Mobility and its temperature dependence in LSCO: viscous motion?

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We argue that charges in underdoped La$_{2-x}$Sr$_x$CuO$_4$ move in a dissipative environment of strong spatial and temporal fluctuations. The unusual temperature dependence of the Hall angle known as “the separation of lifetimes” is reinterpreted and attributed to the appearance of the thermally activated component in the effective number of carriers with the temperature increase. We consider the temperature interval above $T_c$ where localization effects can be neglected.

The normal phase properties of high temperature superconducting (HT$_c$) cuprates differ strongly from those of ordinary superconductors. The fact has been justly attributed to the proximity of new materials to the Mott metal-insulator (MI) transition, where metallic features come about due to doping of external carriers into the CuO$_{2}$-plane. The Mott’s physics has been best traced in evolution of two parent materials, La$_2$CuO$_4$ (LCO, or 214) and YBa$_2$Cu$_3$O$_6$ (YBCO$_6$, or 123), from the antiferromagnetic (AFM) insulator state into the HT$_c$ material at doping. La$_2$CuO$_4$, when doped by the divalent Sr, transforms into the single-plane HT$_c$ superconductor, La$_{2-y}$Sr$_y$CuO$_4$ (LSCO). YBCO$_{6+y}$ is nowadays a classic example of the two-plane HT$_c$ material doped by the excessive oxygen.

We concentrate on transport characteristics of LSCO. Better single crystals have been available for these materials which have been examined extensively. Early resistivity and the Hall effect studies were conducted usually below room temperatures (For brief review of old results, see e.g., [1]). Recent data for resistivity and the Hall effect in LSCO now cover the broad range of concentration and up to 1000 K. Below we apply our analysis mostly to the findings [2].

In this presentation we interpret anew the $T$-dependence of resistivity taking into account the increase of number of carriers with temperature

Transport data for cuprates could not be easy explained in terms of the Fermi liquid (FL) theory. Thus, resistivity in optimally doped LSCO has been found to increase linearly with temperature up to 1000 K without any tendency to saturation [3]. This dependence was interpreted in frameworks of the phenomenological Marginal Fermi Liquid (MFL) theory [4]. According to [4], all measured quantities are expected to scale with the only possible dimensional parameter - the temperature; hence, linear in $T$ dependence of the relaxation rate: $1/\tau \propto T$. A challenge to MFL came up with observation of almost quadratic temperature dependence for the Hall angle (more precisely, of $\cot(\theta_H) = \rho_{yx}/\rho_{yx}$, where $\rho_{xx}$ and $\rho_{yx}$ are the longitudinal and the transverse resistivity components, correspondingly) [3]. Quadratic $T$-dependence for the Hall angle, as opposed to the $T$-linear resistivity, seemed to be the evidence in favor of two scales in the relaxation processes for carriers [3]. (The controversy is sometimes referred to as “the separation of lifetimes”; e.g. see in [5]).

In [6] the puzzle was attributed to “spin-charge separation”, the concept borrowed from the physics of one-dimensional conductors and merely postulated for HT$_c$ cuprates. The quadratic $T$-dependence for $\cot(\theta_H)$ was ascribed in [6] to small angle scattering of carriers on dopants, e.g., on the Sr$^{2+}$ ions located far enough from the conducting CuO$_{2}$-planes.

Treatment of transport phenomena in metals and semiconductors is based on the fundamental concept of quasiparticles and on the subsequent use of the Boltzmann-like equation. In the MFL theory [4] the energy spectrum of electronic liquid bears the singular character and the well-defined quasiparticles are absent. MFL scaling [4] does not immediately include the small angle scattering and the Boltzmann equation approach had to be generalized in [7].

The electron energy spectrum in cuprates was directly addressed in the ARPES experiments. Consensus is that within the current resolution well-defined quasiparticle excitations exist only at crossing of the “Fermi surface (FS) locus” along the nodal directions. These regions of the FS are termed as “the Fermi arcs”, with the arcs’ lengths increasing with the increase of temperature. Broad features are seen instead for all other directions (see a summary of recent ARPES findings in [10] together with a discussion concerning possible implications of the “arcs” to transport properties).

It is worth mention here in passing that the Fermi surface “restoration”, i.e. formation of sharp excitations, takes place below $T_c$ [11].

The text-book expression for conductivity has the form:

$$\sigma = ne^2\tau_{tr}/m^*$$ \hspace{1cm} (1)
tering time (Eq. (1) can be equally expressed through the mobility: \( \mu = \tau /m^* \)).

The Hall coefficient, \( R_H \), in metals and semiconductors must also be derived using the Boltzmann equation. For the parabolic energy spectrum the well-known result is:

\[
R_H = 1/\kappa c
\] (2)

\( R_H \) preserves its form, Eq. (2), for interacting electrons with the isotropic energy spectrum [12]. In a general case, however, the expression for \( R_H \) would depend on the model. Recall that even for semiconductors with small elliptic pockets the expression (2) should be multiplied by a factor that depends on the anisotropy of masses. In metals even the sign of \( R_H \) may depend on the FS topology [13].

Eq. (2) becomes exact in the limit of strong magnetic fields [14]. At weaker fields expression (2) is nothing more than an estimate for effective number of carriers. To the best of the authors’ knowledge, the only example when \( R_H \) in its form (2) measures the exact number of carriers is given by the motion of charged particles in electric and magnetic fields in a viscous media. All the more is it interesting that in case of \( \text{La}_{2-x}\text{Sr}_x\text{CuO}_4 \) experimentally the number of carriers, \( n \), calculated as in Eq. (2) exactly coincides with \( x \) at small \( x \) [2, 12, 16].

It is common in the literature to consider peculiarities in transport properties of cuprates above \( T_c \) as coming due to the non-FL behavior, in other words, due to non-existence of quasiparticles in a system of strongly interacting electrons. Strong interactions are of course important in a system near the Mott MI transition, but the view itself does not lead to theoretical understanding. Below we suggest that anomalies in the cuprates’ transport may actually stem from some qualitatively different physics. It concerns, first of all, homogeneity of the electronic liquid in cuprates.

Interpretations of the electronic spectra as obtained from the ARPES data, for instance, always implicitly infer that studied samples are homogeneous both in space and time. It is definitely not so. Abstracting from non-homogeneity caused by external doping, it is now the well-established experimental fact that spatial and temporal fluctuations between non-magnetic regions and incommensurate antiferromagnetic (ICAFM) regions (known also as “stripes”) constitute the ubiquitous feature of the so-called pseudogap (PG) phase on the \((T, x)\)-plane for LSCO. At lower temperatures the two fluctuating phases realize themselves as static SC regions that coexist spatially with ICAFM areas. Static phase coexistence is established in the elastic neutron experiments both with [17, 18] and without magnetic fields [19], from the NMR data [20] and from the \( \mu \)SR experiments [21]. The “granular” character of LSCO samples manifests itself in the anomalous “ln\( T \)-resistivity” at low temperatures when SC is suppressed by strong enough magnetic fields [22].

Temporal phases’ fluctuations at higher temperatures were seen by the inelastic neutron scattering [23] and in the NMR experiments [24]. Slowing down of the fluctuations at cooling, for instance, was directly traced as “wipe out” of the \( ^{63}\text{Cu} \)-signal at the temperature decrease [25].

In the complex dynamic regime of fluctuating sub-phases kinetic properties cannot be obtained from a Boltzmann-like approach. Note the important role of non-elastic events in such a regime.

The clue to the following analysis is this. As it was already emphasized above, for LSCO at small \( x \) the number of externally doped holes is known \textit{a priori} and is equal to the number of dopants, \( \text{Sr}^{2+} \). The remarkable fact is then that from Eq. (2) and the experimental \( R_H \) one indeed obtains exactly \( x \) carriers per Cu-site (at small \( x \) and temperatures around 100 K) [2, 15]. It encourages us to add more significance to measurements of the Hall coefficient in LSCO. More specifically, \textit{we assume that from expression (2) for \( R_H \) one obtains the true number of carriers, \( n_{eff}(T, x) \), at all given \( x \) and temperature, \( T \) [15].} In accordance with the introductory remarks above, we conclude that at low \( x \) and finite \( T \) single charges move in a dissipative media.

Analysis of the Hall data from [2] performed in [15] has shown that the number of holes per Cu atom, \( n_{Hall}(T, x) = nV_{Cu} \), in LSCO changes with temperature as:

\[
n_{Hall}(T, x) = n_0(x) + n_1(x) \cdot \exp[-\Delta(x)/T]
\] (3)

where \( n_0(x) = x \) at low \( x \); \( n_1 \) is a constant (\( \sim 2.8 \)), but decreases rapidly above \( x \sim 0.2 \). \( V_{Cu} \) is the unit volume per Cu. Note that the activation character of the \( T \)-dependent term in Eq. (3) is the thermodynamic feature.

In the ARPES experiments one also measures the energy position of the “van Hove flat band” with respect to the chemical potential. The gap, \( \Delta(x) \), in (3) and this energy do coincide, and therefore in [13, 14] the activation gap has been interpreted as the ionization energy of coupled electron-hole pairs, i.e., the local formations on Cu-O clusters.

With Eq. (3) in mind, it becomes tempting to extract the proper relaxation rate, \( 1/\tau(T) \), for a single moving charge by making use of Eq. (1). (At least, at small enough \( x \) this quantity should not depend on the holes concentration!) In Fig. 1 we have plotted (for a few concentrations) resistivity, \( \rho(T, x) \), multiplied by \( n_{Hall}(T, x) \) [2, 13]. One sees that all three curves at \( T < 300-400 \) K superimpose on each other, the result consistent with the notion of the single charge carrier mobility.

The \( T \)-dependence in Fig. 1 is very close to the quadratic law, \( T^2 \). One may try to interpret this dependence as the FL behavior of the carriers forming small Fermi-pockets. We show that such interpretation is not correct. Indeed, assuming a Fermi energy, \( T_F \), for such a
concentration also rapidly increases and charges may be equal). Although at higher temperatures the carriers’
peculiar activated holes in Eq.(3) become approximately through the external doping and the number of the ther-
trical fit to the data. Note that the quadratic depen-
dared from the thermopower experiments above
usual processing in [30]. Superconductivity occurs only above $T \sim 100 - 150$ K (in other terms, the mobility becomes extremely low).

It is only natural to wonder whether the concept elaborated above for LSCO does apply to other HT$_c$ materials. Unlike LSCO, in other cuprates there is no easy way to know the amount of holes, $p$, introduced by the external (chemical) doping, especially close to the onset of superconductivity. Judgments about the actual hole concentration are then often based on the shape of the so called “superconducting dome”, its dependence on the dopants’ concentration, and the subsequent comparison with those in LSCO as a template (or estimated otherwise from the thermopower experiments above $T_s$). As to the shape of the “superconducting dome”, it is worth reminding that for a $d$-wave SC $T_c$ is sensitive to defects introduced by the doping process.

Consider briefly two examples. The low temperature Hall effect in the normal state was measured in [29] for Bi$_2$ Sr$_{2-x}$La$_x$CuO$_{4+y}$ (BSLCO, or La-doped Bi-2201) where the hole number, $p$, was defined according to such a procedure in [30]. Superconductivity occurs only above $p \sim 0.10$. We have calculated the number of holes in La-doped Bi-2201 from the $R_H(T,x)$ [29] according to Eq.(3). The results indeed turned out very close to our results for LSCO (See Fig.3). Together with the analysis [15] for LSCO, one may conclude that the Hall coefficient in form of Eq.(2) does indeed serve as the measure of the actual number of carriers. Another argument in favor of applicability of the above physics to other materials is that rough estimations gave us (for 0.12 - 0.15 doping) close values of $T_F \sim 50(m^*/m)$ for LSCO, YBCO [31] and BiSrLaCuO. Correspondingly, the Hall angle (recal-

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**FIG. 1:** The resistivity multiplied by $n_{Hall}(T,x)$ from Eq. (1) plotted against $T^2$ for LSCO at selected $x$ deduced from [2].

**FIG. 2:** The resistivity multiplied by $n_{Hall}(T,x)$ plotted vs $T^2$ for LSCO ($x=0.12$) (deduced from [2]).
dramatic decrease at temperatures above 100 K. We ascribe this behavior to motion of charges in a viscous media. For cuprates spatial and temporal competition between the two phases is ubiquitous at these temperatures.

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