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Fifth sound in superfluid ^{4}He below 1 K

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Fifth-sound propagation has been studied in He II adsorbed on large-diameter alumina (Al_2O_3) powder grains below 1 K. The velocity of the fifth-sound mode in ^{4}He remains in good agreement with the theoretical value $c_5^2 = (\rho_n/\rho) c_2^2$. Using tabulated values for ρ_n/ρ, values of the second-sound velocity are obtained.

In the recent observations of fifth sound in superfluid ^{4}He,[1,2] the measurements of the fifth-sound velocity c_5 were not extended to temperatures below 1 K. The velocity of the mode,[3] $c_5^2 = (\rho_n/\rho) c_2^2$, becomes quite small (< 1 m/sec) in this region because ρ_n/ρ drops off rapidly (as $\sim T^4$ below 0.6 K). In the presence of large surface-tension forces which are also present in the thickness wave,[4] the fifth-sound component becomes difficult to resolve. Now by employing substantially larger superleak-powder particles, we have been able to measure the fifth-sound velocity at temperatures down to 0.27 K. The larger particles serve to reduce the surface-tension sound velocity, which scales roughly as the inverse square root of the particle diameter.[4]

The measurements are made in the same geometry described in Refs. 1 and 4, with the annular resonator packed with Al_2O_3 powder[5] having a nominal grain diameter of 25 μm and a porosity $P = 0.44$. The cell is attached to the mixing chamber of a dilution refrigerator, and the ^{4}He is condensed in through a capillary to a fractional filling of the superleak of 0.63. Temperatures are measured with a calibrated Speer resistor and a CMN-SQUID (cerium magnesium nitrate—superconducting quantum-interference device) thermometer mounted on the mixing chamber. The heater drive power of 10 μW leads to a temperature uncertainty of at most a few mK above 0.3 K. The fundamental resonant frequency of the 11.4-cm circumference annulus is in the range of 10–12 Hz at low temperatures, and is determined using a fast-Fourier-transform (FFT) analyzer [Unigon model 4513 (Ref. 6)] with a resolution of ± 0.01 Hz.

The fifth-sound velocity is obtained from the measured sound velocity c by[1]

$$c_5^2 = n^2(c^2 - c_0^2) , \tag{1}$$

where c_0, which is essentially the surface tension component, is the limiting velocity at the lowest temperatures, and n is the index of refraction of the superleak. c_0 was determined from measurements near 0.2 K and below to be $c_0 = 1.165$ m/sec for the filling fraction of 0.63. By normalizing to the theoretical value of c_5 at 0.80 K, the index of refraction was found to be $n = 1.99$. With these parameters, the measured values of c_5 are shown in Fig. 1. The solid line is the theory, with values of ρ_n/ρ and c_2 taken from the tables of Brooks and Donnelly.[7] The good agreement found at higher temperatures[1] continues to hold below 1 K. The error bars reflect the experimental resolution of 0.01 Hz and the uncertainty in making the subtraction of Eq. (1) as c approaches c_0. The fractional uncertainty becomes quite large for the lowest temperature points.

An application of the present measurements is to extract values of the second-sound velocity at low temperatures using

$$c_2^2 = c_5^2/(\rho_n/\rho) . \tag{2}$$

There have previously been a large number of direct measurements of c_2 using heat pulse techniques,[8–12] with the interest being to verify Landau's prediction[13] that the velocity will become nearly constant at the value of $c_1/\sqrt{3}$ below 0.5 K, where c_1 is the velocity of first sound. In all the experiments, however, the phonon mean free path becomes greater than the container size below 0.6 K,[14] and the measured velocities are generally substantially larger, approaching the phonon speed c_1.[11,12,15] This disadvantage does not apply to the fifth sound, where the phonon mean free path is presumably limited by the pore size of the powder particles. The values of ρ_n/ρ in Eq. (2) are taken from Brooks and Donnelly,[7] which have been confirmed to high precision in recent specific-heat measurements.[16] Using the experimental results of Fig. 1, the values of c_2 are shown in Fig. 2. The solid line is from Ref. 7. Although the data appears to turn over below 0.5 K close to $c_1/\sqrt{3} \cong 138$ m/sec, unfortunately the large fractional uncertainties in c_5 give rise to very large error bars and scatter in the low-temperature c_2 values. It is not possible to conclude from this data that the Landau limit has been observed.

An attempt to improve the resolution of the measurements by using even larger superleak particles was

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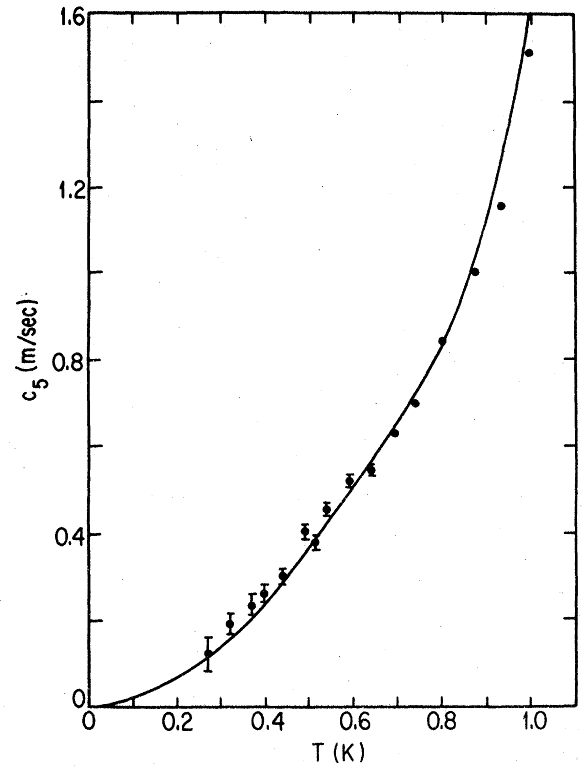

FIG. 1. Experimental values of fifth sound below 1 K obtained from Eq. (1). The solid line is calculated from $c_5 = (\rho_n/\rho)^{1/2} c_2$ using values of ρ_n/ρ and c_2 from Ref. 7.

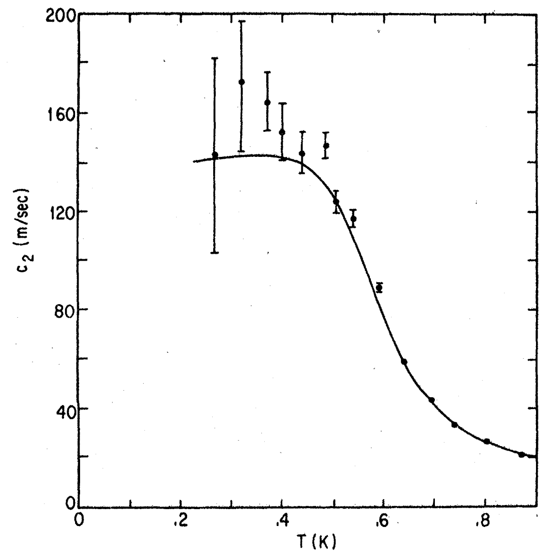

FIG. 2. Values of c_2 obtained from Eq. (2) using the experimental values of c_5 from Fig. 1 and the values of ρ_n/ρ from Ref. 7. The solid line represents the tabulated values of c_2 from Ref. 7.

unsuccessful. Spherical glass beads[17] with a highly uniform diameter of 37 μm were used at a porosity of $P = 0.44$. Although c_0 was somewhat reduced, the quality of the signals was quite poor. The Q of the mode at low temperatures was only $Q \cong 5$ compared to values of $Q \cong 35$ observed in the 25-μm powder (which has a large distribution of particle sizes). The attenuation at low temperatures appears to arise from unlocking of the normal fluid component. Above 1 K there appears to be a second attenuation mechanism. Using pure ^{4}He with the 37-μm glass beads, the signal broadened and disappeared above 1.4 K. Using a nominal 18.4% ^{3}He-^{4}He mixture, however, it became possible to observe the signal to within a few mK of T_λ for this mixture (1.94 K). The quality factor remained roughly constant at $Q \cong 5$ between 1.2 and 1.9 K. The ^{3}He alters the nature of the coupling of the fifth sound to the vapor,[18] and this may account for the difference in attenuation between pure ^{4}He and the ^{3}He-^{4}He mixtures.

An improvement in the resolution of the data in Figs. 1 and 2 will require a further reduction in the magnitude of c_0. This does not seem feasible for the powder geometry because of the attenuation problem. Other superleak materials such as Grafoil, Nucleopore, or Millipore may have more suitable characteristics for this application.

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