# Exponential temperature dependence of the coefficient of the Nernst-Ettingshausen transverse effect in bismuth

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It was determined that the Nernst coefficient $Q$ of bismuth and its temperature dependence depend strongly on the perfection and geometric dimensions of the crystal at low temperatures. In a perfect sample $Q$ increases exponentially with decreasing temperature. This can be accounted for by the two-stage, phonon-phonon drag of the charge carriers.

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It is well known that the thermoelectric and thermomagnetic coefficients of semiconductors and semimetals in the region of helium temperatures are determined primarily by the phonon drag of charge carriers, which increases these coefficients as the temperature decreases according to the power law $T^{-n}$, where $n \leqslant 3.5$.[1–3] However, as shown in Ref. 4, the perfect, massive crystals with a small number of free carriers can have a two-stage, phonon-phonon drag which produces exponentially large values of the thermoelectromotive force and of the Nernst coefficient; these values, like the thermal conductivity, are equal to $\sim \exp \Theta / T$, where $\Theta$ is a temperature of the order of the Debye temperature.

A study of the properties of perfect, massive bismuth crystals[5,6] showed that the thermoelectromotive force $\alpha$ and its temperature dependence at helium temperatures greatly depend on the thickness and perfection of the sample. The $\alpha(T)$ dependence in a perfect, massive crystal is close to an exponential dependence which describes the behavior of thermal conductivity in the same temperature interval. On the other hand, the phonon-phonon drag in pure, massive semimetals has specific properties. As shown in Ref. 7, because the electron density is exactly equal to the hole density, it does not contribute to the thermoelectromotive force if the scattering occurs only inside the electron-phonon system. The nonvanishing phonon-phonon drag contributes to the thermoelectromotive force only when an additional mechanism for the scattering of carriers is present, whose role may be played by the surface in the perfect samples. This has been confirmed by numerical calculations for bismuth in Ref. 6.

In contrast with the thermoelectromotive force, however, the contribution of the phonon-phonon drag to the Nernst effect is not only nonvanishing in the case of the two types of carriers but can also reach exponentially large values in the perfect samples.

We present below the results of measurements of the transverse thermoelectromotive force (Nernst-Ettingshausen coefficient) in bismuth, which were performed in 12- to 80-Oe magnetic fields at temperatures $T \leqslant 10$ K. The measurements were performed using three samples of identical orientation (the $C_3$ axis is perpendicular to the axis of the sample), which were cut out of a single, $18 \times 15 \times 86$-mm, pure bismuth single crystal that had a resistance ratio $\rho_{300}/\rho_{4.2} = 650$. The samples, henceforth referred to as samples 1, 2, and 3, had the following dimensions: $7.4 \times 7.2 \times 74$ mm, $3.4 \times 3.4 \times 25$ mm and $2.3 \times 2.3 \times 17$ mm, respectively. The sample 1 was annealed in a vacuum before the measurements were taken in order to reduce the density of the defects produced as a result of its cutting. The perfection of the crystals can be judged from the resistance ratio $\gamma = \rho_{300}/\rho_{4.2}$: $\gamma_1 = 625$, $\gamma_2 = 3.44$ and $\gamma_3 = 147$ (the subscripts

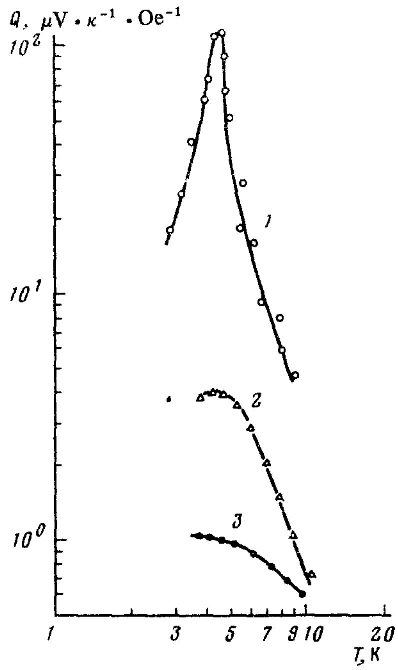


FIG. 1. Temperature dependence of the Nernst coefficient for Bi, $H \| C_3$. 1, $\gamma_1 = 625$; 2, $\gamma_2 = 344$; 3, $\gamma_3 = 147$.

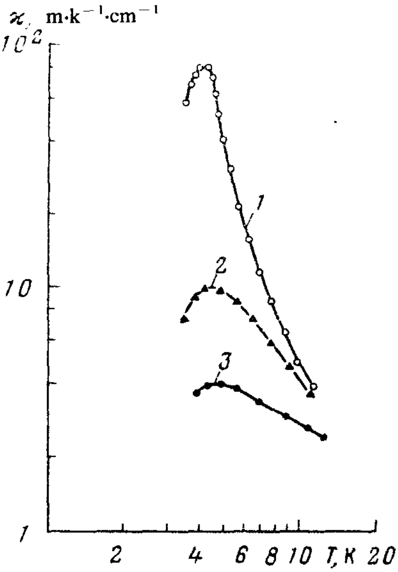


FIG. 2. Temperature dependence of the thermal conductivity of the same samples. The curves are numbered just as in Fig. 1.

correspond to the number of the sample). Therefore, the investigated samples differed not only in size but also in the perfection of the crystal structure. The magnetic field was oriented along the $C_3$ axis for the measurements.

The results of measurements of the temperature dependence of the Nernst coefficient and of the thermal conductivity $\kappa$ are shown in Figs. 1 and 2. As follows from the given data, the temperature dependence of the Nernst coefficient almost coincides with that of the thermal conductivity in the perfect sample 1 in the temperature range 5 K-10 K and is close to the exponential dependence $Q(T) \sim \kappa(T) \sim T^n \exp 40/T$, where the exponent $n$ is close to unity; however, these dependences greatly differ from each other in the less perfect samples. The variation of $Q$ in the samples 2 and 3 in the same temperature range can be described by a power function $Q(T) \sim T^{-(2-3)}$. The maximum values of the Nerst coefficient in the perfect sample 1 are 30 to 100 fold greater than the peak values of the less perfect crystals 2 and 3 and the maximum values of $Q$ obtained in the previous measurements. It should be noted that the data quoted in the literature pertain to the measurement of the properties of insufficiently perfect crystals.[2,3]

Since the magnetic fields, in which the measurements of the bismuth samples of high degree of purity and perfection were performed, turned out to be classically strong fields and since the tensor components of the carrier mobilities in the helium temperature region satisfy the inequality $\mu_{11}^-, \mu_{33}^-, \mu_{11}^- \gg \mu_{22}^-, \mu_{33}^+$ (Ref. 8), the following estimate is valid for the Nernst coefficient under the conditions of a two-stage, phonon-phonon drag at $H \| C_3$:

$$Q \approx \frac{2 s^2 \tau^u}{T c} \cos^4 \eta , \tag{1}$$

where $s$ and $c$ are the velocities of sound and light, respectively, $\tau^u$ is the relaxation time of thermal phonons relative to the transfer processes, and $\eta \approx 6^0$ is the slope angle of the electron ellipsoids relative to the basal plane. If we assume that the temperature dependence $\tau^u(T)$ has the form: $\tau^u(T) \sim T^{5/2} \exp \Theta / T$,[9] then the theoretical dependence of $Q$ on $T$, according to Eq. (1), will be given by the expression $Q(T) \sim T^{3/2} \exp \Theta / T$, in good agreement with our data.

Since the theoretical Eq. (1) for the Nernst coefficient contains a limited number of parameters, we can obtain sufficiently accurate estimates of the relaxation time of thermal phonons for the transfer processes from the measurements of the thermomagnetic coefficients. According to our data, the value of $l^u$ is equal to $\approx 2$ mm at $T = 4.7$ K, in agreement with the results of Ref. 6. Thus, an analysis of the obtained data shows that the attained values of the Nernst coefficient are not the limiting values and that the $Q$ values in the maximum can increase considerably as the perfection and geometric dimensions of the crystal increase.

We have determined the following systematic feature by comparing the obtained data for the Nernst coefficient with the results of the measurement of thermoelectromotive force[5,6] in the absence of a magnetic field: a transition from a power-law temperature dependence of these kinetic coefficients to an exponential dependence in which the perfection and the characteristic dimensions of the samples increase; this indicates that there is a phonon-phonon drag.

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