# Emission of phonons into liquid helium

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(Submitted 14 July 1983; resubmitted 12 September 1983)
Pis'ma Zh. Eksp. Teor. Fiz. **38**, No. 8, 386–388 (25 October 1983)

The flux density of thermal energy from a metal film into liquid helium has been measured. Although the propagation of phonons in helium is of a diffusive nature, the ballistic emission law $Q_{\text{Cu-He}} = \alpha(T^4_{\text{Cu}} - T^4_{\text{He}})$ holds at flux densities up to those which would cause the He to boil. The coefficient $\alpha$ is discontinuous near the $\lambda$ point.

PACS numbers: 67.40.Pm

The heat flux density emitted by a metal film into liquid helium, $Q_{\text{He}}$, has been measured as a function of the film temperature under conditions such that the helium does not boil and there is no heat convection into the helium. Since convection occurs only after a certain time (on the order of $10^{-3}$ s for He I; Ref. 1), we heated the film in pulses 200–400 ns long. At these pulse lengths the heat flux density required to bring helium to a boil is nearly two orders of magnitude greater than that in steady-state heating.[2]

A copper film (9 mm$^2$ in area and 1500 Å thick) was vacuum-deposited on a polished *C*-cut surface of a sapphire crystal. The film was heated by current pulses at a repetition frequency of 50 Hz with a power of 1–100 W/cm$^2$ in the pulse. The energy emitted by the heater into the substrate propagated in the latter in the form of ballistic longitudinal ($L$) and transverse ($T$) phonon pulses and was detected by a superconducting indium bolometer on the crystal face opposite the heater.

The sapphire crystal was pressed through a layer of indium against the lower flange of the measurement cell in such a manner that the heater could be put in vacuum ($< 10^{-4}$ Torr) or in contact with the liquid helium at the saturation vapor pressure; the bolometer was in the helium at all times (see the inset in Fig. 1). The working temperature was kept in the region of a linear temperature dependence of the bolometer's resistance near the point of the transition to superconductivity. The work-

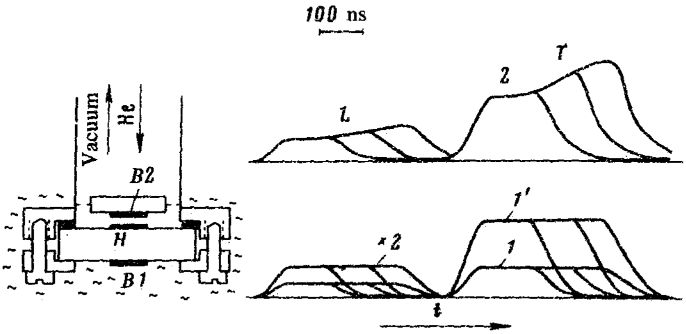

FIG. 1. Pulses of $L$ and $T$ phonons when the heater is in a vacuum (1') and in contact with the liquid helium (1,2). 1,1'—$Q = 21.5$ W/cm$^2$; 2—$Q = 33.6$ W/cm$^2$, $T_0 = 2.99$ K. The inset shows the measurement cell. $H$—Heater; $B$ 1, $B$ 2—bolometers.

ing point of the bolometer was varied with an external magnetic field. This measurement system could detect temperature pulses with an amplitude $\geqslant 10^{-4}$ K and with rise times $\geqslant 30$ ns.

The heater temperature $T_H$ and the heat flux density emitted by the heater into the helium, $Q_{\mathrm{He}}$, were determined in the following way. We first recorded the dependence of the amplitude of the ballistic $L$ and $T$ phonons detected by the bolometer on the electric power in the heater, $Q$, when the heater was in a vacuum. The heater temperature was calculated from[3]

$$Q = \alpha (T_h^4 - T_0^4), \quad \alpha = \pi^2 \bar{e} k^4 / 40 \hbar^3 \bar{s}^2, \tag{1}$$

where $\bar{e} = 0.126$ is the average transmission coefficient of the phonons at the copper-sapphire interface, $\bar{s} = 2.54 \times 10^5$ cm/s is the average sound velocity in the heater, and $T_0$ is the substrate temperature. We monitored the situation to make sure that the phonon flux densities which were detected did not drive the bolometer out of the linear part of its $dR/dT$ characteristic.

We then recorded the analogous dependence with the heater in contact with the liquid helium. We found that the amplitudes of the bolometer signals for the $L$ and $T$ phonons were identical when the heater was in a vacuum and in contact with the helium for a given heater temperature; the difference between the electric power levels delivered to the heater gives us the heat flux density in the helium.

Figure 1 shows the pulses of $L$ and $T$ phonons detected with the heater in a vacuum and in contact with the helium for various values of $Q$ and for various heating pulse lengths, $\tau = 200$–$300$, and 400 ns. With the heater in a vacuum, the $L$- and $T$-phonon pulses reproduce the shape of the heating pulse. The amplitudes of the signals are proportional to $Q$ and independent of $\tau$.

With the heater in contact with the helium and at small values of $Q$ the amplitudes of the $L$ and $T$ pulses are independent of the length of the current pulse in the heater; the shapes of these pulses are the same as those of the pulses detected with the heater in a vacuum. As the power $Q$ is raised to $Q = Q_{\mathrm{cr}}$, the height of the pulses

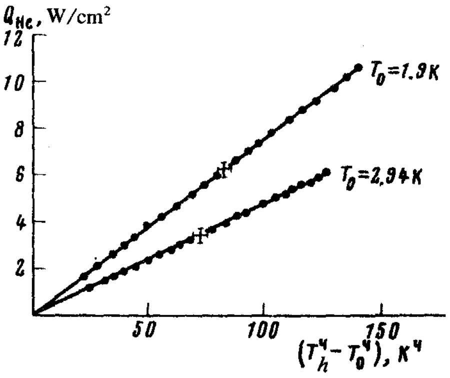

FIG. 2. The heat flux density $Q_{\rm He}$ vs the difference $T_{\rm h}^4-T_0^4$. The experimental errors are indicated by the crossed bars.

remains constant over a time $t$ and then drops sharply. It does not reach a steady value during the current pulse. The sharp increase in the heights of the $L$ and $T$ pulses is evidence of a decrase in the heat flux density emitted by the heater into the helium; this increase is associated with the onset of boiling of the helium.

The heat flux density emitted by the heater into the helium at $Q<Q_{\rm cr}$ is described well by expression (1) (Fig. 2). The temperature dependence of the coefficient $\alpha$ is shown in Fig. 3. The values found for $\alpha$ with various heater films agree within 10%; this scatter may be a consequence of differences in the film surfaces. Near the $\lambda$ point, the coefficient $\alpha$ was observed to change by 30–40% for all the films. This change in $\alpha$ cannot be explained by acoustic matching theory.

The emission of heat into the helium is evidently determined by a ballistic phonon-emission law, although the phonons propagate in a diffuse fashion in the helium and could apparently return to the heater repeatedly in the course of their diffusion, thereby influencing the behavior of the heater temperature (the mean free path estimated for thermal phonons in He I from the value of the thermal conductivity is on the order of $10^{-7}$ cm, while that in He II is $10^{-6}$ cm over the temperature interval from 2.0 to 1.8 K; Ref. 4). Further evidence for a diffusive propagation of the phonons comes from the fact that when the bolometer ($B$ 2) is in the helium (see the

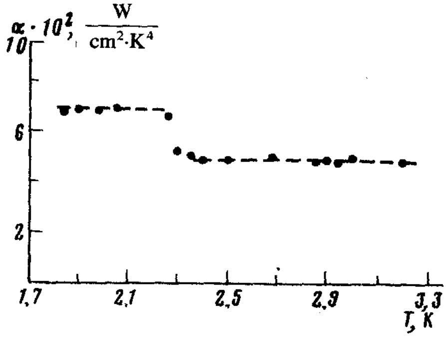

FIG. 3. Temperature dependence of the coefficient $\alpha$.

inset in Fig. 1) it does not detect the heat which is emitted by the heater and which propagates through the helium in the form of ballistic phonons at power levels below $Q = Q_{\mathrm{cr}}$, while the excitations which this bolometer does detect and which are propagating at the sound velocity at $Q > Q_{\mathrm{cr}}$ are caused by the onset of boiling of the helium.

As was shown in Ref. 3, if the coefficient of the transmission of phonons from the medium into the heater, $e$, is small ($e \ll 1$) then although a phonon may, in the course of its diffusion, return to the heater, it cannot enter it, and the behavior of the film temperature over time will be the same as if the phonons emitted by the heater propagated ballistically. This situation is possible under the condition

$$e \ll \xi \ll e^{-1}, \quad \xi = d(s/s)^3/l, \tag{2}$$

where $d$ is the thickness of the heater, $s$ is the average velocity, and $l$ is the mean free path of the phonons in the medium.

The phonon trasmission coefficient $\bar{e}_{\mathrm{Cu\text{-}He}}$ is estimated from the data in Fig. 3 to be 0.3–0.4. The phonon transmission coefficient is estimated to be $e_{\mathrm{He-Cu}} = \bar{e}_{\mathrm{Cu-He}}(S/\tilde{S})^2 = (3 \div 4) \times 10^{-3}$ ($S = 2 \times 10^4$ cm/s is the sound velocity in helium), and condition (2) does in fact hold.

We thank I. B. Levinson for a useful discussion.

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Translated by Dave Parsons
Edited by S. J. Amoretty