Transmission of sound across a boundary between liquid ^{4}He and tungsten in the collisionless region (60–160 mK)

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The angular dependence of the passage of energy of a plane monochromatic sound wave of 30-MHz frequency incident on a tungsten surface from liquid helium is studied at temperatures between 60 and 160 mK. The results are compared with previous measurements at higher temperatures. The main features previously observed are retained. The sound penetrates the tungsten over a narrow angular range $\sim \pm 6°$. A maximum energy transmission is observed at the Rayleigh incidence angle in the supercritical region. The peak parameters are close to those obtained in the range 0.2–0.4 K. The damping of the Rayleigh waves and their contribution to the total flux of transmitted energy are estimated.

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1. INTRODUCTION

The observation and results of investigation of the resonance absorption of sound by the surface of a metal were reported in Refs. 1 and 2. A maximum in the angular dependence of the sound transmission coefficient $\alpha(\theta)$ from liquid ^{4}He to tungsten was observed at the Rayleigh angle of incidence. The phenomenon was predicted theoretically by Andreev[3] and is due to the absorption of the energy of the Rayleigh wave excited on the surface of the metal by the incident sound.

The method of determination of $\alpha(\theta)$ in Refs. 1 and 2 consisted in the measurement of the fraction of the acoustical energy transmitted from the liquid helium into a solid immersed in it with the help of the Kapitza jump[4], i.e., from the heating of the solid relative to the helium bath. The basic measurements were performed on a single crystal of tungsten at temperatures 0.2–0.4 K and sound frequencies of 10 and 30 MHz. It was shown that the Rayleigh waves make approximately the same contribution to the energy flux through the boundary as that of the volume waves in the subcritical angle. From an analysis of the experimental data, carried out in comparison with generalized acoustical theory,[5] it was established that the coefficient of energy absorption of the Rayleigh waves in the tungsten is identical to the volume coefficient of sound absorption by electrons and holes.

The width of the Rayleigh maximum in previous measurements[1,2] depended weakly on the temperature—it changed from 25 to 40′ for a temperature change from 0.2 to 0.4 K. It can be assumed that the effect is connected with the scattering of acoustical phonons by thermal phonons, i.e., with the absorption of sound in the liquid helium, since the density of the thermal phonons increases rapidly with temperature. According to the measurements of Abraham *et el.*,[6] the sound absorption in the phonon region is proportional to T^4 and, at a frequency of 30 MHz it increases in the interval 0.2–0.4 K from ~ 1 to ~ 10 dB/cm, i.e., it becomes a significant quantity at $T \sim 0.4$ K.

At the same time, the formulas of generalized acoustical theory, with which the results of the measurements are compared, are deduced with account of acoustic damping only in the solid. Damping in the liquid is taken to be equal to zero. Strictly speaking, such an assumption is valid only for $T \lesssim 0.1$ K. Therefore, it is of interest to extend the region of investigation to lower temperatures, where the density of thermal phonons in liquid helium is negligible and the sound absorption in the liquid can actually be neglected.

2. RESULTS AND THEIR DISCUSSION

In the present work we have extended the region of investigation to 60 mK. Measurements of the angular dependence of the transmission coefficient from liquid helium to the metal have been carried out on the sample used previously—a single crystal of tungsten of high purity ($r_{300}/r_{4.2} = 6.4 \cdot 10^4$). A plane wave of frequency 30 MHz was generated with the same quartz. The solution cryostat and the measuring apparatus that were used in the research were described in detail in Ref. 2.

To obtain lower temperatures in the solution cryostat, the tubular heat exchanger was replaced by a more effective distributed one with a larger surface; in addition, heat conduction into the measurement chamber was reduced by limiting the power in the angle sensor. A new LC generator was assembled for this purpose.

Upon incidence on the sample (at an angle θ) of a plane wave with flux density N, a fraction of energy $w(\theta)N\cos\theta$ penetrates inside the sample. Here σ is the area of the sample on which the sound is incident and $w(\theta)$ is the sound transmission coefficient. The transmitted energy is absorbed by the solid and in the case of continuous radiation this brings about a heating of the solid relative to the liquid by the amount of the Kapitza jump. It S is the total surface of the sample and R_K is the Kapitza resistance, then, from the balance of energy entering into and radiated from the solid, $\Delta TS/R_K$, we obtain

$$\alpha(\theta) = w(\theta)\cos\theta = \frac{S}{R_K N \sigma}\Delta T.$$

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As before, for the determination of the angular dependence $\alpha(\theta)$ we measure the heating of the sample ΔT as a function of the angle θ.

The absolute value of $\alpha(\theta)$ was calculated from the value of ΔT after normalization at zero angle, where $\alpha(0)$ was taken to be equal to[7]

$$\alpha(0)=\frac{4\rho c D c_l}{(\rho c+D c_l)^2}\approx\frac{4\rho c}{D c_l}=1.4\cdot 10^{-3}.$$

Here ρ and c are the density and the sound velocity in ^{4}He, D and c_l are the density and the velocity of longitudinal sound in tungsten ($\rho = 0.145$ g/cm^3, $D = 19.4$ g/cm^2, $c = 2.4\times 10^4$ cm/sec, $c_l = 5.11\times 10^5$ cm/sec.)

For estimate of the leakage of energy of the sample through mounting, measurements were made of the heating of the sample in a vacuum (relative to the solution bath), whence the shunting resistance R'_K was estimated. The heating in this case was produced by a heater attached to the sample. Experiment shows that at $T\sim 0.5$ K, the heating leakage $\delta Q/Q < 1\%$ and falls off rapidly with decrease in the temperature. Thus the shunting resistance R'_K can be neglected.

Typical results of measurement of $\Delta T(\theta)$ in the interval 60–160 mK are shown in Figs. 1 and 2. Simultaneous traces of the heating of the sample and of the liquid helium bath are shown in Fig. 1 at two different temperatures in the case of a change in the angle of incidence of the sound wave by the angle θ. Plots are given for positive and negative angles θ at the stabilized temperature of liquid helium (stabilization with accuracy to within 3×10^{-5}–10^{-4} K).

As before, the plots show that the sample is heated by the sound only in the narrow range of angles ($\sim 6°$) near normal incidence. At angles of incidence $\theta = \pm 6°$, maxima of the heating of the solid relative to the liquid helium bath are clearly seen. For tungsten, the angle $\sim 6°$ is the supercritical Rayleigh angle, at which the incident sound wave excites Rayleigh waves on the surface. Thus the maxima of heating

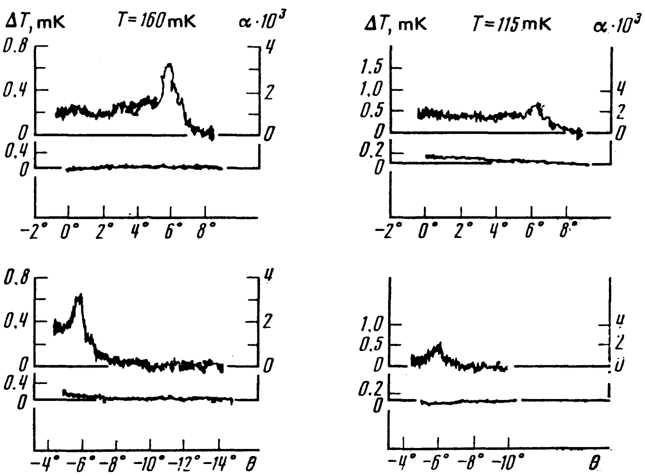

FIG. 1. Records of the heating of a sample of tungsten by sound (upper curves) and the temperature of liquid ^{4}He (lower curves) as a function of the angle of incidence of sound of frequency $f = 30$ MHz at two temperatures of the bath: 160 and 115 mK. The scale at the right is the coefficient of transmission of the sound.

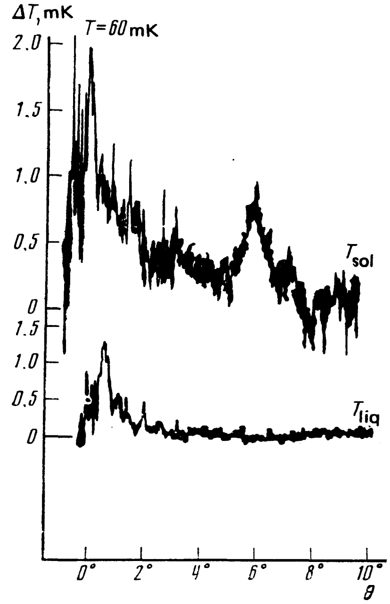

FIG. 2. Record of the heating of a sample of tungsten by sound T_{sol} and the temperature of liquid ^{4}He T_{liq} as a function of the angle of incidence of the sound of (positive) frequency 30 MHz at $T = 60$ mK.

of the sample at $\theta = \pm 6°$ are governed by the absorption of the resonantly excited Rayleigh waves. A distinctive feature here is the identical height of the Rayleigh peaks (~ 0.7 mK) at $\theta = +6°$ and $\theta = -6°$ ($\alpha_P \approx 3.5\times 10^{-3}$). The width of the maximum (at half-maximum) is $\sim 30'$. The dependence of the sound transmission coefficient $\alpha(\theta)$ normalized at $\theta = 0$ is marked the ordinate at the right. Near $\theta = 0$, as previously, a small increase is observed in α, as a consequence of multiple reflection of the sound between the source and the sample.

Figure 2 shows the simultaneous plot of $\Delta T(\theta)$ for positive angles θ at $T = 60$ mK. On the temperature curve for the solid, T_{sol}, the Rayleigh maximum is also seen at $\theta = 6°$ with width $\sim 30'$. The rise in the temperature of the solid near $\theta = 0$ on Fig. 2 is produced by the heating of the liquid because of motion of the frame, which was not compensated by the stabilizer at the lower temperature.

By comparing the results here with the previous results for the interval 0.2–0.4 K,[2] it is not difficult for us to see that the width of the Rayleigh maxima remains constant below 0.2 K. Since the sound absorption is absent in the liquid, the divergence of the plane wave ($\sim 30'$) which exceeds the diffractive spreading λ/d ($\sim 2'$) by an order of magnitude, can be explained by the weak waviness of the surface.

We also note that the height of the Rayleigh maxima for positive and negative angles θ is identical in the measurments, this confirms the assumption made in Ref. 2 that the reason for the different heights of the peaks at higher temperatures can be the nonuniformity of the sound wave, which is governed by the damping of the sound in the liquid helium.

We have calculated the integrals of the transmitted sound energy

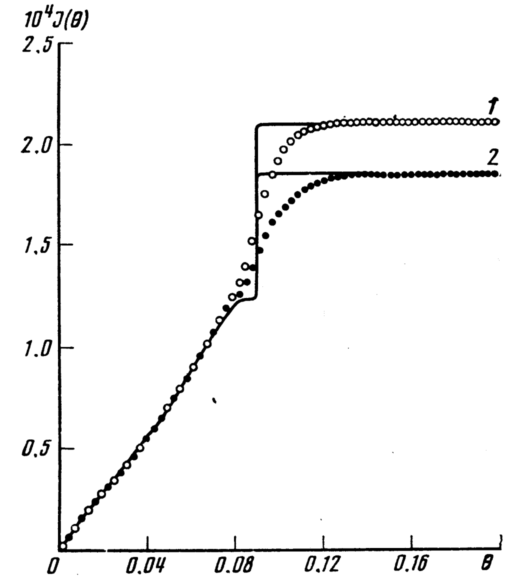

FIG. 3. Integral of the penetrated sound energy as a function of the angle θ for experimental (points) and theoretical (solid curves) dependence of $\alpha(\theta)$: 1—$T=160$ mK, 2—$T=115$ mK; $f=30$ MHz.

$$J(\theta)=\int \alpha(\theta)\,d\theta$$

from the experimental curve $\alpha(\theta)$. These integrals are shown in Fig. 3 for two temperatures. As is seen from the drawing, the contribution of the Rayligh maximum to the total flux of transmitted energy is approximately equal to the contribution of the volume wave at the subcritical angle. From a comparison of the experimental integrals with those computed from the generalized acoustical theory (see Ref. 2) which is shown in Fig. 3 by the solid line, we can estimate the damping parameter of the sound energy in tungsten $p=\gamma_{lt} c_{lt}/2\omega=\lambda/4\pi l$, where γ_{lt} is the absorption coefficient (nepers per unit length), λ is the sound wavelength, l is the characteristic length of the damping of the energy, $\omega=2\pi f$.

For temperature of 115–160 mK and $f=30$ MHz we have $p=(2\text{–}3)\times10^{-4}$. This value is virtually identical with p $(2\text{–}6)\times10^{-4}$ found earlier in Ref. 2 for the interval 0.2–0.4 K and $f=30$ MHz. We recall that the parameter of back sound absorption in tungsten at liquid helium temperatures as measured experimentally in Refs. 8 and 9 is equal to $p=3\times10^{-4}$. This quantity agrees satisfactorily with the calculation of the sound absorption by electrons and holes with account of the deformation potential.[8]

Comparison of the results with those measured at higher temperatures[2] makes it possible to conclude that the energy transmission coefficient at the Rayleigh incidence angle does not depend on the sound absorption in helium at temperatures ~0.3 K, at which the parameter of damping of the sound in the helium $p_{\rm He}=\gamma_{\rm He}c/2\omega=3\cdot10^{-5}$ [6] is still an order of magnitude smaller than the damping parameter in tungsten, $p_W=3\times10^{-4}$. With increase in temperature, $p_{\rm He}$ increases in proportion to T^4 and becomes equal to p_W at $T\sim0.5$ K. In this region ($T\gtrsim0.5$ K) special measurements are necessary for the determination of the contribution of the Rayleigh waves to the transmitted energy.

3. CONCLUSION

The studies of the transmission of sound of 30 MHz from liquid helium to tungsten at temperatures $T\sim0.1$ K have shown that in the collisionless region of ^{4}He the character of the phenomenon remains the same as at higher temperatures (~0.2–0.3 K) where finite damping of the sound in helium exists, due to scattering of acoustic phonons by thermal phonons.

The basic features of the phenomenon in the collisionless region are as follows. The sound penetrates inside the solid with a transmission coefficient $\sim10^{-3}$ only in a narrow range of angles near normal incidence ($\sim6°$). At the Rayleigh supercritical angle of incidence a maximum of transmission of energy is observed, beyond which angle it falls rapidly to zero.

The experimental width of the Rayleigh peaks ($\sim30'$) does not depend on the temperature. The absolute values of the widths of the maxima can be explained by the roughness of the surface of the sample and the nonideality of the source. The peaks are symmetric relative to zero angle and have equal heights.

The contribution of the surface Rayleigh wave to the total integral of transmitted energy is approximately equal to the contribution of the volume waves to the subcritical angle, while the coefficient of absorption of the Rayleigh wave is identical with the coefficient of volume absorption in tungsten.

It follows from what has been said that the coefficient of transmission of the sound absorption in the liquid helium provided that the parameter of sound absorption of helium is much less than the damping parameter in tungsten.

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