Binding Mechanisms in Plasma Crystals

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Motivation—Plasma crystals are formed when particles in an electrical plasma self-assemble into orderly arrangements due to long range and collective interactions. Scientific interest is high not only because of applications to astronomy and the semiconductor industry but also because the crystals serve as a macroscopic platform on which to develop and test theories of collective interactions in many-body assemblies and long range particle interactions. Examples include wave propagation in ionic solids, phase transitions in Coulomb and shielded-Coulomb crystals, lattice stability dynamics of crystallization, charging mechanisms within plasmas, and the physics of the surrounding plasma and sheaths. For this program, we are combining experimental and theoretical studies to develop a mature understanding of the fundamental long-range interactions and multi-particle dynamic behavior of macroion crystals.

Accomplishment—We have measured both the magnitude and shape of the attractive interaction between two negatively charged particles immersed in a charge neutral plasma. While our previous work demonstrated that the dominant force between particles in a stable 2D planar plasma crystal is repulsive, 3D particle assemblies include an attractive interaction that strongly influences the lattice kinetics. The attractive interaction originates from the positive space charge region produced by the focused flow of positive ions around the negatively charged particles. Our measurements are the first to map the entire 3D attractive binding potential and show that the structure of 3D assemblies is due to a delicate balance between repulsive Coulomb interactions and attractive forces.

To characterize the attractive interaction, we developed a new technique to determine the forces present during very low energy head-on particle collisions. By manipulating the electric fields within the plasma using a parabolic, grooved electrode (Fig. 1), a well-defined potential trough is formed. An analysis of the particle trajectories as a function of time yields the time dependent attractive and repulsive forces on the particles. Figure 2 shows an example of the radially dependent attractive force at one distance below the particle, a fit to the functional form predicted by our first principles model, and the attractive binding potential. For this case, the peak force was on the order of 60 fN (femtonewtons), comparable to the forces applied by laser tweezers. By changing the probe particle mass, we measure the force at a range of distances below the upper particle and integrate the force maps to generate a spatial map of the binding potential (Fig. 3).

Significance—Our measurement of the magnitude and shape of the attractive binding potential provides detailed new information about the forces that control the structure and dynamics of 3D, charged particle assemblies. While our measurements show the same trends as published calculations, current codes include a number of simplifying assumptions that must be addressed to improve agreement. In addition to applications to dusty plasmas, these measurements address longstanding and fundamental questions related to the structure of the plasma sheath in the presence of a flowing ion wind. Such sheaths are found in common plasma applications such as lighting, surface cleaning, flat panel displays, and semiconductor processing.

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Figure 1. Side view of the lower electrode assembly and the Argon plasma glow. The arrow is pointing to the slot in the lower electrode that produces the electrostatic trough in which the particles collide.

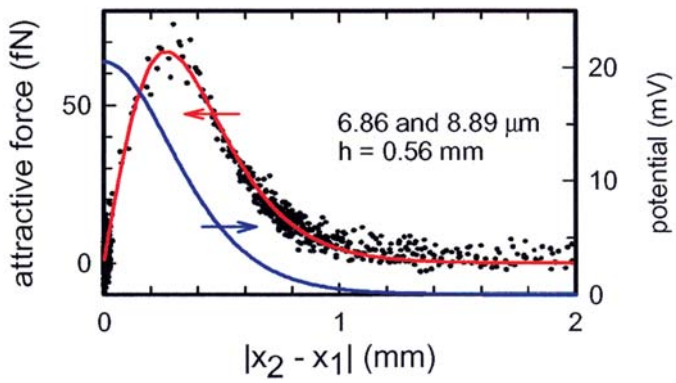

Figure 2. Measured attractive force (dots) that binds two negatively charged particles. The red curve is a fit to the data using a form predicted by our models and the blue curve is the binding potential obtained by integrating the force.

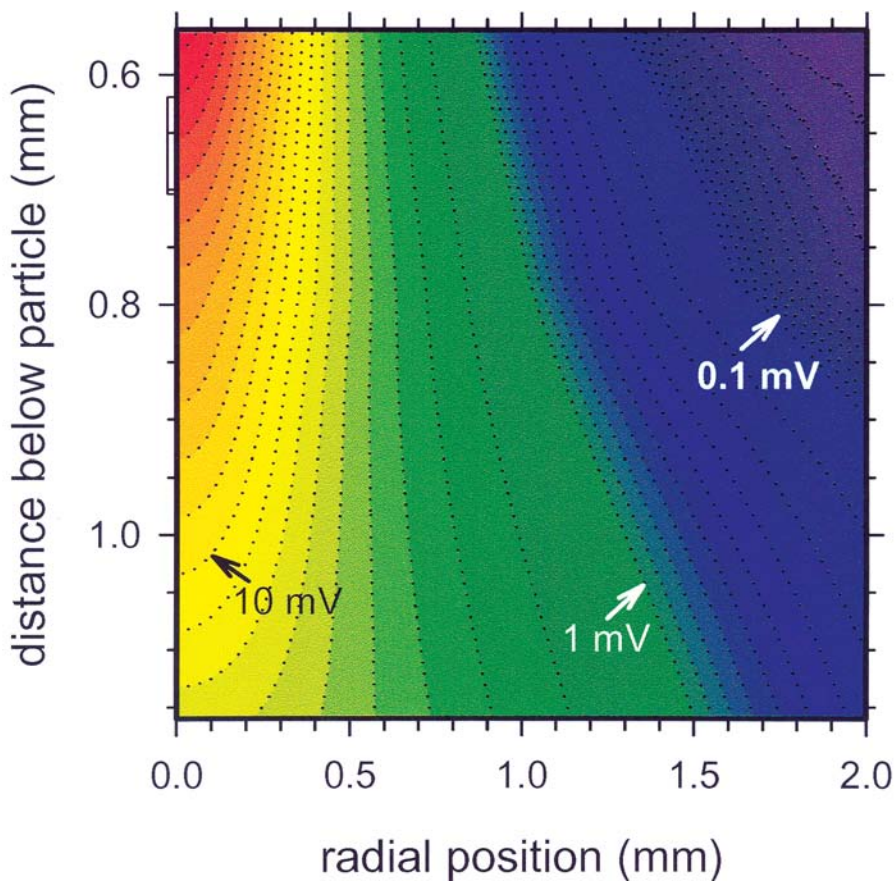

Figure 3. Measured binding potential (mV) as a function of the distance below the particle and the radial position. The 6.86 μm diameter particle is located at (0,0) and has a charge of 6000 electrons.