Possibility of existence of electronic sound waves in superconductors

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It is shown that electronic oscillations of the acoustic type, with finite amplitude, are possible in a superconductor at $T \sim T_c$, although the small-amplitude oscillations attenuate strongly. The velocity of such sound is on the order of the Fermi velocity and depends little on the temperature.

A superconductor at finite temperatures is a two-component system consisting of a superconducting condensate and normal excitations. One could expect the existence of oscillations of the acoustic type in a pure superconductor. During the course of such oscillations, the superfluid component executes wave motion as a result of the unique rigidity of the condensate (which ensures the onset of Bogolyubov sound in a neutral Fermi gas[1]). The normal component, on the other hand, moves without collisions in phase opposition to the superfluid component, so that the quasineutrality condition is satisfied. The oscillation frequency ω should be much higher than the collision frequency τ^{-1} of the normal excitations.[1)]

Neutrality can be preserved only if the normal excitations screen effectively enough the electric fields that are produced when the condensate density oscillates. At $T \ll \Delta$ (Δ is the half-width of the superconducting gap) the number of normal excitations is small, and their velocities are low, so that they cannot "catch up" with the sound wave, the velocity of which is of the order of the Fermi velocity v_F. This means in turn that the temperature interval in which electronic sound could exist in a superconductor is bounded by the inequality $T \gtrsim \Delta$, i. e., T is of the order of the critical temperature T_c.

Actually, however, electronic sound of low amplitude cannot exist. At T on the order of T_c the velocity of the normal excitations in the superconductor is of the order of the velocity of sound, and there is no sound because of the large collisionless damping.

The remaining reasoning is based on the analogy with the results of[3], where a study was made of the damping of ordinary sound in superconductors and normal conductors, and where it was shown that the damping decreases with increasing sound intensity. We show that an analogous phenomenon takes place also for damping of electronic sound in a superconductor.

The complete system of equations used to construct the theory of electronic sound in a superconductor[2)] includes the integral equation for the superconducting gap Δ, which is a functional of the nonequilibrium distribution function of the normal excitations, the kinetic equation, and the continuity equation (or the equivalent quasineutrality condition), which serves to determine the phase of the order parameter.[4]

In the field of a sound wave, all the quasiparticles can be divided into a large group of nonresonant quasiparticles and a small group of resonant ones, whose velocity in the sound propagation direction (the z axis) almost coincides with the sound velocity w. The former (together with condensate) govern the sound dispersion law. The latter are responsible for the sound absorption. They execute periodic motion in the field of the wave, with characteristic frequency ω_0. The sound is regarded as strong if $\omega_0 \gg 1/\tau$.

After the lapse of a time τ, the resonant quasiparticle experiences scattering and joins the nonresonant excitations that make up the thermostat. The work performed by the wave field on the resonant particle is proportional to $1/\omega_0\tau$, inasmuch as after an integer number of periods the work is equal to zero. As a result, the spatial damping coefficient Γ of the sound is of the order of

$$\Gamma \sim \omega/w\omega_0\tau .$$

The change of the quasiparticle energy in the wave field is of the order of wp_s, where p_s is the alternating condensate momentum due to the sound. Hence

$$\omega_0 \sim (\omega/w)\sqrt{p_s w/m^*},$$

where m^* is the effective mass of the resonant quasiparticles. We have:

$$m^*/m = (1/m)(\partial p_z/\partial u) \sim \epsilon_e \xi_r^2/mw^2\Delta^2,$$

where $\xi_r = (p^2 - p_F^2)/2m$, $\xi_r = \sqrt{\xi_r^2 + \Delta^2}$, and u is the quasiparticle velocity component. Inasmuch as at $T \approx \Delta \approx T_c$ the characteristic quasiparticle energies are $\epsilon_r \sim \xi_r \sim T_c$, we have

$$m^*/m \sim T_c/mw^2 << 1.$$

As a result we obtain for Γ the estimate

$$\Gamma w/\omega \sim 1/\omega\tau \sqrt{T_c/wp_s} << 1.$$

In a superconductor with T_c of the order of several degrees, the value of ω (which should be smaller than Δ) can reach 10^{11} sec^{-1}. If we assume $\omega_0 \sim 10^{10}$ sec^{-1} (corresponding to a sound energy flux density on the order of 1 W/cm^2) and $\tau \sim 10^{-8}$ sec, then $\Gamma \sim 10$ sec^{-1}, i. e., such waves can be observed in sufficiently pure superconductors.

The sound dispersion law is determined by the contribution of the nonresonant excitations, for which the nonlinearity is small in terms of the parameter $(wp_s)^2/\Delta^2 \ll 1$. Solving the dispersion equation, we have found that at $\Delta \ll T_c$ the sound velocity is determined by the expression

$$w = v_F [0.83 - 0.52 (\Delta / T)].$$

[1]This is indeed the essential difference between the electronic sound investigated in this paper and second sound in a superconductor,[2] which can exist only in the limit of frequent collisions between the excitations.

[2]A detailed quantative theory of electronic sound will be published elsewhere.

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[2]V. L. Ginzburg, Zh. Eksp. Teor. Fiz. **41**, 828 (1961) [Sov. Phys.-JETP **14**, 594 (1962)].

[3]Yu. M. Gal'perin, V. D. Kagan, and V. I. Kozub, Zh. Eksp. Teor. Fiz. **62**, 1521 (1972) [Sov. Phys.-JETP **35**, 798 (1972)]; Yu. M. Gal'perin, V. L. Gurevich, and V. I. Kozub, Zh. Eksp. Teor. Fiz. 65, 1045 (1973) [Sov. Phys.-JETP 38, 517 (1974)]

[4]A. G. Aronov and V. L. Gurevich, Fiz. Tverd. Tela **16**, No. 9 (1974) [Sov. Phys.-Solid State **16**, No. 9 (1974)].