Magnetotransport in $Bi_2Sr_2Ca_{1-x}Y_xCu_2O_{8+\delta}$ single crystals: From the underdoped to the overdoped regime

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We report on magnetotransport measurements ($B\|c$) in Bi 2212 single crystals for both overdoped and underdoped regions. Modification of carrier concentration induces dramatic changes in the temperature dependence of the zero-field resistivity and longitudinal ($B\|I$) out-of-plane magnetoconductivity. A change of sign in the longitudinal out-of-plane magnetoconductivity occurs in the underdoped to optimally doped region whereas no change of sign is observable in the overdoped region. A qualitative discussion is proposed on the basis of various scenarios such as the renormalization of the interlayer hopping rate or field induced suppression of the pseudogap. Finally, we carry out a quantitative description in terms of superconducting fluctuations conductivity to account for experimental data. [S0163-1829(99)03441-4]

One of the most peculiar issues in the high critical temperature superconductors research is the investigation of their anomalous normal-state transport properties. Cuprates indeed show numerous unusual signatures, especially in the *c*-axis direction, hampering a full understanding despite the considerable theoretical work devoted to this subject. One striking aspect of the transport properties is the *T*-linear in-plane resitivity ρ_{ab} (at least in the high-temperature regime).[1–5] Indeed, ρ_{ab} remains metallic while the out-of plane resitivity ρ_c appears to diverge with decreasing temperature (the so-called ''semiconducting behavior'') for a wide range of carrier concentration.[6–9] Such a behavior is hard to understand in terms of conventional Fermi liquid. However, employing this latter approach, several models explain semiconducting ρ_c by introducing renormalization of the interlayer hopping rate,[10] interlayer scattering,[11,12] phonon assisted tunneling,[13] superconducting fluctuations,[14] and temperature-dependent suppression of the density of states at the Fermi level.[15] On the other hand, in the non-Fermi-liquid theories, resonating valence bound theory (RVB) and in-plane quasiparticles confinement also realize semiconducting *c*-axis transport properties.[16–18] Thus an important issue is to know whether the contrasting behavior of ρ_c and ρ_{ab} is a ground-state property of the normal state. In recent experiments, Ando *et al.*[4] have observed the non-Fermi-liquid nature of $Bi_2Sr_2CuO_y$ whereas, adding further to the confusion, in $La_{2-x}Sr_xCuO_4$ (La 214),[19] ρ_c and ρ_{ab} show the same behavior as $T\rightarrow 0$.

Normal-state magnetoresistivity (MR) measurements on single crystals could help distinguish between the different proposals. Many papers deal with such a topic. An extensive work has recently been achieved by Kimura *et al.*,[8] and later by Hussey *et al.*,[20] on La 214 single crystals over a wide composition range. In Ref. 8, the authors find evidence suggestive of the role of spin degrees of freedom in the charge confinement within the CuO_2 plane in the underdoped region. However, as mentioned above,[19] high-field experiments rule out such an assumption; both in-plane and out-of-plane resistivity are found to diverge with decreasing temperature below the zero-field superconducting transition temperature. This suggests an isotropic three-dimensional (3D) insulator, far from the 2D metallic ground state which is proposed by Kimura *et al.*[8] In the optimally to overdoped superconducting phase of La 214, the in-plane scattering rate is thought to be involved. Other *c*-axis magnetotransport results have been reported by Yan *et al.*[6] in $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi 2212) and underdoped $YBa_2Cu_3O_{6+\delta}$ (YBCO). They interpret the activated form of ρ_c and the negative MR by the opening of a pseudogap (spin gap). Besides, in underdoped Bi 2212 thin films,[21] YBCO single crystals[22] as well as in optimally doped $(Tl,Hg)_2Ba_2Ca_2Cu_3O_{10+\delta}$ single crystals,[23] those experimental features are explained considering the decrease of the density of states at the Fermi energy induced by the superconducting fluctuations. Finally, for completeness, weak localization may cause similar temperature dependence of resistivity and negative magnetoconductivity.[24]

The growth of $Bi_2Sr_2Ca_{1-x}Y_xCu_2O_{8+\delta}$ (Bi[Y] 2212) single crystals has allowed us to vary the doping state from the underdoped to overdoped side through the controlled substitution of Y^{3+} for Ca^{2+}.[25,26] In addition, Pb substitution for Bi in Bi[Y] 2212 single crystals was also carried out. It is well known that such a substitution of lead for bismuth results in an increase in the carriers concentration, which may correspond to the overdoped region of the phase diagram in comparison with the Pb-free samples.[7,27,28] The marked layered structure and the vast number of papers reporting resistivity and magnetoconductivity measurements make these cuprates good candidates for understanding the mechanisms of charge transport across the CuO_2 planes. In order to clarify further this issue, a detailed investigation of *c*-axis magnetotransport properties is carried out with respect to the doping state for our series of Y and Pb substituted Bi 2212 single crystals. We observe a strong doping dependence of the longitudinal out-of-plane magnetoconductivity, defined as follows: $\Delta\sigma=\sigma(B,T)-\sigma(0,T)=1/\rho(B,T)-1/\rho(0,T)$, and of the zero-field resitivity. Various scenarios proposed for charge transport (renormalization of the interlayer hopping rate, field induced suppression of the pseudogap) are discussed on the basis of experimental data and literature reports. In the last section, the density-of-states fluctuations scenario is shown to give a reasonable alternative explanation to account for our magnetotransport results.

The Bi[Y] 2212 and Pb doped Bi[Y] 2212 crystals used in this study were grown by a self-flux method which has been described elsewhere.[25,29] The structural investigations undertaken to check the quality of crystals, in particular their actual cationic composition are reported in an earlier paper;[26] it is demonstrated that substitutions of low concentrations of Y^{3+} on the Ca^{2+} site lead to a set of samples with different T_c values. The actual cation contents were checked by energy dispersive spectroscopy (EDS) x-ray spectroscopy with a Kevex analyzer mounted on a 200-kV electron microscope following the procedure described in Ref. 25 for each batch. In this work, we investigate charge transport in $Bi_2Sr_2Ca_{1-x}Y_xCu_2O_{8+\delta}$ with $x_{EDS}=0,0.2,0.43$ and in $(Bi_{0.8},Pb_{0.2})_2Sr_2Ca_{1-x}Y_xCu_2O_{8+\delta}$ with $x_{EDS}=0.2$.

As shown previously, the increase of x_{EDS} is accompanied by a continuous increase of the oxygen content. This oxygen uptake is too small to exactly compensate the Y^{3+}/Ca^{2+} valence substitution resulting in a regular decrease in the number of holes in the CuO_2 planes as the Y content increases. The initially slightly overdoped Y free Bi 2212 can thus be driven to an optimum doping state, corresponding to approximately $x_{EDS}=0.2$ and also to the underdoped region for higher Y content ($x_{EDS}=0.43$). Hence, associated with this Y for Ca substitution, the Pb substitution for Bi provides a good way to span the whole range of doping, from the overdoped (Y-free Bi 2212 and Pb doped Bi[Y] 2212 with $x_{EDS}=0.2$) to the underdoped region (Bi[Y] 2212 with $x_{EDS}=0.43$).

The crystals, which had typical dimensions $1\times1\times0.1$ mm^3, were contacted in the direct ''cross'' configuration.[30] One can directly derive a good estimate of ρ_c from such a cross measurement providing the sample is small enough to ensure that the current and voltage contacts are close together and close to the edges of the crystal. Several comparative studies with more sophisticated methods,[31,32] such as the measurement of a ''bottom'' voltage, have shown that the direct combination of R_{cross} with the dimensions of the crystals yields reliable values of ρ_c.[32,33] Gold wires were attached to the ''evaporated-silver stripes'' with silver paint. The samples were then annealed in air at 400 °C for 10 min. The c-axis resistivity was measured as a function of temperature at a series of fixed fields ($B\|c\|I$).

The zero-field out-of plane resistivity (ρ_c) temperature dependences are shown in Fig. 1 for the various members of the Y doping study as well as for the Pb doped sample. The absolute values of ρ_c are rather similar to those reported in other papers for Bi 2212 single crystals.[9,6,34,7] We observe that the modification of the doping state induces dramatic changes in the temperature dependence as well as in the magnitude of the out-of-plane resistivity. For the underdoped sample (Bi[Y] 2212 with $x_{EDS}=0.43$), the magnitude of the

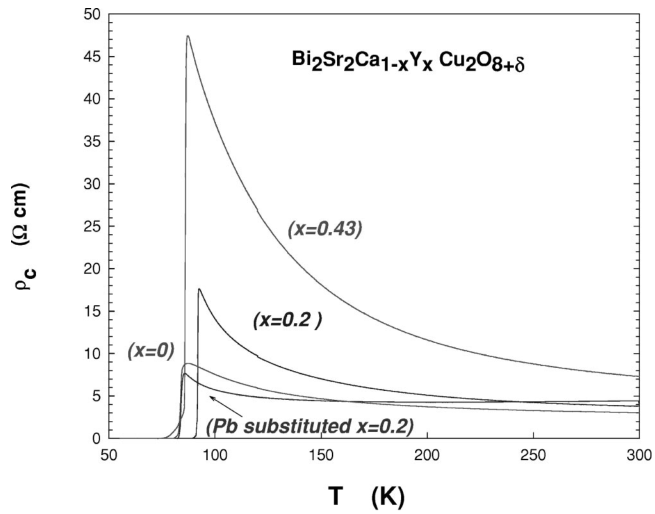

FIG. 1. Out-of-plane resistivity for $Bi_2Sr_2Ca_{1-x}Y_xCu_2O_{8+\delta}$ single crystals versus temperature for various doping states.

ρ_c is large and strongly increases continuously with decreasing temperature below 300 K. For samples around the optimal composition (Bi[Y] 2212 with $x_{EDS}=0.2$), we still observe a slight semiconducting behavior, however, the overall magnitude of the low-temperature resistivity (near the c-axis resistivity peak) is dramatically lowered compared to the underdoped sample. When the doping level is further increased (Y-free Bi 2212 and Pb-doped Bi[Y] 2212 with $x_{EDS}=0.2$), one observes, on the one hand, a persistence in the decrease of the magnitude of the resistivity and, on the other hand, the occurrence of mixed temperature dependence: $\rho_c(T)$ has a positive slope at high temperature but a negative one at low temperature. This is clearly observed for the overdoped Pb doped Bi[Y] 2212. This metallic and semiconductinglike behavior of ρ_c for overdoped Bi 2212 single crystals are similar to those reported in literature.[7,9] It should be added that apart from the high value observed in the underdoped state for the Bi[Y] 2212 with $x_{EDS}=0.43$ sample, the values of $\rho_c(300\text{ K})$ are not strongly different from sample to sample.

In this section, we focus on magnetotransport measurements above T_c. In order to intend connection with the magnetoresitivity (MR), the temperature dependence of $-\Delta\sigma$ is plotted for each sample in Figs. 2(a)–2(d). A quite unusual doping dependence of the longitudinal out-of-plane MR ($B\|I\|c$) is observed. For the underdoped to around the optimally doped side, the MR reveals a change of sign leading to a clear negative MR above T_c. This is usually associated with the strongly semiconducting T dependence of ρ_c. For the overdoped samples, we observe a monotonous decrease of the positive MR with increasing temperature and no change of sign is observable. As found in our experiments for the underdoped case, Yan *et al.*[6] observed a negative MR over a large range of temperature above T_c for all doping states investigated in Bi 2212 single crystals. A negative out-of-plane MR has also been observed in the underdoped La 214 system.[8,20] However, in this latter system, a sign change from negative to positive with increasing T is reported, in contrast with the present results for the Bi[Y] 2212 with

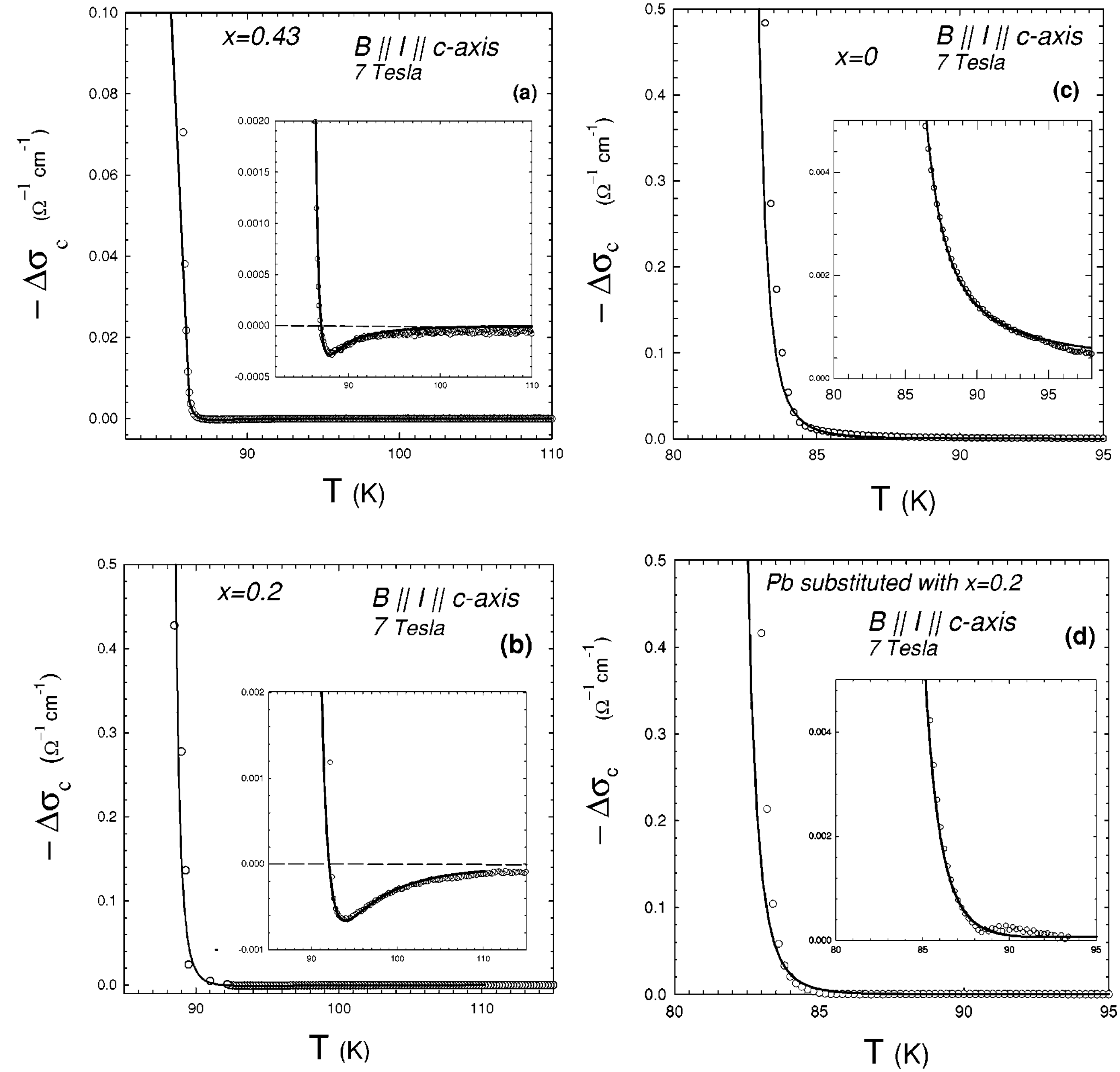

FIG. 2. (a) Temperature dependence of the longitudinal c-axis magnetoconductivity ($B\|c\|I$) at 7T for a $Bi_2Sr_2Ca_{1-x}Y_xCu_2O_{8+\delta}$ single crystal with $x_{EDS}=0.43$ (underdoped). The solid line represents the theoretical calculation with parameters given in Table I. (b) Temperature dependence of the longitudinal c-axis magnetoconductivity ($B\|c\|I$) at 7 T for a $Bi_2Sr_2Ca_{1-x}Y_xCu_2O_{8+\delta}$ single crystal with $x_{EDS}=0.2$ (around the optimal composition). The solid line represents the theoretical calculation with parameters given in Table 1. (c) Temperature dependence of the longitudinal c-axis magnetoconductivity ($B\|c\|I$) at 7 T for an Y free $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystal (overdoped). The solid line represents the theoretical calculation with parameters given in Table I. (d) Temperature dependence of the longitudinal c-axis magnetoconductivity ($B\|c\|I$) at 7 T for a Pb substituted $Bi_2Sr_2Ca_{1-x}Y_xCu_2O_{8+\delta}$ single crystal with $x_{EDS}=0.2$ (strongly overdoped). The solid line represents the theoretical calculation with parameters given in Table I.

$x_{EDS}=0.43$ sample. It should be added that in Ref. 8, the MR remains entirely positive for overdoped and optimally doped La 214 samples.

In an anisotropic Fermi liquid, N. Kumar and A. M. Jayannavar[10] picture electrical transport along the c axis as a coherent interplanar tunneling between neighboring layers blocked by multiple intraplanar coherent scatterings. This mechanism for c-axis hopping takes place for $t_c \ll \Gamma_{ab}$ where t_c is the c-axis hopping rate and Γ_{ab} the in-plane scattering rate. This leads to a renormalization of t_c such as $t_c^* \sim t_c^2(1/\pi\hbar\Gamma_{ab})$ making the c-axis charge transport essentially governed by in-plane scatterings. Yan *et al.*[35] have extended this idea introducing the effects of a magnetic field. The authors claim that when $\Gamma_{ab} \ll t_c$ the intraplanar scattering process no longer occurs and positive MR is then absent. As emphasized by Hussey *et al.*,[20] this scenario may provide a possible explanation for the negative out-of-plane MR in underdoped La 214,[8] YBCO,[6] and Sr_2RuO_4.[36] However, although the in-plane scattering times reported in the literature are an order of magnitude higher in Bi 2212.[21,37,38] compared to YBCO,[22] ρ_c values observed in Fig. 1 are significantly higher. Therefore it is not straightforward that the mechanism invoked above might lead to the observed experimental results for our system.

A negative MR is often interpreted in terms of a pseudogap in underdoped samples. The out-of-plane charge transport is blocked by this normal-state gap which plays, in such a picture, a central role in the temperature dependence of c-axis resistivity and magnetoconductivity. When one applies a magnetic field, this pseudogap is suppressed promoting the conduction along the c axis. This naturally leads to a negative longitudinal out-of-plane MR for underdoped samples. In Bi 2212 single crystals with various doping levels, the deviation of the in-plane resistivity from the T-linear behavior (corresponding to a reduction of ρ_{ab}) has been recently ascribed to the formation of such a pseudogap, possibly due to spin fluctuations induced scattering of charge carriers.[6,9,39–41] Therefore, extending the above idea, the suppression of the gap by a magnetic field should yield an increase of ρ_{ab} and hence a positive transverse in-plane MR $(B\|c\perp I)$. This is indeed the case for the underdoped sample (Bi[Y] 2212 with $x_{EDS}=0.43$) where a positive transverse in-plane MR has been measured (Fig. 3). However, it is generally accepted that the superconducting in-plane fluctuations theory provides a rather good description, for the positive transverse in-plane MR. This has been clearly demonstrated for YBCO (Refs. 42–44) and bismuth based compounds.[45,46] Thus the result exhibited in Fig. 3 cannot be used as a convincing argument for promoting the pseudogap argument.

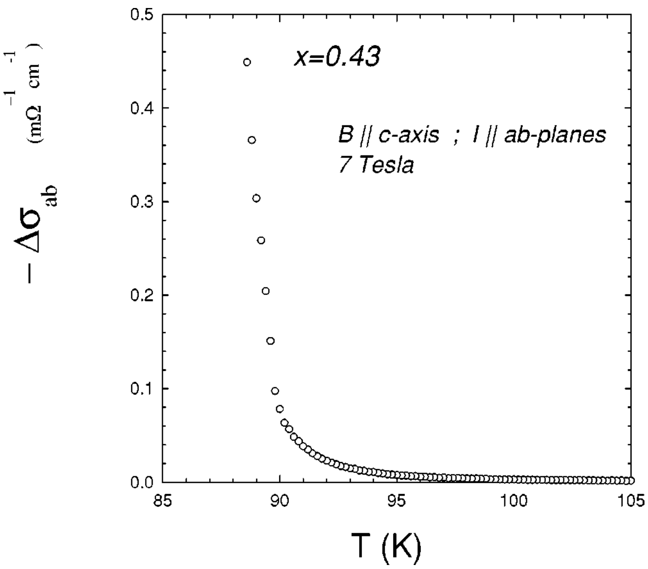

FIG. 3. Temperature dependence of the transverse ab-plane magnetoconductivity $(B\|c\perp I)$ for a $Bi_2Sr_2Ca_{1-x}Y_xCu_2O_{8+\delta}$ single crystal with $x_{EDS}=0.43$ (underdoped).

In many papers, negative longitudinal out-of-plane MR and semiconducting ρ_c are explained in terms of superconducting fluctuations conductivity. These fluctuations reduce the density of states (DOS) of normal carriers at the Fermi level. Such a fluctuation renormalization can also be treated as the opening of a type of pseudogap while one approaches T_c. An extensive theoretical work has been achieved by Dorin *et al.*[14] to account for the experimental features described above (i.e., a change of sign in longitudinal out-of-plane MR and semiconducting ρ_c). The quantitative agreement found with this theory in numerous experimental papers is extremely convincing.[21,23,37,38] In this section, we propose a description of the doping dependence of out-of-plane MR in terms of fluctuations conductivity on the basis of the detailed formalism given by Dorin *et al.*[14]

As it was shown in the framework of a Gaussian model developed by Ioffe *et al.*[47] and Dorin *et al.*,[14] c-axis conductivity fluctuations in high-temperature superconductivity is comprised of four terms. The direct contribution, initially proposed by Aslamasov and Larkin (AL),[48] is due to the acceleration in an electric field of short-lived Cooper pairs in thermal nonequilibrum. The DOS contribution, negative in sign, arises from corrections to the normal quasiparticle density of states owing to fluctuations of normal quasiparticles into the superconducting state. It is possible to observe a negative fluctuation induced c-axis magnetoresistance in the temperature region where the DOS contribution exceeds the positive AL one. The regular and anomalous Maki-Thompson (MT) contributions, which are usually small, respectively result from the scattering of the normal-state particles and the superconducting pairs.[14,49] Finally, the fluctuation magnetoconductivity is given by

$$\Delta\sigma_c=\Delta\sigma_c^{AL}+\Delta\sigma_c^{DOS}+\Delta\sigma_c^{MT(reg)}+\Delta\sigma_c^{MT(an)}, \qquad (1)$$

where $\Delta\sigma_c^{AL}=\sigma_c^{AL}(B,T)-\sigma_c^{AL}(0,T)$, etc.

In the weak-field limit, the resulting expressions for the four terms are then

$$\Delta\sigma_c^{AL}(B,T)=-\frac{e^2 s}{32\eta\hbar}\left(\frac{\beta^2 r^2(\epsilon+r/2)}{32[\epsilon(\epsilon+r)]^{5/2}}\right), \qquad (2)$$

$$\Delta\sigma_c^{DOS}(B,T)=\frac{e^2 s r\kappa}{16\eta\hbar}\left(\frac{\beta^2(\epsilon+r/2)}{24[\epsilon(\epsilon+r)]^{3/2}}\right), \qquad (3)$$

$$\Delta\sigma_c^{MT(reg)}(B,T)=\frac{e^2 s r\tilde{\kappa}}{16\eta\hbar}\left(\frac{\beta^2 r}{48[\epsilon(\epsilon+r)]^{3/2}}\right), \qquad (4)$$

$$\Delta\sigma_c^{MT(an)}(B,T)=-\frac{e^2 s}{16\eta\hbar}\left(\frac{\beta^2 r^2(\epsilon+\gamma+r)\{\epsilon(\epsilon+r)+\gamma(\gamma+r)+[\epsilon(\epsilon+r)\gamma(\gamma+r)]^{1/2}\}}{96[\epsilon(\epsilon+r)\gamma(\gamma+r)]^{3/2}\{[\epsilon(\epsilon+r)]^{1/2}+[\gamma(\gamma+r)]^{1/2}\}}\right). \qquad (5)$$

TABLE I. Values of the parameters corresponding to the theoretical calculation (solid line) given in Figs. 2(a)–2(d). Results from others experiments are given for comparison.

	$\tau(s)$	$\tau_\varphi(s)$	J(K)	v_f (cm/s)	T_c (K)
Ref. 50 Bi 2212 films	3×10^{-14}	3.6×10^{-13}	40	1.4×10^7	93
Ref. 51 Bi 2212 films	1×10^{-14}	7.8×10^{-14}	40	3.1×10^6	93
Ref. 38 Bi 2212 films	5×10^{-14}	8.6×10^{-13}	43		85
Ref. 22	5.0×10^{-15}	$(=\tau)$	225		
YBCO crystals	3.1×10^{-15}	$(=\tau)$	205	2×10^7	92
$Bi_2Sr_2Ca_{1-x}Y_xCu_2O_{8=\delta}$ $x=0.43$	1.95×10^{-14}	1.1×10^{-13}	15	1.4×10^6	84.8
$Bi_2Sr_2Co_{1-x}Y_xCu_2O_{8+\delta}$ $x=0.21$	1.25×10^{-14}	1.2×10^{-13}	28	4.6×10^6	87.5
$Bi_2Sr_2CaCu_2O_{8+\delta}$ $x=0$	0.7×10^{-14}	5.1×10^{-13}	31	5.4×10^6	82
$(Bi,Pb)_2Sr_2Ca_{1-x}YCu_2O_{8+\delta}$ $x=0.21$	0.8×10^{-14}	0.3×10^{-13}	31	6.4×10^6	81.3
Ref. 23 Hg 1201	2×10^{-14}	2×10^{-13}	40	2×10^6	120
Ref. 23 Tl 2223	5×10^{-14}	$(=\tau)$	4	4.4×10^6	92

In these formulas, e is the electron charge, s is the lattice period along the c axis, and

$$\eta=-\frac{v_F^2\tau^2}{2}\left[\Psi\left(\frac{1}{2}+\frac{\hbar}{4\pi k_BT\tau}\right)-\Psi\left(\frac{1}{2}\right)-\frac{\hbar}{4\pi k_BT\tau}\Psi'\left(\frac{1}{2}\right)\right], \tag{6}$$

where v_F is the Fermi velocity parallel to the layers, τ is the quasiparticle scattering time, $\Psi(x)$ and $\Psi'(x)$ are the digamma function and its derivative. $r=4\eta J^2k_B^2/v_F^2\hbar^2$ is the usual anisotropy parameter characterizing the dimensionality of the fluctuations and J is an effective interlayer coupling energy in Kelvin. $\beta=4\eta eB/\hbar$ and $\epsilon=\ln(T/T_c)$. The constants κ and $\tilde{\kappa}$ are ruled by the impurity concentration and are a function of τT:

$$\kappa=\frac{-\Psi'(1/2+\hbar/4\pi k_BT\tau)+\hbar/2\pi k_BT\tau\Psi''(1/2)}{\pi^2[\Psi(1/2+\hbar/4\pi k_BT\tau)-\Psi(1/2)-\hbar/4\pi k_BT\tau\Psi'(1/2)]}, \tag{7}$$

$$\tilde{\kappa}=\frac{-\Psi'(1/2+\hbar/4\pi k_BT\tau)+\Psi'(1/2)+\hbar/4\pi k_BT\tau\Psi''(1/2)}{\pi^2[\Psi(1/2+\hbar/4\pi k_BT\tau)-\Psi(1/2)-\hbar/4\pi k_BT\tau\Psi'(1/2)]}, \tag{8}$$

and

$$\gamma=\frac{2\eta}{v_F^2\tau\tau_\Phi}, \tag{9}$$

where τ_Φ is the pair breaking lifetime.

The first step of our analysis is to compare the prediction of the theory and the experimental data for each doping level following the procedure reported in Ref. 23. In the comparison, we took $s=c/2=1.5$ nm for each Y rate. T_c is determined from the midpoint of the zero-field resistive transition and we assumed τ and $\tau_\Phi\propto1/T$. For the underdoped (Bi[Y] 2212 with $x_{EDS}=0.43$) to around the optimally doped side (Bi[Y] 2212 with $x_{EDS}=0.2$), the weak-field theoretical expressions for $\Delta\sigma$ describe perfectly the temperature at which the sign change occurs and the magnitude of the minimum [see Fig. 2(a) and 2(b)]. Such a result is obtained when one includes the four contributions, AL, DOS, and both MT terms and using the parameters reported in Table I. For the overdoped samples, where no change of sign is observable, the monotonous decrease of the positive MR with increasing T can also be explained in terms of fluctuations conductivity. In such a case, because of the absence of sign change in the T dependence of magnetoconductivity, we have to consider a vanishing negative (DOS+MT regular) contribution compared to the positive (AL+MT anomalous) one. The overall prediction of the fluctuational magnetoconductivity presented in Figs. 2(c) and 2(d) is achieved considering the sole (AL+MT anomalous) contribution with parameters given in

Table I. It can be checked by numerical calculations that those parameters lead to a negligibly small (DOS+MT regular) contribution. The values of parameters for the Bi[Y] 2212 system are collected in Table I and compared with those determined in other papers. Although our experiments focused on single crystals, the obtained values of relaxation times (τ and τ_Φ) are of the same order of magnitude than those derived for thin films[38,50,51] (see Table I). There are so many differences between a polycrystalline film and a single crystal that it is not clear why values of the in-plane scattering time, which is related to the impurity and disordered state of the materials, are so close. Besides, considering the Bi[Y] 2212 single-crystals results, no straightforward correlation can be made between the relaxation times and the doping state of the compounds.

In Fig. 1, as going from the underdoped to the overdoped samples, one observes a weakening of the semiconducting behavior concomitant with an increase of the Fermi velocity (v_F) as observed in Table I. In the framework of the theory developed in Ref. 14, such an increase of v_F results in a decrease of the DOS fluctuations contributions in the predicted magnetoconductivity. Therefore the fluctuations effect on the overall result becomes almost negligible and yields a smoothing of the resistivity peak as the hole concentration increases (see Fig. 1). This vanishing DOS contribution can also be considered as a relevant argument to account for the experimentally observed disappearance of the change of sign of the magnetoconductivity when the hole doping is increased. According to Dorin *et al.*,[14] the negative MR in a temperature range above T_c occurs when the negative DOS contribution to conductivity exceeds the positive Aslamasov-Larkin one. It has been shown[23] that the DOS contribution to conductivity has a weaker interlayer coupling dependence compared to the Aslamasov-Larkin one. Hence this DOS contribution becomes vanishing small in materials exhibiting weaker interlayer coupling. As reported in Table I, through the value of J, as confirmed in Ref. 26, the interlayer coupling has been found to decrease when the carriers concentration increases. Thus, it becomes possible to account for the experimental positive MR in the overdoped region considering the weaker interlayer coupling, consistent with the lower values of J found for this doping state (Table I).

In conclusion, out-of-plane magnetotransport ($B\|I\|c$) measurements have been achieved on Bi 2212 single crystals. Various cationic substitutions have allowed us to carry out a study for both the overdoped region and the underdoped one. The temperature dependence and the magnitude of the zero-field resistivity are heavily carrier dependent. The increase of the carrier concentrations weakens the semiconducting behavior of ρ_c on the one hand, and significantly reduces its low-temperature magnitude. Besides, a change of sign in the longitudinal out-of-plane magnetoconductivity occurs as passing from the overdoped to underdoped region. We have discussed these features on the basis of renormalized hopping rate, field induced suppression of the pseudogap, and fluctuations of density of states. This latter theory appears to give an acceptable framework to describe the doping dependence of magnetoconductivity and resistivity data reported in this paper.

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[1] S. Martin, A. T. Fiory, R. M. Fleming, L. N. Scheemeyer, and J. V. Waszczak, Phys. Rev. Lett. **60**, 2194 (1988).

[2] S. J. Hagen, T. W. Jing, Z. Z. Wang, J. Horvath, and N. P. Ong, Phys. Rev. B **37**, 7928 (1988).

[3] Y. Nakamura and S. Ushida, Phys. Rev. B **47**, 8369 (1993).

[4] Y. Ando, G. S. Boebinger, A. Passner, N. L. Wang, C. Geibel, and F. Steiglich, Phys. Rev. Lett. **77**, 2065 (1996).

[5] K. Takenaka, K. Mizuhashi, H. Takagi, and S. Uchida, Phys. Rev. B **50**, 6534 (1994).

[6] Y. F. Yan, P. Matl, J. M. Harris, and N. P. Ong, Phys. Rev. B **52**, 751 (1995).

[7] N. L. Wang, C. Geibel, F. Steglich, Physica C **260**, 305 (1996).

[8] T. Kimura, S. Miyasaka, H. Takagi, K. Tamasaku, H. Eisaki, S. Uchida, M. Hiroi, M. Sera, and N. Kobayashi, Phys. Rev. B **53**, 8733 (1996).

[9] T. Watanabe, T. Fujii, and A. Matsuda, Phys. Rev. Lett. **79**, 2113 (1997).

[10] N. Kumar and A. M. Jayannavar, Phys. Rev. B **45**, 5001 (1992).

[11] A. G. Rojo and K. Levin, Phys. Rev. B **48**, 16 861 (1992).

[12] M. J. Graf, D. Rainer, and J. A. Sauls, Phys. Rev. B **47**, 12 089 (1993).

[13] R. J. Radke and K. Levin, Physica C **250**, 282 (1995).

[14] V. V. Dorin, R. A. Klemm, A. A. Varlamov, A. I. Buzdin, and D. Livanov, Phys. Rev. B **48**, 12 951 (1993).

[15] Y. Zha, S. L. Cooper, and D. Pines, Phys. Rev. B **53**, 8253 (1996).

[16] N. Nagaosa, Phys. Rev. B **52**, 10 561 (1995).

[17] P. W. Anderson and Z. Zou, Phys. Rev. Lett. **60**, 132 (1988).

[18] D. G. Clarke, S. P. Strong, and P. W. Anderson, Phys. Rev. Lett. **74**, 4499 (1995).

[19] Y. Ando, G. S. Boebinger, A. Passner, T. Kimura, and K. Kishio, Phys. Rev. Lett. **75**, 4662 (1995).

[20] N. E. Hussey, R. J. Cooper, Y. Kodama, and Y. Nishira, Phys. Rev. B **58**, 611 (1998).

[21] G. Balestrino, E. Milani, C. Aruta, A. A. Varlamov, Phys. Rev. B **54**, 3628 (1996).

[22] J. Axnas, W. Holm, Y. Eltsev, and O. Rapp, Phys. Rev. Lett. **77**, 2280 (1996).

[23] A. Wahl, D. Thopart, G. Villard, A. Maignan, V. Hardy, J. C. Soret, L. Ammor, and A. Ruyter, Phys. Rev. B **59**, 7216 (1999).

[24] P. Lindqvist, P. Lanco, C. Berger, A. G. M. Jansen, and F. Cyrot-Lackmann, Phys. Rev. B **51**, 4796 (1995).

[25] G. Villard, D. Pelloquin, A. Maignan, and A. Wahl, Physica C **278**, 11 (1997).

[26] G. Villard, D. Pelloquin, and A. Maignan, Phys. Rev. B **58**, 15 231 (1998).

[27] J. Shimoyama, Y. Nakayama, K. Kitazawa, K. Kishio, Z. Hiroi, I. Chong, and M. Takano, Physica C **281**, 69 (1997).

[28] F. X. Régi, J. Schneck, H. Savary, R. Mellet, P. Müller, and R. Kleiner, J. Phys. III **4**, 2249 (1994).

[29] A. Ruyter, Ch. Simon, V. Hardy, M. Hervieu, and A. Maignan, Physica C **225**, 235 (1994).

[30] V. Hardy, A. Maignan, C. Martin, F. Warmont, and J. Provost, Phys. Rev. B **56**, 130 (1997).

[31] H. C. Montgomery, J. Appl. Phys. **42**, 2971 (1971).

[32] R. Bush, G. Ries, H. Werthner, and G. Seaman-Ischenko, Phys. Rev. Lett. **69**, 522 (1992).
[33] D. Lopez, G. Nieva, and F. de la Cruz, Phys. Rev. B **50**, 7219 (1994).
[34] X. Li, X. Sun, W. Wu, Q. Chen, L. Shi, Y. Zhang, Y. Kotaka, and K. Kishio, Physica C **279**, 241 (1997).
[35] D. Yan, Y. Y. Yi, Z. Su, and L. Yu, Physica C **282-287**, 1647 (1997).
[36] N. E. Hussey, A. P. Mackenzie, J. R. Cooper, Y. Maeno, S. Nishizaki, and T. Fujita, Phys. Rev. B **57**, 5505 (1998).
[37] G. Balestrino, E. Milani, A. A. Varlamov, and L. Yu, Phys. Rev. B **47**, 6037 (1993).
[38] A. S. Nygmatulin, D. V. Livanov, G. Balestrino, E. Milani, A. A. Varlamov, Phys. Rev. B **53**, 3557 (1996).
[39] T. Ito, K. Takenaka, and S. Uchida, Phys. Rev. Lett. **70**, 3995 (1993).
[40] M.-H. Julien, P. Carretta, M. Horvatić, C. Berthier, Y. Berthier, P. Ségransan, A. Carrington, and D. Colson, Phys. Rev. Lett. **76**, 4238 (1996).
[41] M. Takigawa, A. P. Reyes, P. C. Hammel, J. D. Thompson, R. H. Heffner, Z. Fisk, and K. C. Ott, Phys. Rev. B **43**, 247 (1991).
[42] W. Lang, G. Heine, P. Schwab, X. Z. Wang, and D. Baüerle, Phys. Rev. B **49**, 4209 (1994).
[43] J. Sugawara, H. Iwasaki, N. Kobayashi, H. Yamane, and T. Hirai, Phys. Rev. B **46**, 14 818 (1992).
[44] W. Holm, Ö. Rapp, C. N. L. Johnson, and U. Helmersson, Phys. Rev. B **52**, 3748 (1995).
[45] W. Lang, G. Heine, W. Kula, and R. Sobolewski, Phys. Rev. B **51**, 9180 (1995).
[46] T. Watanabe and A. Matsuda, Physica C **263**, 313 (1996).
[47] L. B. Ioffe, A. I. Larkin, A. A. Varlamov, and L. Yu, Phys. Rev. B **47**, 8936 (1993).
[48] L. Aslamasov and A. I. Larkin, Fiz. Tverd. Tela (Leningrad) **10**, 1104 (1968) [Sov. Phys. Solid State **10**, 875 (1968)].
[49] K. Maki, Prog. Theor. Phys. **39**, 897 (1968); K. Maki and R. S. Thompson, Phys. Rev. B **39**, 2767 (1989).
[50] G. Balestrino, E. Milani, and A. A. Varlamov, Physica C **210**, 386 (1993).
[51] G. Balestrino, E. Milani, and A. A. Varlamov, Pis'ma Zh. Eksp. Teor. Fiz. **61**, 814 (1995) [JETP Lett. **61**, 833 (1995)].