PROPAGATION OF FIRST SOUND IN He II *WITH A PARTIALLY DAMPED NORMAL COMPONENT*

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The velocity and absorption of first sound in narrow tubes filled with HeII are investigated experimentally. A detailed study is made of first-sound dispersion due to partial damping of the normal component. The temperature and frequency dependences of the velocity in this case are in good agreement with the theory. The absorption of sound is found to increase appreciably in the region of strong dispersion.

1. INTRODUCTION

THE character of acoustic oscillations in superfluid helium, as is well known[1-8], depends to a considerable degree on the degree of deceleration of the normal component. In this sense, a large influence on the propagation of sound in HeII is exerted by side effects. This is connected with the following circumstance. Near the walls of a vessel filled with helium, there usually arise transverse viscous waves, in which only the normal component oscillates. Such waves attenuate rapidly, their depth of penetration $\lambda_\eta = (2\eta_n/\omega\rho_n)^{1/2}$ is very small (η_n and ρ_n are the viscosity and density of the normal component, $\omega = 2\pi f$ is the frequency of sound). So long as the dimensions of the vessel d greatly exceed λ_η ($\delta = d/\lambda_\eta \gg 1$), the influence of the viscous waves can be neglected, and two independent types of oscillations, first and second sound, can propagate in the liquid. In this case the normal component is completely free. In the other limiting case of very narrow channels ($\delta \ll 1$), the normal component is completely blocked, and then the first sound goes over into fourth sound while the second sound goes over into a strongly damped diffusion wave.

Physical interest attaches also to the intermediate case, when the depth of penetration of a viscous wave has the same order of magnitude as the dimension of the channels ($\delta \sim 1$). Then the normal component is decelerated only partly and the degree of its deceleration, as shown by Adamenko and Kaganov[6], is conveniently described with the aid of the dimensionless complex parameter r:

$$r = \frac{\rho_n}{\rho}\frac{a + i[a^2 - b(1-b)]}{a^2 + (1-b)^2}. \qquad (1)$$

In the case of cylindrical channels with radius d, according to[8]

$$a = \operatorname{Im}\frac{2}{k_3 d}\frac{J_1(k_3 d)}{J_0(k_3 d)}, \quad b = \operatorname{Re}\frac{2}{k_3 d}\frac{J_1(k_3 d)}{J_0(k_3 d)}, \quad k_3 d = \delta(1+i), \qquad (2)$$

where $J_0(k_3d)$ and $J_1(k_3d)$ are Bessel functions of zero and first order. Then the velocity of first sound, with allowance for the deceleration of the normal component, is[6]

$$u_{1\delta}^2 = u_1^2\left(1 - b\frac{\rho_n}{\rho}\right)\left[1 + \frac{3}{8}\left(\frac{a}{\rho/\rho_n - b}\right)^2\right]. \qquad (3)$$

When $\delta \ll 1$ ($a = 0$ and $b = 1$) formula (3) gives the velocity of fourth sound $u_{1\delta}^2 \to u_4^2 = u_1^2\rho_s/\rho$, and when $\delta \gg 1$ ($a = 0$, $b = 0$) we have pure first sound $u_{1\delta} \to u_1$. In the case when $\delta \sim 1$ the velocity of sound given by formula (3) lies between u_1 and u_4 and depends on the value of δ. Such a unique dispersion of sound was observed experimentally[7], and the measured velocity of sound was satisfactorily reconciled with the prediction of the theory[6].

The present research, in which we continued the earlier experiment[7,9], was devoted to a more complete investigation of the temperature dependence of the velocity and absorption of sound at different values of δ.

2. EXPERIMENTAL METHOD

Filter. To realize the conditions of partial damping of the normal component it is important to choose properly the system of channels filled with the liquid. In[7] we used a filter, made of pressed fine powder of corundum, in which the channels did not have the form of straight lines. A shortcoming of such a filter is that the acoustic length of the path differed by 20–30% from the distance between the receiver and the emitter of the sound. In addition, the presence of individual minute particles of the filter, receiving part of the acoustic waves, has made it difficult to calculate the sound absorption accurately.

In this investigation we prepared a filter with practically straight-line channels made up of thin glass filaments. We used commercially produced filaments of ~3–4 μ diameter. Such filaments are usually obtained in special machines and are subsequently wound in a regular manner on a drum. To prepare a filter, a small section of filaments, ~2 cm long, was cut out from the drum and was transferred to a specially slotted sleeve, retaining at the same time the regularity of the arrangement of the filaments. Then the sleeve with the filaments was passed several times through dyes in order to reduce finally the dimension of the channels. The filter was in the form of a cylinder 14 mm in diameter and 22.2 mm long. As shown by a microscopic investigation, the channels obtained in this manner were not strictly uniform over the cross section, but for the purposes of the present investigation it is possible to use certain average effective dimension of the channel, the method of the determination of which is described below.

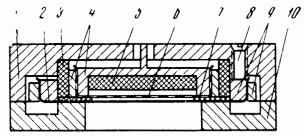

FIG. 1 Diagram of capacitive microphone: 1—housing, 2—membrane, 3—insulating liner, 4—body and ring of stationary electrode, 5—sound-absorbing layer, 6—grid, 7—liner, 8—adjusting screws, 9—rings for stretching the membrane, 10—lower cover.

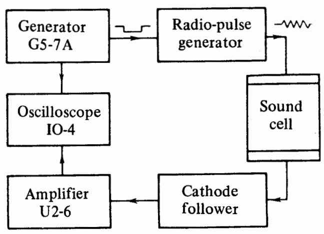

FIG. 2. Block diagram of measurements by the radio pulse method.

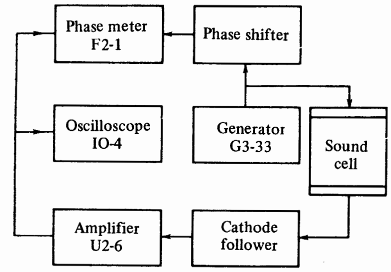

FIG. 3. Block diagram of acoustic measurements by the phase method.

An important advantage of such a filter is the linearity of the channels, the deviation from which amounted to only 2—3%.

Pickups. As the radiator and receiver of sound we used capacitive pickups. Figure 1 shows a diagram of a capacitive microphone used to receive the acoustic oscillations. The moving element of the pickup, membrane 2, was made of a lavsan polyester film 5 μ thick, on which a layer of aluminum of 500 Å thickness was deposited. The membrane was stretched sufficiently strongly by rings 9, and then the degree of its stretching could be varied by means of three adjustment screws 8. The stationary electrode was a copper grid 6 with mesh of 35 μ, stretched between the ring and the body of the electrode. Sound-absorbing material 5 was placed in the latter to decrease the reflectivity of the microphone. Such a construction of the receiver ensured high sensitivity in practically the entire range of the investigated frequencies.

The sound generator was a similar pickup, except that a flat brass electrode was used in place of the grid. Such a radiator operated effectively in the frequency range 20—130 kHz. The frequency characteristics of the pickups did not vary with the temperature.

Measurement method. To determine the velocity of sound we used a method of directly measuring the propagation time τ of the acoustic wave in the liquid. The main measurements were performed with the aid of radio pulses using a scheme shown in Fig. 2. The generator of the shifted pulses G5-7A triggered another generator of radio pulses fed to the radiator. The amplitude of the pulses was ~ 5 V, and the carrier frequency could vary in a wide range. The output of the sound receiver was constructed in accordance with a cathode-follower scheme, from which the pulse was fed after amplification to an oscilloscope. The time τ was determined from the delay of the generator G5-7A, and the pulse amplitude was measured directly on the oscilloscope.

However, the radio-pulse method cannot be used in the low-frequency region, since the pulse signals become nonmonochromatic if their duration is limited. This is connected with the well-known fact that upon passage of the pulse, its individual spectral components attenuate in different manners, and as a result the waveform of the pulse becomes distorted. Then the effective carrier frequency, corresponding to the maximum of the spectrum, shifts from the initial carrier frequency. Estimates in accordance with[10] show that at an oscillation frequency of 30 kHz the change of the frequency spectrum amounts to 2—4% depending on the temperature. The ensuing change of sound velocity does not exceed the measurement errors and therefore does not influence the results. However, at lower frequencies, the change of the spectrum becomes already appreciable and limits by the same token the region of applicability of the pulsed method. Therefore the measurements at very low frequencies were performed by a phase method, using continuous oscillations. A sinusoidal voltage of prescribed frequency was fed from the generator G3/33 simultaneously to the sound radiator and, through a phase shifter, to the electronic phase meter F2-1 (Fig. 3). The received signal was amplified and also fed to the phase meter, which registered the phase difference φ between the signal passing through the liquid and the reference signal. The sound propagation time was defined as $\tau = \varphi/2\pi f$, where f is the oscillation frequency. This method was used to measure as a function of the temperature at a fixed frequency. The amplitude of the signal in the phase method was registered with the aid of a measuring amplifier U2-6.

Cryostat. The sound propagation was investigated in the temperature interval 0.5—2.0°K. Temperatures below 1.4°K were obtained by pumping off the vapor over liquid He^3 with a carbon adsorption pump: the temperature was determined from the vapor tension of the He^3 with allowance for the thermal molecular correction. The construction of the low-temperature cell was perfectly analogous to that used earlier in the measurement of the velocity of fourth sound.

Error sources and estimate of errors. We have already mentioned the error introduced in acoustic measurements by non-monochromaticity of the pulse. To avoid this error at very low frequencies, we used the phase method. In the frequency range 30—70 kHz, on the other hand, the measurements were performed simultaneously by the pulsed and phase methods, and the results obtained by both methods agreed within the limits of experimental accuracy.

Another source of errors was connected with the fact that when a capacitive pickup is used as the sound radiator, oscillations are excited not only at the applied frequency f, but also at the harmonic 2f. Since the pickup is polarized by a constant voltage u_0 and an alternating voltage $u_\sim$ is additionally applied to it, the contribution of the double frequency is proportional to $u_\sim^2$, whereas the contribution of the fundamental frequency f is proportional to $u_0 u_\sim$. However, recognizing that $u_0 \gg u_\sim$, we can neglect the influence of the doubled frequency compared with the frequency f.

Special attention was paid to the absence of one more possible error connected with the presence of acoustic waves of large amplitude. For this reason, the measurements were performed at signal amplitudes which did not influence the values of the velocity and absorption of the sound.

The main error in the measurement of the time τ depended on the accuracy with which the start of the transmitted pulse was determined. The associated error in the determination of the sound velocity by the pulse method increased with increasing temperature and with decreasing frequency, and amounted to 0.3–1.5%. The relative measurements of the velocity by the phase method were more accurate, and the maximum error did not exceed 0.3% in this case.

3. DISPERSION OF THE VELOCITY OF SOUND

Measurements of the sound velocity in He II were performed at different degrees of damping of the normal component, making it possible to trace the continuous transition from first to fourth sound. All the experiments were performed with the same filter, and therefore the parameter that changed the degree of damping of the normal component was the frequency of the sound. The measurements were made at 17.5, 26.0, 35.8, 44.5, 71.0, 80.5, 90, 110, and 125 kHz.

Figure 4 shows the temperature dependences of the velocity of sound at only four frequencies, 17.5, 35.8, 71.0, and 125 kHz (the remaining results have been left out so as not to clutter up the figure). At one and the same temperature, the depth of penetration of the viscous wave increases with decreasing oscillator frequency, and according to formula (3) the sound velocity approaches that of fourth sound. Such a transition from first to fourth sound with changing frequency is illustrated more clearly in Fig. 5, where data are presented on the sound velocity in the transition region at temperatures 1.5, 1.7, and 1.9°K. It is clear from the figures that a noticeable dispersion of the velocity of sound in He II arises at temperatures above 1.5°K and becomes stronger on approaching the λ point. However, the measurements of the velocity could not be continued up to the λ point, owing to the strong absorption of the sound.

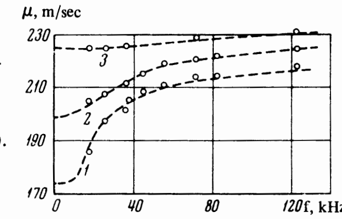

FIG. 5. Dispersion of sound velocity at different temperatures: 1–1.9°K, 2–1.7°K, 3–1.5°K. Dashed–calculation by formula (3).

At temperatures below 1.0°K, the sound velocity at all the investigated frequencies differs little in practice from the velocity of pure fourth sound. In this temperature region, the hydrodynamic analysis is no longer valid[6,8], since the mean free path of the elementary excitations[12] turns out to be much larger than the dimensions of the channel, and this indeed ensures the conditions for realization of the fourth sound.

The velocity of fourth sound in He II at low temperatures differs very little from the velocity of first sound; thus, at a temperature 0.5°K this difference amounts to only 10^{-3}%. This circumstance turned out to be very convenient for an exact determination of the path traversed by the sound wave in the channels of the filter. To this end, the measured sound velocity at 0.5°K was normalized to the exact value of the velocity of the first sound[13] in He^4 at this temperature.

To compare the experimentally obtained data on the sound velocity with the values calculated in accordance with formula (3) it is necessary, as was already indicated, to know the average effective dimension d_{av} of the channels of the filter. The value of d_{av} was determined by normalizing the calculated value of $u_{1\delta}$ to the experimental value at 1.7°K and f = 34.5 kHz. It turned out that d_{av} = 0.92 μ, and this value was then used to calculate $u_{1\delta}$ by means of formula (3) at all frequencies and temperatures. Such a method of comparing experiment with theory makes it possible to evaluate the temperature dependence of $u_{1\delta}$ at 44.5 kHz, and also the frequency dependence of the sound velocity at all the remaining frequencies. The calculated values of $u_{1\delta}$ are shown in Figs. 4 and 5 by dashed lines, and agree well with the experimental results, as can be seen from the figures.

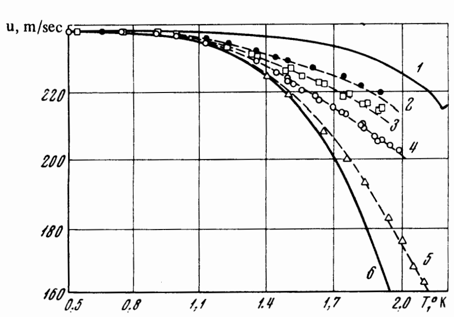

FIG. 4. Temperature dependence of the velocity of sound at different oscillation frequencies: 1–pure first sound, 2–125 kHz, 3–71 kHz, 4–44.5 kHz, 5–17.5 kHz, 6–fourth sound, dashed–calculation by formula (3).

4. TEMPERATURE DEPENDENCE OF SOUND ABSORPTION

The attenuation of the acoustic oscillations in narrow channels filled with helium is due[5,6], first, to volume dissipation connected with second viscosity and thermal conductivity of helium, and second with surface losses due to the slippage of the normal component and heat transfer through the wall. The main contribution to the absorption of sound is made in this case by the losses on the walls, due to the slipping of the normal components[6].

The sound absorption coefficient connected with this mechanism is best expressed, following[6], in terms of the dimensionless parameters a and b, which take into account the degree of deceleration of the normal component:

$$a = \frac{1}{2}\frac{\omega}{u_{1\delta}}\frac{a\rho_n}{\rho - b\rho_n}. \qquad (6)$$

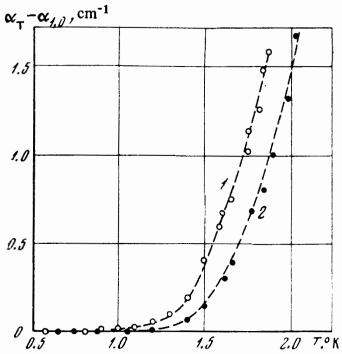

FIG. 6

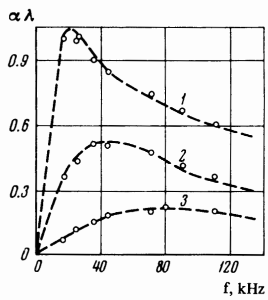

FIG. 7

FIG. 6. Temperature dependence of the difference of the sound absorption coefficients at the running temperature and at T = 1.0°K. 1—71 kHz, 2—35.8 kHz. Dashed—calculation by means of formula (4).

FIG. 7. Absorption of sound at the wavelength as a function of the oscillation frequency: 1—1.9°K, 2—1.7°K, 3—1.5°K. Dashed—calculation in accordance with formula (4).

Formula (4) has been introduced under the assumption that the hydrodynamic case $d \gg l$ is realized (l—characteristic mean free path of the elementary excitations). Therefore, the region of applicability of formula (4) is limited, on the one hand, by low temperatures, where a kinetic analysis is necessary, and on the other hand by temperatures that are not too close to the λ point.

In the present investigation we made only relative measurements of the absorption of sound, by determining the amplitude of the signal, making it possible to establish the temperature dependence of the absorption coefficient α and to compare it with calculation in accordance with formula (4). It turned out that with decreasing temperature, the amplitude of the sound signal first decreases noticeably, and then, starting with ~1.0°K, a certain saturation is reached. The temperature dependence of the absorption of sound was investigated at different frequencies, and its character remained practically unchanged with changing frequency. Typical curves for the frequencies 35.8 and 71 kHz are shown in Fig. 6, where the ordinates represent the difference between the values of α at a certain running temperature and a temperature 1.0°K, and the dashed lines show the values of $\alpha_T - \alpha_{1.0}$, calculated by means of formula (4). The good agreement between the experimental data and the calculated ones show that in the investigated temperature region, when account is taken of the different dissipation mechanisms, it is sufficient to consider only the losses connected with the slippage of the normal component.

Let us call attention to the fact that at 1.0°K the value of the absorption coefficient given by formula (4) is so small, at all the investigated oscillation frequencies, that it does not exceed the errors in the measurement of α. It could therefore be assumed that $\alpha_T - \alpha_{1.0} \approx \alpha_T$, and the values of the absorption coefficient given in Fig. 6, practically coincide with the absolute values of α for the indicated temperatures.

As to the temperatures below 1.0°K, a calculation of the absorption of sound in this region must be carried out with allowance for the interaction of the phonons and rotons with each other and with the walls. Such an analysis was carried out[14] for He II in the region of relatively low sound frequencies, such that $\omega\tau \ll 1$ (τ—characteristic path time of the elementary excitations). In this case the absorption is due to two factors: first, the condition of the elementary excitations with the walls and the transfer of momentum to them, and second, by the fact that when the sound wave propagates the temperature of the gas of the excitations differ from the temperature of the wall and the resultant heat flux decreases the energy of the wave. Unfortunately, the results of the calculation of the absorption performed in[14] are not very suitable for a comparison with the experimental data of the present work, inasmuch as in the calculation of the wall they were assumed to be perfectly smooth and strictly parallel, which greatly overestimates the value of the absorption coefficient.

The elementary data on the absorption of sound are connected with the observed dispersion of sound. In this case, as in the investigation of the velocity (Fig. 3), the most interesting region is that of high temperatures (above 1.5°K), where the dispersion is maximal. Figure 7 shows the values of the absorption coefficient at the sound wavelength $\alpha\lambda$ = Im k/Re k (k—value of the wave vector of the first sound) as a function of the frequency. As expected, the sound absorption due to the slipping of the normal component increases with increasing sound frequency and reaches a maximum when the condition $\delta \sim 1$ is satisfied; with further increase of the frequency, the absorption decreases. With decreasing temperature, the maximum shifts towards higher frequencies, and the value of the maximum itself decreases gradually, thus indicating a weaker dispersion of the sound. As seen from the figure, the frequency dependence of the absorption agrees well with the theory.

Thus, the performed experiments have made it possible to investigate in sufficient detail the features of the propagation of sound in narrow channels filled with He II. The transition from first to fourth sound proceeds via some intermediate region, in which a noticeable dispersion of the sound takes place; this dispersion is connected with the partial damping of the normal component. The dispersion is accompanied, as shown in the paper, by an increase of the sound absorption.

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