For temperatures sufficiently close to T_c and v_n fixed, when $\xi_-(T) \gg r_c$ Eq. (12) must be modified. The quantity $x(T)$ must now be replaced by $1/\ln[\hbar/ma(v_n - u_s)]$.

The authors are indebted to D. Bishop and J. Reppy for discussions of their experimental results, and to N. Grewe for useful conversations. While the present calculations were nearing completion, the authors received preprints by Huberman, Myerson, and Doniach,[13] who examined a similar mechanism for dissipation in the nonlinear, low-frequency regime below T_c.

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Superconducting Al-PbBi Tunnel Junction as a Phonon Spectrometer

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Phonons incident on an Al-PbBi tunnel junction were found to be detectable only if their frequency exceeds a voltage-tunable threshold. Modulating this threshold yielded a phonon spectrometer with a resolution of 10 GHz at a phonon power of 10^{-6} W and a frequency range from 100 GHz up to several hundred GHz.

A complete description of any solid-state system which interacts with high-frequency phonons (> 100 GHz) requires knowledge not only about the frequency of the incident phonons but also of the emitted ones. While it is no longer difficult to generate monochromatic phonons with frequencies tunable up to the terahertz range,[1-3] the analysis of phonon frequencies in this range is still a major obstacle because a phonon spectrometer is lacking.

Several solutions have already been proposed. Some impurities in crystals exhibit frequency-selective phonon absorption which "burns a hole" in the phonon spectrum. Tuning the absorption frequency with an external magnetic field[4,5] or with stress[6] yields information about the phonon frequency distribution. Selective phonon detection was achieved by probing the excited states of selectively absorbing impurities by optical techniques.[7-9] Sidebands of optical luminescence lines can also be used to investigate the frequency distribution of nonequilibrium phonons.[10]

Although these experiments yielded important results, none of the suggested spectrometers found widespread application, mainly because all of them use special bulk materials which cannot readily be applied to the study of all phonon sources of interest. Furthermore, none of them satisfactorily combines resolution, detection speed, and sensitivity.

In this Letter, I report on investigations of tunnel junctions consisting of two superconductors with different energy gaps, which appear to be ideally suited as phonon spectrometers because, as thin-film devices, they can be evaporated on any material of interest, can be tuned simply, and have high sensitivity as well as resolution.

As superconductors I choose Al with the gap Δ_1 and a PbBi alloy with Δ_2. The junction is biased at the voltage $V_0 \leq (\Delta_2 - \Delta_1)/e$. If phonons with energy $\hbar\Omega \geq 2\Delta_1$ but $\hbar\Omega < 2\Delta_2$ strike the junction they are absorbed by pair breaking in the Al only (see inset Fig. 1) leading to a continuous and stationary quasiparticle distribution with a maximum energy of $\hbar\Omega - \Delta_1$. Tunneling is only possible if this energy exceeds $\Delta_2 - eV_0$. Thus, we expect a detection threshold at the phonon energy $\hbar\Omega = \Delta_1 + \Delta_2 - eV_0$. However, this effect will only be observed if the lifetime is long enough to allow for a measurable tunneling current from the "high-energy" states. Therefore, the use of superconductors with long lifetimes such as Al is essential.

For a calculation of the tunneling current as a function of phonon frequency $I_p(\Omega)$ at a given voltage V_0 I take into account that the stationary distribution of quasiparticles is limited by the energy-dependent scattering lifetime $\tau(E)$. In addition I also found it necessary to consider that quasiparticles, when scattered into states with $E \geq \Delta_2 - V_0$, still contribute to the tunneling current. This contribution compensates the expected decrease of $I_p(\Omega)$ with frequency. Further scatterings were considered negligible. To facilitate the calculation let us assume that $T = 0$ and neglect quasiparticle scattering processes other than the emission of phonons. The transition probabilities for the absorption and emission of phonons by the quasiparticles can be taken from established theories.[11-13]

For the numerical calculation let us take the gap values $\Delta_1 = 0.15$ and $\Delta_2 = 1.55$ meV of the junction used in the experiment. The resulting theoretical tunneling current as a function of the incident phonon frequency is shown in Fig. 1 for a set of junction voltages. At the detection thresholds we find steplike current increases due to the combined effect of the square-root singularities in the density of states (in PbBi) and the quasiparticle distribution (in Al). We will see later that this step can be used for a phonon spectrometer if the experimental conditions are favorable.

For the experimental verification I used a sample as shown in the inset of Fig. 2. An Al-oxide-$Pb_{0.85}Bi_{0.15}$ tunnel junction was prepared on one side of an Al_2O_3 crystal with 6 mm thickness by a conventional technique. The thicknesses of both films were about 1000 Å. The Al was granu-

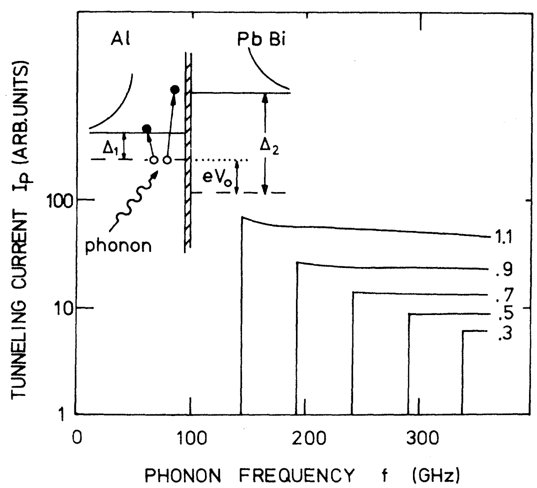

FIG. 1. Tunneling current as a function of the incident phonon frequency calculated with $\Delta_1 = 0.15$ meV and $\Delta_2 = 1.55$ meV. At each trace, the voltage V_0 (in mV) across the junction is given. Note the logarithmic current scale. Inset shows a schematic of the phonon-detection process in a heterogeneous junction. The quasiparticles (●) which result from breaking a Cooper pair (○) can tunnel if their energy exceeds $\Delta_2 - eV_0$.

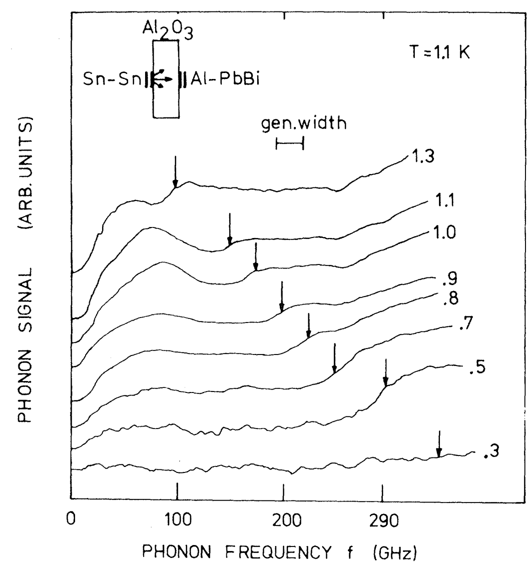

FIG. 2. Measured phonon signal as a function of frequency for several junction voltages V_0 (mV, numbers at each trace). Arrows mark the expected detection thresholds $(\Delta_1 + \Delta_2 - eV_0)/h$. The bar indicates the spectral width of the incident phonons. Inset shows the sample geometry. The phonons were transversely polarized.

lar with a T_c of 1.4 K. The junction area measured 4 mm^2. I used several junctions with impedances varying between 1 and 100 mΩ. As a phonon generator I placed on the other side of the crystal a symmetrical Sn tunnel junction which generates monochromatic phonon pulses of 500-ns duration with frequencies tunable up to 290 GHz corresponding to the energy gap in Sn. The temperature of the He bath was 1.1 K. The further experimental details were similar to the ones described by Kinder.[1]

The result is shown in Fig. 2. The frequency of the incident phonons was swept from zero to 290 GHz. Several traces were taken with different detector voltages V_0. The phonon frequencies which correspond to the anticipated detection thresholds $(\Delta_1+\Delta_2-eV_0)/h$ are marked by an arrow. A steplike signal increase is observed at the expected frequency in each trace as long as the threshold is less than 290 GHz, the maximum generator frequency. The smearing of the step coincides with the phonon spectral width used in this experiment. The background signal which is detected at frequencies below the threshold is due to recombination phonons which are generated in addition to the tunable phonons and have a fixed frequency of 290 GHz. The structure at about 80 GHz which is only visible at low detection thresholds can be interpreted as due to the excitation of thermal quasiparticles to higher energies from which they can contribute to the tunneling current. As soon as pair breaking is possible (at $\hbar\Omega \geqslant 2\Delta_1$) this process is no longer significant. The small dip at about 250 GHz is due to phonon scattering at V^{3+} ions which were present in this sample.[1]

The most important feature of this measurement, however, is the fact that the phonon signal changes only weakly with detector bias. The sensitivity of the electronics was changed only by a factor of about 2 between the first and the last trace. This appears to contradict the above calculations (Fig. 1) which showed a rapid decrease of the tunneling current $I_p(\Omega)$ with increasing detection threshold. However, in the experiment I measured the voltage $V_p(\Omega)$ which depends also on the differential impedance R_D of the junction by $V_p(\Omega)=R_DI_p(\Omega)$. As is well known, R_D increases exponentially with decreasing bias voltage so that the decrease of $I_p(\Omega)$ is balanced by R_D.

This observation allows us to use the Al-PbBi tunnel junction as a phonon spectrometer in a straightforward way. If the detector voltage V_0 is changed by a small fraction the phonon signal changes only if the phonon frequency coincides with the detection threshold. Therefore, I modulated V_0 by a small ac voltage and measured the modulation of the phonon signal by a phase-sensitive technique. A signal is expected only if the phonon frequency equals $(\Delta_1+\Delta_2-eV_0)/h$, i.e., we have a voltage-tunable phonon spectrometer.

The capability of the spectrometer is demonstrated by Fig. 3. The generator frequency was swept while the detector bias V_0 was modulated by an ac voltage of about 50 μV peak to peak which determined the width of the frequency window marked by the bars under each trace. Rather striking peaks show up if the generator frequency

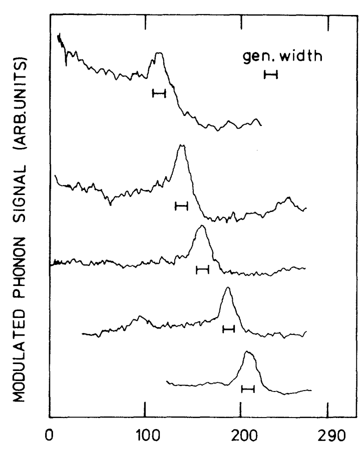

FIG. 3. Signal due to modulation of the detector voltage with fixed detector bias and swept generator frequency. Bars under each trace denote the detector modulation amplitude or spectrometer window.

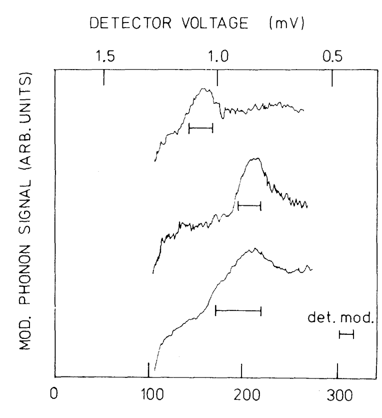

FIG. 4. Same as Fig. 3 but with fixed generator and swept detector. Bars under the traces give the frequency distribution of the generator.

coincides with the spectrometer frequency.

As is shown in Fig. 4, it is also possible to hold the generator at fixed frequencies and to sweep the detector. The bars under each trace mark the frequency distribution of the generated phonons which is determined by the generator modulation.[1] A signal increase is observed as soon as the spectrometer window is swept over the generator frequency.[14]

From Fig. 3 one obtains a half-width of the peaks of 15 GHz. In this experiment, the spectral width of the incident phonons was about 10 GHz.[1] If we assume Gaussian line shapes we can estimate a spectrometer resolution of the order of 10 GHz. The minimum obtainable resolution is probably limited by the combined smearing of the energy gaps Δ_1 and Δ_2 which is about 5 GHz, as can be read directly from the current-voltage characteristic. The frequency range has a lower limit of $2\Delta_1/h$ which was 80 GHz in this case. At zero voltage and below, electrons as well as holes contribute to the tunneling which sets an upper frequency limit of $(\Delta_1+\Delta_2)/h$. I have not yet investigated whether this limit can be reached in practice. With an alloy of the composition $Pb_{0.7}Bi_{0.3}$ it would be close to 500 GHz. A phonon power incident on the detector of only about 10^{-6} W was sufficient for a reasonable signal-to-noise ratio; i.e., the sensitivity is several orders of magnitude greater than that of many previous phonon spectrometers and time-resolved measurements are allowed as well.

Summarizing, it has been shown that heterogeneous superconducting tunnel junctions are phonon detectors with a voltage tunable threshold. By modulating the threshold a phonon spectrometer is obtained. I expect that this spectrometer will find wide application because it combines easy use and superior properties. Investigations concerning phonon processes at helium-solid interfaces and in disordered materials are already under way. I also plan to study the frequency distribution of several broad-band phonon sources which are still in use.

It is a pleasure to acknowledge many discussions with H. Kinder who also suggested this experiment some time ago.

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