Liquid ^{4}He: A Tunable High-Pass Phonon Filter

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Various experiments on the propagation of high-frequency phonons in liquid ^{4}He at $T = 0.1$ K lead to the conclusion that there is a critical wave vector q_c such that phonons with wave vector $q < q_c$ have very short mean paths while those with $q > q_c$ have very long ones. As q_c is adjustable over a wide range we recognize the possibility for phonon spectroscopy, using the helium as a tuneable high-pass phonon filter.

In this Letter we report experiments and their interpretation which allow conclusions to be drawn about the frequency dependence of the propagation and attenuation of high-frequency phonons in liquid ^{4}He. We are concerned with phonons of frequencies up to the maximum in the dispersion curve ($\hbar\omega/k \sim 13$ K) in ^{4}He at temperatures <0.1 K, where thermal phonons can be neglected. We find that the phonon attenuation, by spontaneous decay, changes very rapidly at a certain frequency, from a relatively large to a relatively small value. We are able to tune this frequency over a substantial part of the dispersion curve and hence we have the possibility of phonon spectroscopy in liquid ^{4}He systems.

Early experiments by Guernsey and Luszczynski[1] indicate that at least some phonon frequencies can travel over distances of centimeters. The rectilinear propagation of phonons was used by us[2] to measure the angular emission of phonons from an atomically flat surface. We have also shown[3] that scattering involving angular spreading does not occur above a pressure of 17 bar, but the possibility of collinear decay processes could not be discounted.

With the advent of using recombination phonons from superconductors (Eisenmenger and Dayem[4]), there was the possibility of using a narrow spectrum of phonons of energy $\sim 2\Delta$, the energy gap. The fluorescer of Narayanamurti and Dynes[5] is a convenient method of generating these phonons, and coupled with a superconducting tunnel-junction detector it gives a system for studying quasimonochromatic phonons. Two experiments using this system for helium studies have already been reported. Narayanamurti, Andres, and Dynes[6] concluded that the group velocity of phonons around 10^{11} Hz was the same as the low-frequency phase velocity. This was shown to be incorrect by us[7] and our measurements correlated with the neutron-scattering results of Svensson, Woods, and Martel.[8] We believe the pressure dependence[6] of the received signal, which showed a rapid rise at ~ 13 bar, to be correct in its gross features. However their[6] limited measurements caused them to misinterpret the results in terms of a pressure-dependent bulk attenuation of the 2Δ phonons. Our interpretation is quite different and moreover accounts well for all the available observations.

The new feature of our experiments is that we are able to adjust the separation of the fluorescer and tunnel-junction detector *in situ* at 0.1 K. This allows us to measure the pressure dependence of the received signal at several distances while all other parameters remain constant. We can therefore directly measure the effect of the bulk helium on the phonon propagation, and in fact we are able to draw some strong conclusions about the bulk attenuation at various frequencies.

The experimental details will be published at length elsewhere. The important changes from our previous work[7] are that the fluorescers were made on an anechoic sapphire crystal which was mounted on a trolley which could move the fluorescers between 2 and 11 mm from the tunnel-junction detectors. These latter were also made on a sapphire substrate. We checked that the junction was not sensitive to low-frequency phonons by measuring the group velocity at 24 bar.[7] The value was 345 m/sec which is substantially lower than the value of 363 m/sec for phonons of energy tending to zero.

The pressure dependence of the phonon flux received by the tunnel junction is shown in Fig. 1. (As the tunnel junction is an integrating detector with a time constant much longer than the pulse length of 1 μsec, we use the gradient over the first 1 μsec of the received signal as a measure of the flux of detected phonons. We would like to emphasize that the use of peak heights is erroneous and misleading.) The semilogarithmic plot in Fig. 1 shows that the detected phonon flux (S) increases exponentially with pressure (P) up to

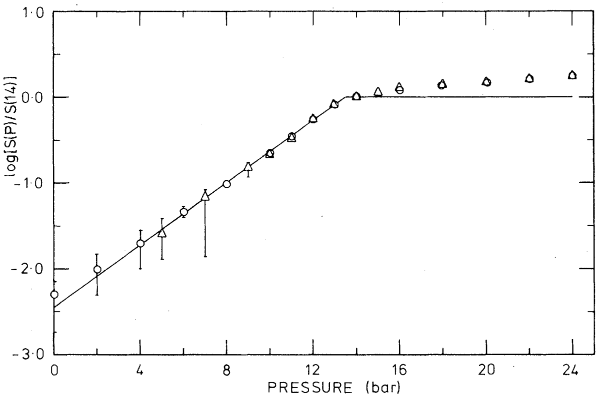

FIG. 1. Semilog plot of the phonon flux $S(P)$ normalized at 14 bar showing the exponential dependence on pressure for $0 < P < 13.5$ bar. The data for 2.2 mm (circles) and 5.0 mm (triangles) show that $S(P)/S(14)$ is independent of distance. Where error bars are not shown, they are less than the size of the datum "point." The solid line is from the theory described in the text.

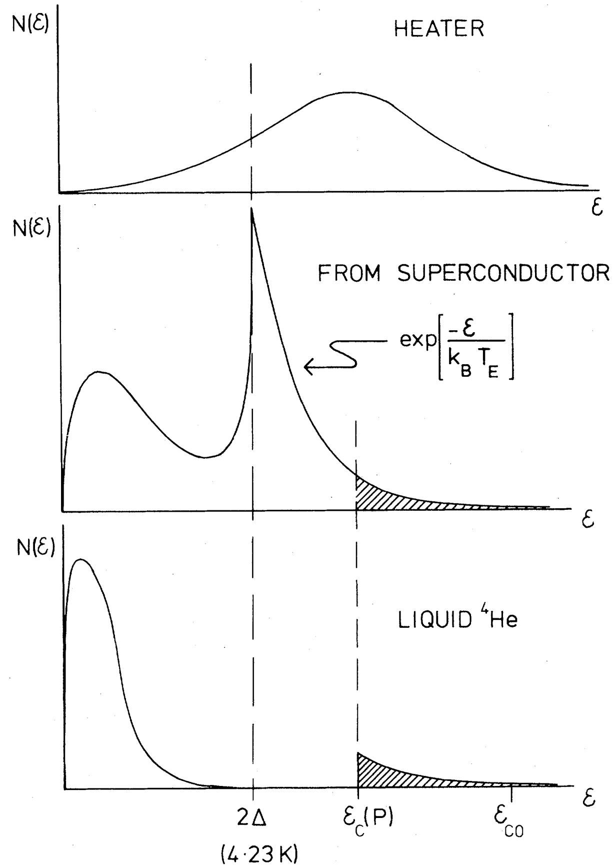

FIG. 2. Schematic representations of the phonon spectrum in the successive components of the system. The black-body spectrum in the heater (top) is modified by the fluorescence in the superconductor (middle). After propagation of < 1 mm in the helium phonons with $\epsilon < \epsilon_c$ have decayed to low energies while those with $\epsilon > \epsilon_c$ remain unchanged (bottom).

13.5 bar and then only changes slowly. The effect of pressures is very large; S increases by a factor of 360 between 0 and 24 bar for 5-mW/mm^2 pulses. This factor depends critically on the pulse power and rapidly decreases as the pulse power increases. For example, for 50-mW/mm^2 pulses the factor has dropped to approximately 40.

This very large increase is dramatic enough; however we also find that the *pressure dependence is independent of distance.* That is, $S(P)$ at different distances (2, 5, and 11 mm) has the same functional form. In Fig. 1 we show the pressure dependence at 2.2 and 5.0 mm normalized at 14 bar. It follows directly from this distance independence of $S(P)/S(14)$ that the mean free path (λ) for detected phonons is independent of pressure, and our experiments indicate $\lambda > 11$ mm. Of course the overall magnitude of $S(P)$ falls off with distance because of geometric factors.

The behavior described above can be accounted for in detail in the following model. We first consider the fluorescer and the spectrum of phonons injected into the helium and then how the helium modifies this spectrum. In the Al of the fluorescer, Cooper pairs are broken by phonons of energy $> 2\Delta$ injected from the heater. The resultant quasiparticles relax rapidly towards the gap edge where they are relatively long-lived. They come into thermal equilibrium which may be characterized by a temperature T and as $\Delta \gg kT$ the distribution function is $\exp(-\epsilon/kT)$. Quasiparticles from this distribution recombine to form pairs and "gap" phonons are emitted. They will have a distribution $\sim \exp(-\hbar\omega/kT_E)$ for $\hbar\omega > 2\Delta$.[9] There will be phonons of energy $< 2\Delta$, but these are not detected by the tunnel junction, and we will ignore them. We will assume that this exponential form is injected into the helium; however we should like to stress that for the following argument all we need is the exponential form and the temperature in the exponent may not necessarily be the temperature of the fluorescer. The spectrum in the heater and Al is shown schematically in Fig. 2.

We now assume that the helium dispersion curve, at low pressures, bends initially upwards from linearity and then bends over towards the maximum. This form may be represented by[10]

$$\epsilon = \hbar c q(1 - \gamma \hbar^2 q^2 - \delta \hbar^4 q^4),$$

where γ is a negative quantity at low pressures and δ is positive at all pressures. The point where the group velocity is equal to the phase velocity at $q=0$ is at a wave vector of q_c, given by[11]

$$\hbar^2 q_c^{\,2} = -3\gamma/5\delta.$$

Phonons with $q<q_c$ can undergo a decay by a three-phonon process whereas those with $q>q_c$ cannot because energy and momentum conservation cannot be simultaneously satisfied.[10,11] Now, q_c is pressure dependent and it has been suggested[11] that the variation is linear. We assume that the energy $\epsilon_c = \hbar c q_c$ corresponding to q_c varies linearly from a value of ϵ_{c0} at zero pressure to 2Δ at 13.5 bar. Sluckin and Bowley[12] have shown that the decay of phonons with $q<q_c$ is expected to be very rapid, so that after a short distance (<1 mm) in the ^{4}He all phonons with energy $\epsilon<\epsilon_c$ have decayed to low-energy phonons with $\epsilon \ll 2\Delta$ and so are not detected. We propose that the other phonons, $\epsilon>\epsilon_c$, do not decay and so travel to the tunnel junction where they are detected. We show the spectrum in the helium schematically in Fig. 2.

The phonon flux (S) is given by

$$S = \begin{cases} A\int_{\epsilon_c}^{\infty} \exp(-\epsilon/k_B T_E)\, dE & \text{for } \epsilon_c \geqslant 2\Delta, \\ A\int_{2\Delta}^{\infty} \exp(-\epsilon/k_B T_E)\, d\epsilon & \text{for } \epsilon_c < 2\Delta, \end{cases}$$

where A is a constant; as

$$\epsilon_c = \epsilon_{c0} - (\epsilon_{c0} - 2\Delta)P/P_c, \quad 0<P<P_c,$$

where P is the pressure and P_c is the pressure where $\epsilon_c = 2\Delta$, which in this case is 13.5 bar, then

$$S = \begin{cases} A k_B T_E \exp\left(\dfrac{-\epsilon_{c0}}{k_B T_E}\right) \exp\left(\dfrac{(\epsilon_{c0} - 2\Delta)P/P_c}{k_B T_E}\right) \\ \qquad\qquad \text{for } P \leqslant P_c, \\ A k_B T_E \exp(-2\Delta/k_B T_E) \text{ for } P_c < P < 24 \text{ bar}. \end{cases}$$

The relationship between ϵ_{c0} and T_E may be expressed in terms of the gradient (G) of the semilog plot shown in Fig. 1:

$$\epsilon_{c0} = 2\Delta + k_B T_E G P_c / \log_{10} e.$$

The pressure dependence predicted from these equations is shown in Fig. 1 with the value of the product $GP_c = 2.45$. We stress that values of ϵ_{c0} and T_E cannot be found independently from the pressure data alone, and some examples of pairs of values (ϵ_{c0}/k_B, T_E; 10, 1.02; 8, 0.67; 6, 0.31) indicate that they are well within the bounds imposed by the dispersion curve,[13] the bath temperature, and the transition temperature. Extrapolating the data from Jäckle and Kehr[11] gives $\epsilon_{c0}/k_B = 5.5 \pm 0.5$ K which implies that $T_E = 0.22$ K, a value which would seem rather low. It can be seen from Fig. 1 that the theory can give excellent agreement with the measured points up to 13.5 bar but does not account for the slight increase above this pressure.

A consequence of the behavior of phonons in liquid helium is that the group velocity at an energy of $2\Delta = 4.23$ K cannot be measured below a pressure of 13.5 bar. The group velocity at the energy ϵ_c is always measured and this by definition is the phase velocity at $q=0$.

In conclusion we would like to emphasize that this explanation depends crucially on the upward (anomalous) dispersion in helium. The success of the model implicitly confirms this form of dispersion together with its pressure dependence characterized by q_c. We have found that phonons with $q<q_c$ have very short mean free paths while those with $q>q_c$ have very long ones. In consequence the helium behaves like a tunable high-pass phonon filter and so introduces the possibility of phonon spectroscopy in this system.

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Probable Observation of the Two-Orifice Macroscopic Interference Effect in Superfluid Helium

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I have observed level differences between two baths of superfluid helium which are multiply connected by two orifices whenever the flow velocity past the orifices was of such value as to cause the quantum-mechanical phase difference between them to be an odd multiple of π.

Ever since the prediction of coherence effects in superconductors by Josephson[1] there has been a great deal of interest in observing similar phenomena in superfluid helium; however, to date none of these effects have been convincingly demonstrated.[2] This experiment is essentially the one proposed by Anderson[3] and is intended to be analogous to the experiment of Jaklevic *et al.*[4] who have observed quantum interference due to current flow in a superconductor joining two Josephson junctions. I observe a level difference between baths of superfluid helium which are multiply connected by two in-line orifices whenever the horizontal flow velocity is of such value as to cause the quantum-mechanical phase difference between the orifices to be an odd multiple of π.

The apparatus, shown in Fig. 1, consists of three reservoirs interconnected by a capillary with open ends at A and C and passing through B. The only openings to B are two laser-drilled holes as shown in the diagram. The reservoirs are completely enclosed except for the capillary and are immersed in a bath of pumped helium, normally held at about 1.4 K. The cryostat is shock mounted to prevent excessive vibrations. To produce the flow past the orifices I have installed two plungers, one in reservoir A and the other in C. Plunger P_A was used for most experiments while the primary purpose of P_C is to make final level adjustments, although it was also used to make several runs as will be discussed later.

Reservoirs A and B each contain a coaxial capacitor. Capacitor C_A is about 30 pF and C_B about 60 pF. Both are continuously monitored with capacitance bridges and lock-in amplifiers, and their values are displayed on a strip chart recorder. The experiment thus consists of monitoring the helium levels in A and B as the plunger is lowered or raised, thus imparting a known flow velocity in the capillary.

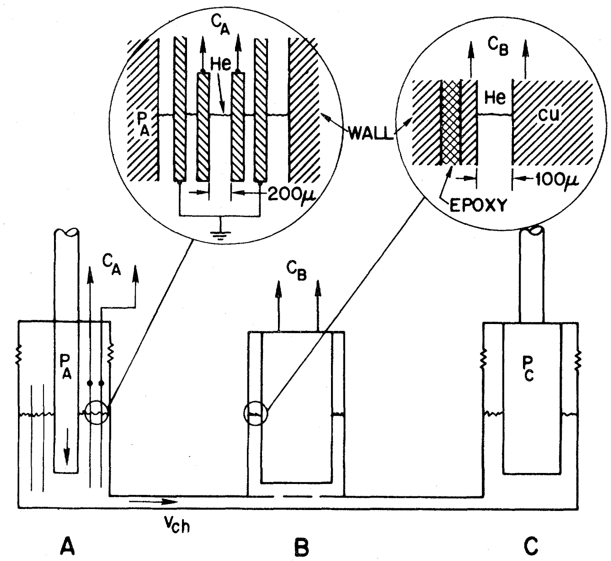

FIG. 1. Apparatus. Three in-line reservoirs are situated horizontally as shown. Their dimensions are 2.5 cm o.d. and 3.2 cm in height, excluding the bellows in A and C. The capillary is 813 μm o.d., 100 μm wall. The orifices are ≈ 10 μm at the narrowest point. C_A is made from four thin-wall tubes; the inner and outer ones shield the capacitor. In B the annular space between the two sides of C_B is the only space available for the liquid to enter. P_A is 0.635 cm o.d. and has a 0.25-cm travel distance. P_C was 2.032 cm o.d. for some runs and 1.854 cm o.d. for others. Both plungers can be driven mechanically by a variable-speed motor.