Collective (Higgs) Excitation Branch in the Broken Pair Continuum of Spin 1/2 Fermi Gases

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The pair-condensed unpolarized spin 1/2 Fermi gases exhibit a collective excitation branch in their broken pair continuum (V.A. Andrianov, V.N. Popov, 1976), sometimes called the Higgs branch. We carried out an in-depth study of it at zero temperature [1]. We start from the eigenenergy equation deduced from the linearized time-dependent BCS theory, which is equivalent to Anderson's RPA, then we carry out its analytical continuation to the lower complex half-plane through its cut line, which is essential to find the collective mode. We compute both the complex dispersion relation and the spectral weights (quasiparticle residues) of the branch.

In the case of so-called BCS superconductors (with charged fermions) where the effect of the crystal lattice is replaced by a short range attractive interaction, but where the Coulomb interaction is taken into account, we restrict ourselves to the limit of weak coupling $\Delta/\mu \to 0^+$ (Δ is the order parameter, μ the chemical potential) and wavenumbers $q = O(1/\xi)$ where ξ is the size of a Cooper pair; when the complex energy z_q is expressed in units of Δ and q in units of $1/\xi$, the branch follows a universal law that we determine, insensitive to the Coulomb interaction.

In the case of cold atoms in the BEC-BCS crossover, the fermions are neutral and only a contact interaction remains, but the coupling Δ/μ can take arbitrary values, and we study the branch at any wave number q. (i) In weak coupling, we predict three scales, the one already mentioned $q \approx 1/\xi$, the one $q \approx (\Delta/\mu)^{-1/3}/\xi$ where the real part of the dispersion relation admits a minimum and that $q \approx (\mu/\Delta)/\xi \approx k_{\rm F}$ ($k_{\rm F}$ is the Fermi wavenumber) where the branch reaches the edge of its domain of existence. (ii) Near the point of chemical potential cancellation on the BCS side, $\mu/\Delta \to 0^+$, where $\xi \approx k_{\rm F}$, we find the two scales $q \approx (\mu/\Delta)^{1/2}/\xi$ and $q \approx 1/\xi$. In any case, the branch has a limit of 2Δ and a quadratic start at $q = 0$, in accordance with what is expected of a Higgs branch, and should be observable at low q in the response of the gas to a laser Bragg excitation, if one measures the disturbance induced on the modulus of the order parameter rather than on the density [2]. (iii) On the BEC side ($\mu < 0$), we also find a Higgs branch of this type (searched in vain by T. Cea, C. Castellani, G. Seibold, L. Benfatto, 2015) but only for $\Delta/|\mu| < 0.222$; it should be noted that, in this case, the starting point 2Δ of the branch is strictly below the edge of the broken pair continuum $2(\Delta^2 + \mu^2)^{1/2}$, unlike what happens on the side $\mu > 0$ (where the edge of the continuum is exactly 2Δ in BCS theory).

References

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