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Superfluid Helium Three in Aerogel

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We report measurements of the superfluid density and transition temperature of ^{3}He confined within 98.2% open aerogel. Both the superfluid fraction and the temperature at which the superfluid is manifested are suppressed strongly from their bulk values. The results suggest that the aerogel reduces the order parameter by a mechanism other than as a diffusely scattering surface.

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1. INTRODUCTION

The structure of aerogel is significantly different from any of the porous media or confined geometries used to study ^{3}He in the past. Aerogels are dilute networks of randomly interconnected thin strands of silica,[1] where the strands resemble strings of beads. The typical strand/bead diameter is thought to be on the order of 50Å. This is smaller than the zero temperature coherence length of ^{3}He, ξ_0, which ranges from ~200Å at high pressure to ~800Å at low pressure. Small angle X-ray scattering experiments and vapour pressure measurements indicate a broad distribution of strand separations ranging from 25Å to nearly 1000Å,[2–4] so that despite it's significant open volume the strands are so closely spaced that almost the entire volume is within a few hundred Angstroms of the silica structure. This geometry, where there are no well defined pores with "walls", is clearly different from that of packed powders, cylindrical channels or parallel plates and films. In this paper we report measurements of superfluid ^{3}He in aerogel which show striking differences from both the behavior of bulk ^{3}He and ^{3}He confined within other structures.

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2. EXPERIMENTAL CONSIDERATIONS

In this experiment we used standard torsional oscillator techniques[5] to measure the superfluid density. We constructed a torsion pendulum (resonant frequency ~ 943 Hz) containing 0.29 cm^3 of 98.2% open aerogel. The ^{3}He used was purified to reduce the ^{4}He content to below 10 ppm, which corresponds to less than 0.001 monolayers. Since the viscous penetration depth δ in ^{3}He is large compared with the strand spacing ($\delta \sim 300$ μm at 2 mK), all the normal fluid is coupled to the oscillator. Experiments with pure ^{4}He in this cell show that only 1% of the fully developed ^{4}He superfluid was not de-coupled from the oscillator.

The superfluid density, ρ_s, is proportional to the period shift ΔP below the superfluid transition. In order to avoid any pressure dependences of the torsion constant, the sensitivity of the oscillator was callibrated using the fill signal at 0 bar, which gives $\rho_s = 0.071$ g/cc-μs ΔP. The superfluid fraction at each pressure, ρ_s/ρ, is obtained by dividing ρ_s by the total density of the bulk fluid at each pressure. Signal from bulk ^{3}He was minimal since open volumes had been eliminated by growing the aerogel directly into the oscillator. A lanthanum diluted cerous magnesium ac susceptibility thermometer, calibrated against the ^{3}He melting curve,[6] was used for thermometry.

3. RESULTS

We have measured[7] the ^{3}He superfluid fraction for pressures ranging from 3.5 bar to 29 bar. The transition temperature and superfluid fraction are strongly suppressed from the bulk value. This can be seen clearly in Fig. 1 and Fig. 2. At the highest pressures, the superfluid fraction, ρ_s/ρ only reaches 35% of the bulk low temperature value, and at pressures below ~3 bar the superfluid fraction is completely suppressed. The transition temperatures, T_{ca}, are ~90% the bulk T_c at high pressures and ~50% the bulk value at low pressures.

There are several striking features of this data that are worth emphasizing. First, the transition is quite sharp (see the inset to Fig. 1), despite the broad range of strand spacings in the aerogel. This is in contrast to what one would expect if the aerogel acted as a boundary scatterer. In such a surface scattering system the superfluid suppression is controlled locally by the relative size of the bulk superfluid coherence length, $\xi(T)$, compared to the length scale of the scattering boundaries.[8,9] A broad range of spacings would imply a range of local T_c suppressions, which would show up as a smeared transition. In parallel plate geometries, for example, geometrical variations of ~3% produce significantly more rounding of T_c (~5%) than is seen in aerogel, especially at low pressure.[10] We find that we can define T_{ca}

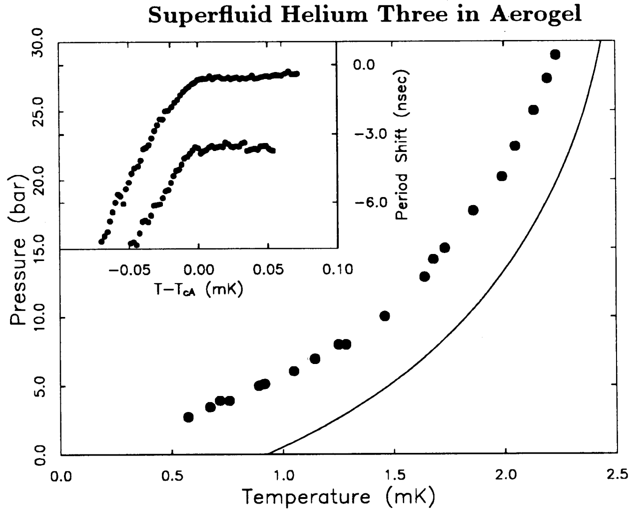

Fig. 1. The superfluid transition temperature at various pressures. Below 2.7 bar no superfluid was detected. T_{ca} was obtained from plots of period vs. temperature, as shown in the inset for 3.4 and 15 bar. T_{ca} can be identified to better than 1% in temperature.

to within 1%.

We can further discount surface scattering suppression by looking at the dependence of T_{ca} on $\xi(T)$. If the superfluid were suppressed by surface scattering, then for a fixed geometry one would expect the transition to occur at fixed values of $\xi(T)$. In the inset to Fig. 3 we plot $\xi(T_{ca})$ at various pressures against the reduced bulk temperature. Clearly the value of the bulk coherence length at which superfluidity is manifested at different pressures is not constant but varies between 610Å at low pressures and 350Å at high pressures, which is different from other confined geometries that have been studied.

An unexpected but exciting discovery was the presence of resonances which are accompanied by dramatic increases in dissipation. These resonances signal the crossing of a temperature dependent hydrodynamic mode of the fluid in the cell with the nearly fixed frequency of the oscillator. These sound modes have relatively low speeds ($<$ 15 m/s, as compared to the first sound speed ^{3}He, which is $\sim$ 250 m/s), and the speeds tend to zero as T_{ca} is approached. We never see any resonance crossings above T_{ca}. We believe these modes are similar to superfluid modes seen in ^{4}He in aerogel,[11,12] where the helium and compliant aerogel move together and are not coupled to the superfluid component. In any case, the sound modes could make an interesting probe of superfluidity in this system.

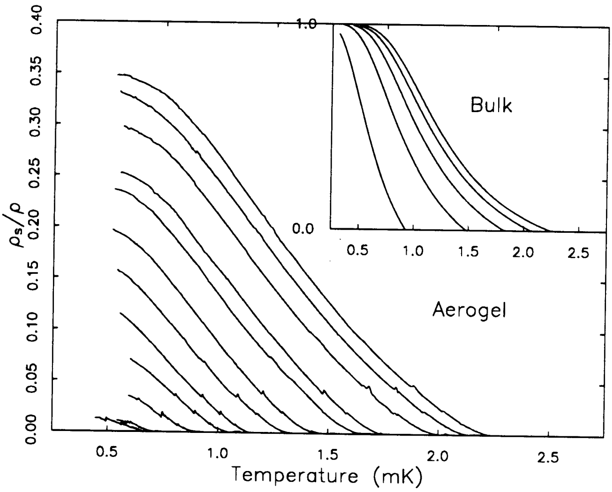

Fig. 2. The superfluid fraction, ρ_s/ρ, at various pressures as a function of temperature. The curves correspond to, from left to right, 3.4, 4.0, 5.0, 6.1, 7.0, 8.5, 10, 13, 15, 20, 25 and 29 bar. The inset shows ρ_s/ρ in the bulk for 0, 5, 10, 15, and 20 bar over the same temperature range.

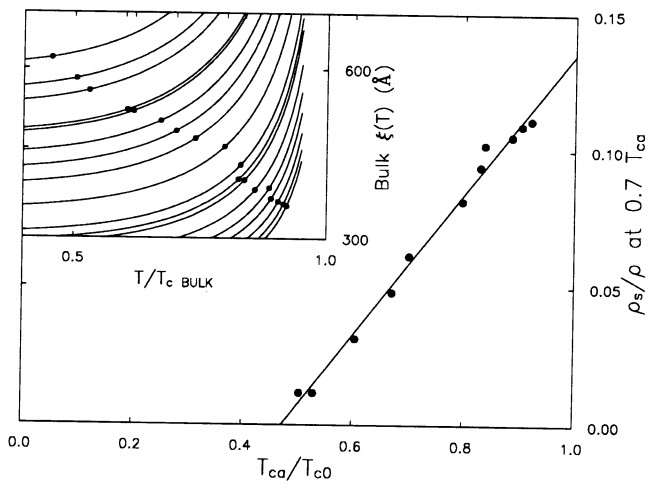

Fig. 3. ρ_s/ρ at 70% of T_{ca} versus T_{ca}/T_{c0}. ρ_s vanishes for pressures below $\sim$ 2.7 bar. The inset shows the bulk temperature dependent coherence length. The coherence length at the aerogel transition, T_{ca}/T_{c0}, is shown at each pressure. The value of $\xi(T_{ca})$ for which superfluidity is manifest ranges from $\sim 600\mathring{A}$ at low pressures to $\sim 350\mathring{A}$ at high pressures.

Having discounted the standard boundary scattering description, there are still some interesting properties of the data that must be accounted for by any model for this system. The superfluid fraction, ρ_s/ρ vanishes with decreasing pressure before T_{ca} does. This can be seen in Fig. 3. We have not seen any superfluid below about 2.7 bar down to a temperature of 0.4 mK. Also, we find that the amount of T_c suppression is roughly proportional to $v_f{}^2/T_{c0}{}^2$, $(1 - T_{ca}/T_c) \propto v_f{}^2/T_{c0}{}^2$.

The temperature dependence of the superfluid differs significantly from the bulk. First, ρ_s/ρ doesn't scale with T_c, as in the bulk. The inset to figure 2 shows the bulk superfluid over the same temperature and pressure range as the aerogel data. In accordance with a Ginzberg-Landau description of ^{3}He, the initial slope of the bulk ρ_s/ρ at each pressure scales roughly with T_{c0}. In aerogel, however, the functional form of the temperature dependence of the superfluid seems almost entirely independent of T_{ca} or T_{c0}. Basically, the bulk superfluid fraction data at all pressures collapses roughly to a single curve when plotted versus $(T - T_c)/T_c$, whereas plotting the superfluid in aerogel as a function of only $T - T_{ca}$ makes the data look the same. In addition, the superfluid does not develop linearly with decreasing temperature as in the bulk. In Fig. 4 we plot the log of ρ_s/ρ versus the log of $T - T_{ca}$. The superfluid's temperature dependence in aerogel is given over a wide range of temperatures by $C(T - T_{ca})^n$, where $n \sim 1.5$, which is appreciably different from the linear behavior of the bulk. This power law behavior extends to nearly within 0.01 mK of the transition.

To summarize, we have observed the strong suppression of the superfluid fraction and the transition temperature of ^{3}He that fills the open volume of 98.2% aerogel. The superfluid transition is well defined, and uncharacteristic of other transitions observed in systems where ^{3}He is confined to pores. The conventional model whereby boundary scattering reduces the superfluid fraction and transition temperature does not explain the observed behavior since we find that the superfluid transition is not manifested at a constant value of the coherence length. Planned experiments on lower density aerogels as well as studies of the effect of surface ^{4}He are likely to provide additional constraints to any model.

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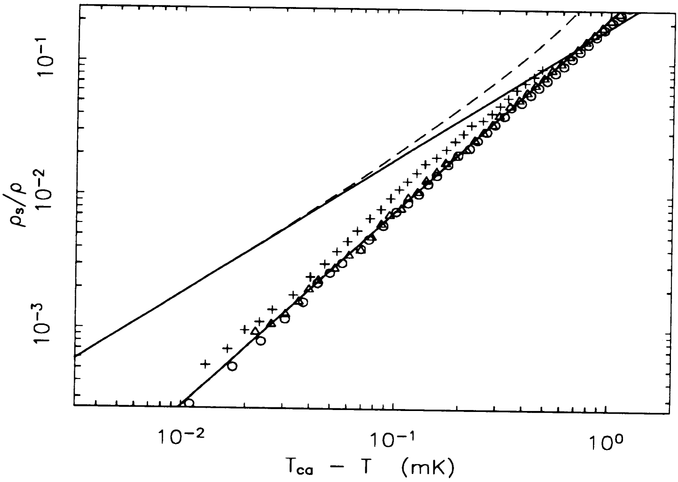

Fig. 4. We plot the superfluid fraction ρ_s/ρ against the temperature below the transition, T_{ca}-T for several pressures. The dashed line is the bulk ρ_s/ρ at 20.5 bar, and the points are for aerogel at 8.5, 20.2 and 29.0 bar, (crosses, triangles and circles). The two straight line fits correspond to exponents of 1 for bulk and 1.46 for aerogel. The coefficient C (see the text) is approximately the same for all pressures in aerogel.

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