Phase transitions and pairing signature in 1D Fermi gases

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Recent achievements in manipulating cold atoms have opened up exciting possibilities for the study of many-body quantum effects in low dimensional systems. Experimental observation of superfluidity and phase separation in imbalanced Fermi atomic gases has stimulated great interest in exploring exotic quantum phases of matter with mismatched Fermi surfaces. The pairing of Fermi atoms with mismatched Fermi surfaces may lead to breached and Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) states, where the bound pairs form a superfluid, while the unpaired fermions remain as a separated gas phase in momentum space. Mismatched Fermi surfaces can appear in different quantum systems, such as type II superconductors in an external magnetic field, mixtures of fermions with different internal degrees of freedom or masses, and charged neutral quark matters.

These exotic phases in the one-dimensional (1D) integrable two-component Fermi gas model have recently attracted renewed interest due to the studies of BCS-BEC crossover and quantum phase separation in a trapping potential [1, 2]. The 1D systems can be experimentally realized by applying strong transverse confinement. In the 1D interacting Fermi gas, the Fermi surface is reduced to the Fermi points. The lowest excitation destroys a bound pair close to the Fermi surface. Charge and spin propagate with different velocities due to the pairwise interaction. The external magnetic field triggers energy level crossing such that the Fermi surfaces of paired fermions and unpaired fermions vary smoothly with respect to the external field. As we demonstrated, the presence of the external field at zero temperature has an important bearing on the nature of quantum phase transitions in 1D interacting fermions.

Exact Bethe ansatz (BA) solutions provide reliable physics beyond mean field theory and also give an elegant way to analyze quantum phase transitions in the presence of an external field by means of the dressed energy formalism. We obtained exact results from this formalism for characteristics of pairing phases and quantum phase transitions in the 1D two-component strongly attractive Fermi gases [3]. We presented a systematic way to obtain the critical fields and magnetic properties at zero temperature for strongly interacting fermions. We found that the bound pairs of fermions with opposite spin states form a singlet ground state when the external field $H < H_{c1}$. A completely ferromagnetic phase without pairing occurs when the external field $H > H_{c2}$. In the region $H_{c1} < H < H_{c2}$, we observed a mixed phase in which paired and unpaired atoms coexist.

On the other hand, atomic Fermi gases with multi-internal degrees of freedom are tunable interacting many-body systems featuring novel and subtle quantum phase transitions. In contrast to the two-component fermions, three-component fermions possess new features: (1) BCS pairing can be favored by anisotropy in three different ways; (2) specifically, strongly attractive atomic fermions with three different hyperfine states can bind to form singlet trionic states. Recently, we extended our research to systems of ultracold three-component Fermi gases [4] to study the nature of trions and pairs, and calculate full ground state phase diagrams and critical fields by solving BA equations and sophisticated dressed energy equations.

References

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