Phase Diagram of the *A* and *B* Phases of Superfluid ^{3}He in Aerogel

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We report the first measurements of the *A*-*B* phase transition of superfluid ^{3}He confined within 98% silica aerogel in high magnetic fields and low temperatures. A disk of aerogel is attached to a vibrating wire resonator. The resonant frequency yields a measure of the superfluid fraction ρ_s/ρ of the ^{3}He within the aerogel. The inferred ρ_s/ρ value increases substantially at the *A*-to-*B* transition of the confined superfluid, allowing us to map the *A*-*B* phase diagram as a function of field and temperature. At 4.8 bars, the *B*-*T* transition curve looks very similar to that in bulk with a simple reduction factor of order 0.45 for both transition field and temperature.

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Liquid ^{3}He at very low temperatures forms a system of virtually absolute purity, since the only likely contaminant, ^{4}He, has a solubility in ^{3}He of order 1 part in 10^{2000} at 100 μK. In any study of bulk superfluid ^{3}He properties, we are therefore justified in ignoring all effects of impurities. Since bulk superfluid ^{3}He is therefore intrinsically pure and also very well understood theoretically, it is natural to investigate how the superfluidity might be modified by the presence of impurities. Aerogels with very high porosities [1] provide an ideal matrix of defects on the scale of the superfluid coherence length.

Aerogel is a loose arrangement of nanometer diameter silica strands providing a fractal structure giving rise to a distribution of voids with dimensions spanning the liquid coherence length. It is to be expected that the effect of the disorder introduced by the aerogel would depress the superfluid transition temperature. Furthermore, since the two common phases of bulk superfluid ^{3}He, the *A* and *B* phases, have rather similar free energies, any differences in the effect of the disorder on the two phases might be expected to have a large influence on the phase diagram of the superfluid in aerogel. Even the basic question, precisely which superfluid phase is stable in the presence of aerogel, has been a matter of some conjecture. Early experiments in relatively high fields [2] suggested that the *A* phase was preferred but lower-field measurements [3] showed a *B*-like phase. More recently, Barker *et al.* [4] saw evidence of a phase transition between the two.

In this Letter we report that by oscillating an aerogel disk through the superfluid we are able to infer the superfluid fraction ρ_s/ρ inside the aerogel down to low temperatures for both the *A* and *B* phases. Moreover, since this fraction is different for the two phases, we can also observe the transition between them and are therefore able to map out the phase diagram as a function of temperature and magnetic field. (We should emphasize that, since we cannot specifically determine the symmetry of the order parameter in the current experiments, we apply the designations *A* phase and *B* phase strictly only as labels in analogy with the corresponding bulk phases, although we have no doubt that these are indeed the phases concerned. The designations are consistent with those of the higher pressure measurements of Refs. [2–4].)

The experiment is made in a Lancaster style nested nuclear cooling stage [5] which also forms the experimental cell. Inside the cell is an open volume of bulk superfluid ^{3}He which incorporates the aerogel resonator, described below, along with a 4.5 μm NbTi vibrating wire resonator [6] for measuring the temperature in the bulk *B* phase. A further resonator situated inside a well-shielded box acts as a heater. The various resonators sit in a bulk region of superfluid located within the copper refrigerant. Since we observe the transition in the final field of the solenoid used for demagnetizing the copper, the lowest temperatures to which we can measure are limited by the typical demagnetization starting conditions of $B = 6.3$ T and $T = 6$ mK. Various sequences of demagnetization and subsequent heating allow us to access a significant range of the *B*-*T* phase diagram.

In the inset of Fig. 1, we show the aerogel resonator which is an adaptation of the conventional vibrating wire resonator. A superconducting Ta wire of diameter 0.124 mm is bent into a 6 mm by 6 mm square shape and glued to a base plate. A 98% aerogel disk of thickness 1.1 mm and diameter 5 mm is glued to the crossbar with a very small amount of Stycast 2651 resin. Since the aerogel is very efficient at soaking up the glue when it is fluid, the Stycast is left to thicken until almost set before being applied. The approximate area over which the Stycast penetrates the aerogel is indicated in the figure.

The resonator is exposed to a steady vertical magnetic field provided by the main demagnetization solenoid of the refrigerator. The Lorentz force produced by an alternating current passed along the wire at the resonant frequency sets the oscillator into motion. The motion of the oscillator is detected by the induced Faraday voltage across the wire proportional to the wire velocity. To perform the experiment we need to monitor the resonant frequency of the resonator as the field and/or temperature is varied through the region of interest. We determine the resonant frequency

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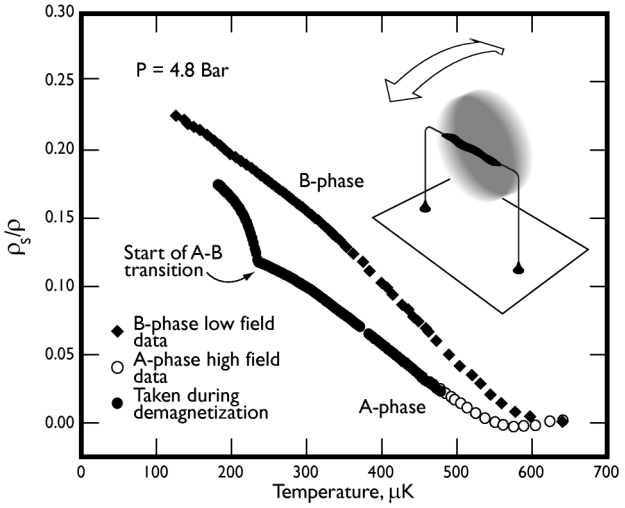

FIG. 1. Inset: the aerogel resonator. Main figure: values of ρ_s/ρ in 98% aerogel at a pressure of 4.8 bars. The upper curve (filled diamonds) shows values made in the B phase, obtained by slow heating after demagnetization to a low field. The open circles show values for the A phase taken in high field, and the filled circles show values taken starting in the A phase during demagnetization, with a clear signature of the A-B transition at about 230 μK.

either by sweeping the ac drive frequency through resonance and observing the amplitude or by recording the frequency continuously while a feedback system automatically holds the system on resonance.

The method by which we infer the superfluid fraction in the aerogel is briefly as follows. The resonant frequency of the aerogel oscillator is set by the ratio of the restoring force provided by the stiffness of the Ta legs to the effective mass m of the resonator. A considerable contribution to the effective mass of the oscillator is provided by the backflow of liquid around the disk as it moves. To take one extreme, suppose that the disk is oscillating in bulk superfluid ^{3}He at very low temperatures such that the superfluid fraction is 100%. If the superfluid fraction within the aerogel were also 100%, then superfluid could pass through the disk freely and there would be no backflow. In this case the effective mass of the resonator would be a minimum and the resonant frequency would have the value which we would have measured in vacuum f_0. In practice, even with pure superfluid, there must always be a small backflow to account for the motion of the fluid around the Ta wire, the resin glue, and the 2% volume of silica strands in the aerogel. This gives only a small contribution when the superfluid fraction is high and can be neglected for the measurements presented below. At the other extreme, if the disk were again moving in bulk superfluid ^{3}He B but the superfluid fraction in the aerogel were zero, then the normal fluid clamped in the disk would be completely opaque to superfluid. In this case the superfluid backflow setup would correspond to the full displaced volume of the moving disk, giving the maximum effective mass and the minimum resonant frequency f_n. We are interested in the intermediate case, where only a fraction ρ_s/ρ of the liquid in the aerogel is superfluid. We assume that this fraction ρ_s/ρ of the bulk superfluid may pass through the disk freely, while the remaining part must flow around the disk and contribute to the backflow, yielding a resonant frequency f. Given that the frequency is proportional to $m^{-1/2}$, by combining the three cases we find that the superfluid fraction corresponding to the measured resonant frequency f is given by

$$\rho_s/\rho = 1 - \frac{(f_0/f)^2 - 1}{(f_0/f_n)^2 - 1}.$$

The simplest measurement we can make is to monitor the resonant frequency as a function of temperature in a constant low magnetic field, as the systems warms after demagnetization to the lowest temperature. This yields the values of ρ_s/ρ of the B phase in our particular aerogel sample, as shown by the upper curve in Fig. 1. The temperature variation of the inferred superfluid fraction in the aerogel is qualitatively similar to, but significantly higher than, that found by torsional oscillator experiments at higher temperatures, showing ρ_s/ρ increasing more gradually with decreasing temperature below T_c than that of the bulk B phase. The transition temperatures are consistent with other measurements made of 98% aerogel samples [7]. Superfluidity is not observed in our sample at pressures below about 2.7 bars.

In practice, the behavior is somewhat more complicated. Our resonator has two resonances, typically at 400 and 480 Hz, from flexing of the aerogel disk, with the two modes corresponding to the in-phase and antiphase motions of the disk with respect to the tantalum legs. The results presented here are all taken from the lower frequency mode. Results from the other mode are essentially identical. However, the small splitting means that frequency measurements become difficult when the frequency width of either resonance exceeds about 30 Hz. This frustrates good measurements at the higher temperatures, where quasiparticle damping from the surrounding bulk superfluid becomes significant. For this reason our measurements are all restricted to temperatures below $\sim$650 μK.

We turn now to measurements in higher magnetic fields. These are readily made during demagnetization or during remagnetization/demagnetization cycles with or without applied heat. The cell is first demagnetized until the bulk superfluid outside the resonator has undergone the A-to-B phase transition. We cannot make the measurements in the bulk A phase since the resonator damping is too large. At this field the superfluid inside the aerogel is in the A phase. The cell is then heated in order to obtain the higher temperature ρ_s/ρ measurements shown by the open circles in Fig. 1. The heating is then stopped and the cell is further demagnetized while the resonator frequency is monitored. The inferred ρ_s/ρ values during demagnetization are shown by the solid circles in Fig. 1. The temperature

of the superfluid falls as the field is reduced (with B/T remaining constant to a few percent, as determined by the vibrating wire thermometer). The A-B phase transition in the aerogel is clearly observed at about 230 μK (and a corresponding field of 200 mT). The transition onset is rather sharp but requires a further reduction in field and temperature of about 5% to be completed. The B phase also shows a considerably smaller superfluid fraction after the transition than that of the low-field B phase. This is to be expected since the B phase in bulk is considerably distorted by magnetic fields close to the A-B transition field.

We note that the A-phase superfluid density appears to be almost a constant fraction of that of the B phase at the same temperature. If maintained to $T = 0$ this implies that the zero temperature A-phase superfluid fraction will be some 40% less than that of the B phase, as implied by the homogeneous scattering model; see, for example, Hänninen *et al.* [8], provided that in our case the ℓ vector in the aerogel is aligned with the flow.

The particular shape of the ρ_s/ρ curve as the transition is crossed is an artifact of our geometry. The main demagnetization solenoid used to provide the field also generates an axial field gradient at the position of the aerogel resonator such that the field at the top of the resonator is a few percent higher than that at the bottom. Consequently, the B phase should nucleate at the bottom of the aerogel disk and gradually grow upwards during the demagnetization. The shape of the curve during the transition thus reflects the shape of the aerogel disk and the trajectory of the A-B phase boundary. A further question is introduced by the flexibility of the aerogel itself which bends horizontally as the resonator moves, as mentioned above. That the motion of the periphery of the aerogel disk is different for the two modes is verified by a different transition shape for the upper and lower resonances, while the transition takes place at the same field and temperature.

In Fig. 2, we show the resonant frequency of the resonator as a function of the applied field while first demagnetizing into the B phase and then remagnetizing back into the A phase at a pressure of 7.4 bars. We have not converted the frequencies into a superfluid fraction at this pressure since we cannot perform the measurements up to a sufficiently high temperature to obtain a reliable value for f_n. The value of B/T remains virtually constant during these measurements. On demagnetizing, a small degree of supercooling/superdemagnetizing is often observed, as shown in the figure, resulting in a sudden upward step at the beginning of the A-B transition. The degree of supercooling is variable but is more pronounced at the higher pressures. On remagnetizing from the B phase, the data first retraces its path along the (distorted) B-phase curve until the transition region where there is significant hysteresis. We believe that such hysteresis arises from the pinning of the A-B interface within the aerogel as follows. On demagnetizing, the interface is moving upwards within the aerogel but is lagging behind its equilibrium position.

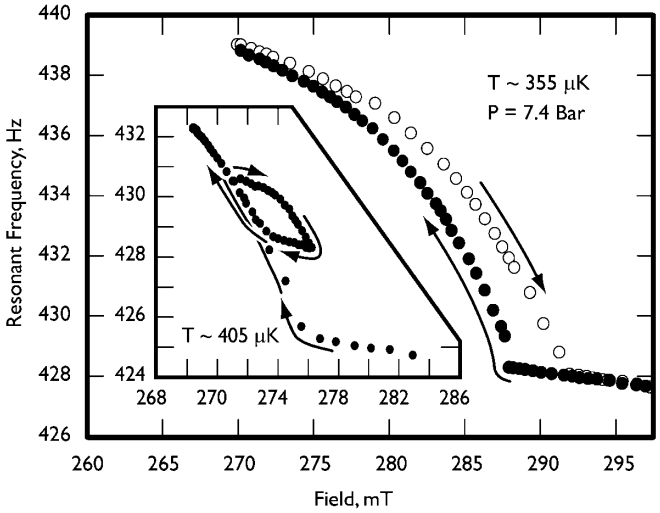

FIG. 2. A transition from the A phase to the B phase during demagnetization at a pressure of 7.4 bars and temperature of 355 μK, followed by remagnetization. The raw frequency of the lower resonance of the aerogel resonator is shown. The hysteresis of the transition is clearly evident. The inset shows a hysteresis loop at the same pressure and 405 μK. The shape of the transition is an artifact of the experiment; see text.

On remagnetizing, the interface is moving downwards but again lagging behind its equilibrium position, resulting in the observed hysteresis. The inset of Fig. 2 shows the behavior when the cell is first demagnetized to a value part way into the transition, then remagnetized by a small amount before further demagnetizing. The resulting hysteresis loop indicates that on changing the direction of the field sweep there is initially very little motion of the interface, as indicated by the almost horizontal regions of the cycle. Later the interface moves along a well-defined trajectory dependent only on the direction of the field sweep. This suggests a rather well-defined pinning energy of the interface. The free energy difference between the phases in finite field is $\Delta G = \Delta\chi B_{AB}\delta B$. Therefore, from the $\sim$1.5% field hysteresis of this data we can estimate the pinning energy in this case to be about 0.75% of the zero-field free energy difference between the phases.

We measured the A-B phase transition at higher temperatures by heating the cell and/or sweeping the magnetic field. We take the transition field to be the field at the base of the aerogel when we observe the sharp kink, where the transition region meets the A phase ρ_s/ρ line. The measurements obtained for both demagnetizing/cooling and remagnetizing/warming are shown in Fig. 3, together with the bulk B_{AB} at 4.8 bars measured by Hahn *et al.* [9] for comparison. As a check we have also made one measurement of T_{AB} in the bulk at 4.8 bars from the signature (the sudden decrease in damping of our oscillator) of the bulk A-B transition observed during demagnetization, which is marked by the solid square.

One might have expected the phase boundary line in B-T space to be somewhat deformed in the aerogel since

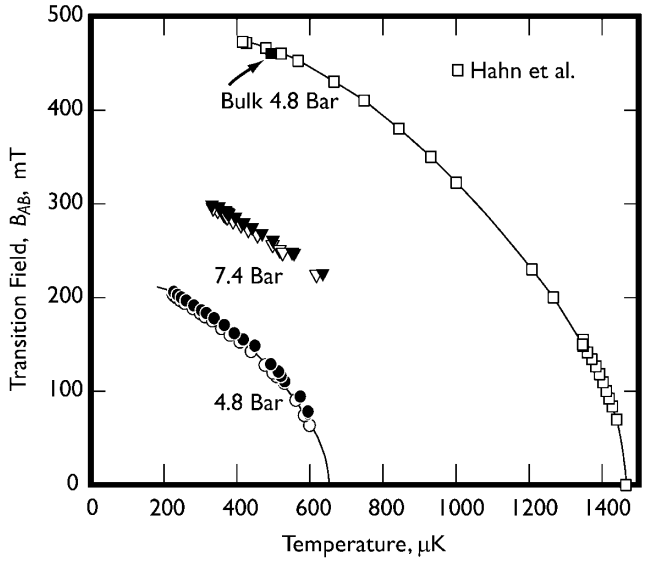

FIG. 3. The *A*-*B* transition as a function of magnetic field and temperature. The open squares are bulk data for 4.8 bars taken from Hahn *et al.* [9]. The filled square is a bulk measurement made by us at the same pressure for comparison; see text. The two lower curves are our measurements of the transition field and temperature in the 98% aerogel at 4.8 and 7.4 bars. The open points indicate measurements made while cooling/demagnetizing and the filled points show measurements taken during warming/remagnetization. To illustrate how similar the behavior is to that of the bulk, the curve through the 4.8 bar aerogel data is simply the curve drawn through the data of Hahn *et al.* [9] scaled by 0.45 along both axes.

this line would be sensitive to any difference in the effect of the aerogel on the stability of the phases. In fact the shape is very close to that seen in the bulk. The line drawn through the 4.8 bar data is simply the curve shown for the bulk data scaled in both B and T by the same factor 0.45. (The short length of 7.4 bar data is consistent with a corresponding scaling factor of 0.59.) This behavior is, in fact, consistent with the homogeneous scattering model of Ref. [8]. This model suggests that simple scaling factors reflecting the depression of the gap, and similar in the two phases, should govern the behavior, which should therefore not show any gross qualitative difference from that in the bulk.

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