Collective excitations in one- and two-band condensed Fermi gases at finite temperatures

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The phononic and Leggett collective excitations in one- and two-band Fermi gases are studied using the effective bosonic action of Gaussian pair fluctuations. The spectra of collective excitations are treated for nonzero temperatures in the BCS-BEC crossover. The obtained results are in good agreement with recent experiments on atomic Fermi superfluids and resolve known issues of some preceding theories.

Phononic excitations in Fermi superfluids

In the present talk, we review our recent results on collective excitations in one-and two-band superfluid Fermi gases with *s*-wave pairing: phononic modes and Leggett collective excitations existing in multiband superfluids and superconductors. The investigation is focused on Fermi gases in the BCS-BEC crossover regime with an attention on the temperature dependence of collective excitations spectra. We use the Gaussian pair fluctuation effective action for one- and two-band systems within the path integral formalism obtained in Ref. [1].

Our method allows us to treat phononic collective modes of the pairing field in a superfluid Fermi gas at all temperatures below the transition temperature T_c.[2]. The coupling of the collective modes to the fermionic continuum of quasiparticle-quasihole excitations is taken into account using a non-perturbative analytic continuation of the pairing field propagator. At low temperature, we recover the know exponential temperature dependence of the damping rate and velocity shift of the Anderson-Bogoliubov branch. In the vicinity of T_c and in the BCS regime, our calculations reveal two phononic branches. The first branch has a velocity that tends to a finite non-zero value at T_c. The second one has a velocity that vanishes with a

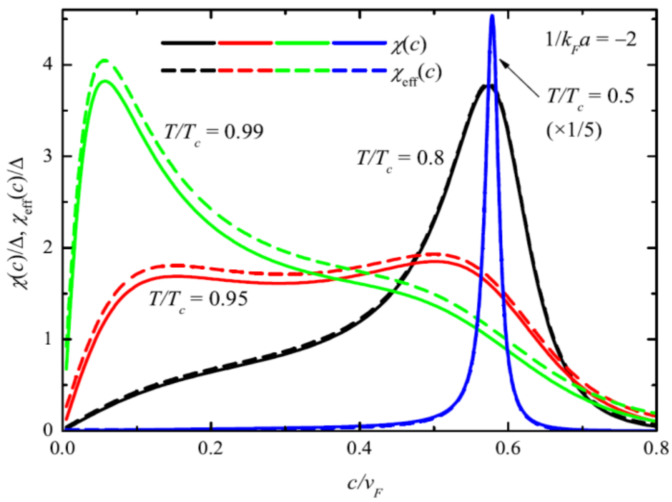

Fig. 1. Long-wavelength phase-phase response function (solid lines) and its two-pole analytic approximation (dashed lines) in the BCS regime for $T = 0.5T_c$, where they show a single quasi-Lorentzian peak, $T = 0.8T_c$, where the peak is displaced and skewed by the increasingly contributing second root, $T = 0.95T_c$ where two resonances are visible, and $T = 0.99T_c$ where the diffusive peak near $c = 0$ dominates. (From Ref. [2].)

critical exponent of 1/2 and a quality factor that diverges logarithmically with ($T_c - T$). At temperatures close to the transition temperature, this results in a double peak structure in the response function of the phase of the pair field, well resolved in the BCS regime as shown in Fig. 1. For intermediate temperatures we develop a semi-numerical method to perform the analytic continuation. This confirms the existence of two branches, and allows us to follow the disappearance of the second branch as the temperature is lowered. Our results generalize to pure fermionic condensates the double peak structure observed by Carlson and Goldman in dirty superconductors (Phys. Rev. Lett. **31**, 880).

Leggett modes in two-band Fermi superfluids

The collective modes in a two-band superfluid or superconductor predicted by Leggett [3] describe oscillations of a relative phase of the two superfluid components. Recently, the two-band superfluidity has been experimentally achieved using the so-called orbital Feshbach resonance (OFR) [5]. The interaction strength parameters of Fermi gases under OFR are highly tunable, allowing for regimes from BEC to BCS. It can be shown that beyond the weak interband coupling regime, the frequently used low-energy expansion of the effective action fails for Leggett modes, as well as for pair-breaking modes [4]. The frequencies and the damping factors for Leggett modes are then determined in a self-consistent non-perturbative way through complex poles of the fluctuation propagator, similarly to Refs. [2, 4], where this method has been applied to pair-breaking and phononic collective excitations in ultracold Fermi gases.

The spectra of Leggett modes are investigated as a function of the coupling parameters, temperature, and the detuning parameter δ, which characterizes the band offset between the two bands. With increasing δ, the Leggett mode frequency may reach and cross the pair-breaking continuum edge, showing an interplay with pair-breaking modes. In the BEC regime, when pair-breaking collective excitations absent [4], the Leggett mode passes the pair-breaking continuum edge acquiring a finite damping, but does not dissolve. At the BCS side, the Leggett modes avoid crossing with the pair-breaking continuum. Strong coupling regimes are favorable for the experimental observation of Leggett modes.

References

[1] S. N. Klimin, J. Tempere, G. Lombardi, and J. T. Devreese, "Finite temperature effective field theory and two-band superfluidity in Fermi gases", Eur. Phys. Journal B **88**, 122 (2015).

[2] S. N. Klimin, J. Tempere, and H. Kurkjian, "Phononic collective excitations in superfluid Fermi gases at nonzero temperatures", arXiv:1811.07796 (2019) (*to be published*).

[3] A. J. Leggett "Number-phase fluctuations in 2-band superconductors", Prog. Theor. Phys. **36**, 901 (1966).

[4] H. Kurkjian, S. N. Klimin, J. Tempere, and Y. Castin, "Pair-breaking collective branch in BCS superconductors and superfluid Fermi gases", Phys. Rev. Lett. **122**, 093403 (2019).

[5] G. Pagano *et al.*, "Strongly interacting gas of two-electron fermions at an orbital Feshbach resonance", Phys. Rev. Lett. **115**, 265301 (2015).