Resonant absorption of sound by a metal surface

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The angular dependence of the coefficient of transmission of a plane sound wave from He^4 into tungsten and gold was investigated at temperatures ~0.1–0.3 K. It is shown that acoustic phonons of frequency 10 and 30 MHz penetrate into the solid only in the region of the pre-critical angle and the angle corresponding to excitation of a Rayleigh wave. The sharp maximum predicted by Andreev and corresponding to resonant absorption of the sound by the surface of the metal is observed in the critical Rayleigh angle.

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The temperature jump on the interface between a solid and liquid helium under heat-flow conditions was first observed by Kapitza.[1] The phenomenon was explained by Khalatnikov.[2]

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Although the "Kapitza jump" is at present subject to no doubt, some aspects are still not quite clear. In particular, it is not clear why the real heat exchange proceeds much better than called for by the theory.

In investigations of the Kapitza jump one usually measures the integral effect due to the passage of the thermal flux averaged over the angles and frequencies. It is of interest to study in greater detail the angular and frequency dependences of the coefficient of sound transmission $\alpha(\theta,\omega)$, since it is on this coefficient that the heat exchange between the helium and the solid depends.

Particular interest attaches to the effect of resonant absorption of sound by the surface of a metal, an effect predicted by Andreev,[3] for the case when the sound is incident from the helium on the surface at an angle θ_1 close to the critical θ_0 and lying in the region of total internal reflection (θ_0 and θ_1 are defined by the relations $\sin\theta_0 = c/c_t$, $\sin\theta_1 = c/v_{\rm Ray} = c/\xi c_t$ and $0.87 < \xi < 0.96$, where c is the speed of sound in the helium, c_t is the speed of the transverse sound in the metal, and $v_{\rm Ray}$ is the velocity of the surface Rayleigh waves in the metal).

At θ_1, the Rayleigh waves that develop in the metal have sharp maxima corresponding to resonance of the incident wave with the Rayleigh waves. If the sound is damped by the conduction electrons, then at $l \gg \lambda$ (l is the electron mean free path and λ is the wavelength of the sound in the metal) the sound energy at θ_1 is practically fully absorbed. A sharp maximum with height of the order of unity and with width of the order of $\rho c^2/Dc_t^2$ will appear in the transmission coefficient $\alpha(\theta)$, where ρ and D are respectively the densities of the helium and of the metal.

In the present study, we have attempted to observe resonant absorption of sound by the surface of a metal in measurements of the angular dependence of $\alpha(\theta)$. To this end we investigated the passage of sound from He^4 into a pure single-crystal tungsten sample $R_{300\rm K}/R_{4.2\rm K} = 64000$ and a polycrystalline sample of pure gold $R_{300\rm K}/R_{4.2\rm K} = 36000$. The tungsten sample was a disk of 8.6 mm diameter and 1.5 mm thickness. The sound was incident and a flat electrically polished surface of the sample. The normal to the plane of the disk made angles 23 and 30° with the [100] and [101] axes.

The measurements were performed in a continuous-action dissolution cryostat, in a separate chamber filled with He^4. Sound at frequencies 10 and 30 MHz was radiated by peizoelectric quartz at a distance ~ 1 cm from the sample. The X-cut quartz (15 mm diam) was excited with a G4-18 generator. Special measurements have shown that the efficiency of the quartz radiation was $\sim 50\%$, and the beam divergence at the fundamental frequency 10 MHz did not exceed 20′.

The frame holding the sample was rotated through an angle $\pm 20°$ relative to the normal to the quartz with the aid of a connecting rod immersed in the helium bath and with a return spring. Motion of the frame altered the capacitance of a variable capacitor connected in the tank circuit of the measuring LC oscillator. The angle of incidence of the sound was determined from the generator frequency. The sensitivity of the method was ~ 1 sec, and the angle error was $\pm 10\%$.

The receiver of the absorbed sound energy was a germanium resistance thermometer glued with a conducting adhesive to the sample on the shadow side of the sound. A similar thermometer was placed in the liquid He^4.

The thermometer resistance was measured with S-71 and S-72 ac bridges manufactured in Czechoslovakia. Simultaneous readings of the parameters on the sample and in the liquid, as functions of the angle of incidence of the sound, were recorded with an x-y two-pen "Bryans" recorder. To this end, voltage from a 43-38 frequency meter was applied to the X coordinate of the recorder, while the voltages from the bridges S-71 and S-72 were applied to the coordinates Y_1 and Y_2. The temperature of the liquid was maintained accurate to 2×10^{-5} K during the recording time. The experimental procedure was the following: At a certain temperature T and at a maximum angle $\theta \sim 20°$, a voltage was applied to the quartz from the generator and the quartz was tuned to resonance. The temperature stabilizer was then turned on, the angle was varied slowly from $-\theta$ to θ, the sound power was maintained constant, and the temperatures of the sample and of the liquid were simultaneously recorded. Both thermometers had short relaxation times ($\tau \leqslant 1$ sec) and recorded in synchronism any thermal disturbance in the chamber. This made it possible to eliminate random fluctuations of the temperature.

Figure 1 shows, at $T = 0.28$ K, a simultaneous plot of the temperature of liquid He^4 (1) and of tungsten (2) as functions of the angle of incidence of sound of frequency $f = 10$ MHz and a voltage $U = 260$ mV on the quartz. The ordinate axis on the left shows the heat rise of the sample relative to the He^4, and the axis on the right shows the sound transmission coefficient $\alpha(\theta)$, referred at the point $\alpha(0)$ to the value

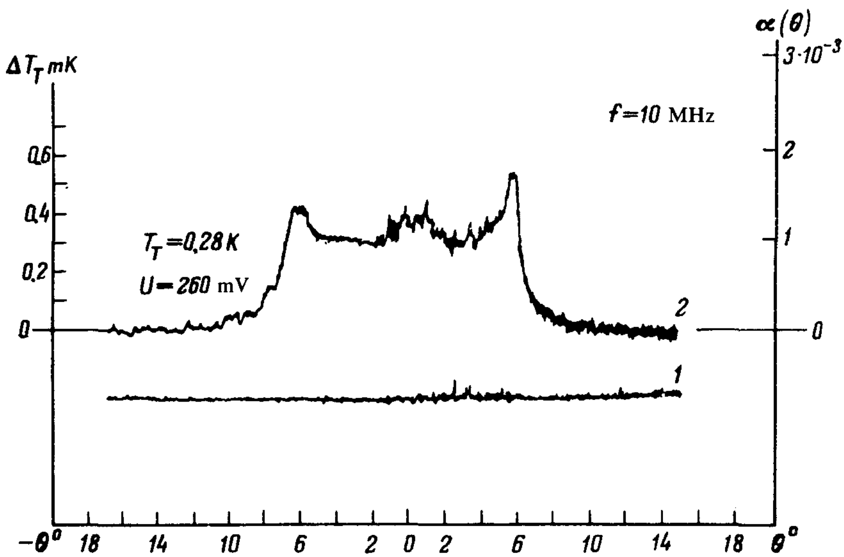

FIG. 1. X-Y plot of the heat rise of tungsten ΔT_T (curve 2) due to sound, as a function of the incident angle θ (left-hand scale), $f = 10$ MHz, $T = 0.28$ K, voltage on quartz $U = 80$ mV. Right-hand scale—sound transmission coefficient. Curve 1—plot of the liquid-He^4 temperature, $T = 0.28$ K.

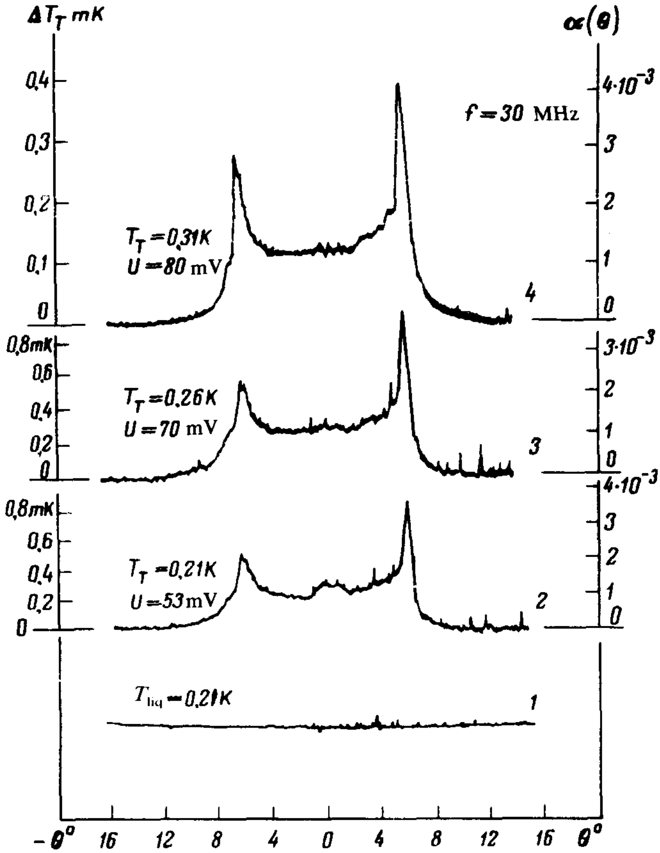

FIG. 2. Plot of the heat rise ΔT_T of tungsten due to sound at $f = 30$ MHz for three temperatures, $T = 0.21$ K (2), $T = 0.26$ K (3), and $T = 0.31$ K (4), as functions of the angle of incidence θ (left-hand scale): U—voltage on the quartz. Right-hand scale—sound transmission coefficient $\alpha(\theta)$. Curve 1—plot of the temperature $T = 0.21$ K of the liquid He^4.

$\alpha_0 \approx 4\rho c/Dc_l$; $\alpha_0 = 1.4\times 10^{-3}$ ($\rho = 0.145$ g/cm^3, $c = 2.4\times 10^4$ cm/sec, $D = 19.2$ g/cm^3, $c_l = 5.11\times 10^5$ cm/sec).

Figure 2 shows analogous curves for sound of $f = 30$ MHz at three stabilized temperatures of the liquid. The liquid temperature was recorded only for $T = 0.21$ K (the two other dependences are similar). It is seen from Figs. 1 and 2 that, first, sound incident on the tungsten surface enters the metal only in the narrow angle from 0 to 6°. The angle region $> 6°$ corresponds to total reflection of the sound (the tail beyond this angle is negligible, $\sim 2°$). Second, at $\theta = 6°$ one observes a sharp maximum that exceeds the value of α at $\theta = 0$ by three times if $f = 30$ MHz and by 1.3 times of $f = 10$ MHz. (One cannot exclude the possibility that α depends on the frequency near θ_1).

Estimates of θ_0 and θ_1 for tungsten yield $\theta_0 = 5°16'$ and $\theta_1 = 5°36'$ ($c_t = 2.6\times 10^5$ cm/sec, $\xi = 0.935$), which agrees with experiment within the limits of accuracy and indicates that Rayleigh waves are excited at θ_1 (the difference between the heights of the $-\theta_1$ and θ_1 peaks is apparently due to non-equivalence of the boundary conditions).

At $\theta = 3°$ (Fig. 1), a small dip is observed in the transmission coefficient and corresponds to the critical angle for longitudinal sound $\theta_l = 2°42'$.

The Rayleigh peak is not fully resolved, $\Delta\theta_1 \approx 30'$, a fact that can be attributed to the large divergence of the ultrasound beam, which smears out the true narrow peak. One cannot exclude, furthermore, additional damping of sound by dislocations.[4-6] The obtained $\alpha(\theta)$ dependence makes it possible to estimate the relative contribution of the Rayleigh waves to the thermal flux for acoustic phonons. Multiplying $\alpha(\theta)$ by $\sin\theta \cos\theta$[2] and calculating the area bounded by this curve, we find that the contribution of the Rayleigh waves for $f = 30$ MHz is $\sim 50\%$.

Similar measurements of $\alpha(\theta)$ were made by us on a polycrystalline sample of pure gold at temperature $T \sim 80$ mK and a sound frequency $f = 20$ MHz. At an incidence angle $\theta \sim 13°$ and $U = 15$ mV we observed a large heat rise of gold, $\Delta T \sim 1$ mK ($\Delta\theta_1 \sim 40'$). The temperature of the liquid remained unchanged in this case. The effect was analogous to that observed on tungsten and offered evidence of resonant sound absorption by the surface in the Rayleigh critical incidence angle ($\theta_1 = 12°12'$, $c_t = 1.2 \times 10^4$ cm/sec, $\xi = 0.945$).

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