ON THE POSSIBILITY OF AMPLIFICATION OF ULTRASOUND IN SEMICONDUCTORS IN AN ELECTRIC FIELD

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THE interaction of a sound wave with the conduction electrons in a crystal leads to dissipation of sound energy. Here the important influence on the propagation of the sound is the presence of an external field **E**. In the work of Hutson, McFee, and White[1] an interesting phenomenon was discovered: the amplification of the ultrasound in the semiconductor CdS in an electric field. In this crystal, there is a strong piezoelectric interaction of the electrons with the sound. However, the possibility in principle of amplification of the sound by the conduction electrons in the electric field does not depend on the specific character of the interaction. The effect has the following nature. In the absence of an electric field the electrons absorb the sound energy Q_0. This leads to the appearance of an electron acoustic current **J**, which is proportional to Q_0. Therefore, the sound energy absorbed by the electrons per unit time is $Q = Q_0 + \mathbf{J}\cdot\mathbf{E}$ in the linear approximation in **E**. If the value of **E** is such that $Q < 0$, then an amplification of the sound by the electrons takes place.

Upon absorption of a sound quantum, the velocity of the electron changes by the quantity $\hbar\boldsymbol{\kappa}/m$ ($\boldsymbol{\kappa}$ is the acoustic wave vector, m is the effective mass of the electron). In the time between collisions τ the electron obtains a mean displacement $\Delta = \hbar\kappa\tau/m$. In the collision, the velocity of the electron changes and it "forgets" about the momentum received. Therefore, the acoustic current is

$$\mathbf{J} = e\hbar\boldsymbol{\kappa}\tau\nu/m, \tag{1}$$

where ν is the number of sound quanta absorbed by the electrons per unit time, e is the charge of the electron.

Taking it into account that $Q_0 = \hbar\omega\nu$ (ω is the sound frequency), we represent the quantity Q in the form

$$Q = Q_0(1 + \boldsymbol{\kappa}\mathbf{v}_d/\omega), \tag{2}$$

here $\mathbf{v}_d = e\tau\mathbf{E}/m$ is the drift velocity.

Thus, if the vectors $\boldsymbol{\kappa}$ and $\mathbf{v}_d$ are antiparallel, and the drift velocity v_d is larger than the phase velocity of the sound s, then the sound absorption coefficient $\Gamma = Q/W$ is seen to be negative ($W = \rho\omega^2u_0^2sV_0/2$ is the energy flux in the sound wave, ρ is the density of the crystal, V_0 is its volume, u_0 is the displacement amplitude in the sound wave). This is a consequence of the non-equilibrium character of the electron distribution in the electric field. The quantity $\hbar(\omega + \boldsymbol{\kappa}\cdot\mathbf{v}_d)$ represents the change in the kinetic energy of the electron (averaged over the distribution) in the absorption of a sound quantum. If this quantity is negative, then the probability of the emission of a quantum becomes larger than the probability of absorption and forced Cerenkov radiation of sound takes place.

The most appropriate crystals for the amplification of sound are evidently the semimetals of the bismuth type. At low temperatures, the coefficient of lattice absorption in bismuth Γ_p is relatively small and the electron coefficient $\Gamma_0 = Q_0/W$ is rather large. At the same time the Joule power $P = nmv_d^2/\tau$ is comparatively small, inasmuch as the concentration of electrons n and their effective mass m in the bismuth are small while τ is large.

It can be shown that the expression (2) for Q remains valid even in the presence of a magnetic field $\mathbf{H} \perp \mathbf{E}$. Here, in the case $\Omega\tau \gg 1$ ($\Omega = eH/mc$; c is the velocity of light) the drift velocity v_d is equal to the Hall velocity cE/H, and is directed perpendicular to the fields **E** and **H**, while the quantity Q_0 should be computed with account of the magnetic field. It is shown that in the case $\kappa R \ll 1$, $\kappa l \gg 1$ ($R = v_F/\Omega$; $l = v_F\tau$; v_F is the Fermi velocity) the expression for the sound absorption coefficient has the form

$$\Gamma = \left(1 + \frac{v_d}{s}\cos\varphi\right)\Gamma_0/|\cos\vartheta|, \tag{3}$$

where φ is the angle between the vectors $\boldsymbol{\kappa}$ and $\mathbf{v}_d$; Γ_0 is the absorption coefficient for $E = H = 0$;[2] the angle ϑ between the vectors $\boldsymbol{\kappa}$ and **H** should satisfy the conditions

$$|\cos\vartheta| > s/v_F, \qquad |\cos\vartheta| \gg 1/\kappa l. \tag{4}$$

Thus the coefficient of amplification of the sound in the presence of a strong magnetic field can be larger by a factor v_F/s than in its absence. The large (in absolute value) magnitudes of the coefficient make it possible in principle to use this effect not only for amplification, but also for generation of ultrasound of high frequencies.

It should be noted that in many cases the linear approximation in E is inadequate for the calculation of the coefficient Γ. The case of a semiconductor in which the heating of the electrons gas in the electric field is important and the case of a magnetic field in which the absorption and emission of sound has a resonance character can serve as examples. However, these questions go beyond the scope of the present note and will be considered in a special paper.

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[1] Hutson, McFee, and White, Phys. Rev. Lett. **7**, 237 (1961).

[2] Akhiezer, Kaganov, and Lyubarskiĭ, JETP **32**, 837 (1957), Soviet Phys. JETP **5**, 685 (1957).

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MEASUREMENT OF TOTAL CROSS SECTIONS OF (π^-p) *REACTIONS AT* π^- *MESON ENERGY OF* 340 MeV

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THE following reactions were investigated with the aid of a 25-cm liquid-hydrogen chamber placed in a 12,000 Oe magnetic field, with the primary π^- mesons having an energy 340 ± 15 MeV:

$$\pi^- + p \to \pi^- + \pi^+ + n, \quad (1)$$

$$\pi^- + p \to \pi^- + \pi^0 + p, \quad (2)$$

$$\pi^- + p \to \pi^- + \gamma + p. \quad (3)$$

The corresponding total cross sections were found to be

$$\sigma_1 = 1.24 \pm 0.14 \text{ mb}, \quad \sigma_2 = 0.13 {}^{+0.06}_{-0.04} \text{ mb},$$

$$\sigma_3 = 0.09 {}^{+0.03}_{-0.06} \text{ mb}.$$

In the determination of the cross section of reaction (3) we took into account only the cases in which the energy of the emitted γ quantum exceeded 100 MeV.

To gain an idea of the contribution of the different isotopic states to the cross sections of reactions (1) and (2), we write the latter in the form

$$\sigma_1 = \frac{1}{9}\left[\frac{1}{5}\left|A_2^{3/2}\right|^2 - 2\sqrt{\frac{2}{5}}\,\mathrm{Re}\,(A_2^{3/2*}A_0^{1/2}) + 2|A_0^{1/2}|^2\right] + \frac{1}{9}\,[|A_1^{3/2}|^2 - 2\,\mathrm{Re}\,(A_1^{3/2*}A_1^{1/2}) + |A_1^{1/2}|^2],$$

$$\sigma_2 = \frac{1}{10}\left|A_2^{3/2}\right|^2 + \frac{1}{9}\left[\frac{1}{2}|A_1^{3/2}|^2 + 2\mathrm{Re}(A_1^{3/2*}A_1^{1/2}) + 2|A_1^{1/2}|^2\right],$$

where A_k^i —invariant isotopic amplitudes (the upper index pertains to the total isotopic spin of the entire system, while the lower one denotes the total isotopic spin of the two-pion system).

The values obtained for the cross sections of reactions (1) and (2) enable us to judge, under certain extreme assumptions, the magnitudes and phases of the isotopic amplitudes:

a) If we set the amplitudes $A_1^{1/2}$ and $A_1^{3/2}$ equal to zero, then the amplitude $A_2^{3/2}$ turns out to be much smaller than $A_0^{1/2}$:

$$3.1\,|A_2^{3/2}|^2 \leqslant |A_0^{1/2}|^2 \leqslant 5.7\,|A_2^{3/2}|^2;$$

b) If it is assumed that the cross sections σ_1 and σ_2 are determined essentially by the amplitudes $A_1^{1/2}$ and $A_1^{3/2}$, then the phases of these amplitudes are shifted by ~ 180°, and their moduli are related by

$$|A_1^{3/2}| \approx 2|A_1^{1/2}|.$$

When the energy of the incoming pions is 340 MeV, the maximum total energy in the c.m.s. of the two pions is 400 MeV. If variant a) is correct, then we can state that pions with energies from 280 to 400 MeV interact predominantly in states with total isotopic spin T = 0, and not with T = 2. This character of the $\pi\pi$ interaction was first suggested by Korenchenko [1] and experimentally confirmed only near the threshold of meson production. [2] A similar result was obtained in the theoretical papers; [3,4] Schnitzer [3] calculated, in particular, the cross sections of reaction (1) and (2). The results of the calculations do not contradict the values of the cross sections obtained in the present paper.

From a comparison of σ_2 and σ_3 we can conclude that the results presented in [5] can pertain to the summary cross section of the two reactions (2) and (3).

In conclusion, the authors consider it their pleasant duty to thank Prof. B. M. Pontecorvo for constant interest in the work and for valuable advice, and to P. F. Ermolov for useful discussions.

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[1] S. M. Korenchenko, Dissertation, Joint Institute for Nuclear Research, 1959.

[2] Deahl, Derrick, Fetkovich, Fields, and Yodh, Proc. of the 1960 Ann. Int. Conf. on High Energy Phys. at Rochester, 1960, p. 185.