Localization and Interaction Effects in Strongly Underdoped La$_{2-x}$Sr$_x$CuO$_4$

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The in-plane magnetoresistance (MR) in La$_{2-x}$Sr$_x$CuO$_4$ films with $0.03 < x < 0.05$ has been studied in the temperature range 1.6 K to 100 K, and in magnetic fields up to 14 T, parallel and perpendicular to the CuO$_2$ planes. The behavior of the MR is consistent with a predominant influence of interaction effects at high temperatures, switching gradually to a regime dominated by spin scattering at low $T$. Weak localization effects are absent. A positive orbital MR appears close to the boundary between the antiferromagnetic and the spin-glass phase, suggesting the onset of Maki-Thompson superconducting fluctuations deep inside the insulating phase.

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Doping of charge carriers drives the high-$T_c$ cuprates from the insulating and antiferromagnetic (AF) phase, to a spin-glass (SG), and to a metallic and a superconducting (SC) phase. Understanding the nature of this evolution is a fundamental but still controversial problem. The properties of the underdoped regime are very unusual, somehow related to the pseudogap opening observed by angle resolved photoemission (ARPES)[$^9$]. Some non-Fermi-liquid theories propose the existence of hidden order, such as charge stripes, spin-charge separation, or orbital currents[$^2$]. On the other hand, a recent Fermi-liquid model, with strong AF and SC fluctuations of Maki-Thompson (MT) type, accounts well for transport anomalies of the pseudogapped state[$^8$].

A related puzzling, but less studied feature, is the conductance in the SG region. It is metallic-like at high temperatures, changing gradually into variable range hopping (VRH) at low $T$ [$^4,5$]. Recent ARPES experiment on the underdoped La$_{2-x}$Sr$_x$CuO$_4$ (LSCO) reveals the emergence of sharp nodal quasiparticle (QP) peak [$^6$]. The peak appears first in the SG at $x = 0.03$, and its spectral weight grows linearly with the increase of $x$, suggesting that it is responsible for the metallic conductance at high $T$. The question arises what is the origin of the low-$T$ localization of the QP states. Calculations show that a narrow QP band may arise in a system with disordered charge inhomogeneities (stripes)[$^7$], and there are suggestions that the charge stripes, combined with the weak localization, may account for the conductance behavior[$^8$]. However, before considering these new approaches, one should study experimentally the low-$T$ localization and compare it to the standard localization and interaction theories (LIT) for disordered systems[$^2$].

In this study we probe, for the first time, the localization and interaction effects in the SG regime of LSCO ($0.03 < x < 0.048$). We use MR measurements in the longitudinal (LMR) and transverse (TMR) configurations, with the magnetic field $B$ parallel or perpendicular to the $ab$ planes, respectively. In two-dimensional (2D) systems the LMR usually probes spin-related effects, while the TMR may, in addition, contain orbital contributions[$^9$]. We find that the high-$T$ metallic-like conduction displays features which are in qualitative agreement with the standard LIT picture. The most important finding is the absence of weak localization and the predominant influence of interactions. The positive orbital MR suggests the onset of superconducting fluctuations of the MT type deep inside the insulating phase, confirming the importance of the MT effect suggested in Ref.$^8$.

Our samples are $c$-axis aligned epitaxial films, about 6000 Å thick, made by pulsed laser deposition on substrates of LaSrAlO$_4$.[$^{10}$] To minimize the substrate-induced strain and the oxygen deficiency we select the films with the lowest resistivity and smallest surface roughness from a large body of specimens, as described in Refs.$^{11,12}$. The films have resistivities about 30 to 60% larger than in the best bulk single crystals with the same $x$[$^3$]. However, the superconductor-insulator (SI) transition occurs in films at $x = 0.05$, just as it does in single crystals. In addition, we have found that the MR is insensitive to strain[$^{11,12}$], and the MR in the films is the same as that in single crystals with the same $x$[$^3$] so that we are led to believe that the data measured in these films reflect the genuine behavior of the MR. The measurements were done in the four-probe configuration, with magnetic fields up to 14 T, and temperatures down to 1.6 K. The data were accumulated either by sweeping the field or by sweeping the temperature, and the results were found to be consistent with one another.

The inset in Fig. 1 shows the $T$-dependence of the $ab$-plane conductivity, $\sigma_{ab}$, at zero magnetic field, for the films with $x = 0.03,0.045$, and 0.048, and $k_F l$ at 20K equal to 0.08, 0.35, and 0.57, respectively. Here $k_F$ is the Fermi wave vector, $l$ is the mean-free path, and we use $k_F l = (h/\sigma_{ab})/e^2$ ($d$ is the distance between the CuO$_2$ planes). This formula underestimates $k_F l$ for nodal QP, ARPES shows that $k_F l$ around node is much larger[$^8$]. The main figures 1(a) and 1(b) show the $T$-dependence of the MR, defined as $\Delta \rho/\rho_0 = (\rho(B) - \rho_0)/\rho_0$, where $\rho_0$ is the resistivity at zero field, measured in the LMR and TMR configurations. Below about 3K $\sigma_{ab}(T)$ approaches the Mott VRH law and both the LMR and TMR are large and negative. The appearance of the negative LMR coincides approximately with the development of
the magnetic quasi-elastic neutron scattering intensity in the SG phase\(^{13}\). The magnitude of the negative MR is similar in two films with larger strontium contents, and it is substantially larger for \(x = 0.03\). This suggests that the negative MR is a spin-related effect, which becomes stronger as the AF correlations grow with the decrease of \(x\). At higher \(T\), there is a gradual transition to a weaker \(T\)-dependence of the conductivity, \(\sigma_{ab} \propto \ln T\). The slope \(S_0 = d(\sigma_{ab})/d(\ln T)\) increases by a factor of 3.5 when \(x\) grows from 0.03 to 0.048. This is accompanied by the gradual appearance of a positive contribution to both LMR and TMR. The TMR is always larger than the LMR, and the difference increases as \(x\) grows. This indicates that there is a substantial orbital contribution to the MR (OMR) related to the presence of delocalized carriers at high \(T\). The existence of the positive OMR is also evident from the dependencies of the LMR and the TMR on the magnetic field, which are shown in Figs. 1(c) and 1(d) for \(x = 0.048\) for several fixed temperatures. By analogy with conventional disordered metals, we call the high-\(T\) range, the "weakly localized regime" (WL), and the low-\(T\) range, the "strongly localized regime" (SL). In the following we focus primarily on the WL regime.

**FIG. 1:** The \(T\)-dependence of the LMR (a) and TMR (b) at the magnetic field of 14 T for La\(_{2-\delta}\)Sr\(_{\delta}\)CuO\(_4\) films with \(x = 0.03, 0.045,\) and 0.048. The inset shows the \(T\)-dependence of the \(\sigma_{ab}\) at zero magnetic field. (c) LMR and (d) TMR as a function of \(B\) for \(x = 0.048\) for several fixed temperatures indicated in the figures. The data below 4.2 K were obtained from temperature sweeps at fixed fields.

Fig. 2 shows the LMR data for \(x = 0.048\), replotted as a magnetic-field induced change of the conductivity, \(-\Delta\sigma_{||} = \Delta\rho_{||}/\rho_{0}^2\), versus \(B/T\). Qualitatively similar behavior is observed for different \(x\). We define three characteristic temperatures, \(T_1\) - \(T_3\), which are shown in Fig. 2 for the data taken in a field of 14 T. At \(T > T_1\), which corresponds to \(B/T << 1\), all data for different fields follow one common curve, \(-\Delta\sigma_{||} = S_L (B/T)^2\) (solid grey line). The parameter \(S_L\) increases by a factor of about 5 as \(x\) grows from 0.03 to 0.048, an increase by about the same order of magnitude as the increase of \(S_0\)\(^{13}\). At \(T_1\) the positive contribution deviates from the quadratic dependence and saturates. This is followed by the appearance of a negative contribution, until at the temperature \(T_2\) the data join a second common curve, best described by a simple functional form \(\Delta\sigma_{||} \sim \tanh^2[c(B/T)]\) (solid black line). At the lowest \(T\) the negative LMR deviates from this curve and a new anomaly appears at \(T_3\).

The inset to Fig. 2 shows the field dependence of \(T_1\), \(T_2\), and \(T_3\). \(T_2\) and \(T_3\), which are related to the negative contribution of the LMR, are field-independent. Apparently the spin-related scattering is influenced mainly by the temperature, not by the external magnetic field. This suggests the presence of strong internal fields and is consistent with SG ordering driven by the temperature-induced localization of carriers. It is most likely that the low-\(T\) LMR results from the suppression of spin-disorder (sd) scattering by the magnetic field, that the simple functional form reflects the dependence of the local magnetization on \(B/T\), and that the reduction of the scattering rate below the SG freezing temperature leads to the anomaly around \(T_3\). More discussion of this behavior will be presented elsewhere.

On the other hand \(T_1\) increases with \(B\). We associate the positive contribution in the WL regime with...
the effect of Zeeman splitting in the particle-hole (p-h) interaction channel. According to LIT, in a 2D system this effect should be described by the dependence \( \Delta \sigma \sim -g_2(h) \), where \( h = g \mu_B B/k_B T \), and \( g_2(h) \) is a function which has limiting behaviors \( g_2 = 0.084h^2 \) for \( h << 1 \), and \( g_2 = \ln(h/1.3) \) for \( h >> 1 \). Therefore, we expect the deviations from the \( (B/T)^2 \) curve to occur when \( g \mu_B B \sim k_B T \), i.e., when \( T/B = g \mu_B /k_B = g \times 0.67 \) K/T. The straight line fitted to the dependence of \( T_1 \) on \( B \) has a slope \( T_1/B \) of about \( (2.0 \pm 0.4) \) K/T, giving an effective \( g \)-factor of about \( (3 \pm 0.6) \), enhanced in comparison with the free-electron value. The fitted line has a finite intercept, which is not predicted by the theory. The deviations from theory are probably the results of the increasing influence of sd scattering as the temperature \( T_2 \) is approached from above, although the enhancement of \( g \) may be also a genuine effect caused by strong internal fields in the SG phase.

Next we consider the TMR. If the spin-orbit coupling is small, one expects that the LMR is isotropic. Assuming tentatively that this is the case, we extract the OMR by subtracting the LMR from the TMR. Fig. 3a shows that \( -\Delta \sigma_{orb} \) is positive, and has the form of a pronounced maximum, which rapidly increases with an increase of \( x \). This OMR of the insulating samples evolves smoothly into a large OMR for SC films with \( x > 0.06 \) which we have studied previously [19]. In SC films the OMR diverges above the SC transition temperature. A recent Fermi liquid theory explains the OMR divergence, together with other anomalous transport properties below the pseudogap opening, by the interplay of strong AF and SC fluctuations of the MT type [4]. The smooth evolution across the SI transition suggests that the origin of the positive OMR may be similar below and above the SI transition, possibly related to MT fluctuations.

Fig. 3b shows \( -\Delta \sigma_{orb} \) as a function of \( B/T \) for \( x = 0.048 \). At the highest temperatures, which correspond to small \( B/T \), the data follow a \( (B/T)^2 \)-dependence. Below the temperature \( T_{o1} \), a crossover occurs to a weaker dependence, and at a still lower temperature, \( T_{o2} \), the OMR decreases rapidly. The field dependencies of \( T_{o1} \) and \( T_{o2} \), shown in the inset, reveal that \( T_{o2} \) is constant. In fact, comparison with Fig. 2 tells us that \( T_{o2} \) closely matches the temperature \( T_2 \), below which sd scattering dominates the LMR. We conclude that the low-\( T \) suppression of the OMR is associated with strong sd scattering. On the other hand \( T_{o1} \) increases with increasing field.

When \( x \) decreases, \( -\Delta \sigma_{orb} \) is still proportional to \( B^2 \), but the \( T \)-dependence changes. We derive the relation for each \( x \), \( -\Delta \sigma_{orb} = S_{orb}(T) B^2 \), where \( S_{orb}(T) \) is the coefficient which depends on temperature as a power-law, \( S_{orb} = T^{-2p} \), with the exponent \( p \) which changes with \( x \). In Fig. 3b we plot \( S_{orb}^{1/2} \) as a function of \( T \) on a double logarithmic scale. Note first that \( S_{orb} \) decreases by two orders of magnitude when \( x \) drops from 0.048 to 0.03. This may be compared with the change of \( S_0 \) or \( S_L \), both of which decrease by a much smaller factor. This shows that the suppression of the OMR is not simply related to the decrease of concentration of delocalized carriers, but involves a process which is more strongly dependent on \( x \). The slope of the linear dependence gives the exponent \( p \), which is shown as a function of \( x \) in the inset to Fig. 3b. It reduces approximately linearly with a decrease of \( x \), from \( 0.99 \pm 0.03 \) for \( x = 0.048 \), to \( 0.27 \pm 0.1 \) for \( x = 0.03 \). Extrapolating the linear dependence \( p(x) \) to \( p = 0 \) we get the value of \( x \) above which the OMR is observed, \( x_c \approx 0.023 \). This is close to \( x = 0.02 \), which is the boundary between the AF phase and the SG phase. Apparently the OMR is detectable as soon as the concentration of carriers is large enough to frustrate the long-range AF order.

According to LIT, a positive OMR may be caused by weak localization in the presence of strong spin-orbit scattering. However, a change of sign of the OMR for high magnetic fields is then expected, and we see no trace of that. Another possible source of the positive OMR is the particle-particle (p-p) interaction channel. A particular type of p-p scattering is analogous to the MT process.
of electron interactions with SC fluctuations. The magnitude of this effect is very small for normal metals with repulsive interactions, but may be large in systems with attractive interactions. The functional form of the OMR is the same as that caused by weak localization, with two distinct dependencies on the magnetic field,

\[ -\Delta \sigma \sim (B/B_m)^2 \quad \text{for} \quad B << B_m \quad \text{and} \quad -\Delta \sigma \sim \ln(B/B_m) \quad \text{for} \quad B >> B_m. \]

Here \( B_m = \hbar/eD\tau_m \), where \( D \) is the diffusion coefficient, and \( \tau_m \) is the inelastic scattering time, usually given by \( \tau_m \sim T^{-p} \), with an exponent \( p \) which depends on the scattering mechanism.

These predictions would be consistent with our experiment, if we interpreted the \( T_{c1}(B) \)-line as a crossover between distinct dependencies on \( B/B_m \). To avoid the influence of sd scattering we fit the straight line to the \( T_{c1}(B) \) data at highest magnetic fields. We get \( T/B_m = 1.2 \, \text{K/T}, \) and from this we obtain \( D\tau_m = 1987T^{-1} \text{nm}^2 \).

The inelastic scattering length, \( L_{\text{in}} = (D\tau_m)^{1/2} \), is about 30 Å at 20 K. The decrease of \( x \) to 0.03 reduces this distance to about 10 Å. This may be compared to the mean-free path estimated from ARPES experiment, 16 Å at 20 K for \( x = 0.03 \). The agreement between these two experiments is very good. Using the diffusion coefficient (from conductivity for \( x = 0.048 \) film, \( D \approx 0.39 \, \text{cm}^2/\text{s} \) at 20 K we get the inelastic scattering time \( \tau_m \approx 2.6 \times 10^{-13} \, \text{s} \) (this should be treated as an upper bound since \( D \) from conductivity is underestimated).

The magnitude of \( \tau_m \) is at least two orders of magnitude smaller than in conventional disordered metals, revealing much stronger interactions. On the other hand, the exponent \( p = 1 \) for \( x = 0.048 \) is consistent with the expectations for electron-electron interactions in a disordered 2D metal. The reduction of \( p \) with the decrease of \( x \) is anomalous, pointing to an unusual strong scattering weakly dependent on \( T \).

The previous MR experiments on metallic (but non-superconducting) high-\( T_c \) systems found a power-law \( T \)-dependence of \( \tau_m \) with small \( p \), close to our results for \( x = 0.03 \), but the OMR was negative, caused by weak localization. It is tempting to speculate that the small value of \( p \) may be a generic feature of a narrow nodal QP band, which becomes evident in the absence of the MT process. However, the differences between the previous cases and the LSCO system may be more profound, including, for example, the differences in the electronic structure and the opening of the pseudogap, the magnitude of spin-related scattering, etc. More experiments on the SG samples for different cuprates are needed to search for similar OMR behavior in other systems.

We now consider what are the implications of these results for the understanding of the SI transition in cuprates. First, the behavior of the positive OMR suggests that it originates in the MT contribution, and this is in a very good agreement with the Fermi-liquid description of the pseudogap state proposed in Ref.\[3\]. However, it is not yet clear how far into the insulating SG phase this description may be extended. In addition, our discussion is based on the qualitative comparison with the standard LIT, which may not exactly hold for the narrow QP band. Secondly, our results indicate that the model of conducting stripes combined with weak localization effect is not sufficient to describe the conductance in strongly underdoped LSCO. On the other hand, it should be stressed that the appearance of the positive OMR deep in the insulating phase does not rule out the theories based on the charge inhomogeneity picture. One can imagine that the MT fluctuations may be enhanced in the regions with high concentration of carriers. More elaborate models based on a stripe picture are needed, incorporating the presence of MT fluctuations.

In conclusion, we have revealed the origin of the effective localization of the QP states at low temperatures in the strongly underdoped LSCO. The MR experiment shows that the weak localization effect is absent. Instead, these are the interaction effects which play the decisive role. The LIT picture gives a good qualitative description of the MR in the WL regime, reproducing the dependence on the field and temperature. It suggests the onset of the MT fluctuations at the AF-SG phase boundary.

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