Temperature distribution in superfluid helium near a heated surface

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A temperature increase ΔT has been observed in superfluid helium, which corresponds to the Kapitsa jump ΔT_K: $\Delta T = \Delta T_0 e^{-x/\lambda}$, where $\Delta T_0 \approx 10^{-3} \Delta T_K$ is the temperature increase in the immediate vicinity of the heated surface, x is the distance from the surface, and λ is a parameter, which falls off by an order of magnitude as the temperature increases from 0.4 to 0.7 K.

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In 1941, Kapitsa[1] observed that the temperature of a solid was quite different from that of the superfluid helium in which the solid was immersed if there was a heat flux across the interface. This effect, the "Kapitsa jump," was attributed to the reflection of thermal excitations (phonons) from the interface because of a difference in the acoustic impedances of the solid and the liquid helium.[2] Research on the Kapitsa jump is reviewed in Ref. 3.

Near a surface in the Knudsen region, a nonequilibrium distribution of excitations is evidently established in helium, and this distribution can be studied by studying the temperature distribution in the helium. (For inhomogeneous and nonequilibrium systems, we must separately specify just what is meant by "temperature." Following Landau and Lifshitz,[4] we will determine the temperature in this case from the average energy of the excitations in the given volume.)

The expected temperature change is not large, and its ratio to the Kapitsa jump ΔT_K should be comparable in order of magnitude to the ratio of the number of phonons transmitted across the interface to the number reflected; i.e., the temperature change should be given in order of magnitude by

$$\frac{\rho_L v_L}{\rho_S v_S} \sim 10^{-3} \Delta T_K .$$

In the present letter we are reporting an effort to study this temperature distribution, which corresponds to the Kapitsa jump, in superfluid liquid helium.

The temperature distribution in the helium was measured with an (Au + 0.03% Fe)–superconductor thermocouple by a comparison method, with a SKIMP device used as a null detector. The temperature difference ΔT could be measured within less than 10^{-6} K. In the experiments, we determined the difference ΔT between a thermocouple junction near the heated surface, *a*, and a junction at some distance from this surface, *b* (see the inset in Fig. 1a). In this manner, we were able to measure the temperature increase near the heated surface directly in the course of the ex-

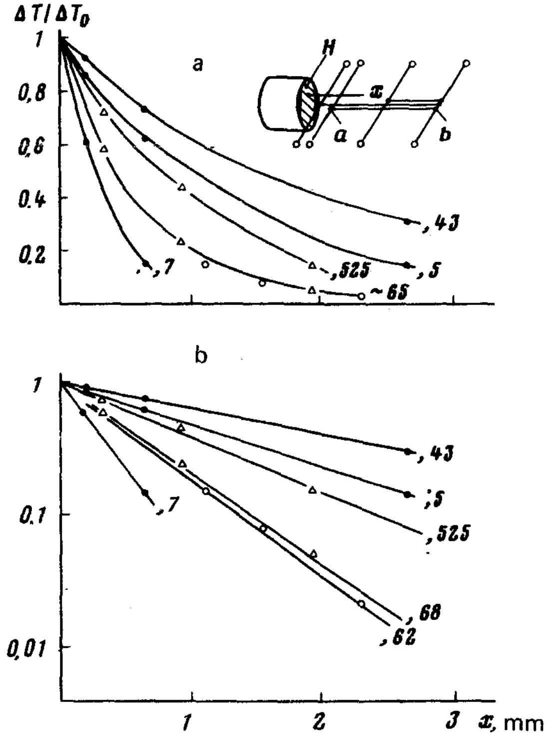

FIG. 1. Profile of the change in the helium temperature, ΔT, near a heated surface. a–Linear plot; b–logarithmic plot. The inset in part a shows the measurement arrangement.

periment. It is important to note that the test object (the thermocouple) in these measurements was nonselective in terms of the energy and in terms of its angular orientation (the latter point was checked in auxiliary experiments). The relative warming of the thermocouple junctions with respect to the helium caused by the Peltier heat evolution at these junctions did not exceed 10^{-10}–10^{-9} K.

Over the measurement interval of 0.4–0.7 K, the volume specific heat of the thermocouple material is an order of magnitude lower than that of the liquid helium. Also noting that the dimensions of the thermocouple are small and that its thermal conductivity is low, we may assume that the presence of the thermocouples does not cause any significant change in the temperature distribution in the liquid.

We were able to measure ΔT between several junctions simultaneously, so that the temperature distribution along the coordinate (x) perpendicular to the heated surface could be determined. This heated surface (H) was either a Joule-heated Cu–Ni alloy film on glass or a flat etched surface of a bulk copper object with $R_{300\,\mathrm{K}}/R_{4.2\,\mathrm{K}} \sim 3 \times 10^4$. In the latter case, an additional thermometer was placed inside the copper for simultaneous measurements of the Kapitsa jump. The heater was placed at a surface of the object which was thermally insulated from the helium.

A temperature difference near the heated surface in the liquid helium was observed over the entire measurement interval. Figure 1 shows profiles of ΔT along x for various measurement temperatures (the curve labels). The three different sym-

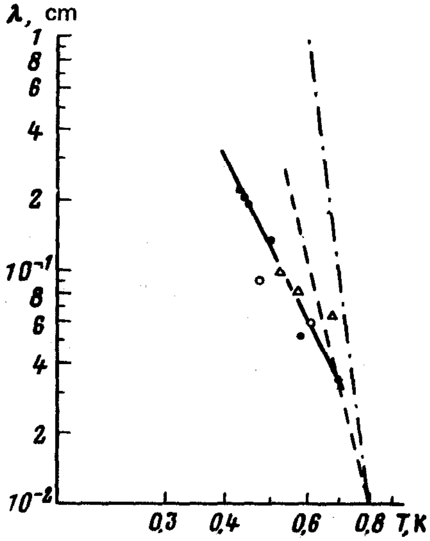

FIG. 2. Temperature dependence of the parameter λ from the equation describing the relaxation to equilibrium in the phonon system.

bols used in this figure correspond to three different versions of the measurement apparatus.

According to Fig. 1b, the profile $\Delta T(x)$ can be described well by

$$\Delta T = \Delta T_0 e^{-x/\lambda}$$

The difference ΔT_0 is $(1\text{–}3) \times 10^{-5}$ K. The results of direct measurements of the Kapitsa jump ΔT_K for the copper surface agree with some previous measurements.[3] The ratio $\Delta T_0/\Delta T_K$ is 10^{-3}, and it falls off by a factor of about 1.5 as the temperature is lowered from 0.7 K.

Figure 2 shows the results on λ. An upper limit is evidently set on the value which can be measured for this parameter by the dimensions of the heated surface, with a diameter ~4 mm, while a lower limit is set by the dimensions of the thermocouple wire, with a diameter ~0.1 mm. The approximately equal values of λ found in different measurement runs show that the measurement system does not substantially distort the distribution of nonequilibrium excitations in the helium.

The quantity $\lambda(T)$ is a measure of the distance over which an energy equilibrium is established in the system of nonequilibrium phonons. This distance may be compared with the phonon mean free path in heat transfer which was calculated by Khalatnikov (see Fig. 7 in Ref. 5 and the dashed curve in Fig. 2 of the present paper) and with the results of a direct determination[6] from the smearing of a heat pulse front carried out at Leiden (the dot-dashed curve in Fig. 2). It can be seen from Fig. 2 that the value found for $\lambda(T)$ in these experiments approaches that calculated by Khalatnikov, although it is apparently not as strong a function of the temperature. This result agrees with data reported by Whitworth,[7] who determined $\lambda(T)$ from measurements of the thermal conductivity of helium in the Knudsen region. Although some other calculations[8] have been used to explain why the temperature dependence λ(T) is weaker than in the theory of Ref. 5, this question requires further study.

A simultaneous study of the Kapitsa jump and of the accompanying change in the temperature of liquid helium in the Knudsen region may prove useful for determining the heat-transfer conditions at a solid-liquid interface.

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1. P. L. Kapitsa, Zh. Eksp. Teor. Fiz. **11**, 1 (1941).
2. I. M. Khalatnikov, Zh. Eksp. Teor. Fiz. **22**, 687 (1952).
3. L. J. Challis, J. Phys. C **7**, 481 (1974).
4. L. D. Landau and E. M. Lifshitz, Mekhanika sploshnykh sred, Moscow, 1944, § 105 (Fluid Mechanics, Addison–Wesley, Reading, Mass., 1959).
5. I. M. Khalatnikov, Usp. Fiz. Nauk **59**, 673 (1956).
6. H. C. Kramers, in: Progress in Low Temperature Physics, Vol. II (ed. C. J. Gorter), 1957, S-59.
7. R. W. Whitworth, Proc. R. Soc. London **246**, 390 (1958).
8. H. J. Maris, Rev. Mod. Phys. **49**, 341 (1977).

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