Magnetic-flux quantization in a cylindrical film of a normal metal

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An oscillatory dependence of the resistance of a cylindrical magnesium film on the longitudinal magnetic field has been observed at helium temperatures. In accordance with the predictions of the Al'tshuler-Aronov-Spivak (AAS) theory {B. L. Al'tshuler, A. G. Aronov, and B. Z. Spivak, in Pis'ma Zh. Eksp. Teor. Fiz. **33**, 101 (1981) [JETP Lett. **33**, 94 (1981)]}, the oscillation period corresponds to a change in the magnetic-field flux in the cylindrical cavity by the amount of a flux quantum $\phi_0 = hc/2e$.

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A new, interesting result obtained by AAS[1] is that a macroscopic quantum effect analogous to magnetic-flux quantization in superconductors (the Parks-Little effect[2]) can occur in a system of noninteracting electrons that undergo multiple random elastic collisions as they move along the trajectories within a cylindrical cavity. This effect was identified by taking into account the superposition of the states of electron motion along the same "broken" trajectory in opposite directions. In the presence of a magnetic field the phase length of the trajectory is different for different alternate paths; however, the phase difference for all trajectories in a thin-walled cylinder is the same and equal to $2\oint (e/\hbar c)\,\mathbf{A}ds$, where $\mathbf{A}$ is the vector potential; this produces oscillations of the sample resistance R with the indicated period. The order of magnitude of the oscillation amplitude of the conductivity per unit area of the film $\sigma_\square = L/pR$, where p and L are the perimeter and length of the cylinder, is determined by the universal coefficient $\Delta\sigma_\square = (e^2/\pi^2\hbar) = 2.47 \times 10^{-5}\ \Omega^{-1}$.

Inelastic collisions and scattering by magnetic impurities destroy the effect, which decreases exponentially if $L_\phi \ll p$, where $L_\phi = \sqrt{l_e l_\phi}$, l_e is the mean free path for elastic collisions, and l_ϕ is the same for processes that destroy the phase coherence.

We have undertaken a search for the AAS effect. Magnesium, in which superconductivity is absent down to at least 0.05 K,[3] was chosen as the material for fabricating the samples. The high vapor pressure of magnesium, which was sublimed from the solid state to fabricate the films, reduced the danger of contaminating the film. The presence of diamagnetic magnesium oxide did not result in an incoherent scattering of electrons at the surface. The initial material had a ratio $\rho(20°\ \mathrm{C})/\rho(4.2\ \mathrm{K}) \approx 10^3$ and contained no more than $10^{-3}\%$ sodium and zinc. The film was condensed on the surface of a quartz filament with a diameter 1.5-2 μm and $L = 1$ cm, which was attached by means of BF cement to two platinum wires that were used as cur-

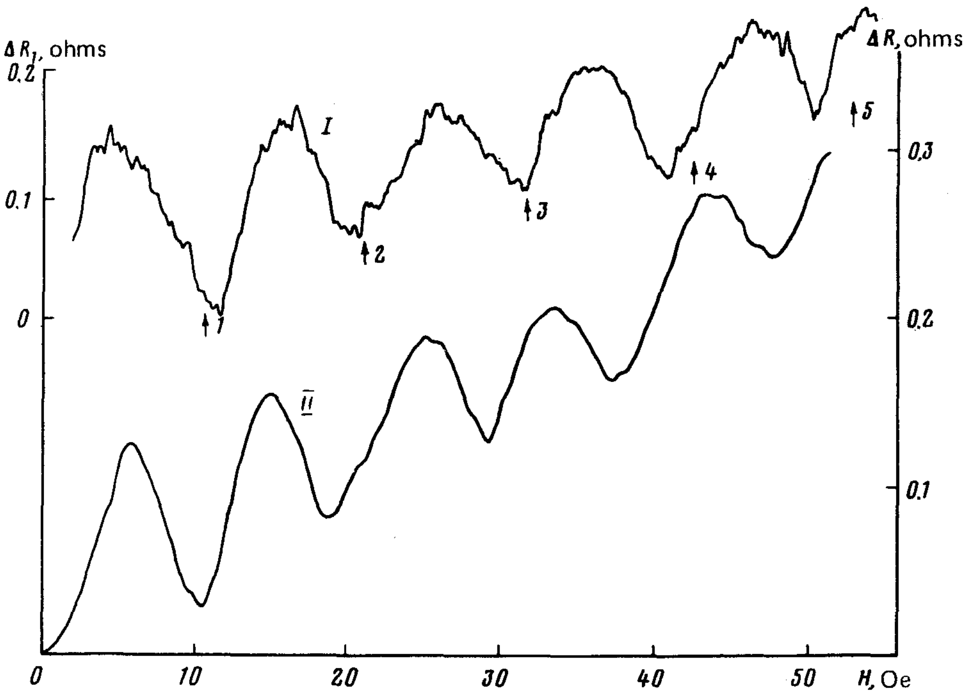

FIG. 1.

rent and potential leads.

Since magnesium condenses poorly at room temperature, the walls of the evaporation chamber were cooled with liquid nitrogen and the evaporation occurred in an atmosphere of pure helium at a pressure of ~10^{-3} mm Hg.

We have investigated two samples, I and II, with R(20° C) values of 12.8 and 15.3 kΩ, which were measured after the samples were immersed into a Dewar filled with helium gas. Sample I was transferred to the Dewar in free air; sample II was transferred in an atmosphere of technical-grade helium. The value of R was measured with an R345 dc potentiometer at a current of 10 μA using an F118 nanoammeter as the null detector. At 4.2 K $R_{I} = 9.2$ kΩ and $R_{II} = 12.3$ kΩ.

The resistance of the samples increased by 7 and 3 ohms, respectively, after cooling them down to 1.12 K.

The dependence of R_I and R_{II} on the longitudinal field at $T = 1.12$ K is shown in Fig. 1. The difference in the noise levels is attributable to the sample properties. The arrows indicate the field values corresponding to a whole number of flux quanta Φ_0 in the cylinder cross section; these values were calculated for sample I, whose 1.58-μm diameter was measured with the aid of an electron microscope. The oscillation amplitude is of the order of magnitude of the predicted (~1 ohm) value. The oscillations gradually smoothed out with a further increase in the field. Figure 2 shows the monotonic $R_{II}(H)$ dependence plotted from the experimental points for

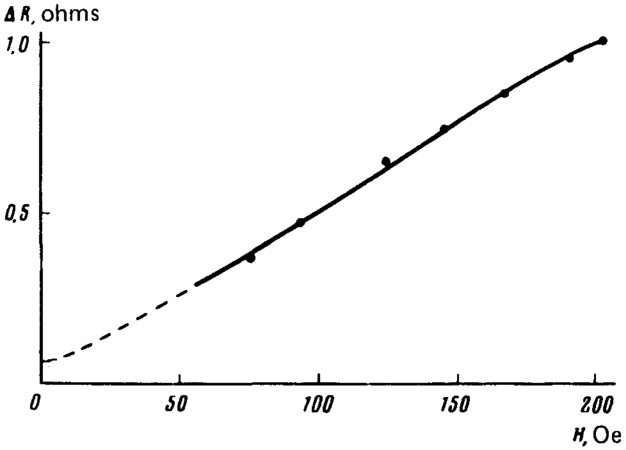

FIG. 2.

$H > 50$ Oe and $T = 1.12$ K (the dashed line represents the curve for $H < 50$ Oe averaged over the oscillations). The temperature dependence of the effect was not investigated; we noticed however, that the amplitude decreased by a factor of about 2.5 when the sample was warmed to 2.2 K.

In the discussion of our results, we raised the following question. To what extent does the interaction of electrons with each other and the spin-orbit interaction with the impurities in a real metal influence the magnitude and sign (phase) of the effect? We should note that there is a direct correlation in magnitude and sign between the oscillation effect in a multiply connected conductor and the magnetoresistance (MR) of plane films in the same region of weak fields. Larkin[4] pointed out that the coefficient $\alpha - \beta(T)$ enters in the expression for the transverse MR, where $\alpha = 1$ for a small spin-orbit interaction of electrons with impurities, and $\alpha = -1/2$ in the opposite case. The quantity $\beta(T) > 0$, which is determined by interelectron interaction, increases significantly in superconductors as $T \to T_c$ $(T > T_c)$; however, $\beta > 0$ even in nonsuperconducting materials, and $\beta \sim 10^{-2}$ in good metals.

In 1974, Shablo, Narbut, Tyurin, and Dmitrenko[5] had observed a flux-quantization effect in aluminum down to $T/T_c \sim 5$ with $\beta = 0.5$; the quantity α must therefore be taken into account in the interpretation of their results. It is also important that the magnitude of the effect is determined by the ratio of the sample perimeter to L_ϕ, rather than the coherence length $\xi(T)$; this probably eliminates the disagreement with theory that was mentioned in Ref. 5.

By assuming in our experiments that $T_c = 0.05$ K for magnesium, we have $\beta = 0.1$ at $T = 2.2$ K. An increase in the resistance of our films with decreasing T is consistent with the assumption that the films are a normal metal. We note that for cylindrical cadmium films with $R = 3$ kΩ, in which a well-defined flux-quantization effect was observed, $R(4.2\text{ K}) - R(1.12\text{ K}) = 2$ ohms. We can assume, therefore, that $|\alpha| > \beta$ in our magnesium films. If we take into account the phase of the oscillations, which have a minimum at $H = 0$, and the sign of the longitudinal MR (Fig. 2), we can assume that $\alpha < 0$ and possibly close to -1/2. The longitudinal MR observed by us can be reconciled with the theory[6] if $aL_\phi \sim 10^{-9}$ cm^2, where a is the film thickness; this corresponds to the predictable estimates such as $a \sim 10^{-5}$ cm and $L_\phi \sim 10^{-4}$ cm, obtained under the conditions of our experiment.

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