Coherent excitations in thermally excited dusty plasma crystals: observations of multi-scale vortical phonons and vorticity wave vortices

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In a crystal, the ordered structure supports the coherent propagation of acoustic waves (phonons), which can be disrupted through stochastic excitation/de-excitation by thermal agitation. The interplay of the above order and disorder makes thermal phonons in cold crystal a good candidates to uncover the coherence out of disorder. However, whether cooperative vibrations exist and how they look like at different scales, remain elusive.

In nature, there are many extended disordered systems exhibiting multiscale spatiotemporal fluctuations. Counterintuitively those systems are not completely disordered. Examples include vortices in nonlinear hydrodynamics turbulence and multiscale acoustic vortices in dust acoustic wave turbulence [1]. They are localized coherent entities (CE) with distinct topological features, and can be used to characterize the dynamical behavior of the disordered system. However, other than the above multiscale dust acoustic wave vortices generated through wave-crest rupturing/reconnection, CEs such as wave vortices, skyrmion, and merons in various classical to quantum systems [2-4], have been mainly passively generated by external wave sources with programmed phase delay through superposition of single-scale linear waves. Whether CEs exist in multiscale linear disordered wave systems excited by stochastic agitation has never been addressed.

From the general wave physics perspective, thermal phonons in cold crystals serve as a model system of linear disordered multiscale waves excited by stochastic agitation. In this talk, we report our studies uncovering the above issues about the basic cooperative excitations and the spatiotemporal waveforms of acoustic vibrations, the existence and the types of CEs in thermal phonons, and their dynamical behaviors, using a two-dimensional dusty plasma crystal through the direct visualization at the discrete level [5]. Through empirical mode decomposition [6] to separate thermal vibrations with a continuous power spectrum into multiscale modes, we demonstrate the following observations: a) multi-scale vortical phonons in the form of propagation swirls with alternating signs of vorticity and varying shapes, which cause spatiotemporal oscillation of local vorticity, leading to the term of *vorticity wave* for vortical phonons; and b) multi-scale vorticity wave vortices, where the wave crests of vorticity waves helically wind around the screw dislocation defect filaments [SDFs] in the *xyt* space, as localized CEs.

Experimentally, a monolayer of a cold dusty plasma crystal composed of melamine resin (MF) particles (9.3 micro-meter in diameter) suspended in a capacitively coupled radio-frequency argon discharge is used for investigation. The individual particle motion is optically tracked. Particle vibrations are underdamped in the low pressure (1.3 Pa) argon background.

We find that the velocity fields of undecomposed vibrations and the first two fast modes exhibit disorder motions. The latter can be attributed to the contributions from the short wavelength longitudinal and transverse phonons with uncertain phases and amplitudes. For each slow mode, the superposition of transverse acoustic waves with uncertain directions, phases and amplitudes in a narrow band leads to the formation of vortical phonons.

The SDFs, serving as the cores vorticity wave vortices, exhibit irregular trajectories in the xyt space. Under the conservation of topological charges, SDFs can be pairwise generated and annihilated. It leads to the finite lifetimes with self-similar stretched exponential distributions over different scale modes, and their short range spatial correlations. Their generic behaviors are similar to those found in the decomposed modes of SDFs in 3D traveling *nonlinear longitudinal* dust acoustic (dust density) wave turbulence of *gaseous* dusty plasma, *spontaneously* generated through wave crest breaking/reconnection caused by nonlinear undulation instability [1]. It manifests the universal robust dynamical feature of those wave vortices, regardless of the different generation mechanisms in different disordered wave systems.

The experimental findings are verified by our molecular dynamics simulations of 2D Yukawa and Lennard-Jones crystals governed by the coupled Langevin equations [5].

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