4. In conclusion, we make two remarks. Assume that the spectra of the particles produced from the nuclei are indeed of the type proposed above. Then the detailed data on the behavior of these spectra at $\epsilon \gtrsim Rm\mu$ (in the laboratory frame of the nucleus) can yield information on the character of the linking of the parton combs [3]. We note also that the most important circumstance in our picture is the fact that the longitudinal distances, which play the important role in the hadron interactions, increase like Em^{-2}; this is precisely why the usual cascades do not develop in the nucleus, and the fast part of the spectrum is not restructured.

The author thanks V. N. Gribov for numerous discussions and hints, and V. A. Abramovskii, E. V. Gedalin, I. D. Mandzhavidze, S. G. Matinyan, and K. A. Martirosyan for interest in the work.

---

1)At small E, of course, the parton picture is quite arbitrary. In addition, the parton comb probably broadens in space near the slow end ($1/\mu$, and not $1/m$) owing to the interaction with the vacuum fluctuations. This can also lead to a certain "delay" and coalescence of the combs, and to a longitudinal stabilization of the slow partons of the nucuels at $E \sim 2Rm^2$, and not at $E \sim 2Rm\mu$.

2)A more detailed exposition will be published elsewhere.

[1] V. N. Gribov, Yad. Fiz. 9, 640 (1969) [Sov. J. Nuc. Phys. 9, 369 (1969)].
[2] R. P. Feynman, Photon-Hadron Interactions, W. A. Benjamin, 1972.
[3] V. N. Gribov, Yad. Fiz. 17, 603 (1973) [Sov. J. Nuc. Phys. 17, No. 3 (1973)].
[4] M. Gell-Mann and B. M. Udgaonkar, Phys. Rev. Lett. 8, 346 (1972).
[5] V. A. Abramovskii, V. N. Gribov, and O. V. Kancheli, Yad. Fiz. 18, 595 (1973) [Sov. J. Nuc. Phys. 18, No. 3 (1974)]; see also the Proceedings of the 16th Internat. Conf. on High Energy Physics, Vol. 1, p. 389.

GIANT SONDHEIMER OSCILLATIONS OF THE NERNST CONSTANT IN ELECTRON DRAGGING BY PHONONS

V. A. Kozlov
Submitted 16 May 1973; resubmitted 31 August 1973
ZhETF Pis. Red. 18, No. 7, 469 — 473 (5 October 1973)

As shown by Sondheimer [1] some time ago, the conductivity of thin films in external magnetic fields oscillates as a function of the parameter $\beta = d/r_H$, where d is the characteristic transverse dimension of the sample and r_H is the radius of curvature of the electron trajectory in the magnetic field. It is natural to expect analogous oscillations to be experienced also by other kinetic coefficients, particularly the thermoelectric and thermomagnetic ones. The latter, however, are determined in semiconductors and semimetals at low temperatures mainly by the dragging of the electrons by phonons, thus distinguishing them from the picture considered by Sondheimer. It is shown in the present paper that even in the absence of dragging the Sondheimer oscillations of the Nernst constant can be so large that this constant can alternate in sign. The dragging effect, however, can increase the amplitude of these oscillations by several orders of magnitude.

We consider an isotropic sample in the form of a plane-parallel plate of thickness d, bounded in the z direction and infinite along the axes x and y. The magnetic field is directed along the z axis and the temperature gradient along x. The kinetic equations for the electrons and phonons in the presence of a magnetic field and a temperature gradient are

$$\frac{\partial f_p^1}{\partial z} + \frac{e}{v_z}\left\{E + \frac{1}{c}[\mathbf{v}\times\mathbf{H}]\right\}\nabla_p f_p + \frac{(\mathbf{v}\nabla_r f_p^\circ)}{v_z} = -\frac{f_p^1}{\tau_p v_z} + \hat{D}^1\{f_p^\circ, F_q^1\}, \quad (1)$$

$$s\frac{\partial F_q^1}{\partial z}\, s\nabla T\frac{\partial F_q^\circ(\omega)}{\partial T} = \hat{I}\{F_q\}, \quad (2)$$

where

$$f_p = f_p^\circ + f_p^1, \quad f_p^1 = (v_x\Psi_x + v_y\Psi_y), \quad F_q = F_q^\circ + F_q^1.$$

The symbols F_q^0 and f_p^0 in (1) and (2) denote the equilibrium distribution functions of the phonons and electrons, respectively, while F_q^1 and f_p^1 denote the non-equilibrium increments. The operator D^1 describes the dragging of the electrons by the phonons, $I\{F_q\}$ is the collision integral in the phonon system, s is the speed of sound, and τ_p is the electron relaxation time under the condition that the phonons are in equilibrium. The boundary conditions for Eqs. (1) and (2) correspond to diffuse reflection.

In the absence of electron dragging by phonons, Sondheimer's analysis [1] can be readily extended to include the presence of a temperature gradient. The solution of (1) with allowance for the foregoing statements is

$$g = \frac{\tau_p}{(1 + i\omega^* \tau_p) m^* v}\left[e\mathcal{E} + \frac{\epsilon - \mu}{T}\nabla T\right]\left\{1 - F(v)\exp\left[-\frac{(1 + i\omega^* \tau_p)}{\tau_p v_z} z\right]\right\}, \qquad (3)$$

where

$$g = \Psi_x - i\Psi_y, \quad \mathcal{E} = E_x - iE_y, \quad \omega^* = \frac{eH}{m^* c}, \quad \nabla T = \nabla_x T - i\nabla_y T.$$

The function F(v) are determined from the boundary conditions. In the calculation of the current with the aid of (3) it should be recognized that $J = J_x - iJ_y$.

The expression obtained for the Nernst constant is

$$N = \frac{\pi^2}{3}\frac{k^2 T}{e\mu H}\left\{\frac{\frac{d}{d\epsilon}\mathrm{Re}\, q(S)\, \mathrm{Im}\, q(S) - \frac{d}{d\epsilon}\mathrm{Im}\, q(S)\, \mathrm{Re}\, q(S)}{\mathrm{Re}^2 q(S) + \mathrm{Im}^2 q(S)}\right\}\Bigg|_{\epsilon = \epsilon_F}. \qquad (4)$$

Here Re and Im denote the real and imaginary parts of the Sondheimer function q(s) [1], $S = (d/\Lambda) + i(d/r_H)$ and Λ is the electron mean free path.

The dependence of the Nernst coefficient on the parameters $g = d/\Lambda$ and β was calculated with the Minsk-22 computer. It was assumed that the electron mean free path has a power-law dependence on the energy, $\Lambda \sim \epsilon^R$. We present below the results of the calculation for three values of the parameter R, namely p, 1, and 2. Figures 1 and 2 show plots of N/N_0 in relative units against the parameter β for two values of d/Λ, 0.02 and 0.1, where

$$N_0 = \frac{\pi^2}{3}\frac{k^2 T d}{\mu m^* c v_F}.$$

To take the dragging effect into account, we assume that the main mechanism of phonon scattering is their interaction with one another and with the sample boundaries, and not with the electrons (absence of saturation after Herring [2]). As shown by experiment, the phonon-phonon processes are decisive in sufficiently pure samples of such a typical semimetal as Bi, down to temperatures on the order of 1°K [3]. In accordance with the foreging, $I\{F_q\}$ in Eq. (2) should be taken to

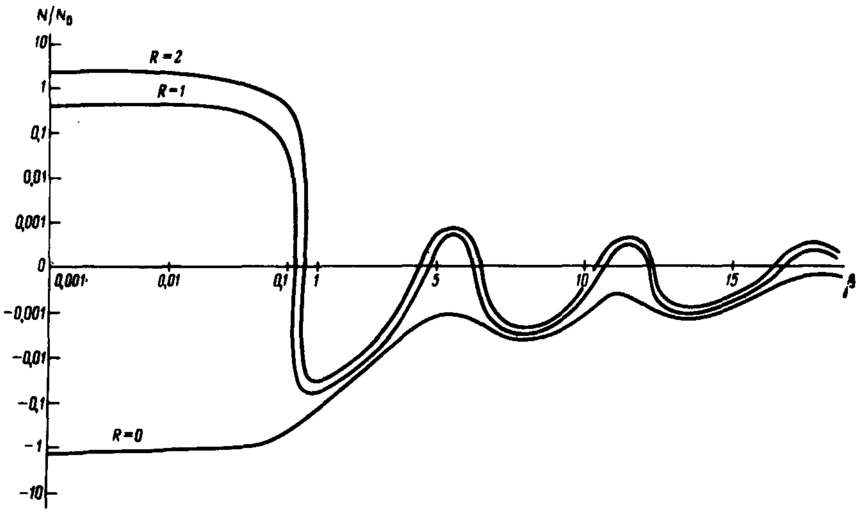

Fig. 1. Nernst constant, in relative units, vs. the parameter $\beta = d/r_H$ without dragging, $g = d/\Lambda = 0.02$.

mean the phonon-phonon collision integral. The low conduction-electron concentration allows us also to disregard the reaction of the electrons on the phonon system.

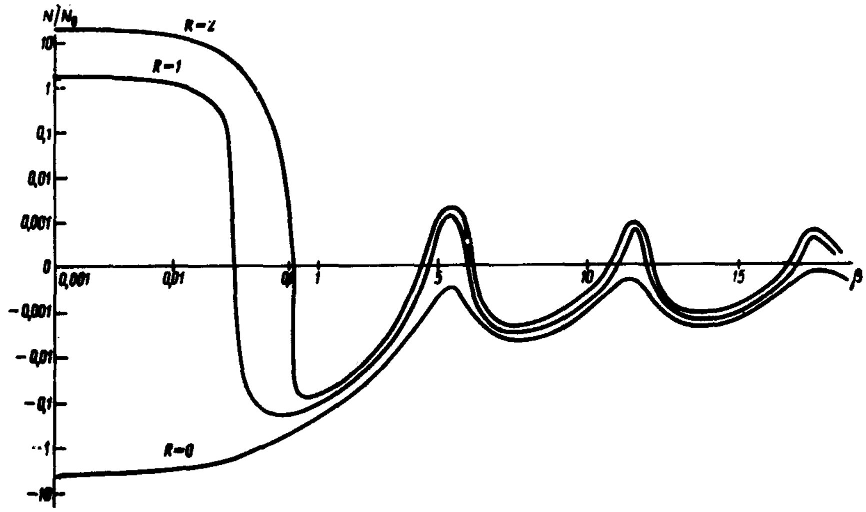

Fig. 2. Nernst constant in relative units vs. the parameter $\beta = d/r_H$ without dragging, $g = d/\Lambda = 0.1$.

A simultaneous solution of the (1) and (2) leads to a cumbersome expression for the contribution made to the Nernst constant by the dragging effect, an expression which will not be presented here. The results of the numerical calculations are shown in Fig. 3. The dependence on the magnetic field was calculated at the same values of the parameter as for the ordinary Nernst effect, at a phonon mean free path equal to 100d and $g = d/\Lambda = 0.1$.

The results indicate that in weak fields the sign of the Nernst coefficient, as expected, is determined by the scattering parameter (R) and its magnitude does not depend on the field. With further increase of the field, the Nernst constant decreases approximately like H^{-2} and oscillates. At the parameter values R = 1 and 2, the oscillations are accompanied by a reversal in the sign. The period of the oscillations is constant and is approximately equal to 2π. The dragging effect increases the oscillation amplitudes appreciably, by approximately $m^* s v_F \ell_0 / kT\Lambda$ times, i.e., by several orders of magnitude at the typical values of the parameters in this expression. Thus, the oscillations of the Nernst constant can be gigantic when the magnetic field is increases and the electron dragging by the phonons is taken into account. The magnitude of the oscillations is determined in fact by the ratio of the electron and phonon mean free paths.

Physically, this effect is a simultaneous realization of the effects of L. E. Gurevich and Sondheimer. The first of these effects, as is well known, is connected with the fact that the phonons deviate much more from equilibrium in the presence of a temperature gradient than the electrons, since the long-wave phonons are very weakly scattered ($\ell_0 > \Lambda$). This phonon flux acts on the electrons, which experience reflection from the surface with simultaneous twisting of their orbits. Since the phonons themselves are not acted upon by the magnetic field, they simply amplify those Sondheimer oscillations which are present even in the absence of the dragging effect.

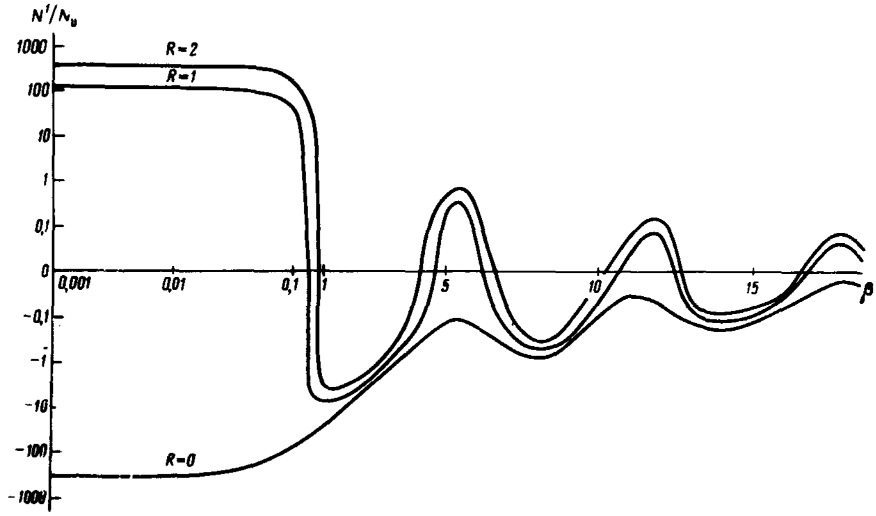

Fig. 3. Nernst constant in relative units vs. the parameter $\beta = d/r_H$ under dragging conditions, $g = d/\Lambda = 0.1$.

The results give grounds for hoping that investigations of the Nernst effect in bulky samples under conditions of the classical size effect (the possibility of realizing these conditions is discussed in [3, 4]) can contribute to an explanation of the carrierscattering mechanism. Investigations of the oscillation amplitude as a function of the plate thickness under conditions of the dragging effect make it possible, in our opinion, to estimate the phonon mean free path in independent measurements of the electron mean free paths. The possibility of the reversal of the sign of the Nernst constant is in itself not a trivial fact.

In conclusion, the author is deeply grateful to E. L. Nagaev for suggesting the problem and discussing the results. He is also grateful to V. M. Matveev for help with the numerical calculations and discussions.

[1] E. H. Sondheimer, Phys. Rev. 80, 401 (1950).
[2] C. Herring, Phys. Rev. 96, 1163 (1954).
[3] V. N. Kopylov and L. P. Mezhov-Deglin, ZhETF Pis. Red. 14, 32 (1971) [JETP Lett. 14, 21 (1971)].
[4] V. N. Kopylov and L. P. Mezhov-Deglin, Fiz. Tverd. Tela 15, 13 (1973) [Sov. Phys.-Solid State 15, 8 (1973)].

ERRATA

In article by L. S. Kornienko et al., Vol. 18, No. 3, p. 127, a factor $(n^2/n_\omega^2)(64\pi/c^2)$ was omitted from the formula (line 2 of the page). This formula should read

$$W = \frac{(4\omega H \chi E^2)^2 L n^2}{\pi n_\omega^2 c \sqrt{n_\omega^2 - n^2}} = \frac{(8\omega \chi W_0 L \pi}{n_\omega^2 c^3 \sqrt{n_\omega^2 - n^2}}.$$

The estimate given in the article for the effect remains in force.

In the article by Yu. I. Grin' et al., Vol. 18, No. 4, p. 156, Figure 2 should be turned through 180°.