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Charge Transport in Spin-Textured $YBa_2Cu_3O_{6.25}$

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The electric transport of the charged particles in a spin texture was investigated in a strongly underdoped $YBa_2Cu_3O_{6.25}$ single crystal in order to identify the characteristic electrical transport mechanism. The in-plane resistivity revealed three different regimes of charge transport: a chiral 2D VRH regime up to 55 K with a characteristic temperature $T_d \approx 12{,}400$ K, an impurity band conduction regime above 55 K, and a metallic-like regime beyond 170 K. The out-of-plane resistivity has only one crossover at 115 K, but the conduction mechanisms controlling the two regimes are not clear.

KEY WORDS: $YBa_2Cu_3O_{6+x}$; charged skyrmion; chiral VRH; magnetic texture; transport mechanisms.

1. INTRODUCTION

The addition of oxygen impurities to the antiferromagnetic Mott insulator $YBa_2Cu_3O_6$ has spectacular effects on the magnetic, transport, and optical properties. The parent compound is usually described in terms of a quantum Heisenberg antiferromagnet ($S = 1/2$) on a square lattice ($Cu(2)O_2$ plane); but the compound $YBa_2Cu_3O_{6+y}$ undergoes dramatic changes with increasing y, from antiferromagnetic (AFM) insulating state to superconducting (for $0.41 < y \leq 1$), to a metallic state ($y > 1$). The extra oxygen, $y > 0$, is inserted between two Cu(1) sites which reside in the plane located between two $Cu(2)O_2$ bilayers. For $y \geq 0.18$ [1], a hole is introduced in the oxygen orbital of the nearest $Cu(2)O_2$ plane. In that plane, for $0.18 < y \ll 0.41$, the hole is partially localized on a plaquette close to the negatively charged oxygen parent because of the Coulomb interaction. In the ground state, the hole rotates clockwise or counterclockwise within the plaquette where it is pinned [2,3], therefore increasing the degeneracy (chiral ground state). The presence of the hole spin in the copper spin system produces both dilution and frustration. The result is a local distortion of the AFM long range, usually referred to as the *magnetic texture*. Because of the reduced dimensionality of the spin system, the texture consists in topological defects called *skyrmions*. This is a kind of vortex-like distortion of the spin background, which was predicted to be located at the hole site [4–8]. The hole and disturbance all together, i.e., the *charged skyrmion*, hops from one impurity site to another and an applied field gives directionality to this movement.

The transport properties of the charged skyrmion have to obey the general laws governing transport in doped Mott insulator [9]. Specifically, the hopping either occurs between nearest neighbors as a thermally activated process at high temperature (impurity band conduction) or between sites with the closest energies, regardless the distance (variable-range hopping (VRH) when the temperature is too low to excite phonons. In the VRH regime, Lai and Gooding [10] have shown that the resistivity follows a law that is slightly different from the ordinary VRH:

$$\rho_{\mathrm{VRH}}(T) \propto T^{\frac{2D}{D+1}} \exp\left[\left(\frac{T_d}{T}\right)^{\frac{1}{D+1}}\right], \tag{1}$$

where D is the dimensionality and T_d is a characteristic temperature.

To our knowledge, the prediction of the skyrmion-based electrical transport model in strongly

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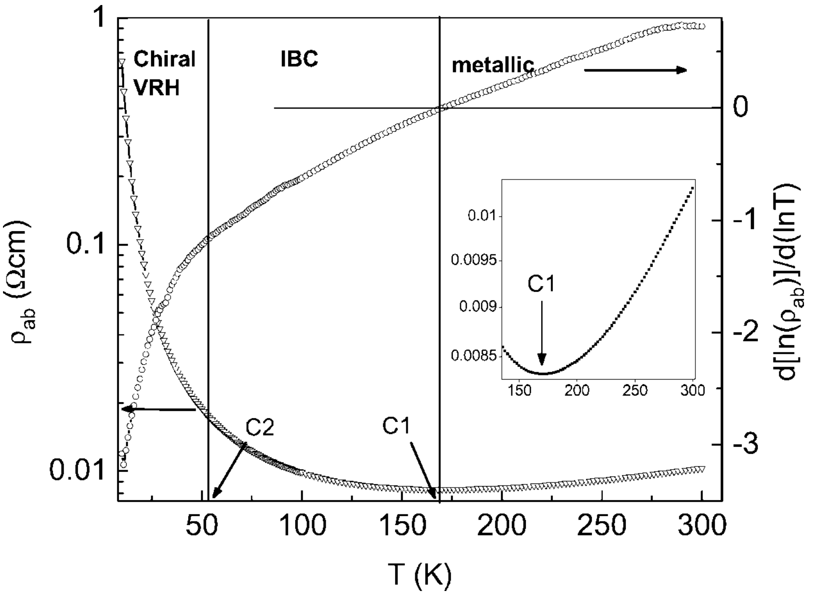

Fig. 1. Temperature dependence of the in-plane resistivity and its logarithmic derivative. C1 and C2 mark the crossover from metallic to impurity band conduction and to VRH conduction, respectively. Inset: detail of the high temperature range of ρ_{ab} vs. T curve.

underdoped cuprates was verified only in $La_{1-x}Sr_x CuO_4$ compounds [10]. In this paper, we analyze the effect of the spin texture on the charge transport in the strongly underdoped $YBa_2Cu_3O_{6.25}$ single crystal.

2. EXPERIMENTAL

$YBa_2Cu_3O_{6.25}$ single crystals were grown in gold crucible using the self-flux method. The oxygen stoichiometry was adjusted by annealing the sample in an O_2–N_2 atmosphere [11]. The crystals have the c-axis oriented along the smallest dimension. Gold leads were attached to thermally treated silver pads using room-temperature silver paint. The temperature of the sample chamber was kept constant using two temperature sensors; a platinum thermometer for $T > 100$ K and a Cernox sensor for $T < 100$ K. In-plane and out-of-plane resistivities were simultaneously measured between 10 and 300 K using a six-terminal configuration. Specifically, a current $I \leq 0.1$ mA was applied on one face of the single crystal ("top face") through the outer leads, and the voltages between the two inner leads on the two crystal faces were measured with a low frequency (17-Hz) bridge. The components of the resistivity tensor were extracted from these measurements using the algorithm described in [12].

3. RESULTS AND DISCUSSION

Figure 1 shows the temperature dependence of the in-plane resistivity as well as its logarithmic derivative $d(\ln \rho_{ab})/d(\ln T)$. A careful analysis reveals three regimes of conduction occurring on the investigated temperature range.

At high temperatures, between 170 and 300 K, the conduction is metallic-like with an increase of the resistivity, with increasing temperature (see the inset to Fig. 1). The best fit of $\rho_{ab}(T)$ showed that the in-plane resistivity obeys the law $\rho_{ab} = 0.088 - 0.02075 \ln T + (16 \times 10^{-5})T$ with the linear contribution dominant at high temperature. With decreasing T, a transition from the metallic to the nonmetallic regime occurs at $T_{c1} = 170$ K (C1 in Fig. 1). The temperature dependence on the metallic side and the existence of strong correlations between holes and the magnetic background rule out the weak localization process. Most likely, this is due to the temperature dependence of the Fermi level that crosses the mobility edge with increasing T and the system becomes metallic. However, the linear T dependence that becomes dominant at high temperatures suggests that the conduction mechanisms must have the same origins as the normal state of the superconducting cuprates (anomalous metal).

At intermediate temperatures, between T_{c1} and $T_{c2} = 55$ K (marked as C2 in Fig. 1), the logarithmic derivative revealed that the conduction is of impurity band conduction (IBC) type:

$$\rho_{\mathrm{IBC}} = \rho_0 \exp\left(\frac{\varepsilon_c}{T}\right), \tag{2}$$

where ε_c (in units of temperature) is the average nearest-neighbor activation energy. The linear fit of the function $f(T) \equiv T \ln \rho = \varepsilon_c + T \ln \rho_0$ works very well in the range 55–135 K with $\varepsilon_c = 63.0 \pm 0.3$ K and $\rho_0 = 0.0053\ \Omega$ cm. Above 135 K there is a crossover range between the activated and metallic conduction that extends over more than 40 K.

At low temperatures, between 10 and 50 K, the IBC law is no longer valid and we have attempted to fit with the general function $\rho_{ab} = AT^{\alpha} \exp[(T_d/T)^{\beta}]$ with α and β considered as independent parameters to be determined. Generally, it is difficult to obtain a reliable value of α from a direct three-parameter fit because of the presence of the exponential that can mask the preexponential factor. Therefore, we first proceeded to determine β from the second derivative rewritten as $\frac{d}{dT}[T\,d(\ln \rho_{ab}/dT] = \beta^2 T_d^{\beta} T^{-\beta-1}$. A log–log plot of this relationship provides $\beta = 0.358 \pm 0.010$ and $T_d = 12{,}376 \pm 3{,}313$ K. With these in mind, we have obtained $\alpha = 1.28 \pm 0.01$ from a log–log plot of the T dependence of $\rho_{ab}\ \exp[-(T_d/T)^{1/3}] = AT^{\alpha}$ (Fig. 2). The as-obtained α or β provide the dimensionality of the process, e.g. $D = \beta^{-1} - 1 = 1.79$. This value is close to 2, indicating that the charged excitation is two-dimensionally localized, in good agreement with the results of Lai and Gooding [10] on strongly underdoped $La_{1-x}Sr_xCuO_4$ (LASCO). Although the value of D is not exactly two, the errors introduced by the use of the second derivative could be responsible for this slight misfit.

In summary, the in-plane resistivity shows three regimes of conduction: a VRH-like conduction between 10 and 55 K, an impurity band conduction up to 170 K, and an anomalous metallic behavior for higher temperatures (see Fig. 1).

The out-of-plane resistivity ρ_c and its T derivative are shown in Fig. 3. The plot clearly evidences the existence of only two conduction regimes with a crossover at $T_{c3} = 115$ K (Point C3 in Fig. 3). The resistivity exhibits nontypical temperature dependence in both regimes. Below T_{c3}, the fit of the derivative suggests an unusual dependence, $\rho_c \propto \exp(A/T^{\beta})$ with $\beta = 0.69$ and $A = 12.03$, whereas in the higher temperature regime $\rho_c \propto \exp(-BT^{\delta})$ with $B = 6 \times 10^{-5}$ and $\delta = 1.69$. The origin of these temperature dependencies is not clear. Generally, the interlayer hopping in cuprates is still an unresolved issue. Most likely, there is a tunneling process through a T-dependent barrier in the low T regime. As was observed in the case of underdoped cuprates, the interlayer coupling

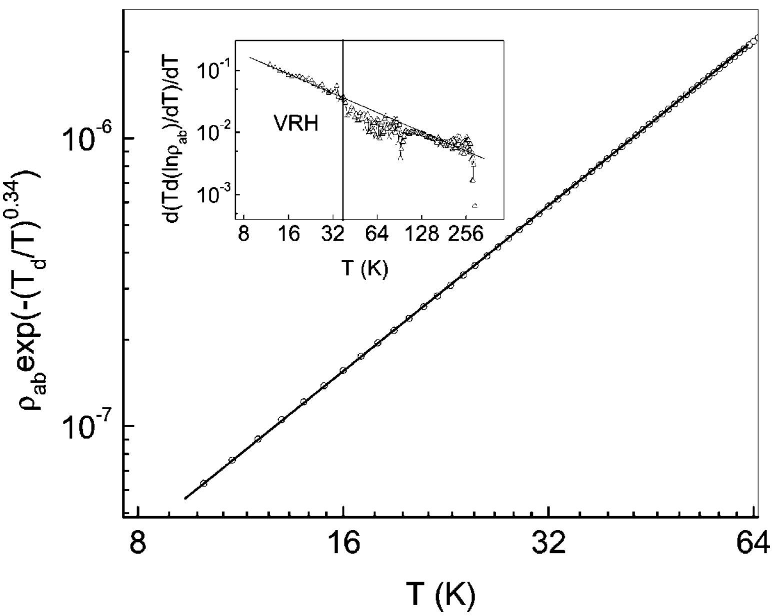

Fig. 2. The preexponential factor obtained from $\rho_{ab}\exp[-(T_d/T)^{1/3}]$. Inset, the second derivative of ρ_{ab} in appropriate coordinates. The lines are guides for the eye.

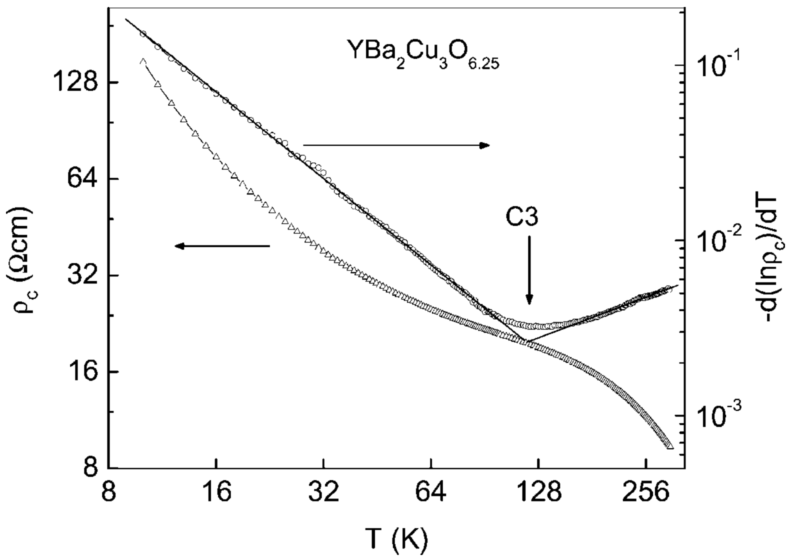

Fig. 3. Temperature dependence of ρ_c and its logarithmic derivative $-d(\ln \rho_c/dT$. The lines are guides for the eye. The crossover between the two regimes is marked as C3.

is not coherent but impurity-mediated [13], hence the tunneling is dependent on impurity scattering potential and its temperature dependence. In the high T regime, where we have already assumed that the Fermi level crosses the impurity band, the probability of interlayer hopping increases fast with increasing temperature.

In conclusion, we have investigated the transport of the charged hole in the spin texture of the strongly underdoped $YBa_2Cu_3O_{6.25}$ single crystal. The in-plane resistivity exhibits three regimes controlled by different conduction mechanisms. A low temperature two-dimensional chiral VRH regime is seen below $T_{c2} = 55$ K. Above T_{c2}, the system crosses over to the impurity band conduction up to $T_{c1} = 170$ K when the system shows a nonmetal-to-metal transition owing to the shift of the Fermi level with increasing temperature. The out-of-plane resistivity is nonmetallic for all the measured temperature ranges. There are, though, two easily distinguishable conduction regimes, separated by a crossover at 115 K. We could not place the experimentally determined T-dependencies of the c-axis transport within the framework of any proposed theoretical models. Most probably, the low temperature regime is controlled by the interlayer tunneling through a temperature-dependent barrier while the high temperature dependence is the result of the increase of the accessible number of intralayer states due to the shift of the Fermi level through the mobility edge.

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