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Heat Transport in Liquid He^3[†][*]

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The thermal conductivity of liquid He^3 at a pressure of $\frac{2}{3}$ atmosphere has been determined experimentally and found to increase slowly from 7×10^{-5} watt/cm°K at 0.24°K to 16×10^{-5} watt/cm°K at 2.7°K with no evidence of superfluidity. Several models of liquid He^3 based on Fermi-Dirac statistics predict a $1/T$ dependence for the thermal conductivity of He^3 at the lowest temperatures, but no such behavior has been observed down to 0.24°K in the present work. A study of the convective heat transport in the liquid has indicated that the coefficient of thermal expansion becomes negative below about 0.5°K. A thermal boundary resistance across a copper-liquid He^3 interface has been found which is similar in magnitude and temperature dependence to that found for a copper-superfluid He^4 boundary.

I. INTRODUCTION

With the exception of helium the macroscopic properties of liquids are changed only slightly by a change in isotopic composition. In contrast liquid He^3 and liquid He^4 are dramatically different in many of their properties. They have been called quantum liquids since their properties appear to be determined in a significant way by Fermi-Dirac and Bose-Einstein statistics, respectively.

The heat transport properties of liquid He^4 have been subject to several investigations[1-9] and found to be highly anomalous. In the helium I region, i.e., above the λ point 2.19°K, the thermal conductivity obeys approximately the kinetic gas relationship $K=2.5\eta C_v$, where η is the viscosity and C_v the specific heat at constant volume.[1-3] This gas-like behavior is consistent with the high zero-point energy and the consequent open structure of the liquid. In the liquid He II region of temperature, below the lambda point, the heat transport increases by many orders of magnitude and can be explained only in terms of the two-fluid model and Bose-Einstein statistics.[4-7,9] The dominant mechanism of heat transport is a countercurrent convective flow of the normal and superfluid components. Below 0.6°K the contribution of the two-fluid convective flow to the heat transport becomes vanishingly small and a true conductivity proportional to T^3 is observed.[8] In this temperature range the only excitations in liquid He^4 are longitudinal phonons with long mean free paths so that heat conduction is limited principally by the scattering of the phonons at the walls of the container. This behavior is similar to that observed at the lowest temperatures in solid dielectric crystals such as diamond.

The thermal transport properties of He^3 are expected to be quite different. No superfluid phase is likely although suggestions have been made that at a sufficiently low temperature a pairing of He^3 atoms might result in the liquid becoming superfluid.[10,11] Early theoretical treatments[12] based on the ideal Fermi gas model predicted a thermal conductivity proportional to $1/T$ at temperatures well below the degeneracy temperature. On the same model the viscosity is proportional to $1/T^2$. Using the Landau model of a Fermi liquid, Abrikosov and Khalatnikov[13] have formulated a theory of the transport properties of liquid He^3 which predicts for the thermal conductivity

$$K=3\times10^{-6}/T \text{ (watts/cm°K)},$$

and for the viscosity

$$\eta=10^{-6}/T^2 \text{ poise},$$

at temperatures below about 0.1°K to 0.2°K. Until this investigation was undertaken no experimental data on the heat transport properties of liquid He^3 had been taken. We therefore set out to make such measurements to as low a temperature as possible. As a check on earlier measurements the thermal conductivity of liquid He^4 above the lambda point was also measured with the same apparatus. Preliminary reports[14,15] of this work were given at conferences in 1957.

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[*] This material has been submitted by D. M. Lee as part of a dissertation for the degree of Doctor of Philosophy at Yale University.

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[1] W. H. Keesom and A. P. Keesom, Physica 3, 359 (1936).

[2] C. Grenier, Phys. Rev. 83, 598 (1951).

[3] R. Bowers, Proc. Phys. Soc. (London) A65, 511 (1952).

[4] Keesom, Saris, and Meyer, Physica 7, 817 (1940).

[5] P. L. Kapitza, J. Phys. U. S. S. R. 5, 59 (1942).

[6] L. Meyer and J. H. Mellink, Physica 13, 197 (1947).

[7] P. Winkel and D. H. N. Wansink, *Progress in Low-Temperature Physics*, edited by C. J. Gorter (Interscience Publishers, Inc., New York, 1957), Vol. 2, p. 83.

[8] H. A. Fairbank and J. Wilks, Proc. Roy. Soc. (London) 231, 545 (1955).

[9] K. R. Atkins, *Liquid Helium* (Cambridge University Press, Cambridge, 1959). See Chaps. 4 and 6 for a detailed review of transport properties of liquid He^4.

[10] R. B. Dingle, Phil. Mag. 42, 1080 (1951).

[11] Cooper, Mills, and Sessler, *Proceedings of the Kamerlingh-Onnes Memorial Conference on Low-Temperature Physics, Leiden, Holland, 1958* [Suppl. Physica 24, S183 (1958)].

[12] I. Pomeranchuk, J. Exptl. Theoret. Phys. U.S.S.R. 20, 919 (1950).

[13] A. A. Abrikosov and I. M. Khalatnikov, J. Exptl. Theoret. Phys. U.S.S.R. 32, 1083 (1957) [translation: Soviet Phys. J.E.T.P. 5, 887 (1957)].

[14] Lee, Donnelly, and Fairbank, Bull. Am. Phys. Soc. 2, 64 (1957).

[15] D. M. Lee and H. A. Faribank, *Proceedings of the Fifth International Conference on Low-Temperature Physics and Chemistry, Madison, Wisconsin, August 30, 1957*, edited by J. R. Dillinger (University of Wisconsin Press, Madison, Wisconsin, 1958), p. 90.

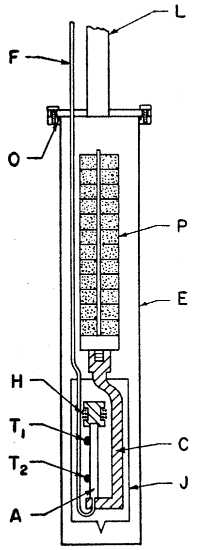

FIG. 1. Diagram of the inner portion of the cryostat containing the salt pill *P*, the sample tube *A* filled with liquid He^3, and the resistance thermometers T_1 and T_2.

In conjunction with the thermal conductivity measurements, the thermal boundary resistance across a copper-liquid He^3 interface was measured.[16] Such a boundary resistance was observed first by Kapitza[17] in 1941 for heat flowing across the interface between copper and superfluid He^4 (He II). In understanding this Kapitza boundary resistance it is important to know whether such a resistance exists in other liquids. However, if it does exist in other liquids it may easily be masked by the thermal resistance of the liquid, inasmuch as the boundary resistance is not large and decreases rapidly with increasing temperature. He^3 is the only other substance which exists as a liquid near 0°K where this boundary resistance appears to be very large and therefore we decided to look for this effect across a copper-liquid He^3 interface at the lowest temperatures attainable.

II. THERMAL CONDUCTIVITY MEASUREMENTS

1. Apparatus and Procedure

Since the temperature region below 1°K was of primary interest, a magnetic cooling method was employed in this experiment. The lower portion of the cryostat (shown in Fig. 1) was immersed in a bath of liquid helium. The conductivity cell and paramagnetic salt pill *P* were contained in a cylindrical brass can *E* which was attached to a brass flange by means of a gold *"O"* ring seal, *O*. A tube, *L*, was silver-soldered to this flange in order to allow He^4 exchange gas to be admitted from a bulb at room temperature or to be removed by a fast diffusion pump. The salt pill was a conventional compressed powder pill similar to that used earlier at Yale[18] typically consisting of about 40 grams of potassium chrome alum with about twenty evenly spaced thin copper disks to provide good heat transfer within the pill. The thermal conductivity cell was screwed tightly onto the salt pill and the whole assembly was kept from touching the walls of the can *E* by means of thin stainless steel spacers in the shape of four-pronged stars. Because of the poor thermal conductivity of stainless steel at these temperatures as well as the poor thermal contact between the spacers and the can wall, the heat leak was very small.

The conductivity cell was similar in design to that used by Fairbank and Wilks.[8] The He^3 was introduced through the capillary fill tube *F* into a thin-walled (0.0565-in. i.d., 0.0625-in. o.d.) cupro-nickel tube *A*. In the apparatus shown in Fig. 1, an electrical heater *H*, consisting of several hundred turns of insulated No. 40 constantan wire wrapped around a copper spool, was soldered to the upper end of the tube. The heat flowed from the heater vertically downward through the liquid column and then passed into a copper heat link *C* which was soldered to the lower end of the tube and was maintained at a low temperature by the salt pill. In a later model of the apparatus the heater was attached to the bottom of the column and the heat flowed vertically upward. The temperature gradient along the helium column was measured by means of 2 IRC 270 ohm carbon resistance thermometers which varied from 750 ohms at 0.2°K to 450 ohms at 3°K. The heater and tube containing the liquid He^3 were isolated from the exchange gas can by means of a vacuum jacket *J* which was permanently sealed to prevent spurious heat transfer by residual exchange gas.

In the first measurements the length of the helium column was 2 cm and the distance between thermometers was 1.18 cm. Because He^3 has a high specific heat and a low thermal conductivity, the time required to reach equilibrium using this geometry was about one

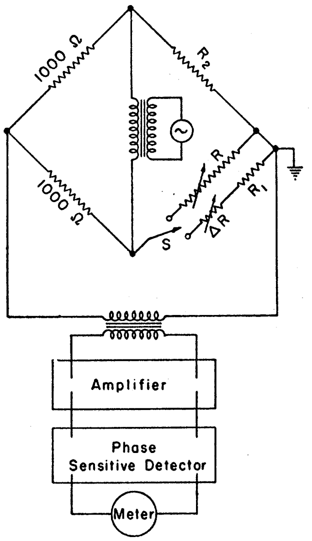

FIG. 2. Schematic diagram of the ac bridge circuit used for measuring the resistance of the thermometers.

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[16] H. A. Fairbank and D. M. Lee, *Proceedings of the Fifth International Conference on Low-Temperature Physics and Chemistry, Madison, Wisconsin, August 30, 1957*, edited by J. R. Dillinger (University of Wisconsin Press, Madison, Wisconsin, 1958), p. 93.

[17] P. L. Kapitza, J. Phys. U.S.S.R. 4, 181 (1941).

[18] J. C. King and H. A. Fairbank, Phys. Rev. **93**, 21 (1954).

hour. Since the equilibrium time is proportional to the square of the length of the helium column, by reducing the length to 0.6 cm the time to reach a steady state was shortened to a few minutes. The distance between thermometers was reduced to 0.28 cm in the shorter tube. The resistance thermometers were soft soldered to small copper tabs which were in turn silver-soldered to the cupro-nickel tube. Considerable care was taken to keep the silver solder fillets as small as possible to minimize the uncertainty in the distance between the thermometers. This distance was carefully measured by means of a traveling microscope.

Above 1°K the helium bath pressure served as the primary temperature standard against which the resistance thermometers were calibrated. Below 1°K the absolute temperature was determined by measuring the magnetic susceptibility of the salt pill using the ballistic method. The absolute temperature T was computed from the Curie temperature T^* using the $T-T^*$ corrections of Bleaney[19] for potassium chrome alum and those of Cooke[20] for manganese ammonium sulfate.

Demagnetization from initial fields of 8 kilogauss and temperatures near 1.2°K gave final temperatures on the order of 0.2°K or slightly lower. The heat leak was quite low and the heater power varied from less than 0.1 to 2 microwatts so that long warm-up times, in some cases more than eight hours, were the rule. The heater and resistance thermometer leads were threaded through the exchange gas pumping tube and were thermally locked to the helium bath by means of binding posts attached to the flange at the top of the can E. The pumping tube contained an optical baffle to trap out radiation from the top of the cryostat, further reducing the heat leak.

Because of the very low heat conductivity of the carbon resistors at the lowest temperatures the power dissipated in these resistors during measurement had to be kept below 10^{-9} watts to avoid a temperature rise in the resistors when measuring power was applied. This necessitated an accurate means of measuring resistance at very low power levels. For this purpose a 1000-cycle alternating current Wheatstone bridge employing tuned amplifiers and a phase-sensitive detector was constructed similar to that used by Fairbank and Wilks.[8] The basic scheme of the bridge is shown in Fig. 2. R_1 and R_2 are the resistance thermometers in the conductivity cell. When the switch S is in the up position, the resistance box R is balanced against R_2; when the switch is in the down position the box ΔR is balanced so that $R_1+\Delta R=R_2$, hence allowing a direct measure of the difference in resistance between R_1 and R_2. By switching quickly from one resistance box to the other it is possible to obtain the value of R_2 and ΔR almost simultaneously. This arrangement is particularly advantageous in demagnetization experiments where the temperatures of both R_1 and R_2 are constantly drifting upward. In these circumstances a more accurate measurement of the resistance or temperature difference can be obtained by measuring ΔR directly than by first measuring R_1 and then measuring R_2.

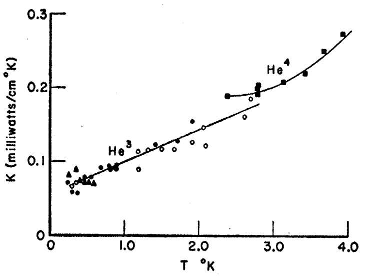

FIG. 3. The thermal conductivity of liquid He³ and liquid He⁴ as a function of temperature. Data were taken with three different apparatus as explained in the text.

The thermal conductivity K of the liquid He³ was calculated from the defining equation,

$$K=\dot{Q}\Delta x/A\Delta T, \qquad (1)$$

where $\dot{Q}$ is the power passing through a column of liquid of cross section A, and ΔT is the temperature difference between two thermometers Δx apart. Because the thermal conductivity of liquid He³ is so very low a sizable correction must be made for the heat carried by the walls of the sample tube. At the beginning of the experiment the thermal conductance of the empty cupro-nickel sample tube was carefully measured as a function of temperature. The thermal conductance of the tube filled with liquid helium is the sum of the conductance of the liquid column and that of the walls. Therefore $\dot{Q}/\Delta T$ in Eq. (1) was calculated from the equation

$$(\dot{Q}/\Delta T)_{\text{liquid}}=(\dot{Q}/\Delta T)_{\text{total}}-(\dot{Q}/\Delta T)_{\text{tube}}. \qquad (2)$$

The tube conductance ranged from about 30% of the total conductance at 0.2°K to about 70% at 2°K.

2. Discussion of Results

The measured thermal conductivity values of liquid He³ are shown in Fig. 3. The thermal conductivity of liquid He⁴ above the lambda point was also measured with the same apparatus and the results are shown in the figure. The open circles correspond to the earliest He³ data taken using the 2 cm liquid column and a manganese ammonium sulfate salt pill; the solid circles correspond to the data taken using a 0.6 cm liquid column and a potassium chrome alum salt pill. The above points were all measured with an apparatus in which the heat flow was vertically downward. In the measurements below 0.6°K only points with heater powers of less than 0.3 microwatts are shown. (The reason for this will become evident later.) At the lowest temperatures, powers as low as a few hundredths of a microwatt were used.

The solid triangles in Fig. 7 indicate the points which were taken with an inverted apparatus in which the heat was applied at the lower end of the liquid He³ column and flowed vertically upwards. The length of the He³ column was again 0.6 cm and the absolute

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[19] B. Bleaney, Proc. Roy. Soc. (London) **204**, 216 (1950).
[20] A. H. Cooke, Proc. Phys. Soc. (London) **A62**, 269 (1949).

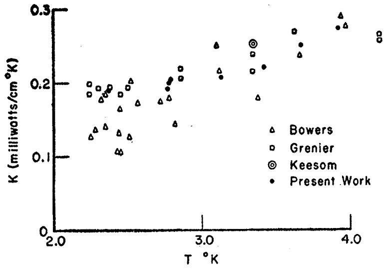

FIG. 4. The thermal conductivity of liquid He^4 above T_λ with the results of Bowers,[3] Grenier,[2] and Keesom[1] shown for comparison.

temperature was determined by the susceptibility of a potassium chrome alum salt pill. In this inverted apparatus, heater powers between one microwatt and 0.08 microwatt were applied in the temperature region below 0.65°K and no points are included above 0.65°K. (The reason for this will also become evident later.)

Challis and Wilks[21] have also reported measurements of the thermal conductivity of nearly pure liquid He^3 (95% He^3, 5% He^4) from 1.3°K to 3.0°K. In their method the heat flow took place between two copper blocks separated by a narrow gap filled with liquid. In this method the measured resistance included the Kapitza thermal boundary resistance at each interface in addition to that of the liquid so that the results are not exactly comparable. However, their values of K show a similar temperature dependence to ours and are a few percent lower in value as would be expected.

Down to the lowest temperatures there was no evidence of either superfluidity or the $1/T$ dependence predicted by the models based on Fermi statistics. Unfortunately no measurements were made below 0.2°K so that no comparisons could be made with the semiquantitative theory of Abrikosov and Khalatnikov.[13] These authors predict that K should be approximately equal to $4\times10^{-6}\ T^{-1}$ watts/cm °K below 0.1°K or 0.2°K. This would give a value of 4×10^{-5} watts/cm °K at 0.1°K and 2×10^{-5} watts/cm °K at 0.2°K. These values are somewhat smaller than extrapolations of our data. Clearly, it would be desirable to perform measurements at lower temperatures in order to give this theory a proper test.

The thermal conductivity values of helium I are in good agreement with the results of Bowers,[3] Grenier,[2] and Keesom[1] within the accuracy of the various measurements. The results of these investigators as well as the present results are shown in Fig. 4. Challis and Wilks[21] from measurements using the same apparatus as for their He^3 measurements report values of the thermal conductivity of He^4 about 25% lower than ours. They suggest that this discrepancy again is probably due to the thermal boundary resistance which has not been subtracted.

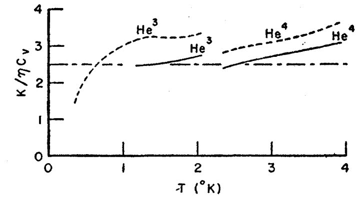

FIG. 5. The ratio of the thermal conductivity to the product of viscosity and specific hea tat constant volume as a function of temperature for liquid He^3 and liquid He^4. The kinetic theory value of this ratio, 2.5, is shown by the dashed curve. The upper curves are calculated using the viscosity data of Zinovieva[24]; the lower using the viscosity values of Taylor and Dash.[22]

Grenier[2] and other[15,21,22] have pointed out that the gas kinetic theory relationship $K=2.5\eta C_v$ between the thermal conductivity K, the viscosity η, and the specific heat at constant volume C_v seems to be reasonably obeyed for liquid He I. Figure 5 is a plot of $K/\eta C_v$ against temperature for both liquid He^3 and He^4 using our values of K and values of C_v computed by Goldstein[23] from the experimental saturated vapor pressure values. In the upper curves the viscosity values of Zinovieva[24] are used and in the lower curves η is taken from measurements of Taylor and Dash.[22] It is clear that $K/\eta C_v$ is strongly temperature dependent below 1°K for liquid He^3 although it becomes nearly constant above 1°K at a value close to 2.5 (using Taylor and Dash's values of η).

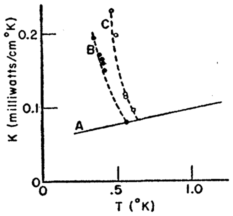

FIG. 6. The apparent conductivity of liquid He^3 showing the increased transport due to convection. The heater power for each curve was as follows: Curve A, less than 0.3 μw; Curve B, 0.86 μw; Curve C, 2.0 μw. The heat flow was vertically downward.

3. Density Maximum

In the apparatus in which the heat flowed vertically downward, a striking anomaly in the thermal conductivity of He^3 was observed below 0.6°K when the heater power was greater than about $\frac{1}{2}$ microwatt. The thermal conductivity at these higher powers showed a sharp increase with decreasing temperature as shown in Fig. 6, where curve B represents points taken with a heater power of 0.86 microwatt and curve C represents points taken with a heater power of 2.0 microwatts. Curve A is taken from Fig. 3 and represents the thermal conductivity data taken at lower powers. The sharp increase in the heat transport for the higher powers suggests the presence of additional convective heat flow which could occur if part of the liquid column were at a temperature for which the density increases with increasing temperature. Since the heat flowed vertically downward through the column of liquid, convection would be expected to occur only if the coldest part of the liquid was less dense than the warmer portions. For

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[21] L. J. Challis and J. Wilks, Symposium on Liquid and Solid He^3, Ohio State University, August 20–23, 1957 (unpublished).

[22] R. D. Taylor and J. D. Dash, Phys. Rev. **106**, 398 (1957).

[23] L. Goldstein, Phys. Rev. **112**, 1465 (1958) and private communication.

[24] K. N. Zinovieva, J. Exptl. Theor. Phys. U.S.S.R. **34**, 609 (1958) [translation: Soviet Phys. J.E.T.P. **7**, 421 (1958)].

both powers shown in Fig. 6, the coldest part of the liquid was at 0.48°K when the break away from the nonconvective thermal conductivity occurred. This would seem to indicate that a density maximum in liquid He^3 at a pressure of $\frac{2}{3}$ atmosphere occurs above this temperature.

Thus below 0.48°K, He^3 would have a negative coefficient of thermal expansion so that in accordance with the Maxwell relation

$$(\partial S/\partial P)_T = -(\partial V/\partial T)_P,$$

the entropy would be an increasing function of pressure. The existence of the density maximum was verified by making measurements with an inverted apparatus in which the heat flow was from the bottom to the top of the He^3 column. With sufficiently high heater power an anomalously large transport of heat was observed above about 0.5°K but below 0.5°K the heat transport was independent of the applied power. The conductivity values obtained with this inverted apparatus below the density maximum were in good agreement with the low-power thermal conductivity values obtained using the earlier apparatus. This indicated that the convective heat transfer could be made negligible for downward heat flow in this temperature region by application of sufficiently small powers, and that the low-power measurements in the earlier runs gave true conductivity values.

A density maximum in liquid He^3 has been predicted by Abraham, Osborne, and Weinstock,[25] by Goldstein[26] and by Brueckner and Atkins,[27] and recent experiments by Lee, Reppy, and Fairbank,[28] Taylor and Kerr,[29] Sherman and Edeskuty,[30] and Brewer and Daunt[31] have confirmed the existence of this maximum.

III. THERMAL BOUNDARY RESISTANCE

1. Experimental Procedure

By soldering a third resistance thermometer to the copper block on which the heater was wound, it was possible to obtain the temperature drop across the copper-liquid interface as a function of heat flux and therefore obtain the thermal boundary resistance with the same apparatus. The essentials of the method of measurement are illustrated in Fig. 7 where a schematic drawing of the sample tube is shown. The liquid He^3 is condensed into the cupro-nickel tube (1.5-mm diameter) capped at each end with a plug of high-purity copper. Power from the electric heater serving as the source of heat passes from the copper plug at temperature T_0 through the column of liquid to the heat sink at temperature T_3. The potassium chrome alum salt pill attached to the bottom copper plug serves as the heat sink and thermometer. The temperature gradient in the liquid is found from two carbon resistance thermometers attached at two points along the tube as previously described. Thus the temperature T_0 of the copper heat source, the temperatures T_1 and T_2 along the liquid column and the temperature T_3 of the copper heat sink can be determined as a function of the heat flow. As illustrated in Fig. 7 it is possible, therefore, to find by extrapolation the temperature of the liquid at each copper surface and hence the temperature drop ΔT across the copper-liquid interfaces. The thermal boundary resistance is then calculated from the relation

$$R = A\Delta T/\dot{Q},$$

where $\dot{Q}/A$ is the heat flux across the interface. As in the case of the thermal conductivity measurement of the liquid, the heat carried by the walls has been subtracted from the total heat flow to obtain $\dot{Q}$.

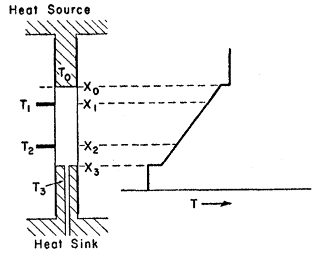

FIG. 7. Schematic drawing of the sample tube for measurement of the temperature drop across the copper-liquid interface as a function of heat flux.

2. Results and Discussion

The results of the thermal boundary resistance measurements at a liquid He^3-copper interface are plotted in Fig. 8. The open circles represent measurements taken at the hot end of the He^3 column using a third resistance thermometer, and the solid circles represent measurements taken at the cold end of the column using the salt measurements to determine the temperature of the copper. As in the case of He^4, a temperature

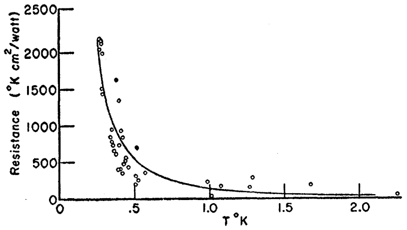

FIG. 8. The thermal boundary resistance of a copper-liquid He^3 interface as a function of temperature. The solid line is the equation $R = 130/T^2$.

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[25] Abraham, Osborne, and Weinstock, Symposium on Liquid and Solid He^3, Ohio State University, August 20–23, 1957 (unpublished).

[26] L. Goldstein, Phys. Rev. **112**, 1483 (1958).

[27] K. A. Brueckner and K. R. Atkins, Phys. Rev. Letters **1**, 315 (1958).

[28] Lee, Reppy, and Fairbank, Bull. Am. Phys. Soc. Ser. II, **3**, 339 (1958).

[29] R. D. Taylor and E. C. Kerr, *Proceedings of the Kamerlingh-Onnes Memorial Conference on Low-Temperature Physics, Leiden, Holland, 1958* [Suppl. Physica 24, S133 (1958)].

[30] R. H. Sherman and F. J. Edeskuty, Bull. Am. Phys. Soc. Ser. II, 4, 240 (1959).

[31] D. F. Brewer and J. G. Daunt, Bull. Am. Phys. Soc. Ser. II, 4, 6 (1959).

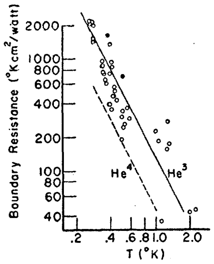

FIG. 9. A log-log plot of the thermal boundary resistance of liquid He^3 as a function of T. The dashed curve represents the empirical relation $R=45/T^2$ obtained by Fairbank and Wilks[8] for a copper-liquid He^4 interface. The solid curve is the relation $R=130/T^2$.

difference across the boundary is found for liquid He^3 proportional to the heat input and increasing sharply as the temperature decreases. Figure 9 is a log-log plot of the same data. For He^4, the boundary resistance found by Fairbank and Wilks[8] is given by the empirical relation, $R=45/T^2$, and is indicated by the dashed curve in Fig. 9. Because of the very high thermal resistance of He^3, the accuracy of the boundary resistance is much lower than in the case of the He^4 measurement. However, it does appear that the temperature dependence is similar and that the magnitude of the boundary resistance is slightly higher for He^3 than for He^4. A possible fit to the He^3 data is given by the relation $R=130/T^2$ shown by the solid curve in Fig. 8 and Fig. 9. In view of the low precision of this measurement, this formula should be considered only as a guide to the order of magnitude of the resistance to be expected.

The fact that a thermal boundary resistance exists in liquid He^3 of comparable magnitude to that found in liquid He^4 would seem to indicate that the major contribution to this boundary resistance is not connected with superfluid effects and, furthermore, that this resistance may be a general property of interfaces between dissimilar substances. Khalatnikov[32] and Mazo and Onsager[33] have attempted to explain this Kapitza boundary resistance as a type of thermal contact resistance which arises because of the different acoustic impedances of the two media. They consider the heat to be transferred by the radiation of sound waves between the solid and liquid which results in a heat resistance proportional to T^{-3} and dependent on the elastic constants of the helium and the solid. On this theory such a resistance should be present for all solid-liquid interfaces. However, the observed temperature dependence below 1°K for the boundary resistance across a solid-liquid helium boundary is not in agreement with the predictions of the theory. Furthermore, measurements of Dransfeld and Wilks[34] for a copper-liquid He^4 interface do not show a dependence of the boundary resistance on pressure as predicted by this theory. Recently, Challis and Wilks[35] have developed a model for the Kapitza resistance which is based on the acoustic mismatch idea but which takes into account the increase in the liquid density near the solid-liquid interface. This model predicts that the Kapitza resistance above 1°K would be almost independent of pressure in agreement with the experimental results of Dransfeld and Wilks.[34] The calculated variation of resistance with temperature, however, is not in agreement with observation.[8] It would appear that further work on this problem, both experimentally and theoretically, is in order.

IV. CONCLUSIONS

Down to the lowest temperatures reached in the experiment, the Fermi-Dirac statistics did not appear to have any dramatic effect on the thermal conductivity of the liquid He^3. No evidence of superfluidity was found. It would be desirable to extend these measurements to lower temperatures where the theory of Abrikosov and Khalatnikov predicts a $1/T$ dependence for this conductivity. Although rough agreement with the gas kinetic equation $K=2.5\eta C_v$ above 1°K was obtained in these measurements, this relation did not hold at the lowest temperatures.

Measurements of convective heat flow show that a density maximum exists in liquid He^3 at about 0.5°K. Therefore, the entropy of the liquid must increase with pressure below this temperature. The existence of this maximum has been predicted theoretically by several authors and has now been confirmed experimentally at a number of laboratories.

The fact that a thermal boundary resistance exists in liquid He^3 makes it seem improbable that this effect can be explained by superfluidity. The acoustic mismatch theories account for some but not all of the boundary resistance behavior. Further work is indicated before a satisfactory understanding of this phenomenon can be achieved.

V. ACKNOWLEDGMENTS

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

[33] R. Mazo, Ph.D. dissertation, Yale University, 1955 (unpublished).

[34] K. Dransfeld and J. Wilks, *Proceedings of the Fifth International Conference on Low-Temperature Physics and Chemistry, Madison, Wisconsin, August 30, 1957*, edited by J. R. Dillinger (University of Wisconsin Press, Madison, Wisconsin, 1958), p. 39.

[35] L. J. Challis and J. Wilks, *Proceedings of the Kamerlingh-Onnes Memorial Conference on Low-Temperature Physics, Leiden, Holland, 1958* [Suppl. Physica 24, S145 (1958)].