PROPAGATION OF SOUND IN He^3†

W. R. Abel, A. C. Anderson, and J. C. Wheatley*
Department of Physics, University of Illinois, Urbana, Illinois
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We have studied the propagation of sound in He^3 over a range of pressures extending from 1.4 psi to 513 psi. At low pressures we have obtained the sound attenuation coefficient and have interpreted it in terms of a viscosity, the results being in satisfactory agreement with experiments on other transport properties in He^3. In a pressure region somewhat above the minimum, P_{min}, in the melting curve, we find a sharp break both in the velocity of propagation of sound and in the temperature dependence of the attenuation coefficient.

The experimental cryogenic apparatus is similar to others which have been described elsewhere.[1,2] The sound cell was sealed into a nonmagnetic epoxy resin bulb with a powder of cerium magnesium nitrate which served as the thermometer. The sound cell consisted of an "X"-cut quartz crystal of nominal frequency 5 Mc/sec separated from an optically flat fused quartz reflector by a fused quartz ring of thickness 0.1890 cm and bore 0.5 cm with parallel and optically flat faces. The ring had four radial grooves ground in one surface to allow entry of He^3. Measurements of velocity were made using standard ultrasonic pulse techniques, no fewer than two echoes being used for this purpose, although in some cases as many as fifteen echoes were used. The attenuation coefficient was obtained by fitting the echo heights, h, to the equation $h = h_0 e^{-\alpha x}$, where α is the attenuation coefficient and x is the distance traversed by the sound.

At a pressure of 3.38 psi, measurements of the attenuation coefficient were made at frequencies of both 5.13 Mc/sec and 14.92 Mc/sec. Near 1°K the ratio of the apparent attenuation coefficients was nearly the ratio of the two frequencies, characteristic of geometric attenuation. However, below 0.1°K the ratio of the attenuation coefficients was, within experimental error, given by the ratio of the squares of the frequencies. This result is characteristic of viscous attenuation, for which the attenuation coefficient is given by[3]

$$\alpha = (8\pi^2\nu^2/3\rho c^3)\eta, \qquad (1)$$

where ν is the frequency, ρ is the density, c is the sound velocity, and η is the viscosity. The experimental attenuation data are shown in Fig. 1. At 5.13 Mc/sec the geometrical attenuation coefficient is approximately 0.2 to 0.3 cm^{-1}. Below 0.05°K to 0.06°K the attenuation coefficient obeys a T^{-2} law to within the accuracy of our measurements, the resulting viscosity being given by $\eta = 2.8\times10^{-6}T^{-2}$ dyne sec $(K°)^2/cm^2$. Using the result that $\eta = (\frac{1}{3}v_0^2\tau_\eta)\frac{3}{5}\rho(m^*/m)$, where v_0 is the Fermi velocity and m^*/m is the ratio of quasiparticle mass to bare particle mass, to evaluate the relaxation time for viscosity, τ_η, from the Fermi liquid theory,[3] we find $\tau_\eta = 17\times10^{-13}T^{-2}$

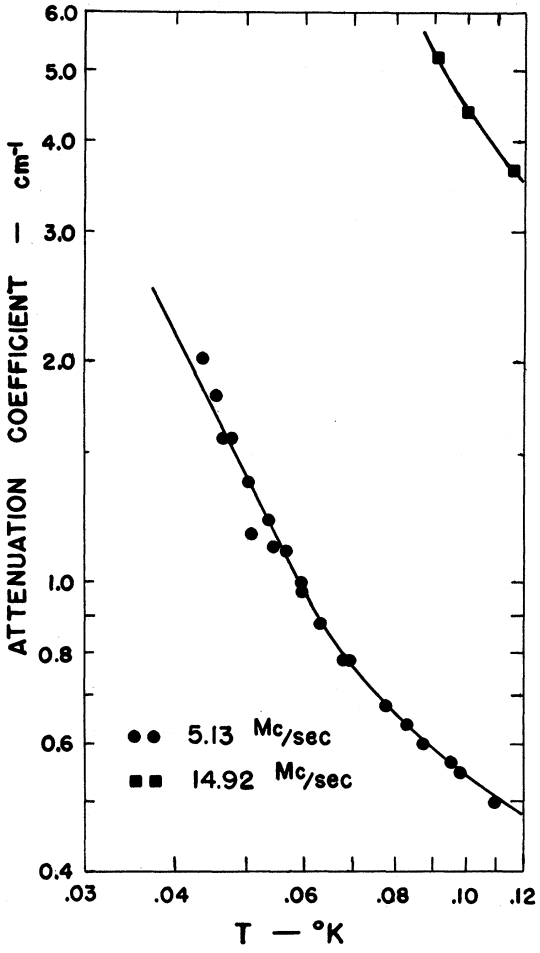

FIG. 1. Ultrasonic attenuation coefficient as a function of temperature in liquid He^3 at a pressure of 3.38 psi and at frequencies of 5.13 Mc/sec and 14.92 Mc/sec. The line through the experimental data at 5.13 Mc/sec for temperatures less than 0.06°K arbitrarily has been drawn with the T^{-2} temperature dependence predicted by the Fermi liquid theory.[3]

Table I. Velocity of sound in liquid He^3 at various pressures and, for pressures less than 426 psi, for T less than 0.1°K.

Pressure (psi)	Velocity (m/sec)	Frequency (Mc/sec)
1.42	184.0	5.13
8.06	192.1	5.13
13.97	198.5	5.13
16.25	201.0	5.13
50.8	231.2	5.13
89.9	260.2	5.13
174.3	306.8	14.92
314.6	361.8	14.92
414.1	394.2	14.92
423.9	396.8	14.92
425.9	397.9	14.92
433.6[a]	397.9	14.92
483.2[a]	408.6	14.92
513.0[a]	416.9	14.92

[a]The velocities at these pressures were obtained with $T \simeq 1$°K.

sec (K°)^2. This relaxation time is 2.7 times that found for the thermal conductivity.[4] Using the values of c, ρ,[5] and[6] m^*/m to compute τ_η/τ_k from the Fermi liquid theory, we find the theoretical estimate to be $\tau_\eta/\tau_k = 1.5$.

At both 25 Mc/sec and 15 Mc/sec, sound measurements were attempted under excellent conditions at 0.008°K, but no echoes were observed.

The velocity of sound in liquid He^3 at various pressures less than P_{min} and at temperatures of 0.1°K and below is given in Table I. We estimate an error of ±0.1% in the pressures and ±0.3% in the velocities. The extrapolated velocity at zero pressure is 182.4 ± 0.6 m/sec, which is to be compared with 183.9 ± 0.3 m/sec given by Laquer, Sydoriak, and Roberts.[7] Also given in Table I are velocities in the liquid near 1°K for a few pressures greater than P_{min}. These probably may be compared meaningfully with those below 0.1°K, for we found that at 424 psi the velocity did not change, within experimental error, between 1°K and 0.1°K.

At pressures greater than P_{min}, a plug of solid He^3 forms above the cell so that subsequent measurements are made at constant volume. In what follows, the pressures referred to are those in the liquid just before the plug is formed, and the frequency of the sound is 14.9 Mc/sec. The most striking features of the measurements in this region are assembled in Table II. For pressures of 435 psi and below, we found velocities at low temperatures which were a few percent larger than those observed for pressures just less than P_{min}. Moreover, the attenuation coefficient had both a magnitude and temperature dependence characteristic of the liquid at somewhat lower pressures. As the temperature increased, echoes were observed until the melting curve was reached, at which point we usually observed "double echoes" corresponding to propagation of sound between transmitter and reflector at both liquid and solid velocities, the latter being about 475 ± 10 m/sec. Eventually, only the solid velocity was observed, followed by more "double echoes" and then the velocity in the high-temperature liquid.

At pressures greater than 439 psi, the behavior of the liquid is remarkably different. At very low temperatures the sound velocity exceeds 500 m/sec, and hence is greater than the velocity in the solid. This effect was demonstrated strikingly at a pressure of 483 psi (not listed in Table II) where we observed a "double-echo" pattern characteristic of two-phase equilibrium and corresponding to a velocity ratio of 14:13 ≅ (510 m/sec:475 m/sec) in which the relative size of the high-velocity component steadily increased as the temperature decreased from 0.035°K to 0.016°K. In addition to having a sound velocity about 25% greater than that in the liquid at somewhat lower pressures, the He^3 in the high-pressure region is characterized by an attenuation which increases, rather

Table II. Characteristic sound parameters in He^3 at low temperatures and at pressures greater than the minimum in the melting curve.

Pressure[a] (psi)	Velocity[b] (m/sec)	Temperature (°K)	Attenuation coefficient (cm^{-1})
431	409	0.030	0.9
431	405	0.1	0.5
431	402	Melting curve	···
435	407	0.026	1.3
435	404	0.1	0.5
435	396	Melting curve	···
439	503	0.030	1.0
439	485	0.1	1.6
454	510	0.022	1.1
454	491	0.1	2.8

[a]These are the pressures at which the capillary plugged.

[b]Accuracy of velocity measurements is about 1%.

than decreases, with increasing temperature. Above the temperature region near 0.1°K we were unable to make measurements because of the high attenuation. Hence, as we increased the temperature above 0.1°K we saw practically no echoes until suddenly large echoes characteristic of the solid became visible, corresponding to the transition back into the solid.

At a pressure of 513 psi we observed echoes in the solid only, the velocity being constant within experimental error from 1°K to 0.017°K. According to the work of Sydoriak, Mills, and Grilly,[8] if the molar volume of the He^3 in the cell after the plug was formed remained constant at that for the liquid just before the plug formed, it would be impossible to have only solid He^3 in the cell for any of the pressures for which we made measurements. At an external pressure of 513 psi, and possibly at lower pressures also, we observed echo patterns characteristic of the solid only. Hence, we conclude that during the process of forming a plug in the tube leading to the cell, a substantial amount of He^3 passes into the cell. This conclusion is supported by work reported in reference 6, where under similar conditions the heat capacity characteristic of the solid only was observed.

In the above measurements the pressure of the He^3 below the plug was not known and probably varied with temperature. Moreover, above 0.1°K the large attenuation made sound measurements impossible. However, the measurements do indicate that below 0.1°K and in a narrow pressure region near 437 psi there is a drastic change in both the velocity and attenuation of sound. Moreover, it has been observed recently[6] that in this same region the specific heat is considerably lower and has the opposite pressure dependence from that in the liquid at pressures just less than P_{min}. Hence, it appears likely that in this high-pressure region we are dealing with a different phase of He^3 from that which occurs at lower pressures.

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