Anomalous Behavior of the Kapitza Resistance between Solids and Liquid Helium II

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We report observations of an anomalous behavior in the Kapitza resistance between Cu or Pb and liquid helium II in the range 1–2 K. Systematic deviations from linearity at small heat fluxes have been observed for the temperature difference as a function of heat current. The dependence of the anomaly upon diameter and temperature is described, as well as possible origins of the effect.

In experiments on thermal conductivity at low temperatures a linear relation between the temperature difference ΔT and the heat current $\dot{Q}$ is usually observed. An exception is provided by liquid helium II, where it has been found that under certain conditions[1] a strongly nonlinear variation occurs, primarily due to the effect of mutual friction between normal fluid and superfluid. Such effects have recently been used to study critical velocities in helium II for the case of heat conduction in narrow capillaries.[2] In the present Letter, we report the first observation of similar deviations from a simple linear ΔT versus $\dot{Q}$ relation for the boundary resistance at a solid–helium II interface, the Kapitza resistance.[3,4] The results suggest that such effects are also related to the creation of turbulence in the liquid, which points to the possible existence of a new tool for the study of critical velocities in liquid helium in the immediate vicinity of a heated solid surface.

The experiments were made using the classical steady-state technique. The specimens were in the form of cylinders a few centimeters long and with diameters ranging from 5 to 15 mm. As shown in Fig. 1 the heat flow was axial across one end face which was in contact with the helium bath. In the work reported here the surfaces were in the as-machined state, being degreased with acetone just before cooling down. The specimens were soldered into $\frac{2}{10}$-mm-thick German silver plates which acted as thermal insulating supports. Temperatures were measured using $\frac{1}{10}$-W, 47-Ω, Allen-Bradley resistors calibrated against the helium bath temperature. Temperature differences were determined by the difference in thermometer resistance with and without an applied heat current, the helium bath being regulated at a constant temperature with a precision of $\lesssim 10^{-4}$ K in both cases. Ample time was taken to ensure that the thermometers were in thermal equilibrium at each point, this being facilitated by the use of a linear ramp heater supply by which the heater power $\dot{Q}$ could be slowly increased over a 20-min time interval. As determined by the maximum observed scatter in the experimental points, the estimated error in ΔT is $<3\%$ for $\Delta T \sim 50$ mK and $<8\%$ for $\Delta T \sim 5$ mK. Absolute accuracy in the determination of $\dot{Q}$ is estimated to be better than 0.5%. A summary of the results for a 10-mm-diam copper specimen is shown in Fig. 2 to illustrate the temperature dependence. A change in slope is observed at a critical heat current $\dot{Q}_c \sim 5$ mW cm^{-2} for $T \lesssim 2$ K and the effect progressively disappears at the lowest temperatures. The size dependence is shown by representative results for Pb in Fig. 3. A significant break in slope is seen for a 15-mm specimen for $T \sim 2$ K while the characteristic is linear for a 5-mm-diam specimen.

The slope change at 2 K is about 25% in both Figs. 2 and 3 although, for a given heat current density (for example, $\dot{Q} = 10$ mW cm^{-2}), the ex-

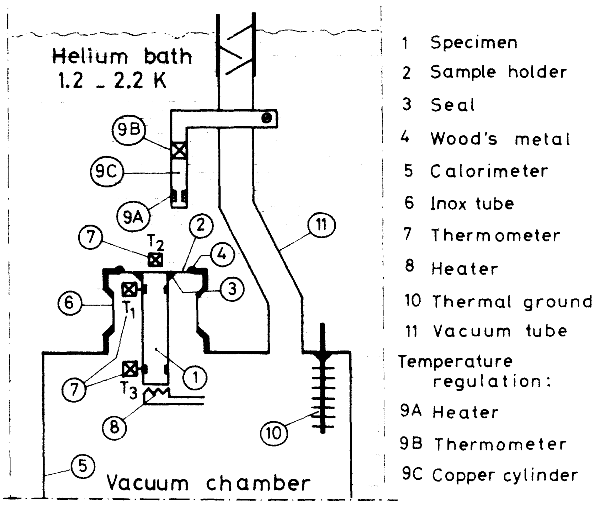

FIG. 1. Kapitza resistance calorimeter.

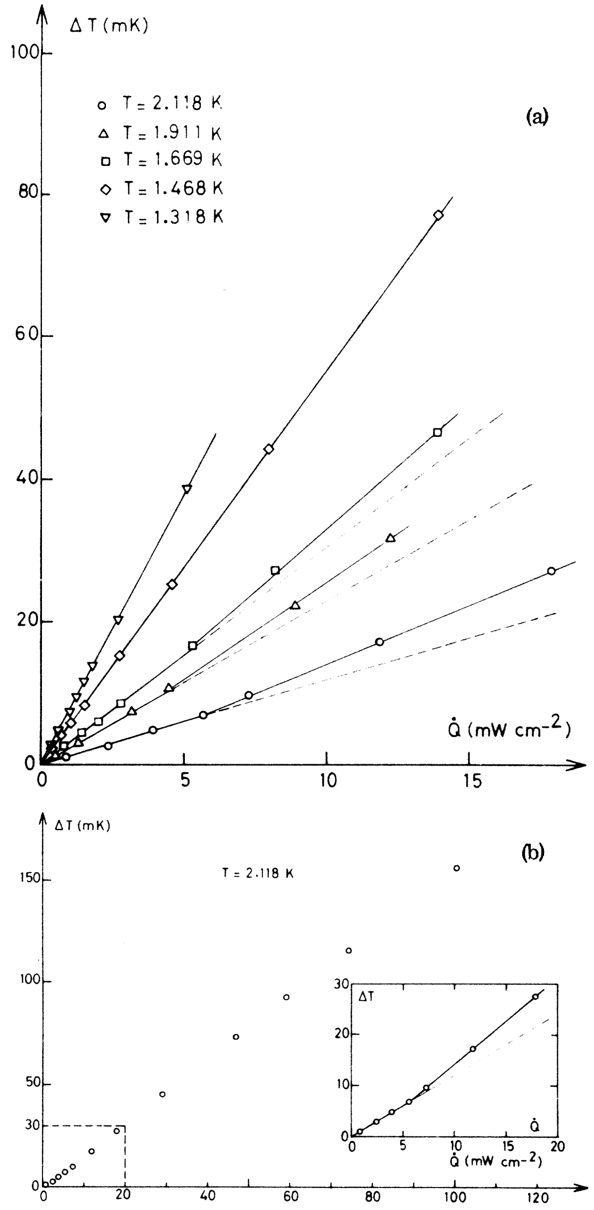

FIG. 2. (a) Summary of the results for copper. In most cases the indicated behavior has been observed to continue for heater powers higher than those shown here. (b) The anomaly shown in the inset may escape attention if only a few points are taken over a wide ΔT range.

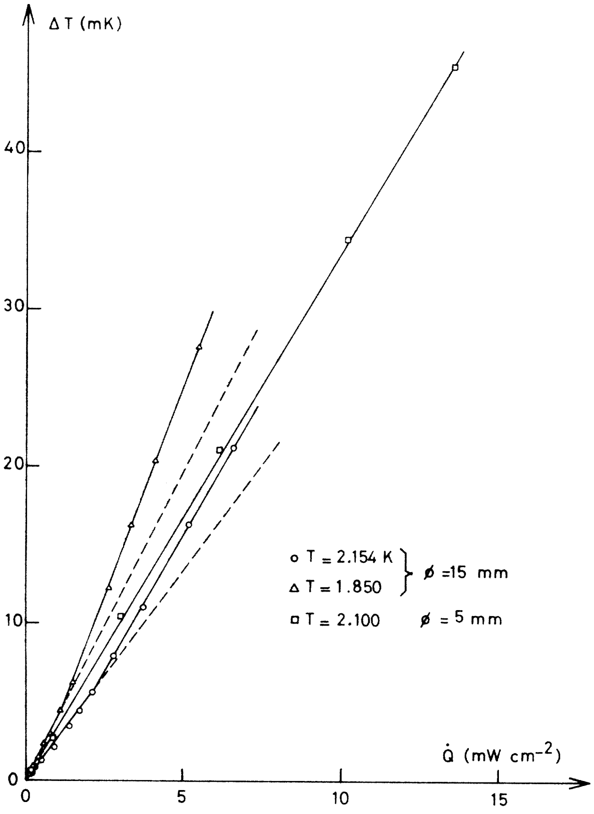

FIG. 3. Size dependence for Pb. Similar results were obtained for normal lead. The results for the 5-mm specimen were obtained in a different investigation (Ref. 5).

cess ΔT above that determined from the slope at the origin is much larger for the 15-mm-diam Pb specimen (7 mK) than for the 10-mm-diam copper (2 mK). At present we feel that there are not sufficient data to pin down the curve shape near and immediately above $\dot{Q}_c$. We have shown the curve above $\dot{Q}_c$ as being approximated by a straight line merely as a visual aid to show the existence of the anomaly. Detailed measurements below $\dot{Q}_c$ on copper revealed the slope to be accurately linear very close to the origin, and to a first approximation the slope is linear above the break. It is interesting to note in passing that for $T \sim T_\lambda$ the solid temperature is above T_λ for most of the curve and nothing unusual in ΔT versus $\dot{Q}$ is observed at the corresponding value of ΔT.

The existence and order of magnitude of the anomaly have been found to be reproducible in all of the work thus far, and from the ensemble of the data we have deduced the following features. (i) There is a marked dependence on the temperature, a simple linear behavior always being observed for $T \lesssim 1.5$ K except for the larger diameter (~15 mm) specimens. However, it has not yet been found possible to determine accurately $\dot{Q}_c$ and hence $\dot{Q}_c(T)$ (Fig. 2 is typical in this regard). (ii) The excess ΔT increases rapidly with specimen diameter; we have not observed the effect in 5-mm-diam Pb specimens for heat currents up to 20 mW cm^{-2} as shown in Fig. 3. The data presently available do suggest that $\dot{Q}_c$ varies approximately inversely as the diameter. (iii) The surface condition seems to be important although further work is needed on this point. (iv) The anomaly has been observed in specimens of Cu, Pb (superconducting and normal), Bi, Fe, Co, Ni, and H_2O and thus seems to be of a quite general nature irrespective of the solid used.

We have gone to some lengths to satisfy ourselves that the observation is not of a pernicious experimental origin. Some checks included measurement of the thermal conductivity K of a wire of commercial grade copper (diameter 2 mm, length 50 mm) and of commercial brass (diameter 7 mm, length 6 mm) in the same conditions of temperature, heat flux, and temperature difference as for when the anomaly was observed. In both cases there was unquestionably no slope increase for K, while a small anomaly was observed for R_K of the same brass specimen. Likewise the fact that the characteristic is generally linear for $T < 1.5$ K immediately eliminated a host of possibilities such as steady heat leaks, faulty wiring, etc., which are common to both temperature intervals. A standard R_K surface not being yet available, we have verified the correctness of our thermal conductivity measurements by determining the Lorenz number for Fe, Co, and Ni.[6]

One might also ask why the effect has not been observed in previous measurements. A clue is given from Fig. 2(b), where we see that the slope change is quite invisible if we look at the variation over a wide range of T and $\dot{Q}$. As seen in the inset, a detailed inspection reveals the anomaly. We note that for the highest values of $\dot{Q}$ there is an apparent decrease in the slope which can be explained simply by the fact that the condition $\Delta T \ll T_0$ is not longer true; a simple Taylor's series expansion of $R_K(T)$ accounts for this difference. Other reasons why the anomaly seems to have escaped notice may be that 5–6-mm-diam specimens have been used in many cases, and more generally that few detailed studies of $\Delta T(\dot{Q})$ have been made. Finally it is interesting to note that the same effect that we have observed here seems to be present to some degree in Kapitza's original work.[4]

Turning to the origin of the effect we may look for a cause in four regions of the system: (a) In the bulk of the solid. This seems unlikely, as such effects do not seem to have been reported in the literature on thermal conductivity work.[7] In particular a linear characteristic was observed in our brass specimen which was chosen specifically so as to put any possible end effects in evidence. (b) In the bulk of the liquid. This is quite unlikely, as we tested for this possibility by moving the bath resistor as close as possible to the specimen surface (about 0.1–1 mm) and no change was observed in the results. Further, work on temperature gradients in bulk helium II in the mutual-friction regime[8,9] predicts excess ΔT's orders of magnitude smaller than those that we observe here. (c) In a thin (perhaps damaged) surface layer of the solid. This is quite possible, but we have no precise model to offer. (d) In a thin layer of liquid near the interface. We presently regard this as being the most likely location of the effect.

The apparently strong dependence of the results on the temperature and surface diameter suggests that the effect can be explained by turbulence in the helium at the interface. The observed $\dot{Q}_c$ could in principle correspond to turbulence in either the normal fluid or the superfluid. The work of Van Alphen *et al.*[10] suggests that for wide channels in counterflow conditions (i.e., when the normal fluid is unclamped as in our case) a critical velocity corresponding to turbulence in the normal fluid is usually observed. It seems reasonable to suppose that this is also the case in our problem.[11] Turbulence in the normal fluid could in turn be due to either mutual friction or the existence of a critical Reynolds number.[12] An extensive investigation would probably be necessary to distinguish between the two possibilities at least as for as the form of the $\Delta T(\dot{Q})$ relation is concerned. However, considerations given below suggest a correlation between $\dot{Q}_c$ and a critical Reynolds number.

As a first step in identifying the phenomenon at hand we define a surface Reynolds number $R_s = \rho v_n d/\eta_n$, where ρ is the total fluid density, $v_n = \dot{Q}/\rho TS$ is the normal fluid velocity, d is the surface diameter, and η_n is the normal fluid viscosity. Values for ρ, S, and η_n for liquid helium have been taken from standard tables.[3]

For these of our results where $\dot{Q}_c$ is sufficiently clearly defined we obtain $R_s \sim 1500$ for $T \sim 1.2$ K (superconducting lead) then falling progressively to $R_s \sim 500$ at $T \sim 1.5$ K (copper) and $R_s \lesssim 50$ for $T \lesssim T_\lambda$ (all specimens). A similar situation is observed in bulk helium, which is encouraging. However, as already pointed out, such an analogy cannot be carried over quantitatively to the present work, at least as far as the magnitude of ΔT is concerned. Unfortunately our experimental results do not permit accurate evaluation of R_s at the lowest temperatures as the anomaly becomes very small and not well defined.

An independent check of the present results and conjectures would clearly be desirable, at which point a detailed theory of initiation of turbulence in helium II at a solid interface will be needed. This is clearly outside of the scope of the present work.

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[11] Some of our data (for example, Fig. 3) also suggest the existence of a first transition at $\dot{Q}_0 < \dot{Q}_c$. This could correspond to a transition to superfluid turbulence, which gives further support to our association of $\dot{Q}_c$ with normal-fluid turbulence.

[12] J. T. Tough and C. E. Oberly [J. Low Temp. Phys. 6, 161 (1972)] have discovered a dimensionless parameter P which seems to characterize the transition to normal-fluid turbulence in the bulk liquid in the range 1–2 K. The parameter P does not seem to describe our data very well ($5 < P < 80$ as opposed to $P \sim 55$ for bulk helium). This is not surprising, as our results already suggest that a different theoretical treatment will be needed for the surface problem. Hence our use of a Reynolds number in the text.

[13] Arp, Ref. 9.

Neutral-Beam Heating in the Adiabatic Toroidal Compressor*

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Experiments have been conducted on an adiabatic toroidal compressor with tangential injection of two 14–15-keV, 3–4-A beams of H^0 or D^0. The ion-temperature rise for both H^+ and D^+ plasmas is 70–80 eV (i.e., 35–40%), consistent with theoretical expectations for charge-exchange–limited energy transport at neutral-atom densities $\approx 10^9$ cm^{-3}. The injected ions are found to decelerate in agreement with classical theory and produce an initial plasma ion heating rate of ~20 keV/sec.

In a toroidal fusion reactor, the plasma temperature will be maintained by the Coulomb collisions of the suprathermal α-particle population produced by DT reactions in the plasma. To attain fusion-reactor temperatures, a similar heating method can be used: namely, injection of a suprathermal ion population by means of neutral-atom beams. These ions need serve merely as a heat source; they need not serve to maintain or build up the plasma density.

For injection into the adiabatic-toroidal-compressor (ATC) precompression plasma, we have used neutral-beam sources developed and built at the Lawrence Berkeley Laboratory.[1] These sources are capable of operation up to 20 kV at 10 A per source; our present results are derived