# Effect of a magnetic field on weak localization and Coulomb interactions in acceptor graphite intercalation compounds

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The magnetic field and temperature dependence of the resistance of low-stage acceptor graphite fiber intercalation compounds have been investigated at low temperature. The magnetoresistance curves are well described by the weak-localization theory in two-dimensional disordered systems. From the temperature and field dependence of the magnetoresistance, values of the temperature-dependent inelastic scattering time are obtained. It is shown that both hole-hole and hole-phonon scattering determine the inelastic lifetime of the conduction carriers. The contributions from the weak localization and Coulomb interaction effects to the logarithmic temperature dependence of the resistance have been separated.

## I. INTRODUCTION

The transport properties of two-dimensional (2D) weakly disordered electronic systems have been the subject of great interest in the last few years. Theoretical and experimental investigations of the low-temperature electrical resistivity of a variety of quasi-2D metallic systems have led to the observation of new and nonclassical metallic effects. The prominent feature of all these systems is a small logarithmic increase of their resistance with decreasing temperature at low temperature.

Two mechanisms have been proposed to account for the observed phenomena. The first is weak-electron localization[1-3] due to constructive quantum interference between elastically backscattered partial electron waves. The second is the electron-electron Coulomb interaction,[4,5] which is enhanced in the presence of defect scattering.

As both theories predict $\ln T$ dependences of the resistance which are comparable in magnitude, the measurement of the temperature dependence of the resistance is not sufficient to distinguish between these two mechanisms. However, for other transport properties such as the magnetoresistance,[3,6] the Hall effect,[4,7] and the thermoelectric power,[8] the predictions of the two theories are different. Low-field magnetoresistance measurement is the most widely used method to discriminate with some success between these two mechanisms. Indeed, the application of a magnetic field perpendicular to the 2D carrier system produces a phase difference between partial waves which interfere constructively in the backward direction in a zero magnetic field, so the effect of weak localization is reduced and, as a result, a small negative magnetoresistance is observed. On the other hand, the logarithmic behavior due to interaction effects is not affected by the application of a low magnetic field.

A large number of systems has been investigated experimentally, including metal films, inversion layers, and metallic superlattice systems. For recent comprehensive reviews on the subject, Refs. 9–11 should be consulted.

It is well known that the insertion of molecular acceptor species between graphite layers is accompanied by a large increase of the hole density due to the charge transfer, which confers a metallic behavior to the material, as far as the electronic properties are concerned. Moreover, the anisotropy of electronic conductivity is considerably enhanced, exceeding $10^6$ in most low-stage acceptor graphite intercalation compounds (acceptor GIC's), so that the quasi-two-dimensional character of these compounds is accentuated.[12-14] The stage of a compound refers to the number of graphitic layers between two successive intercalate layers. Recently, anomalous behaviors, ascribed to localization and interaction effects, have been observed in the low-temperature electrical resistivity of low-stage acceptor GIC's.[15,16] A logarithmic increase of the resistivity with decreasing temperature and a negative magnetoresistance were reported on a set of acceptor GIC's with different host graphite materials and intercalates. The magnitude of the effects and the temperature at which the minimum in resistance occurred were directly related to that of the residual resistivity of the compound.[16] It was also clearly demonstrated that acceptor GIC's are ideally suited for the study of weak localization and interaction phenomena since, as a result of the large number of different types of graphite host materials that may be intercalated, the amount of disorder may be controlled in these materials. Also one may control the charge transfer, i.e., the electronic distribution, by using different intercalates and controlling the intercalation processes.

The paper is organized in the following manner. In Sec. II we give theoretical equations for the 2D resistivity and magnetoresistance that are needed for the subsequent discussion of the experimental results. In Sec. III we first report on the low-temperature dependence of the magnetoresistance of low-stage acceptor GIC's and then analyze the data by using the full expressions of localization and interaction effects. The contributions to the logarithmic temperature dependence of the resistance

 

from weak localization and from Coulomb interaction effects are separated. Finally, in Sec. IV, we present our conclusions.

## II. THEORETICAL BACKGROUND

The temperature dependence of the resistance of two-dimensional disordered systems in zero magnetic field, due to the occurrence of both weak localization and electron-electron interaction effects, is given by[3,4]

$$\frac{\delta R(T)}{R(T_0)} = -\frac{e^2}{2\pi^2\hbar} R_\Box (\alpha p + \gamma) \ln\left[\frac{T}{T_0}\right], \tag{1}$$

where $\delta R(T) = R(T) - R(T_0)$ and $R_\Box$ is the resistance per square—the measured 3D residual resistivity divided by the $c$-axis repeat distance $l_c$ (Refs. 15 and 17)—at the temperature $T_0$ and $\alpha$, $p$, and $\gamma$ are numerical factors.

The localization contribution is determined by the product $\alpha p$ while the electron-electron interaction contribution is given by $\gamma$. $T^p$ is the temperature dependence of the inverse of the inelastic scattering time $\tau_i$. The physical meaning of the inelastic scattering time is that for times shorter than $\tau_i$ the phase coherence of interfering complementary waves, which is the source of weak localization effect, is maintained.[2] The power $p$ depends on the dominant inelastic scattering mechanism, the dimensionality ($d$) of the system, and on whether one is in the clean or dirty limit. For electron-electron scattering in weakly disordered metals it was found that $p = d/2$ in contrast with the result $p = 2$ predicted in the clean limit whatever the dimensionality of the system.[18–21] For electron-phonon scattering[10,22–24] $p$ ranges from 2 to 4 in the dirty limit at low temperatures. The value of $\alpha$ depends on the effect of spin-dependent processes due to magnetic scattering and spin-orbit coupling. In the frame of the theory of Hikami *et al.*,[3] magnetic impurities destroy the phase coherence of constructively interfering complementary waves, thus suppressing the localization. On the other hand, spin-orbit scattering leads to a destructive interference in the backward direction, thus creating an antilocalization effect. The magnetic scattering and the spin-orbit scattering lead, respectively, to scattering times $\tau_s$ and $\tau_{s.o.}$ which are both assumed to be temperature independent.

In the limit where $\tau_i \ll \tau_{s.o.}, \tau_s$, $\alpha = 1$; for $\tau_s \ll \tau_i$, $\tau_{s.o.}$, $\alpha = 0$; and if $\tau_{s.o.} \ll \tau_i, \tau_s$, $\alpha = -\frac{1}{2}$. Since $\tau_i$ is temperature dependent, $\alpha$ takes different values according to the temperature range considered. The strength of the electron-electron interaction contribution[4,25] is given by $\gamma$, where $\gamma$—which is a measure of the screening by other charge carriers—has a value close to 1 in the limit of weak screening.

A measurement of the temperature dependence of the resistivity does not allow us to determine the relative importance of weak localization and interaction effects. We shall see now that the measurement of the magnetoresistance at various temperatures does allow such a separation.

The weak localization theory for 2D systems[3] predicts that a uniform perpendicular magnetic field $H$ weakens the localization effect when the characteristic magnetic time,

$$\tau_H = \frac{\hbar}{4eDH}, \tag{2}$$

becomes comparable to or shorter than $\tau_i$. In this expression $D = (v_F^2 \tau_0)/2$ is the 2D diffusion constant, $\tau_0$ is the elastic scattering time due to defect scattering, and $v_F$ is the Fermi velocity. It is convenient to express each characteristic time $\tau_K$ of the weak localization theory in terms of a characteristic magnetic field $H_K$ through the relation

$$H_K = \frac{\hbar}{4eD\tau_K}, \tag{2'}$$

where $K$ labels the different scattering processes. $H_0$, $H_i$, $H_s$, and $H_{s.o.}$ are, respectively, the characteristic elastic scattering field, the characteristic inelastic scattering field, the characteristic magnetic impurity field, and the characteristic spin-orbit field. For a magnetic field $H$ much higher than $H_i$, the logarithmic increase of the resistance with decreasing temperature due to weak localization effects is suppressed.

According to the weak localization theory of Hikami *et al.*, the magnetoresistance of a quasi-2D system, in which the magnetic field $H$ is oriented perpendicular to the 2D carrier system, is given by[3,26]

$$\frac{\Delta R(H,T)}{R(0,T)} = -\frac{e^2}{2\pi^2\hbar}\lambda R_\Box \left\{ \tfrac{3}{2}\Psi\left(\tfrac{1}{2} + H_1(T)/H\right) - \tfrac{1}{2}\Psi\left(\tfrac{1}{2} + H_2(T)/H\right) + \ln H + \tfrac{1}{2}\ln[H_2(T)] - \tfrac{3}{2}\ln[H_1(T)] \right\}, \tag{3}$$

where $\Delta R(H,T) = R(H,T) - R(0,T)$, $\Psi$ is the digamma function, and where

$$H_1(T) = H_i(T) + \tfrac{4}{3}H_{s.o.} + \tfrac{2}{3}H_s,$$

$$H_2(T) = H_i(T) + 2H_s.$$

The dimensionless factor $\lambda$ should be unity for perfectly homogeneous systems.[27] The general predictions of the theoretical expression may be summarized in some limiting cases such as the following ones. If $H_i \gg H_s, H_{s.o.}$ the magnetoresistance is negative and its temperature dependence reflects that of $1/\tau_i$. When magnetic impurity scattering is important ($H_s \gg H_{s.o.}, H_i$) the magnetoresistance is negative and temperature independent. If spin-orbit scattering dominates ($H_{s.o.} \gg H_i, H_s$), the sign of the magnetoresistance is reversed from negative to positive.

For strictly 2D systems, no magnetoresistance is predicted when the magnetic field is parallel to the plane. However, for a thin film of finite thickness, a negative magnetoresistance also exists in a parallel field but appears at much higher fields than the perpendicular magnetoresistance. The terms "parallel" and "perpendicu-

lar" are relative to the orientation of the magnetic field with respect to the 2D system. As a result, in the low magnetic field range, the magnitude of the parallel magnetoresistance is generally much smaller as compared to the perpendicular magnetoresistance.[28]

## III. ANALYSIS OF THE RESULTS

We have previously reported[15,16] the results of measurements of the temperature dependence of the zero-field resistivity and that of the field dependence of the magnetoresistance at 4.2 K. The samples in which we are interested here are Union Carbide mesophase pitch-based fibers of the type P100-4 intercalated with $CuCl_2$ (stage 1–2) and of the type VSC-25 intercalated with $CoCl_2$ (stage 2). The characteristics of the samples are given elsewhere,[16] while the experimental procedure is described in more detail in Ref. 29.

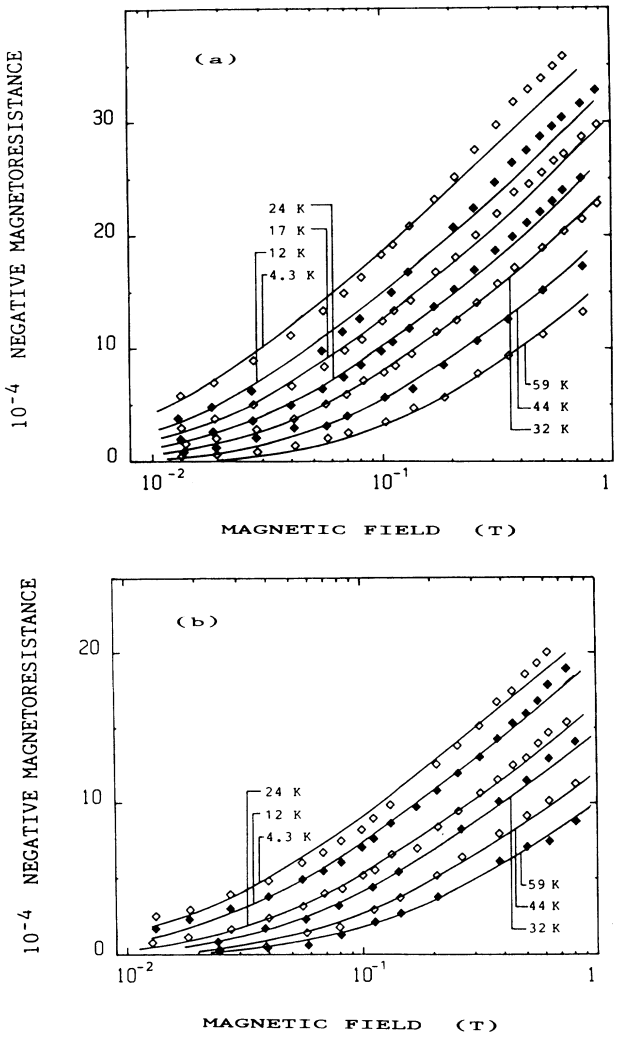


FIG. 1. Transverse negative magnetoresistance vs magnetic field for (a) a P100-4 $CuCl_2$ compound and (b) a VSC-25 $CoCl_2$ compound at various temperatures. The solid lines are calculated from a best fit using the weak-localization theory [relations (3) and (4)].

### A. Magnetic field dependence of the resistance

We first consider the magnetoresistance results and compare them to the above-mentioned theories. In Figs. 1(a) and 1(b) we present new magnetoresistance curves obtained for two samples at different temperatures and as a function of a magnetic field perpendicular to the fiber axis. It may be seen that the magnetoresistance is negative and its magnitude increases with decreasing temperatures. These features are consistent with the localization effect. Of particular importance is the orientation of the magnetic field with respect to the 2D carrier system. The use of the weak localization relation (3) requires the magnetic field to be perpendicular to the 2D system. In our case, a difficulty comes from the arrangement of the graphite layers which constitute the 2D system in the fiber cross section.

For a magnetic field perpendicular to the fiber axis, the angle between the magnetic field and a set of parallel graphite planes is different from one set to another. However, since the degree of crystalline orientation of the pristine material is rather small and is still weakened due to the intercalation processes, the angular dependence of the magnetoresistance, which indicates the cross-sectional arrangement, is weak in intercalated pitch fibers.[15] In the following, we shall assume an isotropic distribution of the graphite layers in our samples. So, when the magnetic field is perpendicular to the fiber axis, the measured magnetoresistance includes contribution from both parallel and perpendicular magnetoresistances.

Let us estimate first the contribution to the magnetoresistance due to the parallel orientation. In graphite fibers, the graphite layers are oriented parallel to the fiber axis. Since, in the frame of weak-localization theory, the magnetoresistance does not depend on the

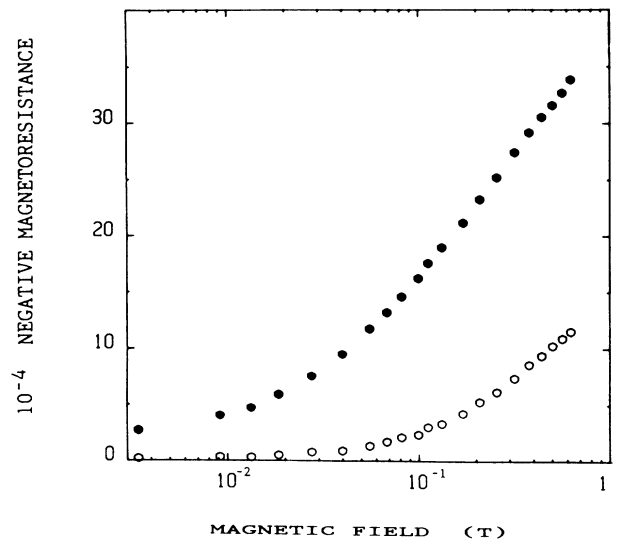


FIG. 2. Negative magnetoresistance as a function of magnetic field for a P100-4 $CuCl_2$ compound at 7.6 K. Perpendicular (●) and parallel (○) magnetic fields with respect to the fiber axis have been considered.

orientation of the current relative to the magnetic field, parallel magnetoresistance measurements may be performed by applying the magnetic field parallel to the fiber axis. Figure 2 shows typical magnetoresistance curves for a magnetic field perpendicular and parallel to the fiber axis at a given temperature. As expected, the magnetoresistance appears at much higher field for a parallel than for a perpendicular magnetic field.

However, certain difficulties are raised in the quantitative experimental study of the magnetoresistance when the magnetic field is parallel to the fiber axis. Indeed, a small deviation ($\approx 5°$) from parallelism between the magnetic field direction and the fiber axis may cause the observed magnetoresistance to be the result of the perpendicular magnetic field component relative to the fiber axis. This is supported by the fact that such a behavior is observed whatever the temperature considered. Moreover, the graphite layers are not strictly parallel to the fiber axis. Thus, in the following, we assume that the magnitude of the measured magnetoresistance depends only on the field component perpendicular to the graphite planes. A detailed analysis of the magnetoresistance curves at many temperatures enables us to determine the different characteristic magnetic fields.[9,10]

In our case, comparison between experimental results and theoretical predictions requires integrating Eq. (3) over the isotropic distribution of the cross-sectional graphite layer arrangement in the fiber (see Appendix):

$$\left[\frac{\Delta R(H,T)}{R(0,T)}\right]_{\text{expt}} = \left[\frac{1}{\pi}\right]\int_{-\pi/2}^{\pi/2}\left[\frac{\Delta R(H\cos\theta,T)}{R(0,T)}\right]_{\text{theor}} d\theta \ , \quad (4)$$

where $[\Delta R(H)/R(0)]_{\text{theor}}$ is the magnetoresistance given by the theoretical expression (3) and $[\Delta R(H)/R(0)]_{\text{expt}}$ is the measured magnetoresistance with the magnetic field perpendicular to the fiber axis.

Before quantitatively analyzing our data, we would like first to discuss the main features and trends we observe. This gives us information on the relative magnitude of the characteristic fields $H_i$, $H_s$, and $H_{\text{s.o.}}$.

(i) Below 4.2 K, the magnetoresistance is nearly temperature independent (not shown in Fig. 1), which suggests that magnetic scattering dominates in this temperature range.

(ii) The pronounced temperature dependence of the magnetoresistance for $T > 10$ K implies that in this temperature region the importance of inelastic scattering due to phonons and other holes becomes comparable to other phase-coherence loss mechanisms in a zero magnetic field.

(iii) For each temperature, the magnetoresistance is always negative down to very low magnetic field. This means that spin-orbit scattering is not important in our samples. Thus we take $H_{\text{s.o.}} = 0$ whatever the temperature range considered.

Best fits were obtained by assuming that the temperature dependence of $H_i(T)$ is represented by a power law of the form $AT + BT^2$. As shown in Fig. 1, the results

TABLE I. Parameters relative to electrical resistivity measurements of the samples. $\lambda$, $A$, $B$, and $H_s$ are the parameters used in fitting the transverse magnetoresistance data. RRR is the residual resistivity ratio.

| | $\rho_{3D}$(4.2 K) ($\mu\Omega$ cm) | $R_\square$(4.2 K) ($\Omega/\square$) | RRR | $\lambda$ | $A$ ($10^{-5}$ T/K) | $B$ ($10^{-6}$ T/K$^2$) | $H_s$ ($10^{-4}$ T) | $D$ ($10^{-2}$ m$^2$/s) | $10^3\Delta R/R\|_{\text{decade}}$ | $\gamma$ |
|---|---|---|---|---|---|---|---|---|---|---|
| P100-4 $CuCl_2$ (stage 1–2) | 33 | 300 | 1.17 | 0.2 | 6.7 | 2.0 | 14 | 0.68 | 3.46 | 0.35 |
| VSC-25 $CoCl_2$ (stage 2) | 36 | 285 | 1.23 | 0.15 | 10.1 | 2.5 | 33 | 0.60 | 1.02 | 0.08 |

agree fairly well with the predictions of localization theory. The values obtained for the adjustable parameters $A$, $B$, $\lambda$, and $H_s$ in the fit to relation (4) are given in Table I for both samples.

We suggest that the values obtained for $\lambda$ are the result of structural inhomogeneities caused by the presence of Daumas-Herold domains[30] and the presence of highly resistive regions which are not intercalated. Absolute values for the scattering times can only be calculated using relation (2) when the diffusion constant $D$ is well defined. We determined $D$ using the formula $D=\frac{1}{2}v_F l_0$, which is strictly valid only for the case of two-dimensional diffusion. In the frame of the Blinowski-Rigaux 2D electronic band model[31] for a low-stage (1 or 2) GIC acceptor, $v_F \cong 8\times 10^5$ m/s while the value of the mean free path for defect scattering $l_0$ is calculated using the value of the low-temperature resistivity.[17] This allows a reasonable estimation of $D$, given Table I. We found for a P100-4 $CuCl_2$ compound

$$1/\tau_i = 2.9\times 10^9 T + 8.4\times 10^7 T^2$$

and for a VSC-25 $CoCl_2$ compound

$$1/\tau_i = 3.9\times 10^9 T + 9.6\times 10^7 T^2 \ .$$

We now compare these results with those of the ideal resistivity $\rho_i$—the temperature-dependent term of the resistivity—previously performed in low-stage acceptor GIC's.[17,29] Such a comparison should be made with reservation since $\tau_i$, the dephasing time due to inelastic scattering, and $\tau_{i\,\mathrm{trans}}$, the transport relaxation time, may be unequal: for example, $\tau_i$ is crucially dependent on the forward scattering while $\tau_{i\,\mathrm{trans}}$ is not. It was shown that the functional form of the ideal resistivity is well represented by a power law of the form $\alpha_t T+\beta_t T^2$ from 3 to 300 K (Ref. 29) and that the magnitude of $\rho_i$ is almost the same for all low-stage acceptor compounds above liquid-nitrogen temperature.[17]

We assume that this feature extends down to 1.5 K and we use $\alpha_t = 3\times 10^{-11}$ $\Omega$ m/K and $\beta_t = 6\times 10^{-13}$ $\Omega$ m/K$^2$ as mean values. Using the relation

$$\left[\frac{1}{\tau_i}\right]_{\mathrm{trans}} = \frac{\rho_i N e^2}{m^* I_c} \tag{5}$$

with $m^* = 0.25 m_0$, $N = 10^{14}$ cm$^{-2}$, and the $c$-axis repeat distance $I_c = 12$ Å as typical values for a stage-2 acceptor GIC, we find

$$(1/\tau_i)_{\mathrm{trans}} = 4.1\times 10^9 T + 8.5\times 10^7 T^2 \ ,$$

close to the values reported above.

In the light of these theories for disordered metallic systems, this temperature dependence may be physically understood in the following manner: the linear temperature-dependent term of $1/\tau_i$, which dominates at low temperature, is due to two-dimensional disorder-induced hole-hole interaction, while the quadratic term is indicative of hole-phonon interaction in the dirty case. We will now compare the observed values of $A$ and $B$ with the theoretical expectations.

Altshuler *et al.*[20] calculated the scattering time $\tau_i$ due to electron-electron interaction in a strictly 2D electron gas and obtained

$$\left[\frac{1}{\tau_i}\right]_{e\text{-}e} = \frac{k_B T}{2E_F\tau_0}\ln\left[\frac{E_F\tau_0}{\hbar}\right] . \tag{6}$$

Using $\tau_0 = l_0/v_F \cong 2\times 10^{-14}$ s and $E_F \cong 0.8$ eV, we find $(1/\tau_i)_{e\text{-}e} \cong 3.8\times 10^9 T$. This is in good agreement with the values obtained from the analysis of other experimental observations as reported above (Table II).

The expression for the electron-phonon lifetime in the dirty limit has been derived by Takayama,[24] who proposed

$$\left[\frac{1}{\tau_i}\right]_{e\text{-ph}} = \frac{2\pi^2 a k_B T^2}{k_F l_0 \hbar\theta_D} \ , \tag{7}$$

where $a$ is a numerical factor of the order of unity, $k_F$ is the Fermi wave vector, and $\theta_D$ is the Debye temperature. In our particular case, taking as the effective Debye temperature for hole-phonon interaction the value of 500 K (Ref. 17), we find, from Eq. (7), $(1/\tau_i)_{e\text{-ph}} \cong 1.5\times 10^8 T^2$, which is in reasonable agreement with the values just reported if we consider the crude assumptions concerning the estimation of $(1/\tau_i)_{e\text{-ph}}$ from relation (7).

From relations (6) and (7) we note that both $(1/\tau_i)_{e\text{-}e}$ and $(1/\tau_i)_{e\text{-ph}}$ should increase linearly with the disorder, i.e., are proportional to the residual resistivity. This theoretical prediction, which is in contrast to all existing experimental results in metal films,[32,33] also fails to explain the experimental results in acceptor GIC's. This should be investigated in more detail.

### B. Temperature dependence of the resistance

We are now in a position to determine the relative contribution of the effects of localization and interaction to the logarithmic temperature dependence of the resistivity. In Fig. 3 we show the low-temperature variation of the electrical resistivity of the P100-4 $CuCl_2$ compound. Below 18 K, the sample exhibits a logarithmic increase of the resistance with decreasing temperature.

TABLE II. Values of the coefficients $a$ and $b$ in the expression $1/\tau_i = aT + bT^2$.

| | Present work | | From ideal resistivity measurements | Theory |
|---|---|---|---|---|
| | P100-4 $CuCl_2$ | VCS-25 $CoCl_2$ | (Ref. 29) | [relations (6) and (7)] |
| $a$ ($10^9$ s$^{-1}$K$^{-1}$) | 2.9 | 3.9 | 4.1 | 3.8 |
| $b$ ($10^7$ s$^{-1}$K$^{-2}$) | 8.4 | 9.6 | 8.5 | $\approx 15$ |

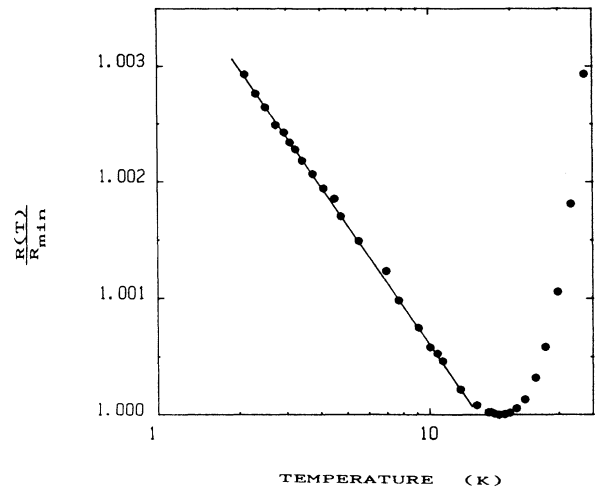


FIG. 3. Temperature dependence of the zero-field resistance of a P100-4 $CuCl_2$ compound. The data are normalized to the minimum value of the resistance.

In Fig. 4, we show the effect of a magnetic field on the rate of the logarithmic increase of resistance for a P100-4 $CuCl_2$ compound. According to relation (1), the variation of resistance over one decade of temperature is given by

$$\delta R/R \mid_{\text{decade}} = 2.84 \times 10^{-5} R_{\square}(\alpha p + \gamma) . \quad (8)$$

The effect of a magnetic field on $\delta R/R \mid_{\text{decade}}$ is shown in Fig. 4. We see that $\delta R/R \mid_{\text{decade}}$ presents a rapid variation at low magnetic field and saturates for $H > 0.2$ T. This observation is coherent with the fact that $H_i \ll 0.2$ T for all temperatures investigated. This means that for values of the magnetic field higher than 0.2 T, the logarithmic behavior, which is still present, is only due to interaction effects. The estimated values of $\gamma$ for both samples are given in Table I. Since the magnetic field allows only little variation in the coefficient of $\ln T$, the importance of hole-hole interaction in acceptor GIC's is clearly demonstrated.

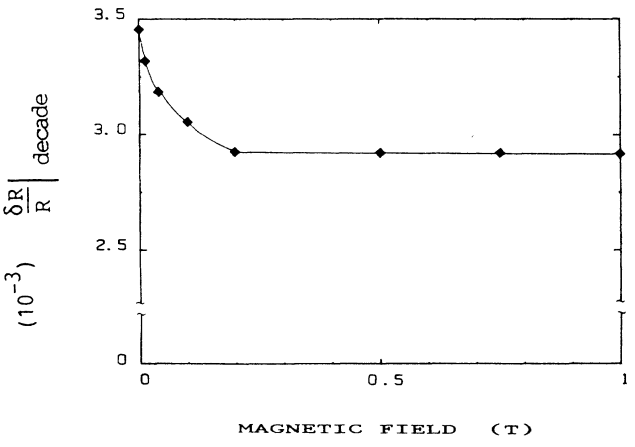


FIG. 4. Variation of $\delta R/R \mid_{\text{decade}}$ with magnetic field for a P100-4 $CuCl_2$ compound. ♦ are the experimental points obtained from the logarithmic temperature dependence of the resistance at various magnetic fields. The solid line is a guide for the eye.

## IV. CONCLUSIONS

Our analysis of the low-temperature behavior of the electronic transport properties of low-stage acceptor GIC's shows that both the logarithmic temperature dependence of the resistance and the negative magnetoresistance are well described by the existing theories of weak localization and Coulomb interaction in 2D disordered systems.

The experimental magnetoresistance data obtained over a wide temperature range enable us to determine the temperature dependence and the magnitudes of the relaxation times that characterize the processes of hole scattering with a change of energy and spin. We find that the temperature dependence of the inverse inelastic scattering time may be represented by the sum of a linear and a quadratic term, indicating the presence of both hole-hole and hole-phonon inelastic scattering processes. Also, the weak temperature dependence of the magnetoresistance at low temperature requires that we take into account the presence of magnetic scattering.

The relative contributions to the logarithmic temperature dependence of the resistance from weak localization and hole interaction effects are also estimated. Since the magnetic field induces only little variation in the coefficient of the logarithmic dependence, we conclude that the logarithmic temperature dependence is largely due to hole-hole interaction effects.

In addition it must be noted that the minimum of resistivity cannot be attributed to the Kondo effect. Indeed, in the vicinity of this minimum, there are no anomalies typical of the Kondo effect in the thermoelectric power which depends linearly on the temperature.[34]

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## APPENDIX: GEOMETRICAL CORRECTION

In Sec. III A we have stated that in a transverse magnetoresistance measurement, the observed magnetoresistance cannot be directly related to the weak localization theoretical relation (3). This is due to the fact that the graphitic planes in the fibers, which constitute the 2D systems, are not parallel to each other and, as a result, are not all perpendicular to the magnetic field. So, different effective magnetic fields act on the charge carriers in the different planes, since it was shown that only

the perpendicular component of the field modifies the conductance. Thus, in order to take this fact into account, the relation between the observed transverse magnetoresistance and the theoretical relation (3) may be modified as follows.

We consider the graphite fiber as a set of 2D subsystems, each of them consisting of parallel 2D graphite layers. Thus the total conductance of the intercalated fiber may be expressed:

$$\sigma_{\text{fiber}} = \sum_i \sigma_i \ , \tag{A1}$$

$\sigma_i$ being the conductance of the $i$th subsystem.

The effect of a magnetic field perpendicular to the fiber axis is the same for each element of a subsystem, but varies from one subsystem to another. As a result, we have

$$\sigma(H) = \sum_i \sigma_i(H \cos\theta_i) \ . \tag{A2}$$

$\theta_i$ is the angle between the magnetic field direction and the normal to the layers of the $i$th subsystem.

We further assume that the fiber may be regarded as a collection of randomly oriented two-dimensional graphite layers. Thus, converting the sum represented in relation (A2) to an integral, we may write

$$\sigma(H) = A\frac{1}{\pi}\int_{-\pi/2}^{\pi/2} \sigma_{2D}(H\cos\theta)d\theta \ , \tag{A3}$$

where $\sigma_{2D}(H\cos\theta)$ is the 2D conductivity of a graphite layer in the presence of a normal component of magnetic field ($H\cos\theta$), and $A$ is a constant factor which depends only on the sample size. Now, since

$$-\frac{\Delta R(H)}{R(0)} \cong \frac{\sigma(H)-\sigma(0)}{\sigma(0)}$$

we obtain

$$\left[\frac{\Delta R(H,T)}{R(0,T)}\right]_{\text{expt}} = \frac{1}{\pi}\int_{-\pi/2}^{\pi 2}\left[\frac{\Delta R(H\cos\theta,T)}{R(0,T)}\right]_{\text{theor}} d\theta \ , \tag{A4}$$

where $[\Delta R(H)/R(0)]_{\text{theor}}$ is the magnetoresistance given by the theoretical expression (3) and $[\Delta R(H)/R(0)]_{\text{expt}}$ is the measured magnetoresistance with the magnetic field perpendicular to the fiber axis. A similar expression was derived by Woolf *et al.*[35]


[1]E. Abrahams, P. W. Anderson, D. C. Licciardello, and T. V. Ramakrishnan, Phys. Rev. Lett. **42**, 613 (1979).

[2]G. Bergmann, Phys. Rev. B **28**, 2914 (1983).

[3]S. Hikami, A. I. Larkin, and Y. Nagaoka, Prog. Theor. Phys. **63**, 707 (1980).

[4]B. L. Altshuler, A. G. Aronov, and P. A. Lee, Phys. Rev. Lett. **44**, 1288 (1980).

[5]H. Fukuyama, J. Phys. Soc. Jpn. **48**, 2169 (1980).

[6]P. A. Lee and T. V. Ramakrishnan, Phys. Rev. B **26**, 4009 (1982).

[7]H. Fukuyama, J. Phys. Soc. Jpn. **49**, 644 (1980).

[8]C. S. Ting, A. Houghton, and J. R. Senna, Phys. Rev. B **25**, 1439 (1982).

[9]*Localization, Interaction and Transport Phenomena,* Vol. 61 of *Springer Series in Solid-State Sciences,* edited by B. Kramer, G. Bergmann, and Y. Bruynseraede (Springer-Verlag, Berlin, 1985).

[10]G. Bergmann, Phys. Rep. **107**, 1 (1984).

[11]P. A. Lee and T. V. Ramakrishnan, Rev. Mod. Phys. **57**, 287 (1985).

[12]M. S. Dresselhaus and G. Dresselhaus, Adv. Phys. **30**, 139 (1981).

[13]M. S. Dresselhaus, J. Chim. Phys. Phys. Chim. Biol. **81**, 739 (1984).

[14]M. S. Dresselhaus, in *Festkorperprobleme,* edited by P. Grosse (Vieweg, Braunschweig, 1985), Vol. 25, p. 21.

[15]L. Piraux, J.-P. Issi, J.-P. Michenaud, E. McRae, and J. F. Marêché, Solid State Commun. **56**, 567 (1985).

[16]L. Piraux, V. Bayot, J.-P. Michenaud, J.-P. Issi, J. F. Marêché, and E. McRae, Solid State Commun. **59**, 711 (1986).

[17]J.-P. Issi and L. Piraux, Ann. Phys. (Paris) **11**, 165 (1986).

[18]A. Schmid, Z. Phys. **271**, 251 (1974).

[19]E. Abrahams, P. W. Anderson, P. A. Lee, and T. V. Ramakrishnan, Phys. Rev. B **24**, 6783 (1981).

[20]B. L. Altshuler, A. G. Aronov, and D. E. Khmelnitzkii, J. Phys. C **15**, 7367 (1982).

[21]H. Fukuyama and E. Abrahams, Phys. Rev. B **27**, 5976 (1983).

[22]A. Schmid, Z. Phys. **259**, 421 (1973).

[23]A. Schmid, in *Localization, Interaction and Transport Phenomena,* Ref. 9, p. 212.

[24]H. Takayama, Z. Phys. **263**, 329 (1973).

[25]H. Fukuyama, in *Percolation, Localizatin and Superconductivity,* edited by A. M. Goldman and S. A. Wolf (Plenum, New York, 1984), p. 161.

[26]S. Maekawa and H. Fukuyama, J. Phys. Soc. Jpn. **50**, 2516 (1981).

[27]M. Gijs, C. Van Haesendonck, and Y. Bruynseraede, J. Phys. F. **16**, 1227 (1986).

[28]B. L. Altshuler and A. G. Aronov, Pis'ma Zh. Eksp. Teor. Fiz. **33**, 515 (1981) [JETP Lett. **33**, 499 (1981)].

[29]L. Piraux, J.-P. Issi, L. Salamanca-Riba, and M. S. Dresselhaus, Synth. Metals **16**, 93 (1986).

[30]N. Daumas and A. Hérold, C. R. Acad. Sci. Ser. C **268**, 373 (1969).

[31]J. Blinowski, Nguyen Hy Hau, C. Rigaux, J. P. Vieren, R. Le Toullec, G. Furdin, A. Hérold, and J. Mélin, J. Phys. (Paris) **41**, 47 (1980).

[32]R. P. Peeters and G. Bergmann, J. Phys. Soc. Jpn. **54**, 3478 (1985).

[33]R. P. Peeters and G. Bergmann, *Proceedings of the International Conference on Localization, Interaction and Transport Phenomena In Impure Metals (Suppl.),* edited by L. Schweitzer and B. Kramer (PTB, Braunschweig, 1984), p. 167.

[34]L. Piraux, B. Nysten, J.-P. Issi, J. F. Marêché, and E. McRae, Solid State Commun. **55**, 517 (1985).

[35]L. D. Woolf, J. Chin. Y. R. Lin-Liu, and H. Ikesi, Phys. Rev. B **30**, 861 (1984).