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Christina A. Knapek

Phase Transitions in Two-Dimensional Complex Plasmas

Doctoral Thesis accepted by
Ludwig-Maximilians-Universität, München, Germany

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Supervisor's Foreword

Two-dimensional particle systems have been widely investigated during the last decades. Prominent examples are the 2D crystals of electrons on the surface of liquid helium and the research in the field of 2D colloids—nanometer-sized particles suspended in a liquid and restrained to a single plane. Since the Nobel Prize for physics in 2010 was awarded for groundbreaking studies of Graphene, a single layer of carbon, two dimensional materials gained even more attention, both in science and also in public.

The experimental studies presented in this thesis refer to 2D systems belonging to the field of "complex plasmas".

A complex plasma, in the most basic sense, consists of a mixture of electrons, ions, neutral gas atoms and charged micrometer-sized particles. These complex plasmas can spontaneously self-organize and form "plasma crystals". The plasma crystals were predicted theoretically by Ikezi in 1986, and were experimentally discovered in 1994 by Thomas et al. In the laboratory, complex plasmas can nowadays be easily generated by inserting, e.g., plastic spheres into plasma reactors, achieving many-particle systems in a multitude of states, which serve as an excellent model system for studying the behavior of the interaction of charged particles in strongly coupled systems. Some of the enormous advantages of complex plasmas are that they are optically thin, observable even with low magnification by conventional video cameras, and they are only weakly damped by neutral gas friction (in contrast to the overdamped colloidal matter), resulting in typical time scales of dynamical processes in the range of 10–100 Hz.

The particles usually arrange themselves in 3D structures, layers of particles stacked above each other. But by careful selection of experimental parameters, it is possible to generate a single layer of particles, yielding a unique opportunity to observe 2D systems of interacting particles at the kinetic level by direct imaging of the individual particle motion within that layer.

The work presented by Dr. Knapek deals with the phase state and phase transitions in the 2D complex plasma, leading to the question how significantly the thermodynamical behavior in two dimensions differs from that in three dimensions.

One important aspect, following from the Mermin-Wagner theorem (1966) and already stated by Peierls in 1935, is the absence of true long-range order in 1D and 2D due to the loss of long-range correlations. Without order, there can be no phase transition in the thermodynamical sense. Fortunately, a new type of a so-called "topological phase transition" to a state of quasi long-range order in two dimensions was soon introduced and the theoretical model was first established by Beresinksii in 1971, and further developed by Kosterlitz and Thouless, leading to the well-known Berezinskii-Kosterlitz-Thouless transition. The model explains a mechanism mediated by the condensation of topological defects (or vortices), and has been applied, e.g., to the XY spin model, 2D neutral superfluids, and also to the solid–liquid phase transition in 2D crystals, where the role of vortices is adopted by lattice defects. Other models attempting to explain the nature of phase transitions in 2D crystals, e.g. a grain-boundary (chain-like structures of concatenated lattice defects) induced melting or the density wave theory, exist, but did not have similar impact.

A different approach to the description of the thermodynamical behavior of a 2D system can be obtained by extending the kinetic theory developed by Yakov Frenkel and published in 1945. Frenkel's theory connects the number of lattice defects to the thermodynamical quantity temperature by means of free energy calculations and considerations of domain formation in a (3D) molecule crystal. Based on this concept, a modified theory was developed and applied to the 2D case to explain the experimental results.

This thesis contains the experimental results of two carefully conducted experiments with single layer complex plasmas: the first one demonstrating a new straightforward method to determine the coupling strength—one of the fundamental quantities characterizing the phase state in the many-particle system and the second one concerning the non-equilibrium phase transition occurring during a rapid cooling process. An extensive analysis of global and local structural order parameters as well as the particle energy as time-dependent quantities during the process of recrystallization from an unordered to an ordered state provides a deep insight into the underlying mechanisms of 2D phase transitions, much better than anything available so far. By connecting the local order—determined by lattice defects—to the dynamical properties of the particle ensemble, a scale-free behavior during the transition was discovered, implying universality. This remarkable new finding, which is not compatible with the standard equilibrium physics relationship has triggered a great deal of discussion among the experts. Thus the analysis of the dynamic evolution of lattice defects in complex plasmas has enabled a new understanding of the fundamental stability principles of condensed matter and the self-organization within the ensemble. If the findings could be identified as generic properties, this could be of high interest in surface and membrane physics and also in nanoengineering. The possible interpretation based on Frenkel's work (described above) provides a new approach towards understanding dynamical self-organization processes, which will trigger much further research.

Garching, April 2011 Prof. Dr. Dr. h.c. Gregor E. Morfill

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