Institute of Physics Publishing Journal of Physics: Conference Series **51** (2006) 231–234
doi:10.1088/1742-6596/51/1/052 Yamada Conference LX on Research in High Magnetic Fields

Signature of the magnetic transitions in $Y_{0.2}Pr_{0.8}Ba_2Cu_3O_{7-\delta}$ in high field angular magnetoresistivity

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Abstract. In-plane (*ab*) and out-of-plane (*c*-axis) magnetoresistivity display different symmetry crossovers and/or transitions in 14 T magnetic field applied parallel to the CuO_2 planes. The in-plane magnetoresistivity crosses over from four-fold symmetry below 6 K to two-fold symmetry at higher temperatures, which becomes dominant at temperatures higher than 40 K. The out-of-plane magnetoresistivity changes at 17 K from four fold symmetry to ordinary $sin^2\theta$ at higher temperatures. The behaviour of the *c*-axis magnetoresistivity can be ascribed to the antiferromagnetic ordering of the Pr spins whereas the symmetry change of the in-plane magnetoresistivity at 6 K might be attributed to commensurate to incommensurate crossovers of the spin subsystems. The antiferromagnetic order of the Cu(2) sublattice seems to have only a week effect on the magnetoresistivity.

Transport in magnetic field in underdoped cuprates with antiferromagnetic (AFM) ordering remains a topic with controversial solutions yet. The insulating state of these compounds evolves to a superconducting one by charge carrier doping above a certain critical concentration x_c. However, few assumptions put on to depict the state and the transport properties are generally accepted for the concentration range below x_c. There are two scenarios, not harmonized yet, which try to answer the question of charge transport in the presence of an external magnetic field.

The first one considers that the charges inserted into a antiferromagnetic system by chemical doping segregate into phase separate regions [1] due to the Coulomb repulsion and low kinetic energy [2-4]. These charge-containing regions are unidirectionally ordered stripes [5] in which the holes are confined within antiphase domain walls stabilizing them by the gain of the hole kinetic energy [6]. The stripes can fluctuate transversally and support a transition to a smectic or even a nematic phase [7]. In the case of cuprates, it is supposed that stripes are filled with a charged fluid which makes them conducting along the stripe. Therefore, we assist in the last decade to real hunting of stripes by any investigative tool and any symmetry reduction is ascribed to this new type of charge organization. In this effervescent environment a lot of data of transport measurement in underdoped cuprates were interpreted in terms of stripes. We remind here the angular dependence of the magnetoresistivity [8, 9], the inequality of the in plane resistivity in zero magnetic field [10], nonlinear conductivity [11] etc. For example, an in-plane magnetic field is supposed to align and drive the stripes giving rise to angular oscillation of the in-plane magnetoresistivity [8].

The second less exotic scenario is based on the spin lattice coupling [12-15]. A magnetic field induces a certain orthorhombic [16] distortion to an AFM system which makes the transfer integrals anisotropic. In turn, these fact should be reflected in the in-plane anisotropy of the localization radius and, finally, in the resistivities [17]. The field orients the AFM domains, hence, produces an angular magnetoresistivity as in the stripe scenario. It is to note that this scenario does not rule out the existence of the stripes but does not connect the transport anisotropy to them. It is interesting, however, that similar oscillation of the magnetoresistivity were reported for electron-doped superconductors [18] where only commensurate order, hence no stripes, should be present [19, 20].

Most of these experiments have been related only to the AFM order, commensurate or not, of copper spin system. However, in many cases, the cuprates contain rare-earth (RE) ions, which also order antiferromagnetically below a specific Néel temperature. It is supposed that due to the small RE ionic radius relative to the large CuO_2 interplane distance, the charge transport, which mainly take place in these latter planes, is less affected by the AFM ordering of the RE ions. For the same reasons in optimally doped cuprates, superconductivity is less sensitive to these RE ions substitution. There is only one exception, the praseodymium. This ion has dramatic effects in hole doped cuprates coupling both charge, Cu and Pr spin subsystems. First, the insertion of Pr in $YBa_2Cu_3O_7$ drastically reduces the charge available for transport grabbing it into a Fahrenbacher–Rice type band. It results a kind of underdoping similar to oxygen depletion (see for e.g. [21] and therein references). Second, the magnetic ordering of both copper and praseodymium ions were found to be interrelated though the Néel temperatures are very different. As a result an incomensurability occurs in the Cu spin subsystem in a temperature range of Δ = 10 K below 19 K where the Pr system exhibits an AFM ordering [22-24]. The interrelations between spin systems as well as the crossovers between commensurable and incommensurable orders rule out the formation of stripe correlations. Therefore, it is of interest to investigate the angular dependence of the charge transport in magnetic field, which is expected to provide information on the role of the spin ordering in all AFM subsystems. Additionally, Pr offers the largest temperature range of AFM ordering of RE subsystem in cuprates.

In this work we show that the spin scattering controls the charge transport at low temperature in nonsuperconducting $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$. The Pr spins results to be extremely effective whereas, unexpectedly, the copper spins seems to be only weakly involved in the charge scattering.

$Y_{0.2}Pr_{0.8}Ba_2Cu_3O_{7-}$ single crystal of size 0.77 × 0.7 ×0.067 mm^3, with the *c*-axis oriented along the smallest dimension, was grown using a standard procedure described elsewhere [25]. In-plane ρ_{ab} and out-of-plane ρ_c resistivities were measured simultaneously over a large range of temperatures T and angle θ between the magnetic field H and the current I direction using a multiterminal configuration. Specifically, a current $I \leq 0.1$ mA was applied on one face of the single crystal and the voltages on the top and bottom faces were measured with a low frequency (16 Hz) *ac* bridge. The components of the resistivity tensor were extracted from these voltages using the algorithm described in Ref. [26]. The magnetic field H was applied parallel to the *ab* plane. The effect of H on the electrical transport was determined at constant temperature by rotating the sample around the *c* axis in a constant applied magnetic field. The angular magnetoresistivity were defined as $\Delta\rho_x/\rho_x = [\rho_x(\theta)-\rho_x(0)]/\rho_x(0)$, where x is either *ab* or *c*.

Figure 1(a) shows the angular dependence of the in-plane magnetoresistivity $\Delta\rho_{ab}/\rho_{ab}$ for different temperatures at 14 T. For temperatures lower than 40 K the magnetoresistivity can be depicted as a contribution of two terms: one displaying a four fold symmetry and another one having the ordinary twofold symmetry. Below 6 K, the fourfold symmetric term is dominant $\Delta\rho_{ab}/\rho_{ab} \sim sin^2 2\theta$, though a small twofold component is present. This angular dependence points to the central role of the spins in the intraplane charge transport. At higher temperatures, the two fold symmetry is dominant $\Delta\rho_{ab}/\rho_{ab} \sim sin^2\theta$ but up to 40 K the fourfold term is also salient. Above this temperature only the ordinary sin $sin^2\theta$ is present suggesting that the role of spin as scatterers is negligible small in this T range.

The out-of-plane magnetoresistivity $\Delta\rho_c/\rho_c$ keeps the four fold symmetry dominant up to 17 K (figure 1 (b)). The amplitude of $\Delta\rho_c/\rho_c$ shows its high sensitivity to the Pr spin ordering. At 20 K it shows large fluctuations, hence, is extremely scattered. Above this temperature, $\Delta\rho_c/\rho_c$ crosses over to a pure $sin^2\theta$ dependence with amplitude increasing with T (Inset to figure 1 (b)).

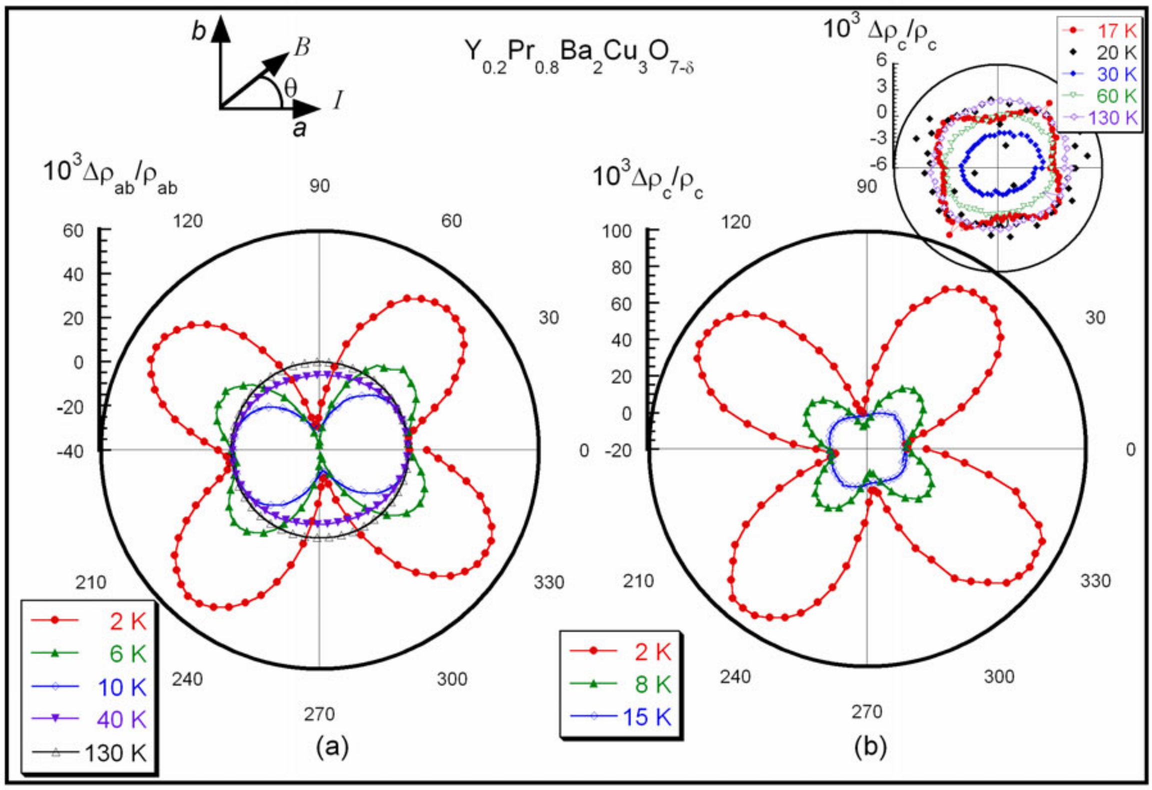

Figure 1. Angular magnetoresistivity of $Y_{0.2}Pr_{0.8}Ba_2Cu_3O_{7-}$ single crystal at 14 T for different temperatures; a) in-plane magnetoresistivity $\Delta\rho_{ab}/\rho_{ab}$; b) out-of-plane magnetoresistivity $\Delta\rho_c/\rho_c$. Inset: High temperature $\Delta\rho_c/\rho_c$ 17 K ≤ T ≤ 130 K

We can correlate the anisotropy change of both resistivities to the phase transitions observed in the spin order of $PrBa_2Cu_3O_7$. It is known that both Pr and Cu orders antiferromagnetically at 19 K and 350 K, respectively. Both Néel temperatures decreases with decreasing Pr content so that for x = 0.8 the ordering temperatures are, correspondingly, lower. However, more precise investigations have uncovered a complex interaction between Cu and Pr spins which gives rise to a series of transitions from commensurate (CO) to incommensurate ordering (ICO) of both sublattices [22-24]. A first transition from CO to ICO was found at 9 K and the transition from ICO to CO at 19 K which also coincide to the Néel temperature of the Pr sublattice. The low temperature transition was rarely reported, there is, however, an early report concerning some anomalies in specific heat and magnetic susceptibility [27] at 5.2 K. It is remarkable that the both ρ_{ab} and ρ_c are sensitive only to the Pr spin ordering whereas the Cu spin sublattice seems to be not involved in the transport process at least at temperatures higher than the Pr Néel temperature. This is a surprising effect due to the fact that the in-plane transport is expected to occur in the CuO_2 planes where the Cu spins are located. It confirms the enhanced Cu-Pr magnetic coupling due to the outstanding *f-p* hybridization occurring in this compound. The increase of the contribution of the twofold symmetric term above 6 K most likely coincides with the crossover to the ICO order of both sublattices. The incomensurability, though small, involves only the in-plane periodicity.

The higher sensitivity of $\Delta\rho_c/\rho_c$ to the field orientation even in the incommensurate regime might be due to the ferromagnetic stacking of the incommensurate component of the Cu spins. Since the interplane transport is mainly a tunneling process, the ferromagnetic component could control the charge transport like a spin valve.

In conclusion, the charge transport in strongly underdoped $Y_{1-x}Pr_xBa_2Cu_3O_{7-}$ .is intimately correlated to the magnetic order. It is conspicuous the dominant role of Pr spin sublattice whereas the Cu spin sublattice seems to be less efficient. However, some specific features noticed in the angular dependences of in-plane and out-of-plane magnetoresistivity are supposed to arise from the Cu-Pr magnetic coupling.

Acknowledgments
This research was supported by the National Science Foundation under Grant No. DMR-0406471 at KSU, the US Department of Energy under Grant No. DEFG02-04ER46105 at UCSD and the Romanian NASR under the Projects CEEX 73 and MATNANTECH 260/2004 at NIMP.

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