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Stability of the axial phase of superfluid ^{3}He in aerogel with globally anisotropic scattering

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It has been suggested that anisotropic quasiparticle scattering will stabilize anisotropic phases of superfluid ^{3}He contained within a highly porous silica aerogel. For example, global anisotropy introduced via uniaxial compression of aerogel might stabilize the axial state, which is called the *A*-phase in bulk superfluid ^{3}He. Here, we present measurements of the phase diagram of superfluid ^{3}He in a 98% porous silica aerogel by using transverse acoustic impedance methods. We show that uniaxial compression of the aerogel by 17% does not stabilize an axial phase.

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When disorder is introduced into superfluid ^{3}He by way of high porosity silica aerogel, a metastable *A*-like phase appears on cooling.[1–4] This phase is thought to be like the *A* phase in bulk superfluid ^{3}He, which is known to be the axial *p*-wave state. At sufficiently low temperatures, this metastable phase undergoes a transition to an isotropic superfluid phase similar to the isotropic state observed in bulk ^{3}He, which is the *B* phase. However, a distinct transition from the *B*-like phase to the *A*-like phase in aerogel is not seen upon warming. Tracking experiments[3–6] have shown that coexistence of *A*-like and *B*-like phases occurs in a narrow window of temperature, $\approx 20-50\ \mu$K, near the normal-to-superfluid transition temperature in aerogel, T_{ca}. This is contrary to the expectation that the *B* phase should be stable at all pressures and temperatures if the disorder introduced is homogenous and the scattering is isotropic.[7] On the other hand, it has been predicted that scattering anisotropy from the strands of aerogel might destabilize the *B*-like phase in favor of the *A*-like phase.[7]

Pursuing this idea, Vicente *et al.*[6] suggested that the introduction of *global* anisotropy into aerogel, for example, by uniaxial strain, might increase the stability of the *A*-like phase. Recent calculations[8] have shown that uniaxial anisotropy (achieved, for example, by compression along one axis) should stabilize the axial state, whereas radial anisotropy (radially compressed or radially reduced by preferential shrinkage during growth) might stabilize the polar state. Our previous results[9] for ^{3}He in aerogel with preferential radial shrinkage suggest a phase with increased stability, but the aerogel was not rigidly adhered to the transducer surface so there is some question as to whether or not this was an effect intrinsic to superfluid ^{3}He in aerogel. In this Rapid Communication, we present our measurements of the phase diagram for superfluid ^{3}He in a sample of 98% porosity silica aerogel directly grown on the surface of a transducer and then subjected to uniaxial strain of 17%.

We used transverse acoustic impedance measurements[2,3,9] at the third harmonic (17.6 MHz) of an *AC*-cut quartz piezoelectric transducer, which is 0.84 cm in diameter. The impedance was measured by using a frequency modulated rf bridge, which is described elsewhere.[14] It has been shown[2,3] that for aerogel directly grown onto the transducer surface, the measured impedance is sensitive to all phase transitions through coupling of the shear transducer to the superfluid and is coincident with transitions in the interior of the aerogel. We grew our aerogel sample in the open space between two parallel transducers separated by two spacer wires, 0.0305 cm diameter, held under tension from a stainless steel spring (Fig. 1). Two additional spacer wires of smaller diameter, 0.0254 cm, were placed alongside and between the larger ones before aerogel was grown to fill the entire assembly.

The aerogel was synthesized at Northwestern University via a one-step sol-gel process followed by supercritical drying.[15] The density was controlled by the ratio of the reactants during the synthesis and was measured after drying to be 97.8% porous. After drying, the excess aerogel was removed, leaving only the aerogel between the two parallel transducers such that their outer surfaces could be exposed to bulk ^{3}He. Next, the 0.0305 cm diameter spacers were removed, maintaining tension with the spring, such that the aerogel was compressed to 0.0254 cm, giving 17% uniaxial strain. This amount of compression was shown by Pollanen *et al.*[15] to result in global anisotropy on the length scale of the correlation length of aerogel, ≈20 nm, causing minimal plastic deformation, as measured by small angle x-ray scattering (SAXS). Additionally, Pollanen *et al.* have used optical birefringence measurements to demonstrate that this method of uniformly imposing strain transmits anisotropy from macroscopic length scales to the microscopic scale probed by SAXS. Samples of the aerogel removed from the assembly region, adjacent to the acoustic sample, were also characterized by using optical birefringence techniques[15] to ensure that, before compression, our aerogel sample was isotropic and homogeneous. After compression, optical birefringence confirmed that the aerogel sample was uniaxially strained.

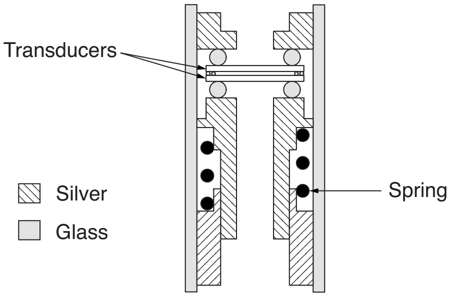

FIG. 1. Assembly diagram for the support structure that allows the aerogel to be directly grown between two quartz transducers and then compressed *in situ*. After aerogel growth and compression, a glass sleeve on the outside of the assembly was epoxied in place.

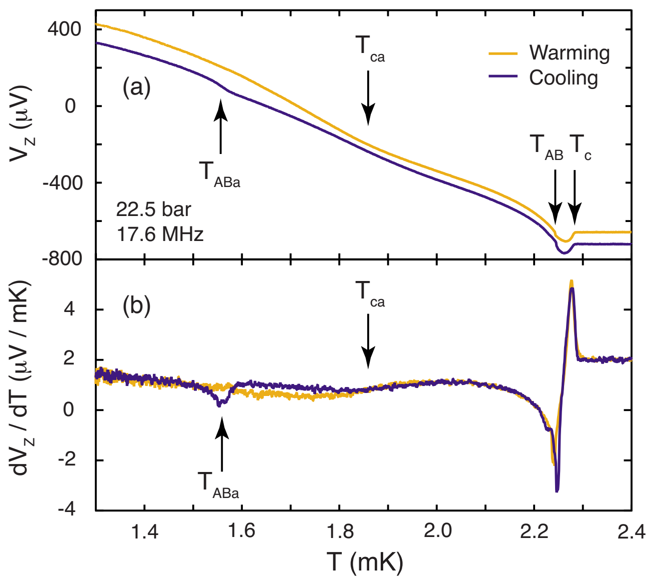

FIG. 2. (Color online) Transverse acoustic impedance measurements, V_z, as a function of temperature at 22.5 bar. (a) The bulk superfluid transitions are T_c and T_{AB} and are very distinct. The aerogel phase transitions, T_{ca} and T_{ABa}, are more spread out but are easier to identify in the derivative of acoustic response with respect to temperature in (b). Note that the warming and cooling trace do not match up in the temperature interval between T_{ca} and T_{ABa}. On cooling, this region corresponds to the supercooled *A*-like phase, whereas on warming, this corresponds to the *B*-like phase.

The aerogel sample and experimental assembly were cooled in liquid ^{3}He by using a dilution refrigerator, followed by adiabatic nuclear demagnetization.[14] A superconducting quantum interference device based paramagnetic salt lanthanum-diluted cerium magnesium nitrate (LCMN) thermometer was used,[14] which is calibrated from the Greywall temperature scale[16] by using bulk superfluid ^{3}He transitions that were easily identified in the acoustic response, V_z [Fig. 2(a)]. We determined the temperature of the aerogel phase transitions by taking the derivative of the acoustic response with respect to the temperature [Fig. 2(b)]. The transition temperature from normal-to-superfluid in aerogel is best indicated by the point of separation of the warming and cooling traces, as shown in Fig. 2(b). Transitions from the *A*-like phase to the *B*-like phase are seen upon cooling, appearing as a dip in the derivative trace. No such transition is seen on warming. Similar signatures of these phase transitions have been previously reported for isotropic aerogel.[2,3]

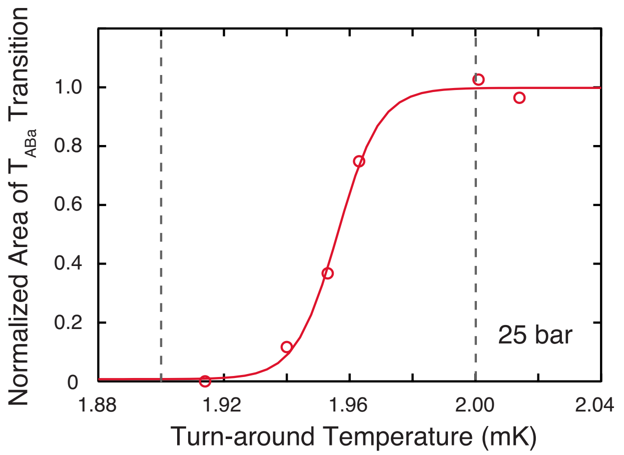

FIG. 3. (Color online) The normalized area of the dip in the dV_Z/dT versus T trace, such as shown in Fig. 2(b), at 25 bar. The transition width is approximately 40 μK, which is similar to that of uncompressed aerogel. (Refs. 3 and 6) The dashed vertical lines are our estimate of the precision with which we can independently identify T_{ca}, which overlaps the coexistence region of *A*-like and *B*-like phases.

Gervais *et al.*[3] and Vicente *et al.*[6] performed tracking experiments by warming up close to, but not through, the aerogel superfluid transition temperature T_{ca}. After stopping at a "turnaround" temperature, the samples were then cooled again to look for an *A*-like to *B*-like transition. In this way, it is possible to find the warming transition and how close the turnaround temperature must be to the critical temperature T_{ca} to observe it. The magnitude of the impedance change is a measure of the amount of superfluid undergoing the *A*-like to *B*-like transition. We performed these tracking experiments at 25 bar in order to determine the window of coexistence of *A*-like and *B*-like phases in uniaxially compressed aerogel. We integrated the area of the dip in the derivative of the acoustic response with temperature and plot this as a function of the turnaround temperature in Fig. 3 at 25 bar. The coexistence region is ≈40 μK, which, to within our precision, is within 50 μK of T_{ca} similar to that reported earlier[3,6] for nominally isotropic aerogel.

In Fig. 4, we show the superfluid transitions, T_{ca}, as well as the amount of supercooling in our uniaxially compressed

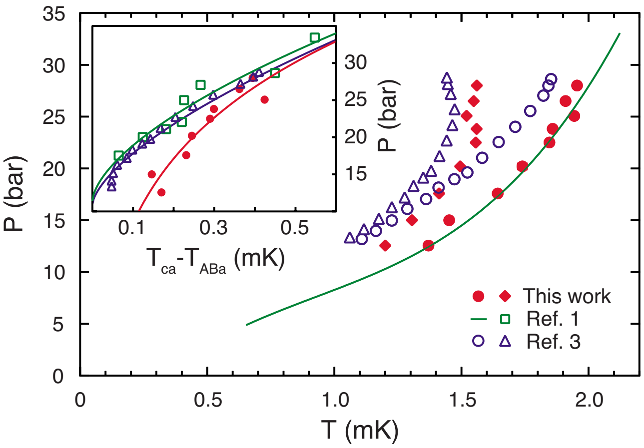

FIG. 4. (Color online) Pressure versus temperature phase diagram for 17% uniaxially compressed aerogel (filled red symbols). Both the aerogel superfluid transition temperature and the extent of supercooling of the *A*-like phase are similar to previous results with uncompressed aerogel: Gervais *et al.* (Ref. 2) (green curve and squares) and Nazaretski *et al.* (Ref. 4) (open blue symbols). Inset: The difference between the temperatures for the aerogel normal-to-superfluid transition T_{ca} and the supercooled *A*-like to *B*-like T_{ABa} transitions as a function of pressure. Note that there is more supercooling in the compressed aerogel at low pressures than in previous work on uncompressed samples. Curves in the inset are guides to the eyes.

aerogel compared to that of Gervais *et al.*[2,3] and Nazaretski *et al.*[4] The similarity is striking given the significant amount of global anisotropy in our sample. The only apparent difference between our results on axially compressed aerogel and previous work is the increase in the supercooling of the *A*-like phase at pressures below 20 bar. This does not directly bear on the stability of the *A*-like phase but suggests that the mechanism for nucleation of the *B* phase is suppressed at lower pressures for uniaxially anisotropic aerogel. We have also found that the signature of the *A*-like to *B*-like transition becomes smaller as the pressure is decreased until it becomes difficult to measure below 12 bar. Although we find that uniaxial compression of the aerogel does not enhance phase stability, nonetheless we note that there are recent reports that the orientation of the superfluid order parameter can be influenced by anisotropy.[10–13]

In summary, we find that the introduction of global anisotropy from uniaxial compression of 17% does not stabilize the *A*-like phase of superfluid ^{3}He in aerogel, which is in contrast to various suggestions.[6,8] The region of coexistence of the *A*-like and *B*-like phases is approximately 40 μK and indistinguishably close to the normal-to-superfluid transition, which is nearly the same as that previously measured in uncompressed aerogel.[3,6] Consequently, it appears that uniaxial strain does not stabilize an *A*-like phase or for that matter any phase, in aerogel. The pressure versus temperature phase diagram is remarkably similar to uncompressed aerogel, except for increased supercooling at low pressures in the range of 12–20 bar.

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