Impurity phases of superfluid ^{3}He in aerogel

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Abstract

Discovery of impurity phases of superfluid ^{3}He, produced by silica aerogel, provides a new approach to investigate the effect of disorder on unconventional pairing. A simple model that assumes homogeneous, isotropic scattering is in agreement with experiment including suppression of the superfluid transition temperature, the amplitude of the order parameter, and phase diagram of magnetic field, temperature, and pressure, with the feature that the polycritical point vanishes in a 98% porous aerogel. We also find a metastable equal-spin-pairing state in zero field although such a phase does not exist in equilibrium.

Key words: superfluid; ^{3}He; aerogel; impurity scattering

1. Introduction and phase diagram

Superfluid ^{3}He is a collective state of a BCS pair type with a p-wave order parameter that exhibits spontaneously broken symmetries of rotation of spin and orbital coordinates and a broken relative-symmetry between spin and orbit degrees of freedom. It has been shown that impurities can be systematically introduced into liquid ^{3}He using high porosity silica aerogel[1,2] and it is of interest to investigate if the competition between these different broken symmetry phases is modified by impurities. Since liquid ^{3}He at low temperatures is the cleanest and purest material known, study of its impurity phases can contribute to the understanding of unconventional pairing more broadly, such as in superconductors which have more chemical and electronic complexity. In this paper we review the current state of this investigation focusing on identification of the equilibrium impurity phases as well as to highlight the significant differences between this new impurity superfluid system and that of the pure superfluid.

The pressure-temperature phase diagram $T_{ca}(P)$ at zero magnetic field for superfluid ^{3}He in 98% aerogel is shown in Fig. 1. There is generally good agreement between various reports as is evident, for example, in the comparison of work shown here[3,4]. The suppression of the transition temperature relative to the pure superfluid phases is accentuated at low pressure where Matsumoto *et al.*[3] found a critical pressure of 6 bar below which the impurity superfluid phase does not exist. This quantum critical point, predicted[5] for magnetic scattering in conventional superconductors, applies to all scattering in unconventional pairing systems where $l_T = 3.7\,\xi$ with l_T the transport mean free path and ξ the pure superfluid coherence length. Since the coherence length in ^{3}He increases with decreasing pressure, and l_T is fixed by elastic scattering from impurities, the observed critical pressure corresponds to $l_T = 144$ nm, taking the coherence length to be $\xi = \frac{\hbar v_F}{2\pi k_B T_c}$ for the pure superfluid state. Phase diagrams for aerogels with higher porosities than 98% have also been reported[6,7] showing systematically less suppression of the transition than that in Fig. 1.

Following the first observations of superfluid behavior of ^{3}He in aerogel[1,2] a central question has been to identify the stable superfluid states. Our natural preju-

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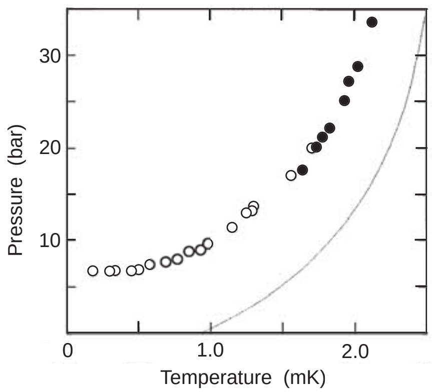

Fig. 1. The pressure-temperature phase diagram (P,T) of the transition from normal state to the superfluid phase of ^{3}He in 98% aerogel in zero magnetic field; data from Matsumoto *et al.*[3](open circles) and Gervais *et al.*[4](filled circles). The pure ^{3}He phase diagram is shown as a solid curve.

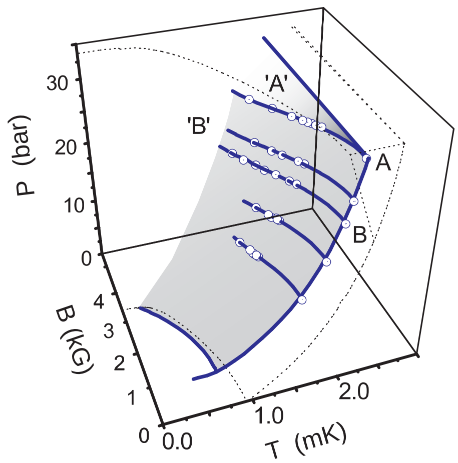

Fig. 2. Three-dimensional phase diagram (P,T,B) of ^{3}He in 98% aerogel. The superfluid aerogel phases are labeled 'A' and 'B' and are delineated by solid lines. The pure phases are labeled A and B (dotted lines). The shaded region shows the equilibrium A-phase in aerogel going to zero in zero field. The lines are fits to the data (open circles)[4,10]. At pressures below 10 bar, T_{ca}, was taken from Matsumoto *et al.*[3], together with the field dependence of the A B-transition observed by the Lancaster group at 4.8 bar[9].

dice is that the bulk phase diagram is only weakly modified and that the states must be either A or B-phases, corresponding to axial and isotropic states having p-wave symmetry. It is relatively simple to determine the spin state, that is either equal or non-equal spin pairing (ESP or non-ESP) through measurement of the magnetization or the magnetic field dependence of the superfluid transition. Our recent work on the phase diagram[4], Fig. 2, shows that in a magnetic field there are two phases and that there is a first order transition between them. The normal-to-superfluid transition is unaffected to within 30μK by magnetic fields up to 0.8 T, indicating that this phase is an ESP state like the A-phase in pure ^{3}He. Furthermore, the transition in a magnetic field to a lower temperature stable phase, as was first reported by Barker *et al.*[8] from the signature of a sudden drop in magnetization on (super)cooling, is likely to be an A to B-transition. This was later confirmed by Brussaard *et al.*[9] using a viscometer and Gervais *et al.*[4,10] from transverse acoustic impedance that provides a precise indicator of phase transitions. In the latter it was found that the equilibrium zero field phase region is entirely a B-phase at all pressures in zero magnetic field with the possible exception of a thin region less than 20μK wide just below T_{ca}. The evidence for such an anomalous region comes from observation by Gervais *et al.*[10] of supercooling of an A to B-transition even in zero applied magnetic field.

At low magnetic fields the A to B-transition temperature is suppressed quadratically with field[4,9,10]. The coefficient, $g(P)$,

$$1 - \frac{T_{ABa}}{T_{ca}} = g_a(P)(\frac{B}{B_0})^2 \tag{1}$$

depends on strong-coupling parameters and consequently on the pressure. The magnetic field B_0 is defined as,

$$B_0 = \sqrt{\frac{8\pi^2}{7\zeta(3)}\frac{k_B T_{ca}}{\gamma\hbar}(1 + F_0^a)}, \tag{2}$$

where γ is the gyromagnetic ratio of ^{3}He and F_0^a is a Fermi liquid parameter. This is a weak-coupling form but has been shown to be accurate for pure ^{3}He at all pressures to $\leq 3\%$[14].

For pure ^{3}He $g(P)$ diverges at the polycritical pres-

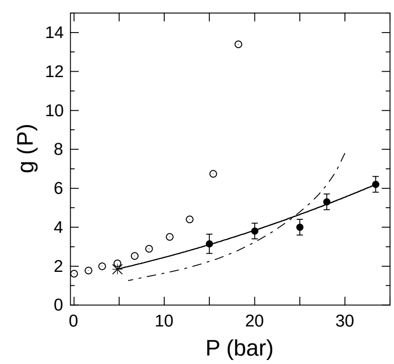

Fig. 3. Pressure dependence of $g(P)$. The aerogel data from Gervais *et al.*[4] (solid circles) are compared to the bulk (open circles)[13]. The data at 4.8 bar denoted by a star are from Brussard *et al.*[9]. The solid line is a guide-to-the-eye. The dot-dashed line is the HSM with l_T = 150 nm using strong-coupling corrections rescaled from pure ^{3}He by the factor T_{ca}/T_{c0}.

sure of 21 bar, as shown in Fig. 3[13] by open circles; a direct manifestation of extreme sensitivity of the AB-transition to magnetic field near the polycritical point (PCP). However similar behavior for superfluid ^{3}He in aerogel is not found at any pressure, closed circles. Impurity scattering stabilizes the B-phase relative to the A-phase in zero magnetic field, displacing the PCP to higher pressure, beyond observability.

The simplest impurity model for superfluid ^{3}He is the homogeneous scattering model (HSM) which predicts[11] that the B-phase is stable relative to the A-phase at all pressures provided $l_T \leq 250$ nm. Our application of this model to the phase diagram in Fig. 2 and the data of Fig. 3 implies $l_T \approx 150$ nm given by the dashed-dot curve. This value is consistent with that inferred from the critical pressure[3] at 6 bar.

There remain, however, several puzzling aspects of the phase diagram. Firstly, why is there supercooling of the A to B-transition in zero field unless there exists some amount of A-phase as the stable phase just below T_{ca}; and if the latter were to be correct how can this be consistent with vanishing of the polycritical point? Secondly, field independence of T_{ca} is strongly indicative of an ESP state; however, we have not observed[4] the expected A_1 to A_2 field splitting of the superfluid transition up to 0.8 T.

2. NMR

Some of the earliest experiments indicating superfluid ^{3}He in 98% aerogel were NMR measurements of magnetization and frequency shifts. Sprague *et al.*[2,12] reported pulsed NMR with an abrupt onset of frequency shift, Fig. 4, that could be identified with superfluidity. They found that the magnetization, even in the normal state, was increased by a layer of solid ^{3}He adsorbed on the surface of the silica aerogel. There was no evidence for change in the magnetization of the liquid in the superfluid state such as might be expected for a non-ESP state like the B-phase[12,14]. Furthermore, the observed frequency shifts were consistent with a homogeneous texture (no significant change in linewidth in the superfluid state) and with a temperature dependence similar to that of the A-phase, scaled to a smaller magnitude implying a reduction in the amplitude of the order parameter. However, our current understanding of the phase diagram in this field and temperature range, is at odds with their identification, leading us to suggest that the NMR experiments of Sprague *et al.* were likely performed on a supercooled ESP phase, like the A-phase.

Sprague *et al.*[12] replaced the localized solid ^{3}He covering the aerogel strands with ^{4}He and found clear evidence for a non-ESP phase since the magnetization decreased with decreasing temperature. Very low field NMR experiments at Manchester[15] found that the NMR lineshape was consistent with a non-ESP phase (B-phase). The Stanford group[8] found a reduced magnetzation in the superfluid, similar to that of Sprague *et al.*[12] using ^{4}He to eliminate solid ^{3}He. Sharma and Sauls[16] show this behavior to be consistent with an impurity B-phase. In addition Barker *et al.* found a transition from a supercooled ESP to non-ESP phase based on discontinuous changes in both frequency shift and magnetization measurements. All the NMR experiments are consistent with Fig. 1 and 2. provided that the early Northwestern work[2,14] is interpreted as being performed on a supercooled ESP phase.

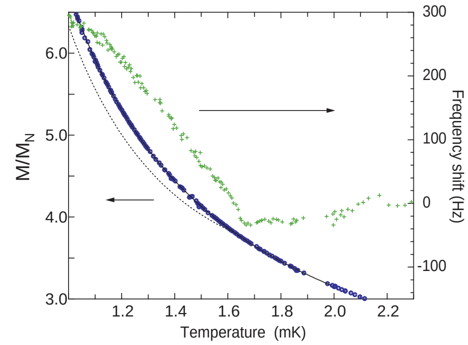

Fig. 4. NMR frequency shifts and magnetization[2,14]. The frequency shifts indicate a sharp onset of the transition in a 98% aerogel at 18.3 bar; $H = 0.112$ T. The temperature dependence of the total magnetization is accurately given over a wide range of temperature, up to 12 mK, by a constant Fermi liquid component added to a Curie-Weiss law for solid ^{3}He adsorbed on the aerogel surface; the data are shown with a fit to this model (solid curve). The dotted curve shows the magnetization that would be expected if the superfluid were an impurity B-phase[12] and is incompatible with the data[2,14].

3. Superfluid density

The superfluid density has been measured using torsional oscillator(Cornell, Manchester), low frequency acoustics(Cornell), fourth sound(Osaka), and vibrating aerogel disc experiments (Lancaster). They all concur that there is a strongly reduced superfluid density at low pressure. But there is no indication from the torsional oscillator measurements that there is a supercooled A to B-phase transition in zero field in contrast to the work above 15 bar of Gervais *et al.*[10,4]. It is possible that the superfluid density of A and B-impurity phases have similar temperature dependences. Calculations[16] show that there is a large density of states at low energy in both A and B-impurity phases that would blur the distinction between them in superfluid density averaged over all $\hat{l}$-orientations.

4. Heat capacity

Recent measurements of the heat capacity of superfluid ^{3}He in a 98% porous aerogel[17,18] show that there is a jump in the heat capacity at the transition temperature. In the Northwestern work[17], shown in Fig. 5, a conventional adiabatic method was used at a ^{3}He pressure of 20 bar and we clearly see the expected signature of a BCS-type transition. The data in the figure have been analyzed to remove the bulk ^{3}He component from the heat capacity measurement using known values of the heat capacity[19]. The liquid ^{3}He in the aerogel at temperatures above T_{ca} is a Fermi liquid since the heat capacity is proportional to the temperature. If we assume that in this region it has the same specific heat as the bulk ^{3}He, we find the following results[17]. The volume of bulk ^{3}He in the calorimeter is 0.71 cm^3 and the aerogel volume is 1.0 cm^3. Based on geometric calculation of volume we expect 0.8 and 1.0 cm^3 respectively, in rather good agreement with the calorimetric measurement. There have been suggestions of a bulk ^{3}He component that resides within the aerogel mass[18,20], but our thermodynamic experiments preclude this possibility.

For a BCS pairing superfluid the jump in the heat capacity at the transition determines the amplitude of the order parameter in the Ginzburg-Landau limit. For the aerogel superfluid we find $\Delta C/C_a = 1.0 \pm 0.1$ substantially reduced from the bulk value of 1.82[19]. From the HSM theory[11] we can estimate the corresponding transport mean free path, $l_T \approx 180$ nm (A-phase) and 220 nm (B-phase). In this comparison we include strong coupling effects rescaled from measurements in bulk ^{3}He by T_c/T_F[4].

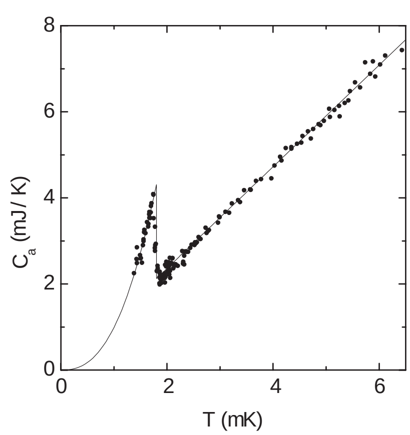

Fig. 5. The heat capacity of superfluid ^{3}He in a 98% porous aerogel at 20 bar[17].

5. Summary

Values of the transport mean free path derived from the relative stability of A and B-phases of superfluid ^{3}He in aerogel and from the heat capacity jump are both consistent with $l_T \approx 200$ nm for a 98% porous aerogel. Together these results provide convincing evidence that the homogeneous scattering model for the impurity phases of ^{3}He is qualitatively correct. Modifications of the model to include inhomogeneities in the aerogel have been shown to improve this agreement[11].

Acknowledgements

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