Glassy charge dynamics and magnetotransport in lightly doped La$_2$CuO$_4$

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Motivation

- Doped Mott insulators
- \( T=0 \) insulator to (super) conductor transition?

Emergence of nanoscale inhomogeneities!

• (infinitely?) many possible arrangements of nanoscopic ordered regions with comparable energies \( \Rightarrow \) glassy dynamics
Motivation

- Doped Mott insulators
- $T=0$ insulator to (super) conductor transition?

[C. Panagopoulos and V. Dobrosavljević, PRB 72, 014536 (2005) and references therein]

Ground state: charge (Coulomb) glass at low $x$?

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Motivation

- Doped Mott insulators
- $T=0$ insulator to (super) conductor transition?

Mott transition with disorder – theory: V. Dobrosavljevic et al., PRLs … (1999-2005)

MIT in a 2DES in Si at $T=0$
[Popović et al., PRLs from 2002 to 2007; many signatures of glassiness; Coulomb glass; $T_g=0$]

Glassy insulator: $|k_F| < 1$; “bad” metal

Metallic glassy phase

Metal

carrier density

$n_c$  
metal-insulator transition  
$n_g$  
glass transition

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Glassy charge dynamics in cuprates?
Nature of the ground state?

Glasses: - many metastable states
- slow, nonequilibrium dynamics

How to probe glassy dynamics?

• measure response of the system to some kind
  of a perturbation ⇒ slow, nonexponential relaxations

• fluctuations – provide complementary information (correlations)

For charge glass: transport (bulk probe; mean values of resistivity)
and resistance noise (fluctuations)
Lightly doped La$_2$CuO$_4$ - a good candidate (well characterized, disorder)

- Sr and Li (no magnetic moment) doped: similar magnetic behavior, but no SC in Li-LCO

La$_{2-x}$Sr$_x$CuO$_4$ in spin-glass phase ($T_{sg}$ ~ 7-8 K)

x=0.03 in this talk:
La$_{2-x}$Cu$_x$Li$_{1-x}$O$_4$ in antiferromagnetic phase ($T_f$ ~ 7-8 K)

Dielectric measurements: an electronic glass state
AF Li-LCO: Park et al., PRL 94, 017002 (2005);
x=0.03 LSCO: Jelbert et al., PRB 78, 132513 (2008)

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Variable-range hopping (VRH): $R \propto \exp\left[\left(\frac{T_0}{T}\right)^n\right]$, $n=1/3$ (2D exponent)

Actually, it depends on how the sample is cooled…

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History dependence in transport: zero-field cooling (ZFC) vs. field cooling (FC)

Difference between FC and ZFC resistance $R(B=0)$

- observed in both $R_{ab}$ and $R_c$, for both $B||ab$ and $B||c$
- difference disappears at much lower $T$ in $ab$ sample

Signature of out-of-equilibrium dynamics

Onset $T < T_{sg} \approx 7$ K

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Memory effects

(observed in both $R_{ab}$ and $R_c$, for both $B||c$ and $B||ab$)

- higher $B$ enable overcoming higher energy barriers
- $R(B=0)$ determined by the highest $B$ previously applied - memory of magnetic history

Also, manganites: Levy et al., PRL 89, 137001 (2002);
YBCO: Ando et al., PRL 83, 2813 (1999)

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Hysteretic behavior of the resistance

Memory in R wiped out for $T \geq 1K$, spin glass transition $T_{SG} \approx 7K$

- hole-rich regions between interacting hole-poor AF domains
- return point memory
- incongruent subloops $\Rightarrow$ interactions between domains

$T_{onset} < T_{SG}$

Do the holes merely "follow" the spins?
Resistencia fluctuations (noise); LSCO

- noise Gaussian at “high” T (e.g. T > 0.18 K for $R_{ab}$ noise)
- at low T, non-Gaussian noise
  metastable states (out-of-equilibrium)
Probability density functions (PDF) of fluctuations

Noise in $R_{ab}$

- Structure depends on the observation time – different states contribute $\Rightarrow$ nonergodic

$T = 0.082$ K
$B = 0$ T

3 h intervals

$\Delta R / R(10^{-4})$
- increase sampling time to 12 hours, but never becomes Gaussian at low $T$

- nonergodic, does not reach equilibrium on experimental time scales at low $T$

Onset of glassiness in transport at $T << T_{SG}$: suggests spin and charge glass not directly related
Noise statistics: T and B dependence

- Power spectrum: $S_R \sim 1/f^\alpha$

- $\alpha$ increases as T is reduced; no effect of B!

fewer metastable states that dominate at low T in the exp. time window

- Slowing down of the dynamics as T→0

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Second spectrum $S_2(f_2, f)$

- the power spectrum of the fluctuations of $S_R(f)$ with time

1) white (1-\(\beta\) =0) for uncorrelated fluctuators (Gaussian)

2) $S_2(f_2, f) \propto 1/f_2^{1-\beta}$ for interacting fluctuators (non-Gaussian)

Increase of correlations as $T \rightarrow 0$

Noise statistics independent of both $B$ and magnetic history

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(Partial) summary of noise results

- **Slowing down** of the dynamics as $T \to 0$

- **Increase of correlations** as $T \to 0$

**Glass transition at $T=0$**

- Noise statistics independent of both $B$ and magnetic history (unlike conventional spin glasses) $\Rightarrow$ charge, not spin!

- Onset of hysteretic and memory effects in magnetoresistance:
  $T_{\text{onset}} \ll T_{\text{sg}}$

$\Rightarrow$ Charge glass transition $T_{cg} = 0$

[I. Raičević et al., PRL101, 177004 (2008)]

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Scaling of the second spectra

- can distinguish between different models:
  - droplet approach
  - hierarchical, tree-like model

\( S_2 \) decreases with \( f \) for a fixed \( f_2/f \), consistent with droplet picture (short-range interactions)

Spatial segregation of holes as a result of competing interactions on different length scales

Cluster charge glass
Origin of large positive magnetoresistance at low T???

LSCO; $R_c$
$B\|c$ axis
$T=0.450K$

Subloops shifted vertically to 0 for comparison

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Out-of-plane MR - LSCO

The pMR mechanism changes below ~1 K:

- Positive MR increases in magnitude again below ~1 K.
- Same sample: onset of charge glassiness below ~1K

Low T positive MR closely related to the onset of charge glassiness

High T – crossover to negative MR

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In-plane MR - LSCO

**High T** – MR negligible
- negative below 10K
  (onset of spin glass order)
- isotropic
- reorientation of weak FM moments

**Low T**
Emergence of low-field positive MR at $T < 1K$

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In-plane MR – LSCO, low T

- Strong positive MR at low T (below 0.5 K)
- Low-T positive MR coincides with the onset of charge glassiness

Only positive MR exhibits hysteresis

Positive MR - glassy features:
- History dependence
- Memory
- Hysteresis

In the same regime:
- Noise – glassy dynamics as $T \to 0$

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Out-of-plane MR – Li-LCO

High T

- B || c
  - negative - steplike decrease (spin flop)
  - strong positive below ~ 12 K

- B || ab
  - negative (∝ B^2; smooth rotation of weak FM moments)

Low T

- B || ab: low-field positive MR below 3 K

[Similar to AF (x=0.01) LSCO: Ando et al., PRL 90, 247003 (2003)]

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In-plane MR – Li-LCO

**High T** – negative MR
- $B \parallel c$ – steplike decrease
- $B \parallel ab$ – $B^2$ dependence

**Low T**
- low-field positive MR below $\sim 4K$

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**Li-LCO: glassy features in transport**

- History dependent behavior

\[ R_{FC} - R_{ZFC} \] decreases with increasing \( T \) and vanishes at a \( B \)-dependent \( T \)

- Memory – the highest applied field determines \( R(B=0) \)
- Hysteresis only in the region of (initial) positive MR
- Return point memory

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Origin of the positive magnetoresistance

Li-LCO – insulating for all x → superconducting fluctuations not the origin

Exponential enhancement

\[ R(B, T) = R(0, T) \exp\left(\frac{B^2}{B_0^2}\right) \]

not observed

Orbital effects not the origin

hole localization length much smaller than the magnetic length

Must be a spin related effect!!

Reorientation of weak ferromagnetic moments leads to

Negative, not positive MR

Remaining possibility: coupling of B to the spins of doped holes, which populate localized states within Mott-Hubbard gap U

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Strongly disordered materials with Mott VRH and intra-state correlations (Coulomb repulsion $U'$ between two holes in the same disorder-localized state)

- Spins of singly occupied states become parallel in strong enough $B$

Zeeman splitting blocks some hopping channels $\Rightarrow$ positive MR

$U' >> T$


Positive MR in various nonmagnetic, disordered materials with strong Coulomb interactions attributed to this effect

Test this prediction:

All data in the regime of positive MR collapse onto one function of a single scaling parameter!

- Scaling works for both LSCO and Li-LCO
- It appears that the magnetic background remains inactive in this regime of $T$ and $B$ (frozen spins/AF domains; holes that “live” in domain walls – analogous to other disordered, interacting systems)

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Conclusions

Lightly doped La$_2$CuO$_4$ : two different transport regimes within the spin glass phase

1) “High T” < $T_{sg}$: - magnetic structure important $\Rightarrow$ negative MR

2) Low T, $T \rightarrow 0$ limit (i.e. $T < 1$ K in practice):
   - glassy charge dynamics (noise); charge cluster glass, $T_{cg}=0$
   - positive MR with hysteresis and memory
   - magnetic structure not important, to leading order
   - U’ on disorder-localized state important (U’~20 K in LSCO)

As $T \rightarrow 0$, behavior characteristic of systems that are far from any magnetic ordering

Use hysteretic, positive MR as an easy tool for detecting charge glassiness confined to the domain walls: intrinsic or driven by disorder?

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