OBSERVATIONS OF THE λ-TRANSITION IN HELIUM IN THE PRESENCE OF A THERMAL CURRENT THROUGH THE PHASE BOUNDARY

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Experiments involving the observation of density and temperature discontinuities at the boundary between superfluid and non-superfluid helium in the presence of a thermal current are described. The reasons for the stability of the boundary are explained, and examples of disturbance of this stability at high thermal current densities are presented.

As has been previously communicated,[1] a clearly visible boundary appears in the presence of a thermal flux from non-superfluid in superfluid helium, and discontinuities in the temperature and density are developed at the boundary. Experiments on the observation of this phenomenon were set up in the following manner. In the Dewar vessel 1 of liquid helium illustrated in Fig. 1 there was placed a chamber 3 attached to the tube 2. The chamber formed an optical wedge, bounded on the sides and rear by the glass aperture 4 and made up of two plane-parallel glass flats 5. A flat heater wound of constantan wire was placed on the rear wall to generate a thermal current along the chamber. The forward end of the chamber was sealed hermetically by a platinum foil 6 using BF-4 polymerizing cement. A pressure of one atmosphere measured by means of the manometer 9, was maintained in the liquid helium within the chamber through the tubes 7 and 8. Two chambers, 1.5 and 3 mm in depth, were used for the experiments. Both chambers were 4 mm wide and 16 mm long. With the aid of the telescope 10 and the optical system illustrated in the figure, fringes of equal optical thickness were observed in the chamber in the light of a low-pressure mercury lamp 11. Since the index of refraction for liquid helium differs but little from unity ($n = 1.027$), the variation in the helium density can be obtained from the simple formula $\Delta\rho = Ak$, where k is the number of fringes passing across a given section of the chamber, $\Delta\rho$ is the density variation, and A is a constant of the apparatus. Inasmuch as the most reliable thermometer is a density thermometer, the temperature of the liquid helium was determined from the density. When sufficient power was supplied to the heater, with the temperature of the external bath somewhat below the λ points, the temperature within the chamber began to rise, and, as it passed the λ-point, a visible boundary appeared within the chamber near the heater and moved toward the cold end. It could be maintained at any point in the chamber by suitable adjustment of the power or of the temperature of the external bath.

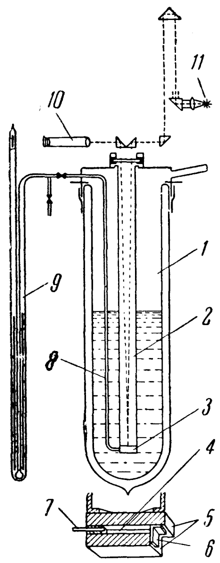

FIG. 1. Apparatus for visual observation of the boundary between superfluid and non-superfluid helium.

In row 1 of Fig. 2 are shown photographs of fringes of equal thickness in the 1.5-mm chamber, containing superfluid helium at a temperature very close to the λ-point, in the absence of a thermal current along the chamber; the photographs in rows 2, 3 and 4 in column a show the interference patterns, respectively, for 0.06, 0.11, and 0.19 w/cm^2. The remaining photos will be discussed in more detail later. The visible boundary shows that in the presence of a thermal current a discontinuity in the density exists at the interface between superfluid and non-superfluid helium. As the thermal flux is reduced the density discontinuity decreases, and the boundary becomes less well-defined and

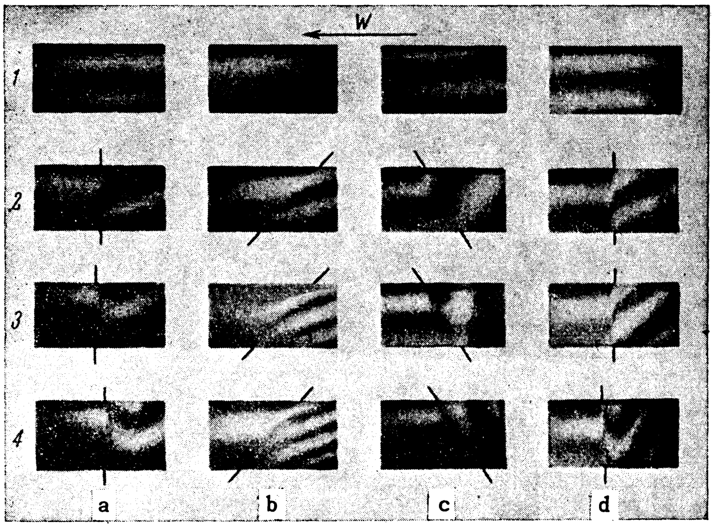

FIG. 2. Fringes of equal optical thickness. Column a) chamber horizontal; columns b and c) chamber inclined laterally by 7° to one side and to the other; column d) chamber inclined by 4.5° with the heater end elevated. Rows correspond, from top to bottom, to thermal fluxes of of 0, 0.06, 0.11 and 0.19 w/cm².

finally becomes invisible. From the corresponding displacement of the interference fringes it is possible to determine the dependence of the magnitude of the density discontinuity upon the intensity of the thermal current.

When the temperature of the external bath was raised and the thermal current was simultaneously reduced in such a way that the boundary remained in one place, no visible displacement of the fringes in the superfluid helium region, and consequently no variation in the temperature, were observed. In the non-superfluid region, however, a gradual procession of the interference fringes took place as the thermal current was decreased. In the 3-mm chamber the pattern was displaced by 2.5 fringes at the boundary as the current density was varied from 0.16 to 0.04 w/cm². The results of these measurements are presented in Fig. 3.

As has already been communicated,[1] the discontinuity in the density is proportional to the square of the thermal current density; at 0.16 w/cm² the density of the non-superfluid helium at the boundary is less than the superfluid helium density by 1.3×10^{-3} g/cm³, or approximately 1%, which is equivalent to a temperature rise of 0.3°. Thus, in the presence of a thermal flux through the boundary, equilibrium between the superfluid and non-superfluid helium is established with discontinuities existing in density and temperature.

If the chamber is tilted by 7° to the right (column b) or to the left (column c), then, since the superfluid helium is heavier than the non-superfluid, the boundary is turned obliquely, through an angle of approximately 45°. If the density or temperature discontinuities are now referred to the thermal current passing through unit area of the increased surface, the magnitude of the discontinuity remains the same, to within the experimental error (20%), as for the horizontal chamber. Tilting of the chamber by 4.5° with the heater upward (column d) leads to the same result. For a more detailed investigation of this phenomenon, a resistance thermometer of 40 μ phosphor bronze was placed in one of the chambers, permitting the temperature of the liquid to be measured as the boundary passed through. With this arrangement it was found that the temperature of the superfluid helium at the boundary falls with increasing thermal flux. The fall is approximately linear, and amounts to 0.0009° at 1 w/cm². Moreover, a temperature gradient $dT/dx = 1.5 \times 10^{-3}$ deg/cm was observed in the superfluid helium for $W = 0.08$ w/cm². In the non-superfluid helium, for inputs in excess of 0.06 w/cm², a phenomenon is observed which is at first glance completely incomprehensible. For a thermal flux of 0.08 w/cm² the temperature rises by 0.03° in a 0.5 mm interval just beyond the boundary; in the next 0.5 mm it falls by 0.02° and there then follows a sharp increase with a gradient of

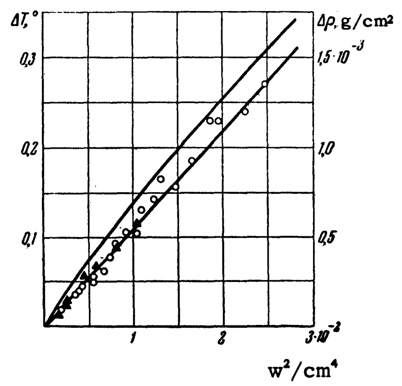

FIG. 3. Dependence of the density discontinuity Δρ (lower curve), and the temperature discontinuity ΔT computed from the change in density (upper curve), upon the square of the thermal current density. o) measurements in the 3-mm chamber; ▲) measurements in the 1.5-mm chamber.

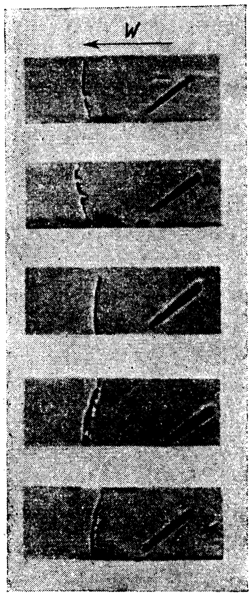

FIG. 4. Vortices extracted by turbulence from the superfluid helium.

10 deg/cm. This phenomenon can also be detected in the photographs of Fig. 2, from the break in the interference fringes in the non-superfluid region at the boundary. In apparent violation of the laws of thermodynamics, a transfer of heat takes place from cold to hot. With lower inputs this phenomenon is not observed.

In order to gain an understanding of what this contradiction involves, the boundary was photographed with flashbulb illumination, under conditions of high thermal flux; the photographs are presented in Fig. 4. As can be seen, vortices of superfluid helium are formed, situated on a thin line at the boundary. The diameter of the vortices is on the order of 0.3 mm. These vortices do not remain in one place, but move from the center of the boundary toward its edges, or, if the chamber is inclined laterally, run toward the lower side. Since both the thermometer and the interference process average the temperature, it is natural that the apparent temperature should be lower in the region of the centers of the vortices than at their origin; no violation of the laws of thermodynamics actually occurs.

It seems strange that a sharp boundary should be able to exist at all. Non-superfluid helium has an extremely small thermal conductivity (6×10^{-5} cal/deg-cm-sec), and in it heat transfer takes place by vigorous convection. Following Prandtl,[2] we shall estimate the effectiveness of convective heat transfer using the formula

$$W = \rho C_p l v \, \partial T / \partial x$$

where W is the thermal current density, ρ is the density of liquid helium, C_p is the specific heat,

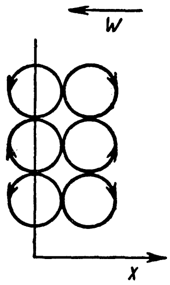

FIG. 5

l is the scale of the turbulence, and v is the pulsation velocity.

The crudest model of turbulent transfer is represented by the diagram shown in Fig. 5. By the pulsation velocity v we may here understand the linear velocity of rotation of the helium at the vortex periphery, and the scale l of the turbulence is determined if we compute the heat transfer for such a model to be

$$W = \frac{1}{2r} \int_{-r}^{+r} \rho C_p \omega r \frac{\partial T}{\partial x} r dr = \rho C_p \frac{\omega r^2}{3} \frac{\partial T}{\partial x} = \rho C_p v \frac{r}{3} \frac{\partial T}{\partial x},$$

i.e., $l = r/3$.

For $W = 0.11$ w/cm^2 the temperature gradient in the non-superfluid helium is 0.8 deg/cm, and from the photograph in Fig. 4 the scale of the turbulence 1 may be estimated from the radius of the vortices as 0.005 cm. Then

$$v = W / \rho C_p l \frac{\partial T}{\partial x} = 80 \text{ cm/sec}.$$

It is clear that at the boundary there can be no forces capable of preventing the penetration of such turbulence into the superfluid helium. Estimation of the velocity with which the superfluid helium moves through the thin vortex line in the photographs of Fig. 4, under the assumption that the thermal current density is the same at the surface of the vortices as at the boundary, leads to values on the order of 30 cm/sec. Estimation of the critical velocity for superfluid motion at the boundary using the formula $v_{SC} = W/\rho_S Q$, where Q is taken from the measurements of Kapitza and ρ_S is determined from the $\rho_S(T)$ curve at the measured $\Delta T = T_\lambda - T$, leads to values on the order of 80 cm/sec. Moreover, the critical velocity is to a first approximation constant, since •

$$\rho_s = \frac{d\rho_s}{dT} \Delta T = \frac{d\rho_s}{dT} \frac{dT}{dW} W = \text{const} \cdot W.$$

Inasmuch as estimates of the critical velocity, the flow velocity in the vortices, and the pulsation velocity yield quantities of the same order, the removal of the vortices from the superfluid and destruction of the sharp boundary at still higher inputs seem natural, since under this condition the velocity of turbulent motion begins to exceed the critical velocity for the motion of the superfluid.

It should be noted that mechanical forces can play no significant part in the processes associated with the displacement of the boundary. If the boundary is displaced by δ, in fact, a thermal energy of order $\epsilon_t = \rho C_p \Delta T \delta$ per unit displaced area must be absorbed or emitted, where ΔT is the temperature discontinuity and C_p is the specific heat of the non-superfluid helium. At the same time, the kinetic energy stored in the volume is $\epsilon_k = \rho v^2 \delta/2$. Thus, the ratio of the energies $\epsilon_k/\epsilon_t = v^2/2C_p\Delta T$; i.e., if we take $C_p \approx 0.6$ cal/g-deg, and, with $W = 0.6$ w/cm^2, $v \approx 50$ cm/sec, and $\Delta T \sim 0.1°$, then $\epsilon_k/\epsilon_t = 5 \times 10^{-5}$. Thus the conditions governing the motion of the boundary must be the thermal relations.

The sharpness of the boundary in this case may be explained on the assumption that, up to some limit at which the turbulent motion begins to remove the vortices from the superfluid helium, heat transfer from the non-superfluid to the superfluid helium for a given temperature discontinuity remains constant, and that any projection on the boundary tends to straighten itself, and the boundary therefore remains even. Since the boundary cannot withstand the penetration of turbulence from the non-superfluid into the superfluid helium and vice-versa, the heat-transfer process may be represented in the following way. Let the boundary move as shown in Fig. 5. The temperature to the left of the boundary is T_λ, while that on the right is T_1 and may in the first approximation be regarded as constant within a distance r from the boundary. The volume taking part in the motion of a vortex centered on the boundary remains for a time $t = \pi r/v = \pi/\omega$ in the superfluid helium region. If we take the relaxation time for the establishment of thermal equilibrium in the superfluid helium to be τ, the temperature of the volume flowing out of it will be $T_2 = T_\lambda + (T_1 - T_\lambda)e^{-t/\tau}$. The thermal flux through the boundary will therefore be written in the form

$$W = \frac{1}{2r}\int_0^r \rho C_p \omega r T_1\, dr + \frac{1}{2r}\int_{-r}^0 \rho C_p \omega r T_2\, dr = \rho C_p \frac{\omega r}{4}(T_1 - T_2);$$

$$W = \rho C_p \frac{v}{4}(T_1 - T_\lambda)(1 - e^{-\pi r/v\tau}).$$

On the basis of this formula it is possible to estimate the relaxation time, which turns out to be of order $\tau \sim 5 \times 10^{-3}$ sec, while the survival time in the superfluid helium $t \sim 10^{-3}$ sec; the formula may therefore be simplified:

$$W \approx \rho C_p \pi r \Delta T / 4\tau.$$

Since from the experiment $\Delta T \propto W^2$, we have in this case $r \sim 1/W$. Although the ideas presented above indicate a pattern for heat transfer through the boundary between superfluid and non-superfluid helium, the question of why the temperature discontinuity is proportional to the square of the thermal flux remains as yet open. It seems to me that an investigation of the phenomena occurring at the boundary between superfluid and non-superfluid helium is of particular interest, since we have here a case in which superfluid helium — a system of strongly-interacting particles particularly subject to quantum-mechanical conditions — interacts with a system which, from its properties, is similar to ordinary liquids for which the classical approximations are completely valid.

I take this opportunity to express my gratitude to Academician P. L. Kapitza for his constant interest and concern with this work, and also to A. I. Filimonov and I. A. Uriutov for their aid in performing the experiments.

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[2] L. Prandtl, Hydroaeromechanics, IIL, 1949, pp. 149-50.

[3] P. L. Kapitza, J. Exptl. Theoret. Phys. (U.S.S.R.) **11**, 581 (1941).

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