DOCTORAL DEFENSE

Dynamics and quantum fluctuations of many-body states of interacting ultracold gases

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Abstract: We explored interaction cold atoms in new quantum regimes that have no prior analogue in condensed matter materials. In terms of types of broken symmetries, dynamic phases, and excitations, thesis research is carried out in three related main topics. First, motivated by recent advance in orbitally tuned Feshbach resonance experiments, we analyze the ground-state phase diagram and related low-energy excitation spectra of a high partial wave interacting Bose gas. A two-channel model with d-wave symmetric interactions and background s-wave interactions is adopted to characterize the gas. Apart from the three interesting phases: atomic, molecular, and atomic-molecular superfluidity, remarkably different from what was previously known in the p-wave case, the atomic superfluid is found to be momentum-independent in the present d-wave case. What is more, we study the quantum fluctuations in the condensates of a mixture of bosonic atoms and molecules with interspecies p-wave interaction. Our analysis shows that the quantum phase of coexisting atomic and molecular condensates is unstable at the mean-field level. The quantum Lee-Huang-Yang correction to the mean-field energy provides a remarkable mechanism to self-stabilize the phase. The order parameter of this superfluid phase carries opposite finite momenta for the two atomic species while the molecular component is a polar condensate. Such a correlated order spontaneously breaks a rich set of global U(1) gauge, atomic spin, spatial rotation and translation, and time-reversal symmetries.

Second, apart from the mean-field and excitation spectra study of the low temperature physics, we also present the dynamics of a 1D quantum gas model. Motivated by the question of whether all fast scramblers are holographically dual to quantum gravity, we study the dynamics of a non-integrable spin chain model composed of two ingredients - a nearest neighbor Ising coupling, and an infinite range XX interaction. Unlike other fast scrambling many-body systems, this model is not known to be dual to a black hole. We quantify the spreading of quantum information using an out-of time-ordered correlator (OTOC), and demonstrate that our model exhibits fast scrambling for a wide parameter regime. Simulation of its quench dynamics finds that the rapid decline of the OTOC is accompanied by a fast growth of the entanglement entropy, as well as a swift change in the magnetization.

Third, to extend the study of the highly chaotic many-body model composed of two ingredients - a nearest neighbor XXZ interaction and an infinite range XX interaction, we analyze the ground state phases of this model. By employing spin-wave theory, we find that there is a large parameter regime where the continuous U(1) symmetry of this model is spontaneously broken. It is worth noting that the Mermin-Wagner theorem forbids this kind of continuous symmetry breaking in the absence of the infinite range interaction. Our analytical calculations are supported by DMRG simulations on finite size chains. Furthermore, we demonstrate that in the U(1) symmetry broken phase, the half chain entanglement entropy violates the area law logarithmically. Our work demonstrates that the interplay of short and long range interactions can lead to novel quantum phases of matter.