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Positive in-plane and negative out-of-plane magnetoresistance in the overdoped high-temperature superconductor $Bi_2Sr_2CaCu_2O_{8+x}$

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The in-plane and out-of-plane magnetoresistances of moderately overdoped $Bi_2Sr_2CaCu_2O_{8+x}$ single crystals have been studied from T_c+5 K to T_c+100 K with the magnetic field oriented perpendicular and parallel to the current, respectively. The in-plane magnetoresistance is positive, the out-of-plane magnetoresistance negative, and their temperature variations depend on the orientation of the magnetic field. A recent theory for superconducting order parameter fluctuations is extended for the interaction of carrier spins with the magnetic field. The anomalous, anisotropic magnetoresistance can be described well by a unique set of physical parameters, which were found to correspond to estimates from the normal-state transport properties. [S0163-1829(99)08317-4]

A detailed understanding of the unconventional anisotropic properties in the normal state of high-temperature superconductors (HTS) is indispensable to successfully clarify the mechanism for superconductivity in these compounds. A large number of features of the in-plane and out-of-plane electrical-transport properties have been collected so far, which are in sharp contradiction to the classical Bloch-Boltzmann transport theory.[1] One of these is the contrasting temperature dependence of the ''metallic'' in-plane (ρ_{ab}) and the ''semiconducting'' out-of-plane (ρ_c) resistivities in some highly anisotropic HTS that persists down to low temperatures.[2] Application of a magnetic field results in a positive in-plane magnetoresistance (MR) $\Delta\rho_{ab}/\rho_{ab}(0)>0$ that violates Kohler's rule[3,4] and a negative out-of-plane MR $\Delta\rho_c/\rho_c(0)<0$.[5,6] Possible explanations for $\Delta\rho_{ab}/\rho_{ab}(0)$ include two different carrier scattering rates[7] far above T_c and the magnetic-field suppression of superconducting order parameter fluctuations close to T_c.[8] $\Delta\rho_c/\rho_c(0)$ has been interpreted in terms of a spin gap,[6] by interplane tunneling together with a renormalization of the carrier density of states as a result of superconducting fluctuations,[9,5] and several other models. In this paper, we report simultaneous measurements of the anisotropic MR and their interpretation in a coherent model.

For the present paper, we have selected the strongly anisotropic ($\rho_c/\rho_{ab}>10^4$) system $Bi_2Sr_2CaCu_2O_{8+x}$ (2212-BSCCO) that can be prepared as slightly underdoped to overdoped single crystals. In order to exclude effects of the ''pseudogap'' or ''spin gap'' to our measurements, we have limited our study to slightly overdoped 2212-BSCCO single crystals, where the characteristic deviation from the linear $\rho_{ab}(T)$ behavior below a certain temperature T^* is absent.[10] The single crystals were grown by a self-flux method and a segregation growth technique.[11] The as-grown crystals were cleaved and cut into pieces of approximately 500×1500 μm^2 in the ab plane and $1-25$ μm along the c direction. All samples were checked for phase purity by x-ray diffraction and showed no traces of the 2223 phase. The oxygen content was adjusted by annealing in flowing oxygen at 500 °C to obtain crystals in the overdoped region of the BSCCO phase diagram with a zero resistance T_{c0} from 78 to 80 K.

The very large anisotropy of BSCCO requires that the transport properties are measured with two different contact arrangements on two identically prepared samples, cleaved from the same large crystal. The very similar properties are confirmed by the agreement of their T_{c0} values within 0.1 K (see Fig. 1). The in-plane transport measurements were performed using a four-probe arrangement with large current

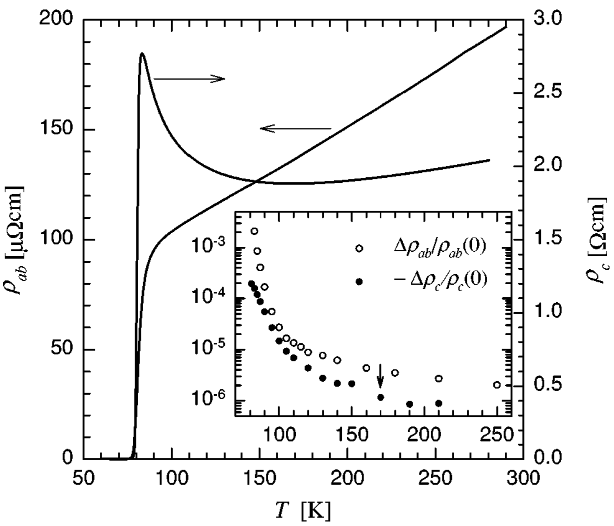

FIG. 1. In-plane and out-of-plane resistivity of slightly overdoped $Bi_2Sr_2CaCu_2O_{8+x}$ single crystals. Inset: In-plane and out-of-plane magnetoresistance of the crystals in a magnetic field $B=1$ T with $B\|c$ axis. The arrow indicates the temperature at which $d\rho_c/dT$ changes sign.

contacts of silver paint entirely covering the ac faces of the crystals to ensure a homogeneous current distribution in the sample. The voltage contacts were established by a thin Au wire on evaporated silver pads. The out-of-plane measurements were performed with two arrangements of ring-shaped current electrodes, with a voltage probe in the center, on the top, and bottom sides of the crystal.

The MR of the crystals was measured in a standard superconducting magnet in magnetic fields up to $B=\pm 13$ T. The temperature was recorded in zero field using a calibrated RhFe sensor, and held constant during the magnetic field sweep with a Cernox (Lake Shore CX-1080-AA) thermometer. A possible MR of the Cernox sensor is a crucial source of error for MR measurements in HTS and was carefully investigated.[12] A lock-in technique at a frequency of 17.4 Hz was applied for all measurements and the in-plane and the out-of-plane current densities were 300 A/cm^2 and 0.4 A/cm^2, respectively. Above 82 K the resistance was independent of the current density within about one order of magnitude. The crystal's ab plane was aligned precisely with respect to the magnetic field in a rotating sample holder with an angular resolution of better than 0.1°.

In the normal state of a superconductor, the conductivity tensor σ_{ij}^N has to be corrected for additional contributions from thermodynamic fluctuations of the superconducting order parameter $\sigma_{ij}=\sigma_{ij}^N+\sigma_{ij}^{fl}$. The latter are usually small, except very close to T_c, in the critical temperature region. The direct, or Aslamazov-Larkin (AL), fluctuation process can be considered as a short-lived, superconducting droplet in thermal nonequilibrium, which is accelerated in an electric and deflected in a magnetic field, resulting in the above corrections to the normal-state transport. In addition, indirect interactions of fluctuations with normal-state quasiparticles [Maki-Thompson (MT)] and the reduction of the quasiparticle density of states (DOS) have been proposed.[13] Outside the critical region the various contributions to the fluctuation conductivity tensor are additive. The at-present most complete microscopic theory[14] calculates several diagonal elements $\sigma_{ii}^{fl}(T,B)$ for direct and indirect contributions and for arbitrary ratios of the mean-free-path and the coherence lengths. The formulas are valid between the clean and the dirty limit[15,8] approximations, and therefore account optimally for the situation in the cuprates, in particular for BSCCO. In this context only the orbital (O) contributions for $B\|c$ have been considered and spin interactions, i.e., the Zeeman (Z) effect,[16] were neglected.

The change of the fluctuation conductivity in a magnetic field [magnetoconductivity (MC)] is $\Delta\sigma_{ii}^{fl}\equiv\sigma_{ii}^{fl}(T,B)-\sigma_{ii}^{fl}(T,0)$. The results for the in-plane ALO effect $\Delta\sigma_{xx}^{ALO}$ (the in-plane DOS effect is considered negligible in HTS), and the out-of-plane ALO ($\Delta\sigma_{zz}^{ALO}$) and orbital DOS ($\Delta\sigma_{zz}^{DOSO}$) contributions in a layered superconductor are given in Ref. 14. The theory contains no phenomenological, but only three microscopic parameters, the interlayer coupling energy J, the Fermi velocity v_F, and a quasiparticle scattering time τ. Their values, in principle, are determined by the normal-state transport properties. We have assumed a temperature dependent $\tau\equiv\tau(100\text{ K})(T/200\text{ K}+\frac{1}{2})^{-1}\sim\rho_{ab}^{-1}$ according to Fig. 1.

For $B\perp c$ and at reduced temperatures $\varepsilon>0.1$ for $B\|c$, the Zeeman interaction with the fluctuations is no longer negligible compared to the orbital process. The corresponding Zeeman terms for the in-plane AL and MT processes were considered previously[16] in the phenomenological fluctuation theory for the dirty-limit case. We use this renormalization of the reduced temperature to account for a shift in T_c due to the pair-breaking of the Zeeman energy

$$\varepsilon_Z=\varepsilon+\mathrm{Re}\left[\Psi\left(\frac{1}{2}+\frac{Ig\mu_B B}{4\pi k_B T_c}\right)-\Psi\left(\frac{1}{2}\right)\right],\qquad(1)$$

where $\varepsilon=\ln(T/T_c)$ is a reduced temperature, Ψ is the Digamma function, g the Landè factor, assumed to be $g=2$, I is the imaginary unit, μ_B is the Bohr magneton, and k_B is the Boltzmann's constant. Using the procedure of Ref. 16, we extend the microscopic model[14] for the Zeeman contributions

$$\Delta\sigma_{xx}^{ALZ}=\frac{e^2}{16\hbar s}\left[\frac{1}{\sqrt{\varepsilon_Z(\varepsilon_Z+r)}}-\frac{1}{\sqrt{\varepsilon(\varepsilon+r)}}\right],\qquad(2)$$

$$\Delta\sigma_{zz}^{ALZ}=\frac{e^2 s}{32\hbar\eta}\left[\frac{\varepsilon_Z+\frac{r}{2}}{\sqrt{\varepsilon_Z(\varepsilon_Z+r)}}-\frac{\varepsilon+\frac{r}{2}}{\sqrt{\varepsilon(\varepsilon+r)}}\right],\qquad(3)$$

$$\Delta\sigma_{zz}^{DOSZ}=-\frac{e^2\kappa s r}{8\hbar\eta}\left[\ln\frac{\sqrt{1+\varepsilon_Z}+\sqrt{1+\varepsilon_Z+r}}{\sqrt{\varepsilon_Z}+\sqrt{\varepsilon_Z+r}}-\ln\frac{\sqrt{1+\varepsilon}+\sqrt{1+\varepsilon+r}}{\sqrt{\varepsilon}+\sqrt{\varepsilon+r}}\right],\qquad(4)$$

with $\hbar$ the reduced Planck constant, the distance between the CuO_2 double layers $s=1.535$ nm, $r=4\eta J^2/(v_F^2\hbar^2)$. η and κ are defined in Ref. 14. The prediction for $\Delta\sigma_{xx}^{ALZ}$ can be compared to the dirty-limit phenomenological theory assuming appropriate parameters and was found to be identical. Now we discuss our experimental results in the theoretical context outlined above.

The temperature variations of ρ_{ab} and ρ_c in two overdoped 2212-BSCCO single crystals prepared from the same batch are shown in Fig. 1. The results are typical for high-quality single crystals of $Bi_2Sr_2CaCu_2O_{8+x}$, $T_{c0}=79\pm0.1$ K for both samples, and from a comparison of the room-temperature values of ρ_{ab} and ρ_c with published data,[10] the oxygen content was estimated $x\approx0.27$. The almost linear $\rho_{ab}(T)$ contrasts with a thermally activated temperature dependence $d\rho_c/dT<0$ below and a metallic behavior above 170 K. The data can be described by an empirical formula $\rho_c(T)=a\exp(\Delta/T)+bT+c$ from 100 to 300 K with $\Delta=273$ K, $a=0.05$ Ω cm, $b=2.4\times10^{-3}$ Ω cm/K, and $c=1.23$ Ω cm. The inset of Fig. 1 shows the anisotropic MR $\Delta\rho_{ab}/\rho_{ab}(0)$ and $\Delta\rho_c/\rho_c(0)$ with $B\|c$ axis. Note the different signs and the fact that $\Delta\rho_c/\rho_c(0)$ does not exhibit a significant feature at 170 K, where $d\rho_c/dT$ turns from negative to positive. This result indicates that the sign of $\Delta\rho_c/\rho_c(0)$ is not directly coupled to that of $d\rho_c/dT$, but rather determined independently by the doping level.[17,18] The

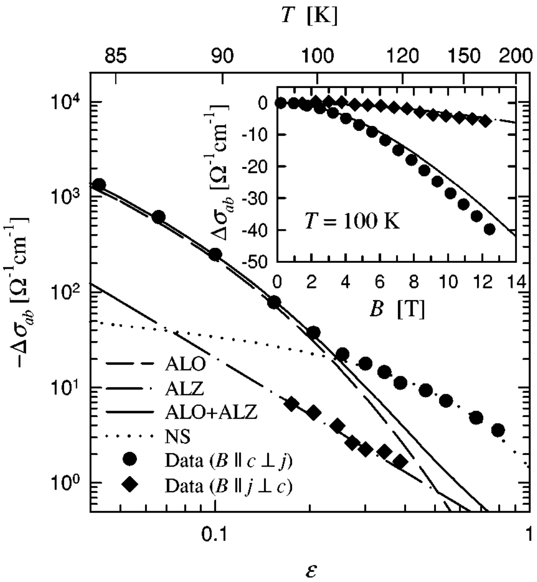

FIG. 2. Transverse (circles) and longitudinal (diamonds) in-plane magnetoconductivity ($B=12$ T) of slightly overdoped 2212-BSCCO crystals as a function of the reduced temperature ε. The lines represent the fits to the fluctuation theory (ALO, ALZ) and an estimate of the normal-state magnetoconductivity. Inset: Magnetic-field dependence of the MC at 100 K ($\varepsilon=0.21$).

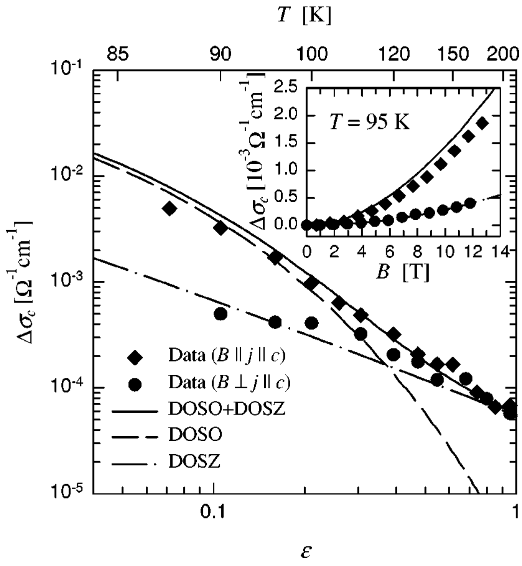

FIG. 3. Longitudinal (diamonds) and transverse (circles) out-of-plane magnetoconductivity ($B=12$ T) of overdoped 2212-BSCCO. The lines represent fits to the fluctuation theory (DOSO, DOSZ), using the same parameters as for Fig. 2. Inset: Magnetic-field dependence of the MC at 95 K ($\varepsilon=0.16$).

MR in both orientations changes tremendously in the vicinity of T_c and exhibits a lower temperature dependence at elevated temperatures. This fact immediately suggests that superconducting fluctuations must be considered.

In Fig. 2 we compare the in-plane MC $\Delta\sigma_{ab}\equiv 1/\rho_{ab}(B)-1/\rho_{ab}(0)\approx-\Delta\rho_{ab}/\rho_{ab}^2(0)$ in the transverse ($B\|c\perp j$) and the longitudinal ($B\|j\perp c$) arrangement with the above theory. Note that a positive MR corresponds to a negative MC. The parameters used to calculate the theoretical curves were $v_F=1.5\times10^7$ cm/s, $J/k_B=4.5$ K, and $\tau=20$ fs, and will be discussed later. The choice of the mean-field T_c is not crucial and was fixed to the midpoint of the ρ_{ab} transition $T_c=81$ K. The ALO process dominates for $\varepsilon<0.25$, but an additional contribution appears at higher temperatures. Like in $YBa_2Cu_3O_7$ (YBCO) this effect cannot be fitted by the MT contributions with reasonable parameters,[19] but appears to originate from the normal-state MR of quasiparticles $\Delta\rho_{ab}/\rho_{ab}(0)=A\tan^2\theta_H$.[3] We estimate this contribution in Fig. 2 from a measurement of the normal-state Hall angle on the very same crystal $\tan\theta_H=[112+0.048(T/\mathrm{K})^{1.8}]^{-1}$, and $A=1.6$. The value for A is close to that in YBCO,[3] but we note that the arrangement of the contacts was optimized for the MR measurements in our experiments and, thus, the magnitude of the Hall coefficient and the result for A is only approximate. A similar temperature dependence of the Hall angle was found in slightly overdoped 2212-BSCCO thin films.[20] Possible small contributions from the DOS effects are masked by the large ALO and quasiparticle MC and have been omitted. On the other hand, the orbital contributions are suppressed due to large anisotropy of 2212-BSCCO and the quasiparticle effect due to absence of the Lorentz force in the longitudinal geometry. In this case, the ALZ term, which is insignificant for the transverse MC, dominates, and the data fit excellently to the ALZ term only.

Figure 3 presents the corresponding data of the longitudinal ($B\|j\|c$) and transverse ($B\perp j\|c$) out-of-plane MC. It is remarkable that $\Delta\sigma_c$ does not exhibit any change of trend at 170 K ($\varepsilon=0.74$), where ρ_c turns from semiconducting to metallic behavior. Above 200 K, the anisotropy of the MC with regard to the B direction almost vanishes despite a pronounced effect close to T_c. This observation is incompatible with the orbital fluctuation effects alone,[6] but is in good agreement with our prediction including the DOS Zeeman contribution. The results can be described by the sum of the DOSO and DOSZ [Eq. (4)] terms in the longitudinal and by the DOSZ term only in the transverse orientation using the *same parameters* as for $\Delta\sigma_{ab}$. The ALO contribution is about two and the ALZ effect about three orders of magnitude smaller than the DOSO term in the temperature range considered here and are neglected. Their relative weakness is caused by the high anisotropy of BSCCO, in contrast to YBCO, where the competition between ALO and DOSO effects produces a sign change of $\Delta\sigma_c$ at about T_c+10 K ($\varepsilon\approx0.1$).[21]

Our results can be compared to normal-state transport quantities using the simple Drude model. Unfortunately, few data of overdoped 2212-BSCCO is available and we had to use results from optimally doped BSCCO. The carrier scattering time $\tau(100\ \mathrm{K})=20$ fs is in fair agreement with results from infrared transmittance, $\tau(100\ \mathrm{K})=35$ fs.[22] From $n=\sqrt{3\pi}[\hbar/(v_F e^2\tau\rho_{ab})]^{3/2}$ we estimate the carrier density $n\approx5\times10^{21}$ cm^{-3}, slightly higher than results from Hall data in optimally doped 2212-BSCCO.[23] The interlayer coupling energy can be compared to the electrical anisotropy[14] $\rho_c/\rho_{ab}=v_F^2\hbar^2/(J^2s^2)=2.7\times10^4$. In our crystals, ρ_c/ρ_{ab} varies from 3.2 to 1.1×10^4 from 85 to 300 K. The results for a second set of similar crystals agree within $\pm20\%$. Keeping in mind that the Drude model cannot accurately describe the anomalous normal-state properties of the HTS,

the agreement of our results with well-accepted values in 2212-BSCCO is surprisingly good.

Finally, we want to comment briefly on the limitations of our analysis. The superconducting fluctuation theory except of the MT terms is rather robust regarding the actual mechanism responsible for high-T_c superconductivity, since essential parts can be also calculated in the framework of the phenomenological Ginzburg-Landau theory. It is expected to hold from a few K above T_c to at least $\approx 1.3T_c$, and all conclusions in this paper are based on this temperature range. Close to T_c it is limited by critical fluctuations and by possible effects related to an inhomogeneous T_c in the samples.[24] Above $1.3T_c$, a cutoff of short wavelength fluctuations might be important,[25] but has not been considered theoretically for the MC so far. It rather appears that the agreement between our data and the theoretical predictions extends to about $2T_c$. On the other hand, our preliminary results of the MR in underdoped 2212-BSCCO indicate that other effects besides superconducting fluctuations, e.g., the ''spin gap'' may become important. We expect that the current understanding of the MR in slightly overdoped BSCCO will help to elucidate these phenomena.

In summary, we have presented comprehensive measurements of the MR above T_c in moderately overdoped 2212-BSCCO single crystals in four different arrangements with the current $j \perp c$ and $j \| c$ and with the magnetic field oriented perpendicular and parallel to j. Although this set of data exhibits very anisotropic features and different signs, it can be described well with the magnetic-field suppression of superconducting fluctuations, if orbital and spin contributions are considered.

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