EVIDENCE FOR ANOMALOUS PHONON EXCITATIONS IN SOLID He^3 †

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Thermal-conductivity measurements in solid He^3 in the bcc phase and at temperatures below about 0.5°K show an unexpected temperature dependence which is less than T^3. Specific-heat measurements, in this temperature range, have been reported as showing a closely similar effect, and this provides evidence for a thermal excitation which must take part in the heat transport. In addition, Poiseuille flow of phonons has been directly observed.

Specific-heat measurements in the body-centered-cubic (bcc) phase of solid He^3 have shown that the Debye temperature behaves anomalously at low temperatures.[1,2] These data have been verified by recent measurements of $(\partial P/\partial T)_v$.[3] The basic result of these experiments is that the specific heat C_v is larger than would be expected from the Debye theory, with a temperature dependence T^n, $n<3$ for $T \lesssim 0.5$°K.

We report here some thermal-conductivity measurements in the bcc phase of He^3 from 0.1°K to the melting curve at molar volumes of 20.4, 21.6, and 22.4 cm^3/mole. The thermal-conductivity sample chamber was a stainless-steel cylinder with i.d. 0.166 cm and o.d. 0.218 cm, 3.75 cm long. The fill line was a stainless-steel capillary, 30 cm long with i.d. 0.015 cm, thermally anchored to the 0.7°K still of a continuous-cycle dilution refrigerator.

Temperature gradients and average temperatures along the sample were measured by carbon resistance thermometers. Above 1°K the resistors were calibrated against the vapor pressure of the He^4 bath, while at lower temperatures they were calibrated against a cerium-magnesium-nitrate thermometer in the tank circuit of a tunnel-diode oscillator.[4]

The crystals were grown at constant pressure from two samples of He^3 gas obtained from the Mound Laboratory, Monsanto Research Corporation. The spectrometric analyses at the time of purchase showed He^4 impurity concentrations of 2 parts per million (pure sample) and 100 parts per million (impure sample).

Figure 1 shows the thermal-conductivity data for $T<0.6$°K plotted as $\log K$ vs $\log T$. The essential features of these data are in good agreement with the results of previous experiments at temperatures above the maximum in the thermal conductivity.[5] We want to call particular attention to the data in the boundary-scattering region at temperatures below the peak in the thermal conductivity.

As a comparison with the bcc samples, the thermal conductivity of 19.5-cm^3/mole hcp crystals was measured. The results for one of these samples is shown by Curve E of Fig. 1. It appears that the small average crystallite size of this particular sample prevented Poiseuille flow from being observed. The hcp crystals from

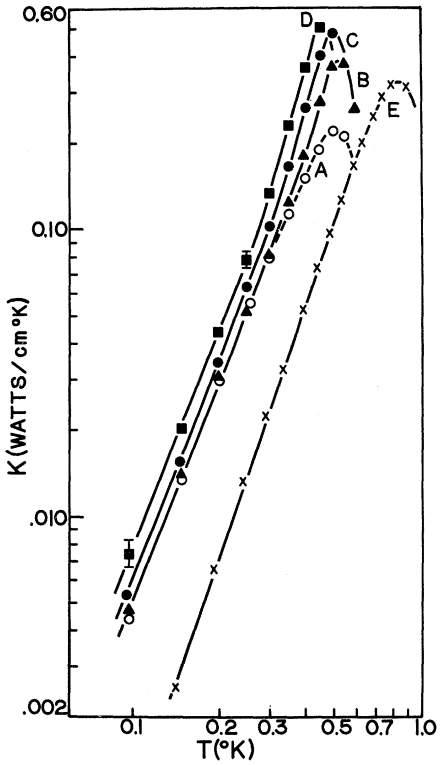

FIG. 1. Thermal conductivity of solid He^3 in the boundary-scattering region. The curve labels correspond to samples with the following properties:

Sample	Structure	Growth pressure (atm)	Molar volume (cm^3/mole)	Purity (ppm He^4)
A	bcc	96	20.6	100
B	bcc	96	20.4	2
C	bcc	70.5	21.6	2
D	bcc	56	22.4	2
E	hcp	127	19.5	2

both the pure and impure He^3 have $K \propto T^n$ with $n \approx 3.00 \pm 0.10$ in the boundary-scattering region.

A typical result for the impure samples in the bcc phase is shown as Curve A, Fig. 1. For the impure crystals, we found $K \propto T^n$ with $n \approx 2.55 \pm 0.10$ at the lowest temperatures. There was no evidence for Poiseuille flow in these samples.

The results for three different crystals grown from the pure gas are shown as Curves B, C, and D in Fig. 1. Estimated uncertainties in the measurement of the conductivity are shown by the vertical bars on Curve D. Enhancement of the conductivity near the peak is evidence for the existence of Poiseuille flow. The different magnitudes of the conductivities at the lowest temperatures are attributed to variations in the growth and annealing procedures which changed the average crystallite size. Below the Poiseuille flow region, $T < 0.35$°K, $K \propto T^n$ with $n \approx 2.55 \pm 0.10$ for the pure bcc crystals down to about 0.1°K. In the Poiseuille flow region, $K \propto T^n$ with n ranging from 3.4 to 3.7. Since K is expected to vary more steeply than T^4 near the peak,[6] we believe that the Poiseuille flow was not fully developed in our crystals.

Specular reflection of the phonons at the walls of the chamber or the crystallite boundaries could result in a thermal conductivity with $K \propto T^n$, $n < 3$.[7] We do not believe that this is occurring in the bcc phase since all the hcp crystals gave $K \propto T^3$. For our crystals, the higher-density hcp phase has a higher sound velocity than the bcc phase.[8] This means that the dominant phonon wavelengths will be longer for the hcp crystals. Since specular reflection is more likely to occur for the longer wavelengths, we do not expect it to occur only in the bcc crystals.

It is convenient to discuss our results in terms of the resistive mean free path of the phonons. We define this quantity, λ, by the kinetic equation, $K = \frac{1}{3} C_v \bar{v} \lambda$. C_v is the specific heat per unit volume and $\bar{v}$ is taken to be the temperature-independent Debye first-sound velocity. For calculating $\bar{v}$, the extrapolated Debye temperatures of Sample and Swenson (SS)[1] are used and the velocities of the longitudinal and transverse modes are assumed to be equal. For the specific heat, we use the data of SS at temperatures down to about 0.25°K where our data overlap. At lower temperatures we extrapolate the specific heat according to a $T^{2.6}$ dependence which is consistent with the data of SS below about 0.4°K. SS reported two types of C_v data which they distinguished as M and S points. We use the M-point data whenever they exist over a given temperature range. The analysis of the M-point data by SS included long equilibrium time effects in the solid helium. Calculations of λ for the pure crystals and one impure crystal are shown in Fig. 2.

Curve A of Fig. 2 is representative of the impure gas. The mean free path reaches a constant value λ_0 at the lowest temperatures. This behavior is what is expected in the absence of Poiseuille flow. The results in the pure gas are quite different in the temperature region corresponding to the thermal-conductivity peak. The mean free path reaches a maximum value, then decreases to a constant value as the temperature gets lower. The fact that λ becomes much larger than the low-temperature limiting value confirms the observation of Poiseuille flow. Figure 2 also illustrates the molar-volume dependence of the peak in λ. The crystal grown at 96 atm (Curve B, Fig. 2) can be compared with the one in which Ackerman and Overton measured second sound.[9] They reported second-sound propagation from 0.58 to 0.42°K, their lowest measured temperature. We observe $\lambda > \lambda_0$ in the temperature range 0.54 to 0.35°K. Since the conditions necessary for second sound are identical to those for Poiseuille flow,[10] these results are in excellent agreement. We find that for the 96-atm crystal at 0.5°K the normal phonon-phonon scattering process mean free path λ_N is approximately 0.06 mm.

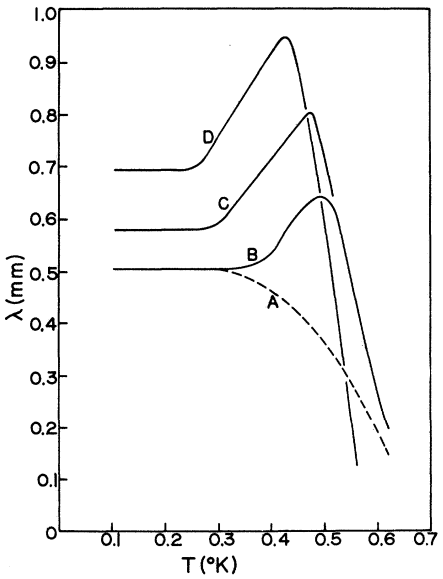

FIG. 2. Computed phonon mean free paths in the boundary-scattering region of body-centered-cubic He^3. Curves are labeled the same as Fig. 1.

At the lowest temperatures the mean free paths reach a constant value which must be on the order of the crystal size. The specific choice of the phonon velocity used to calculate λ introduces a scaling factor in the magnitude of λ_0. For our choice of $\bar{v}$, the crystals have $\lambda_0 \approx \frac{1}{3}D$, where D is the sample-chamber diameter. We conclude that the chamber contains several crystals, not just one. If we use a T^3 dependence for the specific heat, λ does not reach a constant limit but increases indefinitely as T approaches 0°K. The correct behavior, λ constant at low temperatures, is that which is found using the C_v data of SS in the analysis.

We therefore conclude that the excitations responsible for the anomalously high specific heats at low temperatures must transport heat energy in essentially the same way as the phonons in the system. A very low-lying phonon mode would provide such excitations, but there is no evidence for such a mode. An excitation whose energy is localized well below 0.1°K could also be responsible. The identification of these excitations must await more experimental and theoretical effort.

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EFFECT OF ELECTRON-EXCITON COLLISIONS ON THE FREE-EXCITON LINEWIDTH IN EPITAXIAL GaAs

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Broadening of the free-exciton emission band with increasing excitation intensity is observed in photoluminescence from GaAs. This effect is quantitatively accounted for by electron-exciton collisions.

The effect of exciton-phonon interaction on the exciton line shape (absorption or emission) has been widely considered in the past.[1] In contrast, the effect of electron-exciton interaction has been almost completely neglected. We report here what we believe to be the first experimental results regarding the effect of electron-exciton collisions upon the exciton emission line shape.

The free-exciton emission band in GaAs was recently identified by Gilleo, Bailey, and Hill[2] and Bogardus and Bebb[3] from photoluminescence experiments. Supporting evidence for this assignment was obtained by a combined study of photoconductivity and luminescence[4] and by stress experiments.[5] In the present experiment, we have studied this band in photoluminescence, pumping with an argon laser operating at 5145 and/or 4880 Å, with a maximum power of ~0.5 W. A cylindrical lens was used to focus the laser beam on the samples to an area ~0.1×1 mm. Calibrated neutral density filters were used to vary the excitation intensity. A double spectrometer (Spex 1400) was used together with synchronous detection. An S-1 photomultiplier cooled to 77°K was the detector. Both p- and n-type