Heat-flux-induced transport of a magnetic field frozen in an electron-hole bismuth plasma

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A temperature gradient in a high-purity bismuth sample substantially changes the configuration of a static magnetic field.

Experiments have been carried out on the effect of a temperature gradient on the spatial distribution of a magnetic field along a long ($l \approx 12$ cm), approximately cylindrical (radius $a \approx 0.8$ cm) bismuth single crystal at liquid-helium temperature ($\rho_{300}/\rho_{4.2} \approx 600$). A double-helix heater ($R = 80\ \Omega$) was cemented to the upper part of the sample to produce the heat flux. The upper part of the sample, around which coils were wound to produce and detect the magnetic field, was thermally insulated with a tape of a material similar to Teflon, while the lower part ($\sim 1/3l$) was used for heat removal to the helium bath. The temperature of this bath was 1.4 K, although the temperature gradient raised the temperature at the center of the sample by 0.05–0.4 K. In general, the experimental geometry was the same as that described in Ref. 1. Experiments were carried out in the absence of an external magnetic field. The earth's magnetic field was cancelled within 0.02 Oe.

A magnetic field was produced by passing a direct current through one of the coils. The signals in the other coils were detected either with a microwebermeter (with a time constant ~ 0.2 s) or with an ac nanovoltmeter (in the frequency band 1.5–500 Hz). The output voltages from these instruments were digitized by an analog-to-digital converter with a maximum speed of 1.6 ms. By using these two instruments we were able to measure the magnetic field which arose along the sample after the current was turned on and to follow the temporal characteristics of the process.

Passing a direct current through one of the coils in the presence of a temperature gradient was found to give rise to a magnetic flux in the lower coils, while no signal appeared in the upper coils. Furthermore, no signal was detected in the absence of a temperature gradient.

Figure 1 shows some representative recordings of the output signal from the microwebermeter. We see that the steady-state magnetic flux does not vary over time, but it does increase with increasing heater current and decrease with distance from the transmitting coil. The rise time of the signal is determined by the time constant of the microwebermeter.

Figure 2 shows some time records of the voltage in a receiving coil found with the help of the nanovoltmeter. With increasing heater power the signal arrival time decreases, and the area under the curve increases, while with increasing distance the arrival time increases and the area under the curve decreases.

Figure 3 shows the arrival time of the magnetic-field leading edge corresponding

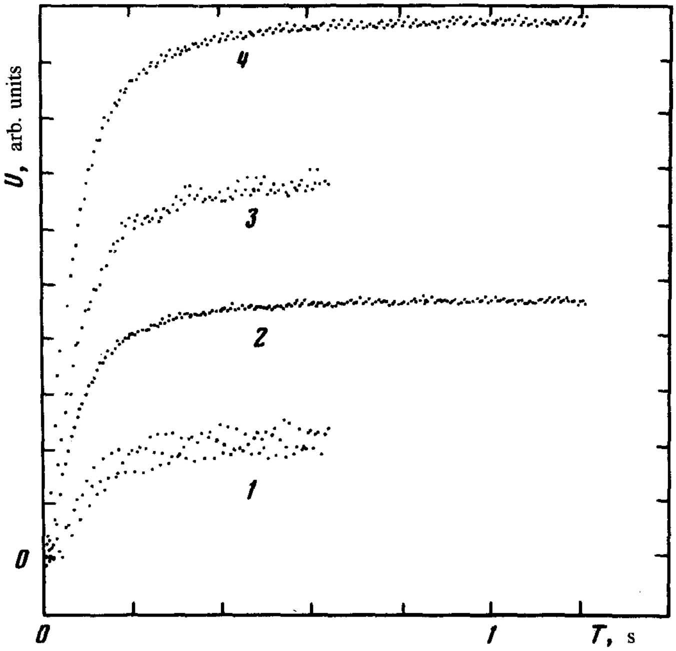

FIG. 1. Time evolution of the output signal from the microwebermeter for coils at distances of 2.2 cm (curves 2 and 4) and 4.7 cm (curves 1 and 3) at two heater currents: 1,2—I_H = 53 mA; 3,4—97 mA.

to the signal peak (Fig. 2) and the magnitude of the magnetic flux for two coils versus the current through the heater.

These experimental results can be interpreted as follows. The annular currents which arise near the transmitting coil move at the velocity of the carrier drift caused

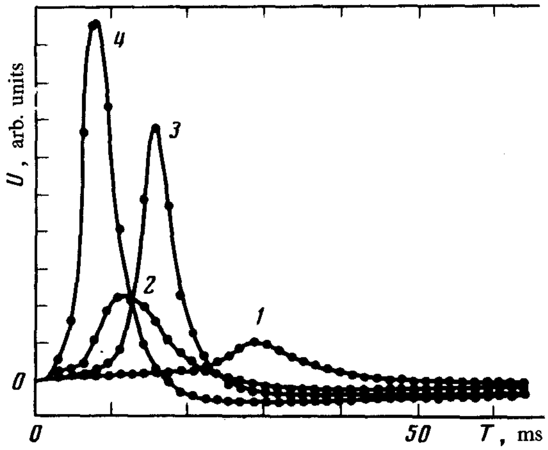

FIG. 2. Time evolution of the voltages in the receiving coils. The curve labels have the same meaning as in Fig. 1.

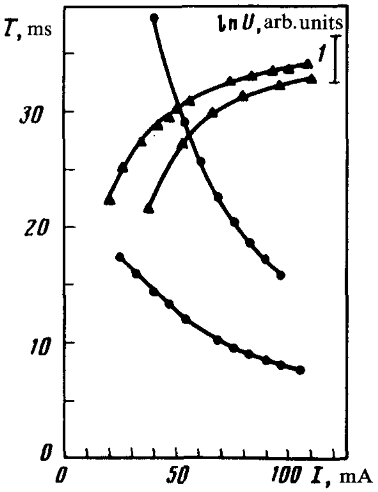

FIG. 3. Signal arrival time and static magnetic field (logarithmic scale) versus the heater current. ●—Arrival time (the upper curve corresponds to the more remote coil); ▲—the magnetic field (the upper curve corresponds to the closer coil).

by the temperature gradient. If this drift velocity is high enough, the annular currents may be displaced a significant distance over the decay time, carrying with them a magnetic field, which is detected by the receiving coil. The scale decay time of the screening currents in a sample of radius a can be estimated from the dispersion relation $k^2 = 4\pi i\sigma\omega c^{-2}$, by setting $\omega = 1/\tau$ and $k = 1/a$. This estimate yields $\tau \approx 0.05$ s. We determine the typical carrier drift velocities in our experiments directly from records similar to those in Fig. 2, finding $v_c = 100$–300 cm/s (this is essentially the velocity of a thermomagnetic wave[1]). The scale decay length (the distance over which the field decreases by a factor of e) is therefore $\bar{x}_0 = v_c\tau = 5$–15 cm, in order-of-magnitude agreement with the experimental results in Fig. 3. According to this model, the time decay of the annular currents is determined by the factor $\exp(-t/\tau)$. Over the time t the carriers are displaced a distance $x = v_c t$, so that the currents and the associated magnetic field are proportional to $\exp(-\rho x/v_c)$. With increasing heater current, the drift velocity increases and the decay decreases; i.e., the ratio of the amplitudes of the signals in the coils should approach unity, as we in fact observe experimentally (Fig. 3).

From the results of these measurements we can estimate the coefficient of the phonon drag of the carriers, defined by $K = v_c/v_{\rm ph}$, where v_c is the carrier drift velocity, and $v_{\rm ph}$ is the phonon drift velocity (the transport velocity of thermal energy). We know that phonons dominate the heat capacity and the thermal conductivity of bismuth at liquid-helium temperatures, so we can find the phonon drift velocity from $\dot{Q} = Ev_{\rm ph}$, where $\dot{Q}$ is the energy flux density, and E is the energy of a unit volume. The energy flux density is determined by the heater power and by the cross-sectional area of the sample. We found the energy per unit volume from the Debye formula for an average temperature at a given heater power. The drag coefficient estimated in this manner is $K = 0.1$ at $T = 1.7$ K ($I_H = 50$ mA). It is determined by the ratio of the rate of carrier-phonon collisions, ν_{ph}, to the total collision rate ν:

$$K = \nu_{\mathrm{ph}} / \nu = (\rho(T) - \rho(0)) / \rho(T),$$

where ρ is the resistivity. The drag coefficient determined in this manner from the measurements of the electrical resistance of samples of approximately the same quality[2] is also ~ 0.1.

The observed transport of the frozen-in magnetic field can be exploited to study the kinetic characteristics of high-purity metals both for directly measuring the average carrier drift velocity at a given temperature gradient and for determining the conductivity.

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