Composite bosons in the 2D BCS-BEC crossover from Gaussian fluctuations

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Trieste, October 28, 2014

Reference: **e-preprint arXiv:1410.3995**

Grand potential in 2D BCS-BEC crossover

Within our beyond-mean-field approach the zero-temperature grand potential of the **2D Fermi superfluid** in the BCS-BEC crossover is given by

$$\Omega = \Omega_{mf} + \Omega_g \ , \tag{1}$$

where

$$\Omega_{mf} = -\frac{mL^2}{2\pi\hbar^2}(\mu + \frac{1}{2}\epsilon_b)^2 \tag{2}$$

is the mean-field term of single-particle fermionic elementary excitations, with μ the chemical potential, ϵ_B the binding energy of paired fermions, and L^2 the area. The beyond-mean-field Gaussian term

$$\Omega_g = \frac{1}{2}\sum_{\mathbf{q}} \sqrt{\frac{\hbar^2 q^2}{2m}\left(\lambda\frac{\hbar^2 q^2}{2m} + 2\ m\ c_s^2\right)} \tag{3}$$

is the zero-point energy of collective bosonic elementary excitations, where c_s is the sound velocity and λ the quartic correction of the familiar low-momentum dispersion $\epsilon_{col}(q) = c_s q$.

Bosonic vs fermionic scattering length

Ω_g is **divergent** but we regularize it by using dimensional regularization. In particular, in the BEC regime ($\lambda = 1/4$) we find

$$\Omega = -\frac{m_B L^2}{8\pi\hbar^2}\mu_B^2 \ \ln\left(\frac{\epsilon_b}{\mu_B}\right) . \qquad (4)$$

where $\mu_B = 2(\mu + \epsilon_b/2)$ is the chemical potential of composite bosons. In terms of the fermionic scattering length a_F we have $\epsilon_b = \frac{4}{e^{2\gamma}}\frac{\hbar^2}{m a_F^2}$, where $\gamma = 0.577$. In this way Eq. (4) becomes exactly the Popov's 2D equation of state[1] of bosons with scattering length a_B, provided that

$$a_B = \frac{1}{2^{1/2} e^{1/4}} \ a_F = 0.551...a_F \ , \qquad (5)$$

in good agreement with Monte Carlo[2] and four-body scattering[3].

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[1] V.N. Popov, Theor. Math. Phys. A **11**, 565 (1972).
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[3] D.S. Petrov, M.A. Baranov, and G.V. Shlyapnikov, Phys. Rev. A **67**, 031601 (2003).