Observation of second-sound-rarefaction shock waves in superfluid helium

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In addition to a second-sound-compression shock wave, a rarefaction shock wave can be observed at distances of the order of several centimeters from the radiator when a short, high-power, thermal pulse propagates in superfluid helium.

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This paper is devoted to an investigation of unique features associated with the propagation of single thermal perturbations in superfluid helium at large distances from the heater at temperatures $T > 1.3$ K. The metallic emitter and bolometer, sputtered on a plane-parallel 2-cm diameter quartz disk, were arranged in the Dewar at separations of $d = 1$ cm (first series of experiments) and 6 cm (second series), i.e., the distance between them was increased by almost two orders of magnitude compared with previous measurements.[1] The emitter area was ~ 2 cm^2 and the area of the superconducting bolometer was 5×10^{-2} cm^2. The bolometer film was sputtered at the center of the disk in order to limit the influence of edge effects. The duration of rectangular electrical pulses fed to the source varied within the interval $\tau = 1$–10 μsec; the power emitted in a pulse was $Q = 0.5$–50 W/cm^2. Typical signal amplitudes recorded by the bolometer were 10^{-4}–10^{-2} K; the signal duration was tens of microseconds, and the time resolution of the recording apparatus (bolometer, external electrical circuit) was better than 0.5 μsec. In the first series of experiments we monitored the variation in the pulse shape with the variation in temperature and power in the direct transit between the source and the bolometer and as a result of multiple reflections of the pulse from the surface of the disks (Figs. 1a and 1b). In the second series of experiments, where the source-bolometer spacing exceeded the disk diameter by several factors, our investigations were limited to observations of the primary pulse [(Figs. 2(a) and 2(b)].

The main results of the measurements are as follows. For $d = 1$ cm, irrespective of τ and Q after the heating wave ($\Delta T > 0$) the bolometer records the arrival of a more extended cooling wave ($\Delta T < 0$), where amplitude is comparable in order of magnitude to that of the heating wave. Here ΔT is the temperature difference between the bolo-

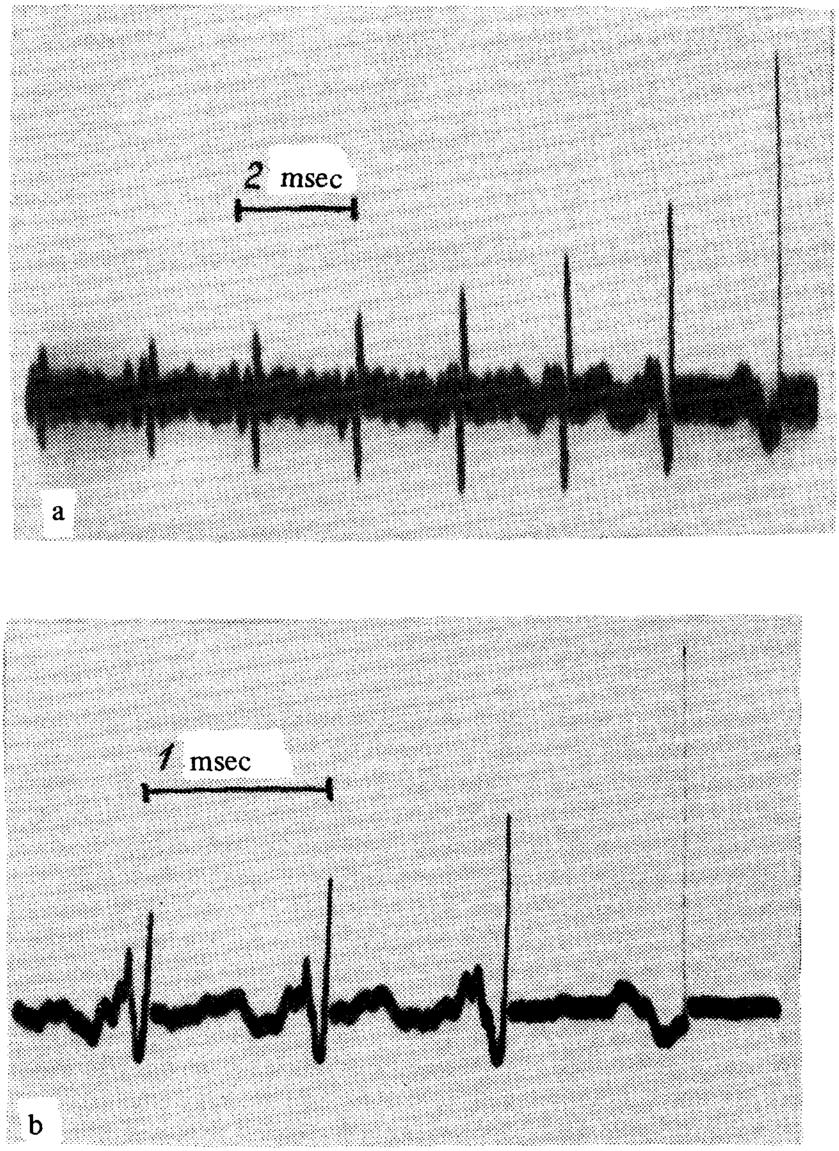

FIG. 1. Oscillograms of the pulses recorded in the cell with a gap $d = 1$ cm at $T = 2$ K(a), and $T = 1.5$ K(b); $\tau = 10$ μsec, $Q = 4\text{W/cm}^2$.

meter and the helium bath. The difference in the amplitudes of the waves with an opposite sign can be greatly reduced for the same Q [Fig. 2a] by increasing the separation to $d = 6$ cm. After the pulse is reflected from the walls of a narrow cell, the amplitudes and durations of the waves with an opposite sign will be equal in magnitude after 2–5 reflections (the total path length of the pulse in the helium is 5–10 cm), i.e., the multiple reflection in first approximation is equivalent to increasing the spac-

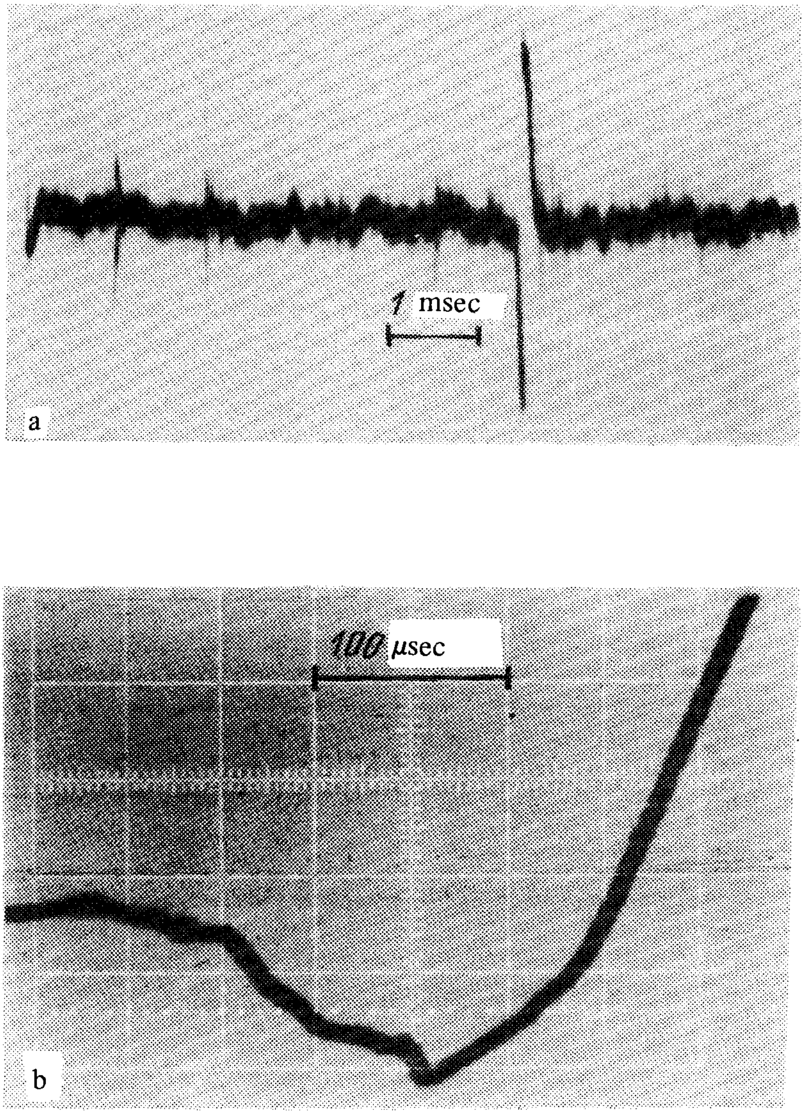

FIG. 2. Oscillograms of the pulses recorded in the cell with a gap $d = 6$ cm for $T = 2.1$ K(a) and $T = 1.4$ K(b); $\tau = 10$ μsec, $Q = 4 \mathrm{W/cm}^2$.

ing d. In both series of experiments the recorded waves with a positive polarity had the form of right triangles whose orientation relative to the time of the pulse emission depended on the temperature: for $T > 1.87$ K the wave amplitude increased linearly with time [Fig. 2(a)], and for $T < 1.87$ K the pulse front was almost perpendicular [Figs. 1(b) and 2(b)]. The shape of the negative-polarity wave also changed accordingly.

We shall briefly discuss the results of observation. It is known[2] that the thermal perturbations in superfluid He II are transported by waves of second should at temperature above 1 K. In the propagation of a second-sound wave, just as in the propagation of normal sound waves in condensed media, the shock waves can appear in helium[3–5] at relatively large distance from the source. The profile of the traveling temperature wave in helium becomes distorted because of the amplitude dependence of the velocity C_2 of the second-sound wave. According to theoretical calculations,[4] $C_2 \approx C_{20} + \tau_2 Q/ST$ in first approximation in the case of propagation of a one-dimensional plane wave of second sound in an infinite medium, where C_{20} is the equilibrium (acoustic) velocity, τ_2 is a temperature-dependent numerical parameter, and S is the entropy of a unit volume of helium. The velocity of the second-sound shock wave-temperature discontinuity in He II, just as the velocity of a normal shock wave, is equal to the average of the velocities C_2 on both sides of the discontinuity, but, in contrast to the normal sound where the shock wave always occurs at the leading edge, the discontinuity in He II occurs either at the leading edge or the trailing edge of the wave, since the parameter $\tau_2 > 0$ (just as in normal media) for temperatures $1.87 > T > 0.95$ K and is negative for $T < 1.87$ K.[4,6]

In the case of ordinary sound for plane wavefronts the sound pulse with a shock wave, regardless of the shape of the emitted pulse, has a triangular velocity profile whose area remains constant when the distance x from the source is increased.[7] We have also observed the appearance of such profiles previously[1] when the spacing d between the source and the bolometer was much less than the diameters of the disks forming the measurement cell. In the present experiments d is comparable to or several times greater than the disk diameter, so that the profile of the leading edge of the emitted pulse is closer to spherical, especially for $d = 6$ cm. The spherical profile differs significantly from the plane profile. Landau[7] showed that a rarefaction wave appears behind the compression wave at large distances from a source of acoustic spherical waves. This is attributable to the fact that the area of the wavefront increases proportionally to r^2 (r is the distance to source), whereas the velocity amplitudes of particles in the wave decreases $\sim 1/r$. Therefore, if the amount of matter in the wave is to remain constant, an increase in the amount of matter in the compression wave must be compensated for by rarefying the region behind it.

A similar argument applied to the waves of second sound, whose propagation is described by the equation $\partial^2\psi/\partial t^2 = C^2_2\, \Delta\psi$, where the quantity ψ is associated with the variation of the temperature and velocity of the superfluid and normal components: $\delta T = -\partial\psi/\partial t, \mathbf{p}/S = \nabla\psi$. Here $\mathbf{p} = \rho_n(\mathbf{v}_s - \mathbf{v}_n)$ is the momentum of the relative motion and S is the entropy. As in the case of density waves, the momentum amplitude of the relative motion is $\mathbf{p} \sim 1/r$ at large distances from the source of acoustic temperature waves. Therefore, to preserve the entropy flux $\sim 4\pi r^2 \mathbf{p}$ we must compensate for the increase of the normal component in the heating wave by its flow from the region behind the heating wave; this leads to the formation of a cooling wave in this region. Such effect—the propagation in helium of a warm front followed by a cold front from a cylindrical heater—was observed in Ref. 8 by using optical methods (from the variation the refractive index of a liquid in a wave).

Just as in ordinary spherical shock waves (see Ref. 7, Fig. 68), the distortion of the profile of a temperature acoustic wave at large distances ultimately leads to formation of two shock waves: one in the condensation region ($\Delta T > 0$), and the other in the rarefaction region ($\Delta T < 0$). The temperature increases suddely in the leading shock wave; this is followed by a region of gradual temperature decrease, which is replaced by a rarefaction. Then the temperature suddenly increases in the second discontinuity (a rarefaction shock wave in the terminology of Landau and Lifshitz [7], but below its unperturbed value, which is approached asymptotically behind the second discontinuity.[7] The shape of the experimentally observed profiles for $\tau_2 > 0$ [see Fig. 2(b)] corresponds to the qualitative description given above. The sudden temperature rise in the rarefaction wave and the subsequent gradual temperature rise are also traced on the oscillograms of the reflected pulses in the narrow cell. We can see from our measurements that the shock waves of second sound at a power $Q \geqslant 1$ W/cm^2 appear in helium at distances $\leqslant 1$ cm. The rarefaction waves, as a rule, are flatter; it is clear that for appearance of rarefaction shock waves at the same Q, we must have much longer path lengths, and to detect them, we must use short, perturbing pulses and small-area sources.

In addition to dependence of the velocity C_2 on the amplitude and the need to allow for the profile curvature of the emitted pulse as possible causes of the compression and rarefaction shock waves produced during the propagation of a short thermal pulse in helium, we should also mention the temperature discontinuity at the solid-liquid boundary,[5] the appearance of gas bubbles at the surface for large Q, and nonlinearities on the profile of the traveling shock wave; however, these corrections are probably small in our experiments. Although a shock wave can appear spontaneously at some instant of time, it cannot disappear in the same manner, but rather dampens asymptotically in infinite time.[7] For example, the reflected pulses in a cell with $d = 1$ can easily be detected 25 msec after the emission of a 1-μsec pulse. This may be the cause of the variation in the ratio of the amplitudes of the waves of opposite sign and the long-period temperature oscillations that were observed in the narrow cells.

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[1] A.Yu. Iznankin and L.P. Mezhov-Deglin, Pis'ma Zh. Eksp. Teor. Fiz. **29**, 755 (1979) [JETP Lett. **29**, 693 (1979)].

[2] V.P. Peshkov, Zh. Eksp. Teor. Fiz. **18**, 857 (1948).

[3] D.V. Osborne, Proc. Phys. Soc. London A**64**, 114 (1951).

[4] I.M. Khalatnikov, Teoriya sverkhtekuchesti (Theory of Superfluidity), Nauka, Moscow, 1971.

[5] S. Putterman, Gidrodinamika sverkhtekuchei zhidkosti (Hydrodynamics of a Superfluid Liquid), Mir, Moscow, 1978.

[6] A.J. Dessler and W.M. Fairbank, Phys. Rev. **104**, 6 (1956).

[7] L.D. Landau and E.M. Lifshitz, Mekhanika sploshnykh sred (Mechanics of Continuous Media), Moscow, 1953.

[8] A.I. Gulyaev, Zh. Eskp. Teor. Fiz. **59**, 59 (1969) [Sov. Phys. JETP **32**, 34 (1971)].