a lattice constant to give the correct density of protons, a comparison can be made. The formula of Lowe and Gade[16] gives $D = 4.1\times10^{-12}$ cm^2/sec. Most of the other theoretical formulas give a smaller value of D. A preliminary *ab initio* calculation based on the proton positions as determined by McColl and Jefferies[11] with the lattice sums carried out over 245 unit cells (66 protons per unit cell) yields an average value of D in $YEtSO_4$ of 6×10^{-12} cm^2/sec.[19]

Several alternative explanations of the data can be readily ruled out. A phonon bottleneck affecting the spin-lattice relaxation of the Yb does not account for the same behavior observed in undoped $YEtSO_4$. A model which assumes very fast spin diffusion to the surface ($D \gtrsim 10^{-10}$ cm^2/sec) and a slower surface relaxation that absorbs spin energy at a rate directly related to the surface area would predict a single exponential decay, with a time constant directly proportional to R. However, the size dependence of the data does not vary as R, nor is it a single exponential. In addition it is not necessary to use a model suggested by Lichti and Stapleton[20] to explain the observed proton polarization decays in $Yb(OH)_3$, which requires extremely fast proton spin diffusion ($D > 10^{-10}$ cm^2/sec), if fast surface relaxation and normal spin diffusion are assumed.

[1]N. Bloembergen, Physica (Utrecht) 15, 386 (1949).
[2]W. E. Blumberg, Phys. Rev. 119, 79 (1960).
[3]D. Tse and I. J. Lowe, Phys. Rev. 166, 292 (1968).
[4]G. W. Leppelmeier and J. Jeener, Phys. Rev. 175, 498 (1968).
[5]G. R. Khutsishvili, in *Progress in Low Temperature Physics*, edited by C. J. Gorter (North-Holland, Amsterdam, 1970), Vol. VI, p. 375.
[6]H. B. Brom and W. J. Huiskamp, Physica (Utrecht) 60, 163 (1971).
[7]E. P. Horvitz, Phys. Rev. B 3, 2868 (1971).
[8]J. P. Wolfe, Phys. Rev. Lett. 31, 907 (1973).
[9]M. Pumkkinen, Phys. Kondens. Mater. 13, 79 (1971).
[10]K. H. Langley and C. D. Jeffries, Phys. Rev. 152, 358 (1966).
[11]J. R. McColl and C. D. Jeffries, Phys. Rev. B 1, 2917 (1970).
[12]W. H. Potter and H. J. Stapleton, Phys. Rev. B 5, 1729 (1972).
[13]See, e.g., D. M. Young and A. D. Crowell, *Physical Adsorption of Gases* (Butterworths, London, 1962), Chap. 10.
[14]G. R. Khutsishvili, Usp. Fiz. Nauk 87, 211 (1965) [Sov. Phys. Usp. 8, 743 (1966)].
[15]P. Borckmans and D. Walgraef, Phys. Rev. 167, 282 (1968).
[16]I. J. Lowe and S. Gade, Phys. Rev. 156, 817 (1967).
[17]A. G. Redfield and W. N. Yu, Phys. Rev. 169, 443 (1968).
[18]L. L. Buishvili and D. N. Zubarev, Fiz. Tverd. Tela 7, 722 (1965) [Sov. Phys. Solid State 7, 580 (1965)].
[19]J. V. Gates, to be published.
[20]R. L. Lichti and H. J. Stapleton, Phys. Rev. B 8, 4134 (1973).

Frequency Dependence of the Transmission of High-Frequency Phonons from a Solid into Liquid Helium

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Heat pulse experiments at 1.8 K show the transmission coefficient of high-frequency phonons from silicon into superfluid helium to exhibit a maximum at a heater temperature of about 5 K.

The investigation of the transmission of phonons through an interface between a solid and liquid or solid helium has received considerable attention recently. Measurements of the Kapitza resistance show that the experimental data at temperatures $T < 1$ K can be explained reasonably well on the basis of a modified acoustic-mismatch model.[1,2] From 1 to 2 K, however, the Kapitza resistance decreases faster than expected for many materials, suggesting an increase of the phonon transmission coefficient with increasing phonon frequency. Indeed, experiments using heat pulse techniques or monochromatic phonons generated by superconducting tunnel junctions yield values ranging from 0.10 to 0.25 for the transmission coefficient at phonon frequencies of about 10^{11} Hz.[3-5] These values are 2 orders of magnitude larger than those predicted by the acoustic-mismatch model.

In a previous Letter[6] we have shown that direct information on the energy transmission can be obtained from the intensity of second-sound sig-

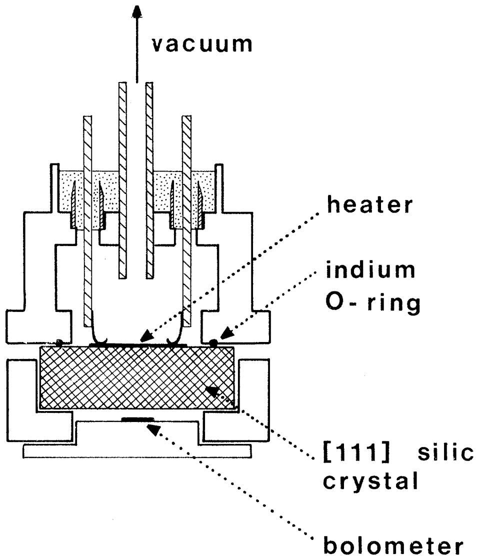

FIG. 1. Sketch of the experimental arrangement.

nals generated by high-frequency phonons which are transmitted from a solid into superfluid helium. Using this technique we have now been able to determine the relative transmission coefficient of thermal phonons emitted by a heater whose temperature is varied between 2.5 and 34 K. The heater temperatures were calculated using the acoustic-mismatch model between the heater and the solid.[7] The thermal phonon frequencies corresponding to these heater temperatures are 1.8×10^{11} Hz and 2.0×10^{12} Hz, respectively, at a bath temperature of 1.8 K.

The experimental arrangement is sketched in Fig. 1. A 50-Ω Constantan heater film is deposited on a (111) surface of a dislocation-free silicon single-crystal disk (2.4 cm in diameter). Both (111) surfaces have been chemically polished so as to remove defects originating from cutting the crystal. The resulting surface dislocation density was measured to be smaller than 200 cm^{-2}, so damage of the surface layer due to the polishing process is negligibly small. The heater is situated in a vacuum can. Electrical contacts are made by means of phosphor-bronze springs and indium dots. The variation of the heater temperature T_H from 2.5 to 34 K is achieved using four heaters with dimensions of 4×4 mm^2, 2×2 mm^2, 1×1 mm^2, and 0.5×0.5 mm^2, and applying pulse powers from 0.1 to 100 W.

The opposite side of the silicon disk is in contact with superfluid helium. A thin-film Al bolometer is situated at a distance of typically 0.2 mm from its surface. The transition temperature of this bolometer is about 1.8 K.

Consider a pulse of fixed amplitude applied to the heater. As the heater is backed by vacuum, all energy dissipated in the heater is converted into (ballistic) phonons in the silicon crystal. Because of the geometrical spreading the energy density at the silicon-helium interface is sufficiently low to prevent evaporation of helium close to the surface, even for heater temperatures much higher than the boiling temperature of helium. Part of the phonons emitted during the pulse cross the interface and excite a second-sound pulse in the superfluid helium, which is detected by the bolometer. For heater dimensions much smaller than the crystal thickness the energy density of the phonons arriving at the interface is independent of the dimensions of the heater. The mean phonon frequency, however, is proportional to the heater temperature T_H, and thus increases with decreasing heater area for a fixed pulse amplitude. If the transmission coefficient were independent of the phonon frequency, then the amplitude of the second-sound signal would also be independent of the heater dimensions. Likewise a variation of the pulse power for fixed heater area would then result in a variation of the second-sound amplitude proportional to the pulse power. On the other hand, if the phonon transmission through the interface is frequency dependent, then the normalized second-sound signal (second-sound signal divided by the pulse power) depends on the heater area.

The input power density (input power divided by the heater area) is proportional to T_H^4. Therefore it is possible to vary T_H by a factor of 10 by varying both the input power and the heater area by 2 orders of magnitude. This procedure has the advantage that the second-sound amplitude varies only by about 2 orders of magnitude over the whole range of heater temperatures. For a constant heater area the second-sound signal varies by a factor of 10^4, and nonlinearities in the propagation or in the detection of the second-sound pulse may occur.[6] By using the four heaters mentioned above the dependence of the normalized second-sound signal on the input power has been determined twice for all heater temperatures: first with high input power for the larger heater, then with low power for the smaller one. This procedure gives a check whether the normalized second-sound signal depends on the absolute magnitude of the energy flux (e.g., via

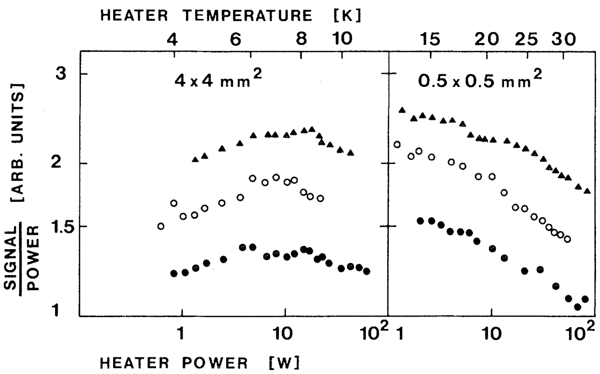

FIG. 2. Normalized second-sound signal as a function of heater power for two different heaters. Closed circles, input pulse length 0.2 μsec; open circles, input pulse length 0.5 μsec; triangles, input pulse length 1.0 μsec. The calculated heater temperatures are indicated at the top of the figure.

saturation of the transmission through the interface or via nonlinearity of the bolometer), or if it depends only on the frequency distribution of the phonons arriving at the interface.

It should be stressed that the bolometer detects small temperature changes in the superfluid helium, and not the arrival of individual high-frequency phonons, so the amplitude of the detected signals cannot be influenced by the frequency distribution of the phonons in the silicon via frequency-dependent electron-phonon interactions in the bolometer.

Some typical results of the experiments are shown in Fig. 2, for a silicon crystal 0.8 cm thick. The normalized second-sound amplitude is plotted in arbitrary units as a function of the input power for two different heater areas, 4×4 mm^2 and 0.5×0.5 mm^2. The calculated heater temperatures[7] are indicated at the top of the figure. All data were obtained with the same bolometer, and the three sets of data correspond to input pulse lengths of 0.2, 0.5, and 1.0 μsec. Because the response time of the bolometer exceeds the pulse duration, the detected signal increases with increasing pulse length, but the dependence of the normalized signal on the input power is the same for all pulse lengths. However, for the large heater the data display a maximum for an input power of approximately 10 W, whereas for the small heater a continuous decrease with increasing pulse power is observed.

The same experiments were carried out with heaters of 1×1 mm^2 and 2×2 mm^2. On a logarithmic scale the slope of the normalized signal versus input power curve is always found to be the same for a given heater temperature. This demonstrates that the normalized second-sound amplitude only depends on the mean frequency of the phonons arriving at the interface, and not on the magnitude of the power flux.

These experiments have been repeated with the same bolometer biased at a slightly different temperature within the transition region, and in a magnetic field in order to obtain a different operating point, and also with different Al bolometers. The results were the same.

The data obtained for a given heater are independent of the pulse length, and the slopes of the experimental curves depend only on the heater temperatures and not on the absolute power level. Therefore the results obtained for all four heaters can be displayed in one graph by matching the curves in the regions of the heater temperature where they overlap. The result for the range of heater temperatures investigated is shown by the triangles in Fig. 3.

Starting at the lowest heater temperature, the transmission increases with increasing heater temperature. This behavior is consistent with Kapitza resistance measurements between 0.1 and 2 K. A maximum is observed for a heater temperature of about 5 K, while at higher temperatures the transmission coefficient gradually decreases by more than a factor of 2.

In order to exclude the possibility that the decrease at high phonon frequencies is due to some frequency-dependent scattering mechanism in the bulk of the silicon crystal (e.g., isotope or impurity scattering), all measurements were repeated with a silicon crystal which is only 0.4 cm thick. As shown by the circles in Fig. 3, the results obtained were the same as for the thicker crystal within the experimental accuracy.

A frequency-dependent coupling between the Constantan heater and the silicon substrate might also produce the observed maximum. Experiments with a bolometer on the opposite surface of the silicon crystal show, however, that for all heater temperatures between 2.5 and 34 K the amplitudes of the transverse and of the longitudinal phonon signals are proportional to the input power. Thus the observed maximum is an effect of the solid-liquid-helium interface.

The thermal phonon frequency corresponding to the heater temperature for which the maximum in the transmission occurs approximately coincides with the top of the phonon branch of the excitation spectrum of superfluid helium. How-

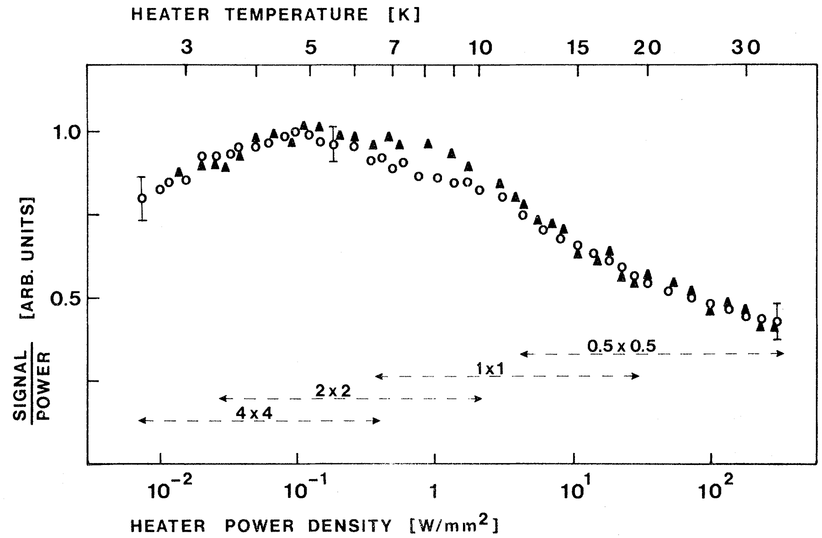

FIG. 3. Normalized second-sound signal as a function of heater power density. The regions covered by each of the four heaters are indicated. Triangles, silicon crystals thickness 0.8 cm; circles, silicon crystal thickness 0.4 cm.

ever, many experimental data indicate that the anomalously small Kapitza resistance occurs both for ^{4}He and for ^{3}He, and in the liquid as well as in the solid phase.[8] Furthermore, it is known that the reflection coefficients of high-frequency phonons at surfaces in contact with ^{3}He or ^{4}He are approximately equal.[9] Thus it seems unrealistic to correlate the observed maximum to this excitation spectrum.

The modified acoustic-mismatch model[1,2] also fails to explain the observed behavior of the transmission. Although phonon scattering by dislocations and point defects might lead to a frequency dependence as observed, the small surface dislocation density in our crystals makes such a process highly improbable. Furthermore, the magnitude of the transmission coefficient[5] can by no means be accounted for in this model.

A mechanism which might explain both the observed maximum and the absolute magnitude of the transmission coefficient is the desorption of bound helium atoms by phonons of sufficiently high energy. This mechanism was first suggested by Johnson and Little,[10] and worked out later by several authors.[11] Weiss[12] recently proposed a model based on these ideas, where phonons arriving at the interface are inelastically scattered by bound helium atoms. Although the results obtained from this model are in good accordance with the experimental data presented above, more theoretical and experimental work will be necessary to confirm these ideas.

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[1] H. Haug and K. Weiss, Phys. Lett. 40A, 19 (1972).
[2] R. E. Peterson and A. C. Anderson, Phys. Lett. 40A, 317 (1972).
[3] C.-J. Guo and H. J. Maris, Phys. Rev. Lett. 29, 855 (1972).
[4] T. Ishiguro and T. A. Fjeldly, Phys. Lett. 45A, 127 (1973).
[5] H. J. Trumpp, K. Lassmann, and W. Eisenmenger, Phys. Lett. 41A, 431 (1972).
[6] T. J. B. Swanenburg and J. Wolter, Phys. Rev. Lett. 31, 693 (1973).
[7] O. Weis, Z. Angew. Phys. 26, 325 (1969).
[8] J. T. Folinsbee and A. C. Anderson, Phys. Rev. Lett. 31, 1580 (1973).
[9] H. Kinder and W. Dietsche, to be published.
[10] R. C. Johnson and W. A. Little, Phys. Rev. 130, 596 (1963).
[11] L. J. Challis, J. Phys. C: Proc. Phys. Soc., London 7, 481 (1974), and references cited therein.
[12] K. Weiss, in Proceedings of the German Physical Society 1974 Spring Conference, Freudenstadt, 1–4 April 1974 (to be published).