Fermion-Boson Quantum Liquid Mixtures in Cold Atom Physics

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In its capacity of many-body physics laboratory, the cold atom trap offers the exciting prospect of revisiting the physics of fermion-boson quantum liquid mixtures. At the time of writing, cold atom fermion/boson gas mixtures are trapped routinely. Bosonic atoms, which, in many of the experiments are condensed into a Bose-Einstein condensate (BEC), serve to refrigerate the fermion atoms and cool them to quantum degeneracy (below the Fermi temperature) in a procedure known as sympathetic cooling. When, in Ketterle's laboratory at Massachusetts Institute of Technology, sympathetic cooling alone appeared incapable of driving the temperature below one quarter of the Fermi temperature, this group added another step to the cooling process. After separating the BEC, they now cool the fermions further by removing those atoms with the highest energy (evaporative cooling). If, however, the BEC were to remain in the trap as the temperature dips below the value at which Fermi-liquid behavior sets in (estimated at 15% of the Fermi-temperature), a very interesting mixture would be realized. At those temperatures the mixture resembles the low temperature He-3/He-4 fluids that, until now, represent the only laboratory realizations of fermi-liquid/boson superfluid mixtures.

The He-3/He-4 experiments uncovered an intricate phase diagram with a temperature/molar fraction region in which part of the fermionic fluid separates out spontaneously to occupy He-3-only spatial regions. The microscopic understanding of the He-3/He-4 phase diagram is, unfortunately, complicated by the strong interaction effects that mask the more fundamental effects of quantum statistics. The cold atom analogue then promises to provide a cleaner testing system, amenable to first principle understanding, and accessible to a very different battery of experimental probes.

In our theoretical investigations, we considered a homogeneous zero-temperature gas mixture of a BEC with a single component fermion gas (all fermion atoms occupying the same spin state). Given the short range of the neutral atom-atom interactions the Pauli-exclusion principle precludes direct fermion-fermion interactions at the densities obtained in atom traps (less than 10^{14} cm^{-3}). Nevertheless, the overlapping BEC mediates an effective fermion-fermion interaction in a process that involves a virtual BEC-excitation.

In the static limit of weak fermion-boson interactions, this BEC-mediated fermion-fermion interaction is described by an attractive Yukawa potential $(\propto -\exp(-r/\lambda_c)/r$ with a range, λ_C, that is the healing length of the BEC. The magnitude and sign of this effective interaction has led to speculations that it can significantly contribute to the Cooper-pairing of the fermion atoms and increase the critical temperature for fermion superfluidity.

In studying the collective excitations of the BEC/normal Fermi-liquid mixture, however, we found that the dynamics of the boson mediation can have a profound effect on the many-body properties. Specifically, we found that in the experimentally relevant regime where the Fermi-velocity, v_F, exceeds the BEC-sound velocity, this dynamics switches the sign of the fermion-fermion interaction in the collective excitation to give a zero-sound-like mode with group velocity close to v_F.

From Fermi-liquid theory, we know that zero sound modes can only be supported by effectively repulsive interactions. The Fermi-liquid-like collective mode equation that we derived also predicts the lifetime and dispersion of BEC-phonon-like modes. We discovered that the BEC-phonon-like mode terminates at a well-defined wavenumber and that the zero-sound-like mode merges into the BEC-sound-like mode in an avoided crossing-like manner. Furthermore, the collective mode dispersion contains the

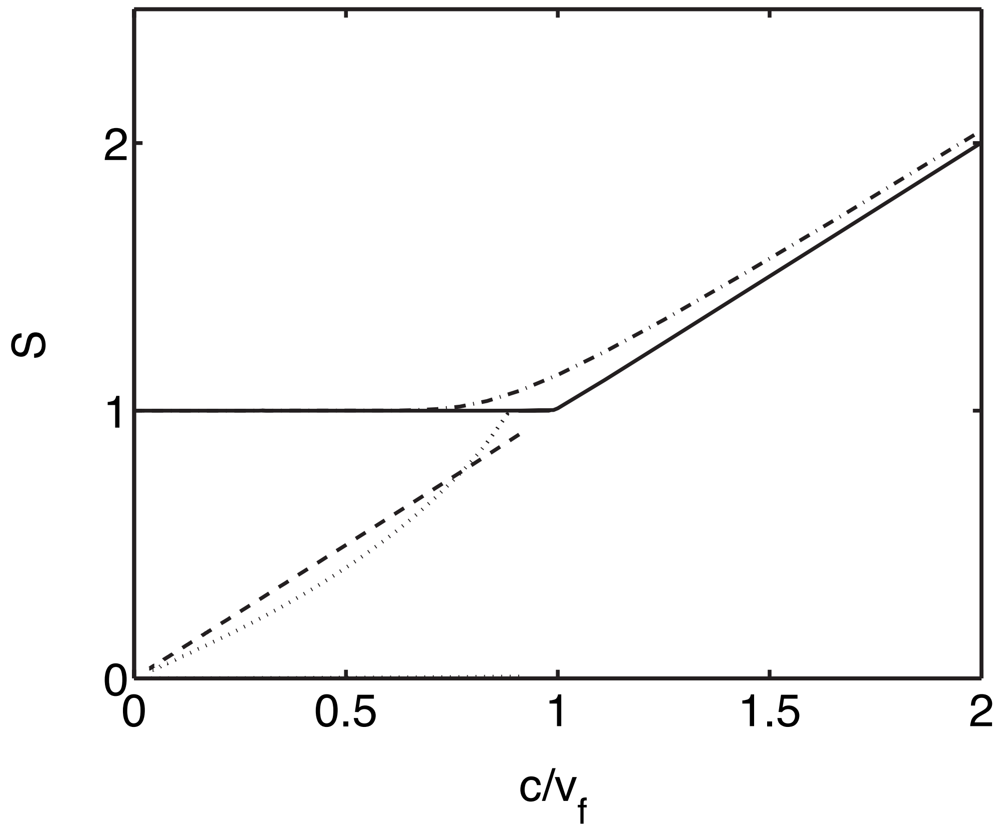

Figure 1—
The figure shows the long wavelength group velocity, s (shown in units of the Fermi-velocity) of the collective collisionless modes of a homogeneous BEC/single component normal Fermi-liquid mixture as a function of the ratio of the Fermi to BEC sound velocities under typical atom trap conditions. The full and dashed lines correspond to the zero sound-like and BEC sound-like modes for interactions that are weaker than the interactions in the system with modes shown by the dash-dotted and dotted lines, respectively.

signature of phase separation. From the dispersion we can infer the time and length scales of the onset of the phase separation process.

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