Size effects in superfluid ^{3}He

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The superfluid density and the transition temperature of ^{3}He filling the pores of packed powders of 3 different sizes, nominally 1.0, 0.3, and 0.05 μm, have been measured using fourth sound. Progressively larger depressions are observed for both the superfluid density and the transition temperature as the powder size is decreased. The depression in the transition temperature has been measured as a function of pressure and is found to be consistent with theoretical estimates of the superfluid coherence length.

The superfluid phases of liquid ^{3}He are described in terms of pairing of ^{3}He atoms.[1] A fundamental quantity in the pairing theory is the size of the Cooper pair called the coherence length. When superfluid ^{3}He is confined in a space comparable in dimension to the coherence length, the superfluid properties are expected to be altered from those of the bulk superfluid.[2] In this paper we report a systematic observation of size effects on the superfluid density and the transition temperature of liquid ^{3}He filling the pores of packed powders using fourth-sound[3] techniques. We observe that as the pore size is decreased both the superfluid density and the transition temperature are much depressed from the bulk values. The observed depression of the transition temperature is directly related to the coherence length.

Fourth sound is a propagating pressure wave in a superfluid contained within a superleak, in our case packed powder, which locks the normal fluid component. Using the two-fluid model of superfluid helium, the fourth-sound velocity to a good approximation is given by[3]

$$C_4^2 = (\overline{\rho_s}/\rho) C_1^2 \quad , \tag{1}$$

where $\overline{\rho_s}$ is the superfluid density, ρ the total fluid density, and C_1 the first-sound velocity.[4] Thus a measurement of the fourth-sound velocity yields the superfluid density fraction $\overline{\rho_s}/\rho$. The superfluid densities of the ^{3}He-A and ^{3}He-B phases are known to be anisotropic and isotropic quantities, respectively. Only a suitably averaged superfluid density can be measured in our experiments since both the anisotropy and size effects may be present in the pores of the packed powder.

A schematic diagram of our cell is shown in Fig. 1. The refrigerant powdered cerium magnesium nitrate (CMN) is precooled to 15 ~ 16 mK and demagnetized from 1 kG to cool the liquid ^{3}He into the superfluid phases. The thermometer is 6 mg of powdered CMN packed into the form of a right circular cylinder. Its magnetic susceptibility was measured with a bridge using a superconducting quantum interference device (SQUID) as the null detector. Our magnetic temperature T^* was converted to the absolute temperature scale using the recent T_c versus pressure phase diagram of Paulson *et al.*[5] T_c^* was determined at a variety of pressures by observing the sudden change in the warm up rate of our thermometer as the cell drifted through the second-order transition. We identify T_c^* determined this way as the bulk transition temperature.

We incorporated within the cell three independent fourth-sound resonators, I, II, and III, packed with

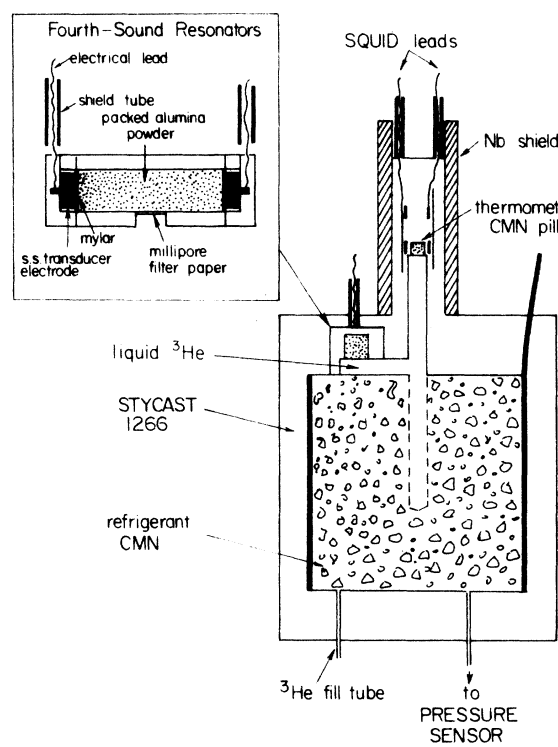

FIG. 1. A schematic of cell and a side view of the resonator. There are three symmetrically placed fourth-sound resonators (only one is shown) within the top cap.

Linde alumina (Al_2O_3) powders[6] of nominal sizes 1.0, 0.3, and 0.05 μm, respectively. The resonators are rectangular tubes with dimensions 10 mm in length and 3×3 mm square cross section. The powders were packed uniformly in several layers. The packing fraction was 20% for all resonators. The two ends of each resonator are terminated with capacitive transducers using gold plated 6-μm-thick Mylar as the active element.[3] One transducer is used as a drive and the other as a pick up. In each resonator there is a 2×3 mm opening at the center covered with Millipore filter paper (80% open area) to retain the powder. The opening provides excellent thermal contact among the resonators and to the thermometer CMN via a 20-mm-long liquid column of 3-mm diameter, while at the same time does not overly degrade the resonator Q for the appropriate sound modes.

The fourth-sound velocity is determined by measuring the frequency of a plane-wave resonance set up in the rectangular resonator. If we take the qth mode frequency f, then the superfluid density fraction is determined by

$$\frac{\overline{\rho_s}}{\rho} = \left(\frac{2nLf}{C_1 q} \right)^2 , \quad (2)$$

where L is the length of the resonator and n is the index of refraction which is introduced to account for the multiple scattering of sound by the powder grains.[7] The values of n were determined in separate experiments by measuring the fourth-sound velocities in the same resonators filled with He II at $T = 1.400$ K. The measured values of n are 1.066, 1.067, and 1.037 for resonator I, II, and III, respectively, and are in reasonable agreement with the empirical formula[7] $n = (2 - P)^{1/2}$, where P is the porosity. In the He II experiments we did not observe significant size effects in any of the three resonators. In our analysis we assume that n is independent of pressure. This assumption should be valid for resonators I and II, but there may be a pressure dependence of n in III owing to a buildup of a solid layer at the powder surface.

In the superfluid phases of ^{3}He fourth-sound resonances were observed in all three resonators. Both the first and the third plane-wave modes could be clearly identified. The second mode is expected to be suppressed due to the thermal contact opening. The signal level was generally lower in resonator III than in I and II. For unexplained reasons, the second plane-wave mode could be observed in III. In resonator I, the maximum frequency of the first mode was 6 kHz and the Q value was about 45. The resonances were followed simultaneously while slowly drifting either up or down in temperature. A magnetic field up to ~30 G was applied for temperature control. It was found that the fringing field produced no observable effects either in A or B phases.

The superfluid densities measured in the three resonators at a pressure of 20.57 bar are displayed as a function of temperature in Fig. 2. The portions of the data were $\overline{\rho_s}/\rho < 0.01$ are expanded in Fig. 2(b). The bulk transition temperature T_c^0 and the transition temperatures T_c (I,II,III) in the resonators are indicated by arrows. The results in Fig. 2 clearly demonstrate the substantial reductions both in T_c and $\overline{\rho_s}/\rho$ as the powder size is decreased.

To determine the transition temperature in the resonators we used both $\overline{\rho_s}/\rho$ extrapolations to zero and plots of signal amplitude of the first plane wave mode versus temperature. An example of the amplitude plot is shown in Fig. 3 for the resonator II data of Fig. 2. The temperature at which the amplitude goes to zero is in good agreement with the $\overline{\rho_s}/\rho$ extrapolation in resonators I and II. T_c(I) could be determined within ± 2 μK and T_c(II) within ± 4 μK. We determine T_c(III) by $\overline{\rho_s}/\rho$ extrapolation alone. The signal amplitude became no longer detectable at a temperature lower than the extrapolated T_c(III).

Though T_c(I) does not show much, if any, shift from the bulk value, the behavior of $\overline{\rho_s}/\rho$ in resonator I is significantly different from the bulk, having a curvature instead of a linear temperature dependence as in bulk superfluid ^{3}He.[8] For comparison we es-

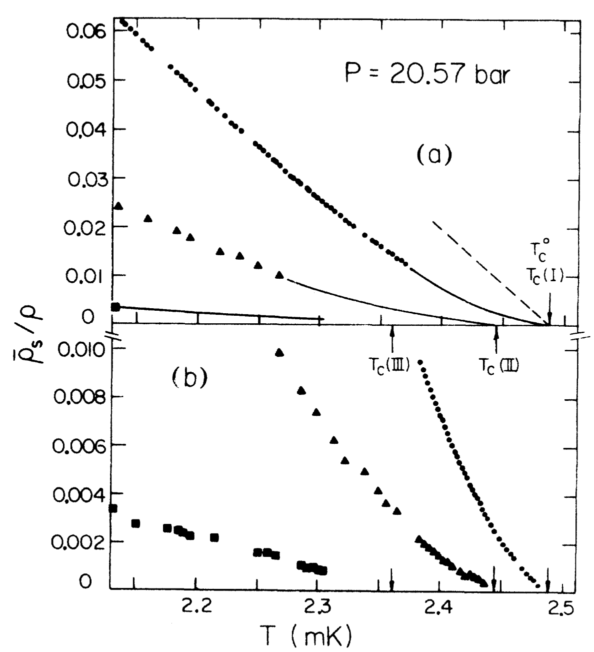

FIG. 2. Measured superfluid density fraction vs temperature at $P = 20.57$ bar with an expanded scale for $\overline{\rho_s}/\rho < 0.01$. Dots are for resonator I ($T_c = 2.487$ mK), triangles for resonator II ($T_c = 2.444$ mK), and squares for resonator III ($T_c = 2.36$ mK). The bulk transition temperature T_c^0 is 2.487 mK.

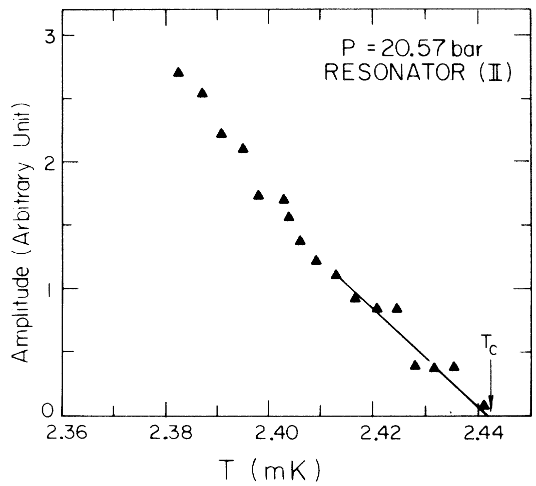

FIG. 3. Amplitude of the first plane-wave mode in resonator II near its transition temperature at $P=20.57$ bar.

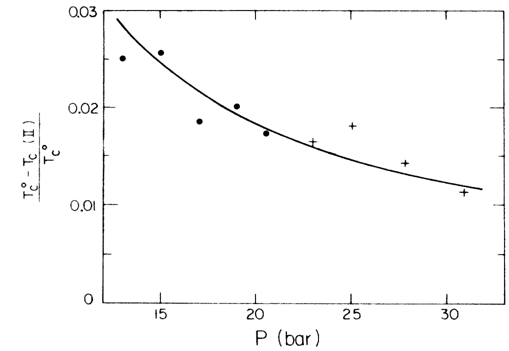

FIG. 4. Fractional depression of the transition temperature in resonator II vs pressure. The dots and crosses are the data from the B- and the A-phase regions, respectively. The solid line is a theoretical fit (see text).

timated the value of ρ_s/ρ from the measurement of ρ_n/ρ, using an oscillating disk technique in a 70 μm parallel channel, by Archie *et al.*[8] This is shown as the dashed line in Fig. 2(a). The $\overline{\rho_s}/\rho$ in resonator I is considerably reduced from the "bulk" value. A similar effect has already been noted in previous fourth-sound experiments.[3,9]

A theoretical expression for the coherence length ξ_s is given by[2] $\xi_s = [7\zeta(3)]^{1/2}\hbar v_F/(48)^{1/2}\pi k T_c^0$, where v_F is the Fermi velocity, $\hbar$ is Planck's constant divided by 2π, and k is Boltzmann's constant. The theoretical expression gives $\xi_s = 114$ Å at $P=33$ bar, and 190 Å at 12 bar.[4] The pressure dependence of ξ_s is expected to be reflected in the depression of the transition temperature. We measured $T_c^0 - T_c(\mathrm{II})$ as a function of pressure and the result is shown in Fig. 4. Kjäldman *et al.*[2] have shown that the size-dependent transition temperature of superfluid ^{3}He in a long cylindrical pore of radius R with diffusely scattering walls is given by $T_c = T_c^0 \exp(-3\xi_s^2\alpha^2/5R^2)$ where $\alpha = 2.4048$. A similar formula is obtained for a flat slab geometry. Though the pore structure in our resonator may not be equivalent to the ideal cylindrical pores, it is useful to compare our measured pressure dependence of T_c with the theory. The solid line in Fig. 4 was obtained from the theoretical expression by adjusting R to be 0.200 μm and the data appears to be consistent with the theory. Furthermore, the value of R used is close to the powder size for resonator II.

Fourth-sound experiments analogous to the present one have been extensively carried out to study size effects in He II.[7,10] For small enough pores, depressions in both the superfluid density and the transition temperature were observed in He II. It was found to be very important to account for the presence of the pore size distribution in the analysis of the depressed ρ_s/ρ in He II. It was also found that the depression in the measured transition temperature could be characterized by an average pore size, of order the size of the powder grains, in spite of the presence of larger pores than the average.[7] It is likely that an average pore size can also be associated with the present measurements of the transition temperature depression in superfluid ^{3}He. Therefore, although it is clear that the complex geometry associated with a packed powder is not ideal with respect to coherence length determinations, experience with He II in packed powder would suggest that reasonable measurements can indeed be obtained.

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[1]A. J. Leggett, Rev. Mod. Phys. 47, 331 (1975).
[2]L. H. Kjäldman, J. Kurkijärvi, and D. Rainer, J. Low Temp. Phys. 33, 577 (1978).
[3]H. Kojima, D. N. Paulson, and J. C. Wheatley, J. Low Temp. Phys. 21, 283 (1975).
[4]We used the tabulation by J. C. Wheatley, in Rev. Mod. Phys. 47, 415 (1975).
[5]D. N. Paulson, M. Krusius, J. C. Wheatley, R. S. Safrata,

M. Kolac, T. Tethal, K. Svec, and J. Matas, J. Low Temp. Phys. 34, 63 (1979).
[6]Linde 1.0C, Linde 0.3A, and Linde 0.05B alumina polishing powders, Union Carbide Corp., Linde Division, 1500 Polco Street, Indianapolis, Indiana 46241.
[7]M. Kriss and I. Rudnick, J. Low Temp. Phys. 3, 339 (1970).
[8]C. N. Archie, T. A. Alvesalo, J. D. Reppy, and R. C. Richardson, Phys. Rev. Lett. 43, 139 (1979).
[9]In the fourth-sound experiment in Ref. 3 where the curvature near T_c in the temperature dependence of $\overline{\rho_s}/\rho$ was observed, a paramagnetic CMN powder was used as a superleak. In the present experiments a nonmagnetic aluminum oxide powder was used. It is interesting that the similar temperature dependence of $\overline{\rho_s}/\rho$ is observed for both magnetic and nonmagnetic wall boundaries.
[10]I. Rudnick, E. Guyon, K. A. Shapiro, and S. A. Scott, Phys. Rev. Lett. 19, 488 (1967).