Evidence for superfluid B-phase of $^3$He in aerogel

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We have made simultaneous torsional oscillator and transverse cw NMR (at $\sim 165$ kHz) studies of the superfluid phase of $^3$He in aerogel glasses of 1% and 2% of solid density. NMR occurs over a range of frequency extending from the Larmor frequency to higher values, but strongly peaked at the Larmor value. This behaviour together with the magnetic field independence of the effective superfluid density provides convincing evidence for a B-phase state with an ordering value. This behaviour together with the magnetic field frequency to higher values, but strongly peaked at the Larmor value.

67.57.Fg, 67.57.Lm, 67.57.Pq

Since the discovery of superfluidity of $^3$He contained within aerogel, this system has been regarded as providing an excellent model for investigating the effect of impurity scattering on Fermi superfluids with non-s-wave Cooper pairing. One of the main theoretical expectations was that the introduction of scattering would increase the stability of the isotropic B-phase relative to that of the strongly anisotropic A-phase. It was surprising therefore that previously published NMR experiments on the superfluid phase were characteristic of an equally spin paired (ESP) state, of which the A-phase is the prime example, even at pressures below those at which the A-phase is stable in bulk. Our experiments were performed at much smaller magnetic fields than those used in these previous experiments and they provide convincing evidence for the occurrence of B-phase under these circumstances. We note that our aerogel samples came from the same source as those used in the measurements in reference and, since the observed superfluid transition temperatures for our 2% aerogel were very similar to those observed in reference, there is no reason to suspect that the difference in NMR behaviour results from a significant difference in aerogel microstructure.

Some details of our experiment along with measured values of the transition temperature and superfluid density have already been published so we do not repeat these here. We studied two samples of aerogel, of 1% and 2% of solid density, each contained within a glass sphere of inner diameter 8 mm. The sphere was supported on a Be/Cu capillary which acted as the fill line and also provided the torsion constant for the measurements of superfluid density. A pair of coils each with 20 turns of filamentary superconducting wire were driven at fixed frequency and current to produce an rf field transverse to the dc field and the NMR signal was detected by another pair of transverse coils wound from the same wire each with 100 turns, arranged as orthogonally as possible to the ‘drive’ coils. The ‘detection’ coils were tuned to a frequency of approximately 165 kHz by a 2200 pF polystyrene capacitor and the signal was observed with the help of a 4.2 K GaAs preamplifier followed by a further differential preamplifier and lockin detector; the quality factors of the tuned circuit were of order 3000 and 5000 for the measurements on the 2% and 1% samples respectively. We observed cw NMR by sweeping the dc field at constant rf drive frequency.

We show in Fig. 1(a) the observed NMR absorption and dispersion for field sweeps through the resonance for 2% aerogel at 14.9 bar pressure; sweeps for temperatures above and below the superfluid transition temperature $T_{ca}$ are shown. The large increase in signal strength at the lower temperature is associated with the contribution from solid $^3$He atoms on the surfaces of the silica strands. As in reference we assume that rapid exchange of $^3$He atoms between liquid and solid results in a single NMR signal with a strength $I$ (integrated absorption) proportional to the sum of the liquid and solid magnetizations, which can be fitted to

$$I = A + \frac{B}{T + T_0},$$

where $A$ represents a temperature-independent contribution from the liquid; for the normal state, the measured variation of $A$ with pressure is the same as that of the susceptibility of bulk liquid. The Curie-Weiss term is the contribution from the solid. $T_0$ is of order $-0.4$ mK and almost pressure-independent. The values obtained for $B$ correspond to an areal density of order $10^{13} \text{m}^{-2}$ of solid $^3$He atoms, i.e., about one monolayer; $B$ increases with pressure by $\sim 30\%$ between 0 and 29 bar. We discuss below the extent to which Eq. (1) is valid for $T < T_{ca}$.

From Fig. 1(a) we see that NMR in the superfluid state occurs over a range of field negatively shifted with respect to the normal state Larmor value. To analyse this spectrum we assume that it arises from a distribution of local Lorentzian oscillators within the aerogel with $f(H_R)$ giving the contribution to the spectrum from oscillators of resonant field $H_R$; we thus write the NMR signal as

$$\text{Signal} = \int \frac{f(H_R) dH_R}{H_R - H + iH_B/2},$$

where we assume that the linewidth $H_B$ is constant across the spectrum. In order to fit the data we assume that the distribution function $f(H_R)$ is zero for $H_R \leq H_1$.
for the 2% aerogel. The linewidths $H_B$ obtained from our fits show a slight increase with decreasing temperature which is not affected by the superfluid transition.

The most likely explanation for NMR to occur over a spectrum of frequencies is a superfluid phase with a space-dependent texture. We now present three pieces of evidence that our observations correspond to superfluid B-phase with a space dependent texture rather than a superfluid A-phase with spatially dependent $\hat{n}$ and $\hat{d}$ textures. First, this would explain why only positive frequency shifts are observed since the transverse NMR frequency $\omega_L$ for liquid $^3\text{He}$-B with the $\hat{n}$ vector at an angle $\beta$ to the applied field, as given by

$$2\omega^2 = (\omega_L^2 + \Omega_B^2) + \sqrt{(\omega_L^2 + \Omega_B^2)^2 - 4\omega_L^2\Omega_B^2\cos^2\beta}, \quad (3)$$

is always greater than the Larmor frequency $\omega_L$; here $\Omega_B$ is the B-phase longitudinal frequency. Spatially varying textures in the A-phase are likely to lead to negative as well as positive shifts [4]. Second, the shape of the NMR spectrum is qualitatively that expected for the $\hat{n}$ texture in a spherical geometry. In particular the strong peak of the spectrum at the Larmor frequency arises because the favoured alignment of $\hat{n}$ in a field is $\beta = 0$ which according to Eq. (3) gives an unshifted resonant frequency, $\omega = \omega_L$; it is difficult to conceive of an A-phase texture which gives a peak at the Larmor frequency but which has only positive shifts. Thirdly, one would expect a spatially varying $\hat{l}$ texture in the A-phase to depend on magnetic field and thus lead to variations in effective superfluid density with field through the anisotropy of the superfluid density. In our experiments we regularly swept the magnetic field from positive to negative values [5] but the associated small change in resonant frequency ($\sim 4$ mHz) of our torsional oscillator was unaffected by the superfluid transition, thus ruling out changes in the effective value of $\rho_s/\rho$ greater than about 0.0003. The possibility that the field independence of the effective superfluid density can be associated with a random dipole-unlocked orbital texture pinned by the aerogel is inconsistent with the observed NMR spectrum.

We now demonstrate that we can explain the observed spectra quantitatively if we assume that the $\hat{n}$ texture in aerogel is determined by the same considerations as for bulk $^3\text{He}$-B. As the characteristic lengths for B-phase textures (see below) are large, we can ignore spatial variation of $\hat{n}$ on the scale of the aerogel microstructure and determine the texture by minimizing the energy [6]

$$E = \int \{-b[\hat{s} \cdot \hat{n}]^2 + \nu[\hat{s} \cdot \hat{n}]^4 - d[\hat{s} \cdot \hat{R} \cdot \hat{H}]^2\} dS + \int \left( f_{bend} - a (\hat{n} \cdot \hat{H})^2 \right) dV \quad (4)$$

where $a$, $b$, $c$, $d$ and $\nu$ (we take $\nu = -5/18$ [7]) are temperature dependent coefficients, $\hat{s}$ is the surface normal to the sphere, the matrix $\hat{R}$ represents a rotation about $\hat{n}$ by $\cos^{-1}(-1/4) \approx 104^\circ$ and the integrals are over the surface

![Diagram](image_url)
and volume of the sphere respectively. For the bending energy density $f_{\text{bend}}$, we take the Ginzburg-Landau form

$$f_{\text{bend}} = c\{16(\nabla \times \hat{n})^2 - 5(\hat{n} \cdot (\nabla \times \hat{n}))^2 + 13(\nabla \cdot \hat{n})^2 - 2\sqrt{15}\nabla \cdot [\hat{n} \nabla (\hat{n} \cdot \nabla \hat{n})] + 16\nabla \cdot ([\hat{n} \nabla \hat{n} - \hat{n}(\nabla \cdot \hat{n})])\}/13. \quad (5)$$

We assume that the $\hat{n}$ texture has rotational symmetry about the field direction (the $z$ axis) with cylindrical polar components $n_r = \sin \beta \cos \alpha$, $n_\phi = \sin \beta \sin \alpha$, $n_z = \cos \beta$. To make the texture calculation tractable we use the variational forms

$$\tan \beta = \frac{2(z - p_1)r}{z(z - 2p_1) - r^2 + p_2^2}, \quad (6)$$
$$\tan \alpha = p_3 + p_4z + p_5z^2 + p_6r^2, \quad (7)$$

for $\beta$ and $\alpha$; the variational parameters $p_1$-$p_6$ are chosen to minimise $E$ for given values of the coefficients in the energy of Eq. (8). For $p_1 = p_4 = 0$ the texture of Eqs. (8) and (9) corresponds to the texture shown in the insert on Fig. 2(b), with $\hat{n} \parallel \mathbf{H}$ (i.e. $\beta = 0$) on the equatorial plane and on the line joining the north and south poles; the second surface term in Eq. (7) causes $\hat{n}$ to point into and out of the paper in the south-east and north-east quadrants respectively. Our investigations of possible $\hat{n}$ textures in a sphere suggest that this variation of the ‘flare-out’ texture in a cylinder has the lowest energy for a spherical container. Finite values of $p_1$ and $p_4$ correspond to moving the $\beta = 0$ plane away from the equator but this always causes an increase in $E$ in practice.

To relate the $\hat{n}$ texture to the observed spectrum, we solved the equations which describe NMR for the situation of rapid exchange between solid and B-phase liquid. The calculation, details of which will be published elsewhere, shows that, at a constant measuring frequency $\omega$, the resonance occurs at a field $H$ given by

$$(\gamma H)^2 = \omega_2^2 = \omega^2 \left(\frac{\omega^2 - \mu \Omega_B^2}{\omega^2 - \mu \Omega_B^2 \cos^2 \beta}\right), \quad (8)$$

where $\mu = M_{\text{liq}}/(M_{\text{liq}} + M_{\text{sol}})$. $M_{\text{liq}}$ and $M_{\text{sol}}$ are the magnetizations of the liquid and solid respectively. In the limit $\mu = 1$ Eq. (8) reduces to Eq. (3) and in the limit $\mu \Omega_B^2 \ll \omega^2$ it reduces to $\omega \approx (1 - \mu)\omega_{\text{liq}} + \mu \omega_{\text{sol}}$ as used in interpreting previous NMR measurements on superfluid $^3$He in aerogel.

To fit our experimental spectra we note that the $\hat{n}$ texture depends only the ratios $a/c$, $b/c$ and $d/c$ and that the only other unknown is $\Omega_B$. We take $a/c = (q_1 + q_2t)/t$, $b/c = (q_3 + q_4t)/t^{1/2}$, $d/c = (q_5 + q_6t)/t^{1/2}$ and $\Omega_B^2 = (q_7t + q_8t^2)$, where $t = 1 - T/T_{\text{ca}}$; these have the expected temperature dependences for $T \to T_{\text{ca}}$ and allow adequately for departures from these asymptotic dependences at lower temperatures. Adjustment of $q_1$-$q_8$ enables us to fit all our spectra at a single pressure within experimental error. To illustrate this we show in Fig. 2 typical examples of fitted spectra obtained for 1% aerogel at 11.6 bar and $T/T_{\text{ca}} = 0.63$. There was some evidence of structure in some of the observed spectra, which may indicate the existence of textural spin waves [2].

The resulting values of the free energy coefficients are best presented in terms of two characteristic distances, $R_H$ and $R_c$, and one characteristic field $H_s$ defined by: $R_H \equiv (c/a)^{1/2}$; $R_c \equiv c/b$; $H_s \equiv (b/d)^{1/2}$. The significance of these quantities in determining the relative importance of different terms in the energy can be seen from Eqs. (8) and (9). The values obtained for $R_H$, $R_c$, $H_s$ and $\Omega_B^2$ are shown in Fig. 3 along with values of $R_H$ for bulk $^3$He-B at 10.2 bar [13]. As can be seen from Eq. (8), only the product $\mu \Omega_B^2$ can be determined from NMR spectra; to obtain $\Omega_B^2$ we used values of $\mu$ deduced from fits to Eq. (3) over the whole temperature range, a procedure which assumes that the liquid susceptibility is constant for $T < T_{\text{ca}}$. At 11.6 bar we could not detect departures from Eq. (3) associated with reduction of the B-phase susceptibility below that of normal $^3$He. The departures are expected to be small because of the strong suppression of the energy gap in aerogel and, as indicated in Ref. [15], it is difficult to evaluate the integrated absorption for a broad NMR spectrum with sufficient accuracy to identify small changes in the liquid contribution. There was evidence for departures from Eq. (3) at the highest pressures studied where the effect is larger and the solid contribution relatively less important. A reduction in liquid susceptibility corresponds to
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FIG. 3. The values of (a) $R_H H$ and $R_c$, and (b) $\Omega_B^2$ and $H_s$, used to obtain fits to NMR spectra for 1% aerogel at 11.6 bar are shown by continuous lines. The dashed lines are for bulk $^3$He-B at 10.2 bar.

a smaller value of $\mu$ and hence to a slightly larger value of $\Omega_B^2$ than that shown on Fig. 3(b). Although this effect would have to be included in any quantitative comparison with theoretical calculations, the qualitative conclusion from Fig. 3(b) remains valid that the depression of the energy gap of $^3$He in aerogel causes the value of $\Omega_B^2$ to be substantially less than that for bulk $^3$He-B. Our values of $R_H H$ are also smaller than bulk value as are our values of $d/a$ [4]. The latter are not shown on Fig. 3 since the ratio $a/c$ used to deduce them is the least well determined of the fitting parameters and it was desirable that it should be used only once (in calculating $R_H H$) in presenting a complete set of fitting parameters; the poor determination of $a/c$ may arise because its role in aligning $\mathbf{n}$ parallel to $H$ is partly usurped by the choice of the variational form [6] for $\beta$. ‘Bulk’ values of $R_c$ and $H_s$ are not shown in Fig. 3 since we are not aware of previous measurements of $b$ for bulk $^3$He at a relevant pressure.

Explanation of the values of $R_H H$, $R_c$, $H_s$ and $\Omega_B^2$ and their dependence on pressure and aerogel density provides a problem for theoreticians. We believe that we have presented convincing evidence for a B-phase superfluid state of $^3$He in aerogel. It is likely that the ESP behaviour observed in Refs. [2] and [3] is associated with the substantially higher field used in these experiments; further evidence that this is the case is provided by the observation that replacement of the very magnetic solid $^3$He layer by $^4$He produced more B-phase-like behaviour in both these experiments [13,14].

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