Interfacial Pinning in the Superfluid ^{3}He A-B Transition in Aerogel

J. E. Baumgardner,* Y. Lee,† and D. D. Osheroff
Department of Physics, Stanford University, Stanford, California 94305-4060, USA

L.W. Hrubesh and J. F. Poco
Chemistry and Material Science, Lawrence Livermore National Laboratory, Box 808, Livermore, California 94550, USA

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Continuous-wave NMR studies of ^{3}He in the presence of 99.3% porosity silica aerogel at 34.0 bars and in a magnetic field of 28.4 mT reveal a first-order phase transition between A-like and B-like superfluid phases on both warming and cooling. NMR spectra show that the phases on warming are the same as the phases on cooling, and the interface between them is found to be strongly pinned, even close to $T_{c,\mathrm{aero}}$. The observed behavior is consistent with spatial variation of pinning strengths within the aerogel.

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Superfluid ^{3}He has been a remarkable system for studying unconventional BCS states, owing partly to its extreme purity at low temperatures. Since other unconventional BCS systems, such as the high-T_c cuprates, are comparatively less pure, it is desirable to create a connection between their behavior and the pure behavior of superfluid ^{3}He. To this end, silica aerogels of nearly zero density have been shown to act as impurity scatterers [1,2] in qualitative agreement with the suppression of T_c by paramagnetic impurities in superconductors [3]. This is because the aerogel strands are only a few nm in thickness, while the zero temperature coherence length, ξ_0, varies from 14 nm at melting pressure to 72 nm at saturated vapor pressure. Detailed theoretical studies [4] show that low-density silica aerogels have a rich internal structure, exhibiting fluctuations in the strand density over a length scale of $\sim$100 nm. Additionally, ^{3}He exhibits two superfluid phases of different symmetries, with a free energy difference rising to $\sim$1% of the condensation energy [5]. Thus, by observing the phase diagram of superfluid ^{3}He in silica aerogels, we can learn how not just one, but two unconventional BCS states are modified [6,7] by impurity scattering.

The superfluid phases of bulk ^{3}He are known to be p-wave BCS condensates with Cooper pair spin $S = 1$ and orbital angular momentum $\ell = 1$. The A phase, or Anderson-Brinkman-Morel (ABM) state [8], is composed only of Cooper pairs whose spins are parallel. As such, the static magnetization of the A phase is nearly equal to that seen in the normal Fermi liquid. The A phase exhibits an anisotropic energy gap, with nodes along the axis of the local angular momentum. In the limit where the static NMR field is large, the transverse NMR frequency shift [9] is $\Delta\omega_A \approx \cos(2\phi)\Omega_A^2(T)/2\omega_L$, where ϕ is the angle between the angular momentum vector and zero-spin projection axis, Ω_A is the A-phase longitudinal resonance frequency, and ω_L is the Larmor frequency, i.e., $\omega_L \equiv \gamma H$. The transverse frequency shift, therefore, can be either positive or negative in the A phase.

On the other hand, the B phase, or Balian-Werthamer (BW) state [10], is composed of all three spin triplet $S = 1$ Cooper pairs, such that the total angular momentum of a Cooper pair is zero. The magnetization of the B phase is always less than the Fermi liquid value, M_{Fermi}. Near T_c, the magnetization changes linearly with temperature [9], extrapolating to M_{Fermi} at T_c in low field. The transverse NMR frequency shift of the B phase [9] is $\Delta\omega_B \approx \sin^2(\theta)\Omega_B^2(T)/2\omega_L$, where θ is the angle between the spin-orbit rotation axis and the static magnetic field. Thus, in contrast to the A phase, the frequency shift must always be positive in the B phase. The B phase energy gap is isotropic; hence, its alignment to surfaces is necessarily weaker than in the A phase. Long-range textures [11], exhibiting a broad spectrum of transverse frequency shifts from zero to $\Omega_B^2(T)/2\omega_L$, can be seen, even in relatively unconfined geometries.

Previous studies on ^{3}He in 98.3% porosity aerogels [12–15] have shown hysteretic behavior in the superfluid fraction [12,13,15], magnetization [14], and average transverse NMR frequency shift [14] seen on warming to and cooling from T_c. As in the case of bulk ^{3}He, these studies showed that ^{3}He in aerogel exhibits two separate superfluid phases on cooling: a phase near T_c with a normal Fermi liquid magnetization and both negative and positive frequency shifts, and a phase at lower temperatures with only positive frequency shifts and a reduced magnetization. Recent theoretical work by Fomin [7] suggests that the A phase cannot be stable in aerogel. Thus, we call these two phases A-like and B-like, respectively. On warming to T_c from the B-like phase, a narrow region of A-like phase was again observed; however, neither the superfluid fraction nor the frequency shift retraced the same values observed on cooling. Thus, it was not clear that this A-like phase seen on warming was equivalent to the A-like phase seen on cooling.

We now report new continuous-wave NMR experiments conducted on ^{3}He confined to a sample of nominally 99.4% porosity aerogel, at a pressure of 34.0 bars and a magnetic field of 28.4 mT. Since the region of A-like phase stability on warming in 98.3% porosity aerogels was narrow, we selected a higher porosity, expecting that the region of A-like phase stability would increase towards the bulk limit. This sample was grown inside a fused silica tube by rapid supercritical extraction [16]. We found that the aerogel pulled away from the fused silica tube after its first cycling in pressure. As a result, for all of our experiments, approximately 20% of the volume of the tube was filled with bulk ^{3}He. Thus, we estimate that the average porosity of the aerogel in this study is 99.3%. Fortunately, the properties of the bulk are well understood, so we were able to subtract its contribution directly from our NMR spectra, except when the bulk was in the B phase. In addition to this bulk term, it was necessary to compensate for localized ^{3}He atoms adsorbed on the aerogel strands. To remove the source of this signal, we preplated the aerogel strands with nearly two (1.9) monolayers of spinless ^{4}He.

Figure 1 shows NMR spectra at 34.0 bars seen on both warming and cooling, after correcting for the localized and bulk contributions mentioned above. On cooling, we see NMR spectra qualitatively similar to those that Barker *et al.* [14] saw in 98.3% porosity aerogels. As in Barker, we use Pt NMR thermometry calibrated to the Greywall [17] temperature scale, in which $T_{c,\mathrm{bulk}} \equiv 2.491$ mK at 34.0 bars. On cooling below $T_{c,\mathrm{aero}} = 2.385$ mK, the spectrum broadens and its average frequency increases monotonically with decreasing temperature. The magnetization retains its full Fermi liquid value, and for this reason, we define the phase seen on cooling to be an A-like phase. We see a portion of the spectral weight below the normal state spectrum, but since this is an A-like phase, negative frequency shifts are possible.

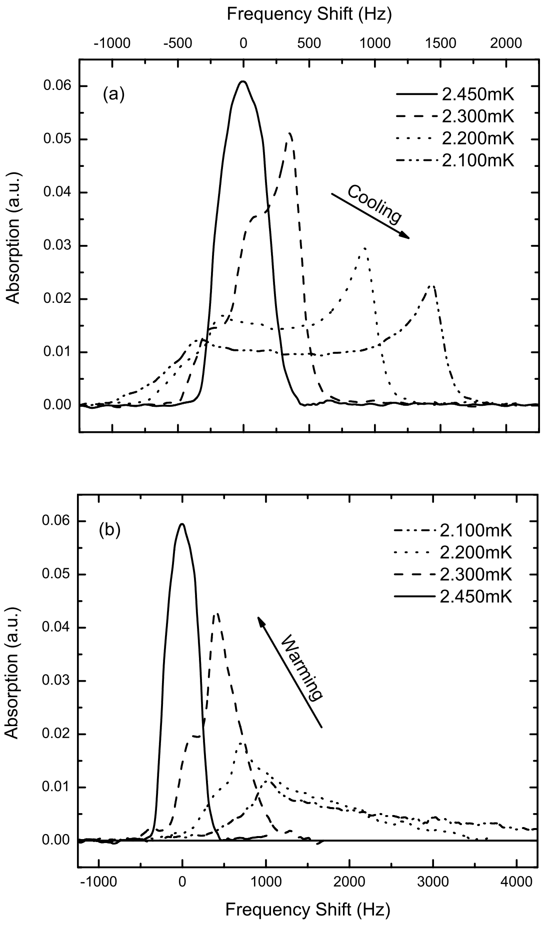

FIG. 1. NMR spectra for ^{3}He in aerogel, preplated with 1.92 layers of ^{4}He, on (a) cooling and (b) warming after further cooling below $T_{AB,c} = 1.558$ mK. These spectra have been corrected for residual localized and bulk ^{3}He spins (see text).

On cooling below the bulk supercooled AB transition temperature, $T_{AB,c} = 1.558$ mK, the NMR spectra of the ^{3}He in the aerogel change discontinuously, in a time shorter than the 0.1 s lock-in amplifier time constant. The new spectrum seen below $T_{AB,c}$ has reduced magnetization and contains only positive frequency shifts with a long high-frequency tail, and thus we define this to be a B-like phase. On subsequent warming above $T_{AB,c}$, we see substantial hysteresis. The system continues to exhibit a long high-frequency tail and a changing liquid magnetization almost completely up to $T_{c,\mathrm{aero}}$. However, on warming through 2.223 mK, a portion of the NMR spectrum crosses below the normal state spectrum, giving the first NMR evidence on warming that the ^{3}He in the aerogel is at least partly in an A-like phase.

From plots of $\chi''(\omega, T)$, such as those in Fig. 1, we determined the total magnetization and average frequency shifts in the aerogel sample. We define the magnetization of the aerogel sample to be $M(T) = \int \chi''(\omega, T)\, d\omega$ and the average frequency shift to be $\Delta\omega(T) = \int(\omega - \omega_L)\chi''(\omega, T)\, d\omega / M(T)$. In both cases, the values are corrected for the presence of localized and bulk ^{3}He spins. Figure 2 shows the normalized magnetization, M/M_{Fermi}, at 34.0 bars as the sample warms

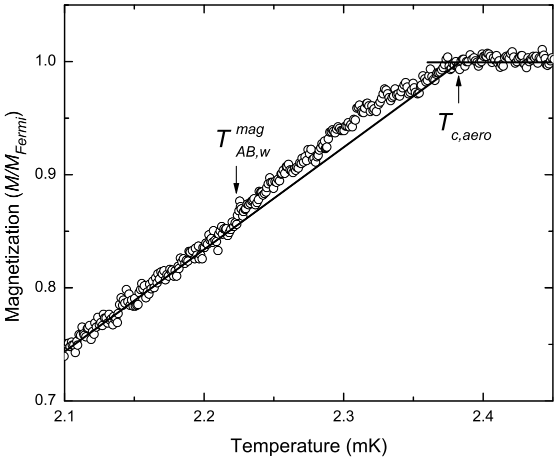

FIG. 2. Magnetization of ^{3}He in aerogel on warming, corrected for localized and bulk ^{3}He spins. Note the slope change at $T^{\mathrm{mag}}_{AB,w}$. The solid line given is a linear fit to the low temperature data that extrapolates to one at T_c.

from below $T_{AB,c}$. Below $T^{\mathrm{mag}}_{AB,w} = 2.223$ mK, $M(T)$ increases approximately linearly with increasing temperature, as expected from the magnetization of a B-like phase [6]. However, above $T^{\mathrm{mag}}_{AB,w}$, the magnetization is anomalously high, again suggesting that perhaps part of the sample is in an A-like phase.

In principle, to determine if the A-like phase seen on warming above $T^{\mathrm{mag}}_{AB,w}$ is equivalent to the A-like phase seen on cooling from T_c, we need only compare their NMR spectra. But in practice, the NMR spectra of both the A-like and B-like phases are remarkably similar close to $T_{c,\mathrm{aero}}$, perhaps owing to line shape broadening by magnetic field inhomogeneities and a softening of the B-phase textures. Thus, we follow the procedure similar to that outlined in the superfluid fraction measurements of Gervais *et al.* [13]. We prepare the A-like warming phase in the usual manner, by warming from below $T_{AB,c}$ to some maximum temperature, $T_{\max}$. Then we wait for two hours, approximately eight thermal time constants of the aerogel, to be certain that enough time is given for the aerogel to thermalize. Last, we cool the sample to lower temperatures, where the frequency shifts are much larger than the linewidth at T_c. We refer to this process of warming from below $T_{AB,c}$ to a maximum temperature $T_{\max}$ and subsequently cooling back below $T_{AB,c}$ as a trajectory with temperature $T_{\max}$.

Figure 3(a) shows the average frequency shift at 34.0 bars seen on four separate trajectories, with a $T_{\max}$ of 2.325 mK $(\triangle)$, 2.340 mK $(\times)$, 2.353 mK (∇), and $\sim$4 mK $(\bigcirc)$, which is well above $T_{c,\mathrm{aero}}$. These data have been corrected for contributions from localized ^{3}He, but not from the bulk liquid surrounding the aerogel (see below). On warming from well below $T_{AB,c}$, all four trajectories necessarily follow the same path in the AB mixture phase space, thus the warming points for all trajectories are indicated by closed circles. On cooling, the 2.325, 2.340, and 2.353 mK trajectories all show separate frequency shifts, intermediate between the pure B phase in the closed circles and the pure A phase in the open circles. We also note that the bulk AB transition on cooling is not coincident with the aerogel AB transition in these trajectories, with the bulk transition always appearing at a higher temperature. The amount of bulk supercooling increases monotonically with increasing $T_{\max}$, as if the presence of the B-like phase in the aerogel nucleates the bulk AB transition.

Figure 3(b) shows three NMR spectra, all taken at 34.0 bars and 1.82 mK. The open circles are a pure A-like spectrum seen on cooling from $\sim$4 mK, the closed circles are a pure B-like spectrum seen on warming from below $T_{AB,c}$, and the crosses are taken on cooling from a trajectory with a $T_{\max}$ of 2.340 mK. The symbols were chosen to correspond to their definitions in Fig. 3(a). Remarkably, the spectrum for the trajectory fits reasonably well to a hybrid spectrum (solid line) composed of 49% of the weight of the pure A-like line and 51% of the pure B-like line. The aerogel is clearly in a mixed state, in which both A and B phases coexist in macroscopic volumes. Above the AB cooling transition, the fraction of A-like phase for a given trajectory does not depend on how far the state is cooled, at least sufficiently far from T_c, suggesting that the AB interface is strongly pinned by the aerogel.

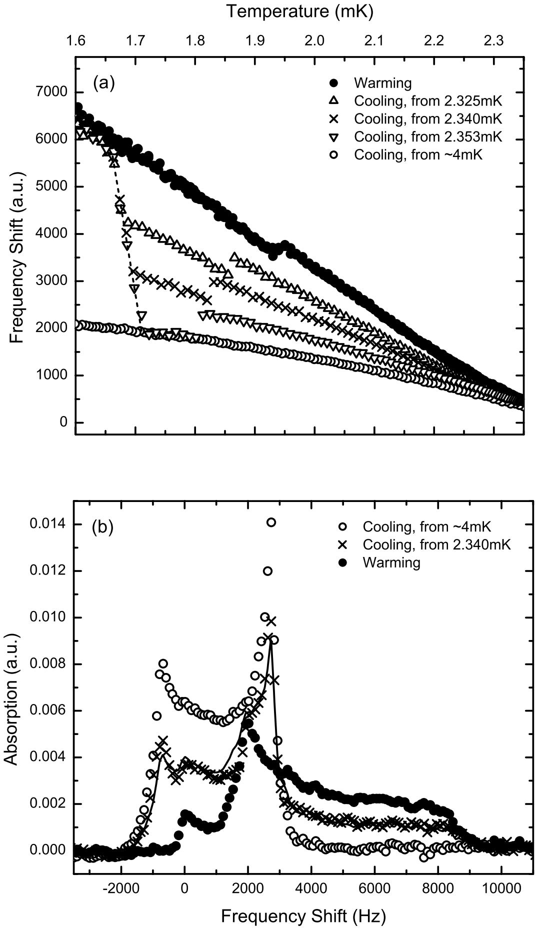

FIG. 3. (a) A comparison of average frequency shifts on cooling from trajectories with four different maximum temperatures (see text). The dashed line represents the displacement of the AB interface on cooling. These data have not been corrected for bulk spins, and thus the bulk AB transition is visible as a discontinuity in the average frequency shift. (b) Three NMR spectra at 1.82 mK, selected from the data in Fig. 3(a). The solid line is obtained by adding 49% of the spectral weight of the open circles to 51% of the weight of the closed circles. Note the fit of the solid line to the crosses.

We can fit all of our trajectory NMR spectra on cooling in this manner, and thus we can determine the precise fraction of A-like phase at temperature $T_{\max}$ from our trajectories. Figure 4 shows a plot of the A-like phase fraction, f_A, at 34.0 bars as a function of maximum trajectory temperature, $T_{\max}$. We see that on warming from below $T_{AB,c}$ to a $T_{\max}$ of less than 2.223 mK, the A-like fraction is zero to within experimental error. Thus, we define 2.223 mK to be the AB transition temperature in the aerogel on warming, $T_{AB,w}$. We do not wish to imply that the A phase is unstable below this temperature.

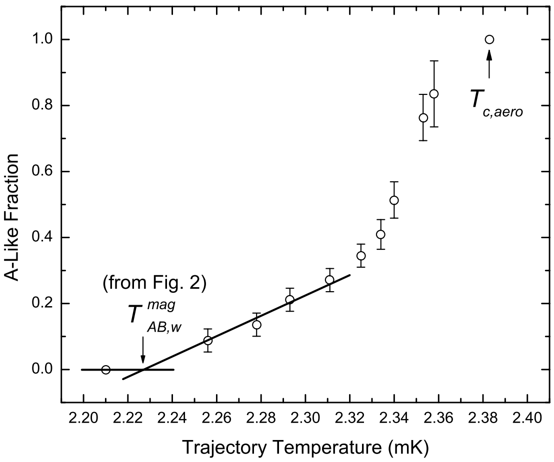

FIG. 4. The fraction of the A-like phase in the aerogel versus the maximum trajectory temperature (see text). The solid line is a linear fit to the lowest-temperature trajectories. The value of $T_{AB,w}$ from Fig. 2 is shown here.

Rather, $T_{AB,w}$ marks only the first displacement of the pinned AB interface. Above $T_{AB,w}$, there is a linear rise in f_A until 2.28 mK, at which point f_A begins to increase more rapidly. Finally, above $T_{c,\mathrm{aero}}$, the sample is completely reset, so that on subsequent cooling, the aerogel is only in the A-like phase.

Revisiting Fig. 3(a), we also find a finite temperature width for the aerogel AB cooling transition, shown as a dashed line. We first note that the presence of the aerogel B phase nucleates the bulk AB transition on cooling. Thus, in Fig. 3(a), the bulk liquid surrounding the aerogel is in the B phase, while in Fig. 1(a), the bulk liquid is in the A phase. When the aerogel is surrounded by the bulk B phase, we find that the aerogel AB cooling transition is no longer instantaneous, but is rather smeared out in temperature from 1.66 to 1.74 mK, both warmer than the value of $T_{AB,c}$ obtained in the presence of bulk A phase, 1.558 mK. We find that this cooling transition is also irreversible, with the fraction of the A-like phase remaining constant on warming up to the AB warming transition. This observation agrees with the coexistence of A-like and B-like phases on cooling first seen in the superfluid fraction measurements of Nazaretski *et al.* [15].

Having thus established the AB transition temperatures on warming and cooling, we conclude with some remarks on the nature of the AB transition itself. Foremost, we observe the first evidence that the A-like phase seen on warming is the same as the A-like phase seen on cooling. Further, we observe that on warming and cooling the AB interface is strongly pinned, even very near $T_{c,\mathrm{aero}}$. This result is consistent with the superfluid fraction measurements of Brussaard *et al.* [12] in high magnetic fields and significantly lower temperatures. With the exception of the cooling transition in the presence of the bulk A phase, the displacement of the aerogel AB interface always occurs over a nonzero range of temperatures. This behavior is consistent with a spatial distribution of pinning strengths for the AB interface in the aerogel. Within these temperature ranges, A-like and B-like phases coexist. The NMR spectra are simply the weighted sums of the results from pure A-like and pure B-like phases, suggesting that the B-phase texture is not substantially affected by the fraction of the A-like phase in the sample. The displacement of the AB interface is in all cases irreversible, revealing only that the true thermodynamic transition temperature lies somewhere between the first presence of the A phase on warming and the first presence of the B phase on cooling. Ultimately, the exact value of the equilibrium AB transition temperature cannot be determined without further information.

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*Electronic address: jbaumgar@stanford.edu

†Current address: Department of Physics, University of Florida, Gainesville, FL 32611-8440.

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