(8) that the time-average power per unit area in the $+\rho$ direction decreases by a factor $\exp(-4\pi|K|)$ in crossing the resonant layer. (The connection from $\rho > \rho_0$ to $\rho < \rho_0$ is carried out with $\rho_0 \to \rho_0 - i\epsilon$, as can be verified by the introduction of a small dissipation factor in the dielectric constant elements.) With $k_\eta > 0$ (propagation in the $-\rho$ direction) we find a decrease in the power density by the same factor. Somewhat similar conclusions are reached by Piliya and Fedorov[5] and by Dolgopolov,[11] but no distinction is made between modes with positive and negative k_z. We therefore conclude, as outlined above in a qualitative way, that plane waves with $4\pi|K| \gtrsim 1$ are essentially completely absorbed at the resonant layer.

Using (8) and a corresponding representation for mode (2), we can again construct the potential due to a localized source at $\rho = a$, $\eta = 0$. The associated resonance cone trajectories are shown schematically in Fig. 1(b). In contrast to the case $\alpha = 0$, the cones do not reach the resonant layer but rather approach it asymptotically along the curves $\Delta\rho = \pm\exp(\eta/l)$, where $l = 2K/k_\eta$, a dimension of order $L/\tan\alpha$ for $(M/m)\tan^2\alpha \gtrsim 1$. For smooth initial perturbations, the total power carried in the η direction is finite and can be shown to be independent of η; this means that the resonance layer represents a point of *deflection* of the wave packet, and not a point of true resonance absorption as in the case $\alpha = 0$. Finite loss will, of course, lead to eventual absorption in the present case.

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Reflection of Phonons at an Interface between a Solid and Liquid Helium*

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The reflection coefficient of phonons at a boundary between several dielectric crystals and liquid helium has been measured by the heat-pulse technique. The reflection coefficient is found to be smaller for transverse phonons than for longitudinal.

Kapitza resistance is a thermal boundary resistance that occurs at interface between liquid helium and a solid. Despite much experimental and theoretical study a satisfactory understanding is still lacking.[1] Khalatnikov[2] proposed that the boundary resistance arose because most phonons incident on the interface were reflected due to the large acoustic mismatch between liquid helium and almost all solids. According to Khalatnikov's ideas the reflection coefficient R_L for a longitudinal phonon at normal incidence should be greater than 0.99 for most solids. For a transverse wave at normal incidence coming from the solid the reflection coefficient R_T should be unity. However, the experimental values of the Kapitza resistance are generally 1 or 2 orders of magnitude smaller than the predictions of Khalatnikov's theory,[1] except at very low temperatures ($T < 0.1$°K) where somewhat better agreement is obtained.[3] This discrepancy suggests that phonons are able to pass through an interface between a solid and liquid helium much more easily than expected on the basis of the acoustic mismatch theory.

Direct measurements of the reflection coefficient have been made using ultrasonic techniques at frequencies up to 10^9 Hz.[4] These gave agreement with the acoustic mismatch calculations. Recently Anderson and Sabisky[5] have been able to make measurements of the reflection coefficient at frequencies between 20 and 312 GHz (1 to 15°K energy phonons). For phonons incident on a boundary between strontium fluoride and liquid He^4 they found a reflection coefficient which decreases with increasing frequency, has the value 0.9 at 40 GHz, and above 100 GHz is less than or equal to 0.5. Their experiments measured the reflection coefficient for phonons incident from the solid side of the interface, averaged over all phonon polarizations and all possible angles of incidence. In order to obtain a better understanding of how the phonons escape into the liquid so easily it would be very helpful to know the reflection coefficients for longitudinal and transverse phonons separately, preferably at normal incidence. We report here the first measurements of this type. These were made using the heat-pulse technique.[6]

A dielectric crystal typically 1 cm long and 2 cm in diameter was mounted inside an evacuated can immersed in liquid helium at 4.2°K. The crystal was thermally linked to a small helium pot A (Fig. 1) whose temperature could be closely controlled in the temperature range 1.3 to 4.2°K by pumping. The upper face of the crystal in chamber B could be exposed to a vacuum, helium gas, or liquid helium. It was also possible to condense solid neon onto the upper face of the crystal. The neon was introduced through a separate tube C in order to avoid excessive condensation on the walls of the helium pot A.

Heat pulses were generated using a Constantan

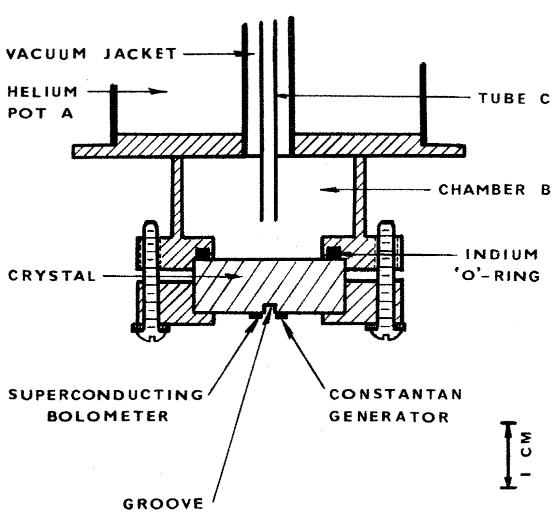

FIG. 1. Experimental apparatus.

film which had been evaporated onto the lower face of the crystal. This film was heated by current pulses of typical duration 10^{-7} sec. Phonons radiated by this film travelled through the crystal, and after reflection at the upper face were detected by a thin-film superconducting bolometer.[6] Measurements were made at ambient temperatures T_0 between 1.5 and 2.0°K using aluminum detectors and between 2.5 and 3.5°K with indium-tin alloy detectors. The experiment consisted of measuring the amplitude of a heat pulse for a given power supplied to the generator film, with and without liquid helium, gaseous helium, or solid neon above the top face of the crystal. The reduction in amplitude of the heat pulse when the helium or neon was added enables one to calculate the reflection coefficient at the interface.

Separate heat-pulse echoes were observed corresponding to longitudinal and to transverse phonons. This made it possible to determine the reflection coefficients for different polarization phonons. In some cases echoes were detected whose time of flight indicated that they had suffered mode conversion on reflection. The reflection coeficient for these phonons was also measured. A background intensity was also present arising from phonons which had been scattered by defects or anharmonic processes in the interior of the crystal. This background intensity was reduced appreciably by cutting a groove approximately 1 mm deep and 1 mm wide on the lower face of the crystal between the detector and generator films (Fig. 1).

A heated metallic film radiates phonons having a broad energy spectrum. The simplest assumption to make is that the film produces a Planck distribution of phonons described by some characteristic temperature T_S. We have calculated T_S as a function of the power supplied to the source using the method described by Weis.[7]

In Fig. 2(a) we show results for the reflection coefficient for phonons in lithium fluoride when the upper face is covered with bulk liquid He^4. The upper face of this crystal was of $\{110\}$ orientation and had been chemically polished. The ambient temperature was 1.72°K. These data were all taken on the same run to avoid possible variation of the surface conditions between different samples. The uncertainty in these results is typically 2–3%. Qualitatively similar results are obtained for other crystals (NaF, Si, and Al_2O_3), and for crystals with roughened surfaces, as regards both the order of magnitude of the reflection coefficient and the effect of varying the

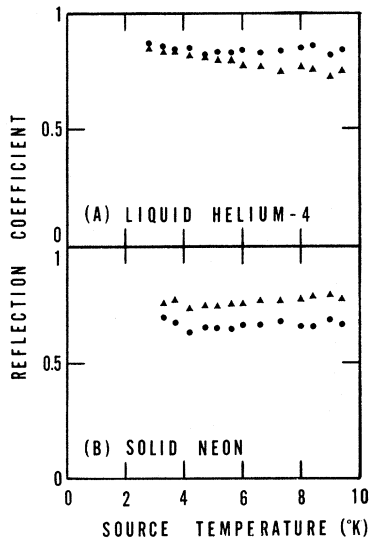

FIG. 2. (a) Reflection coefficient for phonons incident on a {110} face of lithium fluoride covered by bulk liquid He^4 as a function of source temperature. (b) Reflection coeffcient for same surface covered by solid neon. Ambient temperature, 1.72°K. Circles, longitudinal phonons; triangles, transverse phonons.

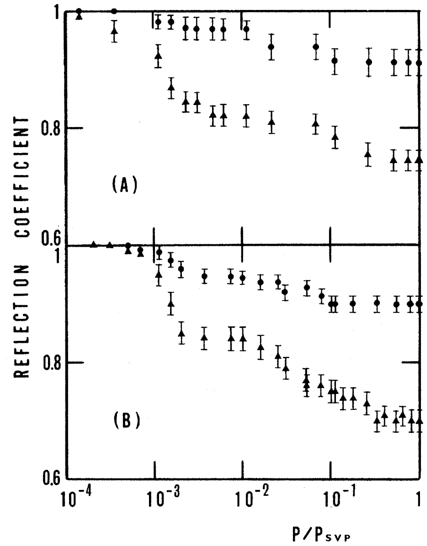

FIG. 3. Reflection coefficient for phonons incident on a {111} face of silicon as a function of P, the pressure of the He^4 above the surface, divided by P_{SVP}, the saturated vapor pressure at the ambient temperature. Source temperature T_S was (a) 3.8°K, and (b) 5.9°K. Ambient temperature, 1.88°K. Circles, longitudinal phonons; triangles, transverse phonons.

heater temperature. Similar data are obtained above and below the λ point but we have not yet made a careful study of whether there is any anomaly in the reflection coefficient at the λ temperature. Figure 2(b) shows results obtained by condensing solid neon on the same lithium-fluoride surface that was used in obtaining the data of Fig. 2(a).

The results obtained for helium are completely reversible in the sense that by pumping with a diffusion pump on chamber B the amplitudes of the heat pulses return to their original values. In Fig. 3 we show the reflection coefficient as a function of helium gas pressure. These results are for phonons reflected at a {111} surface of silicon that had been roughened using emery paper.

The most surprising result is the large transmission of transverse phonons into helium—this being completely unexpected on the basis of Khalatnikov's theory. It is true that not all of the phonons are exactly at normal incidence. The generating and detecting films are of finite size, and are also separated by a distance of typically 3 mm. Moreover, one has no assurance that the reflection of phonons is specular. Thus, phonons which have been reflected from a point on the upper surface several millimeters away from the point nearest the generator and detector could contribute to the heat pulse. This effect was minimized, however, by making the measurements using the peak amplitude of the detected heat pulses. The peak occurred very shortly after the beginning of the pulse and hence there could not be a contribution from phonons which had traveled a distance more than a few percent in excess of the shortest path. We have found that the reflection coefficient for transverse phonons is smaller than for longitudinal phonons in every case that we have investigated. In a typical solid roughly 80% of the thermal energy at low temperatures is carried by the transverse phonons. Since our experiments show that these phonons can pass into helium more easily than longitudinal phonons, it follows that typically 90% of the energy transfer between solids and helium takes place via the transverse phonons.

In contrast to the helium results, the data for a {110} lithium fluoride surface covered with solid neon are not inconsistent with the acoustic mismatch theory. The experimental reflection coefficient for longitudinal phonons is 0.66. The acoustic mismatch theory gives a value of R_L between 0.65 and 0.73 depending upon the orientation assumed for the neon.[8] For transverse phonons, experiment gives 0.76, and the theoretical values range from 0.62 to 0.80. In an experiment with a chemically polished {111} silicon surface we have found the remarkable result that for *the same surface* the transmission into helium was *greater* than into solid neon. This is surprising considering that solid neon has a density more than 10 times that of helium and an average sound velocity at least 3 times larger. The smallest reflection coefficient we have so far observed is 0.3—this being for transverse phonons incident on a {100} silicon-helium interface.

In a more detailed paper we hope to discuss these results in the context of the various theories of the Kapitza resistance.[1] We thank A. C. Anderson, C. H. Anderson, V. Narayanamurti, and H. Kinder for a number of stimulating conversations at the recent heat-pulse conference at St. Maxime.

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Phonon Spectrum of La†

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Observed phonon structure in the tunneling density of states of superconducting La films (T_c =4.9°K, $2\Delta/kT_c$ =3.8) contains resolvable detail not reported previously, with maximum deviations from the BCS prediction amounting to 1.7%. The McMillan-Rowell method of analysis produces a phonon spectrum $\alpha^2F(\omega)$ characterized by parameters which predict T_c=5.0°K via the McMillan equation. Implications of this agreement are discussed.

Tunneling studies of La have assumed added significance in view of suggestions that superconductivity in La may be significantly affected by a narrow band of f states just above the Fermi level.[1] Although sample preparation problems persist, La tunneling data have continued to improve in reliability with improvements in diode quality. For example, $2\Delta/kT_c$ obtained with films[2-6] has increased from an early value of 1.6 to the full bulk value (this work) of 3.7–3.8.[7,8] Nevertheless, tunneling studies continue to indicate an absence of strong structure[4-6,8] directly attributable to f-band effects, revealing instead only modest deviations from the BCS tunneling density of states (TDS) reminiscent of phonon structure[4,6,8] described by strong-coupling theory. This suggests that strong-coupling theory may provide an adequate description of La, and that the tunneling phonon spectrum $\alpha^2F(\omega)$ may be obtained by the method of McMillan and Rowell.[9] Any effects attributable to f levels would presumably be reflected in parameters such as λ (electron-phonon coupling strength) and μ^* (effective Coulomb pseudopotential) obtained inthe course of computing $\alpha^2F(\omega)$. These parameters can then be used to calculate T_c via McMillan's approximate solution of the Eliashberg equations.[10] Failure to obtain reasonable agreement with an independent tunneling measurement of T_c would suggest difficulties with either the tunneling data or the applicability of strong-coupling theory. The significance of obtaining agreement will be discussed.

The critical components of an ideal film diode are (1) a low-leakage barrier in contact with (2) a pure, defect-free, single-phase metal film. Since tunneling results are sensitive to conditions