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Collective dynamics of complex plasma bilayers

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Particle bilayers (parallel planes occupied by interacting particles and separated by a distance comparable to the interparticle distance within the layers) can be viewed as an intermediate stage between two-dimensional (2D) and three-dimensional (3D) systems. It is the interplay of the 3D interaction and the 2D dynamics that creates the rich new physics predicted and observed in interacting bilayers that makes these systems interesting in their own right. At the same time, bilayer configurations are also ubiquitous in widely different physical systems. Of special importance are those of charged particles (with like charges: unipolar bilayer, or with opposite charges: bipolar bilayer). Examples are semiconductor heterostructures [1], cryogenic traps [2], overdamped system of lipid membranes [3], interfacial superconductors [4], etc.

Very recently a seminal observation by Smith *et.al.* [5] has led to the realization that strongly coupled unipolar bilayers can be created in laboratory complex (dusty) plasma environments. This can be accomplished by using a mixture of two differently sized grains: in view of their necessarily different charge to mass (Z/m) ratios, the two species would settle at different equilibrium heights in the plasma sheath, as governed by the local balance of gravitational and electric forces.

We report on the experimental investigation of the collective dynamical properties of a binary dusty plasma system. Our results constitute the first observation of the mode spectrum of a strongly coupled (liquid or solid) bilayer. We confirm the predicted [6, 7] benchmark of the strongly coupled mode structure, the development of optic modes with a wave-number $k = 0$ "energy (frequency) gap".

Our dusty plasma experiments have been carried out in a custom designed vacuum chamber. In our experiment melamine-formaldehyde micro-spheres with diameters $d_1 = 3.63 \pm 0.06$ μm and $d_2 = 4.38 \pm 0.06$ μm are used. During the evaluation of the raw images (typically over 60000 per experiment) identification and position measurement of the particles is performed using the method described in [8]. Visual observation of the recorded images confirms that most of the system is in a hexagonal configuration, sometimes small domains with rhombic and square unit cells were also found, in agreement with theoretical results in [7, 9].

From the particle positions vs. time, first we calculate the microscopic densities, as well as longitudinal and transverse currents: $\rho^{(m)}(\mathbf{k},t) = \sum_j \exp(-i\mathbf{k}\cdot\mathbf{r}_j)$, $\lambda^{(m)}(\mathbf{k},t) = \sum_j v_{j,\parallel} \exp(-i\mathbf{k}\cdot\mathbf{r}_j)$, $\tau^{(m)}(\mathbf{k},t) = \sum_j v_{j,\perp} \exp(-i\mathbf{k}\cdot\mathbf{r}_j)$ for the two layers ($m = 1,2$). From the Fourier transforms of $\rho(\mathbf{k},t) \to \rho(\mathbf{k},\omega)$, $\lambda \to \lambda(\mathbf{k},\omega)$, and $\tau \to \tau(\mathbf{k},\omega)$ one can calculate the power spectra, e.g. $S_{m,n}(\mathbf{k},\omega) \propto \langle \rho^{(m)}(-\mathbf{k},-\omega)\rho^{(n)}(\mathbf{k},\omega)\rangle$, averaging is over the time-slices available.

In our dusty plasma experiment we could create a strongly coupled bilayer system that can be well approximated by a unipolar binary Yukawa bilayer model. This model has served as the basis for molecular dynamics (MD) simulations, lattice summation, and a Quasi-localized

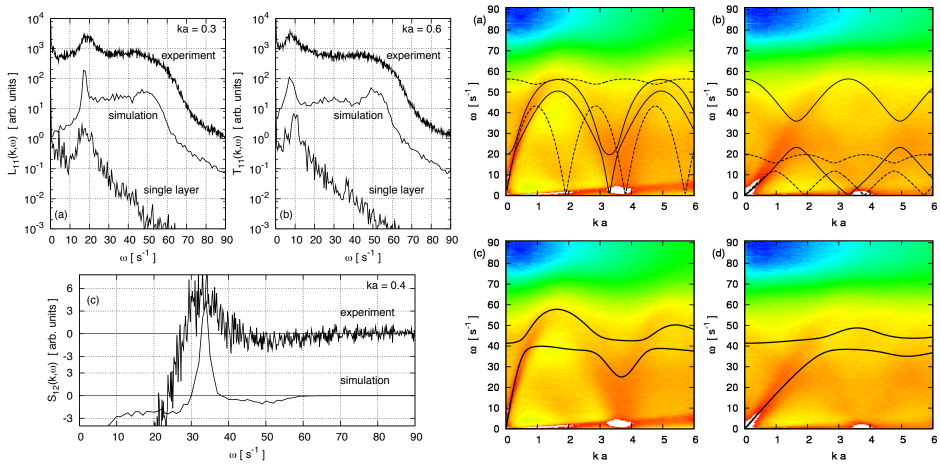

Fig. 1: LEFT: Sample spectra illustrating the principal features of (a) L_{11} longitudinal, (b) T_{11} transverse current fluctuations and (c) S_{12} inter-layer density fluctuations. RIGHT: L_{11} one-layer longitudinal (a,c) and T_{11} one-layer transverse (b,d) current fluctuation spectra. Peak positions (hot colors) mark the dispersion $\omega(k)$. Black symbols in (a,b) are frequencies form lattice summation calculations. Lines in (c,d) are the corresponding QLCA dispersions.

Charge Approximation (QLCA, [10]) calculation. In view of the prevailing local lattice structure in coexistence with a high degree of disorder it is not a priori clear, which of the theoretical models should provide a better description of the mode structure. Inspection of Fig. 1 shows that for low k values the acoustic portions of the low frequency modes are equally well described by either model. For higher k values the repeated Brillouin zone structure is clearly visible, indicating the superiority of the lattice model. For the high frequency optic mode the QLCA predicts a single "frequency gap" at $k = 0$ with: $\omega_{\rm gap}^{\rm exp} = 41.4s^{-1}$ and $\omega_{\rm gap}^{\rm MD} = 43.5s^{-1}$ calculated with the input of experimental and simulation data. This value and the high-k tapering off of the optic modes seem to be more along the line of the QLCA description.

We conclude, that all approaches are in good agreement with the experiment, and verify the presence of an optical collective mode characterized by a finite energy (frequency) gap at $k = 0$ wave-number, distinguishing the strongly coupled bilayer from a weakly coupled one, where all the modes have an acoustic character. For further details see [11].

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