begins an intensified diffusion of the particle longitudinal velocities, leading to escape from the trap. From this we can estimate the attained value of the transverse velocity at

$$V_\perp \sim \frac{\omega}{k} \sim \frac{\omega_c}{k} \tag{5}$$

or, substituting (4),

$$V_\perp \sim \left(\frac{\omega_c}{\omega_0}\right)^{2/3} \left(c^2 |V_z|\right)^{1/3}. \tag{6}$$

Here $|V_z|$ is determined by the thermal velocity of the bulk of the electrons. From this we get the following estimate for the transverse energy of the hot electrons:

$$E_\perp^* / mc^2 \sim \left(\frac{\omega_c}{\omega_0}\right)^{2/3} (\bar{E}/mc^2)^{1/3}, \tag{7}$$

where $\bar{E}$ is the average thermal energy of the electrons.

This explains the main qualitative features of the heating: we see that the energies of the hot electrons should be in the kilovolt range, but the mechanism considered here can never lead to relativistic energies. At an average energy of several hundred electron volts, the proposed estimate leads to a transverse energy $E_\perp^* \sim 50$ keV for the hot electrons, which is sufficiently close to the results of the measurement of the plasma x-radiation [3, 4] in the case of cyclotron heating.

[1] R. A. Dandl et al., Nucl. Fusion 4, 344 (1964).
[2] L. A. Ferrarri and A. F. Kuckes, Phys. Fluids 8, 2295 (1965).
[3] V. V. Alikaev, V. M. Glagolev, and S. A. Morozov, Plasma Phys. 10, 753 (1968).
[4] B. I. Patrushev, V. P. Gozak, and D. A. Frank-Kamenetskii, Zh. Eksp. Teor. Fiz. 56, 99 (1969) [Sov. Phys.-JETP 29, 56 (1969)].
[5] M. Brambilla, Plasma Phys. 10, 350 (1968).
[6] A. F. Kuckes, ibid. 10, 367 (1968).
[7] H. Grawe, ibid. 11, 151 (1969).
[8] V. E. Golant, V. V. D'yachenko, and K. M. Novik, Zh. Tekh. Fiz. 36, 1027 (1966) [Sov. Phys.-Tech. Phys. 11, 756 (1966)].
[9] A. F. Kuckes, Phys. Lett. 26A, 599 (1968).

PHONON DRAGGING BY SOUND IN HYDRODYNAMIC FLOW OF A PHONON GAS

A. I. Sokolov
Leningrad Electrotechnical Institute

Submitted 15 December 1969
ZhETF Pis. Red. 11, No. 2, 138 - 141 (20 January 1970)

At high frequencies Ω, when $\Omega\tau_p \gg 1$ (τ_p is the relaxation time of the thermal phonons), the absorption of sound in a dielectric can be regarded as the scattering of acoustic phonons of energy $\hbar\Omega$ by thermal phonons [1]. In normal collisions, this process is accompanied by transfer of not only energy but also quasimomentum to the gas of thermal phonons. Usually the transfer of quasimomentum does not lead to any particular phenomena, since the quasimomentum transferred in the elementary collision acts attenuates rapidly as a result of V-processes (by V-process is meant here any type of collision with momentum loss). However, when the V-processes are much less intense than the N-processes, the transfer of quasimomentum from the attenuating sound to the thermal phonons should cause drift of the phonon gas and consequently lead to the appearance of a thermal drift flux. We shall show that such a dragging of the phonons by the sound leads to a nonmonotonic distribution of the temperature along the direction of the thermal flux, and the region in which the temperature grows can have appreciable dimensions.

Let us consider a stationary and one-dimensional case in the absence of dispersion. The equations of phonon hydrodynamics [2] with allowance for injection of energy and quasimomentum by the attenuating sound take the form:

$$\frac{q}{\tau_V} - \nu\frac{\partial^2 q}{\partial x^2} + a\frac{\partial T}{\partial x} = S_q(x), \quad \frac{\partial q}{\partial x} = S_E(x), \tag{1}$$

where

$$\tau_V = \frac{\ell_V}{v}, \quad \nu \approx \ell_N v. \tag{2}$$

Here q is the heat-flux density; the remaining symbols, with the exception of $S_q(x)$ and $S_E(x)$, are the same as in [2]. The source densities of the energy, $S_E(x)$, and of the thermal flux (or of the quasimomentum $p = q/v^2$), $S_q(x)$, are equal to:

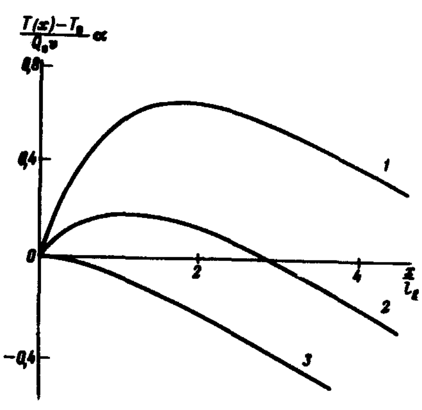
$$S_E(x) = -\frac{\partial Q(x)}{\partial x}, \quad S_q(x) = -\gamma v\frac{\partial Q(x)}{\partial x}, \tag{3}$$

where Q(x) is the energy flux density in the sound wave, $\gamma < 1$ is the relative weight of the N-processes among all other types of acoustic-phonon scattering. Equations (3) are valid only if $|\ell_N[\partial Q(x)/\partial x]| \ll Q(x)$. We write down the solution of (1) and (3), with allowance for (2), at $W(x) = Q_0\exp(-x/\ell_s)$ and at the boundary conditions $q(0) = 0$ and $T(0) = T_0$, in the form

$$q(x) = Q_0[1 - \exp(-\frac{x}{\ell_s})], \tag{4}$$

$$T(x) - T_0 = -\frac{Q_0}{a\tau_V}x + \frac{Q_0}{a\tau_V}\ell_s(1 + \gamma\frac{\ell_V}{\ell_s})[1 - \exp(-\frac{x}{\ell_s})], \tag{5}$$

We have left out of (5) a term due to viscosity and of the order of $\ell_N/\ell_s \ll 1$. The figure shows plots of $T(x) - T_0$ for three values of the parameter γ. We see that when $\gamma = 0$ (there is no quasimomentum transfer) the temperature decreases monotonically along the direction of the heat flux. On the other hand, if $\gamma > 0$, then we get a section along which the temperature increases, the length of which is



Temperature distribution along the thermal flux at $\ell_V/\ell_s = 5$ and at $\gamma = 1$ (1), 0.4 (2), and 0 (3).

$$L = \ell_s \ln\left(1 + \gamma \frac{\ell_V}{\ell_N}\right) . \qquad (6)$$

The rise in temperature along the thermal flux occurs at high phonon drift velocities and is a consequence of the nonlinearity of the gasdynamic equations for phonons [3]. In our case, however, such a behavior of the phonon gas follows already from the linearized equations (1), the validity of which can always be ensured by choosing not too large values of Q_0.

The described effect can apparently be observed experimentally only in solid helium, where Poiseuille flow of the phonon gas [4] and second sound [5, 6] have been observed. In solid He^4 at T = 0.6°K and 54 atm we have $\ell_N \simeq 0.01$ cm and $\ell_V \simeq 10$ cm [5]. For crystals with large cross sections, ℓ_s can be roughly approximated by extrapolating to the low-frequency range the data on the free path of thermal phonons, using the relation $\ell_s \sim \Omega^{-1}$ [1]. For $f = \Omega/2\pi$, which is readily attained in the experiment, this procedure yields $\ell_s \sim 1$ cm. In a thin crystal ℓ_s is smaller, owing to the diffuse scattering of the sound by the boundaries, which leads to a decrease of γ, too. As proposed earlier, when f = 300 MHz and T = 0.6°K we have $\Omega\tau_p \simeq 100 \gg 1$ and $\ell_N/\ell_s \simeq 0.01 \ll 1$ in solid He^4. Thus, under the indicated conditions and at $\gamma = 1$ we get $L \simeq 2.5$ cm. It is possible to observe the growth of the temperature along the flux either by plotting its distribution with the aid of pickups, or by using a sample of length $\lesssim L$ and comparing the values of the temperature on its ends.

By measuring L and ℓ_s in the experiment, it is easy to calculate $\gamma\ell_V$ with the aid of (6), and to obtain directly ℓ_V for a sample with characteristic transverse dimension $d > \ell_s$ ($\gamma \simeq 1$). This makes it possible to compare the values of ℓ_V determined by fundamentally different methods - that proposed above and that used in [5] - and is of independent interest.

The author is deeply grateful to O. G. Vendik and B. I. Shklovskii for a discussion of the results and valuable advice, and also to S. A. Ktitorov for an interesting discussion.

[1] L. D. Landau and Yu. B. Rumer, Phys. Z. Sowjet. 11, 18 (1937).
[2] R. N. Gurzhi, Usp. Fiz. Nauk 94, 689 (1968) [Sov. Phys.-Usp. 11, 255 (1968)].
[3] K. Nielsen and B. I. Shklovskii, Zh. Eksp.Teor. Fiz. 56, 709 (1969) [Sov. Phys.-JETP 29, 386 (1969)].
[4] L. P. Mezhov-Deglin, ibid. 49, 66 (1965) [22, 47 (1966)].
[5] C. C. Ackerman and R. A. Guyer, Ann. Phys. (USA) 50, 128 (1968).
[6] C. C. Ackerman and W. C. Overton, Phys. Rev. Lett. 22, 764 (1969).

CYCLOTRON-PHONON ABSORPTION IN DEGENERATE SEMICONDUCTORS

R. K. Bakanas and I. B. Levinson
Submitted 16 December 1969
ZhETF Pis. Red. 11, No. 2, 141-144 (20 January 1970)

Free electrons placed in a strong magnetic field with $\omega_c\tau \gg 1$ (ω_c - cyclotron frequency, τ - relaxation time) absorb light only at frequencies ω in a narrow band of width $1/\tau$ near ω_c. If we take into account processes in which the absorption of a photon occurs simultaneously with the emission or absorption of a phonon, then absorption becomes possible at all frequencies ω. It was shown in [1] that when electrons interact with optical phonons (of frequency ω_0 without dispersion), there should be observed cyclotron-phonon resonance, i.e., peaks of