Transmission of short, strong thermal pulses through liquid helium

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The relaxation of pulse perturbations in liquid helium was investigated. The width of the recorded pulses of the second sound increases with increasing amplitude of the ~1–μsec exciting thermal pulse; at $T < 1.87$ K the leading edge of the pulse is shifted and at $T > 1.87$ the pulse decreases while its leading edge remains almost stationary. At $T_\lambda - T < 0.2$ K and $T > T_\lambda + 0.2$ K the propagation of the pulses of the first sound can be recorded. The arrival in the receiver of the pulse of the first sound in He II corresponds to a decrease of the temperature and its arrival in He I corresponds to an increase in the temperature, i.e., in both cases a compression wave propagates from the heater in the liquid.

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We investigated the relaxation of short thermal perturbations in helium in a narrow cell with plane-parallel walls at helium-bath temperatures of 1.3–3 K. In most of the experiments described in the literature[1] the duration of the exciting pulses comprised tens and hundreds of microseconds and the typical distances between the source and the receiver were centimeters. We worked primarily with microsecond pulses and millimeter distances. The pulse strength was varied in the interval $Q = 0.5$–$50\ \mathrm{W/cm^2}$. Thin bismuth and indium films ($1\ \mathrm{cm^2}$ in area and 10^{-4} cm in thickness), which were sputtered on polished quartz glass discs, served as the source of thermal perturbations and as the receiver (bolometer). The gap between the discs was 0.6 mm (first cell) and 3 mm (second cell). The first cell, which had spacers between the discs made from copper strips, was open at both ends. The second cell had a ring made from polished quartz whose inner walls were lined with a layer of material to reduce the reflection from the side surface. Helium was admitted into the cell through two 1-mm holes in the ring. The electric square pulse fed to the heater simultaneously triggered the time scanning circuit of the stroboscopic integrator which was connected to an X-Y recorder. The external electric circuit made it possible to record the temperature pulses with an amplitude $\geqslant 10^{-4}$ and a rise time $\geqslant 0.3\ \mu\mathrm{sec}$.

In superfluid helium the heat from the heater is transferred primarily by waves of the second sound.[2,3] It was found that the width of the recorded pulse of the second sound increases with increasing amplitude of the investigated microsecond pulse; moreover, at bath temperatures $T < 1.87$ K the broadening occurs largely due to the shift of the wave front and at $T > 1.87$ K it occurs due to the shift of the decay when the wave front is almost stationary. Figure 1a shows the dependence of the shape of the incoming pulse of the second sound on the strength of the 0.5-μsec exciting pulse. The maximum amplitude of the signal is $\leqslant 10^{-2}$ K.

The observed behavior can be explained in terms of the theory of motion of the temperature waves of finite amplitude in HeII, which was developed by Khalatnikov.[2] The velocity of the finite-amplitude wave of the second sound ΔT is connected with the acoustical velocity c_{20} by the relation

$$c_2 = c_{20}\left[1 + \frac{\Delta T}{2}\frac{\partial}{\partial T}\ln\left(c_{20}^3\frac{\partial S}{\partial T}\right)\right]$$

or by $c_2 \sim c_{20} + \tau Q/\rho ST$, where the coefficient $\tau = (TS/C_V)\,\partial/\partial T \times [\ln(c_{20}^3\, C_V/T)]$ can be both positive ($1 < T < 1.9$ K) and negative ($T > 1.9$ K), depending on the temperature. Here C_V is the specific heat, S is the entropy of the unit mass, and ρ is the density of helium. Thus, the thermal perturbations of large amplitude can overtake or lag behind a wave of small amplitude, which leads to a distortion of the shape of the wave of finite amplitude and to formation of a shock wave at sufficiently large path lengths, depending on the temperature of the helium bath at the wave front or at the decay of the pulse. The nonlinear acoustics of superfluid helium was investigated in detail in Nemirovskiĭ thesis.[4] The formation of shock waves of the second sound was observed for the first time by Osborne[5]; subsequent investigations were described in Refs. 6–8. The observation of shock waves requires fairly large power and space. As our further experiments showed, the width of the recorded pulse depended weakly on the power when the pulsed time was increased to 10 μsec, i.e., to observe the nonlinear effects, the distance between the source and the receiver also had to be greatly increased.

Since the damping of the pulses of the second sound in helium is small, we were

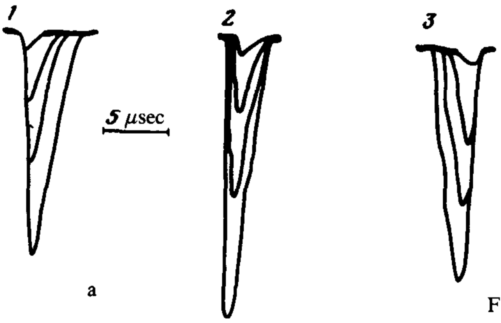

FIG. 1a. Dependence of the pulse width of the second sound on the strength of the 0.5-μsec square pulse in the cell with a 3-mm gap; $T = 1.95$, 1.87, and 1.35 K (1, 2, and 3, respectively): $Q = 1.5$, 8, and 20 W/cm^2).

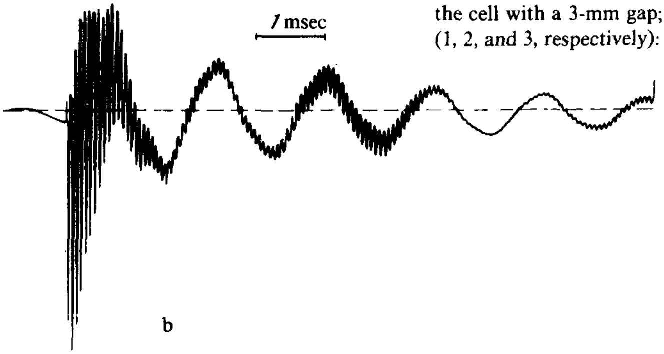

FIG. 1b. Long-period temperature oscillations in the narrow cell $T = 1.6$ K and $Q = 30$ W/cm^2.

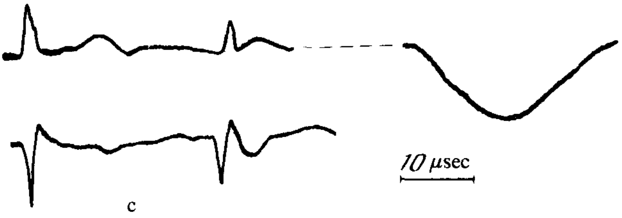

FIG. 1c. The main and reflected pulses of the first sound and the pulse of the second sound in He II at $T = 2.12$ K; the pulses of the first sound in He I and $T = 2.6$ K; the gap is 3 mm and $Q = 8$ W/cm^2.

able to record scores of pulses which were reflected from the walls of the cell. As the strength of the pulse in both cells increased, long-period temperature oscillations (with ~2-msec period), which dampened in about 10 msec, were observed against the background of multiply scattered pulses of the second sound. Although the nature of these oscillations has not been uniquely determined, they are apparently attributable to formation of coupled oscillations in the measuring cell (open cavity)-helium dewar system. Figure 1b shows the recorded oscillations in the first cell at $T = 1.6$ K and $Q = 30$ W/cm^2 and a 0.5-μsec pulse.

In addition to the pulses of the second sound at $T_\lambda - T < 0.2$ K and in normal helium at $T > T_\lambda + 0.2$ K, the bolometer recorded the incoming thermal pulses moving at the velocity of the first sound. The upper part of Fig. 1c shows the arrival of the main and reflected pulses of the first sound and further the wide pulse of the second sound at $T = 2.12$ K and the lower part shows the recorded temperature oscillations in HeI at $T = 2.6$ K. The amplitude of the wave of the first sound in HeII is approximately the same and opposite in direction as that of HeI, i.e., the arrival of the pulse of the first sound in HeII corresponds to cooling (the pulse has a negative polarity relative to the second sound) and its arrival in HeI corresponds to heating. The change in polarity of the pulses corresponds to the change in the sign of the coefficient of thermal expansion of liquid helium α as a result of transition from HeII ($\alpha < 0$) to HeI. Since $(\partial T/\partial P)_S = TV_\alpha / C_P$, where V is the molecular volume, a compression wave, which moves at the velocity of ordinary first sound in liquid, propagates from the heater both in HeI and HeII. The compression waves in HeII were also observed in Refs. 7 and 9. The formation of these waves can be attributed to pulse overheating of the liquid to a much higher temperature than T_λ in a thin layer near the heater or to the formation of bubbles at the surface at $Q > 1$ W/cm^2.

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