Experiments on the attenuation of third sound in saturated superfluid helium films*

Kenneth L. Telschow, Robert K. Galkiewicz, and Robert B. Hallock†

Department of Physics and Astronomy, University of Massachusetts, Amherst, Massachusetts 01003

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Upper limits of the attenuation of third sound in saturated superfluid ^{4}He films have been measured in three separate experiments. Our observations at frequencies from 0.1 to 200 Hz indicate that the attenuation in these thick films is substantially lower than would be inferred from the only previous experiment done on saturated films. We observe the third-sound velocity to have the temperature dependence predicted by Bergman.

The properties of superfluid helium films have often been investigated by measurements of thickness oscillations in these films known as third sound. A hydrodynamic approach appears to correctly predict the velocity of third sound to within 10% for films thicker than approximately 15 atomic layers.[1] However, an understanding of the attenuation of these waves has presented a more difficult problem. Bergman has calculated fully the expected attenuation from two-fluid hydrodynamics[2] and finds results which are generally far below experimental measurements.[3,4] Previous experiments on films show the attenuation, α (cm^{-1}), increasing with decreasing film thickness, becoming diffusive (i.e., $\alpha\lambda \approx 1$) at the superfluid onset thickness and also increasing in very thick films; hence, exhibiting a minimum in the neighborhood of twice the onset thickness.[3] The first experiment[4] detecting third sound has been, until recently,[5] the only one reporting attenuation measurements in thick saturated films and found very high values compared to Bergman's calculation.[2] Thus both very thick- and thin-film experiments appear to exhibit a large discrepancy with the two-fluid hydrodynamic theory. Both quantum-mechanical and classical explanations[6,7] have been presented to account for this discrepancy. We report here measurements of the attenuation at low to intermediate frequencies from three separate experiments involving third-sound resonances in thick saturated films. These results indicate that the third-sound attenuation in these films is substantially smaller than would be inferred from the only previous measurement on saturated films. In addition, our measurements of the temperature dependence of the third-sound velocity are in agreement with the predictions of Bergman.[2]

The first experiment we shall discuss involves third-sound resonances in an apparatus which has been used for the study of persistent currents in saturated films.[8] The basic geometry consists of two liquid reservoirs connected by parallel long and short stainless-steel flow paths (Fig. 1). The primary original objective of this arrangement was the measurement of level oscillations within the reservoirs as a result of flow through the film.[8] Liquid levels in the reservoirs were detected capacitively using the standard three-terminal-bridge method[9] and level changes were produced by heaters within the reservoirs. Typical oscillation amplitudes were on the order of 1 mm. Level oscillations of a much smaller magnitude, typically 0.004 mm, were also seen when either heater centered on the long and short flow paths was pulsed. During these oscillations the levels in both reservoirs move in phase and at several discrete frequencies amplitude maxima occurred corresponding to third-sound resonances within the superfluid film along the flow paths inside the steel tubing. Application of sufficient heat to the short flow path through current[10] in a heater, S, ceased all flow through this path. The resonances observed by pulsing a heater, L, centered on the long flow path under these conditions of S closed were identical with those seen

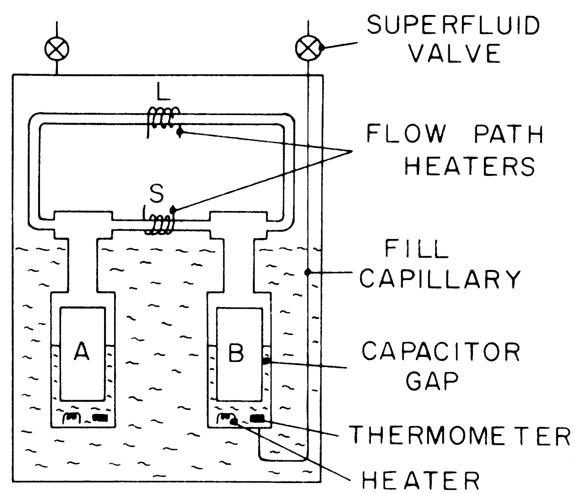

FIG. 1. Stainless-steel resonator. The long flow path is 240 cm long, 1.4 mm i.d. and the short flow path is 2.2 cm long, 1.4 mm i.d.

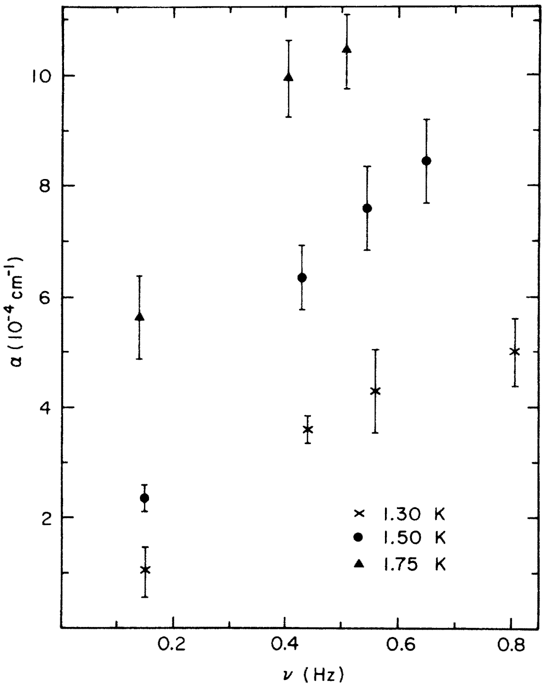

FIG. 2. Observed attenuation of third sound in the long flow path for three temperatures. The film height $H = 4.0$ cm.

with the short path open. The resonances thus are believed to be standing waves set up in the long flow path with the reflecting boundaries consisting of the level surfaces in the reservoirs or more likely bulk fillets of helium trapped by surface tension at the tube connections. As many as five resonances were observed[5] in this manner in the frequency range of 0.15–0.79 Hz at 1.5 °K and with the height (H) from the level surfaces to the mean horizontal long tubing coil being between 4.0 and 6.4 cm. We identify the modes as the first, third, fourth, fifth, and sixth half-wavelength resonances, along the flow path. The existence of bulk liquid at the reflecting boundaries should demand a film thickness oscillation node there with a corresponding particle velocity node halfway along the tubing, where the heater L is located. Even modes are discriminated against by the velocity node since the heater L always draws film from both directions. Probably due to asymmetry in the apparatus or the exact location of heater L some of the higher even modes were observed. The resonance frequencies agree with our interpretation to within 10%. At resonance, amplitude oscillations as large as 0.006 mm were observed in the reservoirs with 50-μW rms heat developed in the heater L. Near this power level an abrupt increase in the measured resonance bandwith corresponding to saturation of the oscillations was seen. In view of this all measurements reported here involved substantially reduced heater powers (typically 10 μW). An attenuation coefficient for these resonances was obtained from the amplitude decay time after abruptly cutting off the drive at the resonant frequency and also from the bandwidth of the response curve as a function of drive frequency. Both measurements agree to within ≈10% and values of the energy decay coefficient $\alpha(\text{cm}^{-1}) = \alpha(\text{sec}^{-1})/C_3$ (cm/sec) are shown in Fig. 2 for three different temperatures.

Experiments with third sound have also been conducted on the outside of Pyrex tubes and rods at higher frequencies. The detector of the film-thickness variations utilizes a tunnel diode oscillator to measure the capacitance between two (0.004 cm) enameled wires bifilarly wound over the glass tube or rod. Upon saturation of helium in the experimental cell, bulk fillets of liquid are formed between the wires and the glass surface by surface-tension forces. This is evidenced experimentally by an increase in the capacitance far greater than that expected by formation of the film alone. Film-thickness variations are seen through changes in the amount of liquid held on the wires. A distance away from the detector another winding of a single manganin wire around the glass tube serves as a heater driver for the third sound. The bulk fillets of the driver and detector form re-

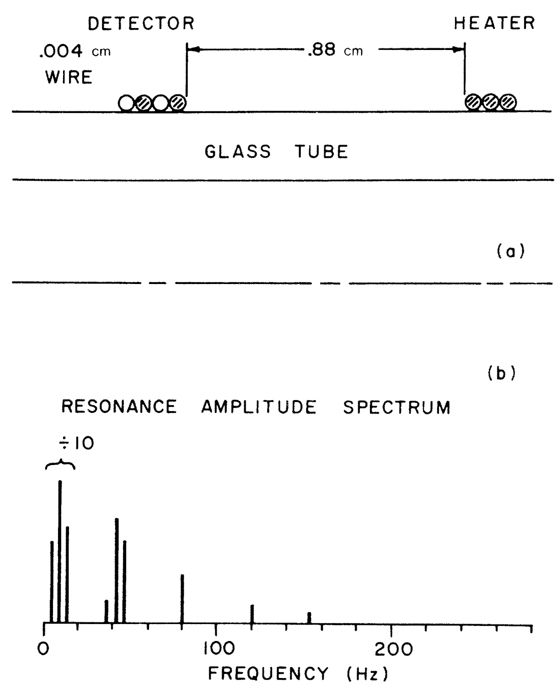

FIG. 3. (a) Glass tube resonator geometry. (b) Observed spectrum of resonances at 1.3 K and $H = 11.2 \pm 0.2$ cm. Higher modes than those shown were observed but not used in the measurements reported here.

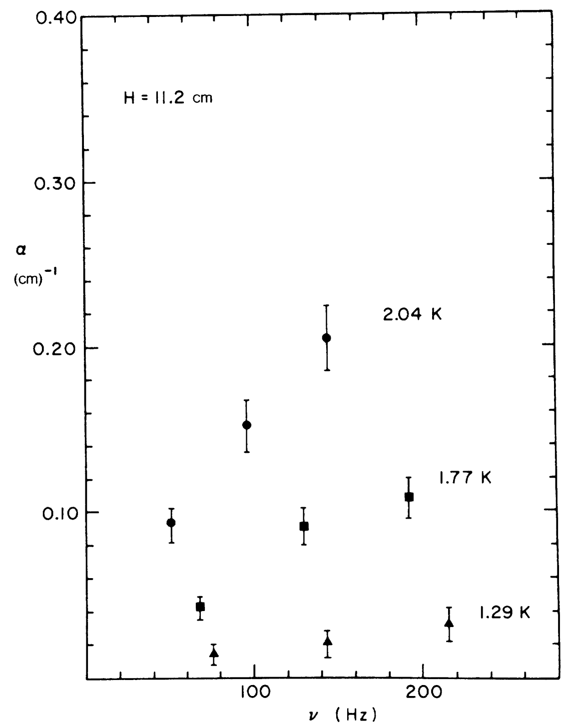

FIG. 4. Observed attenuations of resonances on the glass tube resonator calculated from the bandwidths.

flecting boundaries for the third sound since there is an abrupt change in the phase velocity passing from the film into the fillet, therefore the combination forms a resonator. The resonators formed in this manner function similarly to the stainless-steel resonator previously described.

One resonator utilizing a straight glass tube is illustrated in Fig. 3(a). Here the driver-detector separation is 0.88 cm and the tube outer diameter is 3 mm. The corresponding resonance amplitude spectrum at 1.3 K and $H \approx 11.2 \pm 0.2$ cm displays several features [Fig. 3(b)]. Very strong low-frequency resonances are observed which are thought to result from inverted U-tube-like oscillations between the bulk fillet reservoirs on the wires and other supporting structure at the ends of the glass tube. Above these resonances is an approximately harmonic sequence of resonances which are believed to be half-wavelength modes in the film between the heater and detector. Several additional unidentified resonances were also observed near the fundamental, but this multiplicity was not seen at higher frequencies.

The attenuation coefficients for the first three half-wavelength modes are shown in Fig. 4. These values were obtained from the resonance bandwidths in the same manner as previously described for the stainless-steel resonator. Measurements were taken at three different heights ($H \approx 6.7$, 8.7, and 11.2 cm) and various temperatures from 1.29 to 2.04 K. The attenuation coefficients found were only weakly increasing as H decreased changing by roughly a factor of 2 over the entire range investigated. These coefficients were also slowly varying with temperature increasing more rapidly as the onset temperature is reached near T_λ.

Another experiment was also done on a glass resonator to test our understanding of the resonances and for using third sound to study persistent currents. Some attenuation data was also measured and is presented later for comparison. The geometry is schematically illustrated by the insert in Fig. 5. It consists of a 3-mm-o.d. Pyrex rod closed on itself to form a ring with two side connections which hold the driver and detector wires and also act as structural supports. In the region between the driver and detector along the short path another wire-wound heater (S) was placed for use in the persistent current experiments. For the purposes reported here this heater

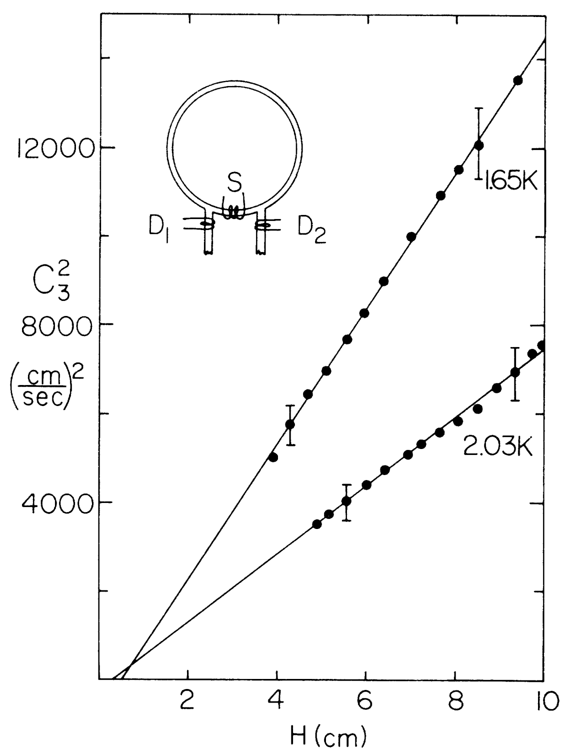

FIG. 5. Square of the third-sound velocity as a function of the height of the film above the bulk helium free surface for two temperatures. In the upper left is depicted the glass ring resonator. D_1 is the heater-driver, D_2 is the capacitive detector, and S is another heater which served only as a boundary for these experiments. The path length around the ring is 19.1 cm.

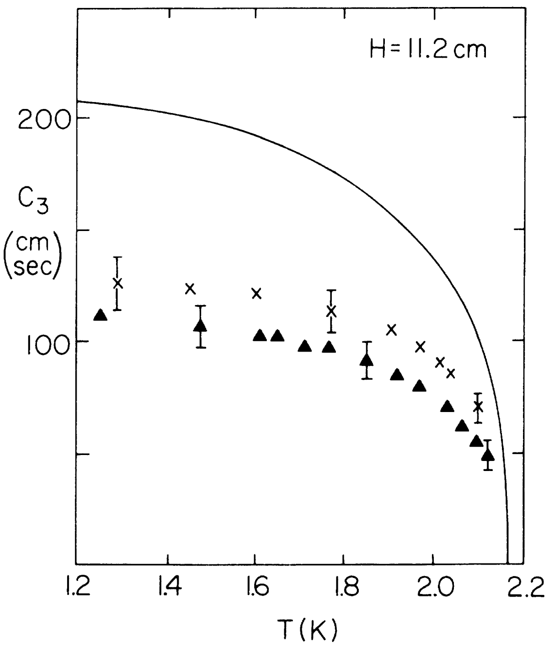

FIG. 6. Observed third-sound velocity measured from the resonance spacings on the glass resonators (cross, tube; triangle, ring) compared to the hydrodynamic prediction (solid line) appropriate for thick films using $n=4$. At constant H our values indicate a temperature dependence consistent with $[\rho_s/\rho(1+TS/L)^2]^{1/2}$ (Ref. 2).

was not used except as a reflecting boundary. The resonance spectrum for this geometry showed features similar to that of the glass tube. Up to 12 modes of a harmonic sequence corresponding to half-wavelength resonances around the ring could be seen. Other modes probably associated with U-tube-like oscillations between the various fillets were also present. The path length around the ring is 19.1 cm and correspondingly all the resonances are at lower frequencies than those seen on the glass tube in accord with our interpretation. A comparison of the third-sound velocities measured from the resonance spacings for the various experiments reported here is shown in Fig. 6 and discussed later. Attenuation coefficients for the ring geometry also showed similar behavior to the glass tube. There was little variation with H seen and the increase in attenuation with temperature was much steeper near the onset temperature. For example, at 1.65 K the attenuation decreased by less than 20% as H was increased from 3.9 to 9.4 cm. The differences between our observations with the two glass resonators are perhaps associated with the much larger path length for the ring than for the tube which diminishes the effects of the fillet boundaries relative to the film. Both the ring and tube experiments are more comparable to that of Ref. 4 than the steel resonator experiment because they do not constrain the vapor at all, however, our results are not in good agreement with this previous experiment.

The third-sound phase velocity was measured from an average of the resonance spacings in all experiments described here. In the isothermal approximation two fluid hydrodynamics predicts $C_3=(ngH\rho_s/\rho)^{1/2}$, where g is the gravitational acceleration, ρ_s/ρ the superfluid fraction, and n the exponent in the Van der Waal's potential ($\sim d^{-n}$), where d is the film thickness. Recent direct film-thickness measurements have found this exponent to be 3 for films of a few atomic layers thick increasing to 4 for thicker films in the saturated region.[11] In the ring experiment provision was made for H to be varied continuously and the velocity dependence measured directly. Figure 5 shows that the velocity is accurately proportional to $H^{1/2}$ as expected. Although a detailed systematic check of the velocity versus H in the tube experiment was not performed the three H values investigated yielded velocities consistent with a $H^{1/2}$ dependence. In both experiments there were zero offsets seen in the velocity versus H curves which are not understood. These small offsets were different for different experiments and depend on corrections for capillary rise in the free surface measuring capacitors. We feel they are very likely experimental artifacts.

Our measured third-sound velocities, although exhibiting the expected H dependence, differ in two distinct ways from the isothermal prediction described previously. First, all the experiments done here show a phase-velocity dependence on temperature like $(\rho_s/\rho)^{1/2}(1+TS/L)$ as predicted by Bergman (here S is the entropy and L the latent heat), as compared to the isothermal $(\rho_s/\rho)^{1/2}$ dependence.[2] This effect was easily seen by monitoring one resonance as a function of temperature and comparing to bulk ρ_s/ρ values. We feel that this is a significant observation since there has been no previous experiment with great enough precision to look for this alteration from the isothermal theory. The second way our results are different from the above prediction is that ours are consistently smaller in magnitude by a constant factor. Figure 6 shows our measured phase velocities compared to the isothermal prediction using $n=4$. Other experimenters, using time-of-flight techniques, have also found values of C_3 below the predicted curve with values of n ranging from less than 3 to 4.[4,12] Typically the scatter in those results prevents an accurate determination of this exponent from the measured phase velocities. As the velocities reported here are inferred from the resonance frequencies an interpretation

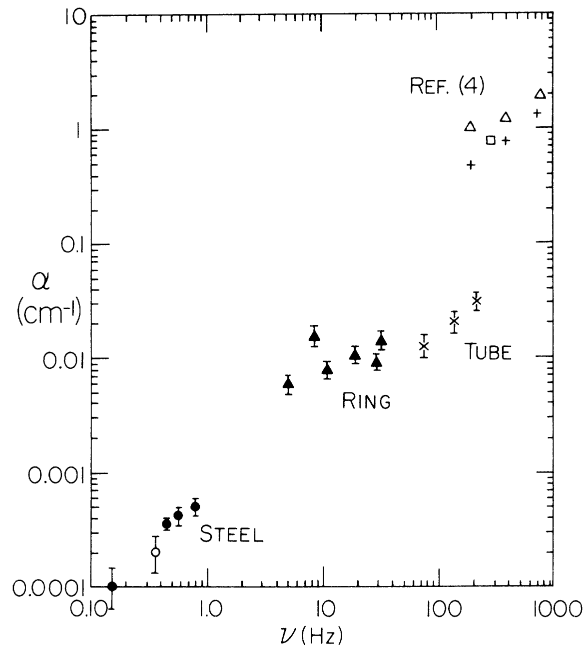

FIG. 7. Comparison of the stainless-steel and glass resonators attenuation results at $T=1.3$ K with the measurements reported in Ref. 4 ($T=1.2$ K, $H=9.0$ cm). The symbols represent stainless steel (closed circle, $H=4.0$ cm; open circle, $H=6.2$ cm), glass ring (closed triangle, $H=7.0$ cm) and glass tube (cross, $H=11.2$ cm). The effects on the attenuation due to changes in the height H are discussed in the text.

of the mode wavelength is required. We have assumed the simplest modes possible and used the harmonic resonance spacings to determine the velocities which should greatly eliminate any loading effects of the fillet boundaries. Other effects which could cause the discrepancy are surface roughness and contamination.[13,14] Scanning-electron-microscope pictures of the stainless-steel tube[14] surfaces do show substantial roughness on the scale of ~1 μm which would increase the effective path length. Although we think the glass surface is much better we do not know its true condition and similar velocities are obtained on it as in the stainless-steel tubing. Surface contamination is known[13] to reduce measured third-sound velocities in saturated films. In view of this precautions were taken in these experiments to minimize surface contaminants. We have no way to judge the success of these precautionary steps, however, since the situation is complicated by the other effects mentioned above. In all cases at least the same precautionary steps were taken here as in Ref. 13.

Undoubtedly some of the acoustic energy in the third-sound wave is lost within or through the boundaries when they are not rigid. We cannot measure this specific loss in these experiments and therefore expect our measured values of the attenuation to contain contributions from these boundary effects as well as possible contributions from the other effects we have mentioned. Hence our attenuation measurements represent *upper limits* to the third sound attenuation. In spite of this, we observe attenuation values substantially below those reported in Ref. 4. Two possible inferences can be drawn from previous measurements[4] of the frequency (ν) dependence of the attenuation of third sound in saturated films: Extrapolation of the results ($\nu \gtrsim 200$ Hz) to zero frequency indicates that either the attenuation is finite ($\alpha \gtrsim 0.2$ cm^{-1}) as $\nu \to 0$ or else an unsuspected strongly frequency-dependent drop in attenuation takes place below $\nu = 200$ Hz so as to allow $\alpha \to 0$ as $\nu \to 0$. Our low-frequency results coupled with the measurements up to 200 Hz just described force us to conclude that neither of these inferences is correct.

All of the measurements shown in Fig. 7 were done at approximately the same temperature and film thickness except for our stainless-steel resonator which involved a film slightly thicker than the others. The cylindrical geometries used here eliminate the possibility of an excess attenuation occurring due to beam spreading. This may account for some of the differences between this work and that of Ref. 4 seen in Fig. 7. *Our conclusion is that the attenuation of third sound in the saturated thick-film region is far less anomalously large than previously thought and that the third-sound velocity displays the temperature dependence predicted by Bergman.*[2] We find our values of the attenuations are above the predictions of Bergman[2] for films in the range of thicknesses and frequencies studied in these experiments. However, given the experimental uncertainties we feel detailed comparisons to Bergman's predictions are not justified. These uncertainties perhaps will make significant improvements in the resonance techniques we have reported here difficult. It is clear however that in order to properly establish whether or not there is *any* anomalous behavior of the attenuation compared to the predictions of the two-fluid theory further measurements of some type are necessary.

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