DEBYE BEHAVIOR OF THE THERMAL CONDUCTIVITY OF bcc 3He AT VERY LOW TEMPERATURES

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Résumé.- Nous présentons des mesures de conductivité thermique de bcc ^{3}He pour les températures de 0,03 K à 0,4 K. Nous trouvons que la conductivité thermique varie comme T^3 pour les températures au-dessous du maximum de conductivité. Nos résultats diffèrent des mesures précédentes pour les températures au-dessous de 100 mK. Pour les températures au-dessous de 100 mK, aucune mesure n'a été publiée jusqu'ici et nous trouvons que nos résultats peuvent être bien décrits par le modèle de Debye, quoiqu'il soit bien connu que ^{3}He solide est loin d'être un solide diélectrique harmonique simple.

Abstract.- We report thermal conductivity measurements of bcc ^{3}He for temperatures between 0.03 K and 0.4 K. We find the thermal conductivity varies as T^3 for temperatures below the conductivity maximum. Our results differ from previous such measurements above 100 mK. For temperatures below 100 mK where no other measurements have been reported, we find our results can adequately be described by the Debye model although it is well known that solid ^{3}He is very much more complex than a harmonic dielectric solid.

In the limit of very low temperatures the principal relaxation process for thermal phonons in a pure Debye dielectric solid is scattering from crystal boundaries or sample chamber walls. If the dominant thermal transport is assumed to be the flow of a phonon gas with a specific heat C_V, then the kinetic theory expression for the thermal conductivity is

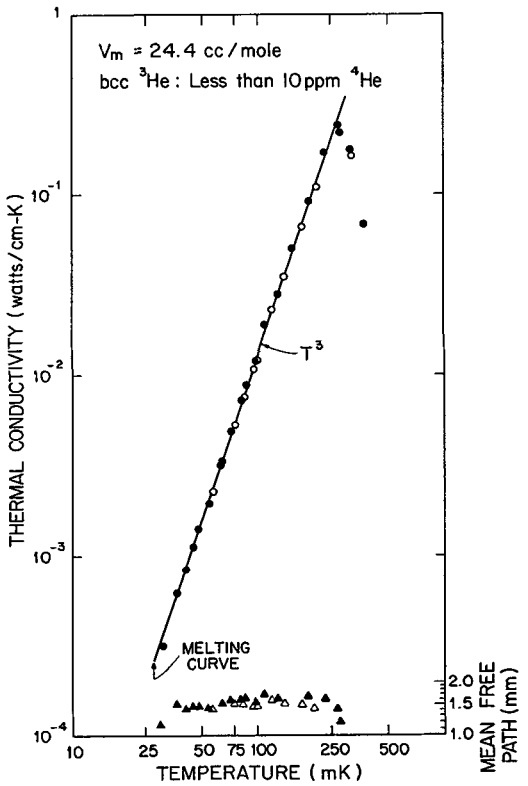
$$k = \frac{1}{3} C_V v \lambda, \qquad (1)$$

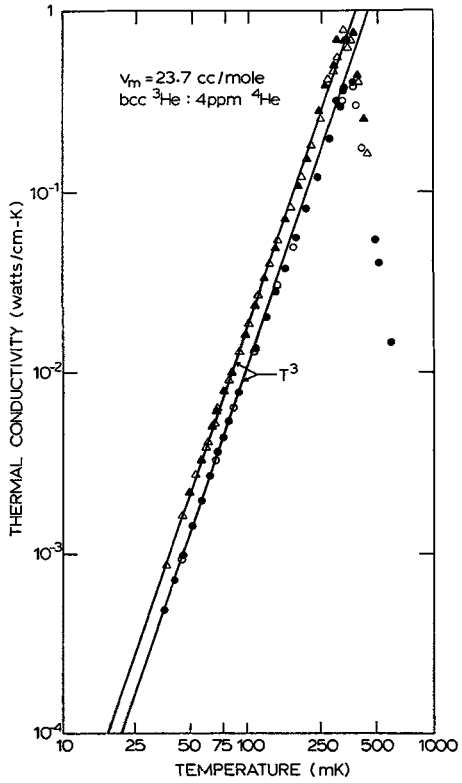
where v is usually taken as the first sound velocity and λ is the effective mean free path of the phonons. In the boundary scattering limit for thermal conduction by phonons, v and λ are generally assumed to be independent of temperature, and thus the thermal conductivity has the same temperature dependence as the lattice specific heat. For a Debye solid therefore : $k \propto C_V \propto T^3$. However, at very low temperatures there may be a lower than cubic temperature dependence of k if the effective mean free path is increased as the reflection of the longer wavelength phonons from the sample chamber walls becomes more specular.

In the experiment reported here, the thermal conductivity of bcc ^{3}He has been measured in a cylindrical sample chamber, 2.3 cm in diameter, cast from Stycast 1266 /1/ with three 100 Ω Speer resistors (grade 1002, .5W) spaced 2.8 cm apart and imbedded off axis in the epoxy cast. A 3.1 mm diameter bore along the axis of the epoxy cylinder nicked the Speer resistors and formed the sample space for the solid helium. A sintered copper heat exchanger was joined to the top of the chamber using additional Stycast 1266, and in a similar manner manganin heaters and a pressure strain gauge were joined to the bottom of the chamber. The Speer resistors were calibrated using a melting curve sample of ^{3}He and the pressure-temperature scale of Trickey, Kirk and Adams /2/.

Figure 1 shows the results of measurements of the thermal conductivity for a solid close to melting pressures which was grown using the bloked capillary technique. The closed (open) circles were taken during cooling (warming). For temperatures below the conductivity peak we find $k \propto T^3$. In the inset at the bottom of the graph we have plotted the effective mean free path, $\lambda = 3.9 \times 10^{-5} v_m^{2/3} \theta_D^2 k/T^3$ (mm), where the Debye temperature, θ_D = 19 K for v_m = 24.4 cc/mole, was taken from the data of Greywall /3/. The resulting mean free path is 1.5 mm ± . 1 mm independent of temperature, as expected, in the boundary scattering region and is comparable in magnitude to the radius of sample chamber. We see no indication of a shift from diffusive to spectacular reflection.

We explored some effects of sample growth and heat treatment procedures figure 2. Four different solids were formed at the molar volume of 23.7 cc/mole. For clarity the results from only two samples are displayed. The upper curve is the thermal conductivity of a sample slowly cooled along the melting curve (≈ 3 hr) and then annealed close to melting (≈ 2 hr). The lower curve is a sample that was quenched; that is, rapidly cooled (≈ $\frac{1}{2}$ hr) along the melting curve.





The conductivity of the annealed sample is a factor of 2 higher than the quenched sample. This difference is attributed to a difference in crystal quality which manifests itself in equation (1) as a change in λ ; λ is 2.6 mm and 1.5 mm for the upper and lower curves respectively. The other samples grown at 23.7 cc/mole have conductivities intermediate between the samples shown in figure 2.

For the sample at 24.4 cc/mole and in each of the samples at 23.7 cc/mole, irrespective of the histories of these latter samples, we find the thermal conductivity decreased from the maximum value as $k \propto T^3$. There are several important observations associated with this result. First, we observe that the rather elementary Debye theory for a dielectric solid in which the crystal is considered to be perfectly harmonic, adequately describes our data for temperatures below the thermal conductivity peak. This result emphasizes the long standing dilemma that though ^{3}He cannot justifiably be treated even approximately as a harmonic solid, nevertheless, the Debye model seems to work.

Secondly, we observe no Poiseuille flow of phonons ; i.e., $k \propto T^6$. Briefly, the conditions for Poiseuille flow are that the crystal is of high quality and isotopically pure and that normal relaxation processes take place much faster than umklapp processes ; i.e., $\lambda_N \ll r$, where r is the sample chamber radius or crystal dimension, and $\lambda_N \lambda_U \gg r^2$. These conditions are similar to those for the observation of second sound. For our maximum conductivities, we estimate that $\lambda_U \approx \lambda_N \approx r$, thus it is understandable that we do not observe $k \propto T^6$. Thomlinson /4/, in reporting measurements of the thermal conductivity of bcc ^{3}He above 100 mK, observed an "enhanced flow" in which the conductivity varied as T^n, $3.4 < n < 3.7$, close to the low temperature side of the peak. Our samples are comparable to those of Thomlinson's : we have approximately 50 % larger magnitudes of thermal conductivity (λ_N's same order), similar levels of isotopic impurities (<10 ppm) and our sample chamber has a factor of 2 larger radius, but we have not observed a conductivity in which the temperature dependence had a power greater than 3 near the peak.

The enhanced phonon flow hat Thomlinson observed near the conductivity peak was probably due to being close to the edge of the window conditions for Poiseuille flow. Apparently, our sample configuration is sufficiently different to put us outside the window

In conclusion, we have measured the thermal conductivity of several crystal samples of bcc ^{3}He containing less than 10 ppm ^{4}He, and we find that on the low temperature side of the thermal conduc-

tivity maximum we can adequatly describe our results using the harmonic dielectric theory of Debye.

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References

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