A-B transition of superfluid ^{3}He in aerogel and the effect of anisotropic scattering

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We report the results of high-frequency acoustic shear impedance measurements on superfluid ^{3}He confined in 98% porosity silica aerogel. Using 8.69 MHz continuous wave excitation, we measured the acoustic shear impedance as a function of temperature for the sample pressures of 28.4 and 33.5 bar. We observed the *A-B* transition on warming in zero magnetic field. Our observations show that the *A* and *B* phases in aerogel coexist in a temperature range of about 100 μK in width. We propose that differences in the relative stability of the *A* and *B* phases arising from anisotropic scattering can account for our observations.

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The effect of disorder on a condensed matter system is one of the most interesting and ubiquitous problems in condensed matter physics. Metal-insulator transitions[1] and the Kondo effect[2] are two examples of phenomena in which disorder, in the form of various types of impurities, plays a fundamental role. The influence of disorder on ordered states such as the magnetic or superconducting phase has also attracted tremendous interest especially in systems that undergo quantum phase transitions.[3] In this work we address the influence of disorder on the first-order phase transition that separates two highly competing ordered states. This situation occurs in superfluid ^{3}He impregnated in high porosity silica aerogel where the ordered states are the *A* and *B* phases with *p-wave* spin-triplet pairing.[4]

High porosity silica aerogel consists of a nanoscale abridged network of SiO_2 strands with a diameter of 3–5 nm. Since the diameter of the strands is much smaller than the coherence length (ξ_0) of the superfluid (72–15 nm in the pressure range of 0 to 34 bar), when ^{3}He is introduced, the aerogel behaves as an impurity with the strands acting as effective scattering centers. The phase diagram of ^{3}He/aerogel (with mostly 98% porosity) has been studied using a variety of techniques.[5–11] To date, three distinct superfluid phases have been observed in ^{3}He/aerogel; these are called the *A*, *B*, and A_1 phases[10] as in the bulk, although the detailed structures of the order parameters (especially the orbital component) have not been identified. Early studies using NMR[6] and torsional oscillator[5] measurements on ^{3}He in 98% porosity aerogel found substantial depression in the superfluid transition and a theoretical account based on the homogeneous isotropic scattering model (HISM) was provided.[12] The NMR studies of ^{3}He/aerogel show evidence of an equal spin pairing (ESP) state similar to the bulk *A* phase[6] and a phase transition to a non-ESP state similar to the bulk *B* phase.[13] A large degree of supercooling was observed in this phase transition (*A-B* transition) indicating the transition is first order. Further studies using acoustic techniques,[8] and an oscillating aerogel disc,[9] have confirmed the presence of the *A-B* transition in the presence of low magnetic fields.

While the effects of impurity scattering on the second order superfluid transition have been elucidated by these early studies, experiments designed to determine the effects of disorder on the *A-B* transition have been rather inconclusive.[8,9,13–16] It is important to emphasize that the free energy difference between the *A* and *B* phases in bulk ^{3}He is minute compared to the condensation energy.[17] Moreover, both phases have identical intrinsic superfluid transition temperatures. The nature of highly competing phases separated by the first-order transition is at the heart of many intriguing phenomena such as the nucleation of the *B* phase in the metastable *A* phase environment,[17] the profound effect of magnetic fields on the *A-B* transition,[18] and the subtle modification of the *A-B* transition in restricted geometry.[19] We expect this transition to be extremely sensitive to the presence of aerogel and conjecture that even the low energy scale variation of the aerogel structure would have a significant influence on the *A-B* transition.

A number of experiments have been performed with the purpose of systematically investigating the *A-B* transition in aerogel.[8,9,13,15,16] In experiments by the Northwestern group[8] using a shear acoustic impedance technique, a significantly supercooled *A-B* transition was seen while no signature of the *A-B* transition on warming was identified. In the presence of magnetic fields, however, the equilibrium *A-B* transitions were observed and the field dependence of the transition was found to be quadratic as in the bulk. However, no divergence in the coefficient of the quadratic term $g(\beta)$ $[1-T_{AB}/T_c = g(\beta)(H/H_c)^2$, where T_{AB} is the equilibrium *A-B* transition temperature] was observed below the melting pressure. This result is in marked contrast with the bulk behavior which shows a strong divergence at the polycritical point (PCP).[20] These authors conclude that the strong-coupling effect is significantly reduced due to the impurity scattering and the PCP is absent in this system. Although this conclusion seems to contradict their observation of a supercooled *A-B* transition even at zero field, other theoretical and experimental estimations of the strong-coupling effect in the same porosity aerogel[10,21] seem to support their result. The Cornell group[15] investigated the *A-B* transition in 98% aerogel using the slow

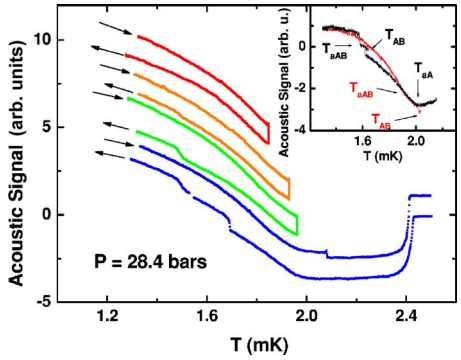

FIG. 1. (Color online) Acoustic traces of tracking experiments at 28.4 bar in zero magnetic field. Each pair of warming and subsequent cooling is color coded. The turn-around temperatures are indicated by the vertical line for each pair. The arrows indicate the direction of temperature change in time. Inset: cooling (black) and warming (red) traces taken at around 28.5 bar. The signatures of the aerogel superfluid transition and the aerogel *A*-*B* transition are labeled as T_{aA} and T_{aAB}.

sound mode in the absence of a magnetic field. While the evidence of the supercooled *A*-*B* transition was evident, no warming *A*-*B* transition was observed. Nonetheless, they observed a partial conversion from $B \rightarrow A$ phase only when the sample was warmed into the narrow band (≈ 25 μK) of aerogel superfluid transition. Recently, the Stanford group conducted low field ($H=284$ G) NMR measurements on 99.3% aerogel at 34 bar.[16] They found about 180 μK window below the superfluid transition where the *A* and *B* phases coexist on warming with a gradually increasing contribution of the *A* phase in the NMR spectrum.

We have observed the *A*-*B* transition on warming in the absence of magnetic field for two sample pressures of 28.4 and 33.5 bar, and have found evidence that the two phases coexist in a temperature window that can be as wide as 100 μK. In this paper, we present our findings along with some considerations that can clarify the seemingly paradoxical observation on the *A*-*B* transition in aerogel and, at the same time, provide a plausible explanation for the observed coexistence of the *A* and *B* phases.

A continuous wave shear impedance technique was employed in this study. In this method, an ac-cut quartz transducer, which is in contact with bulk (clean) liquid and (dirty) liquid in aerogel, is excited continuously at a frequency of 8.69 MHz. Using a bridge type cw spectrometer, the change in electrical impedance of the transducer is measured while the temperature was varied slowly. Typical warming (cooling) rates used in our study are between 0.1 and 0.2 mK/h. A ^{3}He melting pressure thermometer is used as our main thermometer. The strength of stray field at the sample cell from the demagnetization magnet is smaller than 10 G in the experimental condition. The experimental technique and the sample cell are described elsewhere in detail.[8,10,22]

Shown in Fig. 1 are the traces of acoustic signal taken at 28.4 bar in zero magnetic field. The bottom (blue) traces show the acoustic responses between 1.3 and 2.5 mK. The sharp jumps in the acoustic traces around 2.4 mK mark the bulk superfluid transition and distinct slope changes are associated with the superfluid transitions in aerogel (see Ref. 10). The signatures of the supercooled *A*-*B* transition in the bulk and aerogel appear as small steps on the cooling traces. The identification of the step in the acoustic impedance as the *A*-*B* transition has been established by a systematic experimental investigation of Gervais *et al.*[8] In the inset, the warming and cooling traces near 28.5 bar are shown in a narrower temperature range near the aerogel superfluid transition. This trace was the first indication of a possible *A*-*B* transition in aerogel on warming at zero field. The cooling trace (black) from the normal state of bulk reveals a well-defined aerogel transition at 2.0 mK (T_{aA}). The supercooled *A*-*B* transitions from the bulk (T_{AB}) and aerogel (T_{aAB}) are clearly shown as consecutive steps at lower temperatures. After being cooled through both *A*-*B* transitions, both clean and dirty liquids are in the *B* phase. On warming the trace follows the *B* phase and progressively merges into the *A* phase (cooling trace) around 1.9 mK. This subtle change in slope is the signature of the *A*-*B* transition on warming.

In order to test our identification of this feature in aerogel, we performed tracking experiments similar to those described in Ref. 8. The sample liquid is slowly warmed from the aerogel *B* phase up to various points around the feature, and then cooled slowly to watch the acoustic trace for the signature of the supercooled *A*-*B* transition. During the turn around, the sample stays within 30 μK from the highest temperature reached (hereafter referred to as the turn-around temperature) for about an hour. If the warming feature is indeed the *A*-*B* transition, there should be a supercooled signature on cooling only after warming through this feature. The color coded pairs of the traces in Fig. 1 are the typical results of the tracking experiments for different turn-around temperatures. In the bottom (blue) cooling trace from the normal state, one can clearly see two supercooled *A*-*B* transition steps. The sharper step appearing at ≈ 1.7 mK corresponds to the bulk *A*-*B* transition. We find that the size of the step indicating the aerogel *A*-*B* transition depends on the turn-around temperature. We can make a direct comparison of each step size since the supercooled *A*-*B* transitions in aerogel occur within a very narrow temperature range, ≈ 40 μK. Similar behavior was observed for 33.5 bar.

From the data obtained in the tracking experiments, the relative size of the steps at the supercooled aerogel *A*-*B* transition is plotted in Fig. 2 as a function of the turn-around temperature. For both pressures we see narrow temperature regions (shaded regions in the figure) where the size of the steps grows with the turn-around temperature until T_{aA} is reached. For $T > T_{aA}$, no appreciable change in the step size is observed. This suggests that only a portion of the liquid in aerogel undergoes the $B \rightarrow A$ conversion on warming in that region. An inevitable conclusion is that the *A* and *B* phases coexist in that temperature window. Consistent behavior has been observed in 99.3% porosity aerogel, although in the presence of a 284 G magnetic field.[16] It is worthwhile to note that at 10 G, the equilibrium *A*-phase width in bulk below the PCP is <1 μK. A quadratic field dependence in the warming *A*-*B* transition is observed in our study up to 2 kG. No information on the spatial distribution of the two phases can be extracted from our measurements.

In Fig. 3, a composite low-temperature phase diagram of

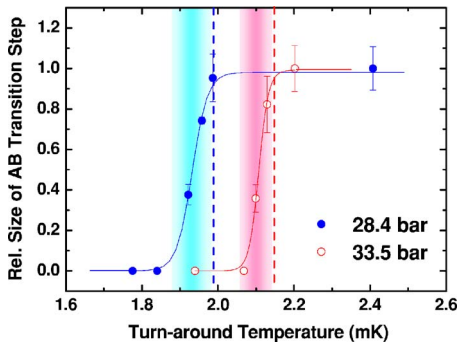

FIG. 2. (Color online) The relative size of the steps for the supercooled aerogel A-B transition is plotted as a function of the turn-around temperature for 28.4 and 33.5 bar. The lines going through the points are guides for eyes. The dashed vertical lines indicate the aerogel superfluid transition temperatures.

^{3}He in 98% aerogel is reproduced along with our A-B transition temperatures. We have plotted the lowest temperatures where the $B \rightarrow A$ conversion is first observed on warming. It is clear that the slope of the A-B transition line in aerogel has the opposite sign of that in the bulk in the same pressure range. However, in a weak magnetic field, the slope of the bulk A-B transition line changes its sign from positive ($p < p_c$ where p_c represents the polycritical pressure) to negative ($p > p_c$) (see the dotted line in Fig. 3).[23] This observation provides indirect evidence that our measurements take place below the PCP, if it exists in this system. It appears that in effect, the P-T phase diagram is shifted to higher pressures in the presence of aerogel.

How can we explain the existence of a finite region of the A phase at pressures below the PCP at $B=0$? We argue that anisotropic scattering from the aerogel structure is responsible for this effect. Although there is no successful quantitative theoretical account of the A-B transition for $p > p_c$, the Ginzburg-Landau (GL) theory presents a quantitative picture for the A-B transition in a small magnetic field, B (relative to the critical field) for $p < p_c$. Under these conditions, the quadratic suppression of the A-B transition arises from a term in the GL free energy

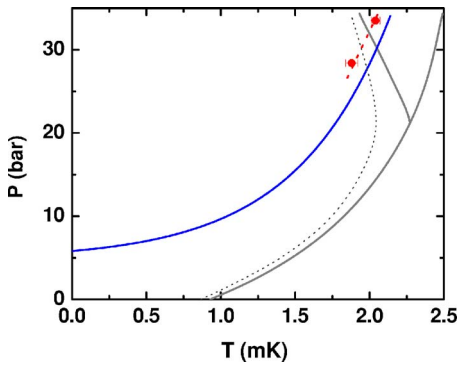

FIG. 3. (Color online) The low-temperature zero field phase diagram of superfluid ^{3}He in 98.4% aerogel along with that of the bulk (solid lines). The dotted line is the bulk A-B transition calculated at 1.1 kG from Ref. 20. The aerogel superfluid transition line shown in blue (darker line in grey scale) is obtained by smoothing the results from Refs. 7 and 8. Two points are the lowest temperatures where the $B \rightarrow A$ conversion starts on warming.

$$f_z = g_z B_\mu A_{\mu i} A^*_{\nu i} B_\nu, \tag{1}$$

where $A_{\mu i}$ represents the order parameter of a superfluid state with spin (μ) and orbital (i) indices.[4] The main effect of this term is to produce a tiny splitting in T_c for the A and B phases. In the GL limit, the free energy (relative to the normal state) of the A (B) phase is $f_{A(B)} = -\alpha^2/2\beta_{A(B)}$ where $\alpha = N(0)(T/T_c - 1)$ with $N(0)$ being the density of states at the Fermi surface, and $\beta_{A(B)}$ is the appropriate combination of β parameters that determine the fourth-order terms in the GL theory. For $p < p_c$, the B phase has lower free energy than the A phase ($\beta_B < \beta_A$). However, when the two phases are highly competing, i.e., $\beta_A \approx \beta_B$, even a tiny splitting in the superfluid transition, $\delta T_c = T_c^A - T_c^B (>0)$ results in a substantial temperature region (much larger than δT_c) where the A phase becomes stable over the B phase.

The simplified representation of the aerogel as a collection of homogeneous isotropic scattering centers is not sufficient to describe minute energy scale phenomena such as the A-B transition. The strandlike structure introduces an anisotropic nature in the scattering, e.g., *p-wave* scattering. This consideration requires an additional term in the GL free energy[25,26]

$$f_a = \alpha_1 a_i A_{\mu i} A^*_{\mu j} a_j, \tag{2}$$

where $\hat{a}$ is a unit vector pointing in the direction of the aerogel strand. In other words, the aerogel strand produces a random field which couples to the orbital component of the order parameter. This random orbital field plays a role analogous to the magnetic field in spin space, thereby splitting the superfluid transition temperature. If the aerogel structure generates anisotropy on the length scale of ξ_0, f_a would give rise to the A-B transition, even in the absence of a magnetic field. Detailed free energy considerations indicate that the anisotropy would favor the $\hat{a} \perp \hat{l}$ configuration for the A phase[24] where $\hat{l}$ indicates the direction of the nodes in the gap. Using the expression for the coupling strength α_1 calculated in the quasiclassical theory,[25] we find that f_a is comparable to f_z produced by a magnetic field $B_e = \sqrt{\alpha_1/g_z} \approx (T_c/\gamma\hbar)\sqrt{\xi_0/l} \sim 1$ kG where γ is the gyromagnetic ratio of ^{3}He and l is the mean free path presented by the impurity scattering off the aerogel strand. Since $B_e \propto \sqrt{\delta l/l}$ [$f_a \propto (\delta l/l)$], where $\delta l/l$ represents the anisotropy in the mean free path, only a fraction of 1% anisotropy is sufficient to produce the observed A phase width. The inhomogeneity of the local anisotropy over length scales larger than ξ_0 naturally results in the coexistence of the A and B phase.

A PCP where three phases merge, as in the case of superfluid ^{3}He, should have at least one first order branch.[26,27] When this branch separates two highly competing phases with distinct symmetry, the PCP is not robust against the presence of disorder. In general, the coupling of disorder to the distinct order parameters will produce different free energy contributions for each phase. Consequently, a strong influence on the PCP is expected under these

circumstances.[28] It is possible that the PCP vanishes in response to disorder (as it does in response to a magnetic field) and a region of coexistence emerges. An experiment on ^{3}He—^{4}He mixtures in high porosity aerogel reported a similar disappearance of the PCP.[29] Strikingly similar phenomena have also been observed in mixed-valent manganites where the structural disorder introduced by chemical pressure produces the coexistence of two highly competing phases (charge ordered and ferromagnetic phases) separated by a first-order transition.[30,31] A growing body of evidence suggests that the coexistence of the two phases is of fundamental importance in understanding the unusual colossal magnetoresistance in this material.

Considering the energy scales involved in the *A*-*B* transition and anisotropy, it is not surprising to see a difference in the details of the *A*-*B* transition in aerogel samples even with the same porosity. However, it is important to understand the role of anisotropic scattering. We propose that the effect of anisotropic scattering can be investigated in a systematic manner, at least in aerogel, by introducing controlled uniaxial stress, which would generate global anisotropy in addition to the local anisotropy.

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