Dimensional Crossover Phenomena in $PrBa_2Cu_4O_8$

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Abstract

Transport measurements have been performed on the quasi-1D cuprate $PrBa_2Cu_4O_8$ (Pr124) in zero and applied magnetic fields. A T^2 resistivity is observed along all three crystallographic directions at low T. As the temperature is increased however, crossovers to states of reduced dimensionality are seen in both interchain resistivities $\rho_a(T)$ and $\rho_c(T)$. A large transverse magnetoresistance is observed in both ρ_a and ρ_c that is consistent with predictions from Boltzmann transport theory, and at sufficiently high fields, Pr124 also undergoes a magnetic-field-induced dimensional crossover. These results provide compelling evidence for a Fermi liquid ground state in Pr124.

Key words:
quasi-1D transport; cuprate; dimensional crossovers; doped Mott insulator

The 1D Tomonaga-Luttinger (TL) model currently provides the only well understood alternative to the standard Fermi liquid (FL) model of interacting electrons. One of the fundamental features of the TL model is that of spin-charge separation, first observed in $SrCuO_2$ [1]. This material contains half filled, Mott insulating double CuO chains. $PrBa_2Cu_4O_8$ (Pr124) can be viewed as the quarter-filled analogue of $SrCuO_2$ with metallic double CuO chains (along the b-axis). Indeed, optical studies carried out on Pr124 at 300 K are consistent with a TL interpretation [2]. Pr124 is also isostructural to the 80 K superconductor $YBa_2Cu_4O_8$ (Y124), which contains both metallic CuO chains and CuO_2 planes. In Pr124 however, carriers on the CuO_2 planes are localised (and hence non-superconducting), thus allowing a unique opportunity to study the properties of the metallic CuO chain system in isolation and down to low T.

Single crystals of Pr124 were grown by a flux method under high oxygen pressure as described elsewhere [3]. Typical size ($a \times b \times c$) of the crystals used was $0.2 \times 0.4 \times 0.03$ mm^3. Gold wires were attached to the crystals in the appropriate geometries applicable to highly anisotropic samples using Dupont 6838 silver paint. Resistivity measurements were carried out on a number of crystals to check reproducibility of the data and to ensure that uniaxial transport was obtained.

Fig. 1 shows the zero-field resistivity of Pr124. The most striking feature of the data is the extremely large anisotropy within the ab-plane. ρ_a (interchain transport) is three orders of magnitude larger than ρ_b (intrachain transport) at low T. This result contrasts with that in Y124, in which the planes are conducting, and $\rho_a/\rho_b \approx 5$ at T_c [4]. $\rho_b(T)$ is metallic over the entire temperature range studied, and exhibits a T^2 dependence below 100 K. From the residual resistivity, $\rho_b(0) = 4\mu\Omega cm$, we can estimate a mean free path $\ell_b \approx 800\mathring{A}$, confirming the high quality of these samples. A T^2 resistivity is also observed below 75 K for $\rho_a(T)$, and below 50 K for $\rho_c(T)$. The metallic $\rho_c(T)$ behaviour at low-T, across *insulating* CuO_2 planes, confirms previous claims that the chains are responsible for metallising c-axis transport in Y124 [4].

For both interchain directions, the low-T metallic be-

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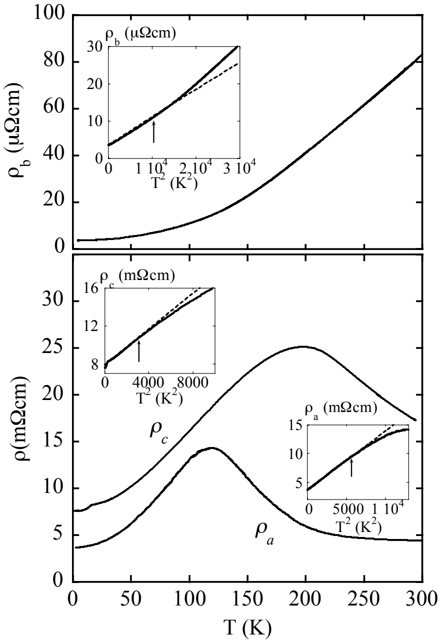

Fig. 1. Zero field resistivity in Pr124. Top: $\rho_b(T)$. Bottom: $\rho_a(T)$ and $\rho_c(T)$. Insets show low-T data plotted against T^2. Arrows indicate onset of deviations from T^2 resistivity.

haviour crosses over to a semiconducting regime at high T after peaking at 130 K (ρ_a) and 200 K (ρ_c). There are two possible reasons for the crossover from metallic to semiconducting behaviour. Firstly, the chains are responsible for the transport across the entire temperature range. In this case the peak in the resistance is due to a gradual crossover to incoherent interchain hopping, as seen, for example, in the Bechgaard salts [5]. Alternatively, the planes are responsible for the high T semiconducting behaviour. The low-T T^2 resistivity, however, is clear evidence for a FL ground state in the chain system. Taking the crossover temperatures T_{cr} from the temperatures at which the resistivity first deviates from a T^2 behaviour, and assuming $k_B T_{cr} \approx 4t_\perp$, we obtain estimates for the warping parameters of the quasi-1D chain Fermi surface: $4t_a \approx 6$ meV and $4t_c \approx 4$ meV [6].

Fig. 2 shows $\rho_c(T)$ at zero field and for $B//a = 30$ T. In the presence of the large transverse magnetic field, the transport has clearly become insulating even at low T. For the low field magnetoresistance, Boltzmann transport theory for a quasi-1D metal gives $\Delta\rho_c/\rho_c = (eBc/\hbar)^2\ell_b^2$. Here c is the c-axis lattice parameter 13.6 Å. At 5 T, $\Delta\rho_c/\rho_c = 0.3$, giving $\ell_b = 600$Å for this sample, in good agreement with the zero field $\rho_b(0)$. The inset shows $d\rho_c/dB$ at 0.5 K. Two kinks are seen in the derivative at 5.5 T and 11 T. These kinks were found to be independent of temperature in Pr124. Similar behaviour was also observed in Y124 for $B//a$, and interpreted as a field induced dimensional crossover along the c-axis [7]. We tentatively ascribe the two features in $d\rho_c/dB$ to the crossover fields for the two Fermi sheets of the double CuO chain in Pr124. Following the analysis of ref [7], $4t_c \approx 4$ meV and 2 meV for the two chain sheets, consistent with that derived from the zero field data. These values are also consistent with the fact that Kohler's rule is obeyed in the c-axis transport up to 30 K [8]. For $I//a$, no crossover effects are seen in magnetic fields $B//c$ up to 30 T, although on extrapolation of the data, a crossover field is observed at 60 T, corresponding to $4t_a \approx 6$ meV [9]. This is again consistent with zero field resistivity data and the breakdown of Kohler's rule for the a-axis transport at 100 K [10].

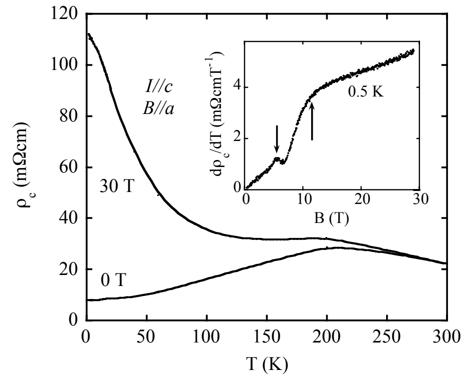

Fig. 2. Magnetoresistance in Pr124. Inset shows $d\rho_c/dB$ at 0.5 K, with arrows at the crossover fields.

These numerous internal consistencies are strong evidence for a FL ground state in Pr124, and that a simple quasiclassical treatment of magnetotransport is appropriate. At elevated temperatures a crossover to TL behaviour can be inferred from optical measurements [2] suggesting that Pr124 is an excellent laboratory for studying dimensional crossover phenomena in more detail. The various dimensional crossovers give warping parameters that are extremely small, making Pr124 one of the most anisotropic Fermi liquids known.

References

[1] C. Kim *et al.*, Phys. Rev. Lett. **77** (1996) 4054.

[2] K. Takenaka, *et al.*, Phys. Rev. Lett. **85** (2000) 5428.

[3] S. Horii *et al.*, Phys. Rev. B **61** (2000) 6327.

[4] N. E. Hussey *et al.*, Phys. Rev. B. **56** (1997) 11423.

[5] J. Moser *et al.*, Eur. Phys. J. B **1** (1998) 39.

[6] M. N. McBrien *et al.*, J. Phys. Soc. Jpn **71** (2002) 701.

[7] N. E. Hussey *et al.*, Phys. Rev. Lett. **80** (1998) 2909.

[8] M. N. McBrien *et al.*, unpublished.

[9] N. E. Hussey *et al.*, unpublished.

[10] S. Horii *et al.*, unpublished.