In-plane anisotropy and possible chain contribution to magnetoconductivity in $YBa_2Cu_3O_{7-\delta}$

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The magnetoresistivity of untwinned $YBa_2Cu_3O_{7-\delta}$ single crystals was measured in magnetic fields up to 12 T, for $\mathbf{B}\|c$ and $\mathbf{B}\|ab$, at temperatures up to T_c+84 K and T_c+50 K, respectively. Two issues were addressed; determination of the in-plane coherence length anisotropy $\gamma=\xi_b/\xi_a$ and discussion of the role of the CuO chains in the magnetoconductivity $\Delta\sigma$. A fluctuation conductivity theory that allows for an in-plane coherence length anisotropy ($\xi_a\neq\xi_b$), as well as an extension of the usual Aronov-Hikami-Larkin theory that does not, were used in analyses. The results suggest that the anisotropy γ is close to 1. The analyses also suggest a contribution to the magnetoconductivity from the CuO chains of a sign which depends on the direction between field and current.

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I. INTRODUCTION

Superconducting fluctuations, i.e., superconducting electron pairs existing above T_c, are more important in high-temperature superconductors (HTSCs) than in conventional superconductors, due to short coherence lengths and high critical temperatures. In this work we investigate the contribution from fluctuations to the electrical conductivity. When studying fluctuation conductivity, the problem of estimating the normal state conductivity arises. To avoid this, magnetoconductivity measurements can be made. This method has been quite frequently used for studying fluctuation conductivity, e.g., for varying current and field directions in $YBa_2Cu_3O_{7-\delta}$ (YBCO), see, e.g., Refs. 1–4. A drawback with this method is that at $T\gg T_c$ the problem of possible contributions from the normal state magnetoresistance then may enter instead.[5]

YBCO is characterized by its double CuO_2 planes, parallel to the crystal *ab* plane, and CuO chains, parallel to the crystal *b* axis, between these planes. The role of the planes and chains in the superconductivity is not yet determined, but it is widely believed that the superconductivity takes place in the planes, while the one-dimensional chains act as a charge reservoir. Experimental signs of superconducting fluctuations in chains have, however, been presented earlier.[4]

One can study the influence of the CuO chains on superconductivity through measurements of in-plane anisotropic transport properties. The in-plane anisotropy γ, of untwinned YBCO has been measured by several methods and for several properties.[6–14] For example, the resistivity anisotropy $\sqrt{\rho_a/\rho_b}$, has been studied,[6–8] effective mass anisotropy $\sqrt{m_a/m_b}$, has been determined from magnetic-torque measurements,[9,10] and penetration depth anisotropy λ_a/λ_b, has been measured through infrared spectroscopy,[11] modulation of the Josephson critical current,[12] and small angle neutron scattering.[13] The coherence length anisotropy ξ_b/ξ_a, in a twinned sample was studied from the direct image of the vortex lattice, obtained from scanning tunneling microscopy.[14] Quite different values of γ have been obtained. Effective mass anisotropy seems to yield low values (1.12, 1.18, Refs. 9, 10) while penetration depth anisotropy results are more spread (1.18–2.93, Refs. 11–13). The coherence length anisotropy $\gamma=\xi_b/\xi_a$, was reported to be 1.5.[14] It has also often been taken to be the square root of the resistivity ratio $\sqrt{\rho_a/\rho_b}$, which has been found to be in the range 1.05–1.48 (Refs. 6–8).

Microscopic properties, such as the coherence length ξ and phase-breaking time τ_ϕ, can be studied through the fluctuation magnetoconductivity. Neither the commonly used Aronov-Hikami-Larkin (AHL) fluctuation theory,[15] nor the extended calculations by Dorin *et al.*,[16] allow for an in-plane coherence length anisotropy ($\xi_a\neq\xi_b$). However, there is a theory by Maki and Thompson[17] which takes this anisotropy into account, and gives the possibility to determine the ratio ξ_b/ξ_a.

In this paper we study the in-plane fluctuation conductivity of untwinned $YBa_2Cu_3O_{7-\delta}$ single crystals for both $\mathbf{B}\|c$ and $\mathbf{B}\|ab$. Such studies have to our knowledge not been made before, due to several difficulties. It is hard to obtain large enough, twin free crystals. The contacts are difficult to align, resulting in Hall-effect contributions. To avoid geometric magnetoresistances, the sample length must be larger than the sample width. Several batches of crystals were prepared and examined to select large enough samples with suitable shapes allowing for reliable measurements.

It was found that for $\mathbf{B}\|c$ the magnetoconductivity is approximately the same for the *a* and *b* directions, and the in-plane coherence length anisotropy is thus close to 1 (1.1 $\pm$0.1), i.e., smaller than expected from the resistivity ratio. From measurements with $\mathbf{B}\|\mathbf{I}\|ab$ we further observe a different field direction dependence for $\Delta\sigma_{I\|a}$ and $\Delta\sigma_{I\|b}$, possibly originating from a CuO-chain contribution.

II. EXPERIMENTAL DETAILS

Single crystals of $YBa_2Cu_3O_{7-\delta}$ were grown by the self flux method,[18] and annealed in flowing oxygen at ~450 °C. Six crystals were selected, from a set of grown crystals which had been cut into suitable oblong pieces along *a* and *b* directions, respectively. They were verified under polarized light to be twin free. The critical temperatures, defined as the temperature where the resistivity is 50% of the normal state value, were in the range 92–93 K with transition widths of

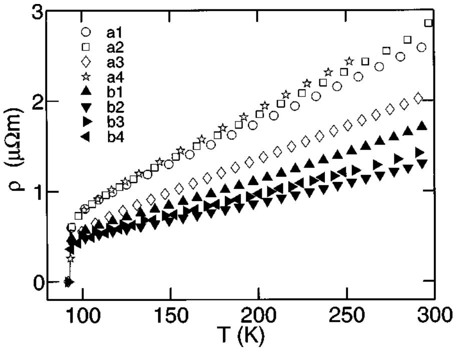

FIG. 1. Normal state resistivity $\rho_n(T)$ up to room temperature (for most samples). For two samples $a1$ and $b3$ the thickness was not known. The resistivity was therefore assumed to be approximately equal to the corresponding results for the other a and b samples, respectively, and the thickness was calculated from the resistivity at 100 K $\{\rho_{a1}(100\text{ K})=\rho_{a2}(100\text{ K})$ and $\rho_{b3}(100\text{ K})=[\rho_{b1}(100\text{ K})+\rho_{b2}(100\text{ K})]/2\}$.

0.15–0.45 K. The sample sizes were about $(300–450)\times(50–200)\times(5–25)\,\mu\text{m}^3$, with the largest side parallel to the current direction. A seventh crystal, with one twin boundary, was also chosen. This crystal had $T_c\approx 93$ K and $\Delta T_c\approx 1$ K. The size was approximately $1050\times 200\times 5\,\mu\text{m}^3$, with one twin free region 800 μm long and the other 250 μm long.

Contacts were made by applying silver paint, followed by a heat treatment in flowing O_2. The current was parallel with the crystal a axis in three of the untwinned samples (named $a1$, $a2$, and $a3$), and parallel to the b axis in the other three untwinned samples ($b1$, $b2$, $b3$). On the seventh crystal one potential contact was placed directly on the twin boundary. Together with two other contacts, one in each twin free region, it was possible to measure resistivity along the a and b axis at the same time on the same crystal. These crystal parts are denoted $a4$ and $b4$.

Resistivity was measured using a standard four probe technique. The normal state resistivities at 100 K were between 50–80 $\mu\Omega$ cm with an error of ~30% due to the uncertain geometrical form factors. $\rho(T)$ for the two crystal axes is shown in Fig. 1 up to room temperature (for most samples). Despite the large error we see consistently smaller resistivities for b samples than for a samples. The magnetoresistance was measured in a flowing gas cryostat, with **B** parallel to the c axis (for all seven samples) and **B** parallel to the ab plane (for four untwinned samples), in the latter case both for $\mathbf{B}\parallel\mathbf{I}$ and $\mathbf{B}\perp\mathbf{I}$. The temperature was varied in the range $(T_c+2\text{ K},T_c+84\text{ K})$. Field sweeps up to 12 T at the rate ~0.75 T/min were made in two opposite directions $(0\text{ T}\rightarrow 12\text{ T}\rightarrow 0\text{ T}\rightarrow -12\text{ T}\rightarrow 0\text{ T})$, to be able to compensate for the Hall drift. (A Hall drift contribution was observed since the small sample sizes made it difficult to perfectly align the contacts.) The temperature of the sample holder was controlled with a Pt thermometer located 20 cm above the samples, where Helmholtz coils canceled the magnetic field. A carbon-glass thermometer was used to measure the temperature at the samples. Temperature drift during a measurement cycle of 60 min was typically a few mK.

It could be argued that microtwin boundaries might exist which are invisible to the eye in the polarizing microscope referred to above. There could not be an odd number of boundaries, since this would be clearly seen as regions of different color. However, even in the presence of such pairs of twins, the average property of a sample should still be either a or b oriented, since twin boundaries only have small effects on the normal state resistivity.

III. ANALYSES

The fluctuation magnetoconductivity $\Delta\sigma(B,T)$ is calculated from the measured resistivity ρ as

$$\Delta\sigma(B,T)=\frac{1}{\rho(B,T)}-\frac{1}{\rho(0,T)}. \tag{1}$$

We used two methods to analyze $\Delta\sigma(B,T)$, the theory by Dorin *et al.* (DKVBL) (Ref. 16) and a theory by Maki and Thompson (M-T).[17]

A. DKVBL theory

The theory by Dorin *et al.*[16] includes four orbital (O) terms [abbreviations O, AL, MT, etc., are used in Eq. (2) to label the contributions]; the Aslamazov-Larkin (AL) term (direct contribution from superconducting electron pairs), the regular and anomalous Maki-Thompson (MT) terms (interaction between superconducting fluctuations and normal state electrons), and the density-of-states (DOS) term (density of states of normal state electrons changes when superconducting electron pairs are created). A cutoff in the MT(reg) and DOS terms were made, according to the regularization method of Refs. 19 and 20. Zeeman (Z) corrections to the orbital terms were also considered. They were calculated from a magnetic field depression of T_c (corresponding to an increase in the reduced temperature $\epsilon=\ln T/T_c$), as in Refs. 15 and 21. The resulting fluctuation magnetoconductivity in this model thus includes eight terms in total:

$$\Delta\sigma(J,\tau,\tau_\phi,v_F,s)=\Delta\sigma^{\text{ALO}}+\Delta\sigma^{\text{ALZ}}+\Delta\sigma^{\text{MT(reg)O}}+\Delta\sigma^{\text{MT(reg)Z}}+\Delta\sigma^{\text{MT(an)O}}+\Delta\sigma^{\text{MT(an)Z}}+\Delta\sigma^{\text{DOSO}}+\Delta\sigma^{\text{DOSZ}}. \tag{2}$$

The Zeeman terms, in contrast to the orbital terms, are independent of field direction. For $\mathbf{B}\parallel ab$ the orbital terms were neglected, leaving only the four Zeeman terms. The complete expressions used in our analyses, were given in Ref. 22.

The coherence lengths can be calculated from J and τ, according to

$$\xi_{ab}=\sqrt{\frac{v_F^2\tau^2 f_0}{2}}, \tag{3}$$

$$\xi_c=\frac{s}{2}\sqrt{\frac{2k_B^2\tau^2J^2 f_0}{\hbar^2}}, \tag{4}$$

where

$$f_0 = -\Psi\left(\frac{1}{2}+\frac{\hbar}{4\pi k_B T\tau}\right)+\Psi\left(\frac{1}{2}\right)+\frac{\hbar}{4\pi k_B T\tau}\Psi'\left(\frac{1}{2}\right), \tag{5}$$

and $\Psi=(d/dx)[\ln\Gamma(x)]$ is the digamma function. J is the hopping integral, τ the in-plane elastic scattering time, τ_ϕ the phase-breaking time (average time between inelastic scattering events), v_F ($\approx 2\times10^5$ m/s) the Fermi velocity,[23] and s (≈ 11.7 Å) the distance between superconducting layers.

B. M-T theory

DKVBL does not treat an in-plane coherence length anisotropy ($\xi_a \neq \xi_b$). Based on the three-dimensional Ginzburg-Landau theory, Maki and Thompson developed a theory which allows for studies of $\xi_a \neq \xi_b$.[17] This theory includes two terms:

$$\Delta\sigma(\xi_a,\xi_b,\xi_c,\tau_\phi)=\Delta\sigma^{\mathrm{reg}}+\Delta\sigma^{\mathrm{an}}. \tag{6}$$

The anomalous terms correspond to the MT term in the traditional Aronov-Hikami-Larkin (AHL) theory,[15] while the regular term corresponds to the AL term.

The regular term depends on the direction of the magnetic field. With the current in the x direction, parallel to a principal crystal axis, the regular contribution to the magnetoconductivity becomes

$$\Delta\sigma^{\mathrm{reg}}=\frac{e^2}{8\hbar}\frac{\xi_x}{\xi_y\xi_z}\left[\frac{1}{\sqrt{b}}S^{\mathrm{reg}}\left(\frac{\epsilon}{b}\right)-\frac{1}{4\sqrt{\epsilon}}\right]. \tag{7}$$

S^{reg} and b are differently defined depending on the direction of the magnetic field $\mathbf{B}\|\mathbf{I}$ or $\mathbf{B}\perp\mathbf{I}$ ($\mathbf{B}\|z$):

$$b_\perp=\frac{2eB\xi_x\xi_y}{\hbar}, \tag{8}$$

$$b_\|=\frac{2eB\xi_y\xi_z}{\hbar}, \tag{9}$$

$$S_\perp^{\mathrm{reg}}(x)=\sum_{n=0}^{\infty}(n+1)\left(\frac{1}{\sqrt{x+2n+1}}-\frac{2}{\sqrt{x+2n+2}}+\frac{1}{\sqrt{x+2n+3}}\right), \tag{10}$$

$$S_\|^{\mathrm{reg}}(x)=\frac{1}{4}\sum_{n=0}^{\infty}(x+2n+1)^{-3/2}. \tag{11}$$

The anomalous contribution does not depend explicitly on the field direction, but the correct b from Eqs. (8) or (9), according to the direction of $\mathbf{B}$, must be used, giving

$$\Delta\sigma^{\mathrm{an}}=\frac{e^2}{8\hbar}\frac{\xi_x}{\xi_y\xi_z}\left\{\frac{\sqrt{b}}{\epsilon-\delta}\left[\frac{\epsilon}{b}S^{\mathrm{an}}\left(\frac{\epsilon}{b}\right)-\frac{\delta}{b}S^{\mathrm{an}}\left(\frac{\delta}{b}\right)\right]-\frac{1}{\sqrt{\epsilon}+\sqrt{\delta}}\right\}, \tag{12}$$

where $\delta=\pi\hbar/8k_BT\tau_\phi$ is the pair breaking parameter,[24] and

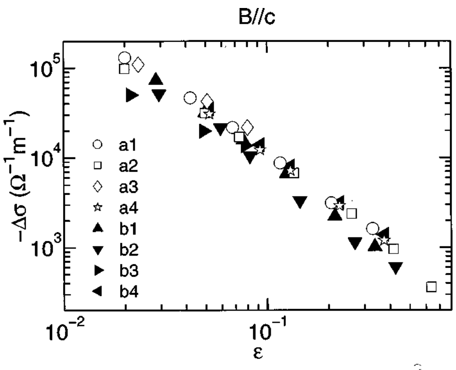

FIG. 2. Magnetoconductivity $\Delta\sigma$, at 12 T for $\mathbf{B}\|c$ as a function of reduced temperature $\epsilon=\ln T/T_c$. Open symbols are a samples ($\mathbf{I}\|a$) and filled symbols are b samples ($\mathbf{I}\|b$).

$$S^{\mathrm{an}}(x)=\frac{1}{x}\sum_{n=0}^{\infty}\left(\frac{1}{\sqrt{2n+1}}-\frac{1}{\sqrt{x+2n+1}}\right). \tag{13}$$

IV. RESULTS

A. Magnetic field parallel to c axis

Figure 2 shows that the systematic difference between samples with $\mathbf{I}\|a$ and $\mathbf{I}\|b$ is small when $\mathbf{B}\|c$, i.e., $\Delta\sigma_{I\|a}\approx\Delta\sigma_{I\|b}$, suggesting that the superconducting fluctuations are almost isotropic within the planes. These data are in qualitative agreement with our previous results for two samples.[25] To investigate this apparent isotropic behavior further, the M-T theory was fitted to our experimental data by adjusting the coherence lengths and phase-breaking time. In the expressions for the magnetoconductivity ξ_a and ξ_b only occur as a product, or as a ratio multiplied with $1/\xi_c$ [Eqs. (7) and (12)]. Therefore varying ratios of ξ_b/ξ_a can give identical fits. To handle this problem, the parameter ξ_b/ξ_a was varied with an additional constraint: Only small differences in ξ_c in different samples were allowed. In particular no systematic deviations between samples with $\mathbf{I}\|a$ and $\mathbf{I}\|b$ were expected since the samples were prepared in the same way. Systematic differences between results for ξ_c for a and b samples are evident in Fig. 3 for $\gamma\gtrsim1.2$. We therefore conclude that γ is likely smaller than 1.2. Sample $b3$ appears to be anomalous, and excluding this sample the conclusion is thus that $\gamma\approx1.1\pm0.1$. The resulting parameters were: $\xi_a\approx11$–14 Å, $\xi_c\approx1.3$–2.8 Å (excluding sample $b3$), and $\tau_\phi\approx34$–340 fs (except for sample $a1$, that seemed to have no anomalous contribution, i.e., $\tau_\phi\approx0$).

As mentioned, there is a substantial error of 30% in the determination of resistivity values due to the uncertain geometrical form factors. This uncertainty could explain the observed scattering of ξ_c values in Fig. 3. However, the results for the anisotropy ratio ξ_b/ξ_a do not depend on ρ.

Analyses of the data for sample $a4$-$b4$ supported the γ value obtained above. Since the two regions are part of the same sample, all physical parameters should be equal. When fitting to the experimental data of $a4$ and $b4$ at the same time, all parameters could then be uniquely determined. The best fit resulted in an anisotropy $\gamma\approx1.07\pm0.03$.[26] The ob-

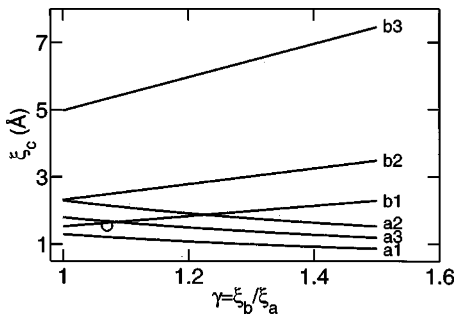

FIG. 3. Resulting ξ_c's of samples $a1$-3, $b1$-3, for different fixed ratios of ξ_b/ξ_a in fits of the anisotropic M-T theory. **B** is parallel to the c axis. From these measurements we conclude that γ is likely smaller than 1.2 as discussed in the text. The open circle shows the result of the best fit using samples $a4-b4$, and keeping all parameters equal in the two crystal parts.

tained coherence lengths and phase-breaking time were then $\xi_a \approx 11.6\,\text{Å}$, $\xi_b \approx 12.5\,\text{Å}$, $\xi_c \approx 1.5\,\text{Å}$, and $\tau_\phi \approx 210\,\text{fs}$.

As an alternative procedure, $\Delta\sigma(B,T)$ of all six untwinned samples was analyzed at the same time, with two constraints; the ratio ξ_b/ξ_a should be equal for all six samples, as well as the out-of-plane coherence length ξ_c. Although crystals from the same batch can have different properties, our samples had similar critical temperatures and transition widths. The variations in microscopic parameters are thus expected to be small. It was then found that $\xi_a \approx 12-15$ Å, $\xi_c \approx 1.7$ Å, $\tau_\phi \approx 40-380$ fs and the ratio $\xi_b/\xi_a \approx 1.04$ gave the best fit.[27] This result is in qualitative agreement with the analyses above.

Since the in-plane anisotropy appeared to be quite small, we also tried to fit the DKVBL theory, which is in-plane isotropic, by adjusting J, τ, and τ_ϕ. As illustrated in Fig. 4 the quality of the fits was almost the same as for the M-T theory. The adjusted parameters were $J \approx 200-700\,\text{K}$, $\tau \approx 2.7-4.4$ fs, and $\tau_\phi \approx 110-820$ fs, which corresponds to $\xi_{ab} \approx 12-14$ Å, $\xi_c \approx 2.1-6.2$ Å. The results for the various M-T analyses can be summarized for most samples and analyses in the following way: $\xi_a \approx 11-15$ Å with $\xi_b/\xi_a \approx 1.1 \pm 0.1$, $\xi_c \approx 1.3-2.8\,\text{Å}$, and $\tau_\phi \approx 34-380\,\text{fs}$.

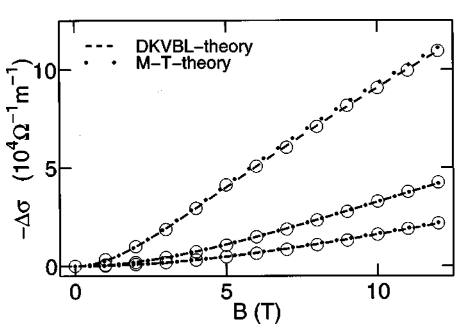

FIG. 4. Magnetoconductivity $\Delta\sigma$, as a function of magnetic field ($\mathbf{B}\| c$) for sample $a3$ at temperatures, from top to bottom, 95, 98, and 101 K. Circles are measurements, dashed lines are the fitted DKVBL theory and dotted lines are the fitted M-T theory. The quality of the two fits is almost identical. The difference between the root-mean-square values r, of the M-T and DKVBL theories in analyses of different samples was $|r^{\text{M-T}} - r^{\text{DKVBL}}| \leqslant 15\ \Omega^{-1}\,\text{m}^{-1}$, $[r = \sqrt{\Sigma_{i=1}^{n}(p_i - f_i)^2/(n-1)}]$. For sample $a3$ shown here, $r^{\text{M-T}} \approx 75\,\Omega^{-1}\,\text{m}^{-1}$.

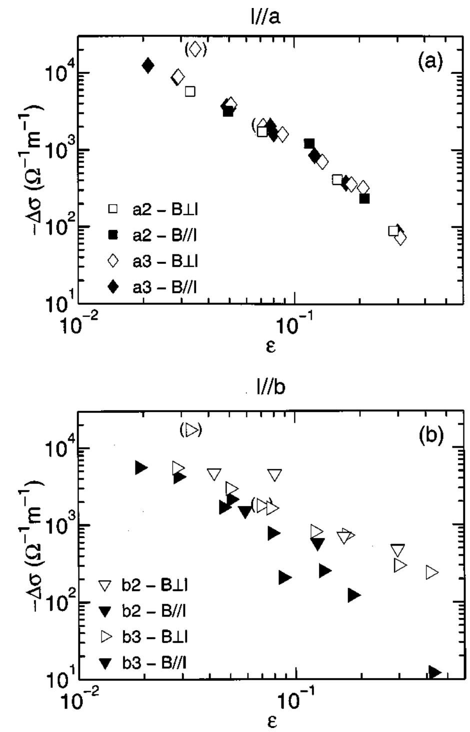

FIG. 5. Magnetoconductivity $\Delta\sigma$, at 12 T as a function of reduced temperature $\epsilon = \ln T/T_c$. (a) a samples ($\mathbf{I}\| a$). (b) b samples ($\mathbf{I}\| b$). In both panels are $\mathbf{B}\|\mathbf{I}$ for filled symbols and $\mathbf{B}\perp\mathbf{I}$ for open symbols. (a) Shows that when $\mathbf{I}\| a$, the direction of the magnetic field has no importance. (b) Shows that when $\mathbf{I}\| b, |\Delta\sigma(B\|\text{chains})| < |\Delta\sigma(B\perp\text{chains})|$. In the measurements of points marked ( ) the temperature error was larger than normal. This is apparent at small ϵ's in the figures.

B. Magnetic field parallel to the *ab* plane

When the magnetic field is parallel to the *ab* plane, the magnetoconductivity is smaller since the orbital contributions are much reduced. Compared to the case $\mathbf{B}\| c$, $|\Delta\sigma|$ is approximately ten times smaller.

If the magnetic field was misaligned out of the *ab*-plane, there would be a contribution from $\Delta\sigma_{B\|c}$. In our measurements the angle θ between the magnetic field and the *ab* plane was not more than a few degrees. Since the measurements were performed above T_c where the resistivity varies smoothly with θ [unlike below T_c where $\rho(\theta)$ may vary abruptly], the contribution from $\Delta\sigma_{B\|c}$ to $\Delta\sigma_{B\|ab}$ should not be significant. An estimation of the error shows that it is of the order ~10%.

In contrast to the case $\mathbf{B}\| c$, we find that for $\mathbf{B}\| ab$, $\Delta\sigma(B,T)$ depends on the relative direction of current and field. For $\mathbf{I}\| a$ the magnetoconductivity is the same for $\mathbf{B}\|\mathbf{I}$ and $\mathbf{B}\perp\mathbf{I}$ as illustrated in Fig. 5(a), while for $\mathbf{I}\| b$ $|\Delta\sigma|$ is smaller for $\mathbf{B}\|\mathbf{I}$ than for $\mathbf{B}\perp\mathbf{I}$, and this difference increases with increasing temperature [Fig. 5(b)]. The same data displayed in Fig. 6 shows that for $\mathbf{B}\| a$ the magnetoconductivity is approximately isotropic [panel (a)], while for $\mathbf{B}\| b$, $|\Delta\sigma|$ for $\mathbf{I}\| b$ is smaller than for $\mathbf{I}\| a$.

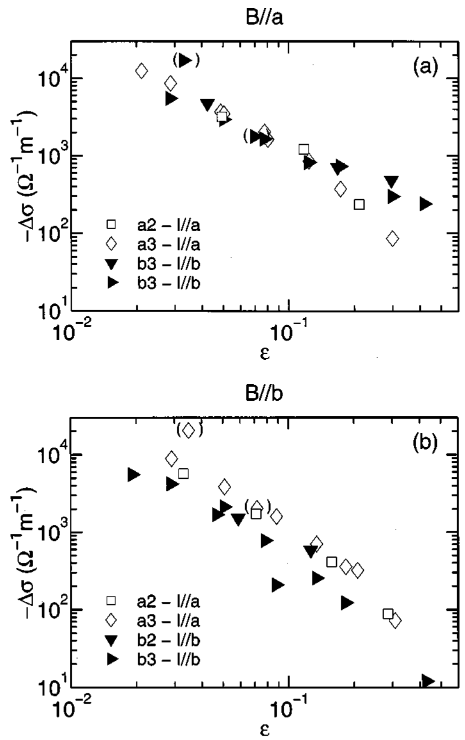

FIG. 6. Magnetoconductivity $\Delta\sigma$, at 12 T as a function of reduced temperature $\epsilon = \ln T/T_c$. The magnetic field is parallel to the crystal a axis, $\mathbf{B}\| a$ in panel (a), and parallel to the b axis, $\mathbf{B}\| b$ in panel (b). In both panels are open symbols a samples ($\mathbf{I}\| a$) and filled symbols b samples ($\mathbf{I}\| b$). In (a) it can be seen that when **B** is perpendicular to the chains $\Delta\sigma$ is independent of the direction of the current. (b) Shows that when **B** is parallel to the chains, $|\Delta\sigma(\mathbf{I}\| b)| < |\Delta\sigma(I\| a)|$. In the measurements of points marked ( ), at small ϵ's in the figures, the temperature error was larger than normal.

The field direction is consequently only important when the current is parallel to the CuO chains. This can be discussed in terms of a simple model, previously often used for $\sigma(T)$.[4,7,8,28] Let σ_a be the resistivity of the CuO_2 plane (a direction), and σ_b the result of a parallel circuit of the resistivity of the CuO_2 plane (b direction) and the CuO chain. The conductivities of the CuO_2 planes are assumed to be isotropic ($\sigma_{\mathrm{plane},a} = \sigma_{\mathrm{plane},b}$). The conductivities thus become $\sigma_a = \sigma_{\mathrm{plane}}$, and $\sigma_b = \sigma_{\mathrm{plane}} + \sigma_{\mathrm{chain}}$. The magnetoconductivity, $\Delta\sigma = \sigma(B) - \sigma(0)$, can then be expressed correspondingly:

$$\Delta\sigma_a = \Delta\sigma_{\mathrm{plane}}, \tag{14}$$

$$\Delta\sigma_b = \Delta\sigma_{\mathrm{plane}} + \Delta\sigma_{\mathrm{chain}}. \tag{15}$$

In this model a few observations can be made. There is good agreement between the results for $\Delta\sigma_a(\mathbf{B}\|\mathbf{I})$ and $\Delta\sigma_a(\mathbf{B}\perp\mathbf{I})$ [Fig. 5(a)], i.e., when the current only passes through the CuO_2 plane. When the current also passes through the CuO chains [$\mathbf{I}\| b$, Figs. 5(b) and 6], the magnetoconductivity differs for different field directions. The fact that this difference only arises for $\mathbf{I}\| b$ thus suggests that CuO chains are important for the magnetoconduction. The CuO_2 planes are isotropic, according to Fig. 5(a), unlike the CuO chains [Fig. 5(b)]. Then, since $\Delta\sigma_a(\mathbf{B}\| b) < \Delta\sigma_b(\mathbf{B}\| b)$ in Fig. 6(b), the magnetoconductivity of the CuO chains is positive for $\mathbf{B}\|\mathbf{I}$, i.e., $\Delta\sigma_{\mathrm{chain}}(\mathbf{B}\|\mathbf{I}) > 0$. From Fig. 6(a) $\Delta\sigma_b(\mathbf{B}\| a)$ is approximately equal to $\Delta\sigma_a(\mathbf{B}\| a)$ at temperatures close to T_c and numerically larger than $\Delta\sigma_a(\mathbf{B}\| a)$ at high temperatures. Thus the chain magnetoconductivity for $\mathbf{B}\perp\mathbf{I}$, [$\Delta\sigma_{\mathrm{chain}}(\mathbf{B}\perp\mathbf{I})$] is negative at high temperatures and becomes vanishingly small close to T_c.

V. BRIEF CONCLUDING REMARKS AND SUMMARY

Our result for γ with $\mathbf{B}\| c$ is smaller than some previously reported results, as quoted in the Introduction. In particular it is smaller than estimates from the normal state resistivity in the range up to 1.5.[7] In Fig. 1 $\gamma = \sqrt{\rho_a/\rho_b}$ is about 1.2 at 100 K. However, there are significant differences between these two types of measurements. The normal state resistivity may be regarded as a parallel circuit of the CuO chains and CuO_2 planes, while superconductivity is confined to the planes. This may account for a difference in anisotropy for normal conductivity and superconductivity measurements.

The results for $\mathbf{B}\| ab$ are more difficult to interpret. The experimental results can, however, be summarized as $\Delta\sigma_a(\mathbf{B}\|\mathbf{I}) = \Delta\sigma_a(\mathbf{B}\perp\mathbf{I})$ [Fig. 5(a)], $\Delta\sigma_b(\mathbf{B}\|\mathbf{I}) > \Delta\sigma_b(\mathbf{B}\perp\mathbf{I})$ [Fig. 5(b)], $\Delta\sigma_a < \Delta\sigma_b(\mathbf{B}\|\mathbf{I})$ [Fig. 6(b)], $\Delta\sigma_a \approx \Delta\sigma_b(\mathbf{B}\perp\mathbf{I})$ at low temperatures and $\Delta\sigma_a > \Delta\sigma_b(\mathbf{B}\perp\mathbf{I})$ at high temperatures [Fig. 6(a)].

In conclusion, we have made magnetoresistivity measurements above T_c, on $YBa_2Cu_3O_{7-\delta}$, with **B** parallel to the a, b, and c axes, and **I** parallel to the a or b axes. $\mathbf{I}\| a$ and $\mathbf{I}\| b$ gave approximately the same magnetoconductivity when $\mathbf{B}\| c$. Using a fluctuation theory which allows for an in-plane coherence length anisotropy, the anisotropy was found to be close to 1, 1.1 ± 0.1. $\Delta\sigma$ for $\mathbf{B}\| ab$ was found to depend on the relative directions of **B** and **I**, suggesting a contribution from the CuO chains to the magnetoconductivity.

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