Onset of Superfluid Flow in ^{4}He Films Adsorbed on Mylar

J. Maps and R. B. Hallock
Laboratory for Low Temperature Physics, Department of Physics and Astronomy, University of Massachusetts, Amherst, Massachusetts 01003
(Received 8 January 1981)

Detailed studies of the thermal conductance of a Mylar strip on which an adsorbed film of ^{4}He resides have been made at several temperatures as a function of the thickness of the helium film. The conductance in the vicinity of the superflow onset transition is observed to rise in a manner consistent with the predictions of Ambegaokar *et al.*

PACS numbers: 67.40.Rp, 67.40.Hf

In recent years a great deal of attention has been focused on thin superfluid films, which appear to be a system suitable to test the predictions which arise from the Kosterlitz-Thouless[1] theory of two-dimensional phase transitions. In particular, the universal prediction[2] of a jump in the superfluid density, ρ_s, at the phase transition has been confirmed by use of a number of techniques.[3,4]

Ambegaokar *et al.*[5] have pointed out that while the Kosterlitz-Thouless[1] transition is usually considered in a strictly two-dimensional context, the general predictions should hold in superfluid films of finite thickness. Specifically, they predict the functional dependence of the divergent correlation length on the normal side of the transition, ξ_+, for the situation where the film thickness changes at fixed temperature.

In the present work we have made detailed measurements of the thermal conductance of a helium film adsorbed on a Mylar substrate as a function of film thickness at several temperatures. The thermal conductance should be related to the quantity ξ_+. This is because the thermal conductance is expected[5] to be inversely proportional to the number density of free vortices in the film and this in turn is inversely proportional to the square of ξ_+. Thus, we should have $K \propto \xi_+^2$ and hence a measurement of the thermal conductance constitutes a measure of the important quantity ξ_+.

Previously there have been several studies[6-9] of the thermal conductance of a helium film but none has been accurate enough nor directed at a study of the functional dependence of the conductance[10]; rather, they have been focused on the determination of the onset curve (the locus of critical film thickness–critical temperature coordinates). In some of these experiments the temperature difference across the substrate is observed as a function of heater power for a variety of fixed film thickness values. In an effort to explore the vicinity of superflow onset in much greater detail we have utilized a variation[8] of this technique in which the temperature difference across the sample is monitored for fixed heater power as a function of a gradual increase in the thickness of the helium film. This allows data which can be compared with the recent detailed theoretical predictions[5] for the conductivity of a helium film. In this work we have made studies in the region of superflow onset for transition temperatures in the range $1.2 < T_c < 2.1$ K.

The apparatus (Fig. 1) used for the work we re-

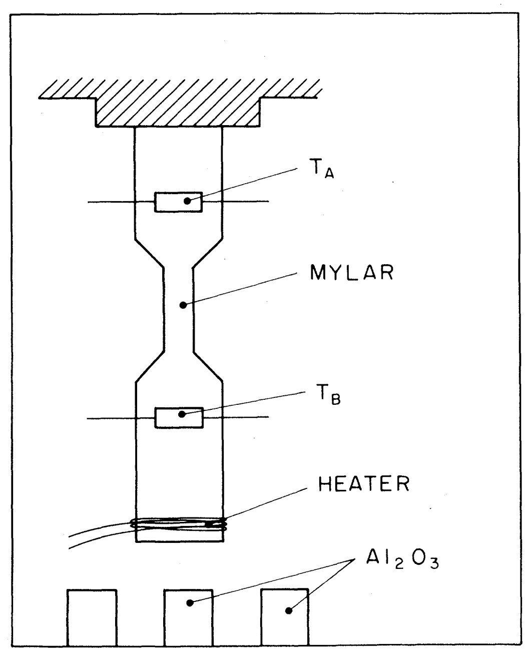

FIG. 1. Schematic representation of the apparatus. At fixed power $\dot{Q}$ to the heater the temperature of the two thermometers T_A and T_B is monitored as a function of the thickness of the helium film, d. The temperature of the thermal reservoir T_0 is maintained constant during the process. The Mylar strip is of dimensions $6.5\times 1.5\ \text{cm}^2\times 125\ \mu\text{m}$. The strip is narrowed to 2.5 mm in width for a length of 0.8 cm at the center.

port here consists of a sealed chamber into which varying amounts of ^{4}He may be admitted.[8] The chamber contains a Mylar strip thermally anchored at one end and wound with a 500-Ω Constantan heater at the other. Thermometers are affixed along the Mylar with GE 7031 varnish. In typical operation the temperature difference between the two thermometers is measured for fixed heat to the heater as a function of increasing film thickness. Relative temperatures can be measured to within a few microkelvins without difficulty by use of standard bridge techniques. We report the film thickness values in terms of atomic layers through use of $d^3 = 27[T\ln(P_0/P)]^{-1}$, where P is the measured pressure in the experimental chamber and P_0 is the saturated vapor pressure at the temperature T.

Data typical of those obtained in these measurements are shown in Fig. 2 as a function of increasing film thickness for fixed thermal reservoir temperature T_0 and for several fixed values of the power $\dot{Q}$ to the heater. Several features are observed: (1) large values of ΔT in the thin-film region, (2) a dramatic decrease in ΔT (i.e., the onset of superflow) at a film thickness characteristic of the temperature T_0, and (3) a more gradual decrease in ΔT in the thicker film region well beyond onset.

In the thin-film regime the temperature difference, $\Delta T_<$, is due to the thermal conductance in the Mylar substrate and in the helium vapor. The data can be described by $\Delta T_< = \dot{Q}/K_s$ where K_s is observed to be a constant as would be expected. The constancy of K_s is illustrated in the inset to Fig. 2 where $\Delta T_<$ is seen to be a linear function of $\dot{Q}$. We find $K_s = 2.1$ μW/mK for our geometry at $T_0 = 1.46$ K.

As the film thickness is increased a dramatic decrease in ΔT is encountered which begins at a value of the film thickness, d_c, which depends on the temperature. The coordinates d_c and T_c represent the *traditional* onset curve and our results for d_c for helium on Mylar are shown in Fig. 3. We have fitted these data (solid line, Fig. 3) with the functional form discussed by Ambegaokar *et al.*,[5] $T_c(d_c) = T_\lambda(1 - Ad_c^{-\gamma})$, and find $\gamma = 1.40 \pm 0.1$ with $A = 1.6 \pm 0.1$ and T_λ chosen to be 2.17 K. The parameter γ is unchanged with-

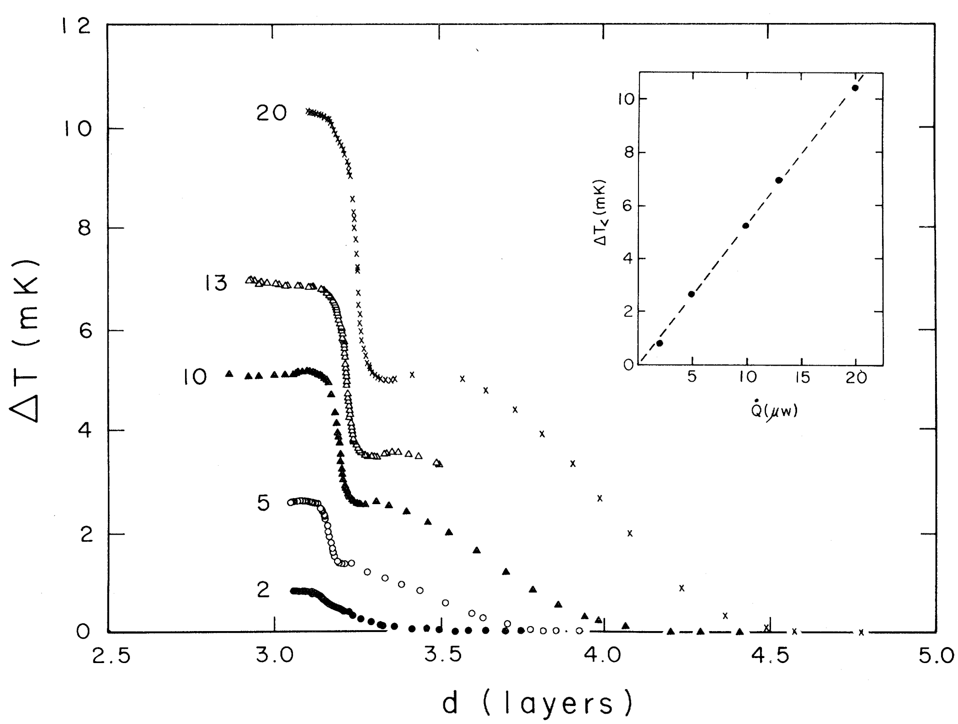

FIG. 2. Temperature difference observed across the Mylar sample as a function of the thickness of the adsorbed film. The reservoir temperature was fixed at $T_0 = 1.452$ K for these measurements. Each set of symbols refers to a different fixed value of the heater power $\dot{Q}$ in microwatts. The inset shows that the temperature difference for thickness values below onset scales linearly with $\dot{Q}$ as it should. The thickness, d_c, at which ΔT abruptly falls here shows a small apparent dependence on $\dot{Q}$ because for larger heater powers T_A is nearly but not exactly T_0.

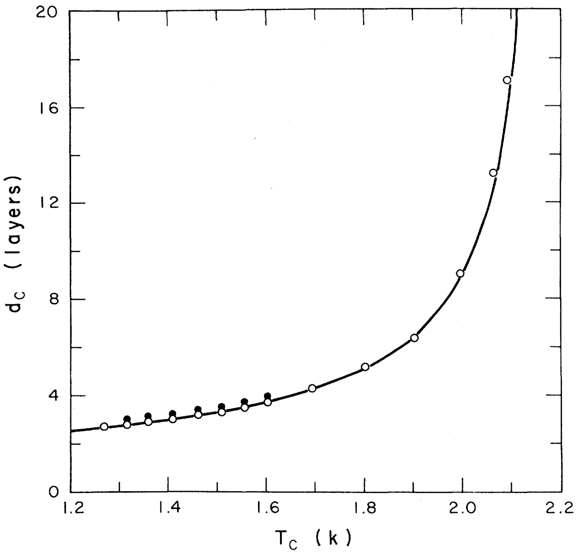

FIG. 3. The onset of superflow. The locus of observed T_c and d_c values represents the onset curve for helium on substrates—here Mylar. For this curve d_c is selected as the value of the film thickness where as a function of film thickness a conductivity enhancement first appears. (See text for a discussion of d_c*, solid dots.)

in its errors whether determined from the full data set shown in Fig. 3 or only from the restricted data set $d_c > 4.8$ atomic layers. The expected value for γ is $\frac{3}{2}$ and this is seen to be in good agreement with our experiments.

The dramatic decrease in ΔT is related in a fundamental way to the rapid change in ξ_+ at superflow onset. The value of ΔT for thickness values just beyond onset, $\Delta T_>$, can be written as $\Delta T_> = K_s^{-1}(\dot{Q} - \dot{Q}_f)$ where $\dot{Q}_f = \rho_s d v_s p(L + TS)$ is the heat removed from the heater by the mobile film of thickness d moving at speed v_s along a perimeter p. Here L is the latent heat and S is the entropy.[11] In this paper we are primarily concerned with the detailed manner in which ΔT decreases with thickness. To facilitate this examination, data of the sort shown in Fig. 2 for ΔT can be inverted in the vicinity of onset and analyzed for consistency with the theory of Ambegaokar *et al.*[5] Several examples of such data as a function of film thickness for $\dot{Q} = 13$ μW and for various fixed reservoir temperatures T_0 are presented in Fig. 4. We have carried out fits to the data of the form predicted by Ambegaokar *et al.*,[5] $K = K_0 + B\exp(C|d_c^* - d|^{-1/2})$ where the parameter K_0 is the measured finite conductance in the case of a helium film where $d < d_c$. The exponential character of the data is more clearly

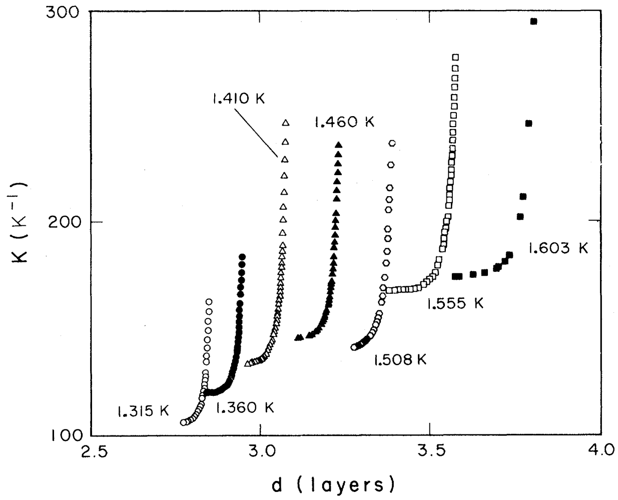

FIG. 4. The thermal conductance $K = (\Delta T)^{-1}$ as a function of the film thickness for various fixed temperatures T_0 of the thermal reservoir. All the data are reproducible; we do not understand why the 1.508-K data has a baseline somewhat off the trend.

illustrated in Fig. 5 where the solid line is the fitted predicted form[5] for a typical case. The agreement is excellent.

The prediction for the functional dependence of ξ_+ requires that $C = (dT_c/dd_c^*)^{-1/2} 4\pi T_c^{1/2}/b$ where b is a nonuniversal parameter. Note that the parameter d_c* above is the thickness at which the conductance diverges, and differs from the thickness, d_c, at which the temperature difference ΔT *begins* to drop. Use of the data of Fig. 3 so

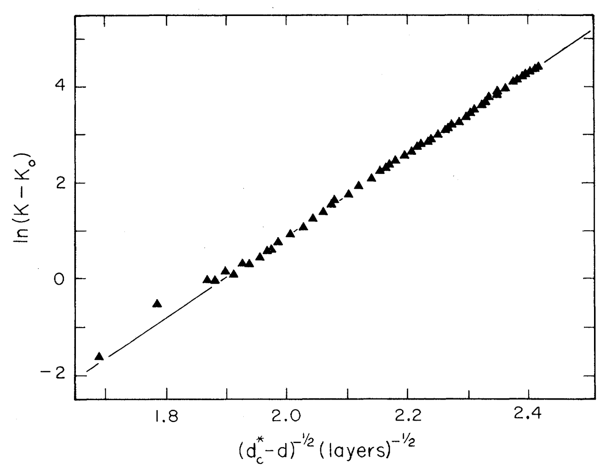

FIG. 5. Comparison between the $T = 1.46$ K data and the fit of the predicted functional form (Ref. 5) (solid line) to the data. For this fit $b = 3.0$ and $D/a_0^2 = 1.7 \times 10^{11}$ sec^{-1} where D is the vortex diffusion constant and a_0 is the vortex-core radius.

as to obtain dT_c/dd for $d = d_c{}^*$ allows a determination of the parameter b in the expression for the divergent correlation length.[12] We find $b = 2.7 \pm 0.9$ at $T_c = 1.46$ K with no temperature dependence over the range studied in Fig. 4. The values we obtain for b are similar to the value $b = 5.5$ obtained by oscillator techniques by Bishop and Reppy[3] for a helium film on Mylar at $T = 1.2$ K. They are substantially smaller than the values ($b \simeq 20$) found by Hess, Muirhead, and Dash[9] in recent studies of helium adsorbed on Au-plated Cu. Since b is not expected to be universal, the difference between the Mylar results and those for Au-plated Cu may not be significant.

Data of the sort shown in Fig. 2 scale as a function of heater power through the region of superflow onset. That is, data at different $\dot{Q}$ values superimpose when plotted as $\Delta T/\dot{Q}$ versus d. This provides us with strong evidence that critical-velocity effects are playing no major role in the vicinity of onset and hence that the rapidly changing conductivity is due in fact to the dramatic change in ξ_+.

We believe that the gradual, power-dependent decrease in ΔT for $d > d_c{}^*$ is due to finite-velocity-induced vortex unbinding in the vicinity of the constriction. The general features of our data in this region are predictable from a detailed consideration of the work of Ambegaokar *et al.*[5]

In conclusion we have shown that a helium film on Mylar appears quite consistent with the detailed predictions of Ambegaokar *et al.*[5] at finite thickness for the dramatic increase in thermal conductance in the vicinity of onset on the normal side of the transition. Also revealed by the measurements is a very broad transition region following the sharp appearance of superflow onset.

We have benefited from conversations with B. I. Halperin and D. R. Nelson. We are also grateful to G. B. Hess, J. G. Dash, D. J. Bishop, and J. D. Reppy for a discussion of their experiments. This work was supported by the National Science Foundation through Contract No. DMR79-09248.

Note added.—While this manuscript was in process, we learned of another manuscript[13] which reports similar results as a function of temperature, rather than film thickness.

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

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

[3] D. J. Bishop and J. D. Reppy, Phys. Rev. Lett. 40, 1727 (1978), and Phys. Rev. B 22, 5171 (1980).

[4] I. Rudnick, Phys. Rev. Lett. 40, 1454 (1978); M. Chester and L. C. Yang, Phys. Rev. Lett. 31, 1377 (1973).

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

[6] S. E. Polanco and M. Bretz, Surf. Sci. 94, 1 (1980).

[7] E. S. Sabisky and C. H. Anderson, Phys. Rev. Lett. 30, 1122 (1973).

[8] J. Maps and R. B. Hallock, in *Ordering in Two Dimensions*, edited by S. K. Sinha (North-Holland, New York, 1980), p. 271.

[9] G. B. Hess, R. J. Muirhead, and J. G. Dash, private communication, and to be published.

[10] Exceptions to this are Ref. 9, in which an attempt was made to study the functional dependence of the conductance on MgO by a technique different from that employed here, and the work of Ratnam and Mochel [Phys. Rev. Lett. 25, 711 (1970)], who measured the thermal resistance of a helium film as a function of *temperature*.

[11] See, for example, R. J. Donnelly, *Experimental Superfluidity* (Univ. of Chicago Press, Chicago, 1976), pp. 231, 233.

[12] Differences between d_c and $d_c{}^*$ are unimportant for the determinations of the parameter b we report here. This is because detailed data have only been obtained for $T \lesssim 1.6$ K where dd_c/dT_c is relatively constant and small. (See Fig. 3; $d_c{}^*$ = solid circles.)

[13] G. Agnolet, S. L. Teitel, and J. D. Reppy, following Letter [Phys. Rev. Lett. 47, 1537 (1981)].