Observation of kinetic diamagnetism and paramagnetism in bismuth

I. N. Zhilyaev
Institute of Solid State Physics, Academy of Sciences of the USSR

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The kinetic diamagnetism and paramagnetism predicted by Gurevich {Pis'ma Zh. Eksp. Teor. Fiz. **11**, 269 (1970) [JETP Lett. **11**, 175 (1970)]} have been observed in bismuth samples at helium temperatures.

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The bismuth samples used in these experiments were grown by the Czochralski method and had a resistivity ratio $\rho_{293K}/\rho_{4.2K} \approx 430$. Samples with a regular geometric shape (bars with a square cross section of area $S = 0.9 \times 0.9$ cm and a length of 7.5 cm) were formed by cutting the original samples in an arc cutting machine and then etching them in HNO_3 to remove the work-hardened layer. The longitudinal axis of the samples was parallel to the C_2 axis. A resistance heater was cemented to the sample near one end; this heater had a bifilar winding to prevent electrical interference. The surface of the sample was heat-insulated by means of cigarette paper and a polytetrafluoroethylene film (similar to Teflon), by the method of Ref. 2, in order to arrange a directed heat flux Q in the sample. The uninsulated end of the sample was in thermal contact with liquid helium and served as a heat sink. Several coils K_i with $n = 200$ turns were wound on top of the polytetrafluoroethylene film; the turns consisted of type PĒL-0.06 wire. An F190 microfluxmeter connected to these coils measured the change in the magnetic fluxing linking them, $\Delta\Phi$. The geomagnetic field was cancelled within 0.01 Oe. The samples were oriented within 1° in the longitudinal magnetic field $H_\parallel$.

Figure 1 shows the experimental $H_\parallel$ dependence of the specific magnetic flux $\Delta\phi = \Delta\Phi/Sn$, which arose when a heater power of 0.9 W was applied; this flux was measured by coils K_1 and K_4. Curves are not shown for coils K_2 and K_3, since the corresponding signals were essentially zero. The temperature of the helium bath was ≈ 1.3 K. In these experiments we used a heater, H_1, wound around the perimeter of the sample near its end; we call this heater a "ring" heater. It can be seen from Fig. 1 that (1) $\Delta\Phi$ is observed through the coils where the heat "flows in" (K_1) and "flows out" (K_4), i.e., where Q has a radial component [$\Delta\Phi$ is essentially zero in regions in which Q is predominantly axial (K_2, K_3)]; (2) the sign of the effect is antisymmetric with respect to $H_\parallel$; (3) the signs of the effect are opposite for coils K_1 and K_4 (K_1 detects a paramagnetic effect, while K_4 detects a diamagnetic effect); and (4) the signal increases with increasing $H_\parallel$, reaches a maximum, and then falls off. Figure 2 shows the corresponding results for the same sample, under the same conditions for K_1, but for experiments in which the sample was heated by different heaters, of a two-dimensional construction. One of these heaters covered the entire end of the sample (the "planar" heater), and another covered only a central part of the end (an area of $0.5 \times$

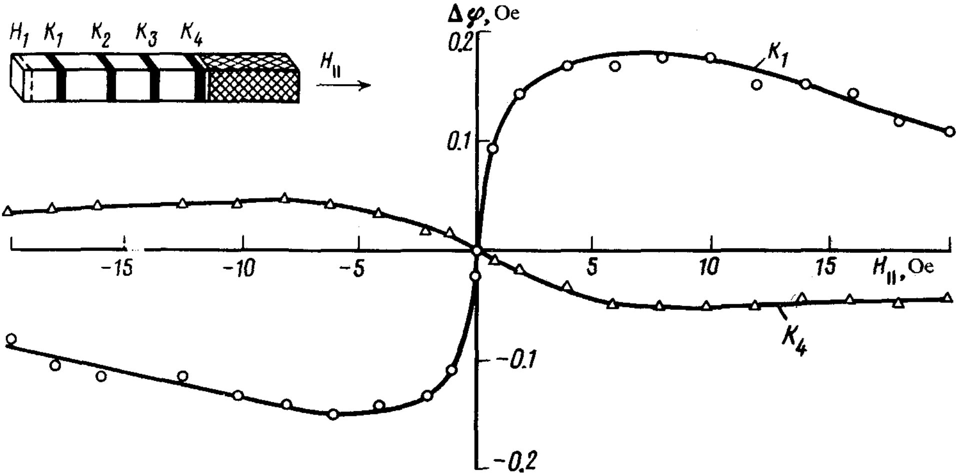

FIG. 1. Effect of the longitudinal magnetic field $H_\parallel$ on the longitudinal magnetic flux $\Delta\phi$ detected by coils K_1 and K_4. The diagram of the sample is drawn to scale.

0.5 cm; this was the "point" heater). The power levels dissipated in these heaters were the same as in the measurements with the ring heater. From Fig. 2 we see that (1) the sign of the effect changes when the point heater is used, but all the characteristic features of the behavior remain the same, and (2) the magnitude of the effect is several times lower in the case of the planar heater. For coils K_2, K_3, and K_4 the behavior is essentially the same in the case of the point heater. As the temperature of the helium bath is raised at a fixed value of $H_\parallel$, the magnitude of the effect falls off. Qualitatively similar results were obtained with a different sample with the same properties.

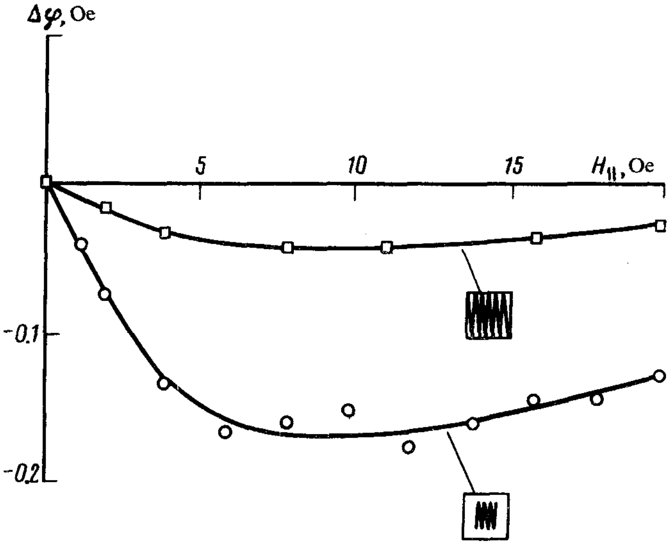

FIG. 2. The behavior $\Delta\phi(H_\parallel)$ for coil K_1 with the different types of heaters.

These results are attributable to the kinetic diamagnetism and paramagnetism predicted by Gurevich.[1] According to Ref. 1, an azimuthal Nernst-Hall current is produced in a long conducting cylinder in an external magnetic field $H_{\parallel}$, directed parallel to the cylinder axis, if there is an axisymmetric temperature gradient ∇T in the cylinder. The direction of this current is antisymmetric with respect to that of $H_{\parallel}$. If the heat flux is directed outward, and the Nernst coefficient is positive, we are seeing a diamagnetic susceptibility; if the heat flux is inward, we are seeing a paramagnetic susceptibility. According to the model of Gurevich, the azimuthal current density i is linear in $H_{\parallel}$ at low values of $H_{\parallel}$; at $H_{\parallel} \approx H_0$, corresponding to $\Omega\tau \approx 1$ (Ω is the cyclotron frequency and τ is the relaxation time), i reaches a maximum; and then it falls off with a further increase in $H_{\parallel}$. In our opinion, the anisotropy of bismuth and its multivalley nature should not cause any qualitative changes in the behavior of $(H_{\parallel})$. For the orientation of the samples in the present experiments the effect should be determined primarily by two electron ellipsoids whose longitudinal axes make an angle of 30° with $H_{\parallel}$. An estimate of H_0 for these samples gives $\approx$ 6 Oe, in approximate agreement with the position of the maximum on the experimental curve of $\Delta\phi\,(H_{\parallel})$. Let us find the prediction of the model regarding the value of $\Delta\phi$ which should arise in these samples during heat flow, specifically, in the cross section passing through the plane of the coil K_1, for low values of $H_{\parallel}$ under these experimental conditions. For low values of $H_{\parallel}$ the magnetic field varies exponentially with distance into the interior of the sample: $\sim \exp r/\delta$, where r is the distance from the surface, $\delta = c/4\pi\, Q_{\perp}\,\sigma\,\Delta T$, $Q_{\perp}$ is the Nernst-Ettinghausen coefficient, c is the speed of light, and σ is the conductivity. At $r << \delta$ for a sample of cylindrical cross section of diameter d we would have $\Delta\phi \approx d/6\delta\, H_{\parallel}$. The values of $Q_{\perp}$ and κ were measured in Refs. 3 and 4, respectively, for samples with properties similar to those of the present experiments. Assuming $Q_{\perp} \approx 3\times10^{-6}$ V/ (Oe·deg), $\kappa \approx 3.3$ W/(cm·deg), and $d = 0.9$ cm, and noting that the transverse gradient ∇T in a cross section passing through the plane of K_1 is roughly one-fifth of ∇T along the sample, we find $\Delta\phi \approx 0.20 H_{\parallel}$. From the experimental results (Fig. 1) for K_1 we have $\Delta\phi \approx 0.15 H_{\parallel}$ for low values of $H_{\parallel}$.

The qualitative agreement between the observed behavior and the predictions of the model regarding the diamagnetism and the paramagnetism and also the order-of-magnitude agreement of the numerical estimates found from the model and the observed results imply that the effect observed in these experiments consists of kinetic diamagnetism and paramagnetism.

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