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AN INVESTIGATION OF THE TEMPERATURE DISCONTINUITY AT THE BOUNDARY BETWEEN A SOLID AND SUPERFLUID HELIUM

KUANG WEY-YEN

Institute for Physics Problems, Academy of Sciences, U.S.S.R.

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Results are given of measurements of the temperature jump at the boundary between superfluid helium and various metals (Cu, Pb, Sn, Ni, and Pt) and quartz, for a constant heat current. The measurements on copper were made over a wide range of temperature and pressure, from the λ -point to 0.57°K, throughout the whole region of existence of helium II. It is shown that the temperature jump for heat transfer from copper to superfluid helium is of the same nature as from helium to copper. It is suggested that the main cause of the discrepancy between the experimental results and Khalatnikov's theory is the existence of amorphous and deformed layers on the metal surfaces.

Results of measurements of the temperature jump are also given for: a) the boundary between tin and liquid helium II when the tin goes over to the normal state in a magnetic field.

1. INTRODUCTION

P. L. Kapitza^[1] was the first to find that a temperature discontinuity occurs in heat transfer from a solid to liquid helium II, and he established that this jump is directly proportional to the heat current, and for a given current is inversely proportional to T^3 .

On the basis of Landau's theory of superfluidity, Khalatnikov^[2] considered heat transfer at the boundary between a solid and liquid helium II as a process of emission (and absorption) of sound from the vibrating surface of the solid. This model agrees well with Kapitza's experiments. The following equation is found for the coefficient of heat transfer:

$$m = \frac{W}{\Delta T} = \frac{16\pi^2 k^4 \rho_L c_L}{15 (2\pi\hbar)^3 \rho_S c_L^3} F\left(\frac{c_t}{c_l}\right) T^3, \quad (1)$$

where W is the heat current density, ΔT the temperature jump, ρ_L and ρ_S are the density of liquid helium II and of the solid, c_L is the velocity of

first sound in liquid helium, c_t and c_l are the velocities of longitudinal and transverse sound waves in the solid and $F(c_t/c_l)$ is a function of the elastic constants of the solid.

Gorter, Taconis, and Beenakker^[3] gave a formal theory of the phenomenon of heat transfer across the boundary between a solid and helium II, considering the boundary resistance effect as a specific property of a superfluid liquid. However, since a similar temperature jump was found^[4] at the boundary between a solid and liquid He³, there must be some doubt about this theory.

It was shown by Osborne^[5] and by Zinov'eva^[6] that the temperature dependence of the heat transfer coefficient fits the law $m \sim T^3$ within the accuracy of the experimental errors. However, this dependence was nearer to $m \sim T^{2.6}$ in the work of White, Gonzales, and Johnston,^[7] while it corresponded to T^3 in the work of Fairbanks and Wilks^[8] who carried out measurements from 0.3 to 1°K.

The absolute values of ΔT differ even more among different authors. For example, the value

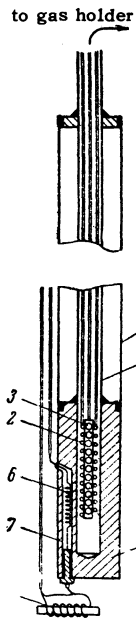


FIG. 1. Apparatus for studying the reversibility of the heat transfer at the boundary between a solid and liquid helium II.

of ΔT recently found in a second-sound resonator by Brow and Osborne^[9] was 20 times less than the theoretical value. From studying the heat transfer between copper and helium II at high pressures and from comparisons between copper and lead, Dransfeld and Wilks^[10] concluded that the dependence of ΔT on pressure and on the elastic constants of the solid, as predicted by Khalatnikov's acoustic model, was not confirmed by experiment.

In spite of the existence of a considerable amount of work devoted to studying the heat transfer from a solid to superfluid helium, this problem is not yet fully understood. The present work is an attempt to elucidate the reasons for the discrepancy between the existing experimental and theoretical data, in order to determine the true nature of the phenomenon.

2. THE REVERSIBILITY OF THE EFFECT

Since there have not been direct measurements of the temperature discontinuity for heat transfer from superfluid helium to a cold wall (the attempt by Andronikashvili and Mirskaya^[11] ended unsuccessfully), we made an apparatus in which to make these measurements and verify the reversibility of the effect.^[12]

The apparatus consisted of a thick-walled copper vessel 1 (M1 copper—99.90% pure) 40 mm long, 14 mm o.d., and 5 mm i.d. A 40 μ phosphor bronze thermometer 2 and a constantan heater 3 are contained inside the vessel. The stainless steel tube 4, through which helium is condensed, is soldered to the vessel. Tube 4 is

surrounded by the vacuum jacket 5 to prevent heat exchange between the helium inside the vessel and the bath. The temperature of the copper vessel is measured by the phosphor bronze thermometer 6, inside the sealed recess 7, filled with helium gas. Thermometer 8 is for measuring the temperature of the bath.

The experiment consisted in measuring the resistance of three thermometers under stationary conditions when power is dissipated inside the copper vessel. During the measurements the temperature was kept constant to an accuracy of $\pm (1.5-3) \times 10^{-4}$ °K. The temperature jump on both boundaries of the wall of the copper vessel was determined from the change of resistances of thermometers 2 and 8. The total error in determining the temperature jumps was $\pm (1-3) \times 10^{-4}$ °K. According to calculation, the heat loss through the inner tube did not exceed 2%.

The results of the experiments show that at both boundaries ΔT increases linearly with the power conducted.^[12] The linearity breaks down only at high flows, and is preserved longer at lower temperatures. The temperature dependence of the heat transfer coefficient m satisfies the relation $m \sim T^{2.3}$ for both boundaries. (The power of T is determined in these experiments within ± 0.3). However, the coefficients of proportionality are different for the two boundaries. The discrepancy is evidently to be explained by the different degrees of roughness of the surfaces of the copper vessel.

The experiments carried out allow one to conclude that there is a temperature discontinuity of the same order of magnitude, with the same temperature dependence, at the boundary between a solid and superfluid helium when there is a heat transfer from the solid to the liquid or the reverse.

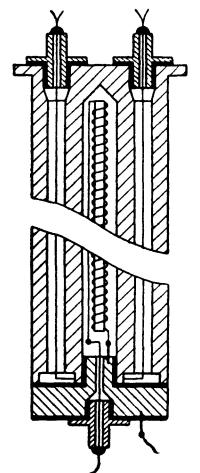


FIG. 2. Apparatus for measuring the temperature jump over a wide temperature range and at elevated pressures.

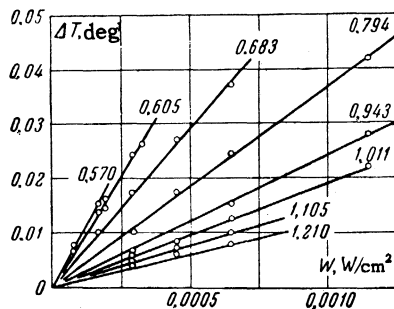


FIG. 3. The dependence of the temperature jump at the boundary between copper and helium II on the heat current (data of experiments carried out in a He³ cryostat). The numbers on the curves are the bath temperature in °K.

3. THE TEMPERATURE DISCONTINUITY AT VERY LOW TEMPERATURES

A second apparatus (Fig. 2) was constructed, capable of measuring the temperature discontinuity over a wider temperature range, and measurements were made between 0.570 and 2.075°K.^[12]

This apparatus was also made of M1 copper in the form of a 5 mm i.d. cylinder 50 mm long. A constantan heater was placed in the center of the cylinder cavity. Two channels were drilled in the wall of the cylinder and 40 μ phosphor bronze wire drawn through them. The cylinder and channels were filled with helium gas at atmospheric pressure.

Temperatures below 1°K were obtained by pumping He³ vapor.^[13] The bath temperature below 1°K was determined by a 30 μ diameter phosphor bronze thermometer. The resistance thermometer was first calibrated against the vapor pressure of He³, pumped in a closed system.

Figure 3 shows the measured temperature jump ΔT as a function of heat flow per unit area of surface. The temperature dependence of the slope of these curves $m = W/\Delta T$ is shown on a logarithmic scale in Fig. 4 (curve 2). As can be seen from the graph, the following law holds in the temperature range measured

$$m = 0.48 T^{2.6} \text{ W/cm}^2 \text{ deg} \quad (2)$$

The power of T in these experiments was determined to an accuracy of ± 0.1 . Within the limits of experimental error, the temperature dependences obtained with both apparatus thus agree among themselves.

We measured the thermal conductivity of M1 copper in the temperature range 1–2.1°K in order to calculate the correction for the thermal resistance of the wall. The results of the measurements

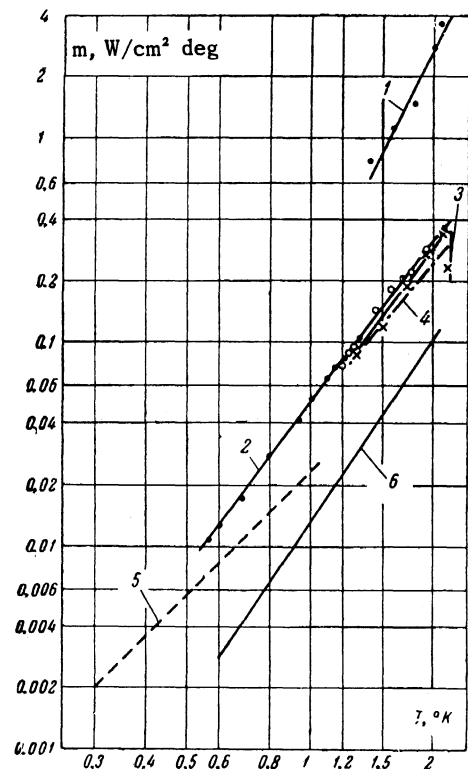


FIG. 4. The temperature dependence of the heat transfer coefficient between copper and liquid helium II: 1—data of Brow and Osborne^[9], 2—data from our measurements (o—points obtained at $p = 1$ atm), 3—data of White et al.^[7] 4—data of Zinov'eva,^[6] 5—data of Fairbank and Wilks,^[8] 6—theoretical curve of Khalatnikov.^[2]

show that the correction for the temperature drop along the copper wall is 3% of the measured value of the temperature jump at 2°K and 0.2% at 0.5°K, i.e., has practically no effect on the power of T in (2).

Nearly all the results obtained up to now on copper specimens are collected in Fig. 4 for comparison. The departure from the T^3 law observed in earlier work^[6,7,14] is also confirmed in our experiments.

4. THE TEMPERATURE DISCONTINUITY AT ELEVATED PRESSURES

Khalatnikov's theory^[2] predicts a dependence of the effect on the acoustic impedance of liquid helium $\rho_{\text{L}}c_{\text{L}}$. The compressibility of liquid helium is extremely high, so that an external pressure should have a great effect on the magnitude of ΔT . Experiments under pressure were made for examining this question.

The apparatus shown in Fig. 2 was put into a thick-walled copper vessel into which helium was admitted under pressure. The connecting system and the pressure measuring arrangement were the same as in Peshkov's and Zinov'eva's work.^[15]

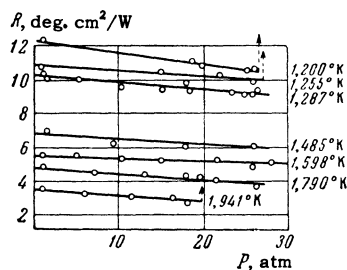


FIG. 5. The pressure dependence of the heat resistance of the boundary $R = \Delta T/W$ at different temperatures.

The dependence of the heat resistance of the boundary, $R = \Delta T/W$, on the external pressure P at different temperatures is shown in Fig. 5. ΔT decreases gradually with increasing pressure. At all temperatures $|dR/dP| \leq 0.07$ deg. cm²/W atm. Measurements become impossible on passing into the regions of solid helium and helium I because of the sharp increase in the heat resistance of the medium. The corresponding points are marked by dotted arrows in Fig. 5. As can be seen from Fig. 4, the points (○), determined from experiments carried out at atmospheric pressure, fall well on the curve taken at the saturated vapor pressure. Dransfeld and Wilks^[10] found the same behavior.

One of the peculiar properties of a quantum liquid is its great compressibility. According to the literature data, at 1.25°K $1/\rho_L c_L$ at $P = 25$ atm is decreased, for example, to 60% of its initial value under the saturated vapor pressure. The weak dependence of the effect on pressure, which we observed, does not agree with Khalatnikov's equation (1). To explain the smallness of the effect in the pressure experiments it is evidently necessary to assume the existence of a denser layer of helium at the surface of the solid, formed under the action of the van der Waals forces. This layer has a higher impedance $\rho_L c_L$. In this way the small effect of external pressure on the magnitude of the Kapitza temperature jump can be explained. Challis and Wilks^[16] draw the same conclusion in a brief communication.

The higher value of $\rho_L c_L$ in the layer at the wall than in the free helium can also explain, albeit in part, the fact that a larger heat transfer between copper and helium II is observed in the experiments than suggested by the theory.

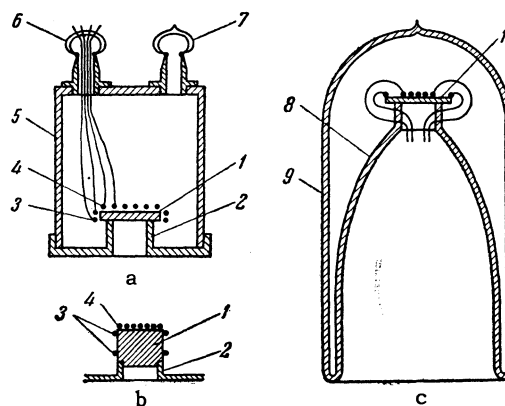


FIG. 6. Schematic drawing of apparatus for measuring the temperature jump at the boundary between liquid helium II and a solid.

5. THE DEPENDENCE OF THE KAPITZA TEMPERATURE JUMP ON THE MATERIAL OF THE SOLID

According to (1) the heat transfer coefficient of the boundary m depends on the elastic constants of the solid, being inversely proportional to $\rho_S c_t^3$. To verify this dependence, experiments were carried out with specimens of different metals (Pb, Sn, Ni, Pt) and with a quartz single crystal. Diagrams of the apparatus are shown in Fig. 6 (see also^[17]).

The specimens 1 of different metals were prepared in the shape of a disk (specimens Pb-I and Ni-I) or of a short cylinder (Fig. 6b, specimens Sn, Pb-II and Ni-II). The stainless steel tubes 2 of wall thickness 0.1 mm were soldered to the specimens. One or two thermometers 3, of 40 μ phosphor bronze wire, were wound on the side surfaces of the specimen. The heater 4 of constantan wire was bifilarly wound on the end of the specimen (on the vacuum jacket side). The electrical leads through the vacuum jacket were platinum wires sealed into the glass of the copper-glass seal 6. The copper-glass seal 7 is used to seal off the apparatus after the air has been pumped out. In addition, the leakage of helium into the apparatus can be observed through it at the end of each experiment.

Specimen	Degree of purity, wt %	Specimen dimensions mm		Specimen	Degree of purity, wt %	Specimen dimensions mm	
		diameter	height			diameter	height
Sn	>99,997	10,2	12,5	Ni-II	99,99	10,2	2,8
Pb-I	>99,9997	14,0	2,8	Pt	99,90	7,3	0,1
Pb-II	>99,9997	9,2	5,5	Cu	99,90	5,0	52,5
Ni-I	99,99	14,0	2,6	Quartz	—	12,5	10,9

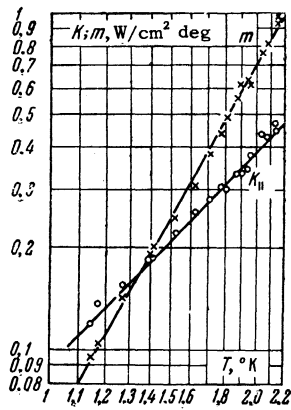


FIG. 7. The temperature dependence of the heat transfer coefficient m between quartz and liquid helium II and of the heat conductivity of quartz $K_{||}$.

The platinum specimen (Fig. 6c) was cut from 0.1 mm thick foil and sealed to the glass tube 8. The specimen and tube were surrounded by the glass vacuum jacket 9. The apparatus, when assembled, was annealed in an oven at 500°C for 3 hours to relieve the stresses in the glass.

In the case of quartz, the specimen in the form of a short cylinder was glued to the steel tube by BF-4 adhesive. The tube with the specimen was in turn sealed to a copper vacuum jacket with a low melting point solder. The surface of the single crystal quartz was ground and polished. Its plane was perpendicular to the principal optical axis of the crystal.

The purity and dimensions of the specimens are listed in the table (data are also given here for the copper specimen used in the previous experiments).

The surfaces of the specimens were carefully cleaned with alcohol and carbon tetrachloride before the assemblies were lowered into the dewar. Before filling with liquid helium, the dewar was filled with gaseous helium through a charcoal trap cooled to nitrogen temperatures.

Several such assemblies were immersed in the same helium bath during the measurements. The bath temperature in these experiments was held constant to $\pm 5 \times 10^{-5}$ °K, using an electronic ther-

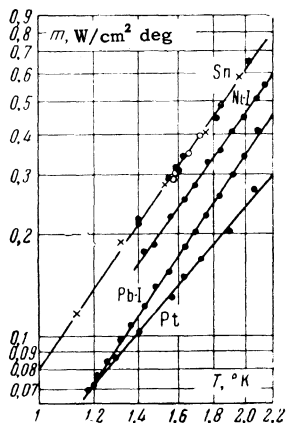


FIG. 8. The temperature dependence of the heat transfer coefficient m between different metals and liquid helium II. Data are also given for tin in a magnetic field of 300 Oe (\times) and in rotating helium (o).

mostabilizer with a photomultiplier^[18] and was measured by a thermometer in the bath.

Figure 7 shows the temperature dependence of the heat transfer coefficient m and the thermal conductivity $K_{||}$ of the quartz specimen. A correction was made to the data for ΔT at the boundary, for the temperature drop along the specimen itself. In the temperature range of the measurements $1.151 < T < 2.157$ °K the temperature dependence of m for quartz can be represented by the relation

$$m = 0.057 T^{3.6} \text{ W/cm}^2\text{-deg} \quad (3)$$

The uncertainty in determining the power of T is ± 0.2 . The deviation from the T^3 law is thus in the opposite direction, compared with copper.

The observed heat conductivity for the quartz single crystal specimen along its optic axis follows the relation

$$K_{||} = 0.09 T^{2.1} \text{ W/cm}^2\text{-deg}.$$

The results obtained with the apparatus with the Sn, Ni-I, Pb-I, and Pt specimens are shown in Fig. 8. The temperature dependence of m for these specimens in the temperature range mentioned is given by the following formulae (m in units of $\text{W/cm}^2\text{-deg}$):

$$\begin{aligned} m = 0.042 T^3 \text{ for Pb,} & \quad m = 0.081 T^{2.9} \text{ for Sn,} \\ m = 0.062 T^{2.9} \text{ for Ni,} & \quad m = 0.047 T^{2.3} \text{ for Pt.} \end{aligned} \quad (4)$$

The uncertainty in determining the power of T for these metal specimens is ± 0.1 .

The data for ΔT were used here without correction for the thermal resistance along the solid, since this correction, except for Pt, is only 1–2% of the measured quantity.

6. COMPARISON WITH KHALATNIKOV'S THEORY

A linear dependence of the temperature jump on heat current was confirmed in all our experiments, although linearity is destroyed for large flows.

The T^3 law, discovered by Kapitza and also derived from Khalatnikov's theory, really holds for the three specimens of extremely pure metals (Pb, Sn, and Ni). The deviation from the cubic law for the other specimens (Cu, Pt, and quartz) evidently indicates the presence of some spurious effects.

In the case of quartz the deviation from the T^3 law can be explained by the high degree of roughness of its polished surface, differing from a metallic surface in its brittleness. According to Little's suggestion^[19] the area of the effective heat transfer area S' depends on the phonon fre-

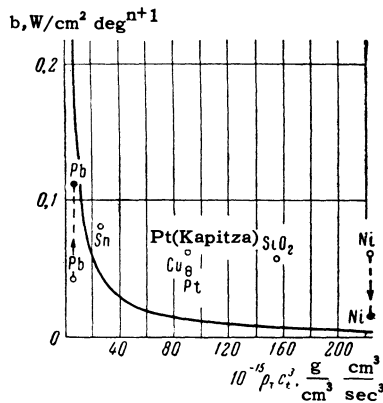


FIG. 9. A comparison of the experimental values of b in the expression $m = bT^n$ with the theoretical curve of Khalatnikov: \circ —specimen before electropolishing, \bullet —after electropolishing.

quency. The effective area is equal to the geometrical area for those phonons whose wavelength is greater than the mean amplitude of the surface roughness \bar{A} . It will, however, be larger than the geometrical surface for phonons of wavelength less than \bar{A} . Our results agree with the theory if we assume $S'(\nu) = S_0\sqrt{\nu}$, where S_0 is a constant.

We cannot yet explain the deviation from the cubic law in the other direction for two metal specimens (Cu and Pt). We must point out that in the case of platinum we used a specimen of technical purity, whose thermal conductivity was not determined in the experiment, so that there is a possibility of a large correction for the thermal resistance along the foil itself, which precisely lowers the power of T in (4) for Pt considerably.

It is of interest to compare the absolute values of ΔT obtained with the values calculated theoretically from (1). In Fig. 9 the experimental values of b in the expression $m = bT^n$ are compared with Khalatnikov's theoretical curve. The full curve in Fig. 9 is drawn according to (1) with the value $F(c_t/c_l) \equiv F(\eta, \xi) = 2.0$.^[2] The function $F(\eta, \xi)$ depends weakly on the substance, and for the metals used in our experiments has the following values:

Metal:	Ni	Pb	Sn	Cu	Pt
η :	0.508	0.32	0.495	0.48	0.425
ξ :	0.935	0.947	0.935	0.938	0.990
$F(\eta, \xi)$:	2.10	2.00	2.08	2.06	2.06

A strict comparison between theory and experiment in the case of quartz is complicated since quartz is very anisotropic, while Khalatnikov's theory is worked out for isotropic bodies. In Fig. 9 the point for quartz is determined from the average velocity of transverse sound $c_t = 3885$ m/sec. At first sight the disagreement between theory and experiment is enormous, since according to the theory the coefficient b should be 40 times less for nickel than for lead, while according to our data it is not very different and, to the contrary, b for nickel exceeds the value of b for lead. Instead of the theoretical dependence b

$\sim 1/\rho_S c_t^3$, we obtained values of b of the same order of magnitude for all specimens studied (from 0.042 for lead to 0.081 for tin), including Kapitza's data.

To some extent the disagreement between theory and experiment can be explained by taking account of the difference of the real boundary separating two media and the ideal for which (1) was derived.

First, the real surface of a solid has some degree of roughness. However, an account of this fact does not explain correctly the following facts: a) the temperature jump at the lead surface is many times greater than its theoretical value; b) the experimental points (Fig. 9) do not form a curve displaced parallel to the theoretical, although all the metallic surfaces had the same treatment.

In addition, the surface of a solid is nearly always covered by a layer of adsorbed gas. The thickness of the adsorbed layer usually does not exceed $3-5 \times 10^{-8}$ cm. Such a monomolecular layer naturally does not produce any appreciable effect on the transfer of acoustic phonons of wavelength of the order $10^{-5}-10^{-6}$ cm. The situation is, however, changed when we consider the Beilby layer.^[20] As is well known, an amorphous layer (the Beilby layer) is formed on the surface for all forms of cold working of metals. It was found^[21] that after cold working, a surface does not give interference rings characteristic of the crystal structure of a given substance in the reflexion of an electron beam. Instead of this, two diffuse haloes are formed, the positions of which are unrelated to the rings from the crystal lattice. A strongly deformed Beilby layer has a thickness $\sim (0.5-1) \times 10^{-6}$ cm.^[21] The degree of destruction of the normal metal structure gradually changes on passing from the surface to deeper layers: under a completely amorphous surface layer there is a layer with gradually increasing crystallite size and finally, at a depth of several thousand Angstroms, is the untouched structure. Normal polycrystalline electron diffraction is obtained only after removing a layer of 10^{-5} cm by etching or by cathode sputtering.

In comparing our results with Khalatnikov's theory (Fig. 9) we used the elastic constants for metals with the normal crystal structure. This is, however, incorrect since the thickness of the transition region of deformed metal, is of the order of $10^{-4}-10^{-5}$ cm, and is many times greater than the mean wavelength of phonons in the temperature range of the measurements.

Since the elastic constants of the amorphous

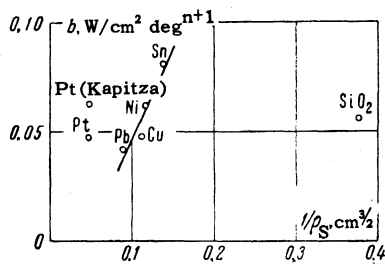


FIG. 10. The dependence of the experimental values of the coefficient b on $1/\rho_S$.

layer were unknown, and considering Khalatnikov's theory to be correct, we substituted the experimental values of b in (1) and derived the values of $\rho_S c_t^3$. If we take for the density the value corresponding to the crystalline state (the error due to this assumption is only $\sim 1\%$ for all the metals studied), then an effective velocity of sound c_t' can be determined for the amorphous metals. The values of c_t' calculated in this way for our metal surfaces, except platinum, not only agree as to order of magnitude, but have nearly the same value (1300 m/sec), while the values of the velocity of sound in the metals with a crystalline structure are very different.

It should be pointed out that the effective velocity of sound in the Beilby layer is determined within an accuracy of some factor, the magnitude of which depends on the ratio of the effective surface area to the geometrical surface area of the specimen. These numerical factors should be approximately the same for all the metals studied, since their surfaces were treated in the same way (the platinum specimen was annealed at 500°C for 3 hours, so that it is possible that the amorphous layer was partly recrystallized because of the long heating).

A graph of the dependence of b on $1/\rho_S$ is shown in Fig. 10. It can easily be seen that the data for all specimens except platinum and quartz fit a straight line well. As has already been noted above, it is possible that the surface of the platinum foil was partially recrystallized, owing to the long heating during the preparation of the apparatus. In Kapitza's experiments^[1] the platinum surface was formed by cathode sputtering. It was shown^[22] that a platinum deposit in vacuo is catalytically active. Films formed by sublimation have surfaces that are completely different from mechanically worked surfaces. Finch^[23] showed that a polished layer of quartz is unchanged crystallographically (the electron diffraction picture consists of spots and rings) and a continuous amorphous Beilby layer is not formed. Figure 10 thus shows that the experimental points for metals which have an amorphous layer on their surfaces fall on a straight line, while the points for specimens which do not have a Beilby layer fall outside this straight

line. The experimental points in Fig. 9 are not grouped together but fall irregularly in a narrow band of b values. This is in favor of our suggestion that the Beilby layer has an appreciable influence on the process of heat transfer at the boundary between metals and liquid helium II.

Besides roughness, adsorption of gas, and a deformed layer, a real surface of a solid can differ from the ideal by oxidation. Apart from gold, not a single pure metal (including platinum) is immune to oxidation in air at room temperatures. However, the thickness of the oxide layer is one order of magnitude less than the phonon wavelength in the solid in the temperature range $1-2^\circ\text{K}$, and is only comparable with the phonon wavelength in liquid helium II at these temperatures. The influence of this factor on the heat transfer between a solid and liquid helium II is considerably less than the influence of the deformed Beilby layer, which has a large characteristic length.

If we also take into account the fact that the layer of liquid at the walls has an increased density and its elastic constants ρ_L and c_L differ from the constants of free helium, then the agreement between theory and experiment is improved for all specimens except lead.

7. THE INFLUENCE OF THE STATE OF THE METAL SURFACE ON THE KAPITZA TEMPERATURE JUMP

Effect of polishing the metal surface. It is possible to obtain surfaces completely free of deformation by electrolysis over a time long enough to remove completely the deformed region. To study the influence of the amorphous Beilby layer on the Kapitza temperature jump we measured ΔT on electropolished surfaces of three metal specimens made of lead, tin, and nickel. The apparatus shown in Fig. 6b was used for this purpose (with specimens Ni-II, Pb-II, and Sn).

The nickel surface was polished three times. The total thickness of metal removed after each electrolysis was 14, 56, and 140μ . The long polishing necessary for removing the thick layer of deformed metal led not to a smooth surface but to a slightly wavy one.

The lead surface was polished twice. The overall thickness of the layer removed was 34 and 102μ . After the first electrolysis the lead surface was washed and dried and the apparatus was rapidly lowered into the dewar containing an atmosphere of gaseous helium, so that the oxide film formed on the lead surface after electro-polishing was

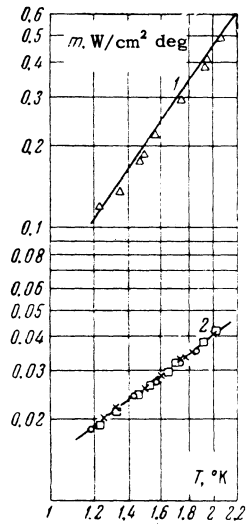


FIG. 11. The temperature dependence of the heat transfer coefficient between nickel and liquid helium II: the full lines 1—data for specimen Ni-I; Δ —data for specimen Ni-II before electrolysis, \times —after the first electrolysis, \circ —after the second electrolysis, \square —after the third electrolysis.

very thin and had no significant effect on the heat transfer process. On the other hand, after the second electro-polishing the lead surface was left in contact with an atmosphere of air for seven days. After this the surface of the lead was covered with a thick oxide film and darkened, whereas immediately after electrolysis the surface was shiny as usual.

A 2.5μ thick layer was removed in polishing the tin surface.

The results of the measurements for specimen Ni-II are shown in Fig. 11, where the temperature dependence of the heat transfer coefficient between nickel and liquid helium II is shown before (curve 1) and after (curve 2) electro-polishing. The experimental points (Δ) obtained on the apparatus with Ni-II fall well on curve 1, which is taken from Fig. 8 for Ni-I. The temperature jump at the boundary between nickel and liquid helium II increases sharply after electro-polishing the nickel surface. The experimental points obtained on measuring ΔT for specimen Ni-II after each electrolysis lie on one curve 2. It is described by the equation

$$m = 0.0142 T^{1.5} \text{ W/cm}^2\text{-deg} \quad (5)$$

After removal of the Beilby layer the coefficient b actually fell to a value three times greater than the theoretical, while before electro-polishing it was 13 times greater. However, the temperature dependence in the new measurements ($T^{1.5}$) agreed less with the T^3 law. In addition, the linear dependence of ΔT on the heat current is only observed for $W \geq 6 \times 10^{-4} \text{ W/cm}^2$, and fails at small flows.

The latter circumstance can evidently be attributed to the porosity of the surface of the nickel specimen after electrolysis. The amorphous Beilby layer is reminiscent of the film of a vis-

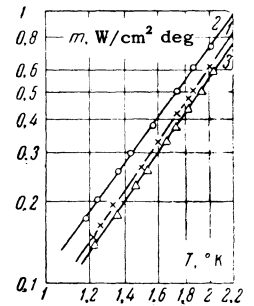


FIG. 12. The temperature dependence of the heat transfer coefficient between lead and liquid helium II: curve 1—specimen before electro-polishing, 2—after the first electro-polishing, 3—after the second electro-polishing.

cus liquid. This film fills the small cracks or pores, which exist on the nickel surface before working, so that the normal linear law for the dependence of ΔT on heat current can be obtained, although the magnitude of ΔT is anomalously small for it. After removal of the upper compacted Beilby layer by electro-polishing, the surface has the normal crystal structure. The absolute value of the temperature jump then agrees better with theory. However, after electrolysis the small cracks or pores on the nickel surface appear again and they evidently produce some capillary effect in the heat transfer between the wall and the superfluid helium. The nonlinearity of the dependence of ΔT on heat current for small flows and the decrease in the power of T in the expression $m = bT^n$ can be explained in this way.

Curve 1 in Fig. 12 is for a lead surface before electro-polishing. The curve is described by the equation

$$m = 0.082 T^3 \text{ W/cm}^2\text{-deg} \quad (6)$$

As will be seen later, the magnitude of the temperature jump for a lead surface changes from experiment to experiment, due to the gradual annealing of the Beilby layer at room temperature. The agreement between results of measurements on both specimens (Pb-I and Pb-II) should therefore only be to within a constant factor.

After removing the Beilby layer by electro-polishing, the value of the temperature jump fell (curve 2 in Fig. 12) to half the theoretical value, calculated from (1). The heat transfer coefficient between lead and superfluid helium then followed the law

$$m = 0.11 T^{2.9} \text{ W/cm}^2\text{-deg} \quad (7)$$

The results obtained from measurements on a lead surface covered by a thick oxide film are also shown in Fig. 12 (curve 3). The film of oxides on the lead surface increases the heat resistance of the boundary.

The magnitude of the temperature jump at the tin surface did not change after electrolysis. It is

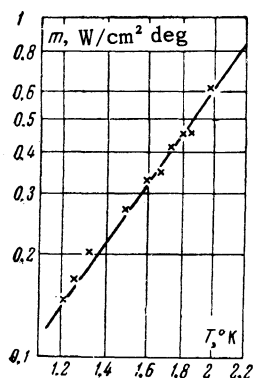


FIG. 13. The temperature dependence of the heat transfer coefficient between tin and liquid helium: full curve—specimen before electropolishing, \times —after electropolishing.

seen from Fig. 13 that the points (\times) obtained with the electropolished surface lie well on the curve obtained earlier for the tin surface before its electrolysis.

The tin from which our specimen was prepared was extremely pure (99.9997%) with a melting temperature of 232°C. As is well known, the surface of pure tin oxidizes very slowly. Evidently the thermomechanically unstable state (the amorphous phase of the metal) cannot be stable for a specimen of pure tin which does not include a large amount of foreign atoms. The observed fact, namely the invariance of the magnitude of the temperature jump with electropolishing, indicates the absence of an amorphous layer on the tin surface.

As can be seen from Fig. 9, the coefficient b increased after electropolishing for lead and fell for nickel. In both cases the value of b then differed from the theoretical values by not more than three times. After electropolishing of the tin surface the magnitude of the temperature jump practically did not change. It is half the theoretical value in absolute magnitude.

It is easy to see that after electropolishing some regularity appears in the dependence of b on $\rho_S c_t^3$, while the disagreement between the theoretical and experimental data is reduced significantly.

Our suggestion that the main reason for the disagreement between the experimental results and the theory is the existence of a thick (compared with the phonon wavelength at the given temperature) amorphous and deformed layer at the surface of a metal, is thus demonstrated experimentally.

8. THE EFFECT OF MECHANICALLY WORKING THE SURFACE OF LEAD AT HELIUM TEMPERATURES

Two months after the first measurements we repeated the measurements on the apparatus with

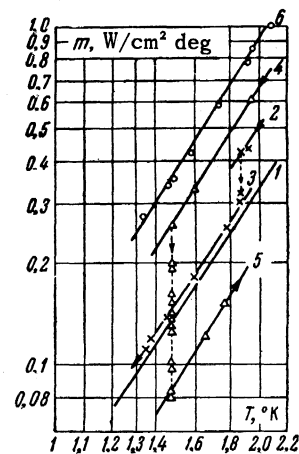


FIG. 14. The effect of the state of the lead surface on the heat transfer process between lead and liquid helium II.

the specimen Pb-I. The magnitude of the temperature jump decreased sharply (curve 2 in Fig. 14) compared with the old data (curve 1). The lead surface was cleaned directly in the liquid helium bath with the help of a steel cutter fastened inside the dewar. ΔT increases after each cleaning operation (shown by dotted lines in the figure). At the end of the experiment the surface of the specimen was kept at room temperature for seven days. In the subsequent experiment with liquid helium the magnitude of the temperature jump decreased again (curve 4). This time the cleaning of the surface was taken so far that further action of the cutter no longer changed the magnitude of the temperature jump. Curve 5 is drawn from data on the limiting cleaning of the surface. This corresponds to the formula

$$m = 0,024 T^{3.2} \text{ W/cm}^2\text{-deg.} \quad (8)$$

The last measurements on the apparatus with specimen Pb-I were made after four further months had elapsed after the measurements described, and gave the following law for the heat transfer coefficient (curve 6)

$$m = 0,106 T^3 \text{ W/cm}^2\text{-deg.} \quad (9)$$

In the last case the absolute value of ΔT is only 1.9 times greater than theoretical.

As mentioned above, the surface of a metal forms on mechanical working a Beilby layer which has an amorphous structure. The high degree of purity (99.9997%) and the low melting point (327°C) of lead help the gradual establishment of a crystalline structure of the surface layer. The process of recrystallization goes slowly at room temperature, so that in the experiments a shift of the $m = f(T)$ curve is observed in the experiments in the direction of the theoretical dependence, calculated for the crystalline surface (see Fig. 14, curve 2).

Working of the surface of lead by the cutter at helium temperatures, besides cleaning the surface of a layer of oxides, produces plastic deformation of the surface of the specimen. The observed gradual increase in the temperature jump (Fig. 13) after each action of the cutter is evidently the result of the gradual increase in the degree of deformation of the surface.

Since the mechanical working of the lead surface was carried out in a bath of liquid helium, introduction of foreign atoms and chemical reactions evidently did not take place. The process of recrystallization during the subsequent annealing of the specimen at room temperature is eased to a considerable extent for this chemically pure surface. The facility for heat transfer to liquid helium (curves 4 and 6 of Fig. 14) increases with the increase in the degree of recrystallization. The results obtained for the lead surface with different degrees of deformation again shows the appreciable influence of the elastic constants of the surface layers on the heat transfer mechanism between a mechanical wall and superfluid helium.

9. THE DEPENDENCE OF THE KAPITZA TEMPERATURE JUMP ON THE SUPERCONDUCTING TRANSITION OF TIN IN A MAGNETIC FIELD

In order to carry out measurements in a magnetic field the bronze thermometer in the apparatus with the Sn specimen was surrounded by a superconducting shield of lead foil and the bath thermometer was placed inside a lead tube. Under these conditions the calibration of the bronze thermometers was practically unchanged on application of a magnetic field up to 300 Oe.

The results of the measurements show that the transition of the tin into the normal state in a magnetic field ($H \approx 300$ Oe) has no effect on the magnitude and character of the temperature jump at its boundary with liquid helium II. The change in ΔT was determined to an accuracy of 2% (Fig. 8).

10. EXPERIMENTS WITH ROTATING HELIUM

The apparatus with the Sn specimen was put into a vessel of liquid helium which was in a liquid helium bath. Rotation of the liquid helium in the vessel at a speed up to 400 rpm had no effect on the heat transfer at the boundary between tin and liquid helium II. The change in ΔT was determined with an accuracy of 1%. These results are compared with those obtained in helium at rest in Fig. 8. The points (○) obtained from the new

measurements lie well on the curve obtained earlier (Fig. 8).

In another experiment a phosphor bronze wire was stretched on a glass frame, serving simultaneously as thermometer and heater. The resistance of the bronze stayed unchanged on rotating the liquid at a speed up to 120 rpm (it was estimated that the maximum change in ΔT did not exceed 2%). In addition, it was established in one of the experiments that the resistance of the bronze did not change on rotating the liquid helium at 56 rpm over a period of 33 min.

CONCLUSIONS

1. It is established that the process of heat exchange between a solid and liquid helium II is reversible.

2. It is established that on increasing the pressure from the saturated vapor pressure of helium to 25 atm the temperature jump at the boundary between copper and liquid helium II at constant temperature decreases by 10–20%, instead of the 40% expected from Khalatnikov's theory. It is possible that the weak pressure dependence of ΔT is related to the presence of a transition layer of helium of increased density immediately at the solid wall. The decreases in the value of the temperature jump obtained in the experiments for all the specimens except lead can partly be explained by this effect.

3. It is shown that although the T^3 law holds for lead, tin, and nickel (before electropolishing) a departure from the T^3 law is observed in the cases of copper, platinum, and quartz.

4. It is shown that the cause of a considerable quantitative disagreement between theory and experiment is the presence of amorphous and deformed layers formed after mechanically working a metal surface.

Instead of the theoretical dependence $b \sim 1/\rho_S c_t^3$, the coefficient b in the experiments (before electropolishing) has a value of the same order of magnitude (0.042–0.081). After electropolishing, i.e., after removing the Beilby layer on the surfaces of lead, nickel, and tin, the value of ΔT differs from the theoretical by only a factor of two to three.

It is found that on a lead surface ΔT decreases from experiment to experiment, but increases after mechanically working the surface of the specimen at helium temperatures. It is possible that this is showing up the effect on the heat transfer process between lead and helium II of the gradual recrystallization of the amorphous layer at room

temperature and the gradual increase in the degree of deformation of the surface of the lead after working with a cutter at helium temperatures.

5. It is established that the magnitude and character of ΔT is unchanged during the transition of tin to the normal state in a magnetic field $H \approx 300$ Oe.

6. Measurements of ΔT were made in rotating helium. No change in ΔT was found up to speeds of rotation of 400 rev/min.

In conclusion I must express my sincere thanks to my director, Prof. V. P. Peshkov who gave me valuable advice and constant help with the work, and Academician P. L. Kapitza for his constant interest in the work. I should also like to express sincere thanks to Prof. I. M. Khalatnikov for taking part in the discussion of the results.

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