Effect of the transition from the normal state to the superconducting state on the phonon transmission through liquid ^{4}He–metal interface

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The passage of low-frequency phonons through the liquid ^{4}He–aluminum single-crystal interface has been studied. The measurements were carried out at temperatures 100–300 mK and frequencies 13–91 MHz for normal and superconducting states of aluminum. It is demonstrated that Rayleigh wave contribution to the total energy flux across the boundary decreases markedly on going from the normal state to the superconducting state of the metal. Experimental data are compared with the data on copper reported previously. It is concluded that the scattering of surface waves (similarly to the bulk waves) is due to conduction electrons. The bulk interference of phonons (analogous to the Fabry–Perot interference) has been observed for a superconducting metal, while for the normal state this effect is absent.

The possibility for the existence of an anomaly during the transmission of acoustic energy through a liquid ^{4}He–metal interface was first considered by Andreev[1] in 1962. He found that the angular spectrum of the energy transmission coefficient should consist of two main parts: continuous spectrum and a resonant peak; the former corresponds to an ordinary elastic scattering of phonons within the critical angle, while the latter occurs due to the resonant excitation of a surface Rayleigh wave and the subsequent adsorption of its energy. He suggested that at $l_e \gg \lambda$ (where l_e is the electron free path and λ is the sound wavelength in a metal) the scattering of an acoustic wave on conduction electrons predominates. Starting from this assumption he found that at an angle of phonon incidence corresponding to the surface Rayleigh wave excitation almost all of the phonon energy should pass through the surface.

The angular spectrum of the energy transmission coefficient should therefore have a sharp singularity $\alpha \sim 1$, at the Rayleigh angle. Confirming Khalatnikov's conclusion,[2] Andreev found that the contribution of the Rayleigh wave to the total transmitted energy is about the same as that of the bulk sound waves, and that it does not depend on the phonon frequency. The Kapitsa resistance should therefore decrease by one-half because of the Rayleigh wave contribution.

First studies of the angular dependence of the acoustic energy transmission coefficient $\alpha(\vartheta)$ across the liquid helium–tungsten single-crystal interface and the observation of the Rayleigh maxima were reported in Refs. 3 and 4.

In 1972, a general model was proposed.[5–7] This model described the heat transfer between liquid helium and a solid, known as the generalized acoustic theory. This theory allows for the attenuation of bulk acoustic waves in a solid by introducing the dissipation parameter

$$p=\frac{\gamma c}{2\omega}=\frac{1}{4\pi}\frac{\lambda}{l}, \tag{1}$$

where γ is the energy absorption coefficient per unit length, λ is the sound wavelength, and l is the characteristic energy attenuation length (the distance required for the intensity to be reduced e times). This theory, therefore, does not involve a specific mechanism of dissipation in a solid.

Numerical calculations carried out according to the generalized acoustic theory[5,8] give a comprehensive pattern of the angular spectrum of the energy transmission coefficient. In the vicinity of the Rayleigh angle the results are analogous to those obtained by Andreev: At certain values of p, $p \geqslant 10^{-4} \sim 10^{-3}$, an extremely sharp and narrow Rayleigh peak appears. A detailed analysis of the continuous spectrum shows that it includes longitudinal and transverse parts. The transmission coefficient of the longitudinal wave remains nearly constant at all possible angles: $\alpha_{\text{long}} \simeq 4\rho_{\text{He}} c/\rho_{\text{solid}} c_l \simeq 5\times 10^{-3}$. The transverse wave transmission coefficient α_{trans} is of the same order of magnitude but 1.5–2 times larger. Therefore only an insignificant part of the energy incident within the critical angle can pass through the interface because of the strong acoustic mismatch between the liquid ^{4}He and the solid. Both α_{long} and α_{trans} depend only slightly on the dissipation (see also the calculated curves in Figs. 1a–1d). In contrast, the surface Rayleigh wave transmission strongly depends on the dissipation in a solid.

A new method of studying the phonon transmission across liquid ^{4}He–solid interface has been developed previously.[4] It provides a way of investigating the angular spectrum of the energy transmission coefficient with a high angular resolution (about 5′). It thus enables one to verify Andreev's theory and to determine the role of conduction electrons in the heat transfer through ^{4}He–metal boundary.

In this letter we report the measurements of the low-frequency (up to 90 MHz) phonon transmission across an interface between liquid helium and an aluminum single crystal in both the superconducting and normal states. The data for each state are compared with each other, as well as with the data for a Cu single crystal reported earlier.[8]

The following experimental procedure was used. A plane monochromatic sound wave at a frequency ω, emitted by a piezoelectric quartz transducer, was incident continuously on a metal surface at an angle ϑ. A fraction of the acoustic energy passed through the interface and was absorbed in the bulk of the metal. This process resulted in the overheating of the metal sample relative to the ambient liquid. The energy transmission coefficient is given by

$$\alpha(\omega,\vartheta)=\frac{\Delta TS}{NR_K\sigma}, \tag{2}$$

where N is the heat flux density, R_K is the Kapitsa resistance, S is the total surface area of the sample, σ is the area exposed by sound, and ΔT is the value of the temperature

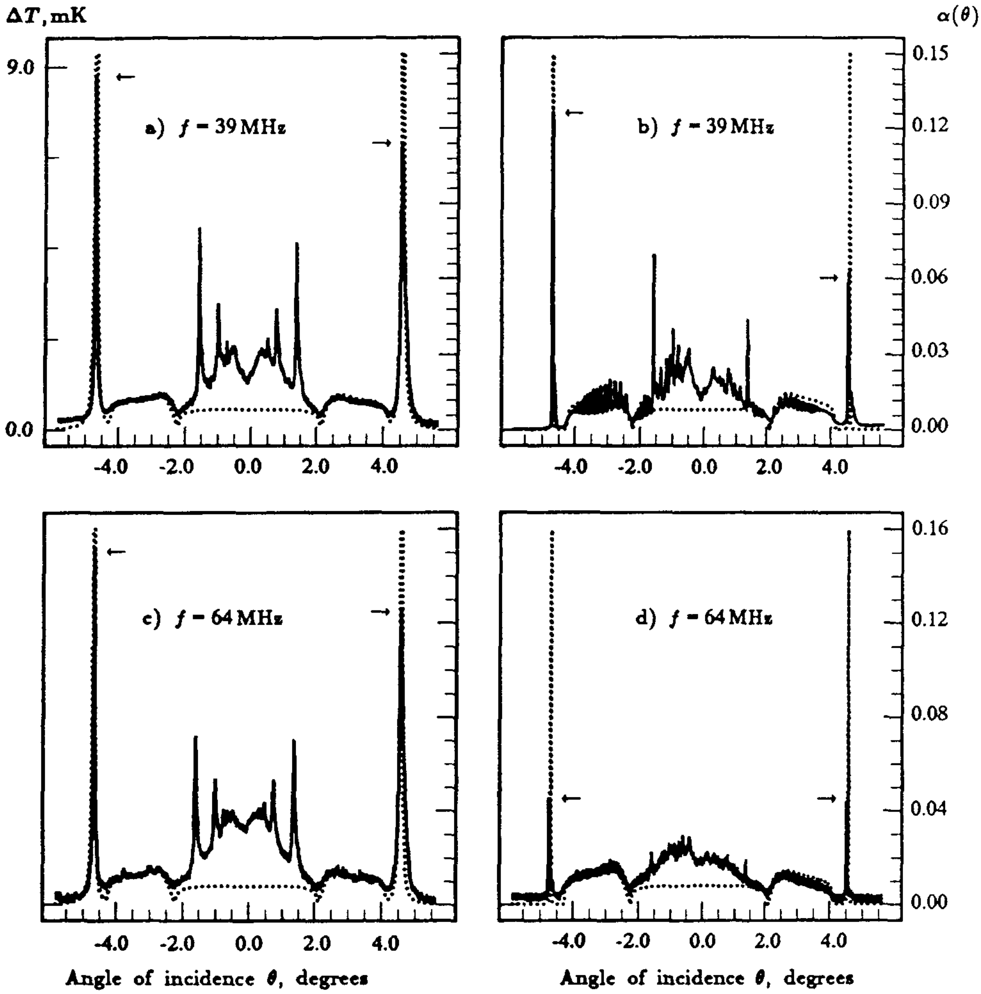

FIG. 1. The angular spectrum of phonon transmission coefficient for normal (a,c) and superconducting (b,d) Al crystal, $T = 140$ mK. The solid line represents the experimental data; the dotted line denotes calculation. Each arrow points to the crest of the experimental peak.

difference between the sample and the liquid. Measuring the ΔT-vs-ϑ curve, we can therefore find the relative values of $\alpha(\omega,\vartheta)$. To obtain the absolute values of $\alpha(\omega,\vartheta)$, we normalized α by comparing the experimental curve with the theoretical curve, calculated by using the generalized acoustic theory. The normalization was performed at the angles of incidence corresponding to the excitation of a transverse vibration mode. Such normalization was motivated by the fact that under conditions of our experiment the transverse wave transmission across the interface is not affected by repeated reflection of sound between the quartz transducer and the sample surface (see below). With the calculated curve in agreement with the experimental data, we obtained the absolute scale of $\alpha(\omega,\vartheta)$ and estimated the value of the dissipation parameter p.

The apparatus was the same as that described in Ref. 4. The aluminum single crystal was grown from a starting material of high purity (RRR=40 000), and the electron mean free path was about 0.5 mm. The crystal was a disk 18 mm in diameter and 2 mm thick. The [100] axis lay on the free surface of the sample and the (010) plane deviated by 2° from the normal to the free surface. The sagittal plane passed through the [100] axis and the surface was electropolished to eliminate irregularities greater than 0.1 μm. The measurements of $\alpha(\omega,\vartheta)$ were carried out in the temperature range between 100 and 300 mK at the saturated vapor pressure at frequencies 13, 39, 65, and 91 MHz. The sample was carried to the normal state in a 1-kOe magnetic field, which was aligned with the vertical axis of the measurement chamber passing through the centers of the quartz and the sample.

The experimental data, along with the theoretical calculations, are shown in Fig. 1. As expected, the overheating of the sample is observed in the narrow range of angles, $-5° < \vartheta < 5°$. In accordance with the theory, the experimental spectra have two parts: 1) a continuous region between $-4.5°$ and 4.5°, which in turn consists of two parts corresponding to the excitation of the longitudinal and transverse bulk modes; these parts are divided by the minima which appear at the critical angles for the longitudinal mode, $\vartheta_{\text{long}} \sim 2°$; 2) two peaks beyond the critical angles. These peaks are caused by absorption of the Rayleigh wave energy.

There is also a set of smaller peaks in the region of continuous spectrum. These peaks appear due to the multiple reflections of the sound wave between the surface of the sample and the quartz transducer. They appear at angles $\vartheta_R/3$, $\vartheta_R/5$, etc., where ϑ_R is the angle of the Rayleigh wave excitation.[1)]

Data for the normal state of the aluminum sample are shown in Figs. 1a and 1c. We easily see that the experimental curves are similar to the theoretical predictions. The Rayleigh peaks are narrow and high; their width is about 30′ and their amplitude reaches 0.18, while the height of the spectrum in the continuous region is only about 0.01. It should be noted that spectra for the normal state of the sample are identical to those obtained previously for a copper single crystal.[8] We can thus extend the results to a more general case of the normal metal. The values of the dissipation parameter p for Al_n found from fitting the experimental and calculated curves lie in the range 5×10^{-3}–8×10^{-3}, consistent with the results of ultrasound dissipation in aluminum obtained by other investigators.[9] As can be seen from the figures, the integrated contribution of the Rayleigh peaks is approximately the same as that of the continuous region.

The experimental data for the superconducting state of metal, shown in Figs. 1b and 1d, differ essentially from those for the normal state. The Rayleigh peaks are considerably more narrow—their width is about 5′ and their height is slightly greater than that of the continuous region. In addition, the crest of the peaks can be seen within the critical angle. The crest appears because the sample thickness is finite. By analogy with the Fabry–Perot interferometer, the sound waves reflected repeatedly

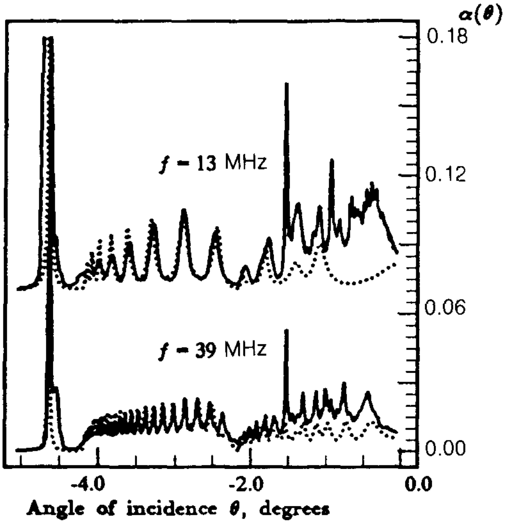

FIG. 2. Bulk interference. Solid line represents the experimental data and the dotted line denotes the calculation.

between two parallel surfaces of the crystal interfere in the bulk of the metal. The calculations were based on this assumption (see Fig. 2). From this figure we see that the experimental and the calculated curves fit reasonably well. The values of p obtained for the superconducting state are 60–70 times lower than those for the normal state, suggesting that the prevailing mechanisms of sound scattering in the two states differ from each other.

From the above line of reasoning it can be deduced that in the normal state of the metal the scattering of sound is chiefly by conduction electrons. In going from the normal state to the superconducting state the dissipation of sound waves drops considerably, and in the latter case the surface wave does not contribute to the energy transfer across the interface because of the absence of an adequate relaxation mechanism.

Noteworthy also is the noticeable frequency dependence of the spectra for the superconducting state (see Fig. 3), which is brought about by the fact that the surface wave scatters mainly at the sample boundaries. If so, then the characteristic length of dissipation would be greater than the sample diameter d, and (see Eq. 1) the dissipation parameter would be $p \sim \lambda/d$. Hence, the width of the Rayleigh peaks would diminish as the ultrasound frequency increased. In contrast, we did not observe a frequency dependence for the normal state. This result is consistent with Andreev's theory. We also did not detect a temperature dependence.

In summary, we have demonstrated experimentally that the contribution of the surface Rayleigh waves to the heat flux through the ^{4}He–metal interface decreases markedly on going from the normal state to the superconducting state. We can state, therefore, that in a normal metal at $l_e \gg \lambda$ the electron mechanism for phonon scattering predominates. It was shown that for the normal state the shape of the Rayleigh peaks and the absence of frequency dependence correlate well with the theory.[1] In the superconducting state of aluminum, the Rayleigh wave does not greatly influence the

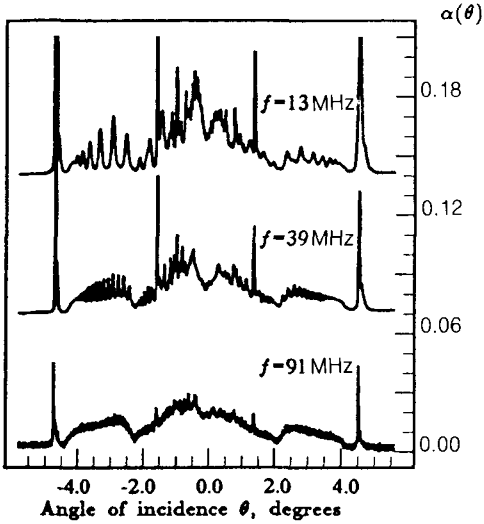

FIG. 3. Frequency dependence of $\alpha(\theta)$.

total energy flux through the interface, while in the normal state its contribution is about the same as that of bulk waves. On the basis of this assumption we can infer the influence of the normal-to-superconducting transition on the Kapitsa resistance: it should be much larger for a superconducting metal than for the normal state, which correlates with the results of Challis.[10]

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[1)]Upon each double reflection at the sample and then at the quartz transducer, the angle of incidence increases by an angle 2ϑ. At the initial angle of incidence, say, $\vartheta_R/3$, the sound wave after one reflection decreases at an angle $\vartheta_R/3+2/3\vartheta_R=\vartheta_R$ and excites the surface Rayleigh wave.

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