Investigation and control of two-dimensional Coulomb crystals for atom-ion mixtures

Naoto Mizukami

Abstract

Trapped particles with long-range repulsive interactions self-organize into crystalline structures at sufficiently low temperatures. In two-dimensions, the crystal configuration exhibits a geometry that strongly depends on the trapping potential and the number of particles. Notably, excitation modes characterized by extremely low energies may emerge, in particular when the trapping potential is isotropic within the two-dimensional plane. Such systems offer the unique advantage of allowing direct observation of particle arrangements and dynamics within a plane, making them ideal platforms for not only studying fundamental aspects of crystallization and collective behavior but also simulating molecules.

In this thesis, we use a specially designed Paul trap to form and control two-dimensional ensembles of Ba^+ ions, and study their crystallization and melting. In particular, we report the observation of orientational melting, in which a Coulomb crystal melt in a rotational degree of freedom while maintaining localized in the radial direction. Additionally, we have experimentally observed the structural evolution of a Coulomb crystal transitioning from a metastable configuration to a lower energy configuration.

These studies were possible by making a number of technical advancements, including the development of dedicated laser sources, significant upgrades to our experimental control system, and the implementation of an imaging system capable of detecting the dynamics of the ion crystal formation. Additionally, a Monte Carlo simulation was developed to provide a theoretical analysis of the experimental observations.

Our long-term strategy is to immerse the Ba^+ ions into a cloud of Li atoms for studying atom-ion interactions in the ultracold regime. Part of the work of this thesis is to realize some of the resources for realizing this mixture. In particular, we have successfully trapped neutral Li atoms in a magneto-optical trap. Moreover, we have developed an optical cavity for creating a deep optical potential for Ba^+ ions. The strategy is to use this potential confining the ions in a static trap and study atom-ion collisions in an RF-free environment.

Finally, extending the control capabilities over these 2D mesoscopic systems, we have developed a method for precisely controlling the rotation of a trapped ion crystals.