Exploring Many-body Physics with Ultracold Gases: From the 2D Bose Gas to the Strongly Interacting Fermi Gas

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Over the past decade, ultracold atom experiments have undergone a rapid growth promoted by their ability to provide a new angle of attack for the many-body problem, crucial in condensed matter and nuclear physics. The possibility to place ultracold atomic gases in arbitrarily tunable landscapes allows, for instance, for the realization of model Hamiltonians originally devised for condensed matter systems, free of impurities and with dynamic control over the microscopic parameters.

One can as well use a strongly confining potential to constrain an atomic gas in one or two dimensions where many-body systems give rise to new phenomena, nonexistent in their 3D counterparts. In this context, the 2D Bose gas with repulsive interactions is particularly interesting as it exhibits a transition of the Berezinskii-Kosterlitz-Thouless (BKT) type to a superfluid state, characterized by a topological order in the low temperature regime. In the first part of my talk, I will present an experimental study of the thermodynamic and transport properties of a weakly interacting two-dimensional Bose gas. In this work, we measure the scale-invariant equation of state of this quantum fluid, thus providing the full information on its macroscopic properties. We also realize Loundau's textbook experiment for superfluidity and directly observe the frictionless motion of an impurity below the BKT transition.

Finally, experiments on ultracold atoms benefit invaluably from the capability to tune the interaction strength between atoms using Feshbach resonances. In particular, ultracold Fermi gases near Feshbach resonances realize a unique form of fermionic matter which allowed for the first realization of the crossover between Bardeen-Cooper-Schrieffer (BCS) superfluidity and Bose-Einstein condensation (BEC). The second part of my talk will be devoted to the study of strongly-interacting Fermi superfluids out of thermodynamic equilibrium. In these experiments, the system is prepared in an excited state where the phase of the superfluid order parameter is strongly, but locally, disturbed. The presence of such phase defects in the system leads to a rich and complex dynamics that can be highly non-trivial from a theoretical perspective, and which is relevant for other fermionic matter such as neutron stars. Our measurements provide a novel input for the theories of non-equilibrium dynamics of strongly-interacting Fermi superfluids.