Electron sound in metals

N. G. Burma, E. Yu. Deĭneka, and V. D. Fil'
Physicotechnical Institute of Low Temperatures, Academy of Sciences of the Ukrainian SSR

(Submitted 10 May 1989)
Pis'ma Zh. Eksp. Teor. Fiz. **50**, No. 1, 18–21 (10 July 1989)

A propagation of signals at the Fermi velocity has been observed in samples of ultrapure gallium. The effect is interpreted as a manifestation of vibrations of a zero-sound type.

Although the possible existence of collective vibrations of a zero-sound type in a charged Fermi liquid was pointed out more than 30 years ago,[1] these vibrations have yet to be found. Some skepticism has naturally arisen with regard to the theory of the effect.[2] Furthermore, second-sound vibrations,[3] which could propagate in charge-neutral metals, have not been found.

In our experiments we have observed a propagation of signals at velocities on the order of the Fermi velocity in samples of ultrapure gallium. These signals were excited by a longitudinal sound wave of relatively low frequency ($\omega/2\pi = 50$–200 MHz). We believe that the behavior of these signals is a fairly certain indication that they should be classified as zero-sound waves.

Figure 1 is a simplified diagram of the experimental arrangement. The thicknesses of the test samples were $L \sim 2.5$–5 mm; the length of the envelope of the rf pulses was 0.5–1 μs; and the delay in the delay line was $t_{\rm del} \sim 2\ \mu$s (so that all of the signals could be reliably separated in time). Signal A represents a penetration of some of the energy of the exciting rf pulse to the receiver input; signal C is an acoustic signal which has passed through the delay line and the sample. The time of arrival of signal B is essentially equal to $t_{\rm del}$, implying (a) that signal B has passed through the sample at a velocity well above the sound velocity or (b) that it has completely bypassed the sample, as a result of stray pickup due to an imperfect grounding of the sample during the transformation of the elastic wave into an electromagnetic signal at the interface of the sample with the delay line. The latter possibility might be the sole cause of a possible artifact. We accordingly took a serious look at the question in order to rule out this possibility. Signal B retained an amplitude U_B essentially unchanged with respect to that of signal C when yet another delay line was inserted, on the other side of the sample. In case (b) the conversion should have occurred twice (sound to electromagnetic signal to sound), and U_B should have been reduced substantially because of the low conversion coefficient. Furthermore, signal B (like C) was absent when a transverse cut was placed in the path of the sound beam in the sample.

Here are the basic properties of signal B:

1. The shape of the envelope of signal B is essentially the same as those of signals A and C.

2. The velocity v_B was estimated by comparing the delay of signal B with respect to the sound propagation time in delay line DLII, which was identical to DLI (Fig.

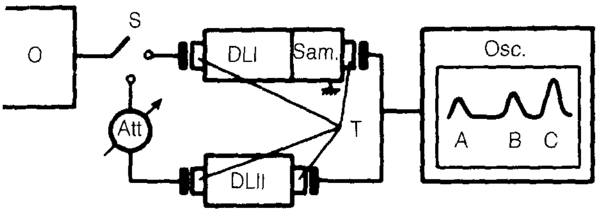

FIG. 1. Experimental layout. O—Oscillator; S—switch; Att—attenuator; T—piezoelectric transducers; DL—delay lines; Sam.—sample; Osc.—Oscilloscope.

1). We found $v_B = (1.8 \pm 0.9) \times 10^7$ cm/s; this figure was independent of the frequency within the error of the estimates.

3. With regard to the conditions for the existence of this signal, note the temperature dependence of U_B and v_B in Fig. 2 ($\Delta v_B / v_B$ was measured by a phase method which required knowledge of the absolute value of v_B for the generation of numerical values; the relative accuracy of $\Delta v_B / v_B$ is thus the same as that of the estimate of v_B). Signal B appears at liquid-helium temperatures and decreases below T_c. The pulse relaxation time τ in our samples in the temperature interval 4.2–1.7 K varied from 2×10^{-9} s to 6×10^{-9} s, so a necessary condition for the existence of the signal seems to be the relation $\omega\tau \gg 1$.

4. Figure 3 shows the dependence on a magnetic field H. In weak fields there are some fairly large variations in U_B, which may be a consequence of geometric-resonance effects. A more important point, however, is that signal B exists over the field range from $H = 0$ to at least 15 kOe. A deviation of **H** from the direction perpendicu-

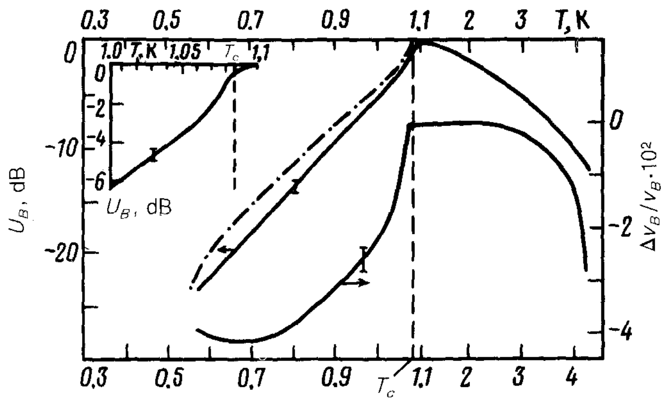

FIG. 2. $U_B(T)$ and $\Delta v_B / v_B(T)$. $H = 0$, $\mathbf{q} \| \mathbf{b}$, $\omega / 2\pi = 50$ MHz. Here T_c is the superconducting transition temperature. The T scales are different to the left and right of T_c. Dot-dashed line—theoretical curve of $\alpha_s(T)$; inset–$U_B(T)$ near T_c.

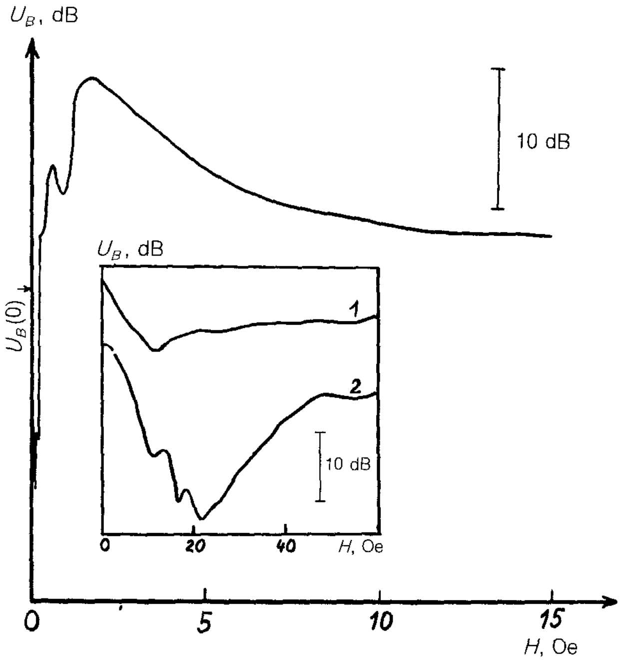

FIG. 3. $U_B(H)$. $L = 3.7$ mm, $\mathbf{q}\|\mathbf{b}$, $\mathbf{H}\|\mathbf{c}$, $\omega/2\pi = 150$ MHz. The inset shows the weak-field region. 1–50 MHz; 2–150 MHz.

lar to the sound wave vector $\mathbf{q}$ does not cause any substantial changes, although the oscillatory effects disappear at small values of H in the case $\mathbf{H}\|\mathbf{q}$.

5. The maximum value of U_B at $L = 3.7$ mm is 60–65 dB below the level of the exciting signal. On the other hand, U_B is essentially unrelated to U_C; in particular, under conditions corresponding to the deviation effect we can find $U_B > U_C$. This circumstance, combined with property 1, is unambiguous evidence that the direct and inverse conversion of the elastic energy into signal B occur at the boundaries of the sample, probably over the length of the sound wave.

6. With regard to the attenuation Γ, we can assume that U_B is described by the expression $U_B \sim K^2 \exp(-\Gamma L)$, where K is the conversion coefficient. The possibility of using a representation of this sort is indicated by the circumstance that the temperature-induced changes in $\log U_B$, measured at the same frequency in samples of different thicknesses, are proportional to L. A comparison of U_B in samples of various thicknesses under the assumption that their electronic characteristics are identical yielded an estimate of Γ. For $\omega/2\pi = 50$ MHz at $T = 1.7$ K and $H = 0$ we found $\Gamma \sim 6$ cm^{-1}. On the whole, the ratio of the real part (ω/v_B) and the imaginary part of the wave vector (~ 3) can be judged to be close to $\omega\tau(\sim 2)$, since τ was found from a different physical effect (the change in the sound velocity in a strong field in the orientation $\mathbf{H}\perp\mathbf{q}$).

The Fermi-range values of v_B indicate that signal B is of electronic origin. That it can be excited and received by means of piezoelectric transducers indicates a significant coupling of the wave with the lattice, at least at the boundaries of the sample. We believe that the physical nature of signal B is the same in the case $H=0$ and in a strong field $\mathbf{H}\perp\mathbf{q}$, since neither the amplitude nor the phase velocity of the signal changes substantially upon a change in H. It is thus understandable that no ballistic effects of the quasiwave type discussed in Ref. 4 could explain the propagation of a signal at a Fermi velocity in our case. Second-sound waves[3] exist under the condition $\omega\tau_N \ll 1$ (τ_N^{-1} is the rate of normal collisions); this relation is at odds with property 3. We are left with the assumption that signal B represents either zero sound or a transitional region from second sound to zero sound. As we know, the existence of acoustic vibrations in a charged Fermi liquid is possible if the coefficients X_n ($n>1$) of the expansion of the nonequilibrium distribution function in spherical harmonics are sufficiently large.[2] We note in this connection that in a neutral metal the values of X_n corresponding to in-phase vibrations of the electron and hole components may be accentuated. Note also that a uniaxial deformation could not disrupt the neutrality by altering the density of charge carriers, and elastic forces are conjugates of the required distortions of the distribution function; the effect is to promote the excitation of zero sound.

To the best of our knowledge, there has been no theoretical work on the influence of a superconducting order on electron sound, so all we can do is invoke the analogy with superfluid He^3. The experiments of Ref. 5 and the calculations of Ref. 6 indicate that the attenuation of zero sound depends only weakly on the temperature except in a narrow vicinity of T_c and that the velocity decreases to values characteristic of first sound (the difference is $\sim 5\%$). Surprisingly, v_B behaves in an extremely similar way. In a superconductor there is no reason to expect significant changes in the attenuation of a zero sound, and the entire evolution of U_B would apparently be associated with a change in K, which is determined by the force of the interaction of the elastic wave with the electrons and which is proportional to the sound attenuation $\alpha_s^{1/2}$. Figure 2 shows, in the same logarithmic scale, the BCS behavior of α_s, which agrees fairly well with the behavior of U_B [the agreement can be improved by adjusting the value of the energy gap $\Delta(0)$].

It is clear from the discussion above that neither the quality of the samples nor the experimental procedure must meet any extremely severe requirements for signal B to be observable. The circumstance which was of the greatest help in making this signal observable was an unconventional combination of a long sample, which made it possible to distinguish a fast signal from an acoustic signal, with a delay line, which separated the fast signal from parasitic pickup.

We wish to thank E. V. Bezuglyĭ, R. N. Gurzhi, A. I. Kopeliovuich, and V. G. Peschanskiĭ for useful discussions.

After this paper was written, Ya. B. Bazaliĭ called our attention to an earlier paper {L. P. Gor'kov and I. E. Dzyaloshinskiĭ, Zh. Eksp. Teor. Fiz. **44**, *1650 (1963) [Sov. Phys. JETP* **17**, *1111 (1963)]}, of which we had, unfortunately, been unaware. In that earlier paper, the conditions for the existence of zero sound in a real anisotropic metal were analyzed. The primary conclusion reached there was that zero sound should exist* *in metals even with a relatively weak Fermi-liquid interaction (1) during the propagation of a wave along a symmetry element and (2) if the momenta of electrons having the maximum velocity projection onto the propagation direction do not belong to any of the symmetry elements of the symmetry group of the crystal. The experimental geometry and Fermi surface of gallium correspond to these conditions.*

[1] V. P. Silin, Zh. Eksp. Teor. Fiz. **35**, 1243 (1958) [Sov. Phys. JETP **8**, 870 (1959)].
[2] A. A. Abrikosov, *Basic Theory of Metals*, Nauka, Moscow, 1987.
[3] R. N. Gurzhi and V. M. Kontorovich, Zh. Eksp. Teor. Fiz. **55**, 1105 (1968) [Sov. Phys. JETP **28**, 577 (1969)].
[4] M. I. Kaganov, Usp. Fiz. Nauk **145**, 507 (1985) [Sov. Phys. Usp. **28**, 257 (1985)].
[5] G. C. Wheatley, Physica **69**, 218 (1973).
[6] P. Wölfle, Phys. Rev. Lett. **30**, 1169 (1973); **31**, 1437 (1973).

Translated by Dave Parsons