^{161}Tb decay and from the 26-keV photons is so small that the ion is not expected to be dislodged from the initial terbium site.

We are not the first to report an unconventional temperature dependence for the ^{161}Dy recoilless fraction: Ofer *et al.*[4] have reported that for a ^{161}Dy-Gd_2O_3 source and Dy_2O_3 absorber, the recoilless emission and abosrption efficiencies for the 26-keV γ ray were less at liquid-air temperature than at room temperature. In addition, Cohen[5] has reported that the Mössbauer-effect efficiencies of ^{161}Dy-Cu and ^{161}Dy-Gd_2O_3 sources are slightly less at liquid-air temperature than at room temperature. Whether ^{161}Dy in these hosts will show an anomaly similar to molybdenum at lower temperatures remains to be seen.

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Angular Distribution of Phonons Radiated from a Heated Solid into Liquid ^{4}He†

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We have measured the angular distribution of phonons radiated from a cleaved (100) face of a sodium fluoride crystal, pulse heated to $T \sim 0.5$ K, into liquid ^{4}He at $T < 0.1$ K. The distribution shows a sharp peak superimposed on a low-amplitude background extending to ~35° to the normal. The peak width is consistent with a critical cone $\theta_c = 4.25°$ calculated under the assumption of conservation of phonon wave vector parallel to the interface.

Acoustic mismatch theories[1] of the heat transfer across solid–helium-II interfaces (Kapitza conductance) are well known to be unsatisfactory. This is particularly so for high–Debye-temperature solids at temperatures above 1 K when the observed heat transfer may be a factor of 100 or more greater than can be explained theoretically,[2] although it is interesting that the experimental phonon reflection coefficient at 1 GHz is close to the theoretical value.[3]

A basic assumption of these theories is the conservation of the component of phonon wave vector parallel to the interface ($q_\parallel$). If this is so then all phonons transmitted from a solid into liquid helium will have their wave vectors contained in a cone of half-angle $\theta_c = \sin^{-1}(c_{\rm He}/c_t)$ about the normal to the interface—the so-called critical cone—where $c_{\rm He}$ is the sound velocity in the helium and c_t the velocity of the slow transverse mode which propagates parallel to the surface in the solid. To investigate this prediction we have measured directly the angular distribution of phonons radiated into liquid helium at $T < 0.1$ K from the cleaved (100) face of an NaF crystal which was pulse heated to $T_{\rm sol} \sim 0.5$ K. At the lowest crystal temperatures we find an angular distribution consistent with radiation into the critical cone $\theta_c = 4.25°$ appropriate to NaF superimposed on a broader background with amplitude ~10% of the peak amplitude and "wings" extending out to ~35° to the normal.

The feasibility of experiments of the type to be described depends upon the existence of long phonon free paths in the helium so that phonons leaving the solid surface reach bolometers with negligible scattering. The existence of long phonon mean free paths for large-angle scattering is well established[4] although the position is less clear for small-angle decay processes associated with the possible upward bend in the phonon dispersion curve.[5] As will be seen, however, our results imply that phonon beam spreading from this cause is small and an upper limit on these processes is estimated to be less than 1° over a 2-cm path.

In the experimental arrangement employed, eight discrete graphite film bolometers were arranged on an arc of 20 mm radius centered about the surface of a heated solid. The angular width of each bolometer was 2.2° and their positions were adjustable, although after initial experiments spanning the full range of angles between +90° and − 90° to the normal, they remained set at 0°, ± 5°, +10°, − 20°, +30°, − 40°, and + 50°. The bolometer sensitivities, which were always equal to within 20%, were normalized from their responses to the heat pulse from a cylindrical heater which produces a uniform energy flux at each bolometer regardless of the detailed angular distribution from each point on its surface. In addition, the absolute sensitivity of each bolometer was obtained from a steady-state resistance against temperature calibration. The relative sensitivities of the bolometers obtained from these two calibrations were always in excellent agreement.

In initial experiments cleaved crystals of NaF approximately 1 mm × 1 mm × 0.2 mm were glued with thin G.E. varnish onto a 1-mm^2 Constantan heater evaporated onto glass. The angular distribution measured with this arrangement showed, in addition to a narrow maximum about 0°, some structure at angles > 50°. This was attributed to stray radiation from the heater substrate and the edges of the crystal. To overcome this problem subsequent experiments were done with the NaF crystal cemented into a hole in the center of a 10-mm-diam glass disk, the front (radiating) face of the crystal being cleaved off flush with the glass immediately prior to final assembly to minimize contamination. Thus the bolometers were shielded from any direct unwanted radiation, except possibly from a small region of the glass surface which would be heated by diffusion of phonons from the crystal. The heater assembly was then mounted at the center of the bolometer semicircle and its alignment adjusted (to within 2°–3°) by a laser-beam reflection from the crystal face. After alignment the whole assembly was mounted in the experimental cell—a 70-ml can attached to the mixing chamber of a simple dilution refrigerator. The cell was evacuated (to a few Torr) and flushed with clean dry ^{4}He gas several times before cooling commenced, typically approximately 5 h after the radiating face of the crystal was cleaved.

After cooling to ~1 K the cell was filled with high-purity ^{4}He from a cylinder of fresh well gas and then cooled further to the base temperature of ~80 mK. During the experiment the heater pulse repetition rate was adjusted to always keep the cell temperature below 0.1 K

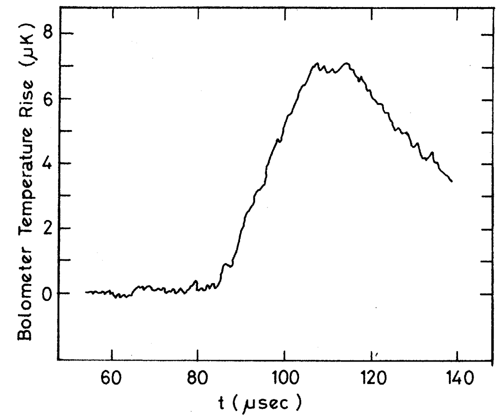

FIG. 1. A pen-recorder tracing of a typical bolometer signal as a function of time showing the reception of a 20-μsec heater pulse.

where the shape of the received pulses was completely independent of cell temperature. The pulse repetition frequency was typically in the range 1 Hz to 1 kHz. The pulse width of 20 μsec, corresponding to a pulse length in the helium of 4.8 mm, was sufficiently short that there was no possibility of any reflections reaching the bolometers during the first 20 μsec after the start of the received signal. A typical bolometer signal as a function of time is shown in Fig. 1 where it is seen to rise linearly during the receipt of the pulse and then relax back.

Unfortunately, a direct measure of the temperature of the radiating crystal during the heating pulse is not easily made, if indeed a well-defined temperature exists.[6] A very approximate value can be estimated on the assumption that all the heat from the heater goes into the crystal where a dynamic thermal equilibrium is established with the radiating surface alone. Using the measured Kapitza conductance for a cleaved LiF crystal[7] in this calculation gives $T_{sol} \sim 0.4$ K. Clearly, however, parallel heat losses or large heater-crystal boundary resistances would lower or raise this estimate considerably, and we prefer to quote $T_{sol} = 0.5 \pm 0.4$ K to span these uncertainties.

The normalized slope of the bolometer signal rise during the first 20 μsec after the start of the received signal is a direct measure of the relative incident energy flux, and is shown plotted as a function of bolometer position for two separate crystals at the lowest heater power in Fig. 2. Also shown in Fig. 2 for comparison is the angular distribution calculated assuming a

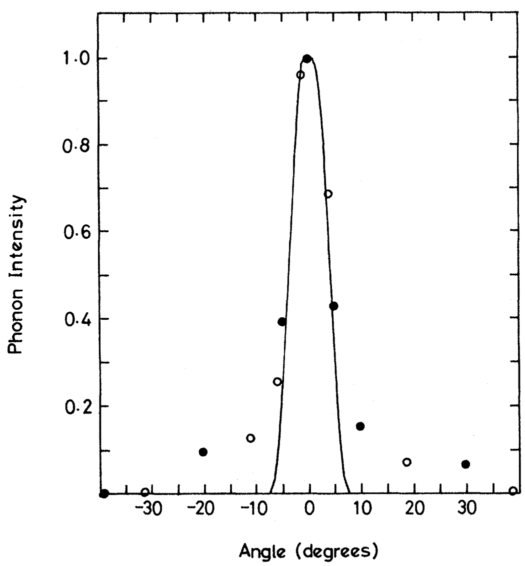

FIG. 2. The angular distribution of the intensity of phonons emitted from a NaF crystal. The solid line is calculated using $q_{\parallel}$ conservation and includes the broadening due to the finite size of the crystal and bolometer surfaces. The experimental points are from two separate crystals and the error range on each point is approximately ± 0.05. The measured intensity is zero (within the experimental error) at all angles $>40°$.

uniform intensity of radiation for $0<\theta<\theta_c$, where $\theta_c = 4.25°$ appropriate to $c_t = 3.17\times10^3$ m $\sec^{-1}$ in NaF, and no radiation at $\theta>\theta_c$. (This is an excellent approximation to the actual form of the radiation intensity calculated using acoustic-mismatch theory, the structure which is actually present being much too fine to be resolved in this experiment.) Note that in calculating this theoretical distribution the finite sizes of the radiating crystal faces (1.6 mm×1.6 mm) and of the bolometers have been taken into account. The peaks in the measured and theoretical distributions have been set at 0° to allow for the slight misalignment of the crystal radiating surfaces. It is seen that there is excellent agreement between the widths of the experimental and theoretical distributions except for the existence of small-amplitude "wings" extending to $\theta>\theta_c$ in the experimental distribution.

The origin of these wings is at present not clear. One possibility already mentioned is that they arise from phonons which have diffused into the glass surround. The front surface of this glass is rough (polished with 6-μm diamond grit) and the angular distribution from such a surface would be expected to have an approximate cosine form. (Such a distribution has, in fact, been recently observed from a rough graphite surface.[8]) We believe, however, that a more likely explanation is that the wings are due to the phonons in the high-frequency (short-wavelength) tail of the distribution. Clearly, surface roughness on the scale of the phonon wavelength would lead to radiation outside the critical cone, and the wavelength of the dominant phonons (in the helium) of a blackbody distribution at temperature T is only $39/T$ Å. The fact that a sharp peak in the distribution at $\theta \leq \theta_c$ is observed indicates that the crystal surface and its adsorbed gas layers are smooth on the scale of a few tens of angstroms and that a significant number of phonons crossing the interface do obey the $q_{\parallel}$ conservation condition assumed in acoustic-mismatch theory. However, if the transmission into the wings is a real crystal surface effect, then because of the phase space occupied by the wings they will give the major contribution to the total energy flux.

At higher heater powers the width of the distribution is observed to increase but the details are complicated, and at present we have insufficient data to enable us to distinguish between different possible causes. Experiments with improved angular resolution and using monochromatic phonons are planned to clarify the situation.

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