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THE INFLUENCE OF NORMAL-TO-SUPERCONDUCTIVE TRANSITION ON 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 both normal and superconductive states of aluminum. It is demonstrated that Rayleigh wave contribution into total energy flux across the boundary drops drastically in going from normal to superconductive state of metal. Experimental data are compared with those on copper reported before and the conclusion is made that the scattering of surface wave (similarly to the bulk waves) is due to conduction electrons. The bulk interference of phonons (analogous to Fabri-Perot interference) is also observed for superconductive metal, while for normal state this effect is missing.

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

Therefore, the angular spectrum of energy transmission coefficient should have a sharp singularity $\alpha \sim 1$ at Rayleigh angle. Confirming Khalatnikov's conclusion [2], Andreev has also found that the contribution of Rayleigh wave into the total transmitted energy is about the same as that of bulk sound waves and does not depend on phonon frequency. Hence, Kapitza resistance should fall to half due to Rayleigh wave contribution.

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

In 1972 a general model was suggested [5, 6, 7] to describe the heat exchange between liquid helium and solid, which is known as generalized acoustic theory. This theory allows for attenuation of bulk acoustic waves in solid by introducing dissipation parameter

$$p = \frac{\gamma c}{2\omega} = \frac{1}{4\pi}\frac{\lambda}{l} \qquad (1)$$

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 intensity to be reduced by e times). Thus this theory does not involve any specific mechanism of dissipation in solid.

Numerical calculations made according to the generalized acoustic theory [5, 8] give comprehensive pattern of angular spectrum of energy transmission coefficient. In the vicinity of Rayleigh angle the results were analogous to those by Andreev – at certain values of $p \geq 10^{-4} \sim 10^{-3}$ an extremely sharp and narrow Rayleigh peak appeared. The detailed consideration of continuous spectrum region showed that the continuous spectrum included longitudinal and transverse parts. The transmission coefficient of longitudinal wave remains practically constant at all possible angles: $\alpha_{long} \simeq 4\rho_{He}c/\rho_{solid}c_l \simeq 5 \cdot 10^{-3}$, the transverse wave transmission coefficient α_{transv} has the same order but 1.5 – 2 times greater. Therefore only an insignificant part of energy incident within critical angle can pass through the interface because of strong acoustic mismatch between liquid ^{4}He and solid. Both α_{long} and α_{transv} depend only slightly on dissipation (see also calculated curves in fig.1$(a-d)$). By contrast, the surface Rayleigh wave transmission strongly depends on dissipation in solid.

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

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

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

$$\alpha(\omega, \vartheta) = \frac{\Delta T S}{N R_K \sigma}, \tag{2}$$

where N is the heat flux density, R_K is Kapitza resistance, S is the total surface area of the sample, σ is the area exposed by sound and ΔT is the value of temperature difference between sample and liquid. Hence, by measuring ΔT vs. ϑ one can find the relative values of $\alpha(\omega, \vartheta)$. To obtain the absolute values of $\alpha(\omega, \vartheta)$ we made the normalization of α through comparing the experimental curve with theoretical one calculated by using generalized acoustic theory. The normalization was performed at the angles of incidence corresponding to the excitation of a transverse vibration mode. Such normalization is 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 quartz transducer and sample surface (see below). With calculated curve and experimental data coincident we obtained the absolute scale of $\alpha(\omega, \vartheta)$ and estimated the value of dissipation parameter p.

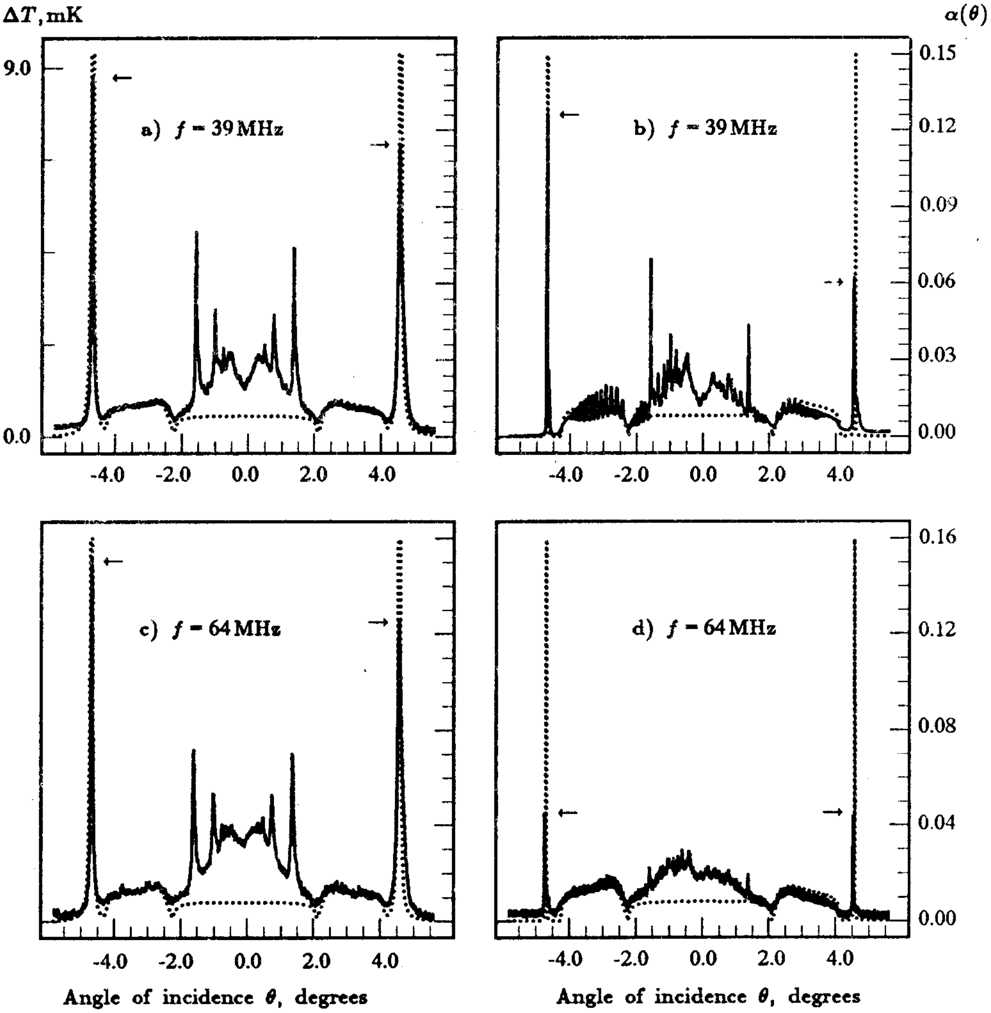

Fig.1.The angular spectrum of phonon transmission coefficient into normal(a,c) and superconductive(b,d) Al crystal;, $T = 140mK$. Solid line represents the experimental data, dotted line - calculation. Each arrow points to the top of experimental peak.

The apparatus was the same as described in [4]. The aluminum single crystal was grown from a starting material of high purity (RRR = 40000), the electron free path was about 0.5 mm. The crystal was a disk 18 mm in diameter and 2 mm thick. The [100] axis lies in the free surface of the sample, the (010) plane being deviated by 2° from the normal to the free surface. The sagittal plane went through the [100] axis, the surface was electropolished so that its irregularities were no greater than 0.1μ. The measurements of $\alpha(\omega, \vartheta)$ were carried out in the temperature range between 100 and 300 mK at saturated vapor pressure at frequencies 13, 39, 65 and 91 MHz. The sample was carried to normal state using magnetic field of 1 kOe that was aligned with the vertical axis of the measurement chamber passing through the centers of quartz and sample.

The experimental data along with the theoretical calculations are shown in fig.1. As it would be expected, the overheating of the sample has just been observed within the narrow range of angles $-5° < \vartheta < 5°$. Confirming to the theory, experimental spectra involve two portions: 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 appearing at critical angles for longitudinal mode $\vartheta_{long} \sim 2^\circ$; 2) two peaks beyond the critical angles. The peaks are caused by absorption of Rayleigh wave energy.

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

Data for normal state of aluminum sample are represented in fig.1(a, c). One can readily see that experimental curves are similar to the theoretical predictions. Rayleigh peaks are narrow and high, their width being about $30'$ and their amplitude reaching 0.18 whereas the height of spectrum in continuous region being only about 0.01. It should be noted that spectra for normal state of the sample are identical to those obtained before for copper single crystal [8], thus we might extend the results to more general case of normal metal. The values of dissipation parameter p for Al_n found from fitting the experimental and calculated curves lie in the range from $5 \cdot 10^{-3}$ to $8 \cdot 10^{-3}$ that is in line with findings of ultrasound dissipation in aluminum of other investigators [9]. As it can be seen from the figures, the integrated contribution of Rayleigh peaks is about that of continuous region.

The experimental data for superconductive state of metal shown in fig.1(b, d) differ essentially from those for normal state. Rayleigh peaks are considerably more narrow, their width is about $5'$ and their height is slightly greater than that of continuous region. In addition, the "comb" of peaks reveals within the critical angle. The "comb" arises because the sample thickness is finite. By analogy with Fabri-Perot interferometer, the sound waves reflected repeatedly between two parallel surfaces of crystal interfere in the bulk of metal. Based on this assumption calculations were made (see fig.2). From this figure we notice that both the experimental and calculated curves fit reasonably well. The values of p obtained for superconductive state are $60-70$ times less than those for normal state, suggesting that the prevailing mechanism of sound scattering in two states differ from each other.

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

Noteworthy also is the tangible frequency dependence of spectra for superconductive state (see fig.3), that is brought about by the fact that the surface wave scatters mainly on the sample boundaries. If so, characteristic length of dissipation is greater than sample diameter d and (see eq.1) dissipation parameter is given as $p \sim \lambda / d$. Hence, the width of Rayleigh peaks will diminish as ultrasound frequency increases. By contrast, we did not observe any frequency dependence for normal state. This finding is consistent with Andreev's theory. We also did not detect any temperature dependence.

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

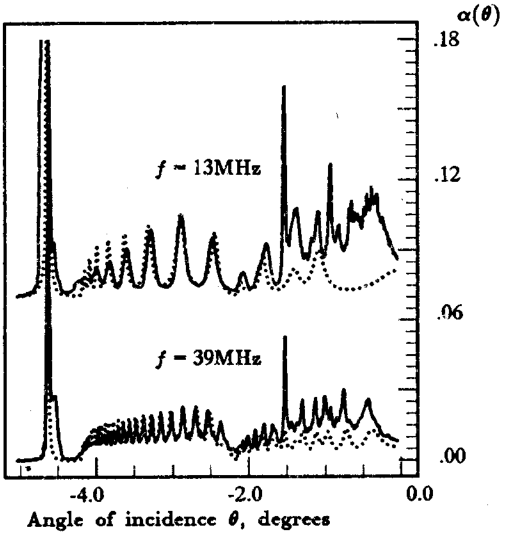

Fig.2. Bulk interference.
Solid line represents the experimental data, dotted line - calculation.

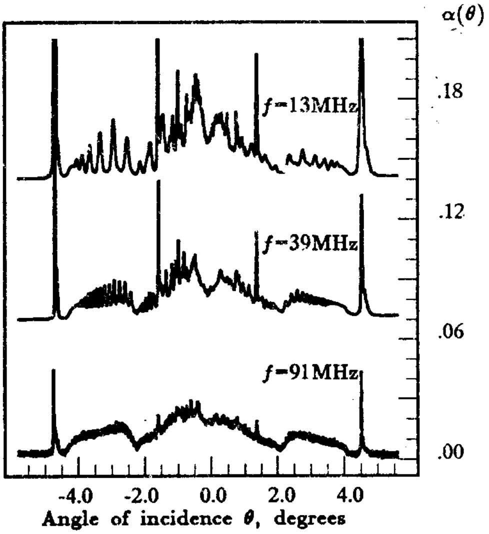

Fig.3. Frequency dependence of $\alpha(\theta)$.

In summary, it was experimentally demonstrated that the surface Rayleigh wave contribution to the heat flux through the ^{4}He – metal interface dropped drastically in going from normal to superconductive state. Thus we can state that in normal metal at $l_e \gg \lambda$ the electron mechanism of phonon scattering predominates. It was shown that for normal state the shape ot Rayleigh peaks as well as the lack of frequency dependence correlates well with the theory [1]. In the superconductive state of aluminum Rayleigh wave does not influence considerably the total energy flux through the interface whereas in normal state its contribution is about the same as that of bulk waves. Relying on such speculations we can infer the influence of normal-to-superconductive transition on Kapitza resistance: it is to be noticeably large for superconductive metal than for normal state, that correlates with the results by Challis [10].

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