Critical temperature and phase diagram for a 2D superfluid Fermi-gas with repulsion.

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Abstract

In the framework of a 2D Fermi-gas with short-range repulsive interaction we find the critical temperature of the superfluid phase transition based on Kohn-Luttinger effect, and analyze its dependence on magnetic field. We calculate strong-coupling corrections to the Ginzburg-Landau free energy functional and analyze the stability of 2D superfluid phases. Possible applications of the results to real systems are discussed.

Keywords: Two-dimensional Fermi-liquid, $^3$He-$^4$He mixtures, superfluidity, superconductivity.

1. Introduction

Recent experiments on $^3$He submonolayers absorbed on graphite [1], $^3$He atoms bound to the surface of $^4$He films [2–4] and discovery of superconductivity in layered HTSC materials stimulate theoretical studies of superfluid phase transition in a 2D Fermi liquid. It was shown [5,6], that even in the case of a bare repulsive $s$-wave interaction in a 3D Fermi system, there is a transition to the $p$-wave superfluid state due to a singularity in the effective interaction near the momentum transfer $q = 2p_F$ (Kohn-Luttinger effect), $\Gamma_{\text{sing}}(q) \sim (2p_F - q) \ln[2p_F - q]$, where $p_F$ is the Fermi momentum. Further analysis [7] shows that the similar effect takes place also in 2D case.

2. Theoretical model and results

We consider a 2D non-ideal Fermi gas with a short-range repulsive interaction, $r_0p_F \ll 1$, where $r_0$ is the range of potential, such that the perturbative expansion in a gas parameter $f_0$, related to the $s$-wave scattering amplitude between two particles on the Fermi surface, is legitimate. For the considered case the gas parameter is given by

$$f_0 = \left[4\pi/mU_0 + \ln(r_0p_F)^{-2}\right]^{-1},$$

where $U_0$ is the $s$-component of the potential.

It turns out that for a 2D Fermi gas the Kohn-Luttinger mechanism works in the third order in $f_0$, because the singular contribution of the second order in $f_0$ to the effective interaction,

$$(m/4\pi)\Gamma_{\text{sing}}^{(2)}(q) = -f_0^2 \text{Re} \sqrt{1 - (2p_F/q)^2},$$
Fig. 1. The p-wave critical temperature $T_{c1}/\tilde{\varepsilon}$ as a function of polarization $\alpha = (n_{x_{3}}-n_{x_{1}})/(n_{x_{1}}+n_{x_{2}})$ for typical $f_{0} = 0.3$. is zero for $q \leq 2p_{F}$, and, therefore, does not contribute to the $p$-harmonic. The result for $\Gamma_{\text{sing}}(q)$ in the third order in $f_{0}$ is

$$(m/4\pi)\Gamma_{\text{sing}}^{(3)}(q) \sim -f_{0}^{3}\text{Re}\sqrt{1-(q/2p_{F})^{2}},$$

and it leads to an effective attraction in the $p$-wave channel. Numerical calculations of third-order diagrams give for the $p$-wave critical temperature

$$T_{c1} = \tilde{\varepsilon} \exp\left(-\frac{1}{6.1f_{0}}\right),$$

where $\tilde{\varepsilon} = A \cdot \varepsilon_{F}$, $A$ is the unknown numerical prefactor, $\varepsilon_{F} = p_{F}^{2}/2m$ is the Fermi energy.

The typical value of scattering amplitude obtained from the experiments on $^3$He atoms on the surface of $^4$He is $f_{0} \leq 0.3$ for $^3$He coverages corresponding to the dilute Fermi-gas situation. In this regime the critical temperature is $T_{c1} \sim 10^{-3}K$.

The critical temperature $T_{c1}$ can be significantly increased by applying an external magnetic field, because in this case the effective interaction contributes to $T_{c1}$ already in the second order. The separation of polarization and pairing effects leads to a strongly non-monotonic dependence of the critical temperature on the polarization (Fig. 1).

In the weak coupling (BCS) limit for zero magnetic field, two different phases correspond to the minimum of the free energy (the axial and the planar phases) [8]. To lift this degeneracy one has to consider next order ($\sim T_{c}/\varepsilon_{F}$) corrections. Following [9], we have calculated the difference between free energies of axial and planar phases to this order:

$$\Phi_{\text{axial}} - \Phi_{\text{planar}} \sim -\frac{N(0)}{T_{c}^{2}}\left(\frac{T_{c}}{\varepsilon_{F}}\right)$$

$$\times \int \frac{d\varphi}{2\pi} \sin\varphi |T_{\alpha}^{2}(\hat{k}_{1}, \hat{k}_{2}; \hat{k}_{3}, \hat{k}_{4})|,$$

where $N(0)$ is the density of states on the Fermi surface, $T_{\alpha}(\hat{k}_{1}, \hat{k}_{2}; \hat{k}_{3}, \hat{k}_{4})$ the spin-antisymmetric part of quasiparticle scattering amplitude with momenta $\hat{k}_{i}$ on the Fermi surface and $\varphi$ the angle between $\hat{k}_{1}$ and $\hat{k}_{2}$. Clearly, the energy difference (2) is always negative, therefore in the absence of a magnetic field the superfluid Fermi-gas forms the axial phase.

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