A Thesis for the Degree of Ph.D. in Science

Strong-coupling Properties of an Ultracold Bose-Fermi Mixture with a Hetero-nuclear Feshbach Resonance

July 2017

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Thesis Abstract

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Thesis Summary

In this thesis, I theoretically investigate normal-state properties of a gas mixture of single-component Bose and Fermi atoms, with a tunable inter-species pairing interaction associated with a hetero-nuclear Feshbach resonance. Including Bose-Fermi hetero-pairing fluctuations associated with the inter-species interaction, I clarify single-particle properties of the system above the Bose-Einstein condensation temperature $T_{\rm BEC}$, from the weak-coupling regime to the strong-coupling regime. I also examine strong-coupling effects on thermodynamic quantities.

After an overview of cold atom physics, I present my formulation. I point out that the ordinary non-self-consistent T-matrix approximation (TMA), which has extensively been used for the study of strongly interacting ultracold Fermi gases, has room for improvement, when applied to a Bose-Fermi mixture. This is because TMA uses the bare Bose Green’s function that does not satisfy the required gapless Bose excitations at the $T_{\rm BEC}$, in evaluating self-energy corrections. To overcome this, I improve TMA so that the gapless condition can be satisfied.

Using this improved T-matrix approximation (iTMA), I study single-particle excitations near $T_{\rm BEC}$. Hetero-pairing fluctuations are shown to couple Fermi atomic excitations with Bose atomic and Fermi molecular excitations. Although a similar coupling phenomenon is known in the unitary regime of an ultracold Fermi gas, while it causes the pseudo-gapped density of states in the latter Fermi system, such a phenomenon is found to be absent in a Bose-Fermi mixture even at the unitarity. A shallow pseudo-gapped density of state is only obtained in the strong-coupling regime.

I also examine strong-coupling effects on thermodynamic properties of a unitary Bose-Fermi mixture. To minimize ambiguity coming from approximate treatment of hetero-pairing fluctuations, I employ a combined iTMA with exact thermodynamic relations, where complicated iTMA calculations are only done to calculate Fermi and Bose chemical potential. Various thermodynamic quantities are then evaluated from the calculated chemical potential by using exact thermodynamic identities. I find that the specific heat at constant volume is a useful quantity for the study of strong-coupling properties of the system, because it is sensitive to hetero-pairing fluctuations, to exhibit anomalous non-monotonic temperature dependence.