Observation of the kinetic paramagnetic effect in bismuth

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When heat flows through a sample of bismuth in a longitudinal magnetic field, circulating currents with a paramagnetic sign are observed at liquid-helium temperatures.

Kinetic dia- and paramagnetism, which was predicted by Gurevich,[2] was observed by Zhilyaev.[1] When heat flows through a long sample of bismuth with a resistivity ratio of $\gamma = \rho_{293}\text{K}/\rho_{4,2}\,\text{K} \simeq 430$, which placed into a longitudinal magnetic field $H_{\parallel}$, circulating currents (CC) are observed near its end-faces, i.e., where there is radial heat flux.

In studies of the kinetic dia- and paramagnetism in more perfect samples of bismuth with $\gamma \gtrsim 700$ circulating currents were observed not only near the end-faces, i.e., where there is a radial heat flux but also at the center of the sample.

The procedure for preparing the samples, the method of thermal insulation, and the procedure for performing the measurements are analogous to those used in Ref. 1, the only difference being that after the samples were cut by using the electric spark method and the cold-hardened layer were removed, in order to decrease the concentration of structural defects the samples were annealed in a vacuum of $\simeq 10^{-7}$ mm Hg at a temperature of 265° for one hour. Samples whose axis was parallel to C_1 or C_2 to within 1° were used in the measurements. The results of the measurements for both orientations do not differ qualitatively. The earth's magnetic field was cancelled to within 0.01 Oe.

Figure 1 shows the dependences of the specific magnetic flux $\Delta\varphi = \Delta\Phi / Sn$ on $H_{\parallel}$ for one of the samples, measured at a temperature of $T \simeq 1.3$ K. $\Delta\Phi$ is the change in the magnetic flux through the coils K_1 and K_2, measured by a microwebermeter, when the fixed heat flux is switched on with the help of a heater H, with power $W = 0.064$

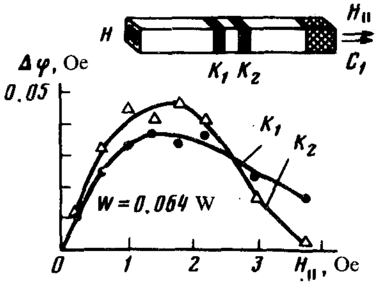

FIG. 1.

W, distributed in a bifillar fashion uniformly along the end-face surface; S is the surface area of the coils (0.9×0.9 cm); and n is the number of loops in the coils. The drawing of the sample retains the correct proportions. The dependences for only one of the orientations of $H_{\parallel}$ are shown, since the experimental dependence turned out to be antisymmetrical.

Since it was of interest to determine whether the effect is related precisely to the longitudinal heat flux, special attention was given to the thermal insulation of the lateral surface and to checking its thermal insulating properties. A special method was used to check the thermal insulating properties. The sample was placed into a cryostat so that its axis was oriented vertically, while the refrigeration line entered at the bottom. The helium was poured in so that its level was located at the upper end of the sample. At $T = 4.2$ K the helium level was gradually brought down to the refrigeration line through evaporation; the Nernst-Ettinghausen emf $E_{\text{n.e.}}$ was measured at the same time. No changes were noted in $E_{\text{n.e.}}$ with a change in level and, therefore, with a change in the properties of the heat-removing medium near the lateral surface of the sample (the thermal conductivity of the gaseous helium at $T \simeq 4.2$ K is approximately three times lower than that of liquid helium), which indicated that heat did not flow out through the lateral surface. The temperature in the cryostat was then reduced to $\simeq 1.3$ K and the absence of a jump in the dependence $E_{\text{n.e.}}(T)$ at the λ point and the independence of $E_{\text{n.e.}}$ on the helium level at $T \simeq 1.3$ K were checked.

The influence of the thermal conditions at the end of the sample on the measured effect was also checked for the purpose of establishing whether it is a result of the radial heat flux at the end of the sample. The geometry of the heater, which was cemented onto the end-face of the sample, was varied so that radial gradients of different signs appeared near the end-face (which was controlled with the help of a special coil that was used to measure the effect near the end-face[1,2]). The magnitude of the effect did not change significantly by changing the geometry of the heater without changing the power, indicating that this effect is attributable to the longitudinal heat flux.

Figure 2 shows for the same sample at $T \simeq 1.3$ K the dependences $\Delta\varphi$ on W for different coils with fixed $H_{\parallel} = 1.75$ Oe. It is evident that the dependence increases with W more rapidly than linearly, which generally could be attributed to overheating relative to the helium bath. A check of overheating with the help of simultaneous

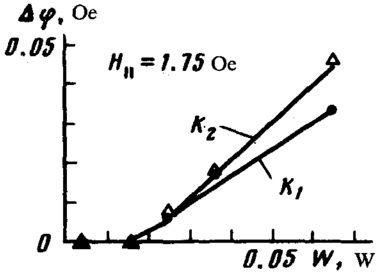

FIG. 2.

measurements of $E_{\text{n.e.}}$ as a function of W for fixed transverse magnetic field gives a linear dependence $E_{\text{n.e.}}(W)$, which indicates that in this range of W the nonlinearity of the observed effect is not attributed to overheating. At large values of $W(\sim 1\text{W})$ $\Delta\varphi$ can reach magnitudes of $\sim H_{\parallel}$ (at $H_{\parallel} \lesssim 1$ Oe). As T is raised, the magnitude of the effect decreases at values of fixed W and $H_{\parallel}$.

We can propose the following mechanism of the effect. When heat flows through the sample, closed circulating currents, oriented along the axis of the sample near its core in one direction and in the opposite direction near the surface, appear in the sample due to the entrainment of charge carriers by phonons and interaction of quasiparticles with the boundaries of the sample. Under conditions when the effective mean free path of charge carriers in our samples is comparable to the thickness of the sample,[3] we can assume that such currents in order of magnitude are $j \simeq \sigma\alpha[(W/\kappa)(L/S)]$, where σ is the electrical conductivity, α is the thermo-emf, κ is the thermal conductivity, and L is the length of the sample. Numerical estimates, using the experimentally obtained kinetic coefficients[3,4] show that in our samples these currents can be strong: $j/W \sim 10^2$ A/cm$^2 \cdot$ W. As was shown in Ref. 5, under conditions such that the electric field E causes a current to flow along the sample which is so strong that its magnetic field appreciably affects the motion of charge carriers, a compensated system of circulating currents, whose magnitude is proportional to E^2, arises in the transverse cross section of the sample. In our case, the role of E is played by the longitudinal temperature gradient, so that the effect increases with W more rapidly than in the linear case. The superposition of an external longitudinal magnetic field apparently leads to unbalancing of the system of circulating currents in the transverse cross section, thereby producing the paramagnetic effect that we observed.

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