Resonant absorption of sound by surface of copper single crystal

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(Submitted 22 December 1990; resubmitted 21 February 1990)
Pis'ma Zh. Eksp. Teor. Fiz. **51**, No. 6, 332–335 (25 March 1990)

The passage of acoustic phonons from liquid ^{4}He into an anisotropic copper single crystal has been studied experimentally for the first time in the temperature interval 100–400 mK and in the frequency interval 13–91 MHz. The angular dependence of the coefficient of the transmission of phonon energy into the crystal has been studied. Sharp peaks have been found in this transmission coefficient in the case of the (001) basal plane of the crystal and the (100) plane of incidence of the sound at an angle of incidence equal to the critical angle θ_R. The width of these peaks is $\delta \approx 5$–$10'$, and their height is $\alpha \approx 0.1$. A significant increase in the transmission coefficient for ballistic phonons at angles near normal incidence has been observed for the first time. It is explained.

In this letter we are reporting a study of the transmission of sound across an interface between liquid helium and a copper single crystal. Interest was originally attracted to this topic by the theoretical paper by Andreev,[1] who studied the resonant absorption of sound by a metal surface. The effect was attributed to a dissipation of the energy of a Rayleigh wave excited in the metal by the incident sound. The damping of the Rayleigh wave by free electrons of the metal resulted in a nearly complete absorption of the acoustic energy at an angle of incidence equal to the Rayleigh critical angle, $\theta = \theta_R$: A sharp peak, with a height on the order of unity and a width on the order of a fraction of an arc minute, should be observed in the sound transmission coefficient. Correspondingly, the sound reflection coefficient vanishes at θ_R.

Later, Anderson and Peterson[2] and (independently) Haug and Weiss[3] found similar results in a study of a liquid–solid interface on the basis of a generalized acoustic theory incorporating the bulk attenuation of sound in the solid.

First studies of the angular dependence $\alpha(\theta)$ of the coefficient for the transmission of acoustic energy out of liquid helium into a tungsten single crystal and observations of maxima on this angular dependence at an angle of incidence θ_R were reported in Refs. 4–6. Tungsten is a transition metal which forms an acoustically isotropic crystal. The experimental results of Refs. 4–6 generally supported the theoretical conclusions of Refs. 1–3. However, the results of those measurements were difficult to compare with the theory of Ref. 1, not only because the electronic properties of tungsten are described poorly by free-electron theory but also because the technical state of the art at the time did not permit an adequate measurement accuracy.

We have accordingly carried out a second study, using a copper single crystal. The properties of copper are described well by free-electron theory. A copper crystal differs from a tungsten crystal in that it is highly anisotropic from the acoustic standpoint. Several special measures which we took made it possible to measure small absolute values of $\alpha(\approx 5\times 10^{-3})$ with a significantly better resolution and better sensitivity and to observe some new effects.

In these measurements we used the method and apparatus described in Refs. 4–6. Under steady-state conditions, with sound at a frequency ω incident continuously on a metal surface at an angle θ from liquid helium, the sound transmission coefficient $\alpha(\omega,\theta)$ is related to the heating of the sample with respect to the liquid, ΔT, by

$$\alpha(\omega,\theta) = \Delta TS/NR_K\sigma .$$

Here N is the flux density of acoustic energy, R_K is the Kapitsa resistance, S is the total surface area of the sample, and σ is the area on which the sound is incident.

The temperature of the copper sample, that of the liquid ^{4}He, and their difference were measured by germanium thermometers. Two thermometers were immersed in the liquid, and two were cemented to the rear of the sample with electrically conducting cement.

The copper single crystal was grown from a starting material of high purity ($RRR = 50\,000$). This crystal was a disk 10 mm in diameter and 1.4 mm thick. The disk was cut from a single-crystal cylinder by an electric-arc method, polished with a diamond paste (the particle size ranged from 1 to 0.01 μm), and finally electropolished in a 50% solution of orthophosphoric acid to eliminate surface stress. A layer ≈ 10 μm thick was removed in the course of the electropolishing.

The surface quality of the sample was monitored with a Linnik interferometer. It was found that the surface irregularities were no greater than 0.1 μm and that the deviation of the surface from a plane was less than 10 μm over the length of the sample.

Since the copper single crystal is highly anisotropic (its anisotropy factor is $\eta = 3.2$), the phase velocity and group velocity of the Rayleigh wave, and also the polarization of this wave, depend on the particular plane in which the crystal is cut and also on the propagation direction in this plane.[7]

In some first experiments we studied the simple case in which the free surface was the (001) basal plane of the cubic crystal, and the plane of incidence conincided with the (100) plane. This case is the closest to isotropy. The surface displacement also describes an ellipse which lies in the sagittal plane, with the same penetration depth, $(2\text{–}2.5)\lambda$.[8]

The only deviation from isotropy is in the variation of the displacement components along depth: In the isotropic case, the variation would be exponential, while in the anisotropic case, with an anisotropy factor $\eta > 1$, the variation is an exponentially damped sinusoid.[7]

The measurements of $\alpha(\omega,\theta)$ were carried out over the temperature interval 100–400 mK at frequencies of 13, 39, 65, and 91 MHz (the fundamental frequency of the quartz transducer and three harmonics). Curve 3 in Fig. 1 shows typical plots of $\Delta T(\theta)$ and $\alpha(\theta)$ for $T = 107$ mK and $f = 65$ MHz.

The following results were found.

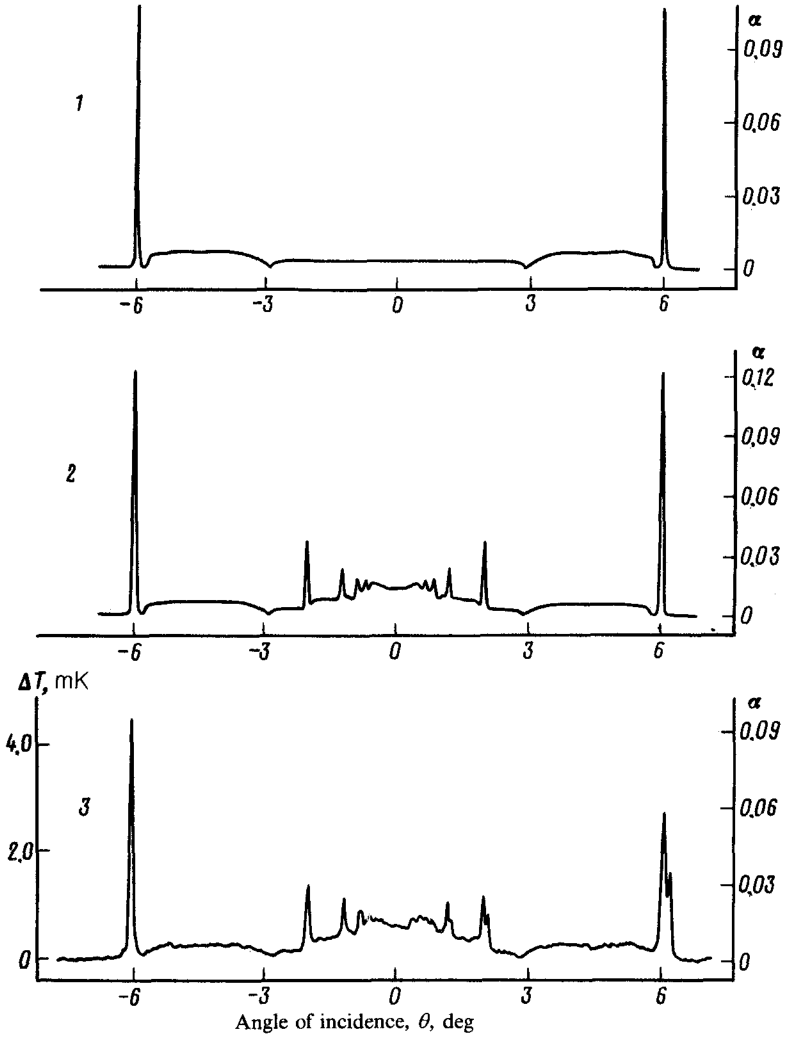

FIG. 1. Angular dependence of α (scale at right), the coefficient of the transmission of acoustic energy out of ^{4}He into a copper single crystal, for the (001) plane. The plane of incidence of the sound is the (100) plane. *1*—Calculation of α for an ideal plane wave which is incident from liquid ^{4}He on an infinite copper half-space (the attenuation in the copper is $p = 4\times10^{-4}$; $\alpha_R = 0.4$; $\delta \approx 1'$); *2*—calculation of α for the given geometry with allowance for multiple reflections of the sound between the sample and the quartz transducer, the instrumental broadening of the peaks, the attenuation of the sound in the helium ($\gamma = 0.15$ dB/cm), and that in the copper ($p = 4\times10^{-4}$); *3*—experimental record of the heating of the sample by the sound, ΔT (scale at left), at a radiated power ~ 5 μW, a temperature of 107 mK, and a frequency of 65 MHz. The value of $\alpha(\theta)$ was found from $\Delta T(\theta)$ after a normalization at angles of incidence corresponding to the excitation of a transverse vibration mode.

1. A heating of the sample by the sound, $\Delta T(\theta)$, is observed only in the angular interval $\pm 6.3°$ (curve 3 in Fig. 1).

2. At angles of incidence $\pm 6.0°$, at all frequencies and temperatures, we find sharp absorption peaks with a height $\alpha \approx 0.1$ and a width $\delta \approx 5$–$10'$. These peaks are

caused by a dissipation of Rayleigh waves. The width and height of the peaks are close to the theoretical predictions. (The remaining difference should apparently be attributed to diffraction effects.) Here we are essentially seeing, for the first time, the resonant absorption of sound by a metal surface in the form which was predicted by Andreev.

3. The width of the Rayleigh peaks at a given frequency does not depend on the temperature. As the frequency is raised from 13 to 91 MHz, the width of the peaks decreases slightly, indicating that two mechanisms are operating to broaden the beam: a diffraction mechanism ($\approx\lambda /d$) and a mechanism associated with the surface irregularities of the sample.

4. On the angular dependence $\alpha(\theta)$ we have managed to observe, for the first time, two symmetrically positioned minima, which correspond to the first and second critical angles of incidence of the sound: $\theta_l = \pm 2.8°$ and $\theta_t = \pm 5.8°$. The angle θ_l is the boundary between bulk longitudinal and bulk transverse excitations, while θ_t is the boundary between bulk and surface excitations of the copper single crystal.

5. For the first time with a good resolution and a large signal-to-noise ratio, the sound transmission coefficient has been recorded over the entire angular range, including angles of incidence near the normal. It has been found that in the angular interval $\pm 2°$ the transmission of acoustic energy is higher than the theoretical prediction (curves 1 and 3 in Fig. 1), as a result of the appearance of numerous, well-resolved peaks of smaller height. These peaks correspond to angles of incidence which are 1/3, 1/5, 1/7, ..., of θ_R. They are Rayleigh maxima caused by the incidence of ultrasound which is multiply reflected from the surfaces of the quartz transducer and the sample, as is verified well by a calculation which takes such reflections into account (curve 2 in Fig. 1). In general, the excitation of Rayleigh waves is thus detected when the sound is incident at angles $\theta_n = \theta_R /n$, where $n = 1, 3, 5, \ldots$ are odd numbers. The decrease in the amplitude of the Rayleigh peaks with increasing number of reflections conveys useful information about the absorption of sound in the liquid helium. As expected, the "comb" of these peaks becomes noticeably shorter with increasing frequency and temperature. This effect might be utilized for simultaneous measurements of the attenuation of sound in a solid and in a surrounding liquid.

Multiple reflections are possible because of the small distance between the sample and the transducer, i.e., because of the small dimensions of the chamber (in order to completely eliminate the peak which appears at $\theta = \pm 2°$, for example, it is necessary to move a sample 10 mm in diameter 7.5 cm away from the transducer).

In the ideal case, the nth peak should be narrower than the main peak by a factor of n. This circumstance makes it possible to distinguish the instrumental and natural widths of the observed peaks. On the recordings found, all the peaks have the same width, so this width is instrumental.

At sufficiently low temperatures, where the sound is propagating ballistically, without attenuation, the resonant absorption of the thermal phonons reflected repeatedly in a confined volume might make a substantial additional contribution to the heat flux into the solid.

We believe that the agreement, which extends to the fine details, between the experimental and theoretical curves of $\alpha(\theta)$ confirms the validity of the ideas on which the calculations are based. It is true that the reason for the splitting of the peak at the right is not clear.

We wish to thank A. F. Andreev, Yu. A. Kosevich, and A. V. Dubrovin for useful discussions; Yu. F. Orekhov for an x-ray diffraction study of the sample; and V. N. Krutikhin for assistance in the preparation for the experiments and in the experiments themselves.

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Translated by Dave Parsons