Critical thickness of A-B phase transition in superfluid ^{3}He film

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Abstract

The anisotropic A phase becomes stable in thin film because of the axial symmetry. From NMR measurements with 0.8-μm and 1.1-μm superfluid ^{3}He films, we observed A phase even at low pressures and we have obtained the critical thickness δ for A-B phase transition occurrence in wide pressure range. This thickness is the ratio of real film thickness to temperature dependent coherence length at which A-B transition occurs. This δ depended nearly linearly on pressure p [MPa] as $\delta \approx 13.1 + 9.8p$, which was estimated about 8 in the weak coupling approximation. It is estimated that in the superfluid ^{3}He film thinner than 0.3 μm only A phase appears in all pressures below the superfluid transition temperature T_c.

Key words: superfluid ^{3}He film, coherence length, A-B phase transition, critical thickness

The superfluid ^{3}He is well known as a Cooper pair condensate whose orbital pairing is p-wave. This means that superfluid ^{3}He has an anisotropic property intrinsically. B phase, however, has the isotropic energy gap and the anisotropy appears in more small energies like dipole energy. On the other hand A phase has the axial symmetric energy gap, which has two gapless nodes along the symmetric axis. For the anisotropy in real space, it is important to consider quasiparticle scattering condition at wall. When an incident wave function of quasiparticle normal to wall surface is reflected, the incident and the reflected waves cancel out each other. Consequently a condensate wave function becomes quasi-two dimensions. A phase in this case can lose no condensation energy by setting the direction of gapless node normal to the wall surface. In B phase this gives rise to a loss of condensation energy. So it is expected that the superfluid ^{3}He near wall favors A phase more than B phase within a length scale of temperature dependent coherence length $\xi(T)$. $\xi(T)$ is a length scale of spatial change in order parameter and diverges near transition temperature T_c. This means that A phase is also favored near T_c.

To study the effect of two-dimension anisotropy at wall upon the stability of superfluid states in superfluid ^{3}He, we performed cw NMR experiments on thin film in slab geometry, which was made between parallel plates [1,2]. We are interested in the relation of the real film thickness d and ξ_{AB} which is the coherence length at T_{AB} when the phase transition between A phase and B phase really occurs. So the film thickness d should be short enough to suppress one component order parameter partly but should not be so short to suppressed it completely. In latter case only A phase (or planar phase) might appear in equilibrium. A critical thickness δ is defined as the ratio of d/ξ_{AB}. In the weak coupling approximation, δ is about 8 [3] and about 20 with including the strong coupling effect [4]. Therefore a film thickness d needs to be larger than $\xi(T)$. We made two slab spaces with film thickness of 1.1 μm and 0.8 μm and experiments were performed at pressure from 0.14 MPa to 2.7 MPa [1,2]. In spite of the NMR static field $H < 30$ mT, the stable A phase appeared even at low pressure. Furthermore, at 0.14 MPa only A phase appeared even at 0.3 mK in 0.8 μm film. The A-B phase transition in thin film was characterized by the change in resonance frequency shift and in magnetization for NMR absorption signals [1,2]. In analyzing

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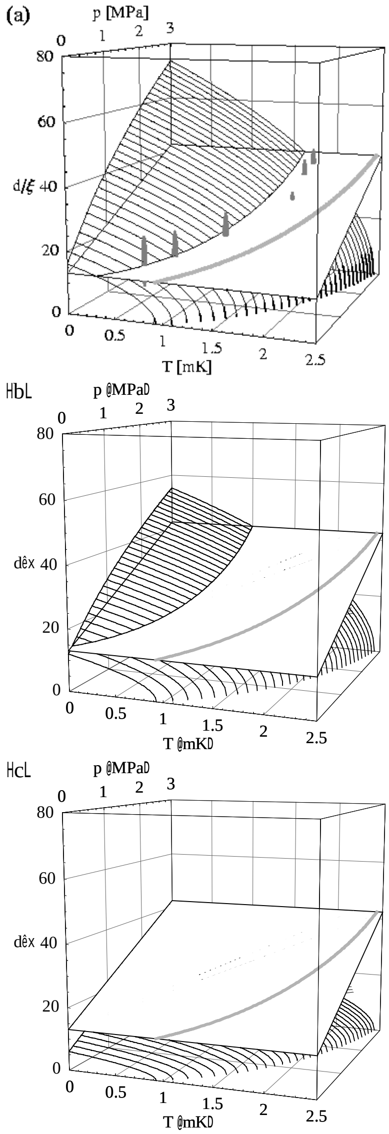

Fig. 1. The ratio $d/\xi(p,\ T)$ and the critical thickness $\delta(p)$ as a function of temperature and pressure. The cigar-shaped plots in (a) are experimental values of the superfluid ^{3}He film of 0.8 μm. These plots tell whether the phase of the superfluid ^{3}He is the A or the B phase in any slab geometry. For details, see in the text.

data we use the coherence length as follows;

$$\xi(p,T) = \sqrt{\frac{3}{5}}\sqrt{\frac{7\zeta(3)}{48}}\frac{\hbar v_F}{\pi k_B T_c}\sqrt{\frac{1}{1-T/T_c}}, \tag{1}$$

where $\zeta(3)$ is Riemann's zeta function k_B is the Boltzmann constant. The Fermi velocity v_F and T_c are dependent on pressure.

The obtained values of the critical thickness are 19.9(1.0 MPa), 30.5(2.0 MPa), 40.7(2.4 MPa) and 49,8(2.7 MPa) in 1.1 μm film and are 17.0(0.3 MPa), 18.2(0.5 MPa), 22.2(1.0 MPa), 25.6(1.9 MPa), 34.0(2.4 MPa), 35.6(2.7 MPa) in 0.8 μm film. Except higher pressures δ is almost independent of film thickness and depends only on the pressure. From these results we obtained a universal linear relation between δ and pressure p as

$$\delta(p) = 13.1 + 9.8p. \tag{2}$$

By using Fig. 1 we can explain the A-B phase transition phenomena in any thin superfluid ^{3}He film. In Fig. 1 the critical thickness $\delta(p)$ and $d/\xi(p,\ T)$ are plotted in three dimensions space as a function of temperature and pressure. The common white plane in each figure indicates $\delta(p)$ and a gray curve in this plane is a projection of the superfluid-normal transition line in bulk liquid. Many solid curves correspond with calculated $d/\xi(p,\ T)$ for every 0.1 MPa, which becomes zero at T_c. Comparing $\delta(p)$ to $d/\xi(p,\ T)$, we can know which phase is stable in superfluid ^{3}He film. At the point satisfying $\delta(p) = d/\xi(p,\ T)$ the A-B transition will occur. For the region satisfying $\delta(p) > d/\xi(p,\ T)$ A phase will appear and for the region satisfying $\delta(p) < d/\xi(p,\ T)$ B phase will appear. The calculated $d/\xi(p,\ T)$ for d =0.8 μm, d =0.6 μm and d =0.3 μm are plotted in Fig. 1 (a), (b) and (c), respectively. The intersection points in $\delta(p)$ plane with solid curves in Fig. 1 (a) correspond with experimental data of A-B phase transition in 0.8 μm film. In Fig. 1 (b) the intersections shift toward lower temperatures and there is no intersection at 0 MPa, which means B phase will not appear even at absolute zero. In Fig. 1 (c) no intersection exists and only A phase is the stable state down to zero at any pressure. This estimation about 0.3 μm is consistent with the result of Freeman et al. [5] that a phase of superfluid ^{3}He in 0.3 μm film was only A phase. Furthermore, our estimation suggests that they observed the thermodynamically stable A phase, not a supercooled A phase.

In summary we obtained the critical thickness δ from the A-B transition temperature in the experiments of the superfluid ^{3}He films of 1.1 μm and 0.8 μm. δ was nearly a universal function on only pressure. From $\delta(p)$, it became clear for the first time that a thermodynamically stable state was A phase in superfluid ^{3}He in the film thinner than 0.3 μm.

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