Novel Superfluid Transitions of ^{3}He in the Bulk and on the Surface Layer

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Abstract

The novel superfluid (SF) transitions of ^{3}He in the bulk and on the surface layer are studied within the two-stage Fermi-Bose-liquid model of superfluidity in Fermi systems. We argue that the novel superfluidity in ^{3}He results from the BCS-like p-wave pairing of fermions and the SF condensations of two-fermion composite bosons. We show that the A-phase is formed both in the bulk and on surfaces at SF pair condensation of triplet composite bosons with parallel spins, while the B-phase is formed only in the bulk at SF single particle condensation of such bosons with antiparallel spins and the surfaces destabilize the B-phase.

Key words: Superfluid ^{3}He; novel superfluidity; surfaces

1. Introduction

During the last decades, the superfluid (SF) phase transitions of ^{3}He have been studied within the BCS-like Fermi-liquid theories [1, 2]. It is well known that when the liquid ^{3}He is cooled at high pressures first it undergoes a second-order phase transition into the SF A-phase at the temperature $T = T_c$ and then the SF ^{3}He undergoes a first-oder phase transition at $T = T_{AB} < T_c$ into the B-phase. These SF phase transitions of ^{3}He and the natures of the A and B phases cannot be understood properly in terms of the BCS-like pairing (or Fermi-liquid) theories [3, 4]. Because the BCS-like pairing theories may explain only the precursor second-order phase transition. But the true SF phase transitions (in partucular, the first-order phase transition), the specific features of the A-B transition in the bulk and surfaces and the effects of pressure, magnetic field, rotation and surfaces on nucleation processes of the A and B phases in ^{3}He remain long-standing mysteries to these theories. We develop in this paper a novel two-stage Fermi-Bose-liquid model of superfluidity in ^{3}He [4]. This novel superfluidity results from the BCS-like p-wave pairing of fermions and the SF single particle and pair condensations of attracting two-fermion composite bosons. Here we study the distinctive SF transitions of ^{3}He in the bulk and on surfaces within the proper SF Bose-liquid model.

2. Precursor BCS-like p-wave pairing scenario

Our first postulate reads as follows: any BCS-like pairing state of fermions (i.e. ^{3}He atom) is the precursor state but not SF one. In particular, the BCS-like p-wave pairing of He atoms leads to the formation of the precursor Anderson-Brinkmann-Morel (ABM) state of Cooper pairs with angular momentum $l = 1$ and spin $S = 1$ below the temperature T_F. The equations for the BSC-like gap $\Delta_F(k)$ and transition temperature T_F are [1, 2]

$$\Delta_F(k) = -\sum_{k'} V_F(k,k')\frac{\Delta_F(k')}{2E_F(k')}tanh(\frac{E_F(k')}{2k_BT}) \qquad (1)$$

and

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$$k_BT_F = 1.14\epsilon_c exp[-1/N_F(0)|V_{Fl}|], \quad (2)$$

respectively, where $E_F(k) = [\varepsilon_F^2(k) + \Delta_F^2(k)]^{1/2}$ is the excitation energy of a BCS-like Fermi-liquid, $\varepsilon_F(k)$ is the normal state energy, measured from the Fermi level, $V_F(k,k')$ is the pairing interaction between fermions, ϵ_c is the cutoff energy for $V_F(k,k')$ which is constant and equal to V_{Fl} for $\varepsilon_F(k) < \epsilon_c$, $N_F(0)$ is the density of states at the Fermi surface.

3. Superfluid single and pair condensations of two-fermion composite bosons in the bulk and on surfaces

Our another postulate is that the superfluidity of triplet Cooper pairs (i.e. cooperons) in ^{3}He is driven by their attractive pair and single particle condensations below the temperature $T_c = T_B$ and $T_B^* < T_B$ respectively. In the weak-loupling limit the formation of Cooper pairs and the SF condensations of the composite bosons with total angular momentum $L = l_1 + l_2 = 0$ and spin $S = s_1 + s_2 = 2$ occur simultaneously (i.e. automatically) at the same temperature $T_c = T_F = T_B$. The SF order parameter Δ_B and transition temperature T_B for the bulk ^{3}He liquid are determined from the equations [4]

$$\Delta_B(k) = -\sum_{k'} V_B(k,k') \frac{\Delta_B(k')}{2E_B(k')} coth \frac{E_B(k')}{2k_BT} \quad (3)$$

and

$$T_B = T_{BEC}[1 + 1.42\gamma_B \sqrt{k_BT_{BEC}/\xi_{BA}}], \quad (4)$$

where $V_B(k,k')$ is the interaction between composite bosons, $E_B(k') = [(\varepsilon_B(k) + \tilde{\mu}_B)^2 - \Delta_B^2]^{1/2}$ is the excitation energy of a SF Bose-liquid, γ_B is the interboson coupling constant, $\varepsilon_B(k)$ is the kinetic energy of composite bosons, $\tilde{\mu}_B$ is the chemical potential including repulsive Hartree-Fock energy, $T_{BEC} = 3.31\hbar^2 n_B^{2/3}/k_B m_B$, n_B and m_B are the concentration and mass of composite bosons, ξ_{BA} is the cutoff energy for the attractive part of $V_B(k,k')$.

In a three-dimentional Bose-liquid (with $\gamma_B < 1$) the first-order SF phase transition temperature $T_B^* = T_{AB}$ has the property $T/\sqrt{2} < T_{AB} < T_c = T_B$ [4]. The energy gap in the excitation spectrum of such a SF Bose-liquid vanishes at $T = T_B^* = T_{AB}$. It means that the SF pair and single particle condensation of attracting composite bosons in the bulk of ^3He liquid lead to the formation of the A- and B-phases, respectively. So, the A-phase is formed at pair condensation of composite bosons (with $L = 0$ and $S = 2$) at $T_B^* < T < T_c$ while the B-phase is formed at single particle condensations of composite bosons (with $L = 0$ and $S = 0$) at $0 < T < T_{AB}$. In a two-dimensional Bose-liquid (with $\gamma_B < 1$) the first-order SF phase transition occurs only at $T = T_{AB} = 0$ [4]. Thus the A-phase nucleation on surfaces is possible at very low temperature and this phase of ^{3}He exists even near absolute zero. While the B-phase did not nucleate on surfaces. This phase can nucleate on the surface layer (where $T_B^* = T_{AB} \neq 0$) at significantly lower temperatures than in the bulk. So, the surface layers play a role similar to a magnetic field or a rotation, which shifts the A-B transition to lower temperatures. The above results agree with experimental findings, such as the A-B transition at $T = 0.78T_c$ in the bulk, the decreasing of the A-B transition temperature in ^{3}He contained within narrow spaces between thin flat plates and the supercooling of the A-phase to temperatures as low as 0.36 mK (or $0.15T_c$) [3].

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