Superfluid ^{3}He in Aerogel

J. V. Porto and J. M. Parpia
Laboratory of Atomic and Solid State Physics, Cornell University, Ithaca, New York 14853-2501
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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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In ^{4}He the nature of aerogels as a quenched impurity has been shown to exert a profound effect on the character of the superfluid phase transition [1]. Recent results on ^{3}He-^{4}He mixtures reveal a striking modification of the phase diagram of helium mixtures in aerogel [2], indicating the possible coexistence of ^{4}He and ^{3}He superfluids. In order to explore this possibility, we undertook a study of pure ^{3}He in aerogel. In this paper we report on the behavior of pure ^{3}He confined in 98.2% open silica aerogel.

Aerogels are very dilute networks of randomly interconnected thin strands of silica [3]. The typical strand diameter is thought to be on the order of 50 Å. Small angle x-ray scattering experiments together with vapor pressure measurements have been interpreted as showing a broad distribution of strand separations ranging from 25 to nearly 1000 Å [4–6]. The open geometry together with the small diameter of the strands make aerogel distinct from other substrates or materials for the study of the confinement of ^{3}He.

To explore superfluidity of pure ^{3}He in this medium 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 monolayer. Since the viscous penetration depth δ in ^{3}He is so 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 decoupled 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 calibrated using the fill signal at 0 bar, which gives $\rho_s = 0.071$ g/cm^3 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 melting curve [7], was used for thermometry.

The superfluid fraction is plotted in Fig. 1 against the temperature. There are several noteworthy features. First, the transition temperature of the ^{3}He in aerogel, T_{ca}, is strongly suppressed from its bulk value, T_{c0} (see Fig. 2). A close examination of the period shift data shows that there is no superfluid signal at the level of 0.1% for temperatures above T_{ca}, even at a temperature well below T_{c0}. (This also confirms that there is no connected bulk volume in our cell.) Also, the transition is well defined despite the broad range of spaces between strands. The inset of Fig. 2 shows the period shift data for a narrow region of temperature for two of the pressures studied to date. Clearly T_{ca} can be identified with an uncertainty less than 1%. As will be discussed later, this is unlike the behavior of ^{3}He confined between parallel plates, and strikingly different from what one would expect given the large range of sizes within aerogel.

The superfluid density is also suppressed by a substantial amount, and has a pronounced pressure dependence. Below 2.4 bars no superfluid was detected down to the lowest temperatures of 0.39 mK, and at 28.5 bars the superfluid density is 35% of the bulk value. The develop-

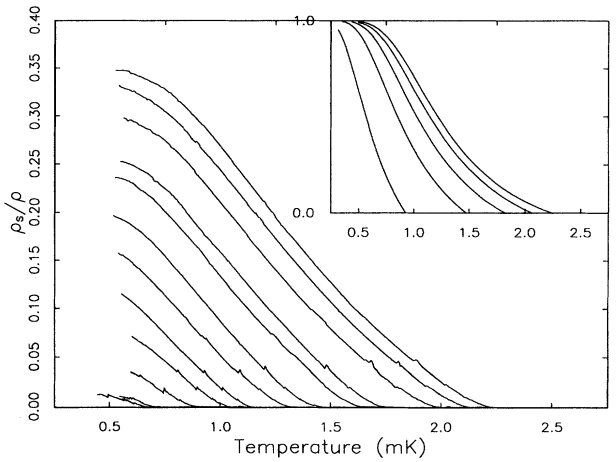

FIG. 1. The superfluid fraction, ρ_s/ρ, at various pressures as a function of temperature. The curves correspond to, from left to right, 3.4, 4.0, 5.0, 6.1, 7.0, 8.5, 10, 13, 15, 20, 25, and 29 bars. The inset shows ρ_s/ρ in the bulk for 0, 5, 10, 15, and 20 bars over the same temperature range.

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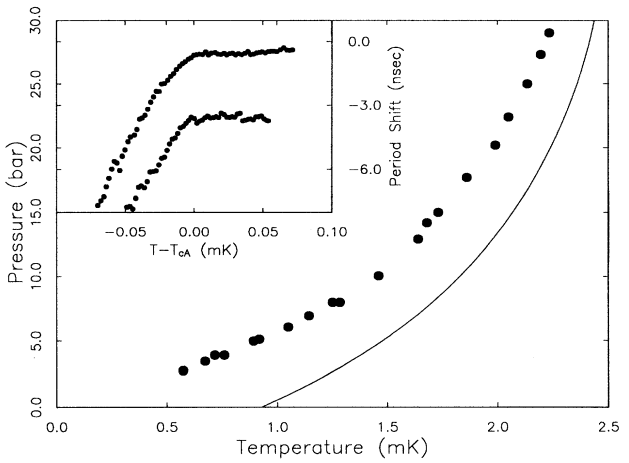

FIG. 2. The superfluid transition temperature at various pressures. Below 2.7 bars no superfluid was detected. T_{ca} was obtained from plots of period vs temperature, as shown in the inset for 3.4 and 15 bars. T_{ca} can be identified to better than 1% in temperature.

ment of the superfluid fraction with temperature is quite different from that of the bulk superfluid [8] as can be seen from the inset of Fig. 1. In bulk, the initial slope of ρ_s/ρ with temperature scales as T_{c0}, so that the curves of ρ_s/ρ vs temperature are steeper at lower pressure than at higher pressure by a factor of ~2.5. In contrast, the slopes of ρ_s/ρ in aerogel are independent of pressure and T_{ca}, except perhaps at the lowest pressures. It also appears that the superfluid fraction vanishes at low pressure before T_{ca} goes to zero.

In all of our superfluid data we note the presence of resonances, which are accompanied by dramatic increases in dissipation. These resonances signal the crossing of a temperature dependent "slow" mode of the fluid in the cell with the nearly fixed frequency of the oscillator [9,10]. These sound modes have relatively low speeds (<15 m/s, as compared to the first sound speed of ~250 m/s), and the speeds tend to zero as T_{ca} is approached. We never see any resonance crossings above T_{ca}. These sound modes taken together with the torsional oscillator data strongly suggest that there is no superfluid in the temperature interval between T_{c0} (the bulk superfluid transition temperature) and T_{ca}.

To understand why the behavior of the superfluid transition is surprising, one must reexamine the behavior of ^{3}He confined in other restricted geometries [11–13], where the behavior of ^{3}He has been interpreted in terms of a "healing length." Diffuse scattering of ^{3}He quasiparticles suppresses superfluidity within a distance of roughly one coherence length, $\xi(T)$, of a surface [14]. The coherence length is given by [15]

$$\xi(T) = \frac{\hbar v_F}{\pi \Delta(T)},$$

where $\Delta(T)$ is the temperature dependent gap, and near T_c this diverges as $(1 - T/T_c)^{-1/2}$. If the ^{3}He is confined within a pore or between parallel plates, superfluidity will be suppressed until $\xi(T)$ decreases to less than the pore radius or plate separation [16].

In previous porous media experiments the medium was modeled as a collection of cylindrical pores having a broad distribution of sizes and corresponding T_c's. In this model the superfluid signal from each of the different pores (each with its own temperature dependence) is summed over the distribution of pore sizes to produce the total superfluid signal. The superfluid fraction measured in a flow experiment (such as a torsional oscillator) is further reduced by a temperature dependent tortuosity factor, which arises because small pores connecting larger pores will not admit superflow close to the transition. Because of the broad range of sizes in the porous media, only a weak suppression from the bulk T_c is observed [11,12]. The superfluid fraction may be strongly suppressed, however, due to the large tortuosity correction imposed by the narrow channels in the medium. In any event, the superfluid fraction reflects the temperature dependence of the coherence length, and the healing length approach has been successful in explaining most of the behavior of ^{3}He in porous media.

In well defined geometries such as parallel plates [13] one can readily observe the suppression of T_c, but the superfluid onset is sensitive to the distribution of plate separations. In the work of Freeman, for example, geometrical variations of ~3% produce significantly more rounding of T_c (~5%) than is seen in aerogel, especially at low pressure. In addition, with such restricted geometries that have a narrow range of sizes, the T_c suppression is governed by the coherence length $\xi(T)$. Consequently the onset of superflow for all pressures occurs at fixed $\xi(T)$, for a given plate spacing.

Despite the aerogel's significant open volume, the strands are so closely spaced that almost the entire volume is within a few hundred angstroms of a strand. If the aerogel strands did act as surface scatterers, suppressing the superfluid over roughly a coherence length, then one would not expect to see superfluidity at all. In addition, in both random porous media and in the case of relatively well characterized parallel plate geometries with narrow size distributions, the behavior of the superfluid reflects the temperature and pressure dependence of the coherence length. This is not the case for ^{3}He in aerogel. For comparison, we plot $\xi(T_{ca})$ at various pressures against the reduced bulk temperature (Fig. 3). Clearly the value of the bulk coherence length at which the superfluidity is manifested at different pressures is not constant but varies between 610 at low pressures and 350 Å at high pressures. The existence of superfluidity, together with the pressure dependence of $\xi(T_{ca})$, argue against a purely healing length mechanism for the suppression of the superfluid.

We can put forward two other hypotheses to address the observed behavior. The first is that the ρ_s/ρ *is* locally governed by the strand density, and that the regions of low strand density, which become superfluid nearer

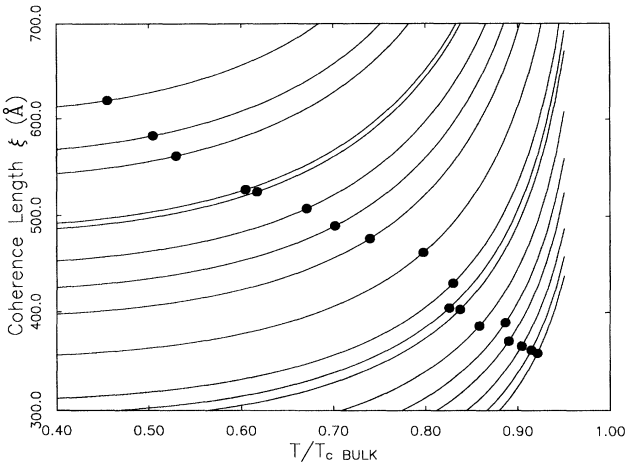

FIG. 3. The bulk temperature dependent coherence length for all the pressures at which we have observed a superfluid transition, plotted against the reduced temperature T/T_{c0}. The bulk coherence length at T_{ca}/T_{c0}, the reduced transition temperature in aerogel, is shown at each pressure. It is readily evident that the superfluidity is not manifested at a fixed value of the bulk $\xi(T)$, since the value of $\xi(T_{ca})$ ranges from ~600 at low pressures to ~350 Å at high pressures.

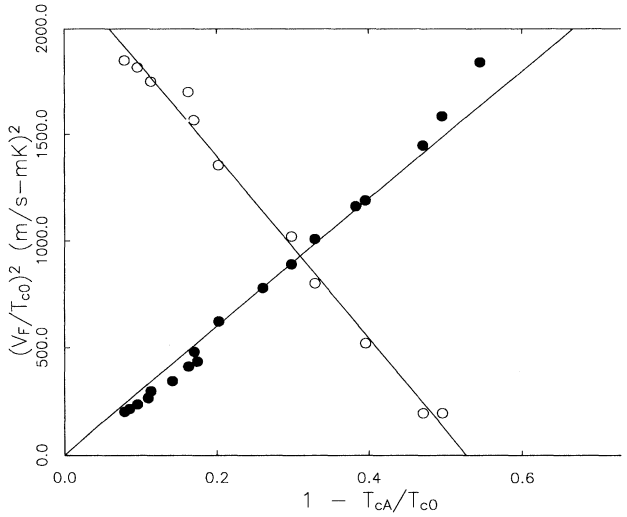

FIG. 4. We plot the linear reduction of the superfluid transition temperature as with v_F^2/T_{c0}^2 (closed circles). We also plot the value of the superfluid density measured at $0.7T_{ca}$ against T_{ca}/T_{c0} (open circles). The superfluid fraction appears to vanish at a finite transition temperature.

to T_{c0}, are not macroscopically connected. Then the flow would be controlled by the connections between isolated regions of superfluid, and these connections would become superfluid at a reduced temperature. This would be in keeping with the large distribution of strand spacings in the aerogel and would account for the apparent vanishing of ρ_s with decreasing pressure before T_{ca} vanishes. However, the fact that the onset temperature does not occur at a fixed value of the coherence length would imply either that the temperature dependence of $\xi(T)$ is altered or that the actual thermodynamic T_c is shifted from the bulk value. This hypothesis is further discounted by the NMR results of Sprague and Halperin [17] which will be discussed below. The second possibility is that the aerogel strands function as impurities. The aerogel is so dilute (<2% of the open volume) and strand diameter so small (less than the zero temperature coherence length at all pressures) that its role as an impurity is plausible. Impurities would suppress pairing so that the entire system would undergo a thermodynamic transition at a reduced but still sharp T_c [18]. If this hypothesis is correct, then superfluid ^{3}He in aerogel is the first system to show impurity induced modification of a p-wave BCS state.

As an aid to the development of models, we have examined the behavior of both the superfluid transition temperature and ρ_s/ρ as the pressure was varied. Since the pressure is not a particularly useful parameter, we have focused our attention on the pressure dependent quantities T_{c0} and v_F. We find that the suppression of the transition temperature, $1 - T_{ca}/T_{c0}$, depends linearly on v_F^2/T_{c0}^2, so that the bulk transition temperature is nearly recovered at higher T_{c0}. In addition, we find that ρ_s/ρ at any fixed reduced temperature decreases linearly with $1 - T_{ca}/T_{c0}$, and it appears to vanish at a finite value of T_{ca}/T_{c0}. Both of these results are plotted in Fig. 4. Near T_{c0}, ρ_s/ρ in bulk increases linearly in temperature. In Fig. 5 we show a log-log plot of ρ_s/ρ in ^{3}He in aerogel as a function of temperature. The superfluid's temperature dependence is given by $C(T_{ca} - T)^n$, where $n \sim 1.5$, appreciably different from the linear behavior of the bulk. In addition, in aerogel the prefactor, C, is

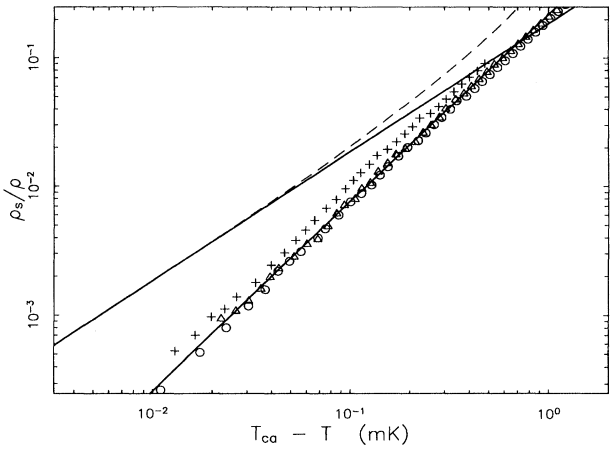

FIG. 5. We plot the superfluid fraction ρ_s/ρ against the temperature below the transition, $T_{ca} - T$ for several pressures. The dashed line is the bulk ρ_s/ρ at 20.5 bars, and the points are for aerogel at 8.5, 20.2, and 29.0 bars (crosses, triangles, and circles). The two straight line fits correspond to exponents of 1 for bulk and 1.46 for aerogel. The coefficient C is approximately the same for all pressures in aerogel.

roughly the same for all pressures above 6 bars. This is also different from the bulk, where the initial slopes scale as T_{c0}.

This paper and the work to be published of the Northwestern University group [17], which used NMR as a probe of superfluidity, show similar characteristics for the behavior of ^{3}He in aerogel. While the observed transition temperatures are different, it is likely that the origin for those effects is a different sample density [19]. The characteristics that we have noted, namely the linear suppression of T_{ca}/T_{c0} with v_F^2/T_{c0}^2, the pressure dependence of $\xi(T_{ca})$, and the apparent vanishing of the superfluid fraction before T_{ca} disappears are present in the NMR signatures. Thus it is likely that this behavior has a common origin, strikingly different from that of the bulk B phase. In addition, the observation of a sharp frequency shift provides evidence for the absence of "local" superfluidity above T_{ca}. The absence of local superfluidity above T_{ca} argues against the first hypothesis that we advanced earlier in the paper.

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. In fact the sharpness is comparable or more pronounced than that observed for ^{3}He confined in an array of stacked plates. The conventional model based on the presence of boundary scattering and the consequent reduction of 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. While there are no published models that can be used to compare our result to those of a "dirty" superfluid, it is certainly plausible that the aerogel acts as an impurity. We have provided some simple empirical dependencies for the observed behavior that may serve for comparison of future models. 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 proposed model.

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