# Quantum Phase Transition of $^3$He in Aerogel at a Nonzero Pressure

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We present evidence for a nonzero pressure, $T = 0$ superfluid phase transition of $^3$He in 98.2% open aerogel. Unlike bulk $^3$He which is a superfluid at $T = 0$ at all pressures (densities) between zero and the melting pressure, $^3$He in aerogel is not superfluid unless the $^3$He density exceeds a critical value $\rho_c$. About 90% of the $^3$He added above $\rho_c$ contributes to the superfluid density. [S0031-9007(97)03585-0]

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The only known substance naturally free of impurities is the low temperature liquid phase of $^3$He which allows the study of Fermi superfluids in their purest forms. This self-purification of $^3$He has made it impossible to introduce disorder or impurities into the system. Experiments show that $^3$He superfluids in aerogel display behavior [1–3] very different from earlier studies in confined geometries where diffuse surface scattering that suppresses $T_c$ dominates [4] and the size distribution smears out the sharp magnetic and mechanical responses of the bulk [5,6,7]. It was generally believed that $p$-wave superfluids are easily damaged by disorder [8], but the newest experiments [1–3] show that notwithstanding the $T_c$ suppression, superfluid coherence remains robust in aerogel. However, the phase diagram is completely modified despite the small volume fraction occupied by the aerogel.

Aerogel is a tenuous random solid network of $SiO_2$ particles ($\approx$25 Å radii) with fractal correlations between 30 and 1000 Å [9]. Aerogels have very large surface areas and very low densities (22.9 $m^2/cm^3$ and 39.4 g/l, respectively, for our samples), and very dilute aerogels occupy less than a few percent of the volume. Despite the tenuous fractal structure, the mean distance from a point in the open volume to a silica strand can be 100 Å. Since the silica diameter is smaller than the superfluid coherence length ($\xi_0 = 150 - 800$ Å), the aerogel will not behave like a surface. Instead it acts more like a collection of impurities, thus allowing the study of impurity effects on strongly interacting Fermi liquids. This "impurity" view is supported by the fact that superfluid $^3$He in aerogel is coherent and homogeneous [2]. In many ways, the depairing effect of aerogel on the $p$-wave superfluid is similar to that of magnetic impurities on $s$-wave superconductors [10]. An aerogel concentration of $\sim$2% strongly suppresses $T_c$ [1,2]. The possibility that this strong suppression can result in a $T = 0$ phase transition and the very low temperature behavior of this system are the subject of this investigation.

To put our results which we present later in perspective, we first summarize recent experimental findings: (i) The superfluid behaves as a homogeneous fluid with sharp magnetic [2,3,11] and mechanical [1,11] responses. (ii) In magnetic fields of the order of 1 kG, the superfluid phase appears to be $A$-like [2]. Recent experiments [3] show that the superfluid behaves like the $B$-phase if the $^3$He on the surface of the aerogel is replaced with $^4$He. Experiments in Manchester [11] in much lower fields (50 G) show that the magnetic response of the $^3$He is $A$-like below 7.5 bars and $B$-like at higher pressure, displaying a reversal of the relative stability with pressure of the bulk $A$ and $B$ phases. (iii) The temperature dependence [1,11] of the superfluid density near $T_c[\rho_s/\rho \propto (1 - T/T_c)^{1.4}]$ cannot be described by the mean-field behavior as in the bulk. (iv) Even though the superfluid appears to be $A$-like, the lack of dipole restoring torque [2] for large angle tipping pulses cannot be explained by any homogeneous $p$-wave structure. (v) The transition temperature ($T_c$) is suppressed quadratically in relatively small magnetic fields [3].

In this paper, we report yet another distinct feature of $^3$He in aerogel—a quantum (normal to superfluid) phase transition (QPT) at a density above the zero pressure ($P = 0$) value. A quantum phase transition is a *continuous* phase transition at $T = 0$ that reflects the alteration of the ground state of the system brought about by a change of the parameters [12,13] (in this case, the density, $\rho$) of the system. This behavior is in contrast to bulk $^3$He, which is a superfluid for all densities at $T = 0$. In the new data (sample I) described in this Letter, we varied $P$ at a fixed low temperature, $T$, so that a superfluid signal could be observed above $P_c(T)$ [or above a critical density $\rho_c(T)$]. This allowed us to map out the low temperature portion of the phase diagram of $^3$He in aerogel. We compare this behavior to that of an earlier sample II which had an identical open volume (98.2%) but which may have had different correlations arising from differences in the growth $p$H [9,14]. We find that in sample I an extrapolation of the data shows that the system remains normal at $T = 0$ unless the $^3$He density exceeds a critical value $\rho_c(T = 0)$. For sample II, we were unable to observe $T_c$ for pressures below 2.7 bar and temperatures below 0.5 mK. The extrapolation of the $\rho_c(T > 0.5$ mK) data for $^3$He in sample II does not extend down sufficiently in temperature to unambiguously resolve whether or not there is a superfluid at $T = 0$ for all densities. The normal and superfluid densities

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($\rho_n$ and $\rho_s$) of these two samples behave completely differently as a function of density. In the following, we first describe the experiments leading to these results followed by a discussion of the implications of these data.

We use the period of a torsional oscillator (inset to Fig. 2 below) operated at its resonant frequency to measure the superfluid density. The oscillator head contains a sample of 98.2% open aerogel filled with liquid $^3$He. A small (5%) bulk superfluid sample is located immediately below the aerogel in this cell. All the normal fluid (both bulk and in the aerogel) is coupled by viscosity to the oscillator, so the period shift, $\Delta P$, below $T_c$ is proportional to the sum of the superfluid densities in the aerogel and the bulk. In the earlier experiments at Cornell [1] on sample II and at Northwestern [2,3], $T_c$ was observed by slowly warming at constant pressure. The transition temperature could not be observed below about 0.45 of $T_{c0}$ (the bulk $T_c$) because the period shift was too small at lower pressures and extinguished the $T_c$ signature in an experimentally accessible temperature range. A similar effect was noted in the NMR measurement [2] below about 0.65 of $T_{c0}$.

The period signal seen while warming at a fixed pressure is shown in Fig. 1. The $T_c$ for both bulk $^3$He and $^3$He in aerogel can be clearly seen. The superfluid fraction, $\rho_s/\rho$, shows many of the characteristics observed in our earlier study (see Fig. 1 of Ref. [1]), with a well defined $T_c$ for the $^3$He. We observe resonances near $T_c$, which we associate with a slow mode (first observed for $^4$He in aerogel [15]) similar to second sound and also seen in our earlier study. The presence of the bulk superfluid, while useful as a calibration of absolute temperature, makes it difficult to accurately determine the temperature dependence of the $^3$He superfluid density particularly at low pressures. The data clearly show that $\rho_s/\rho$ of $^3$He in aerogel diminishes at lower pressures and the presence of the bulk fluid is a detriment, since the additional period shift due to the signal from the aerogel becomes too small to fix $T_c$ accurately. We had to modify our experimental approach in order to explore the low temperature part of the phase diagram.

To proceed with the experiment we employed a technique used by Movshovich *et al.* [16] and varied the pressure at fixed temperature [17]. The superfluid density of the bulk $^3$He changes smoothly and any sharp features of the measured period with pressure must be due to the $^3$He in the aerogel. Below 0.3 of $T_{c0}$, the normal fraction of the bulk $^3$He is nearly pressure independent and is of the order of 4% [18]. As the pressure is increased, the contribution of the bulk $\rho_n$ to the period change between 6 and 14 bars is $<5$ ns and can be neglected. In the discussion that follows, we will designate the density of superfluid $^3$He *in aerogel* as $\rho_s$. The results of a pressure sweep at 0.295 mK for sample I is shown in Fig. 2(a).

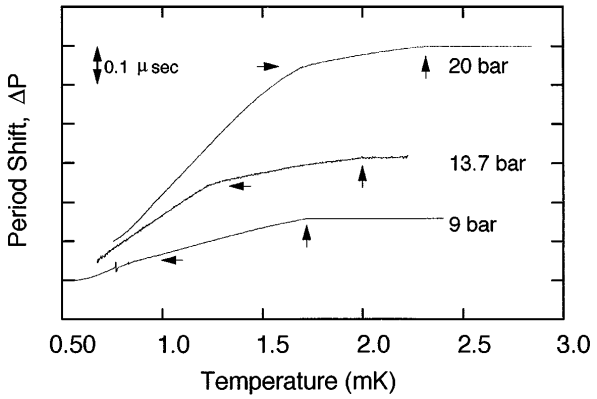


FIG. 1. Three data sets of period vs temperature obtained at 20, 13.7, and 9 bars. Vertical arrows indicate the onset of the bulk superfluid transition, $T_{c0}$, and horizontal arrows show the onset of $T_c$ of $^3$He in aerogel. The superfluid signal at 9 bars is nearly undetectable.

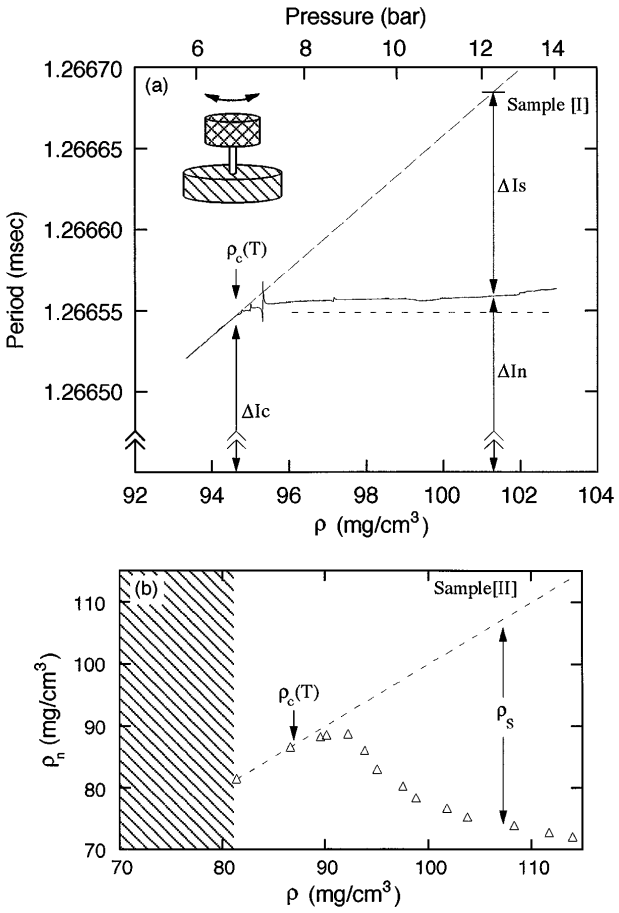


FIG. 2. (a) A pressure sweep from 14 to 5.6 bars for sample I at $T = 0.295$ mK. The dashed line represents the period for rigid body rotation. At $\rho_c(T)$, the measured period falls below the dashed line, signaling the onset of superfluidity. The measured period $\Delta I_n$ is directly proportional to the normal fluid density, whereas $\Delta I_s$ is directly proportional to the superfluid density. In this sample, $\Delta I_n > \Delta I_c$. In (b) we show a composite obtained from constant pressure runs between 0 and 29 bar for sample II at 0.5 mK. In this sample, $\rho_n$ falls below $\rho_c$ as the density is increased. The shaded region corresponds to the unphysical region of density below $P = 0$.

This data can be contrasted with a composite [Fig. 2(b)] assembled from runs at constant pressure from sample II at a higher temperature of 0.5 mK. The dashed lines that pass through the low density data in Figs. 2(a) and 2(b) represent the expected behavior if all the $^3$He in the aerogel were participating in rigid body rotation ("rigid body period"). At a critical density, $\rho_c$ (arrow), the signals of both samples stop increasing linearly and fall below the dashed line, signaling a *continuous* transition into the superfluid phase. The measured period shift is directly proportional to $\rho_n$, the density of the normal fluid in the aerogel. The superfluid density, $\rho_s$, is directly proportional to the difference between the observed period and the rigid body period [indicated as $\Delta I_S$ in Fig. 2(a) and $\rho_s$ in Fig. 2(b)].

By carrying out similar measurements at different temperatures below 0.93 mK, we obtain the low temperature portion of the phase boundary $P_c = P_c(T)$ for sample I represented as circles in Fig. 3. For higher temperatures the period shift has some contribution due to the bulk normal fluid, but below $T_{c0}$ this is a smooth function of temperature and the determination of $T_c$ in aerogel is unambiguous. Data from sample II (triangles in Fig. 3) are also shown for comparison. Extrapolation of the data show that the normal-superfluid phase boundary obtained with sample I intersects the pressure axis. Thus, a normal to superfluid transition at $T = 0$ at a nonzero pressure and the existence of a critical density $\rho_c(T = 0)$ for the onset of superfluidity are features of the sample I. The corresponding phase boundaries in the temperature-density plane are shown in the inset to Fig. 3. In this view, the very rapid drop in $T_c$ near $\rho_c(T = 0)$ reflects the flattening of the $P(T_c)$ phase diagram. On the other hand, it is ambiguous whether the phase boundary of sample II extrapolates to a $T = 0$ transition and a $\rho_c(T = 0)$. In fact, the behavior of sample II appears to be closer to that of the bulk than to sample I. The absence of $T = 0$ transition in sample II would imply that differences in the internal structures of these two identical density aerogels must result in the difference between their phase diagrams. It is known [9,14] that the microscopic correlations of aerogel structure can be very sensitive to the $p$H of the growth environment, and it is certainly plausible that the two aerogels differ in structure.

Another difference between samples I and II can be seen in Figs. 2(a) and 2(b). In sample I, for $\rho > \rho_c$ the period rapidly flattens and displays a small positive slope. This means that for sample I, $\rho_n$ is always above $\rho_c$. Moreover, if we plot $\rho_s$ against $\rho$ (Fig. 4), we find that $d\rho_s/d\rho = 0.9$ ($<1$) for a broad range of densities $\rho > \rho_c$ [19]. Consequently, about 90% of the $^3$He atoms added contribute to the $\rho_s$ in aerogel (Fig. 5). At higher temperatures, $\rho_s/(\rho - \rho_c)$ decreases so that, like $P_c(T)$ in Fig. 3, $d\rho_s/d\rho = 0.9$ is the limiting behavior as $T \to 0$. In contrast, $\rho_n$ of sample II [Fig. 2(b)] has a negative slope as density increases with $\rho_n$ falling below $\rho_c$. When we plot $\rho_s$ vs $\rho$, we find $d\rho_s/d\rho = 1.6$ ($>1$) (Fig. 4) so that a fraction of $\rho < \rho_c$ must contribute to $\rho_s$ as mass is added above $\rho_c$. For sample I the superfluid fraction above the critical density, $\rho_s/(\rho - \rho_c)$, is shown in Fig. 5. The result is obtained from the ratio of the inertia decoupled from the pendulum ($\Delta \mathbf{I}_s$) to the inertia of the fluid added above the critical density ($\Delta \mathbf{I}_s + \Delta \mathbf{I}_n - \Delta \mathbf{I}_c$) [see Fig. 2(a)], and we find that this fraction approaches a constant (0.90) as the density is increased for sample I.

We now turn to the behavior of the QPT for $^3$He in aerogel. The immediate questions relate to the size of the

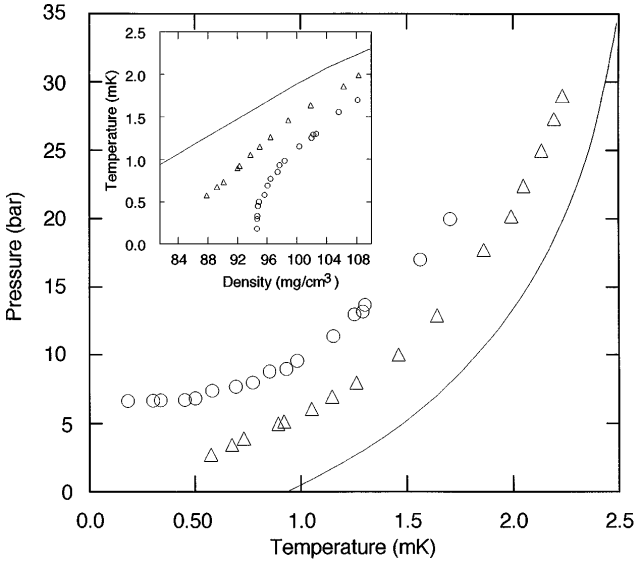


FIG. 3. The phase diagram for superfluid $^3$He in bulk (solid line), data from Ref. [1] (Δ), and this experiment (○). Inset shows $T_c$ vs density (same symbols).

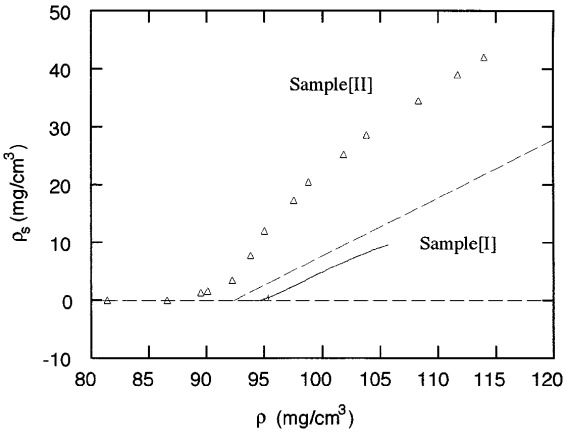


FIG. 4. The superfluid density (in aerogel), $\rho_s$, as a function of density $\rho$ for samples I: $T = 0.295$ mK (continuous line); and sample II: $T = 0.5$ mK (△). Above the region of rounding visible in Fig. 2(a) near $\rho_c$, $d\rho_s/d\rho = 0.9$ for sample I. As $\rho > \rho_c$, $d\rho_s/d\rho = 1.6$ for sample II. For reference we show a dashed line of slope 1.0 between the two data sets.

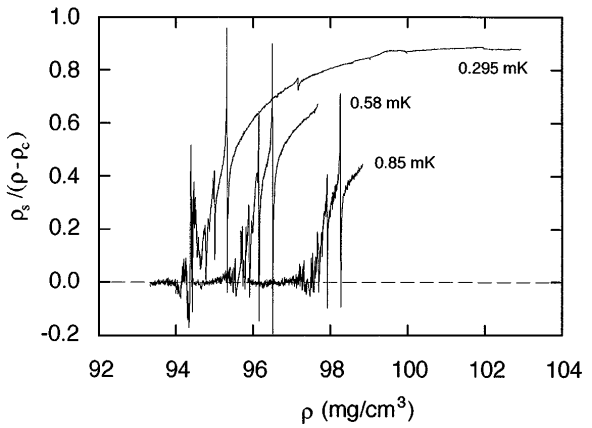


FIG. 5. $\rho_s$ of $^3$He in aerogel normalized to $\rho$ above $\rho_c$ against the density at $T = 0.295$, 0.58, and 0.85 mK for sample I. The coldest trace approaches the limiting $T = 0$ behavior.

quantum critical region and the nature of the normal state The steep behavior of $T_c$ near $\rho_c$ is the best indicator that thermal excitations play a diminishing role, which may imply a sizable quantum critical region. To explore this possibility, we apply the standard phase fluctuation model for critical behavior [20], which finds $T_c \propto (\rho - \rho_c)^{z\nu}$ and $\rho_s \propto (\rho - \rho_c)^{(d+z-2)\nu}$. Here $d = 3$ is the dimensionality, $z$ is the dynamical critical exponent characterizing the asymmetry in space and time of the quantum critical phenomena, and $\nu$ is the critical exponent representing the divergence of the correction length $\xi$ as $\rho$ approaches $\rho_c, \xi \propto (\rho - \rho_c)^{-\nu}$. We find that $(d + z - 2)\nu = 1.24 \pm 0.18$ (for $0.01 < \rho - \rho_c < 10$[mg/cm$^3$]) and $z\nu = 0.42 \pm 0.04$ [21] (for all $T_c$ in Fig. 3), which yields $z = 0.5 \pm 0.1$ and $\nu = 0.82 \pm 0.16$ [22]. However, these fits are not ideal since the thermometry lacked resolution and the sound resonances prevent us from accurately finding the exponent. Thus it is not clear that the transition is truly dominated by quantum behavior or whether a mean-field description is more appropriate.

In conclusion, we have found that $^3$He in 98.2% open aerogel undergoes a quantum phase transition between a normal and superfluid state at $\rho_c$ greater than the $P = 0$ value. The nature of the normal state of $^3$He in aerogel needs to be explored further to examine the possibility that the normal fluid for $\rho < \rho_c$ is significantly modified by the aerogel. The strong difference between the behavior of superfluid $^3$He in aerogels with identical density implies that the role of correlations in the aerogel structure needs to be investigated and understood.

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