RAPID COMMUNICATIONS

PHYSICAL REVIEW B VOLUME 28, NUMBER 1 1 JULY 1983

Dimensionality of the superfluid transition in ^{4}He films adsorbed on 500-Å Al_2O_3 powder

Vincent Kotsubo and Gary A. Williams
Department of Physics, University of California, Los Angeles, California 90024

(Received 11 March 1983)

The dimensionality of the superfluid transition in thin ^{4}He films adsorbed on 500-Å-diameter Al_2O_3 powder has been investigated with use of third-sound measurements. A sharp drop in $\langle\rho_s\rangle/\rho$ is observed at film thicknesses just below the critical Kosterlitz-Thouless value, indicating that the transition remains two dimensional for this pore size above 1.2 K. The sound signal can be observed to very low values of the superfluid density because the measured attenuation near onset is much smaller than that observed previously on flat substrates.

It is now well established[1,2] that the superfluid transition in thin ^{4}He films adsorbed on flat substrates is a two-dimensional (2D) vortex-unbinding transition of the type proposed by Kosterlitz and Thouless,[3] Nelson and Kosterlitz,[4] and Young.[5] However, the situation for porous, multiply connected substrates is less clear. Measurements at Cornell by Berthold, Bishop, and Reppy[6] on films adsorbed in porous Vycor glass (pore size ~50–80 Å) displayed the characteristics of a 3D transition. A continuous decrease of the superfluid mass to zero at the transition temperature T_c was observed, with the superfluid mass proportional to $(T-T_c)^{2/3}$, very similar to the behavior found for the bulk helium 3D transition.

The question is, then, at what length scale (or pore size) does the system cross over from the 2D behavior on flat substrates to the 3D behavior seen in the Vycor? The earlier measurements of Rosenbaum *et al.*[7] seemed to indicate that the transition still appeared to be 2D for films adsorbed on 500-Å Al_2O_3 powder. Because this pore size is only one order of magnitude larger than the Vycor, we have undertaken high-resolution third-sound measurements to check the earlier results. Our results confirm that the transition remains strongly two dimensional for this powder size at temperatures above 1.2 K. However, we do observe substantially less attenuation of the third-sound mode than seen on flat substrates, and this might possibly be a precursor indication of the crossover from 2D to 3D.

The experiments are carried out in an annular resonator similar to those used previously.[7,8] The annulus is 11.4 cm in mean circumference, with a rectangular cross section of width 1.1 cm. It is packed with nominal 500-Å-diameter Al_2O_3 powder[9] to a depth of 8 mm. The powder is packed in steps of about 1-mm depth (to keep the density uniform), with use of a hydraulic press at pressures of about 50 bars. The resulting porosity (ratio of open volume to total volume) of the powder was 0.75. Superconducting aluminum film bolometers are lightly pressed against the top surface of the powder by a covering Plexiglas top plate. The third sound is adiabatic in this geometry,[8] and hence the thermal oscillations are relatively large. The waves are generated by very lightly tapping the top of the cryostat insert. The resulting free decay of the fundamental resonance (of wavelength 11.4 cm) is analyzed with use of high-resolution fast Fourier-transform techniques, and both the resonant frequency f_0 and the quality factor $Q=f_0/\Delta f$ of the mode are obtained, where Δf is the width of the resonance at the half-power points.

Measured amounts of helium gas are condensed into the cell to build up the films on the powder, and the difference in pressure between the vapor in the cell and the saturated vapor of the outer helium bath is measured with a capacitance manometer. Film thicknesses d are determined from the pressure following the procedures in Ref. 7, using a van der Waals constant[10] of $\alpha=31$ K (atomic layer).[3] An atomic layer is taken to be 3.6 Å. For the very thin films considered here ($d<4.5$ atomic layers) the surface tension corrections to d arising from the curvature of the powder particles never exceeded 10%, and were much less for the thinnest films. For film thicknesses just below the superfluid onset it was found necessary to avoid temperature and thickness inhomogeneities in the normal He films. This was achieved by first filling past the onset thickness to assure a uniform distribution, and then extracting gas to reduce the thickness to just below onset. Minute amounts of gas were then slowly recondensed, allowing the transition region to be observed in detail.

Figure 1 shows the measurements of the sound velocity at four different temperatures. The primary feature of interest is the sharp drop in velocity which is observed at each temperature as the film thickness is reduced. The film thickness where the velocity begins to drop appears to correspond quite well with the Kosterlitz-Thouless critical thickness for 2D vortex unbinding. Nelson and Kosterlitz[4] showed that at onset the average superfluid density should be given by the universal relation

$$\frac{\langle\rho_s\rangle d}{T}=\frac{2}{\pi}\left(\frac{m}{\hbar}\right)^2 k_B \ , \tag{1}$$

where m is the helium atom mass, k_B Boltzmann's constant, and T the temperature. Experiments have shown that to a good approximation $\langle\rho_s\rangle$ is related to the bulk superfluid density ρ_s^b by[11]

$$\langle\rho_s\rangle d=\rho_s^b(d-D) \ , \tag{2}$$

where D is an effective nonsuperfluid thickness, related to the solid layer and healing effects. With use of this expression in (1), a critical thickness is determined:

$$d_{\mathrm{KT}}=D+\frac{2k_BT}{\pi\rho_s^b}\left(\frac{m}{\hbar}\right)^2 \ , \tag{3}$$

and these values are shown as the arrows in Fig. 1. Because the van der Waals constant is close to that of glass, we have taken values of D using the empirical relation[11] $D=0.5+2.47(T/T_\lambda)(\rho/\rho_s^b)$ in atomic layers. We note that

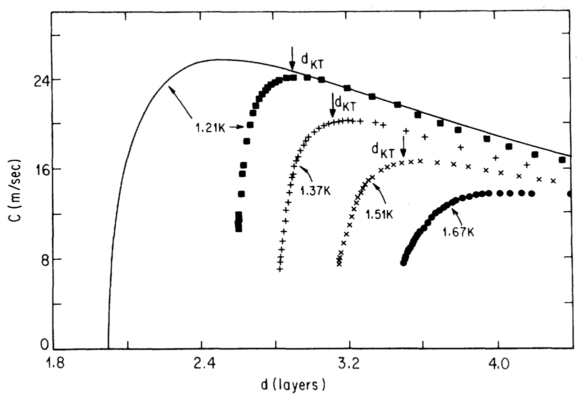

FIG. 1. Sound velocity as a function of the He film thickness for four different temperatures. The solid line is the theoretical velocity at 1.21 K from Eq. (4), with use of the 3D superfluid density of Eq. (2). The arrows indicate the 2D critical thickness.

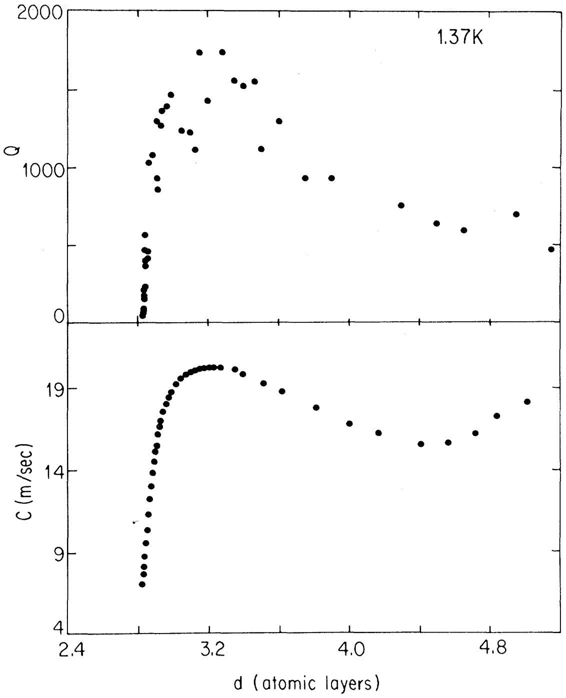

FIG. 2. The bottom curve is the 1.37-K velocity data from Fig. 1 plotted on a more expanded scale. The upturn in velocity above 4.5 layers is due to the onset of capillary condensation, as discussed in more detail in Ref. 7. The upper curve shows the corresponding quality factor Q of the mode at each thickness.

these values for d_{KT} are quite close to the onset values listed by Rudnick.[2] The solid line in Fig. 1 is computed for $T = 1.21$ K with use of the expression for the third-sound velocity in the powder

$$C_3^2 = \frac{1}{n^2}\frac{\langle\rho_s\rangle}{\rho}\frac{3\alpha}{d^3} \quad . \qquad (4)$$

The index of refraction, n, is obtained by comparing the velocity at $d = 3.4$ layers with the velocity measured at the same thickness on glass; the result $n = 2.1 \pm 0.1$ is very similar to the previous determination.[7]

It is clear from Fig. 1 that Eq. (4), with $\langle\rho_s\rangle$ given by (2), no longer describes the mode velocity for film thicknesses below d_{KT}. In this thin-film regime n should be a geometrical constant independent of thickness, and it is unlikely that it would suddenly increase. We feel that we are, in fact, observing the sharp drop in $\langle\rho_s\rangle$ from the 2D vortex unbinding. The finite width of the decrease (over 0.1–0.2 layers) is probably due to finite-frequency effects. The mode frequency ranges from 220 Hz at the peak of the 1.21-K data to 45 Hz at the lowest point. This observed width is, however, about 4–5 times larger than rough estimates based on the Ambegaokar, Halperin, Nelson, and Siggia (AHNS) theory[12] and the parameters obtained by Bishop and Reppy.[1] It is not entirely clear that the AHNS theory is applicable to our situation where the pore size is very much smaller than the vortex diffusion length.

Previous third-sound measurements have been unable to observe a decrease in the superfluid density, because the attenuation rises sharply near onset,[13] due to the vortex dissipation.[12] We are able to observe a signal in the critical regime because the attenuation we measure in the powder is substantially reduced compared to the flat-substrate case. Figure 2 shows the 1.37-K velocity data on an expanded scale, and the corresponding quality factor Q of the mode at each thickness. As the thickness is decreased toward onset the Q begins to drop rapidly, but it still remains high enough that the mode is very well defined throughout the onset region. The last point on the graph, before the signal was lost, still had a $Q \approx 20$. The significance of this reduced attenuation, two to three orders of magnitude smaller than the flat-substrate case,[13] is not completely clear. A characteristic of the Cornell measurements in the 3D Vycor films[6] was the absence of any measurable attenuation at the transition, while their 2D flat substrate[1] showed a strong dissipation peak from the vortex unbinding. A possibility is that the crossover from 2D to 3D as the pore size is decreased may proceed as first a reduction in the vortex dissipation, and then finally an increase in the superfluid density as the vortex unbinding is suppressed more completely.

The question of the dimensionality crossover in the XY model has recently been studied theoretically by Akopov and Lozovik.[14] They find that the crossover for the correlation function from 2D to 3D behavior occurs at a characteristic distance R_c,

$$R_c = a_0 \frac{\hbar c_1}{k_B T}\left(\frac{\langle\rho_s\rangle d}{m}\right)^{1/2} \quad , \qquad (5)$$

where c_1 is the first-sound velocity and a_0 is the vortex core radius. In this theory a system with a transverse size smaller than R_c will have 3D characteristics, while a system larger than R_c will be 2D. For a rough estimate of R_c, the values $\langle\rho_s\rangle d \approx 5\times10^{-9}$ g/cm^2 and $c_1 = 240$ m/sec can be used in (5). This gives $R_c \approx 5a_0/T \approx 20/T$ (Å) if we assume $a_0 \approx 4$ Å. If, in fact, the pore size is the limiting length for the adsorbed films, then this result might suggest that indeed the Vycor films should be 3D below 1 K, while our 500-Å $\mathrm{Al_2O_3}$ powder should be 2D until temperatures well below 0.1 K.

In summary, we find that the superfluid transition remains 2D for films adsorbed on 500-Å powder particles above 1.2 K. To gain a detailed understanding of the nature of the dimensionality crossover it appears necessary to study smaller pore sizes and lower temperatures.

ACKNOWLEDGMENT

This work is supported by the National Science Foundation, under Grant No. DMR 81-00218.

---

[1] D. J. Bishop and J. D. Reppy, Phys. Rev. B 22, 5171 (1980).

[2] I. Rudnick, Phys. Rev. Lett. 40, 1454 (1978).

[3] J. M. Kosterlitz and D. J. Thouless, J. Phys. C 6, 1181 (1973).

[4] D. R. Nelson and J. M. Kosterlitz, Phys. Rev. Lett. 39, 1201 (1977).

[5] A. P. Young, J. Phys. C 11, L453 (1978).

[6] J. Berthold, D. J. Bishop, and J. D. Reppy, Phys. Rev. Lett. 39, 348 (1977).

[7] R. Rosenbaum, G. A. Williams, D. Heckerman, J. Marcus, D. Scholler, J. Maynard, and I. Rudnick, J. Low Temp. Phys. 37, 663 (1979).

[8] G. A. Williams, R. Rosenbaum, and I. Rudnick, Phys. Rev. Lett. 42, 1282 (1979).

[9] Linde 0.05 B alumina powder, Linde Division, Union Carbide Corp., Indianapolis, Indiana.

[10] E. S. Sabisky and C. H. Anderson, Phys. Rev. A 7, 790 (1973).

[11] J. H. Scholtz, E. O. McLean, and I. Rudnick, Phys. Rev. Lett. 32, 147, 569(E) (1974).

[12] V. Ambegaokar, B. I. Halperin, D. R. Nelson, and E. D. Siggia, Phys. Rev. B 21, 1806 (1980).

[13] T. Wang and I. Rudnick, J. Low Temp. Phys. 9, 425 (1972).

[14] S. G. Akopov and Y. E. Lozovik, J. Phys. C 15, 4403 (1982).