

Evidence for Superfluid B Phase of ^3He in Aerogel

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We have made simultaneous torsional oscillator and transverse cw NMR (at ~ 165 kHz) studies of the superfluid phase of ^3He 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 is strongly peaked at the Larmor value. This behavior, together with the magnetic-field independence of the effective superfluid density, provides convincing evidence for a B -phase state with an \hat{n} texture, in our spherical geometry, governed by the same energetic considerations as for bulk superfluid ^3He - B .

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Since the discovery [1,2] of superfluidity of ^3He contained within aerogel, this system has been regarded [3] 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 [3] 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 [2,4] 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 Ref. [2] and, since the observed superfluid transition temperatures for our 2% aerogel were very similar to those observed in Ref. [2], there is no reason to suspect that the difference in NMR behavior 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 [5] so we do not repeat those 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 [6] followed by

a further differential preamplifier and lock-in detector; the quality factors of the tuned circuit were of the order of 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 bars pressure; sweeps for temperatures above and below the superfluid transition temperature T_{ca} are shown. The large increase in signal strength at the

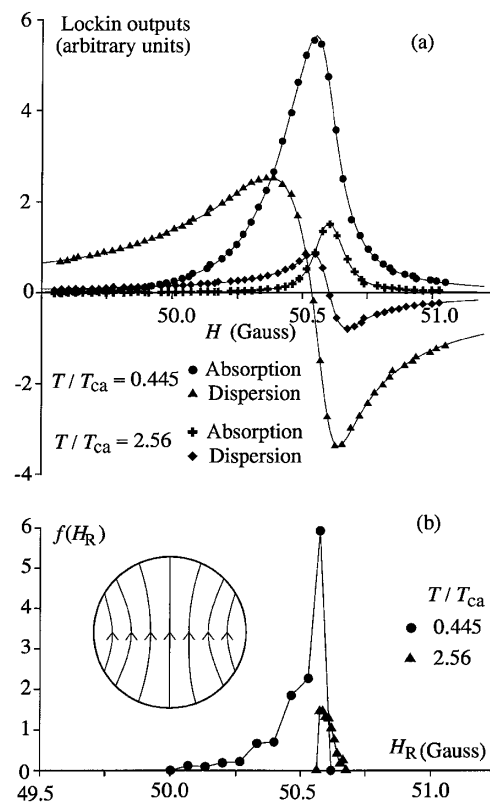


FIG. 1. (a) Absorption and dispersion NMR signals from 2% aerogel at 14.9 bars. (b) The spectrum functions $f(H_R)$ which give the fits indicated by the solid lines in (a). The inset in (b) shows, schematically, the projection into the r - z plane of the flare-out \hat{n} texture believed to be responsible for the spectra.

lower temperature is associated with the contribution from solid ^3He atoms on the surfaces of the silica strands. As in Ref. [2] we assume that the rapid exchange of ^3He 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

$$I = A + \frac{B}{T + T_0}, \quad (1)$$

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 the order of -0.4 mK and almost pressure independent. The values obtained for B correspond to an areal density of the order of 10^{19} m $^{-2}$ of solid ^3He atoms, i.e., about one monolayer; B increases with pressure by $\sim 30\%$ between 0 and 29 bars. 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 analyze 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

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

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 $H_R \leq H_1$ and for $H_R \geq H_2$, and that, for $H_1 < H_R < H_2$, it can be represented by its value at nine values of H_R ; these were normally equally spaced but when the spectrum was very broad it proved desirable to limit the spacing of the two intervals nearest the Larmor field to be no greater than 50 mG in order to obtain a satisfactory fit to this end of the spectrum. Using nine points to fit the spectrum allows us to obtain a reasonably detailed shape for $f(H_R)$ without introducing spurious detail associated with the noise on the data. Figure 1(b) shows the ‘‘nine-point’’ spectra used to obtain the fits shown by solid lines in Fig. 1(a); the values of H_1 and H_2 were fitting parameters. The finite width of the spectrum for the normal state can be associated with field inhomogeneity; for the superfluid state the spectrum confirms that only negative field (i.e., positive frequency) shifts are observed and that the spectrum is strongly peaked towards the Larmor field. These features of our data are common to all pressures where superfluid transitions were observed; i.e., from 1.5 to 29.3 bars for the 1% aerogel and from 4.8 to 29.3 bars 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 $\hat{\mathbf{n}}$ texture rather than A phase with spatially dependent $\hat{\mathbf{I}}$ and $\hat{\mathbf{d}}$ textures. First, this would explain why only positive frequency shifts are observed since the transverse NMR frequency ω for liquid ^3He - B with the $\hat{\mathbf{n}}$ vector at an angle β to the applied field, as given by [7]

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

is always greater than the Larmor frequency ω_L ; here Ω_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 $\hat{\mathbf{n}}$ texture in a spherical geometry. In particular, the strong peak of the spectrum at the Larmor frequency arises because the favored alignment of $\hat{\mathbf{n}}$ 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. Third, one would expect a spatially varying $\hat{\mathbf{I}}$ texture in the A phase to depend on the 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 [8] but the associated small change in resonant frequency (~ 4 mHz) of our torsional oscillator was unaffected by the superfluid transition, thus ruling out changes in the effective value of ρ_s/ρ 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 $\hat{\mathbf{n}}$ texture in aerogel is determined by the same considerations as for bulk ^3He - B . As the characteristic lengths for B -phase textures (see below) are large, we can ignore a spatial variation of $\hat{\mathbf{n}}$ on the scale of the aerogel microstructure and determine the texture by minimizing the energy [9]

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

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

For the bending energy density f_{bend} , we take the Ginzburg-Landau form

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

We assume that the $\hat{\mathbf{n}}$ 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 β and α ; the variational parameters p_1 - p_6 are chosen to minimize E for given values of the coefficients in the energy of Eq. (4). For $p_1 = p_4 = 0$ the texture of Eqs. (6) and (7) corresponds to the texture shown in the inset of Fig. 1(b), with $\hat{\mathbf{n}} \parallel \mathbf{H}$ (i.e., $\beta = 0$) on the equatorial plane and on the line joining the north and south poles; the second surface term in Eq. (4) causes $\hat{\mathbf{n}}$ to point into and out of the paper in the south-east and north-east quadrants, respectively. Our investigations of possible $\hat{\mathbf{n}}$ textures in a sphere suggest that this variation of the "flare-out" texture in a cylinder [10] 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 caused an increase in E in practice.

To relate the $\hat{\mathbf{n}}$ 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 ω , the resonance occurs at a field H given by

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

where $\mu = M_{\text{liqu}}/(M_{\text{liqu}} + M_{\text{sol}})$. M_{liqu} and M_{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 $\omega \approx (1 - \mu)\omega_{\text{sol}} + \mu\omega_{\text{liqu}}$ as used in interpreting previous NMR measurements [2] on superfluid ^3He in aerogel.

To fit our experimental spectra we note that the $\hat{\mathbf{n}}$ texture depends only on the ratios a/c , b/c , and d/c and that the only other unknown is Ω_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 $T \rightarrow T_{\text{ca}}$ and allow adequately for departures from these asymptotic dependences at lower temperatures. The adjustment of q_1 - q_8 enables us to fit all our spectra at a single pres-

sure within experimental error. To illustrate this we show in Fig. 2 typical examples of fitted spectra obtained for 1% aerogel at 11.6 bars. The data at this pressure provided a stringent test for our explanation since measurements were made at three different magnetic fields (37.0, 50.6, and 61.0 G) [11].

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 $R_H H = (c/a)^{1/2}$; $R_c = c/b$; $H_s = (b/d)^{1/2}$ [9]. The significance of these quantities in determining the relative importance of different terms in the energy can be seen from Eqs. (4) and (5). The values obtained for $R_H H$, R_c , H_s , and Ω_B^2 are shown in Fig. 3 along with values of $R_H H$ and Ω_B^2 for bulk ^3He - B at 10.2 bars [13]. As can be seen from Eq. (8), only the product $\mu\Omega_B^2$ can be determined from NMR spectra; to obtain Ω_B^2 we used values of μ deduced from fits to Eq. (1) over the whole temperature range, a procedure which assumes that the liquid susceptibility is constant for $T < T_{\text{ca}}$. At 11.6 bars we could not detect departures from Eq. (1) associated with the reduction of the B -phase susceptibility below that of normal ^3He . The departures are expected to be small because of the strong suppression of the energy gap in aerogel and, as indicated in Ref. [4], 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. (1) at the highest pressures studied where the effect is larger and the solid contribution relatively less important. A reduction in liquid susceptibility corresponds to a smaller value of μ and hence to a slightly larger value

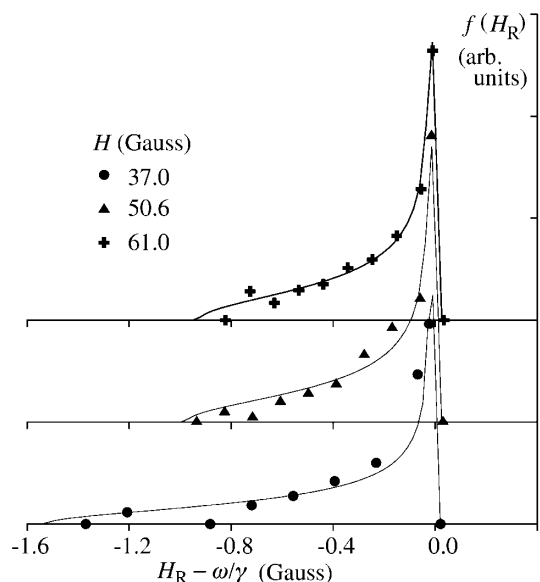


FIG. 2. Experimental (circles, triangles, and crosses) and fitted NMR spectra (continuous lines) for 1% aerogel at 11.6 bars and $T/T_{\text{ca}} = 0.63$. There was some evidence of structure in some of the observed spectra, which may indicate the existence of textural spin waves [12].

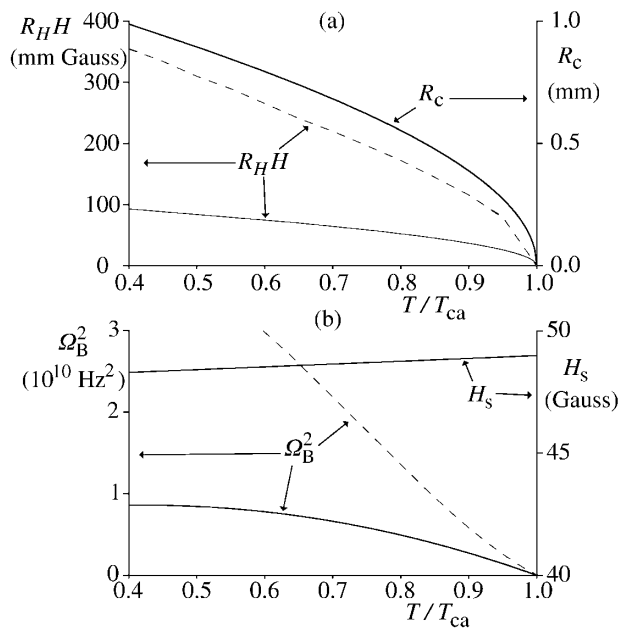


FIG. 3. The values of (a) $R_H H$ and R_c , and (b) Ω_B^2 and H_s , used to obtain fits to NMR spectra for 1% aerogel at 11.6 bars are shown by continuous lines. The dashed lines are for bulk ${}^3\text{He-B}$ at 10.2 bars.

of Ω_B^2 than that shown in 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 so that the depression of the energy gap of ${}^3\text{He}$ in aerogel causes the value of Ω_B^2 to be substantially less than that for bulk ${}^3\text{He-B}$. Our values of $R_H H$ are also smaller than bulk value as are our values of d/a [14]. The latter values are not shown in 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 may arise because its role in aligning \hat{n} parallel to H is partly usurped by the choice of the variational form (6) for β . “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 ${}^3\text{He}$ at a relevant pressure.

Explanation of the values of $R_H H$, R_c , H_s , and Ω_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 ${}^3\text{He}$ in aerogel. It is likely that the ESP behavior observed in Refs. [2] and [4] 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 ${}^3\text{He}$ layer by ${}^4\text{He}$ produced more B -phase-like behavior in both these experiments [4,15].

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- [1] J. V. Porto and J. M. Parpia, Phys. Rev. Lett. **74**, 4667 (1995).
- [2] D. T. Sprague, T. M. Haard, J. B. Kycia, M. R. Rand, Y. Lee, P. J. Hamot, and W. P. Halperin, Phys. Rev. Lett. **75**, 661 (1995).
- [3] E. V. Thuneberg, S. K. Yip, M. Fogelström, and J. A. Sauls, Phys. Rev. Lett. **80**, 2861 (1998).
- [4] B. I. Barker, L. Polukhina, J. F. Poco, L. W. Hrubesh, and D. D. Osheroff, J. Low Temp. Phys. **113**, 635 (1998).
- [5] H. Alles, J. Kaplinsky, P. Wootton, J. D. Reppy, and J. R. Hook, Physica (Amsterdam) **255B**, 1 (1998).
- [6] V. Ruutu, J. Koivuniemi, Ü. Parts, A. Hirai, and M. Krusius, Physica (Amsterdam) **194B–196B**, 159 (1994).
- [7] D. Vollhardt and P. Wölfle, *The Superfluid Phases of Helium 3* (Taylor and Francis, London, 1990). Note that we cannot make the usual approximation $\omega_L \gg \Omega_B$ since it is not valid at high pressures and low temperatures for NMR frequencies as low as ours. The rapid exchange between liquid and solid ensures that the NMR signal is transverse to a good approximation.
- [8] We made NMR measurements in both positive and negative fields in order to correct for the small changes in the dc magnetic field associated with flux creep in our demagnetization solenoid.
- [9] W. F. Brinkman and M. C. Cross, in *Progress in Low Temperature Physics*, edited by D. F. Brewer (North-Holland, Amsterdam, 1978), Vol. VIIa.
- [10] G. F. Spencer and G. G. Ihas, Phys. Rev. Lett. **48**, 1118 (1982).
- [11] The NMR signal was much smaller away from the resonant frequency of our detection circuit, but measurements were possible.
- [12] D. D. Osheroff, Physica (Amsterdam) **90B**, 20 (1977).
- [13] P. J. Hakonen, M. Krusius, M. M. Salomaa, R. H. Salmelin, J. T. Simola, A. D. Gongadze, G. E. Vachnadze, and G. A. Kharadze, J. Low Temp. Phys. **76**, 225 (1989).
- [14] J. S. Korhonen, A. D. Gongadze, Z. Janú, Y. Kondo, M. Krusius, Yu. M. Mukharsky, and E. V. Thuneberg, Phys. Rev. Lett. **65**, 1211 (1990).
- [15] D. T. Sprague, T. M. Haard, J. B. Kycia, M. R. Rand, Y. Lee, P. J. Hamot, and W. P. Halperin, Phys. Rev. Lett. **77**, 4568 (1996).