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A simple model for normal state in- and out-of-plane resistivities of hole doped cuprates

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ABSTRACT

The highly anisotropic and qualitatively different nature of the normal state in- and out-of-plane charge dynamics in high-T_c cuprates cannot be accommodated within the conventional Boltzmann transport theory. The variation of in-plane and out-of-plane resistivities with temperature and hole content are anomalous and cannot be explained by Fermi-liquid theory. In this study, we have proposed a simple phenomenological model for the dc resistivity of cuprates by incorporating two firmly established generic features of all hole doped cuprate superconductors—(i) the pseudogap in the quasiparticle energy spectrum and (ii) the T-linear resistivity at high temperatures. This T-linear behavior over an extended temperature range can be attributed to a quantum criticality, affecting the electronic phase diagram of cuprates. Experimental in-plane and out-of-plane resistivities ($\rho_p(T)$ and $\rho_c(T)$, respectively) of double-layer Y(Ca)123 have been analyzed using the proposed model. This phenomenological model describes the temperature and the hole content dependent resistivity over a wide range of temperature and hole content, p. The characteristic PG energy scale, $\varepsilon_g(p)$, extracted from the analysis of the resistivity data, agrees quite well with those found in variety of other experiments. Various other extracted parameters from the analysis of $\rho_p(T)$ and $\rho_c(T)$ data showed systematic trends with changing hole concentration. We have discussed important features found from the analysis in detail in this paper.

1. Introduction

Superconductivity in hole doped cuprates poses an outstanding problem for the scientific community. After almost 3 decades of its discovery a number of unsolved puzzles exist and a proper understanding of the normal and superconducting (SC) ground states of these strongly correlated electronic systems remains elusive till date [1–3]. In high-T_c cuprates, non-Fermi liquid charge transport in the normal state and other anomalous physical properties have provided with many challenging issues and have stimulated significant interest [4–7]. One of the key questions to be answered is that why the out-of-plane resistivity differs so much from the in-plane resistivity in the normal state. The resistivity anisotropy ratio, ρ_c/ρ_p, shows a temperature dependent behavior that begs explanation. In the underdoped (UD) region, below certain characteristic temperature, $\rho_c(T)$ is "semiconductor" like ($d\rho_c/dT < 0$), in contrast to the in-plane resistivity, $\rho_p(T)$, which is metallic ($d\rho_p/dT > 0$). This marked difference between $\rho_c(T)$ and $\rho_p(T)$ is not what one might expect within the conventional Fermi-liquid theory [6]. Such different temperature dependence and very large ($\sim 10^5$ in Bi2212 at certain doping) value of the resistivity anisotropy have stimulated vigorous theoretical and experimental investigations on the in-plane and interlayer charge dynamics of high-T_c cuprates and their possible link with superconductivity itself [6,8–10]. However, a complete, empirically relevant, and unified description of the *ab*-plane and *c*-axis charge transport in hole doped cuprates is still lacking.

Experimental studies reveal that the generic features of the temperature and hole content dependences of resistivity are qualitatively identical in all the families of hole doped cuprates, even though structural and electronic anisotropies vary over a large range. Therefore, it is reasonable to assume that the dominant electronic correlations present in all hole doped curates, irrespective of the structural or other finer electronic details (e.g., strength of spin-charge *stripe* correlations [11,12]) are also responsible for the non-Fermi-liquid behavior temperature dependent resistivity and its evolution with number of added holes, p, in the copper

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oxide planes. Besides superconductivity at high T_c itself, the pseudogap (PG) correlation in the normal state is the single most robust characteristic of all hole doped cuprates. Various physical properties including the resistive features of cuprates are dominated by the PG, especially in the UD regime [13,14]. Any formalism aimed to explain the T and p dependent resistivity must take into consideration of the full impact of the p-dependency of the PG in quasiparticle (QP) energy density of states (EDOS).

A number of theoretical study have been carried out to model the in- and out-of-plane dc charge transport of hole doped cuprates [15-20]. Theoretical approaches vary from conventional Fermi-liquid, nonconventional, phenomenological, to outright exotic. It is fair to say that these models have limited success. One major drawback of most of these models is that the theoretical framework used to describe the doping and temperature dependent resistivity does not hold when wider bodies of other experimental facts are considered.

In a previous study [21], we have modeled the c-axis resistivity of some bi-layer cuprates by taking into account of the effect of PG on the interlayer charge transport. In this study we wish to extend the model for in-plane charge transport. We show that the essential difference between in- and out-of -plane charge transport lies within the way in which the PG affects in- and out-of-plane charge dynamics. Our proposed model also yields mutually consistent set of values for the characteristic energy scales for the PG from the analysis of in- and out-of-plane resistivity data.

The paper is organized as follows. In Section 2, we describe the outline of the proposed model. Next, in Section 3, experimental $\rho_p(T)$ and $\rho_c(T)$ data of double-layer Y(Ca)123 single crystals have been analyzed. Discussion on the important findings constitutes Section 4, and finally, conclusions are drawn in Section 5.

2. Phenomenological model

As mentioned in the previous section, T-linear resistivity and the ubiquitous effect of PG in the quasiparticle on the charge transport are the two generic features present in all hole doped cuprates. Strange T-linear resistivity calls for an unconventional approach and quantum criticality seems to be the most plausible answer, especially when its potential to induce Cooper pairing at high temperature in systems with strong electronic correlations is considered [22].

Ordinary phase transitions are driven by thermal fluctuations and involve a change between an ordered and a disordered state. At absolute zero, where there are no thermal fluctuations, a fundamentally new type of phase transition can occur—a quantum phase transition. Quantum phase transitions are triggered by quantum fluctuations associated with the uncertainty principle. This type of phase transition involves no change in entropy and can be accessed only by varying a non-thermal parameter such as the doped holes as in case of cuprate superconductors. The point that separates the two distinct quantum phases at zero temperature is called a quantum critical point (QCP). The detailed description of how such a QCP affects the temperature dependent charge transport is still lacking. But a T-linear resistivity may originate from quantum criticality quite naturally. The basic physics is outlined below.

From critical scaling, it follows that the thermal equilibrium time, Γ_{qcp}, at a QCP is given by [22,23]

$$\Gamma_{qcp} = \frac{Ch}{2\pi k_B T} \tag{1}$$

where h is the Planck's constant, k_B is the Boltzmann's constant and C is a dimensionless universal parameter depending on dimensionality of the system. The most intriguing feature of Eq. (1) is that this characteristic time depends only on temperature; no other characteristic energy scale (e.g., Fermi energy, exchange energy etc.) relevant to the Fermi-liquid description of the system appears in this expression. The transport properties are drastically affected by the presence of quantum criticality. Because the values of various transport coefficients depend on the same process that establish local thermal equilibrium inside the system under consideration.

At high-T above the QCP, thermal timescale is much shorter than the quantum timescale, the physical properties at finite temperatures are, therefore, seriously influenced by the presence of the QCP at a particular value of the non-thermal parameter (say, $g = g_c$, where g_c is the critical value of the non-thermal parameter). The system in this regime cannot be simply described by the ground state wave function at g. In this quantum critical regime, the temperature dependence of the physical quantities often exhibits a striking deviation from conventional Fermi-liquid behavior. As temperature becomes the only relevant energy scale; the scattering rate is given by the inverse of Eq. (1), and the resistivity becomes completely linear in this region of the T–p phase diagram. This T-linearity should affect both in- and out-of plane normal state resistivities of cuprates in the same qualitative way.

In general the dc electrical resistivity of a metal is expressed via the Drude formula given by

$$\rho = \frac{m^*}{ne^2\tau} \tag{2}$$

where $m*$ is the carrier effective mass, n is the carrier concentration, e being the charge of the carrier and τ is the relaxation time. For ordinary Fermi-liquids the temperature dependence of ρ arises from the temperature dependent scattering rate, $1/\tau$. PG affects the in-plane resistivity by reducing the carrier scattering rate [24]. The link between the PG in the QP EDOS and the scattering rate can be established using the time-dependent perturbation theory. Using Fermi's golden rule for transition probability, we get

$$\frac{1}{\tau} = \frac{2\pi}{\hbar} N(\varepsilon_F) |\langle i|H'|f\rangle|^2 \tag{3}$$

where $N(\varepsilon_F)$ is the EDOS of the Fermi level and H′ is the scattering Hamiltonian, i and f denote the initial and final states of the scattered charge carrier. At finite temperatures the scattering rate will, in fact, be determined by the thermally averaged EDOS at the Fermi-level, $\langle N(\varepsilon_F)\rangle_T$. To explain a number of diverse physical properties of different families of high-T_c cuprates, $\langle N(\varepsilon_F)\rangle_T$ has been modeled quite successfully using the following expression [25]

$$\langle N(\varepsilon_F)\rangle_T = N_0\left[1 - \left(\frac{2T}{\varepsilon_g}\right)\ln\left\{\cosh\left(\frac{\varepsilon_g}{2T}\right)\right\}\right] \tag{4}$$

where N_0 is the flat EDOS outside the PG region and ε_g is the characteristic PG energy scale expressed in temperature. Thus, considering the effects of QCP and PG, the in-plane resistivity of hole doped cuprates is dominated by two terms, the first one, due to quantum criticality, has the form

$$\rho_{QCP} = \alpha_p T \tag{5}$$

and the second one proportional to the depleted EDOS due to PG is

$$\rho_{PG} = \beta_p N_0\left[1 - \left(\frac{2T}{\varepsilon_g}\right)\ln\left\{\cosh\left(\frac{\varepsilon_g}{2T}\right)\right\}\right] \tag{6}$$

where α_p is a constant, depending on hole content, measuring the strength of hole scattering and β_p is a weight factor taking into account of the effect of the overall momentum dependence of $\langle N(\varepsilon_F)\rangle_T$ and the scattering matrix elements on in-plane resistivity. Thus the total in-plane resistivity can be expressed as

$$\rho_p(T) = \rho_{0p} + \alpha_p T + \beta_p N_0\left[1 - \left(\frac{2T}{\varepsilon_g}\right)\ln\left\{\cosh\left(\frac{\varepsilon_g}{2T}\right)\right\}\right] \tag{7}$$