Propagation of nonlinear waves of first sound in liquid helium

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It was determined that the pulses of first sound, [Kabetskaya *et al.* Sov. Phys. Dokl. **24**, 37 (1979)] which was excited in liquid helium by optical pumping of germanium, are low-intensity shock waves. The velocity of the sound pulse as a function of its amplitude was measured.

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It was reported earlier[1] that pulses of first and second sound can be excited in He II by pulsed optical pumping of a germanium crystal immersed in the liquid helium. The appearance of sound pulses has a threshold nature in pumping intensity; the relative change of the liquid density in the pulse of first sound was 10^{-2}–10^{-3}, and it extended for a distance $\lesssim 50\,\mu$m. We have investigated the dependence of the propagation velocity of the pulse of first sound on its amplitude at $T = 1.76$ K and at saturating vapor pressure. It is shown that the velocity increases linearly with increasing pulse amplitude, and for pulses of maximum amplitude it exceeds the velocity of first sound by about 1.5%. The results obtained make it possible to assume that in our experiments we are observing low-intensity shock waves of first sound[2] with Mach numbers $M < 1.02$. It should be noted that the nonlinear effects in the propagation of waves of first sound in liquid helium have not been investigated in detail. We are aware

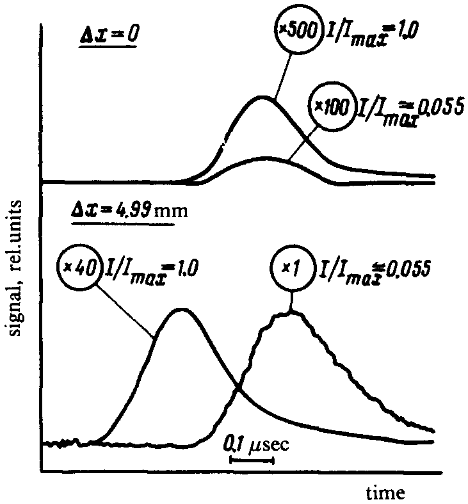

FIG. 1. Traces of diffraction signals for different pumping intensities.

of only one study[3] in which a cryogenic shock tube was used to excite the shock waves with $M = 1.10$–1.13.

The geometry of our experiments is shown in the upper right corner of Fig. 2. The exciting radiation of a molecular nitrogen laser (radiation wavelength $\approx 0.34\ \mu$m, ~ 10-nsec, pulse 50-Hz repetition frequency, maximum energy $I_{\text{max}} = 120$ ergs/pulse) was focused into $\approx$4-mm-diam spot on the surface of a 10-mm-diam germanium disk. The sound pulses propagated from the excited crystal surface and, after passing through the probing laser pulse, caused a diffraction of the probing radiation because of the difference in the optical densities of the excited and unexcited helium. A CW He-Ne laser with 0.63-μm wavelength was used as the source of probing radiation. The probing beam with a diameter of $\approx 100\ \mu$m traveled parallel to the excited surface at a specified distance from it.

The diffracted radiation was collected on the photocathode of a photomultiplier by means of a lens. The electrical pulse, whose amplitude was proportion to the energy of the sound pulse, was sampled and traced on an x-y recorder. The time constant of the recording system was $\approx$20 nsec.

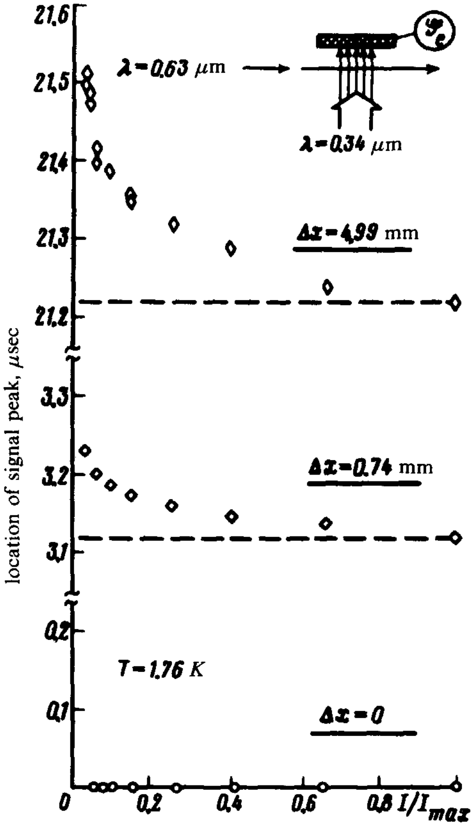

FIG. 2. Dependence of the propagation time of sound pulses on the pumping level.

The traces of the recorded signals for two different excitation intensities are shown in Fig. 1 for two positions of the probing beam relative to the sample surface. The traces in the upper part of the figure correspond to a distance of 80–100 μm between the sample and the light probe; in this case the time position of the pulses corresponding to different pumping intensity is almost indentical, i.e., the sound pulses of different amplitudes transverse the distance between the sample and the laser beam in identical time intervals within the time-resolution accuracy of the instrumentation. The signal traces for a displacement of the probing beam by $\Delta x = 4.99 \pm 0.01$ mm from the original position are shown in the lower half of Fig. 1. The origin of the trace in this case is shifted by 21.42 μsec with respect to its initial location with an accuracy of ≈ 0.01 μsec. We can see that the larger amplitude sound pulse propagates with a higher velocity and reaches the light probe faster.

The experimental results are summarized in Fig. 2, in which the propagation time of the sound pulses over distances $\Delta x = 0.74$ mm and $\Delta x = 4.99$ mm is shown for different pumping intensities: the propagation velocity of sound pulses increases monotonically with increasing pumping level. The data shown in Fig. 2 were obtained by measuring the propagation time of the sound pulses with respect to the location of the maximum of the pulse signal. However, the recorded pulse shape, which is almost independent of the pumping level and propagating time of the sound pulse, reflects the intensity distribution in the probing laser beam (the spatial extent of the sound pulse is less than the diameter of the light probe). Therefore, the same results were obtained by determining the time relative to the other points of the pulse signal, for example, relative to the time position of the leading edge of the pulse, which is located at its half-height.

For pulses with a minimum amplitude which still can be reliably recorded (pumping intensity $I \approx 0.037 I_{\max}$), the average propagation velocity in the region from

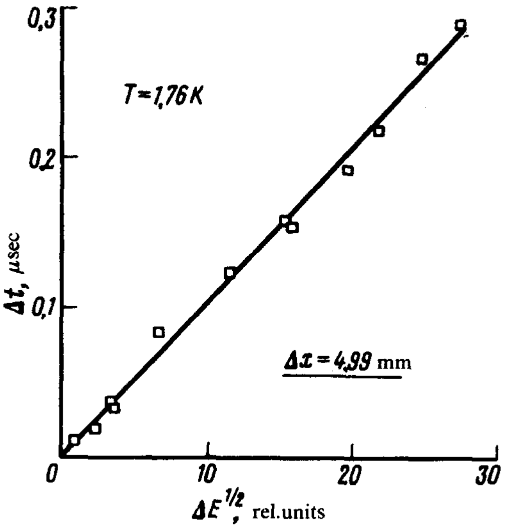

FIG. 3. Dependence of Δt on the noise pulse amplitude.

$\Delta x = 0.74$ to $\Delta x = 4.99$ mm was $(2.32 \pm 0.01)\times 10^4$ cm/sec, in good agreement with the known sound velocity.[4–6]

The propagation velocity of a weak density (pressure) shock wave is determined by the expression[2]:

$$u_1 = u_{10}\left[1 + \frac{1}{2}\Delta\rho\,\frac{\partial}{\partial\rho}\ln(\rho\,u_{10})\right], \tag{1}$$

where ρ is the density of the liquid, $\Delta\rho$ is the amplitude of the density perturbation, and u_{10} is the velocity of first sound $\Delta\rho\to 0$. When two sound pulses with amplitudes $\Delta\rho$ and $\Delta\rho_0$ propagate a distance Δx, the difference in their propagation time will be $\Delta t = (t_0 - t)\sim(\Delta\rho - \Delta\rho_0)$, if $u_1 - u_{10} \ll u_{10}$. In our case $\Delta\rho\sim E^{1/2}$, where E is the signal amplitude and $\Delta t\sim\Delta E^{1/2} = E^{1/2} - E^{1/2}{}_0$ (E_0 is the amplitude of the minimum recordable signal). Experiment yields a similar result (Fig. 3). The average propagation velocity of the maximum-amplitude sound pulses was $(2.35 \pm 0.01)\times 10^4$ cm/sec. We shall estimate the relative perturbation of the density of the liquid in the maximum-amplitude sound pulse. To do this, we rewrite Eq. (1) in the form

$$\frac{\Delta\rho}{\rho} = 2\,\frac{u_1 - u_{10}}{u_{10}}\left(1 + \frac{\rho}{u_{10}}\,\frac{\partial u_{10}}{\partial\rho}\right)^{-1}.$$

If $\frac{\rho}{u_{10}}\frac{\partial u_{10}}{\partial\rho}\approx 3$ (Ref. 6), we obtain $\Delta\rho/\rho\approx 0.007$, in good agreement with the estimate of Ref. 1 obtained from measurements of the diffracted light intensity.

Similar results were obtained when other semiconductor crystals (Si, GaAs, GaSe, GeS) and also a copper foil were excited: the pulses of first sound, whose velocity increased with increasing amplitude according to the propagation theory of weak shock waves, in this case were generated in the helium.

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