Seminar

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Institute for Plasma Research

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Title: Experimental and Molecular Dynamics Studies of Transport Phenomena in a Complex Plasma

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Date: 15th April 2025 (Tuesday)

Time: 03.30 PM

Venue: Seminar Hall, IPR

Abstract

A complex plasma, also known as a dusty plasma, is a type of plasma that contains ions, electrons and dust grains. Dusty plasmas are widely utilized as convenient model systems for understanding various complex physical phenomena in naturally occurring or laboratory many body systems. The understanding of transport phenomena is an important area of fundamental studies in plasmas that has also important practical applications [1]. The present thesis explores transport processes in a dusty plasma system, focusing on mechanisms that are either a consequence of spontaneous thermal fluctuations or are driven by an external agent. A systematic approach is adopted in which an appropriate theoretical framework is first developed followed by validation through computer simulations and subsequently tested in carefully designed experiments to obtain physical insights.

The theoretical part of this work includes obtaining an analytical form of a density autocorrelation function (DAF), a marker of the time dynamics of density fluctuations, for a complex plasma in the strongly coupled regime. The strong coupling effects are included in the framework of the generalized hydrodynamics (GH) model. The accuracy of the derived expression is evaluated by comparing it with existing results in the literature in relevant asymptotic limits. For an alternative and more comprehensive validation, molecular dynamics (MD) simulations of a particle system interacting with a Yukawa potential are performed. The analytic functional form of DAF is employed to extract transport coefficients from the MD data and compared with past studies [2]. For a practical application of the technique, an experimental system is set in a new Capacitively Coupled Dusty Plasma Experimental (CCDPx) device designed and commissioned at the Institute for Plasma Research. A plasma discharge of argon gas is produced using a dual-channel radio frequency source. The dusty plasma is produced by the introduction of mono-dispersive microspheres of melamine formaldehyde in the discharge. The device features an innovative lower electrode capable of creating a variety of potential wells to trap dust particles in one-, two- or three-dimensional equilibrium configurations. The DAF of the spontaneous dust density fluctuations is determined by optically tracking the trajectories of the dust particles in a 2D configuration. The experimentally obtained DAF is found to be consistent with theoretical and numerical predictions. It is also employed to measure the microscopic heat diffusion rate for different fluctuation wave-numbers (k), and to extrapolate the macroscopic diffusion rate in the $k \to 0$ limit [3].

The strongly coupled regime shows conduction as the predominant mode of heat transfer in a complex plasma. In order to explore the weakly coupled regime, the experiments of CCDPx are operated with smaller spatial correlations, leading to a fluid state of the complex plasma. In this regime, the formation of self-sustaining convective patterns in 3D dust clouds is observed. The patterns consist of a self-sustained pair of convective cells.

Particle tracking velocimetry measurements reveal the existence of an ion flux-induced dust temperature gradient that is responsible for the convective counter-rotating patterns [4]. The experimental results compare reasonably well with the findings of MD simulations of the laboratory system. Finally, the thermal relaxation of different phonon modes is studied in the context of energy transfer rates at different length scales. A 1D chain of dust particles is formed in the CCDPx device by modifying the transverse confining potential. Collective oscillations are excited by applying an oscillatory force on the particles using a tunable laser. The relaxation of modes, a nonlinear phenomenon, is observed by 'switching off' the excitation. The experimental findings, covering a wide parameter regime, are then compared with classical MD simulations to provide valuable physical insights into some of the observed novel features of the nonlinear phenomena. The results of the present thesis could prove useful in understanding spontaneous and driven transport in strongly coupled systems that are associated with nonlinear pattern formations and/or nonlinear mode interactions.

[1] Morfill, G. E., & Ivlev, A. V. (2009). Complex plasmas: An interdisciplinary research field. *Reviews of Modern Physics*, *81*(4), 1353–1404.

[2] Dhaka, A., Subhash, P. V., Bandyopadhyay, P., & Sen, A. (2022). Auto-correlations of microscopic density fluctuations for Yukawa fluids in the generalized hydrodynamics framework with viscoelastic effects. *Scientific Reports*, *12*(1), 21883.

[3] Dhaka, A., Bandyopadhyay, P., Subhash, P. V., & Sen, A. (2024). Experimental validation of the analytic model for the temporal decay of the density auto-correlation function in a strongly coupled dusty plasma. *Physics of Plasmas*, *31*(4).

[4] Dhaka, A., Bandyopadhyay, P., Subhash, P. V., & Sen, A. (2024). Spontaneous convective pattern formation in a dusty plasma. *Physics of Plasmas*, *31*(7).