PHYSICAL REVIEW LETTERS

VOLUME 9 SEPTEMBER 1, 1962 NUMBER 5

FOURTH SOUND IN He II †

I. Rudnick and K. A. Shapiro
Physics Department, University of California, Los Angeles, California
(Received July 25, 1962)

In addition to the well-known first and second sound in helium II, two other unattenuated modes of wave propagation in this liquid are possible and have been identified as "third sound" and "fourth sound." Both are characterized by the fact that the normal component of the fluid is locked in place and only the superfluid component oscillates in the wave propagation. Third sound, which has been recently detected,[1] is found in helium II films and depends for its existence on body forces. It is an oscillation in thickness of the film, and the temperature and pressure variations are very small. Fourth sound is a compressional wave in which the pressure and temperature variations are first-order quantities. Its wave velocity can be obtained from the linearized thermohydrodynamic equations by setting the velocity of the normal component equal to zero and is given by the expression[2,3]

$$C_4^2 = (\rho_s/\rho)C_1^2 + (\rho_n/\rho)C_2^2(1-2\alpha C_1^2/s), \quad (1)$$

where C_1, C_2, and C_4 are, respectively, the first, second, and fourth sound velocities, ρ_s and ρ_n are, respectively, the superfluid and normal fluid densities, ρ is the density of helium II, α is the isobaric coefficient of expansion, and s is the specific entropy of the fluid. In the range between 2.1°K and 1.2°K, $-2\alpha C_1^2/s$ is positive and of the order of magnitude of unity. In this temperature range, errors of approximately 1 % or less are incurred by retaining only the first term in Eq. (1).

Pellam[4] in 1948 first pointed out the existence of such an unattenuated wave in a superleak[5] (a porous medium in which the normal fluid component is locked). He obtained the expression

$$C_4^2 = (\rho_s/\rho)C_1^2 + (\rho_n/\rho)C_2^2. \quad (2)$$

In addition to this mode he found a root to the wave velocity equation which was a diffusion wave and had a limiting velocity of zero when the normal fluid component was firmly locked. He identified (2) as a second-sound wave and the latter mode as a first-sound wave. Actually the wave whose root is given by Eq. (2) is, in the limit that the normal fluid component becomes unlocked, first sound, and in the same limit the diffusion wave becomes second sound. The question of whether one regards the unattenuated mode as a special case of first sound or second sound is unimportant since in fact it is neither, and Atkins[3] in a different context—namely, mode propagation in a narrow channel—appropriately gave it a unique name, fourth sound.

The purpose of this Letter is to present experimental results which verify the existence of fourth sound.

The apparatus consisted of a standing wave tube 3.16 cm long and 1 cm i.d. filled with Gelman Polypore AM-6 filter material[6] and terminated at each end by identical transducers, one of which served as a sound source and the other as a receiver. The filter material is described by the manufacturer as having an average pore size of 0.45 ± 0.02 micron and a porosity of 85%. Each transducer consists of a gold-coated film of Mylar approximately 7×10^{-4} cm thick which is stretched in a plane parallel to a flat back electrode and is separated from the electrode by a distance of the order of 10^{-3} cm. The source transducer is driven by an alternating voltage (100 volts) applied between the back electrode and the gold-coated outside surface of the film. This generates a mechanical oscillation of the Mylar film of twice the voltage frequency. The receiver transducer is polarized by a dc voltage of 200 volts, and the voltage variations produced by capacitance changes associated with diaphragm displacements are measured by a high-impedance electrical circuit. Thus the signal picked up has twice the frequency of the electric signal energizing the source and cross-talk problems are greatly reduced.

The system acts like a closed-closed tube with a fundamental frequency which ranged from 3286 cps at 1.19°K to 1874 cps at 2.1°K. Figure 1 contains the results of the measurements. The curve labelled "fourth sound" is a plot of Eq. (1). For comparison purposes a curve giving the velocity of first sound is also plotted. With a given driving voltage the received signal was a monotonically decreasing function of temperature, the sharpest drop occurring in the neighborhood of the λ point. At 2.1°K the level was 30 db below that at 1.19°K. There was absolutely no indication of a signal when the temperature

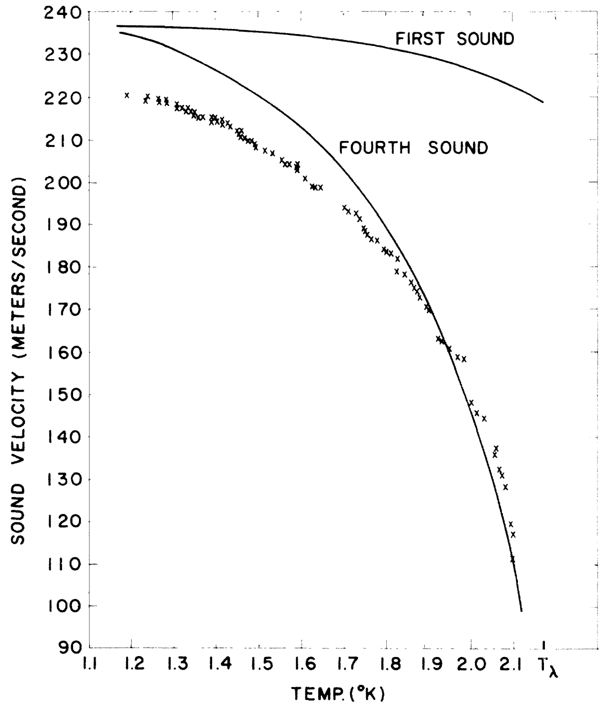

FIG. 1. Measured values of the compressional wave velocity in a half-wave resonant tube filled with superleak material. The curve labelled fourth sound is a plot of Eq. (1). The first-sound velocity is also shown.

was 0.01°K above the λ point (or indeed at any temperature above the λ point) although it was searched for at levels approximately 60 dB below the signal levels at 1.19°K. When the superleak was removed very substantial signals were observed throughout this temperature range.

The measured Q of the resonant mode decreased with increasing temperature. Its value was 82 at 1.3°K and 25 at 1.79°K. If these Q's are assumed to be due to the attenuation coefficient of fourth sound one obtains values of 0.006 cm^{-1} and 0.02 cm^{-1}, although it is much more likely that the Q's were limited because the locking of the normal fluid component was incomplete. This could be caused by residual normal fluid motion in the larger pores of the filter material, gaps between tube walls and filter material, etc. In any case the data lend support to the result that fourth sound is, in the ideal case, unattenuated.

The spirit of this investigation has been to detect the existence of fourth sound with only such accuracy as is necessary to lend credence to the results. The absolute accuracy of the measurements is probably not far from the 6% discrepancy between the observed and theoretical values at the lowest temperature. More definitive experiments are now being planned.

*Work supported in part by the Office of Naval Research.

[1]C. W. F. Everitt, K. R. Atkins, and A. Denenstein, Phys. Rev. Letters 8, 161 (1962).

[2]Walmsley in reference 3 finds a different expression for the bracketed term in Eq. (1), namely $(1-\alpha C_1{}^2/s)^2$.

[3]K. R. Atkins, Phys. Rev. 113, 962 (1959).

[4]J. R. Pellam, Phys. Rev. 73, 608 (1948).

[5]The presence of the superleak introduces no added attenuation provided one can neglect irreversible heat conduction in this material or in the locked normal fluid.

[6]Gelman Instrument Company, 106 North Main Street, Chelsea, Michigan.

EXISTENCE OF MINIMA IN THE MELTING CURVES OF He^3-He^4 MIXTURES*

H. Weinstock,† F. P. Lipschultz, C. F. Kellers, P. M. Tedrow, and D. M. Lee
Laboratory of Atomic and Solid State Physics, Cornell University, Ithaca, New York
(Received June 25, 1962)

Measurements have been made on the melting curves of He^3-He^4 mixtures in the temperature region below 1°K. The results, shown in Fig. 1, indicate that the melting curves of a 25 mole % He^3-75 mole % He^4 mixture and a 38 mole % He^3-62 mole % He^4 mixture have minima in the neighborhood of 0.8°K. The curves shown represent smoothed data from a large number of runs, each taken at a different starting pressure. The disagreement between runs was on the order of our experimental error, thus indicating that the melting curves and freezing curves are not too dissimilar at these concentrations. This would suggest that the concentrations of He^3 in the liquid and solid phases are about the same for these mixtures. Results of melting-curve measurements on pure He^4 with the same apparatus as well as the curve obtained by Baum et al.[1] for pure He^3 are shown for comparison. It can be seen from Fig. 1 that the melting-curve minima of the mixtures occur at considerably higher temperatures than the minimum for pure He^3 and that the temperature of the minimum appears to be depressed by increasing the He^3 con-

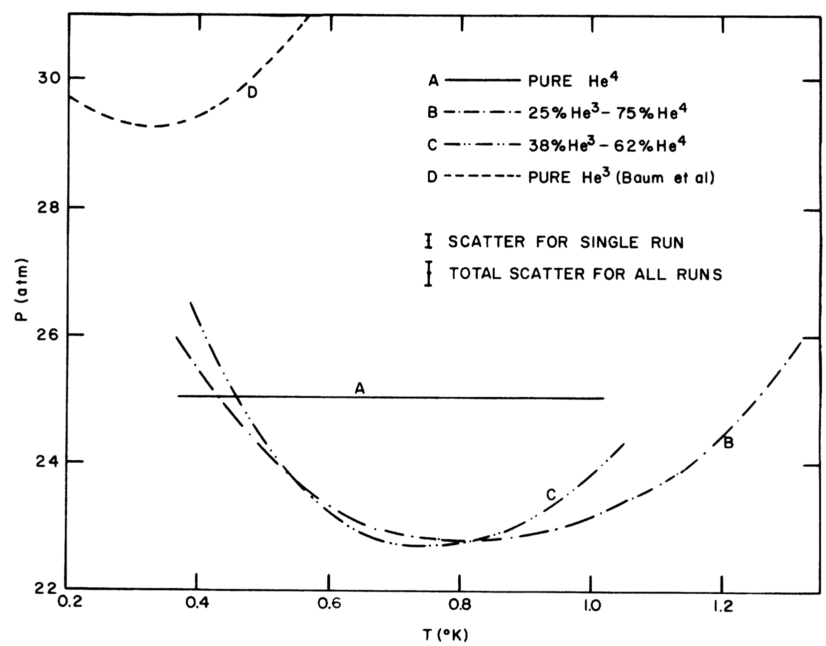

FIG. 1. Melting curves of He^3-He^4 mixtures, pure He^4, and the pure He^3 data of Baum et al.[1]