EMISSION AND PROPAGATION OF SOUND IN SUPERFLUID He^3—He^4 *SOLUTIONS*

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It is found that a surface with a periodically varying temperature in a superfluid He^3—He^4 solution emits not only second sound but also first sound whose intensity is much greater than the corresponding value for He^4. The temperature dependence of the pressure amplitude in the wave excited in this way is studied; the dependence is in satisfactory agreement with theory.

1. INTRODUCTION

THE propagation of first and second sounds in superfluid solutions diffesr significantly from that in pure He^4. As was shown previously,[1-2] it is important that the oscillations of pressure and temperature in the sound wave produce oscillations of the impurity concentration. This then leads to the result that in the solutions the character of the relative motion of the normal and superfluid components is changed, a stronger coupling is developed between the oscillations of pressure and temperature and, finally, a difference appears in the emission of the sounds. By taking into account the coefficient of thermal expansion of helium, one can generalize somewhat the results of[2] and calculate the amplitudes of the oscillations of different quantities in the sound wave: the velocities v_n and v_s, the pressure P', the temperature T', the entropy σ' and the concentration c'.

It is found that for propagation of first sound in the solution,

$$v_{n1}=\left[1+\frac{\mu\rho}{\rho_n(1-\mu)}\right]v_{s1},$$
$$P_1'=\frac{u_1\rho}{1-\mu}v_{s1},$$
$$T_1'=\frac{\rho_s}{\rho_n}\frac{T}{C_p}\frac{\bar\sigma}{u_1}\frac{\mu+\alpha\rho_n u_1^2/\rho_s\bar\sigma}{1-\mu}v_{s1}, \tag{1}$$
$$\sigma_1'=\frac{\rho_s}{\rho_n}\frac{\sigma}{u_1}\frac{\mu}{1-\mu}v_{s1},\quad c_1'=\frac{\rho_s}{\rho_n}\frac{c}{u_1}\frac{\mu}{1-\mu}v_{s1},$$

and in a wave of second sound,

$$v_{n2}=-\frac{\rho_s}{\rho_n}\frac{1-\mu}{1+\rho_s\mu/\rho_n}v_{s2},\quad P_2'=\frac{\rho_s}{\rho_n}\frac{\rho\mu u_2}{1+\rho_s\mu/\rho_n}v_{s2},$$
$$T_2'=-\frac{\rho_s}{\rho_n}\frac{T}{C_p}\frac{\bar\sigma}{u_2}\frac{1}{1+\rho_s\mu/\rho_n}v_{s2}, \tag{2}$$
$$\sigma_2'=-\frac{\rho_s}{\rho_n}\frac{\sigma}{u_2(1+\rho_s\mu/\rho_n)}v_{s2},\quad c_2'=-\frac{\rho_s}{\rho_n}\frac{c}{u_2(1+\rho_s\mu/\rho_n)}v_{s2},$$

where $\rho = \rho_s + \rho_n$ is the total density of the solution; u_1 and u_2 are the velocities of first and second sounds; α is the coefficient of thermal expansion of the liquid; C_p is the heat capacity of the solution for constant pressure; c the weight concentration of He^3; $\bar\sigma = \sigma - c\partial\sigma/\partial c$, and the parameter μ which enters into all formulas is written in the form

$$\mu=\alpha\bar\sigma\frac{T}{C_p}-\frac{c}{\rho}\frac{\partial\rho}{\partial c}. \tag{3}$$

Formulas (1)—(3) allow us to explain graphically the physical reasons leading to the features enumerated above, which are connected with the sound propagation in the solutions. First, we have the thermal expansion of the liquid which estimates show, however, to be very small, and second, the change in the helium density upon change in concentration.

For these reasons, a coupling arises between the oscillations of pressure and the oscillations of temperature, and is much stronger than in He^4. Temperature oscillations occur in the propagation of first sound, and pressure oscillations greatly exceeding the corresponding values for He^4 occur in second sound.

The peculiarity of solutions also appears in the conditions for sound radiation. If a plate that is impenetrable to the helium is used for the sound source, with periodic change in the temperature, then the conditions at this boundary lead to the simultaneous emission of first and second sounds, the ratio of the intensities of which is

$$\frac{I_1}{I_2}=\frac{\rho_s}{\rho_n}\frac{u_1}{u_2}\mu^2; \tag{4}$$

but if the plate executes mechanical oscillations, then

$$\frac{I_2}{I_1}=\frac{\rho_s}{\rho_n}\frac{u_2}{u_1}\mu^2. \tag{5}$$

As is seen from Eqs. (4) and (5), the ratio of the intensities of the simultaneously emitted first and second sounds is determined to a great degree by the parameter μ. As a consequence, the mechanical method produces in He^4 mainly first sound; second sound is generated by the thermal method. Nevertheless, the effect of simultaneous excitation of both sounds by thermal pulses was observed in He^4[3,4]. In solutions, as estimates show, this effect appears very strongly. The present research was carried out with the purpose of experimentally demonstrating this phenomenon.

2. EXPERIMENTAL PART

In the experiments, we used a cylindrical sound cell of diameter 16 mm and length 40 mm (Fig. 1). A sound radiator was set at one end of the cylinder, in the form of a thin carbon film with a resistance of 80 ohms deposited on a dielectric substrate. A detector of either first or second sound was placed at the other end of the cylinder.

The first sound detector was an ordinary condenser microphone, recording pressure oscillations. The membrane 4 of aluminized lavsan polyester formed the

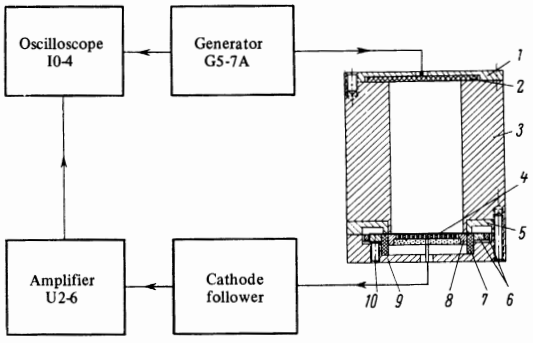

FIG. 1. Drawing of the acoustic cell and block diagram for observation of first sound: 1 – upper cover, 2 – radiator, 3 – housing, 4 – membrane, 5 – mounting collar, 6 – rings, 7 – washer, 8 – electrode, 9 – lower cover, 10 – adjustment screw.

movable element in it. It was 14 microns thick. The tension in the membrane was produced by means of the ring 6 and was regulated by the three screws 10. The second capacitor plate of the pickup was the brass electrode 8 with a large number of apertures, behind which was placed sound absorbing material to decrease the reflection coefficient of the sound wave. The pickup was polarized by a potential of 200 V, and the change of pressure in the sound wave was recorded as the change in capacitance. Because of the difficulty of absolute calibration of the condenser pickups, only relative measurements of the pressure amplitudes were carried out.

As a detector of second sound, we used a phosphor-bronze resistance thermometer made in the shape of a helix of wire of 40 micron diameter. The resistance of the detector at room temperature was ~60 ohms, and the sensitivity to a change in temperature was $R^{-1}dR/dT \approx 0.5\ \text{deg}^{-1}$ in the temperature range 1.4–2.0°K.

To record first and second sound, we used the ordinary pulse method. Video pulses of length 1.6 μsec and amplitude up to 50 V were fed to the radiator at a repetition rate of 100/sec. Here the mean power introduced amounted to $10^{-6}-10^{-4}$ W/cm^2. A block diagram of the apparatus for observation of first sound is shown in Fig. 1. In the study of second sound, only the part of the circuit connected with the detector was somewhat changed. Inasmuch as the detector was fed by long pulses with potentials up to 50 V, an ordinary bridge circuit was used to protect the amplifier against saturation. The mean power taken from the second-sound detector amounted to ~10^{-8} W/cm^2.

Observation of first and second sound, emitted by thermal pulses, was carried out in He^3-He^4 solutions with a weight concentration of He^3 of 4.56 and 8.52%, and also in pure He^4 in the temperature range 1.4–T_λ. It is curious to note that the second sound can propagate in solutions only at a small mean introduced power (not exceeding ~10^{-5} W/cm^2); otherwise, evidently, the equilibrium distribution of impurities in the same fluid is destroyed. In pure He^4, this effect is absent. Therefore, for excitation of second sound in solutions, pulses were used with very low repetition rate. So far as first sound is concerned, in the range of power studied, it was not very sensitive to superheating in the liquid. We also note that the pulse of first sound appeared in He^4 only at powers greater than ~10^{-4} W/cm^2.

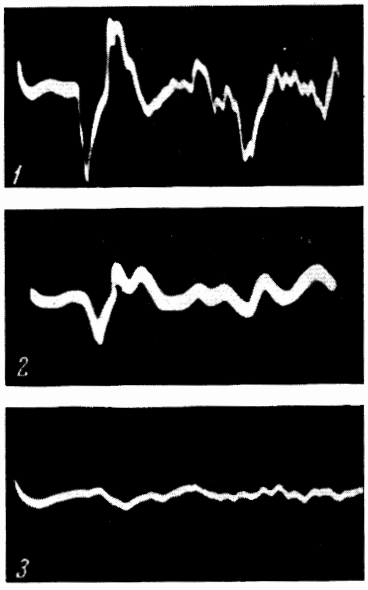

FIG. 2. Oscillograms of pulses of first sound at 1.4°K: 1 – 8.52% He^3, 2 – 4.56% He^3, 3 – He^4.

3. RESULTS AND THEIR DISCUSSION

The experiments that were carried out enabled us to establish the fact that the heater with periodically changing temperature emits first sound of significant intensity, in addition to second sound (in the solutions). The oscillograms of the pulses of first sound excited in this fashion in the two solutions studied are shown in Fig. 2, where an oscillogram referring to He^4 is introduced for comparison. It is quite evident that as the concentration of He^3 decreased, the amplitude of the pulse of first sound fell off, and for He^4, as was to be expected, became very small. For second sound on the other hand, the pulses received in pure He^4 were sharper and more intense.

The fact that the observed pulses correspond to first and second sound can be monitored by measuring the sound speed up to the time of emission of the corresponding pulses. For example, the temperature dependence of the speed of first sound in the 4.56- and 8.52-percent solutions is shown in Fig. 3, while the continuous lines correspond to the literature data.[5] In this same drawing are shown the temperature dependences of the pressure amplitudes P_1' in the wave of first sound for solutions and He^4.

A comparison of the experimentally observed dependence of P_1' with the theoretical predictions can be carried out with account of the boundary conditions at the heater, which require, first, the vanishing of the component of the total liquid flow perpendicular to the plane of the radiator:

$$\rho_s(v_{s1}+v_{s2})+\rho_n(v_{n1}+v_{n2})=0, \tag{6}$$

and second, the uninterrupted character of the heat flow at the boundary, i.e.,

$$q=(\rho\sigma T+Zc)(v_{n1}+v_{n2}), \tag{7}$$

where q is the heat flux released in the heater, and the potential Z is connected with the chemical potentials of He^3 and He^4 in the solution, $Z=\rho(\mu_3-\mu_4)$. The boun-

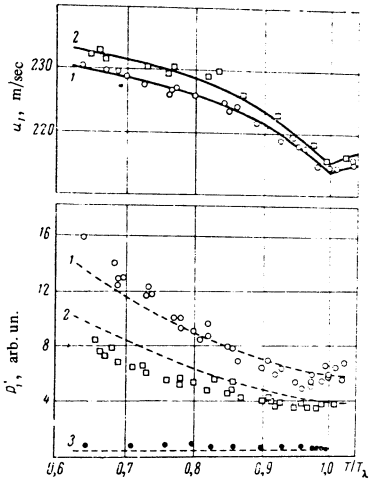

FIG. 3. Temperature dependence of the velocity of first sound and the amplitudes of pressure oscillations in the wave of first sound, excited by the thermal method: 1 – 8.52% He, 4.56% He^3, 3 – He^4. The dashed curves were computed from Eq. (8).

dary conditions (6) and (7), together with the equations of hydrodynamics for superconducting solutions[6] give, in the low-concentration approximation,

$$P_1' = \mu q u_1 / T\sigma. \qquad (8)$$

The values of P_1', computed by Eq. (8), are shown in Fig. 3 by the dashed lines. The "joining" to the experimental data is carried out for the 8.52-percent solution at a temperature of 1.8°K, so that the computed curve for this solution reflects only the temperature dependence of P_1'. Inasmuch as the same normalizing factor was chosen for the 4.56-percent solution and He^4 in the construction of the theoretical curve, such a method of comparison allows us to assess the concentration dependence of P_1', which is also in excellent agreement with experiment.

In conclusion, we note that the effect of simultaneous emission of first and second sound must be considered in the study of absorption of second sound in He^3–He^4 solutions. In this case, at constant power fed to the radiator, that part of the energy which is expended in the generation of second sound will change with the temperature and concentration of the solution.

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