a few millikelvins of the λ point. The attenuation does not appear to come from unlocking of the normal fluid because of the very low frequencies used, but may arise from attenuation in the unsaturated film which connects the filled pores.

In summary, we have observed a new sound mode in superfluid helium which is in excellent agreement with theoretical predictions. This mode should have many useful applications in the study of clamped superfluids (including ^{3}He), and also appears to be a good tool for studying the nature of adsorption in porous materials.

We benefitted greatly from earlier attempts in our laboratory to observe the fifth-sound mode. Professor Julian Maynard using aluminum superconducting film transducers first experimentally demonstrated the existence of the mixed third-sound, fifth-sound, and surface-tension modes [Eq. (2)]. David Scholler in even earlier experiments, using a vibrating diaphragm transducer to investigate third sound, first demonstrated the feasibility of using resonators of the type used here. We take the opportunity here to acknowledge the importance of this ground work.

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[a]Permanent address: Department of Physics and Astronomy, Tel Aviv University, Ramat Aviv, Israel.

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Observation of Fifth Sound in a Planar Superfluid ^{4}He Film

G. J. Jelatis, J. A. Roth, and J. D. Maynard
Department of Physics, The Pennsylvania State University, University Park, Pennsylvania 16802
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We report an observation of a superfluid helium-4 film sound mode consisting predominantly of a temperature wave, as in second sound, but with the normal-fluid component clamped. Our measurements indicate that this wave, called fifth sound, results in a contribution to the velocity of propagation which varies as $C_5 = (\rho_n/\rho)^{1/2} C_2$, as predicted by the two-fluid theory.

When third sound propagates in a thin superfluid helium-4 film, evaporation and condensation exchanges between the film and the helium vapor above the film result in heat transfers which render the wave motion isothermal rather than adiabatic. The isothermal third-sound velocity is given by[1]

$$C_{3T}^2 = \frac{\bar{\rho}_s}{\rho} d \frac{\partial \Omega}{\partial d}\left(1+\frac{(TS)}{L}\right)^2, \tag{1}$$

where $\bar{\rho}_s/\rho$ is the superfluid fraction averaged over the film thickness d, Ω is the van der Waals energy for the helium atoms on the substrate, and S and L are the entropy and latent heat of evaporation at the temperature T. Most film experiments are performed with sufficient vapor present so that the observed third-sound velocity is indeed C_{3T}. However, if the evaporation-condensation effects are limited, then the coupled film-vapor thermohydrodynamic equations yield a wave propagation velocity of the general form[2]

$$C_{3A}^2 = C_{3T}^2 + \bar{C}_5^2/(1+K^2), \tag{2}$$

where $\bar{C}_5^2 = (\bar{\rho}_s/\rho)\bar{S}S(\partial\bar{S}/\partial T)_p^{-1}$ ($\bar{S}$ is the entropy per unit mass averaged over the film thickness), and K is proportional to the amount of evaporation-condensation exchange. In most experimental situations, K is large and $C_{3A} \to C_{3T}$. If the evaporation-condensation exchanges are eliminated ($K \to 0$), then there is no heat flow from the film,[3] and since the flow of the superfluid component transports no entropy, the wave motion is adiabatic, and significant temperature variations accompany the crests and troughs of the superfluid wave. The temperature variations result in a "thermal restoring force" analogous to that which governs the propagation of second sound (C_2), and this is represented by the second term in Eq. (2). For thick films, C_{3T}^2 becomes negligible, the film averages become unnecessary ($\bar{\rho}_s \to \rho_s$, $\bar{S} \to S$), and there remains a pure superfluid (normal fluid clamped) temperature wave (assuming $K \approx 0$) with a propagation velocity given by

$$C_5^2 = (\rho_n/\rho) C_2^2 \tag{3}$$

which we shall refer to as fifth sound. We report here measurements of C_{3A} for film thicknesses sufficiently large, and K values sufficiently small, so that the fifth-sound component [i.e., the second term in Eq. (2)] accounts for 75% of C_{3A}^2. Thus we have observed a dominant superfluid component temperature wave. The fifth-sound mode given by Eq. (3) should be considered as a fundamental superfluid mode since it follows from the equations of two-fluid hydrodynamics as naturally as C_1^2, C_2^2, and $C_4^2 = (\rho_s/\rho) C_1^2$.[4]

In the experiment, the evaporation-condensation exchange with the vapor is limited by using two flat, parallel substrates separated by a small spacing h. The helium film coats the opposite faces of the substrates and the vapor is confined in between. If h is greater than the thermal and viscous penetration depths in the vapor, then the thermal and mechanical effects of the vapor are complete. However, if h is less than the mean free path of the atoms in the vapor, then the effects of the vapor are eliminated, since atoms leaving the film on one substrate simply enter the film on the opposite substrate and never achieve thermal equilibrium with the vapor. When h is intermediate, the vapor and the film are in quasi-equilibrium, and a calculation of K from kinetic theory is difficult. However, in all cases the crucial quantity is the mean free path l. Furthermore, when h is some fraction of the thermal or viscous penetration depths, then K ought to be proportional to this fraction. Since the penetration depths are proportional to $l^{1/2}$, then $K \propto l^{-1/2}$ and Eq. (2) takes the form[5]

$$C_{3A}^2 = C_{3T}^2 + C_5^2/(1+Bh/l). \tag{4}$$

The quantity B depends on the nonequilibrium details, and a calculation of its value is difficult. However, for the values of h/l relevant to our experiment, B should be practically a geometric factor and have little temperature and pressure dependence; nearly all the variation is contained in the mean free path. By comparing Eq. (4) with our measured sound velocities, we find that $B = 0.07$ fits our data at all temperatures and film thicknesses to within 10%, with the exception of a few thick film points where large attenuations made accurate velocity determinations difficult.

It would be nice if C_{3T} and K could be made sufficiently small so that C_5 could be observed directly. However, the mean free path at higher temperatures is only a fraction of a micron and it is difficult to obtain substrates with the required degree of flatness, separation, and parallel alignment. Even if such a close separation were possible, the thick-film limit would be difficult to obtain because of the onset of capillary instabilities.[6] In our experiment we have used a substrate separation of 5 μm and have obtained film thicknesses of ~300 Å before the capillary instability occurs. Treating the vapor as an ideal gas, we have for the mean free path[7]

$$l = 0.04T/p, \tag{5}$$

where p is the vapor pressure in Torrs. For saturated film vapor pressures, l ranges from 2.5 to 0.06 μm at 1.0 and 1.7 K, respectively.

A schematic representation of the experiment

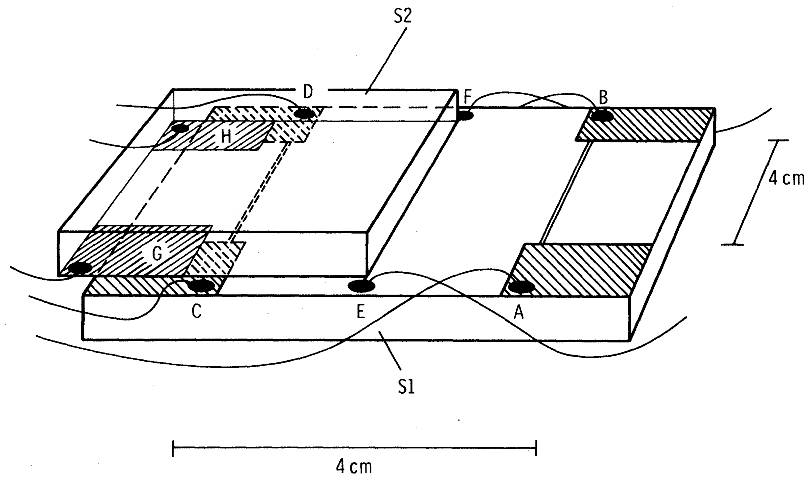

FIG. 1. Schematic representation of the apparatus. Bolometers: AB and CD. Resistance wire heater: EF. Capacitors: G and H. Substrates: $S1$ and $S2$.

is shown in Fig. 1. Two parallel superconducting aluminum strip bolometers,[8] AB and CD, are evaporated onto a quartz optical flat substrate $S1$. A resistance wire heater, EF, is located midway between the bolometers. In this configuration, a current pulse through the heater would produce identical third-sound signals in the bolometers, and the time of flight for the received pulses would yield the isothermal third-sound velocity. However, the substrate to one side of the heater is covered with a second quartz flat $S2$, which is spaced away by an extremely sparse sprinkling of alumina powder and held in place with small beads of epoxy. In this configuration the bolometers AB and CD simultaneously measure C_{3T} and C_{3A}, respectively. Metalized areas G and H on $S2$ overlap similar areas on $S1$ forming parallel plate capacitors. These capacitors are used to determine the thickness of the saturated films. Optical interference fringes indicate that the substrates $S1$ and $S2$ are flat and parallel to within 2 μm. Measurements using the capacitors indicate a mean spacing of 5 μm.

Measurements were taken with the temperature regulated and with the film thickness increasing in steps from the third-sound onset. The thickness of the unsaturated films was determined by measuring the differential pressure Δp between the vapor pressure above the film and the helium-bath pressure p_0, and using[9]

$$d^3(1+d/\beta)=\Gamma[T\ln(1-\Delta p/p_0)]^{-1}, \qquad (6)$$

where $\beta=41.7$ layers and $\Gamma=27$ (layers)^3-K (1 layer = 3.6 Å). When Δp became less than ~0.02 Torr, the film thickness was determined with the capacitors, which were calibrated with the unsaturated film measurements. The capillary instability was indicated by a sudden extreme change in the capacitance.

The pulses received by the bolometers were recorded simultaneously and sample averaged

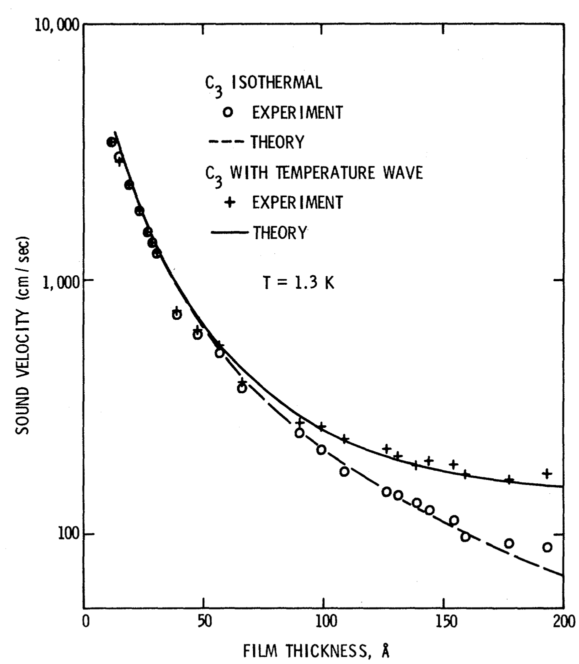

FIG. 2. Velocity of isothermal third sound (circles) and third sound with temperature wave (crosses) vs film thickness. Dashed and solid lines are the theoretical calculations.

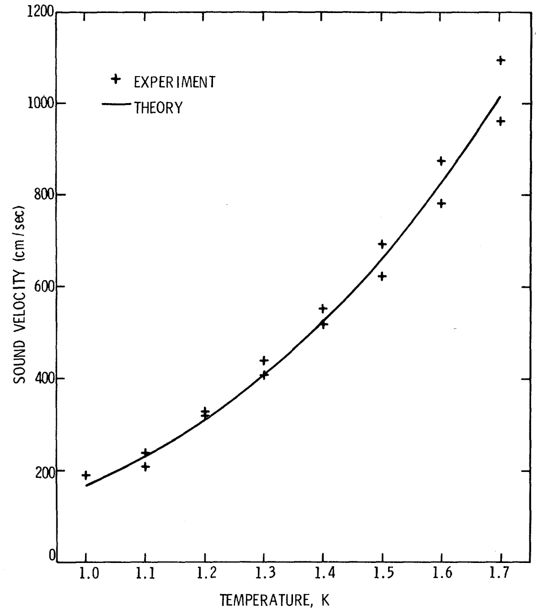

FIG. 3. Experimental and theoretical values of the fifth-sound velocity, C_5. Solid line is the theoretical value, $(\rho_n/\rho)^{1/2}C_2$.

by an on-line minicomputer. Typical data are shown in Fig. 2 where C_{3T} and C_{3A} are plotted versus film thickness for a fixed temperature of 1.3 K. It should be noted that the vertical scale is logarithmic and the separation between the C_{3T} and C_{3A} values at large film thicknesses represents a factor of 2 difference in sound velocity. The solid lines in Fig. 2 are calculated from the theory: The C_{3A} curve is from Eqs. (3) and (4), and the theoretical value for C_{3T} is calculated with Eq. (1) with $\bar{\rho}_s/\rho = \rho_s/\rho(1-D/d)$,[10] D(layers) $= 0.5 + 1.13T/(\rho_s/\rho)^{10}$ and $\Omega(\text{erg/g}) = 5.61\times 10^8/(d^3 + d^4/\beta)^9$ (with d expressed in layers). For all the calculations involving Eq. (4), $B = 0.07$.

The most precise determination of the splitting between C_{3T} and C_{3A} was for film thicknesses between 100 and 150 Å, because here the splitting was large and the received pulses had higher amplitude and were not as dispersed as for the thicker films. At each temperature, we have taken experimental values of C_{3T} and C_{3A} for thicknesses near 125 Å, put them into Eq. (4) and solved for C_5. These values of C_5 are plotted versus temperature in Fig. 3. The solid line in the figure is a plot of $(\rho_n/\rho)^{1/2} C_2$, with values taken from Maynard.[11] The agreement (10%) is within the experimental error.

Hence we have demonstrated that the effects of the helium vapor on third sound can be limited and, at low temperatures, nearly eliminated (at 1.0 K, Bh/l is only 0.14), and we have measured the C_5 factor of Eq. (4) and shown that it varies as $(\rho_n/\rho)^{1/2} C_2$. The limiting of the evaporation-condensation exchanges should also result in less attenuation and dispersion for C_{3A}, and we have observed this qualitatively. For the thin films, the C_{3A} and C_{3T} pulses are identical, but for the thick films, the C_{3A} pulses are ~4 times narrower and typically 15 dB greater in amplitude. (We have verified that the bolometers have sufficiently identical sensitivities.) The larger amplitude of C_{3A} may be an indication of less attenuation; however, it may also be due to the dominance of the temperature wave in the adiabatic propagation. We are presently developing a four-bolometer apparatus to measure the relative attenuations of C_{3T} and C_{3A}.

One of the authors (J.D.M.) began the search for fifth sound at the University of California at Los Angeles with I. Rudnick and S. J. Putterman and would like to acknowledge gratefully their contributions. He is also in receipt of an Alfred P. Sloan Research Fellowship. We also thank M. W. Cole for helpful discussions.

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