Magnetic Field Induced Dimensional Crossover in the Normal State of $YBa_2Cu_4O_8$

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$YBa_2Cu_4O_8$ is unique among underdoped cuprates in that its low-T c-axis response is metallic. When a magnetic field is applied perpendicular to the CuO chains ($\boldsymbol{B} \parallel \boldsymbol{a}$), however, the c-axis resistivity ρ_c changes dramatically and, at sufficiently high fields, $\rho_c(T)$ begins to show localized behavior. This observation reveals the critical role of the CuO chains in metallizing the c axis in $YBa_2Cu_4O_8$. In the field range where $\rho_c(T)$ is insulating, $\Delta\rho_c/\rho_c$ varies linearly rather than quadratically with field, suggesting a new magnetoconductivity regime in a state of lower dimensionality. [S0031-9007(98)05670-1]

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The contrasting behavior of the in- and out-of-plane conductivity of high-T_c cuprates remains an issue of fascinating debate [1]. In optimally doped $Bi_2Sr_2CuO_6$ [2], for example, $\rho_c(T)$ is divergent while the in-plane resistivity $\rho_{ab}(T)$ remains metallic, even below 1 K, thus invalidating the standard Fermi-liquid (FL) picture for anisotropic conductors. In underdoped $YBa_2Cu_3O_{7-\partial}$ [3], the presence of the normal-state gap appears to have opposing effects on the behavior of $\rho_{ab}(T)$ and $\rho_c(T)$; while $\rho_{ab}(T)$ shows a marked decrease below some characteristic T^*, $\rho_c(T)$ *increases* sharply [3]. This qualitatively anisotropic behavior has been viewed as strong evidence for charge confinement within the CuO_2 planes, possibly associated with a non-FL ground state and/or spin singlet pair formation [4–7].

$YBa_2Cu_4O_8$ is a naturally underdoped cuprate that, in principle, can be prepared with negligible disorder. Its structure comprises an alternate stacking of two CuO_2 units within the ab plane and two highly conducting CuO chains oriented along the b direction (see Fig. 2). Recently, we succeeded in measuring its c-axis response up to 450 K [8]. At high T, $\rho_c(T)$ is essentially T independent as found for other underdoped cuprates. Surprisingly, however, as T is reduced, $\rho_c(T)$ drops sharply, implying the onset of *metallic* c-axis transport at low T. Although this observation appears to contradict the charge confinement picture, it may be argued that, in $YBa_2Cu_4O_8$, only carriers in its unique double chains form coherent bands along the c axis and that the carriers in the plane band still remain "confined."

In order to try and resolve this issue, we have carried out a detailed investigation of the out-of-plane magnetoresistance (MR) of $YBa_2Cu_4O_8$ in pulsed magnetic fields up to 35 T. First, by suppressing superconductivity with $\boldsymbol{B} \parallel \boldsymbol{c}$, we were able to confirm the metallic nature of $\rho_c(T)$ down to 30 K. In the normal state, we observed an extremely large, positive MR $\Delta\rho_c/\rho_c$ only when the field is applied perpendicular to the CuO chains ($\boldsymbol{B} \parallel \boldsymbol{a}$), suggesting that coherent c-axis transport at low temperatures is associated only with carriers in the chain band, leaving the issue of charge confinement on the CuO_2 planes intriguingly open. The most remarkable finding of this work, however, is that the chains become decoupled along the c axis at high fields ($\boldsymbol{B} \parallel \boldsymbol{a}$), resulting in a magnetic field-induced dimensional crossover and nonmetallic $\rho_c(T)$.

The $YBa_2Cu_4O_8$ crystals were grown by a flux method in Y_2O_3 crucibles and an Ar/O_2 mixture at 2000 bars, with a partial O_2 pressure of 400 bars [9]. Typical dimensions of the crystals used in this study were $0.2 \times 0.2 \times 0.1$ mm^3. Large current and voltage pads were mounted on the top and bottom of several crystals with different geometrical ratios in a quasi-Montgomery configuration. All zero-field $\rho_c(T)$ curves were consistent with our previous report [8]. The MR measurements were performed in two superconducting magnet systems (using an ac resistance bridge circuit) and in a pulsed high magnetic field cryostat. For the pulsed field measurements, two field pulses were applied at each set temperature with reversed current to take into account effects of induced (dB/dt) voltages. A series of pulses with different maximum field values [and, hence, different $(dB/dt)^2$ effects] were also taken at an initial temperature to check for eddy-current heating in the samples. Excellent agreement was found for all pulses, indicating that sample heating was not important in our measurements.

In order to corroborate our previous claim that the low-T c-axis response in $YBa_2Cu_4O_8$ is metallic, we measured $\rho_c(T)$ for two crystals down to lower T by suppressing the superconductivity under high fields with $\boldsymbol{B} \parallel \boldsymbol{c}$. The inset of Fig. 1 shows a selection of resistivity-field profiles for one crystal between 16 and 90 K. The evolution of $\rho_c(T)$ down to lower T is represented in Fig. 1, where we show

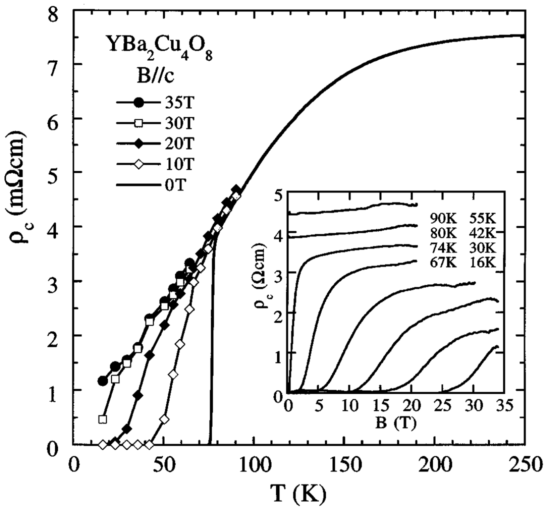

FIG. 1. $\rho_c(T)$ for $YBa_2Cu_4O_8$ extended below $T_c = 80$ K by suppressing superconductivity with $\boldsymbol{B} \parallel \boldsymbol{c}$. The figure shows $\rho_c(T)$ at 0 T (solid line), 10 T (open diamonds), 20 T (closed diamonds), 30 T (open squares), and 35 T (closed circles). Inset: Selected low-T $\rho_c(B)$ sweeps with $\boldsymbol{B} \parallel \boldsymbol{c}$.

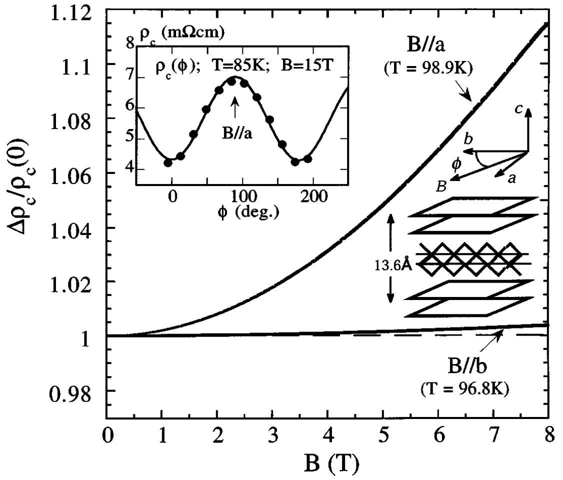

FIG. 2. c-axis MR field sweeps up to 8 T with $\boldsymbol{B} \parallel \boldsymbol{a}$ and $\boldsymbol{B} \parallel \boldsymbol{b}$ at $T \approx 100$ K. Top inset: angular dependence of c-axis MR at $T = 85$ K and $B = 15$ T. The field was rotated within the ab plane. The fit is a single cosine with twofold symmetry. Bottom inset: Schematic of the crystal structure of $YBa_2Cu_4O_8$.

the zero-field $\rho_c(T)$ curve (solid line) together with values of $\rho_c(T)$ at 10, 20, 30, and 35 T. It is clear from both the inset and the main figure that the normal state is accessible down to at least 30 K in a field of 35 T. Note, also, that the normal state MR is small in this field orientation ($\approx 15\%$ in 35 T at $T = 85$ K) and, thus, does not affect strongly the T dependence of $\rho_c(T)$ at high fields. $\rho_c(T)$ continues to fall rapidly with decreasing T, and, at $T = 30$ K, $\rho_c(T)$ reaches a value ≈ 1.6 m Ω cm, corresponding to a conductivity $\sigma_c \approx 600\ \Omega^{-1}\,\mathrm{cm}^{-1}$ that is well above the Mott-Ioffe-Regel limit for metallic c-axis conductivity in high-T_c cuprates [10], confirming that c-axis transport in underdoped $YBa_2Cu_4O_8$ is indeed coherent at low T.

As a further test of the metallicity of the c axis in $YBa_2Cu_4O_8$, an initial MR study was carried out just above T_c in an 8 T magnet with the field applied parallel ($\boldsymbol{B} \parallel \boldsymbol{b}$) and perpendicular ($\boldsymbol{B} \parallel \boldsymbol{a}$) to the CuO chains [11]. According to Boltzmann transport theory, if c-axis transport is coherent and the Fermi surface (FS) is open in the c direction, the c-axis MR should be positive and significantly larger than the in-plane MR. It is also particularly sensitive to anisotropy of the *in-plane* properties when the field is rotated within the ab plane [12]. Figure 2 shows two orthogonal $\rho_c(B)$ field sweeps at $T \approx 100$ K. $\rho_c(B)$ is positive for both field sweeps, but there exists a striking anisotropy between the two field directions; for $\boldsymbol{B} \parallel \boldsymbol{a}$, $\Delta\rho_c/\rho_c$ is extremely large (≈ 0.12 in 8 T), while for $\boldsymbol{B} \parallel \boldsymbol{b}$, it is negligibly small (≈ 0.004). The angular dependence of $\Delta\rho_c/\rho_c$ is shown in more detail in the inset of Fig. 2 for a second crystal in a 15 T field at $T = 85$ K. An extremely large cosine angular dependence with twofold symmetry is observed.

Band calculations for $YBa_2Cu_4O_8$ indicate the presence of two quasi-2D FS of plane character and two strongly nested quasi-1D Fermi sheets of chain character with faces parallel to the a axis [13]. The simple twofold cosine relation for $\Delta\rho_c/\rho_c$ suggests that the carriers responsible for c-axis transport only experience Lorentz force due to the field component parallel to the a axis. Therefore, we conclude that the flat regions of the FS parallel to the a axis, namely, the 1D chain sheets, must dominate the c-axis MR and c-axis conductivity. The large MR for $\boldsymbol{B} \parallel \boldsymbol{a}$ is then not so surprising if we consider the highly conducting nature of the chain carriers, whose resistivity is known to be significantly smaller than the in-plane resistivity [8,14]. This strong anisotropy in the c-axis MR, therefore, reveals a vital role for the chain bands in forming coherent c-axis transport in $YBa_2Cu_4O_8$ [15].

From the inset of Fig. 2, we note that $\rho_c \approx 7$ m Ω cm at 85 K when $\boldsymbol{B} \parallel \boldsymbol{a} = 15$ T. Since the zero field $\rho_c(T)$ becomes essentially flat and, hence, incoherent at around 8 m Ω cm, ρ_c was expected to reach this threshold value with only slightly higher applied fields. In order to study the MR profile in this interesting regime, therefore, two crystals were mounted inside the 35 T pulsed field cryostat with $\boldsymbol{B} \parallel \boldsymbol{a}$.

Figure 3 shows a series of 35 T field pulses between 80 and 200 K for one of the crystals mounted with $\boldsymbol{B} \parallel \boldsymbol{a}$. There are several striking features to note from this figure. First, $\Delta\rho_c/\rho_c$ is extremely large. For example, at $T = 85$ K, ρ_c increases its value by well over 200% in 35 T, reaching a value ≈ 13.5 m Ω cm that is almost double the saturation value of ρ_c at high T [8]. Second, all $\rho_c(B)$ sweeps appear to go through a single crossing point around $B_{\mathrm{cr}} \approx 20$ T. At B_{cr}, $\rho_c \approx 8$ m Ω cm, the value at which the zero field $\rho_c(T)$ becomes essentially T independent. More important, $d\rho_c/dT$ is positive below B_{cr}, while above B_{cr}, it is negative. These observations suggest strongly that the crossing point represents the

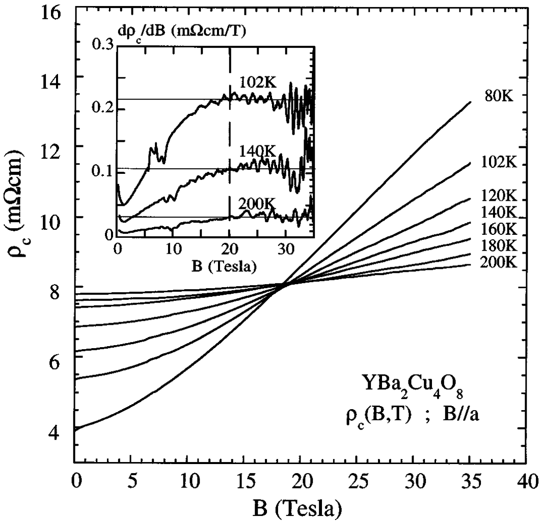

FIG. 3. c-axis MR field sweeps up to 35 T with $\boldsymbol{B} \parallel \boldsymbol{a}$. Inset: $d\rho_c/dB$ at various temperatures (displaced vertically for clarity). The dashed line indicates the field at the crossing point. The noise at high fields is due to increased vibration of the measurement wires.

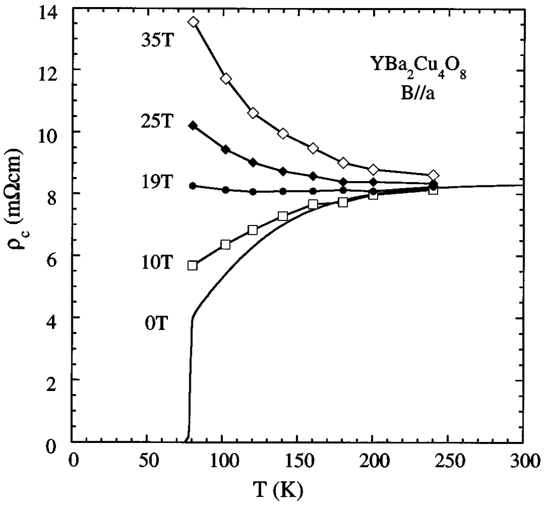

FIG. 4. $\rho_c(T)$ curves for $YBa_2Cu_4O_8$ at several fields ($\boldsymbol{B} \parallel \boldsymbol{a}$) obtained from the MR field sweeps shown in Fig. 3.

coherent-incoherent boundary for $\rho_c(T)$ in $YBa_2Cu_4O_8$. Surprisingly though, rather than saturating at the incoherent boundary, as expected from zero field $\rho_c(T)$, ρ_c continues to increase rapidly with increasing B.

Figure 4 shows the resultant $\rho_c(T)$ for different fixed B derived from the pulsed MR sweeps in Fig. 3. One can see clearly in this figure how $\rho_c(T)$ changes from metallic (below 200 K) to T independent for $B = 19$ T to localized for $B = 35$ T. This field-induced dimensional crossover in the normal-state transport has not, to our knowledge, been observed previously in any other cuprate system, and seems remarkable given the high temperatures and relatively modest fields that are involved. The same MR experiment was extended down to 60 K on a second crystal, and the result was reproduced exactly. Furthermore, it was confirmed in this sample that $YBa_2Cu_4O_8$ still superconducts above B_{cr} (at $B = 35$ T, $T_c \approx 65$ K), implying that c-axis coherence in the normal state has no influence on the occurrence of superconductivity.

The field-induced dimensional crossover also manifests itself in the MR field dependence as a crossover from B^2 to a B-linear dependence. The inset of Fig. 3 shows this more clearly, where we have plotted the derivatives of selected MR sweeps taken from the main plot. Remarkably, the onset of the linear MR (i.e., constant $d\Delta\rho_c/dB$) occurs at the same field B_{cr} for all temperatures 80 K $\leq T \leq$ 200 K. Since the scattering rate on the chains, which we believe is responsible for the large c-axis MR, is reduced by more than a factor of 4 in this temperature range [8], we conclude that the onset of the linear MR is not a signature of the intermediate field regime, even though the large positive MR at low B is clearly orbital. The crossing point, therefore, seems to mark the onset of a new magnetoconductivity regime in $YBa_2Cu_4O_8$ beyond the coherent boundary, i.e., in the state of lower dimensionality. An unusual B dependence of the c-axis MR ($B^{3/2}$) has also been observed in the 1D conductor $(TMTSF)_2PF_6$ once the interchain transport becomes incoherent [16].

Since the chain bands clearly dominate c-axis transport in $YBa_2Cu_4O_8$, we have attempted first to understand the behavior of the high-field c-axis MR and the appearance of B_{cr} by considering c-axis hopping along the double chain sheets only. Although we are close to the coherent/incoherent boundary for c-axis transport and, therefore, on the limit of applicability of Boltzmann transport theory, as a first approximation, we consider a simple band picture in which the chain bands are represented by two parallel sheets with cosine dispersion along the a- and c-axes. The c-axis dispersion is given by $\varepsilon_\perp = -2t_\perp \times \cos(k_\perp c)$, where $c \approx 13.5$ Å is the inter-double-chain spacing and $t_\perp$ is the interchain overlap integral. Since the main velocity component $v_\parallel$ lies along the b axis, the Lorentz force for $\boldsymbol{B} \parallel \boldsymbol{a}$ is directed along the c axis, i.e., $\hbar dk_\perp/dt = ev_\parallel B$ [17]. In real space, this leads to a periodic orbit for carriers along the b axis with a c-axis velocity component $v_\perp = 2t_\perp c/\hbar \sin(k_\perp c) = 2t_\perp c/\hbar \times \sin(ev_\parallel Bct/\hbar)$. The amplitude of the real-space orbit is then simply $A_\perp = 4t_\perp/ev_\parallel B$.

From this expression, we see that, as B increases, the amplitude of the real-space orbit decreases. This has the obvious effect of making the conductivity more 1D and, eventually, we expect the carriers to be confined to the b axis once $4t_\perp/ev_\parallel B \approx c$. Note that this expression does *not* depend on τ, only B. Taking $B = 20$ T and $v_\parallel = 4.5 \times 10^5$ m/s [18], we obtain $t_\perp \approx 3$ meV. Although this value is much smaller than that predicted by band structure ($t_\perp \approx 50$ meV) [18], it is consistent with the observation that the zero field $\rho_c(T)$ becomes incoherent above around 200 K, since we expect coherence to be lost once $k_BT \approx 4t_\perp$. This scenario may suggest that it is $t_\perp$, and not the normal-state gap, that governs the behavior of

$\rho_c(T)$ in $YBa_2Cu_4O_8$, though clearly more investigations are needed (e.g., pressure and doping studies) to confirm this possibility.

Returning to the issue of the role of the plane bands in c-axis transport in $YBa_2Cu_4O_8$, we recall from band calculations [13] that there are large regions of the plane FS lying parallel to the b axis that do not experience a Lorentz force when $\boldsymbol{B} \parallel \boldsymbol{a}$ and whose c-axis transfer should be unaffected by the applied field. The localized behavior of $\rho_c(T)$ for $B = 35$ T, as shown in Fig. 4, indicates, therefore, that the contribution to the c-axis current from these regions of the plane bands is negligibly small. This observation provides further evidence that the chain bands dominate c-axis conductivity in $YBa_2Cu_4O_8$, but does not preclude a finite contribution from the plane carriers, since a certain plane character in the chain band is also expected through hybridization [13]. However, the substantially reduced $t_\perp$, derived from B_{cr}, casts a serious doubt that c-axis dispersion, namely, the interchain coupling, occurs through hybridization with the plane carriers. Indeed, it may be interesting to infer that if the plane carriers are confined, the two subsystems, i.e., the chains and planes, act independently of one another, and that c-axis transport occurs solely via hopping between double CuO chain units and bypasses the planes altogether. In this case, interchain coupling may be achieved through some kind of virtual hopping process, possibly involving empty states in the CuO_2 plane band structure, which then leads to the much reduced $t_\perp$.

In conclusion, we have observed several remarkable new features in the c-axis MR of the underdoped cuprate $YBa_2Cu_4O_8$. We have shown that we are able to tune the dimensionality of the normal state using a high magnetic field as a control parameter, thus opening up new possibilities for exploring the role of dimensionality in these strongly correlated metals. The large anisotropy in the MR reveals the critical importance of the CuO chains for coherent c-axis transport in $YBa_2Cu_4O_8$. The magnetic field decouples the chains above B_{cr}, resulting in a 3D to 2D crossover in the transport behavior of the whole system. The unusual field dependence of $\Delta\rho_c/\rho_c$ above B_{cr} suggests the onset of a new regime beyond the coherent/incoherent boundary. This interesting regime should be investigated further, in particular, looking for changes in the MR profile of the plane and chain resistivities when $\boldsymbol{B} \parallel \boldsymbol{a}$. Finally, these surprising results provide us with a compelling possibility that, in $YBa_2Cu_4O_8$, we may realize a unique coexistence of alternatively stacked but independent subsystems; i.e., a highly anisotropic 3D (or 2D, depending on the strength of the interchain coupling along the a axis) metallic ground state on the chains and a 2D unconventional metallic ground state on the CuO_2 planes. Such an exciting possibility clearly warrants further investigation.

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