the powered electrode. To produce the sinusoidal RF voltage a waveform generator is connected via a power amplifier with a standard matching box to reduce the reflected power. The input power is 15 -180 W measured at the electrical feedthrough. A compensated single Langmuir probe is used to make measurements of the plasma parameters. The probe position can be moved in two directions, vertically and radially, with respect to the electrodes. The measurements are transferred, via a SPIB connection, to a PC for analysis.
Experimental Setup

- rf discharge 15 MHz
- Pressure from 10 to 400 mTorr
- Input power from 15 to 200 W
- Self-bias voltage from 5 to 180V
- Carbon (C) particles diameter $\sim 1 \ \mu m$
- Melamine formaldehyde - $2.79 \ \mu m \pm 0.06 \ \mu m$
- Melamine formaldehyde - $6.13 \ \mu m \pm 0.10 \ \mu m$
- Argon plasma $T_e \sim 2 \text{ eV}, \ V_p = 50 \text{ V} & n_e \sim 10^9 \text{ cm}^{-3}$
In our experiments, 2.79 µm diameter melamine formaldehyde particles have been used. The particles are loaded on to a (2 cm x 1.5 cm) square brass mesh tray. A 5-cm wire connected to an isolated screw, which is fixed on the upper electrode, supports this tray. The whole assembly can be moved vertically in the chamber. For most experiments, the tray is positioned approximately 1 cm directly above the grounded electrode.

The dust particles suspended in the plasma are illuminated using a Helium-Neon laser. The laser beam enters the discharge chamber through a 40-mm diameter window. A window mounted on a side port in a perpendicular direction allows a view of the light scattered at 90° by the suspended dust particles and provides a vertical cross-section of the dust structure. In addition, we use the top-view window to view the horizontal dust-structure. The laser beam can be expanded in the vertical and horizontal directions into sheets of light by a system of cylindrical lenses. Images of the illuminated dust cloud are obtained using a charged-coupled device (CCD) camera with a 60 mm micro lens. The video signals are stored on a videotape recorder or are transferred to a computer via a frame-grabber card with an 8-bit gray scale and 640X480-pixel resolution. The coordinates of particles were measured in each frame, and two dimensional pair correlation function G(r) was obtained for each separate layer.

In our experiment we studied the mono layer and two, three, five, and seven layer crystals. The images of different dusty plasma statements (crystalline, flow and floe, ...) are shown on Figure below. The correspondent pair correlation plotted. As on can see the variation of input power and pressure of neutral gas lead to phase transition in dust plasma system.
Phase transitions of plasma crystals consisted of several layers of dust particle in a planar rf discharge in argon have been investigated. Phase transitions were produced as results of variation in power and pressure. Dust plasma crystal melts with reduction in pressure (input power ~ 80 W).
Pair Correlation Function

The graph shows the pair correlation function $g(r)$ over the range of $r$ from 0 to 1500 $\mu$m. The fluctuations in the function correspond to the phase transition of the previous slide.

The behavior of the correlation function can be approximated by $\sim 1/r^{0.38}$ and $\sim 1/r^{0.285}$, indicating the power-law decay of the correlation with distance.
Power and Exponential Fit

pair correlation function $g(r)$

exponential fit

power fit
Possible Criterion for Phase Transition
Max to Min Ratio

$g_{\text{max}}(r)/g_{\text{min}}(r)$

Pressure, mTorr

P=50W
P=70W
P=100W
Phase Diagram for Upper Layer of a Multilayered Crystals

1 - One Layer Crystal
2 - Five Layers Crystal
3 - Nine Layers Crystal

Input Power, W
Pressure, mTorr

solid

liquid
Phase Diagram for the Individual Layers in a 5 Layers Crystal

1 - Upper Layer
2 - Second Layer
3 - Third Layer
4 - Fourth Layer
5 - Fifth Layer
Conclusions

- Melting point was determined by analysis of the 2-D pair correlation function.
- A new empirical rule for fluid-solid transition was suggested, based on the ratio of the minimum $G_{\text{min}}$ and maximum $G_{\text{max}}$ value of the pair correlation function.
- We have found the transition occur at point $G_{\text{max}}/G_{\text{min}} < 10$
- Using this rule it was been found that the phase transition in a multilayer crystal differs from that in monolayer crystal.
- The monolayer plasma crystal is solid at high pressures (100mTorr) and low discharge power (20 W)
- Melting occurred when gas pressure was reduced or discharge power was increased.
- In the case of a multilayer structure the phase state dependence on discharge power is non-monotonic. A frozen structure obtained by decreasing power can be melted again as power decreases.
- Position and behaviour of interstate equilibrium curve is strongly dependent on number of layers in crystal structure.