

New phases of liquid ^3He at low temperature

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1. Abstract

This paper introduces the properties of superfluid ^3He by a brief review of the history of experimental discovery and theoretical understanding of the new phases. Experiments that led to the discovery and confirmation of the new phases are introduced and discussed.

2. Introduction

With the success of BCS theory in explaining the phenomenon of superconductivity of metal at low temperature, it was anticipated that similar phenomenon could also happen in liquid ^3He . Like electron, ^3He is fermion with spin $\frac{1}{2}$. But since ^3He is neutral, the new phases of liquid ^3He would have the property of superfluidity not superconductivity.

The cooling method improved rapidly in the sixties. A breakthrough was made by Osheroff, Richardson, and Lee in 1972, who discovered two distinctive features on the melting curve of liquid ^3He , although the so called "A" and "B" features were erroneously interpreted as effects in the solid at first. Their following experiment of nuclear magnetic resonance (NMR) showed that the A and B features were due to transitions in liquid ^3He . These two experiments represent the discovery of the new phases in liquid ^3He at low temperature.

By measuring the specific heat of liquid ^3He , Webb, Greytak, Johnson, and Wheatley (1972) were able to show that the A feature actually corresponds to a second-order transitions. In 1973, Alvesalo, Anufriyev, Collan, Lounasmaa, and Wennerstrom measured the amplitude of a vibrating wire in ^3He and thus confirmed the property of superfluidity of the new phases.

A theoretical understanding of the new phases began with people's efforts to extend the BCS theory to ^3He in the late fifties. Because of the strong repulsion between ^3He atoms at short distances, it was expected that the Cooper pair formed in ^3He would have nonzero angular momentum, which is different from the Cooper pair in conventional superconductor and made it more difficult to determine the microscopic structure.

In 1961, Anderson and Morel studied a case in which the p state pair ($l = 1$) only form in the $S_z = +1$ ($\uparrow\uparrow$) and $S_z = -1$ ($\downarrow\downarrow$) states. This state was later named as Anderson-Brinkman-Morel (ABM) state, which is a special case of equal spin pairing state (ESP).

In 1963, Vdovin, Balian and Werthamer proposed another state (BW state) in which the pair is formed in all three Zeeman sub-states, and the orbital angular momentum is anti-parallel with the total spin so that the total angular momentum is zero. They showed that the BW

state is more stable than any ESP state within the generalized BCS calculation.

In 1972, right after Osheroff *et al*'s NMR experiments, Leggett came up with the idea of spontaneously broken spin-orbit symmetry (SBSOS) and explained the experimental data of the NMR resonance frequency. Leggett determined that the *A* phase should be an ESP phase in order to explain the experiment. The question remained is why the ESP phase is more stable than a BW phase here.

The problem of the stability of the *A* phase was solved by Anderson and Brinkman in 1973, who showed that the effect of spin-fluctuation render an ESP state stable over a BW state in a small region of high pressure and temperature in the $P - T$ phase diagram. So finally, the *A* phase is identified as ABM state and *B* phase as BW state.

In Section 3, the phase diagram of ^3He is shown with micro-description of the phases. In Section 4, experiments on melting pressure, nuclear magnetic resonance, specific heat and viscosity are introduced with brief discussion.

For a review on detail experiments, please refer to reference [1]. For a review on theoretical works, please refer to reference [2]. References [3-5] provide good sources of the history how people discovered and understood the new phases.

3. Phase diagram

Figure 1 shows the phase diagram of ^3He when there's no external magnetic field. Under low pressure and when temperature is higher than about 3mK, ^3He forms normal Fermi liquid, the properties of which can be well described by Landau's Fermi liquid theory.

As temperature drops and when then pressure is not so low, there's a second order phase transition and the substance enters a superfluid phase called *A* phase as is indicated in the figure as a small triangular region. *A* phase is identified as ABM state, and the wave function of Cooper pairs in this state can be written as:

$$\Psi_{ABM} = F_{\uparrow\uparrow}(\mathbf{r})|\uparrow\uparrow\rangle + F_{\downarrow\downarrow}(\mathbf{r})|\downarrow\downarrow\rangle.$$

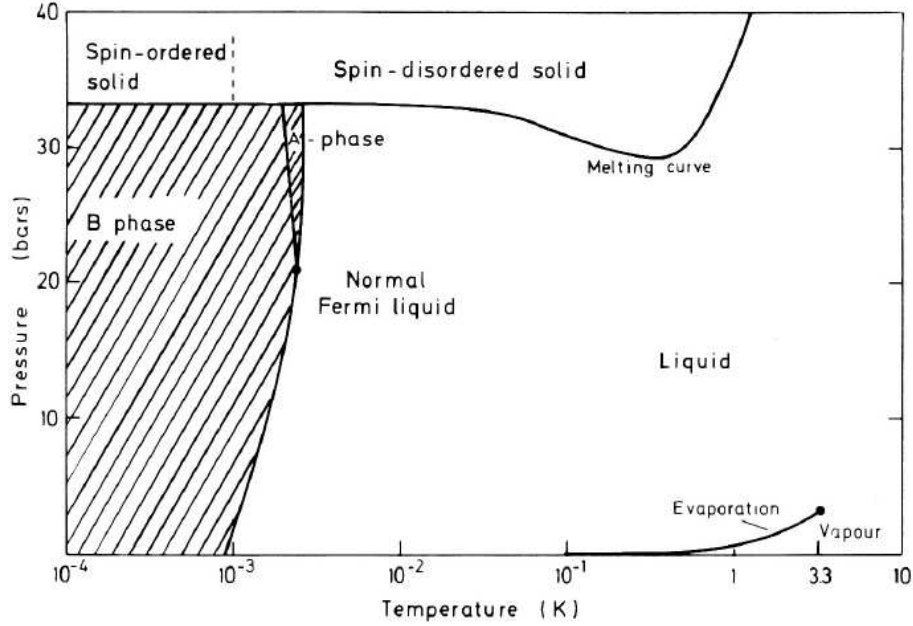


Figure 1: Phase diagram of ^3He . After [6].

Here, $F_{\uparrow\uparrow}(\mathbf{r})$ and $F_{\downarrow\downarrow}(\mathbf{r})$ take the same form, which corresponds to the pairs' having an orbital angular momentum \hbar along a direction [5].

As temperature drops further, there's a first order phase transition and a new phase called *B* phase appears. *B* phase is identified as BW phase which was studied first by Vdovin, Balian and Werthamer, who observed that, in the odd-*l* case, it is possible to form pairs simultaneously in all three Zeeman substates in such a way that the pair wave function is a superposition of the form [5]:

$$\Psi_{BW} = F_{\uparrow\uparrow}(\mathbf{r})|\uparrow\uparrow\rangle + F_{\downarrow\downarrow}(\mathbf{r})|\downarrow\downarrow\rangle + F_{\uparrow\downarrow}(\mathbf{r})\left(\frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)\right).$$

Here, $F_{\uparrow\uparrow}(\mathbf{r})$ corresponds to angular momentum $L_z = -1$, and $F_{\downarrow\downarrow}(\mathbf{r})$ and $F_{\uparrow\downarrow}(\mathbf{r})$ similarly correspond to $L_z = -1$, and $L_z = 0$, respectively [5]. So BW state is a state with $L = S = 1$ but $j = |\mathbf{L} + \mathbf{S}| = 0$, i.e., in atomic notation a 3P_0 state.

Properties of phases *A* and *B* can be derived from their microscopic wave functions and the calculations results are in good agreement with

experiments.

4. Experiments

Melting pressure

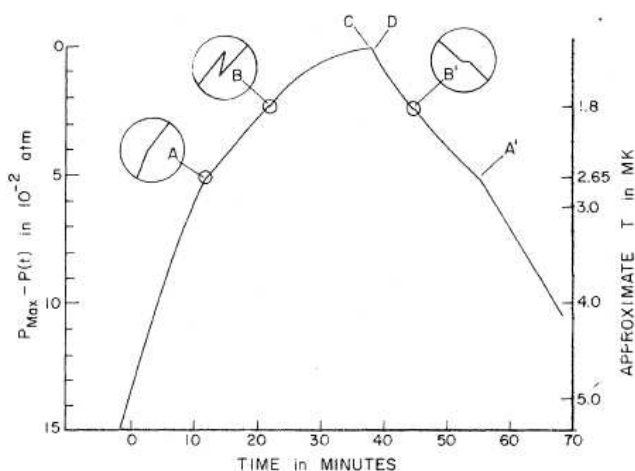


Figure 2: Time evolution of the pressure during compression and subsequent decompression. After [7].

The first evidence of new phases of liquid ^3He was discovered in 1972, by Osheroff, Richardson and Lee at Cornell. They measured the melting pressure of a mixture of solid and liquid ^3He in a Pomeranchuk compression cell. Figure 2 shows the features observed on a plot of cell pressure vs time during compressional cooling to the minimum temperature followed by warming the cell during decompression. The A and A' features were changes in slope. They always occurred at precisely the same pressure. Lower temperature features B and B' were also observed. On cooling through B a sudden pressure drop appeared, and on warming through B' a small plateau was observed. The pressure at B was always greater than or equal to the pressure at B' [4]. However, the features were at first thought to be associated to new phases in solid. The authors in the original paper stated that the A transition corresponded to a second-order magnetic phase transition in solid ^3He .

It was not until their next experiment that the possibility that transitions in solid contributed to the features were excluded.

Nuclear magnetic resonance

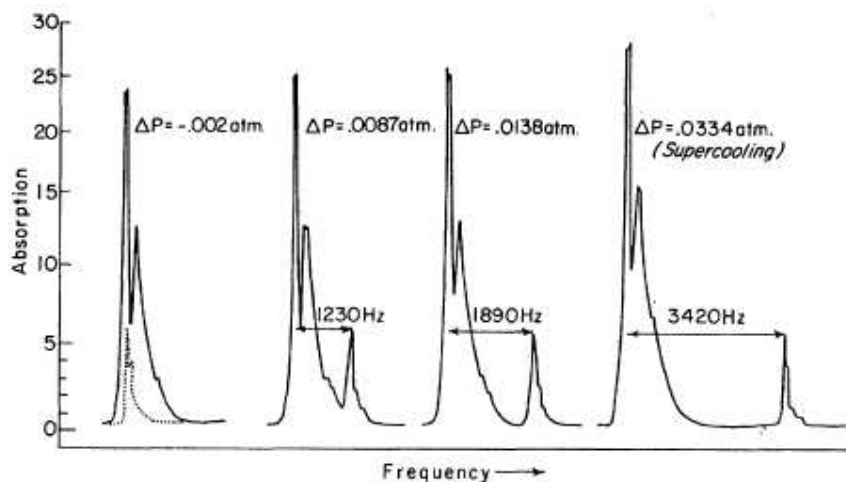


Figure 3: Frequency profiles obtained at various pressures above $P(A)$ as indicated by $\Delta P = P(t) - P(A)$, showing the frequency splitting. After [8].

Because the experiment on melting pressure could not distinguish whether the effect was due to transitions in solid or liquid, the authors performed NMR studies on ^3He later that year. Figure 3 shows a sequence of NMR profiles of a sample ^3He , the liquid phase of which is in A phase. We can see a small peak, which is due to the liquid part, shifts to higher frequency when the temperature drops. And it was also found that at the B transition, the small satellite peak suddenly jumped back into the main peak. By this experiment, it became clear that all these phenomena that the group discovered in that year were related to new phases in liquid ^3He .

A theoretical understanding of the resonance frequency was later given by Leggett [9] with an idea of spontaneously broken spin-orbit symmetry (SBSOS): although the weak interaction between the tiny nuclear dipole moments is much less than one microkelvin, the presence of Cooper pairs lead to a coherent addition of all the dipole moments and

produce an effective internal field large enough to produce the observed frequency shifts [4].

Specific heat

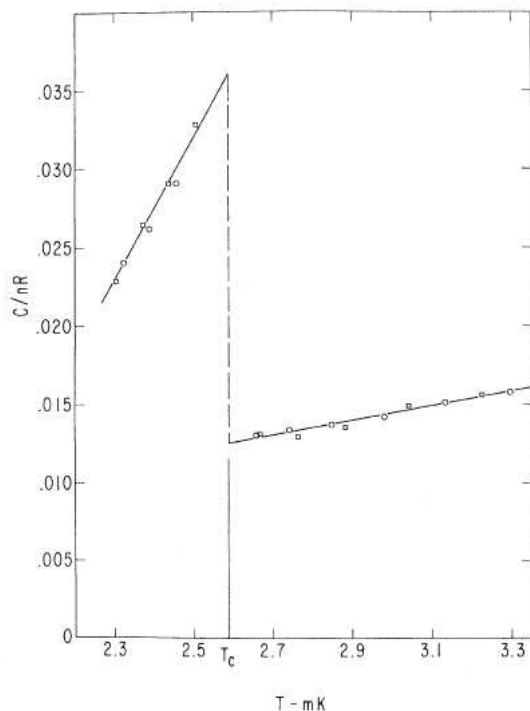


Figure 4: Total molar heat capacity as a function of temperature of liquid ^3He . After [10].

In 1973, Webb et al. measured the liquid specific heat. Figure 4 shows that the transition is second-order phase transition, because there's a discontinuity but no divergence in the specific heat as a function of temperature [10]. The transition shown in Figure 4 corresponds to the feature *A* found by Osheroff *et al's* earlier work. The curve has a characteristic of a BCS type transition with behavior below the transition showing a rapid rise with temperature, associated with pair breaking and the greater availability of quasi-particles, followed by a sharp drop at the transition. Above the transition, the typical linear temperature

dependence of a normal Fermi liquid was found [10].

Viscosity

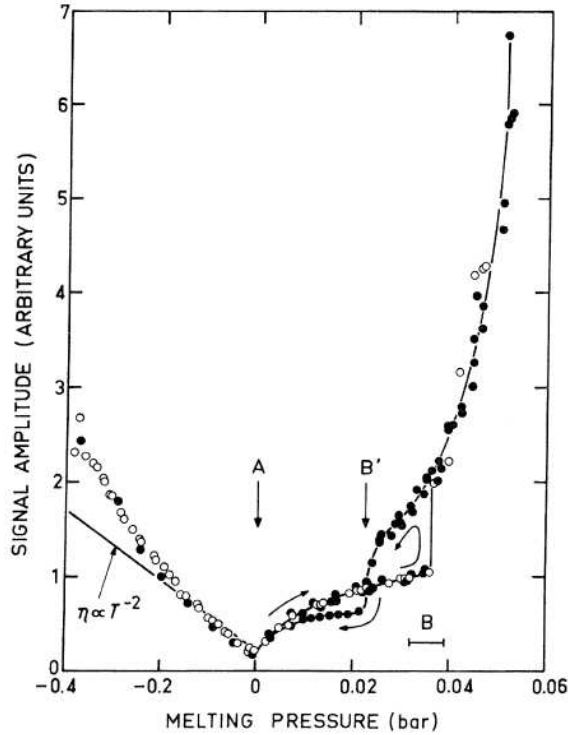


Figure 5: Normalized viscometer signal amplitudes as functions of the ^3He melting pressure, with the zero set at the A transition. After [11].

In 1973, Alvesalo *et al* measured the relative viscosity of liquid ^3He along the melting curve with a vibrating-string viscometer. Figure 5 shows the signal amplitudes as functions of the melting pressure, which is a function of temperature. The amplitude is proportional to $(1/\eta)^{1/2}$ to a reasonable approximation. So it can be seen that as the temperature is reduced, the viscosity first increases until the pressure anomaly A is reached. The viscosity then starts to decrease, has a discontinuous drop at the pressure anomaly B , and then continues to diminish rapidly. The lowest measured value of the viscosity is 1000 times smaller than

that at point A , which is a strong evidence for superfluidity [11].

References

- [1] J.C. Wheatley, *Rev. Mod. Phys.* **47**, 415 (1975)
- [2] A.J. Leggett, *Rev. Mod. Phys.* **47**, 331 (1975)
- [3] D.D. Osheroff, *Rev. Mod. Phys.* **69**, 667 (1997)
- [4] D.M. Lee, *Rev. Mod. Phys.* **69**, 645 (1997)
- [5] A.J. Leggett, *Rev. Mod. Phys.* **76**, 999 (2003)
- [6] P. Wolfle, *Rep. Prog. Phys.* **42**, 269 (1979)
- [7] D.D. Osheroff, R.C. Richardson, and D.M. Lee, *Phys. Rev. Lett.* **28**, 885 (1972)
- [8] D.D. Osheroff, W.J. Gully, R.C. Richardson, and D.M. Lee, *Phys. Rev. Lett.* **29**, 920 (1972)
- [9] A.J. Leggett, *Phys. Rev. Lett.* **29**, 1227 (1972)
- [10] R.A. Webb, T.J. Greytak, R.T. Johnson, and J.C. Wheatley, *Phys. Rev. Lett.* **30**, 210 (1972)
- [11] T.A. Alvesalo, Yu.D. Anufriyev, H.K. Collan, O.V. Lounasmaa, and P. Wennerstrom, *Phys. Rev. Lett.* **30**, 962 (1973)