Isotropic quantum magnetoresistance in cold-deposited cesium films

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Combined measurements in perpendicular and parallel magnetic fields have made it possible to determine the localized part of the magnetoresistance at low temperatures and to obtain new results on the inelastic and spin-orbit scattering. A new quantum magnetoresistance, which may be associated with the electron-electron interaction, has been observed.

It was found in Ref. 1 that in cold-deposited cesium films the plot of the conductivity $G \equiv 2\pi^2\hbar/e^2R$ versus the magnetic field, directed at right angles to the plane of the film, cannot be described by the theoretical formula for localization of noninteracting electrons[2]

$$\delta G \equiv G(H_\perp) - G(0) = \ln(H_\perp H_3^{1/2}/H_2^{3/2}) + \frac{3}{2}\Psi\left(\frac{1}{2} + \frac{H_2}{H_\perp}\right) - \frac{1}{2}\Psi\left(\frac{1}{2} + \frac{H_3}{H_\perp}\right), \qquad (1)$$

where $\Psi(x)$ is a digamma function, and the characteristic values of the magnetic fields $H_2 = H_i + 4/3H_{so}$ and $H_3 = H_i + 2H_s$; the subscripts refer to the inelastic scattering (i), spin-orbit scattering (so), and spin scattering (s).

The divergence of the experimental curves from theoretical dependence (1) increases with decreasing temperature as the function $h \equiv g\mu_B H/kT$. We can thus assume that in cesium films the measured magnetoresistance is caused by the interaction[3]

$$\delta G(H, T) = \frac{\lambda}{2(\hbar D)^{d/2-1}} \int_0^\infty d\omega \frac{\partial^2(\omega c \tanh(\omega/2T))}{\partial^2\omega}$$

$$\times \{\Phi_d(\omega + g\mu_B H) + \Phi_d(\omega - g\mu_B H) - \Phi_d(\omega)\}. \qquad (2)$$

In the two-dimensional case $d = 2$, $\Phi_2(\omega) = \ln(\omega)$ this formula is a function of h and does not depend on the diffusion coefficient D.

A comparison of the dependences measured experimentally in Ref. 1 showed them to be in qualitative agreement with expression (2). It should be noted, however, that it is very difficult to clearly distinguish these two effects solely on the basis of the measurements in a perpendicular magnetic field. Since only $H_\perp$ appears in expression (1), and since expression (2) does not depend on the orientation of H, a direct observation of interaction (2) can be achieved experimentally by measuring the same film in a perpendicular and parallel magnetic fields.

Our experimental procedure is similar to that described in Refs. 1 and 4. The

perpendicular magnetic field up to 5 T was produced by a superconducting solenoid and the parallel magnetic field up to 3 T was created by a superconducting Helmholtz coil. The detector, mounted on a sliding rod, could be moved from the solenoid to the coil in a helium bath. The measurements and the analysis of the experimental data were carried out on an IBM AT computer.

We studied newly deposited cesium films of various thicknesses, formed on a glass substrate at liquid-helium temperature. The most reliable results were obtained in the resistance range 20 000–100 Ω. The thinner films had a high temperature resistance coefficient. The temperature instability of the helium bath affected the accuracy of the measurements. The magnetoresistance was far too low in thicker films.

As was hypothesized, the parallel magnetic field gave rise to a positive magnetoresistance (Fig. 1). The difference between the curves for magnetoresistance in the perpendicular and parallel magnetic fields (Fig. 1) was well approximated by the localization formula (1), allowing us to accurately determine the values of H_i and H_{so}. As expected, the value of H_s turned out to be zero within the measurement error, since the method[1,4] of fabricating cesium films precluded the possibility of the presence of any magnetic impurities.

A surprising result was that τ_i^{-1} and τ_{so}^{-1} were found to depend on the temperature in all the tested films. The frequency of the loss of phase coherence of the wave function of an electron, $\tau_i^{-1} = \hbar c/4eDH$, in disordered films is determined by the electron-electron scattering[5]

$$\hbar\tau_i^{-1} = kT\frac{e^2R}{2\pi\hbar}\ln\frac{\pi\hbar}{e^2R} \tag{3}$$

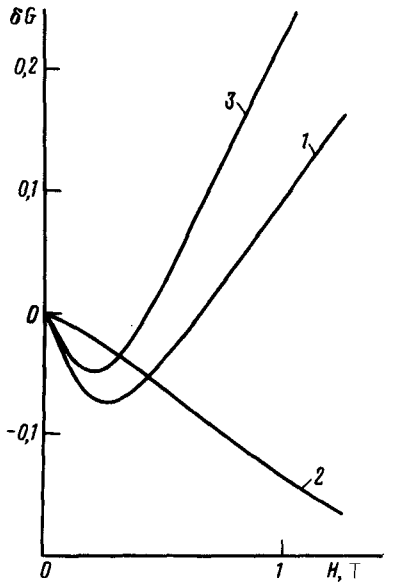

FIG. 1. Magnetoresistance curves for a film with $R = 1033$ Ω, measured at $T = 1.34$ K. *1*—$H_\perp$; *2*—$H_\parallel$; *3*—the difference between 1 and 2, which matches at the scale of this figure the approximation based on Eq. (1).

and must vary considerably with resistance. Experimentally, we found the coefficient of kT on the right side of Eq. (3) to be 1.4 ± 0.4 for all films. The probability for spin-orbit scattering in each electron collision should be on the order of $(\alpha z)^4$, where α is the fine-structure constant, and z is the nuclear charge. This gives us the large values of τ_{so}^{-1} and H_{so} for cesium films. The spin-orbit scattering was found to be not only smaller by several orders of magnitude but also independent of the mean free path.

The differences between the films which we studied and the results of other investigators can be attributed to the thinner films and to their greater homogeneity, as well as to the small content of impurities. In cold-deposited cesium films even several tens of angstroms thick, all of the scattering occurs at the surface, rather than by defects or impurities inside the film.[1,4] There is reason to assume that the probability for spin-orbit scattering is smaller by a factor of $(v_F/c)^4$ (v_F is the Fermi velocity) in the case of surface reflection. The value $\tau_{so}^{-1} \approx 2 \times 10^{11}\ s^{-1}$ which we measured can be attributed to scattering by rubidium atoms: Rubidium is the only impurity which can be present in a film in appreciable quantities.

The magnetoresistance in a parallel field turned out to be surprisingly large. It is not only on the order of the localized part of the magnetoresistance but may even exceed it, so that the magnetoresistance of thin films in a perpendicular field changes sign when the temperature is lowered. In addition to a large absolute value (which is tens of times larger than the theoretical estimate, $\lambda = -0.18$), the shape of the magnetoresistance curve differs from that found from Eq. (2), which cannot be used to approximate the shape of these curves at any value of λ. The curves measured at different temperatures do not fully coincide in the coordinates $(G, g\mu_B H/kT)$ and

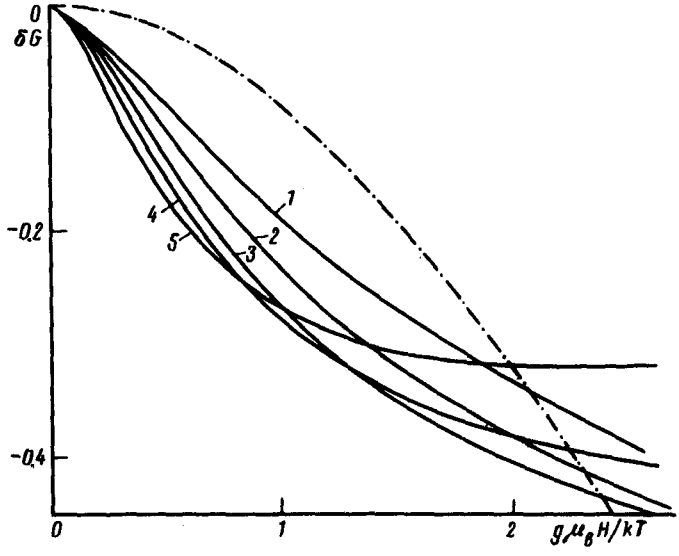

FIG. 2. Magnetoresistance curves for the films, measured at 1.3 K. *1*—3488 Ω; *2*—1438 Ω; *3*—687 Ω; *4*—337 Ω; *5*—166 Ω. Dot-dashed curve—Eq. (2) for $\lambda = -1$.

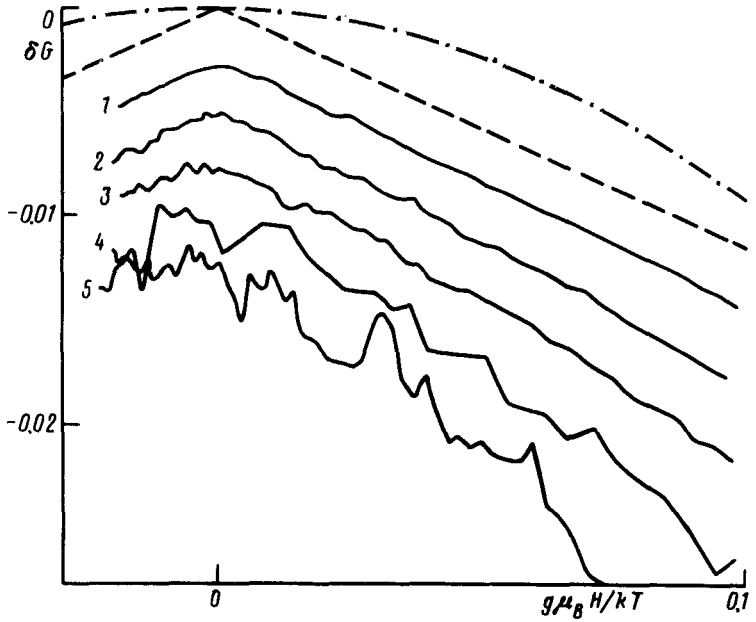

FIG. 3. The same as in Fig. 2. Dashed curve—$\delta G = 0.12\ |g\mu_B H/kT|$; dot-dashed curve—Eq. (2) for $\lambda = -10$. The curves are shifted along the ordinate.

become saturated in large fields and at high temperatures. These deviations cannot be attributed to the presence of a part of the localization magnetoresistance due to microscopic irregularities of the substrate surface, because the initial parts of the curves match each other. The best match occurs at low temperatures.

The magnetoresistance curves measured for films of various thicknesses also do not match (Fig. 2), whereas Eq. (2) does not depend on the resistance or the diffusion coefficient in the $2D$ case. In low fields ($H < 1$ T) magnetoresistance increases with increasing thickness in proportion to $D^{1/3}$, consistent with the dimensionality $d = 4/3$. Since the length scales of electron-electron interaction are shorter than the localization lengths, there can in principle be a situation in which the film behaves in a $2D$ manner with respect to the localization effects and has a smaller dimensionality (of a percolation cluster) with respect to the electron-electron interaction. This situation could explain the large amplitude of the effect and the dependence on D. Estimates show, however, that a situation of this sort can occur only in a narrow range of small thicknesses, while the D dependence applies to all films (Fig. 2).

An attempt to study in greater detail the region of small fields, in which a parabolic asymptotic curve $\delta G \approx H^2$ should be seen, led to a new, surprising result. In small fields $H < 0.1$ T the magnetoresistance was found to be linear in the field $\delta G \approx |0.12h|$ (Fig. 3). Theory[7] shows that magnetoresistance is linear in the region of activated conductivity, $R \gg 2\pi^2\hbar/e^2$, but in the region which we studied, $R \ll 2\pi^2\hbar/e^2$, it should be shorted out by the metallic conductivity.

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