Master 2 internship proposal in theoretical quantum physics

Nonequilibrium dynamics in binary quantum fluids

Laboratory: Laboratoire de Physique Théorique et Modèles Statistiques (LPTMS)
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PhD opportunity after internship: Possible

Quantum fluids represent a cornerstone of modern quantum physics, manifesting across a diverse spectrum of physical platforms that includes both bosonic and fermionic realizations. Within the realm of dilute, weakly interacting bosonic systems, three prominent realizations dominate current research: Bose-Einstein condensates (BECs), achieved by cooling atomic gases to ultracold temperatures; exciton-polariton condensates, which emerge in semiconductor microcavities via strong light-matter couplings at cryogenic temperatures; and paraxial superfluids of light, engineered by propagating intense laser fields through nonlinear optical media, remarkably, at room temperature.

A particularly compelling and fertile subset of these quantum fluids is uniquely defined by the presence of two coupled internal degrees of freedom. This inherent binary nature enriches the underlying phase space, transcending the complexity of standard, single-component quantum fluids. This intricacy mandates the appearance of two excitation modes whose interplay provides an opportunity to explore a richer spectrum of quantum many-body and nonlinear phenomena, both proximate to and significantly distant from equilibrium.

Recent experiments in the group of David Clément and Christoph Westbrook at Laboratoire Charles-Fabry (LCF) in Palaiseau have enveiled the anomalous k^{-4} tail of the momentum distribution of a BEC of metastable helium-4 atoms in the $m_J = +1$ sublevel, coupled to very dilute impurities in the $m_J = 0$ sublevel, following an expansion. These observations are striking for two reasons: first, the amplitude of this characteristic power-law decay significantly exceeds expectations for a trapped condensate at equilibrium; second, it is absent when the impurity bath, however ultradilute, is removed. These results underscore the paramount role of the interactions between the major condensed component and the minor impurity component, defining an interesting problem in the far-from-equilibrium dynamics of coupled quantum gases. The core objective of this internship is to provide a rigorous, comprehensive theoretical model for these experimental insights.

I seek an enthusiastic, committed student with keen intellectual curiosity for the many-body physics of dilute quantum systems. Ideally, the candidate will possess a strong inclination for analytical approaches, while simultaneously being proficient with numerical methodologies. The intern will benefit from close exchange and collaboration with David Clément and Christoph Westbrook. Local collaborative opportunities with Leonardo Mazza, Nicolas Pavloff, and Dmitry Petrov are also readily available.

This engagement is not confined to the immediate subject and offers latitude for expansion, potentially serving as the foundation for a subsequent PhD thesis. Such extensions could encompass the theoretical investigation of: the relaxation dynamics of a binary quantum fluid following a quantum quench; the emergence of a Kardar-Parisi-Zhang dynamics through coupling with a noisy component; spin superfluidity in the hydrodynamic flow of a two-component superfluid; or the dynamics of spin dispersive shock waves stemming from a Riemann initial-value problem. The supervisor maintains work in close synchronization with experimental reality, ensuring the student will benefit from interaction with experimental groups, notably at LCF locally (Thomas Bourdel, David Clément, and Christoph Westbrook, focusing on Bose-Einstein condensates) and at Laboratoire Kastler Brossel (LKB) in Paris (Quentin Glorieux, focusing on paraxial superfluids of light). Available funding from Agence Nationale de la Recherche (ANR) could ensure the provision of necessary installation and computing infrastructure.