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Some Aspects of the Kapitza Resistance*

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The Kapitza resistance of tin and indium, in both the superconducting and normal states, and sapphire have been measured in the temperature range of 1.3 to 2°K. The results are compared with those reported for superconducting and normal lead as well as with the predicted values from current theory. Although qualitative agreement with the theory is obtained, large discrepancies in the absolute value of the Kapitza resistance as well as its temperature dependence for metals in their superconducting state are observed, suggesting the existence of other, as yet undiscovered, parallel mechanisms. The effect of electric field on the Kapitza resistance between platinum and liquid helium was investigated with the hope of determining the influence of the coupling between the phonons of the liquid and the part of the electronic wave functions of the metal which decay into the liquid on the Kapitza resistance. Under our experimental conditions, no effect is observed.

INTRODUCTION

THE existence of a thermal contact resistance between a solid body and liquid helium was first observed by Kapitza[1] and this phenomenon has since been referred to by the name of its discoverer. Khalatnikov[2] showed that, indeed, a temperature jump was to be expected at the interface between the solid and liquid helium under the conditions of heat flow between the two media because of the acoustic mismatch at the boundary. His calculations predicted values of Kapitza resistance which varied as T^{-3}, but were several orders of magnitude larger than the experimental values available at the time.

Little[3] analyzed, in detail, the conduction of heat across the interface between two dissimilar solids via phonon transport. Again, because of the mismatch of acoustical properties, he calculated the heat transport to be proportional to $T^3\Delta T$ in the limit of small heat flow, where ΔT is the temperature discontinuity at the interface between the two media. Whereas Little's calculations seemed to compare favorably with the observations of heat transfer between dissimilar solids, particularly between metals and paramagnetic salts, the theory, when applied to a metal-liquid helium interface, led to anomalously high values of Kapitza resistance. This, perhaps, was to be expected in view of Khalatnikov's calculations. The reason for the high calculated value of Kapitza resistance became clear. Because of the very large acoustical mismatch between liquid helium and a metal, only those phonons of the liquid which impinge on the metal surface and whose velocities are confined to a very narrow cone about the normal to the interface can be refracted into the metal, all the remaining phonons being totally reflected. The resulting inefficient transfer of phonons across the interface gives rise to a very large temperature discontinuity in order to maintain a given heat flow.

Little speculated that, in the case of a metal-liquid helium interface, the totally reflected phonons of the liquid were coupled to the conduction electrons of the metal thereby providing a mechanism for heat transport which acted in parallel with that derived from the Khalatnikov-Little theory which might substantially lower the net Kapitza resistance. Recently, Little[4] has calculated the heat transport across the interface based on the above model. The "totally reflected" phonons produce a periodic disturbance of the metal lattice which decays exponentially with distance from the interface. The resulting displacement of the lattice ions in the neighborhood of the interface then provides the interaction which couples the conduction electrons with the "totally reflected" phonons. Little estimates, from his calculations, a Kapitza resistance of the order of $(10^3/T^3)$ °K-cm^2/W which, though somewhat less than that computed from the simple phonon transport theory, is, as we shall see, still about two orders of magnitude larger than the experimentally reported values.

Little[3,4] pointed out that if this mechanism is an important one, there should be a difference between the values of the Kapitza resistance of a superconductor in its superconducting state and in its normal state. In Little's theory, for a superconductor, it is only the quasiparticles which can interact with the surface phonons, and since the number of such particles which are thermally excited decrease, roughly, as $\exp(-3.5T_c/T)$ and the number of surface phonons capable of creating such particles decrease in like manner, at sufficiently small T/T_c, the Kapitza resistance for a metal in the superconducting state should be larger than when the metal is in its normal state.

In order to check the importance of this mechanism, we have measured the Kapitza resistance of superconducting and normal tin and indium specimens and a crystalline sapphire specimen for which Little's mechanism should not apply because of the absence of conduction electrons. We have also attempted to observe the effect of electric fields on the Kapitza resistance of platinum. We delay discussion of this latter effect until

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[1] P. L. Kapitza, J. Exptl. Theoret. Phys. (U.S.S.R.) **11**, 1 (1941).

[2] I. M. Khalatnikov, J. Exptl. Theoret. Phys. (U.S.S.R.) **22**, 687 (1952).

[3] W. A. Little, Can. J. Phys. **37**, 334 (1959).

[4] W. A. Little, Phys. Rev. **123**, 435 (1961).

later. Preliminary results for tin and indium have been reported earlier,[5] and the more complete work is described here along with a comparison of similar work reported elsewhere.

EXPERIMENTAL PROCEDURE

The measurements on all specimens were made in a cell of the type shown in Fig. 1. All the thermometers were $\frac{1}{10}$-W, 220-Ω Allen-Bradley resistors with the outer casings replaced by thin copper sleeves insulated from the resistors by a thin layer of GE7031 adhesive in a manner suggested by Lindenfeld.[6] For the metal specimens, the thermometers were soldered directly to the metal; for the sapphire specimen, the thermometers were attached using the GE7031 adhesive. The thermometer resistances were measured on a 20-cps wheatstone bridge.

The specimens were in the form of rods about 0.2 in. in diameter and about $1\frac{3}{4}$ in. long which were sealed into a stainless-steel tube having a wall thickness of 0.005 in. which formed the supporting wall for the column of liquid helium which was in contact with the specimen end surface. The metal specimens were soldered directly to the tube, whereas the sapphire specimen was sealed to the tube with an epoxy resin. The ends of the specimens in contact with the bath were machine polished in the case of the metals and hand polished in the case of the sapphire.

The thermometers were calibrated against the vapor pressure of the liquid helium bath with helium exchange gas in the cell and under high vacuum conditions in the temperature range of 1.3 to 2.0°K to insure that the thermometers achieved thermal equilibrium with the latter via contact with the specimens only. Since all measurements were made below the λ point of liquid helium, the thermometers mounted on the stainless-steel tube indicated the bath temperature for all heat levels used in the experiments.

The Kapitza resistance was measured in the following way. A dc heat current was made to flow along the specimen into the helium column by means of a heater cemented to the vacuum end of the specimen as shown in Fig. 1. The temperature rise of each of the thermometers mounted on the specimen was measured as a function of the heat input. The temperature rise per unit heat flow on the solid side of the helium-solid interface was determined by extrapolating the temperature gradient along the rod to the interface, although, with the exception of superconducting lead, for our specimens the temperature rise of the thermometer located nearest to the interface did not differ from that at the interface by an experimentally significant amount. The temperature on the liquid side of the interface was taken to be the same as the bath temperature. The Kapitza resistance was then calculated from

$$R_k = (\Delta T_k/\dot{q})a,$$

where R_k = the Kapitza resistance, $\Delta T_k/\dot{q}$ = the temperature discontinuity at the interface per unit heat flow, and a is the interface cross-section area.

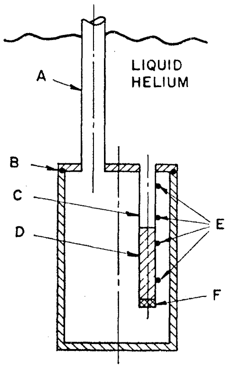

FIG. 1. Schematic diagram of thermal conductance cell. A—stainless steel pump line and electrical conduit; B—gold "O" ring; C—thin-wall stainless-steel tube; D—specimen; E—thermometers ($\frac{1}{10}$-W Allen-Bradley resistors); F—heater.

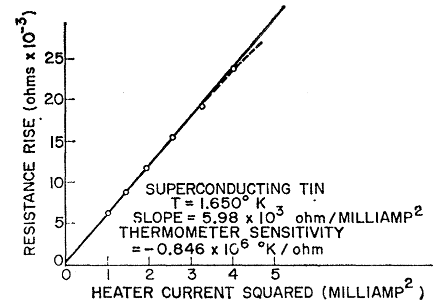

FIG. 2. Typical resistance change of thermometers vs power into specimen heater.

In the case of the metal specimens, data were taken over the entire temperature range when the specimens were superconducting. Then the entire procedure was repeated when the specimens were made normal with a magnetic field. This procedure was adapted, rather than switching the specimen between its superconducting and normal phases at a given temperature, in order to avoid the trapping of normal regions in the vicinity of the interface and thus introducing unnecessary errors and scatter. The magnetoresistance of the thermometers was checked at magnetic fields greater than the critical value and was found to be small enough to be experimentally insignificant.

The effect of magnetic field on the Kapitza resistance of (normal) lead has already been shown to be quite small by Challis.[7] We have not made a similar study for either tin or indium.

Temperature rise data were taken for heat inputs up to about 5 mW since, for higher heat fluxes, the nonlinear relationship between resistance and temperature of the resistance thermometers made the determination of the temperature rise awkward. Figure 2 is typical of

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[5] J. I. Gittleman, Bull. Am. Phys. Soc. **6**, 268 (1961).

[6] P. Lindenfeld (private communication).

[7] L. J. Challis, *Proceedings of the Seventh International Conference on Low-Temperature Physics, Toronto, 1960* (University of Toronto Press, Toronto, 1961), p. 476.

the resistance rise vs heat flux data obtained in our experiments. The dashed portion is the expected deviation from linearity due to the nonlinearity of the resistance thermometers. For the data shown the heater resistance was 760 Ω.

RESULTS AND DISCUSSION

Figure 3 is typical of the Kapitza resistance vs temperature data for all our specimens in both form and scatter. The circles represent our experimental points. The curve was determined by assuming that the Kapitza resistance had the form

$$R_k = A/T^3,$$

and computing A for each experimental point. The average value of A for all the data was then used to plot the curve. In like manner T^{-2} and T^{-4} relations were attempted but each failed to fit the data over the whole of the temperature range. We make no claim that a noninteger exponent near 3 would not produce a better fit to the data; we simply made no effort to determine it. Table I is a summary of all of our results. We have included in the table, for comparison's sake, the results for lead as reported by Challis.[7]

In order to ensure that the large differences in the normal and superconducting Kapitza resistance values of lead as reported by Challis[7] and the small differences observed by us for tin and indium were not due to experimental discrepancy, we measured the Kapitza resistances of lead at a few temperatures. Essential agreement with Challis' results were obtained. Qualitatively, at least, an explanation for the difference between lead and tin or indium can be found in Little's theory.[4] First, since lead has a larger superconducting energy gap (approximately 3.5 kT_c) than either tin or indium, in the experimental temperature range, there are fewer quasi-particles to interact with the surface phonons and there are fewer surface phonons which are energetic enough to excite quasi-particles from the superconducting ground state. Thus, the superconducting Kapitza resistance should be larger for lead. Second, since the coupling between the electrons and the surface phonons is proportional to the phonon-electron interaction, which is larger in lead than in either tin or indium as evidenced by its higher critical temperature and larger room-temperature resistivity, the Kapitza resistance for lead should be less than for the other metals.

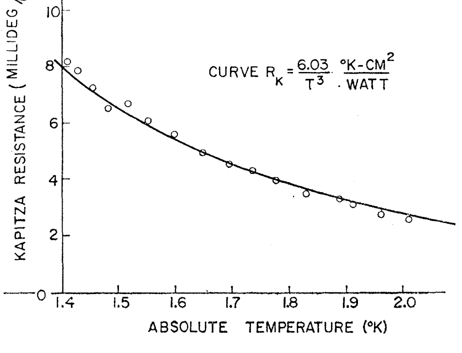

FIG. 3. Kapitza resistance for superconducting tin.

Unfortunately, the reported value of the Kapitza resistance for normal lead is not less than for normal tin but is larger by about 15%. This, however, may be due to experimental uncertainties in determining the absolute value of the Kapitza resistance, such as the uncertainty in knowing the total effective area in contact with the helium. A more serious discrepancy with theory is the fact that, well below the critical temperature, the superconducting Kapitza resistance is expected (provided the electron-phonon mechanism is, in fact, the dominant one) to vary as $\exp(3.5T_c/T)$ rather than as T^{-3} which is predicted for normal metals. This has never been observed although Challis[7] does report departures from the T^{-3} law for superconducting lead.

As can be seen from Table I, the Kapitza resistance of the normal metals appears to be about 2 orders of magnitude smaller than that predicted by Little's theory.[4] The Kapitza resistance was measured for a single crystal sapphire rod which has essentially no conduction electrons and, therefore, should behave according to the older Khalatnikov-Little theory.[2,3] Although, as is shown in Table I, the Kapitza resistance of the sapphire was appreciably higher than for the normal metals, its value falls far short of the nearly $(10^4/T^3)$ °K-cm²/W value expected from the theory.

TABLE I. Kapitza resistance of tin, indium, lead, and sapphire.

Substance	Normal state Kapitza resistance (°K-cm²/W)	Superconducting state Kapitza resistance (°K-cm²/W)	Diff. (%)	T_c (°K)	Room temperature resistivity (Ω-cm ×10⁶)
Tin	$5.48/T^3$	$6.03/T^3$	10.6	3.74	11.5
Indium	$9.54/T^3$	$10.1/T^3$	5.9	3.37	8.4
Lead	$7/T^3$	Faster than T^3	200–300	7.2	22
Sapphire	$44.1/T^3$	···	···	···	···

There exists, then, a strong suggestion that there are other important processes, acting in parallel with the one proposed by Little, for transporting heat energy across an interface. The mechanisms for these processes, if they exist, have thus far eluded discovery. It is,[3] perhaps, appropriate to mention a possible shorting mechanism which was present in our experiment. In sealing our specimens into the stainless-steel tube a lap-type joint was made so that a fraction of the heat flux was able to bypass the solid-liquid interface via the stainless steel. However, a simple calculation showed that even in the case of sapphire, which exhibited the highest measured Kapitza resistance, the diverted heat flux should amount to not more than a percent or two of the total.

Quite recently, Little[8] has proposed an additional mechanism by which heat may be transported across the interface. This mechanism involves the adsorption of bath temperature helium atoms on the metal surface along with the desorption of the metal temperature helium atoms from the surface, thus transferring thermal energy between the metal and the helium. The relative importance of this mechanism rests with future calculations of its magnitude and temperature dependence.

ELECTRIC FIELD DEPENDENCE OF KAPITZA RESISTANCE

Bloch[9,10] suggested a possible new mechanism for the transport of heat across a liquid-metal interface. It was, in a sense, the inverse of the mechanism proposed by Little,[4] in that it involved a coupling between the phonon wave functions of the liquid and that part of the electronic wave functions of the metal which "leaked" into the helium bath.

In order to test for the existence of this mechanism and, at the same time, to separate it from other possible mechanisms we proceeded to set up the following experiment. In the apparatus shown in Fig. 1, a platinum rod was mounted in the manner described earlier for a Kapitza resistance measurement. Platinum was chosen because of its relatively high resistance to surface corrosion and because of its high thermal diffusivity at low temperatures. A high-voltage probe was located in the helium column in close proximity to the platinum surface and was designed to give a minimum field gradient to the stainless-steel supporting tube. The arrangement is shown schematically in Fig. 4(a).

With a dc heat flux flowing through the platinum rod to the helium bath it was hoped that an ac electric field would periodically vary the distance the electronic wave functions "leaked" into the helium, and thus modulate the coupling between these wave functions and the phonons. The resulting modulation of the Kapitza resistance could then be observed as an ac temperature variation at one of the thermometers attached to the platinum in a manner as indicated in Fig. 4(b).

The maximum electric field available to us was about 100 000 V/cm peak to peak. The electric field was calculated from the measured voltage applied to the probe and the measured spacing between the probe and the platinum surface. The spacing was also estimated by assuming that the probe and platinum surface formed a parallel plate condenser and calculating its capacity by measuring the displacement current observed at the frequencies used. The spacing was about 0.3 mm. The output of the phase detector was observed both with the heat current on and off and with the electric field on and off. With the above field values and with dc heat currents up to about 5 mWs no significant signal was observed at frequencies of 500 and 150 cps. From the sensitivity of our detection apparatus we were forced to conclude that, in the temperature range of 1.4 to 1.8°K, the ratio of the ac part of the Kapitza resistance to the total Kapitza resistance was less than about 1 part in 10^7.

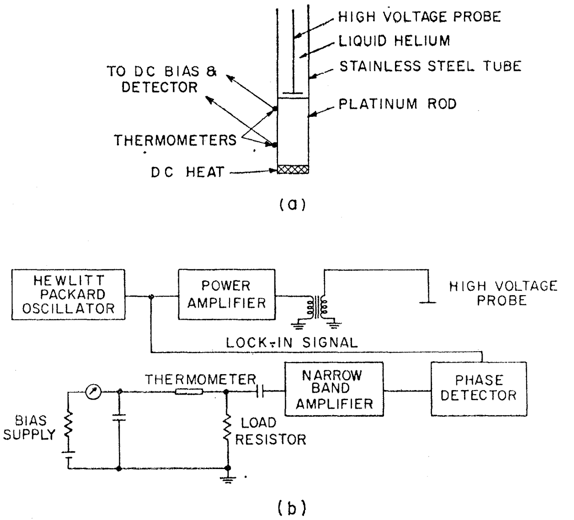

FIG. 4. (a) Schematic arrangement in cryostat. (b) Schematic arrangement of detection system.

Since we had none but the crudest of means at our disposal to estimate the size of the effect which should be expected, we cannot, at the moment, evaluate our negative results in relation to the proposed mechanism. It is possible, for example, that, in the light of a complete theory of the mechanism, the high work function of platinum may preclude observation of the mechanism at the electric fields which we could use. It is also possible that an adsorbed layer of helium atoms on the platinum surface could severely inhibit the effect.

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[8] W. A. Little (private communication).

[9] F. Bloch, post-paper discussion, spring meeting of the American Physical Society (Washington, D. C., April 24–27, 1961).

[10] A brief description of the mechanism proposed by Professor Bloch has recently been given by W. A. Little, IBM J. Research and Devel. **6**, 31 (1962).