Superconductor-Insulator Transitions in Highly Underdoped Cuprates

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Theory: V. Dobrosavljević, Florida State University, USA
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Questions

1. **Strongly correlated 2D systems:**
   
   Nature of the **insulating ground state**?
   
   **Quantum phase transition** from an insulator to a superconductor with doping?

2. **Cuprates:**

   Emergence of high-$T_c$ superconductivity from a doped Mott insulator?

   • Quantum criticality
   • Role of disorder
   • Competing orders
   • Vortex matter physics
   • …
Our experiments on La-based cuprates probe charge order:

- **Nature of the insulating ground state** at low doping: charge cluster glass
- **Doping-driven transition** from insulator to superconductor: coexistence and competition between different orders
- **Magnetic-field-driven** superconductor-insulator transition (SIT): the interplay of quantum criticality and vortex matter physics
- **Dynamics near** thermally-driven superconducting transition: dynamical heterogeneities

![Diagram of phase diagram for La$_{2-x}$Sr$_x$CuO$_4$](chart_image)
Y. Ando, May 2005 talk in Dresden:

**Phase Diagram**

La$_{2-x}$Sr$_x$CuO$_4$

- LSCO is peculiar in that:
  - Metallic behavior is observed when it should *not* be a metal.
  - Insulating behavior is observed when it should *not* be an insulator.

Y.A.: Electron self-organization?

Top right: Ando *et al*., PRL 87, 017001 (2001);
Nature of the ground states and evolution with doping?

[C. Panagopoulos and V. Dobrosavljević, PRB 72, 014536 (2005) and references therein]
Lightly doped La$_{2-x}$Sr$_x$CuO$_4$: Experimental protocols

A. Resistance noise spectroscopy: Fluctuations

- PDFs, power spectrum, second spectrum


B. History-dependent transport

1) Zero-field cooled vs. field-cooled resistance

2) Hysteretic magnetoresistance


C. Dielectric measurements


Short-range AF order: in-plane AF domains; holes in domain walls
In-plane resistance fluctuations (noise)

- Single crystal La$_{2-x}$Sr$_x$CuO$_4$, x=0.03; $T_{SG} = 7$-8 K
- Variable-range hopping transport at low T

- noise: Gaussian at “high” T
- at low T (<0.2 K), non-Gaussian noise metastable states (out-of-equilibrium)
Noise statistics

- **Very low** $T$: magnetic background frozen
- **Power spectrum**: $S_R \sim 1/f^\alpha$

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

- **Increasing non-Gaussianity of the noise as** $T \to 0$
Second spectrum \( (S_2) \) – “noise of the noise”

(Voss&Clarke, Restle&Weissman, Seidler&Solin)

- \( S_2(f_2,f) \): power spectrum of the fluctuations of \( S_R(f) \) with time
  (Fourier transform of the autocorrelation function of the time series of \( S_R(f) \); fourth-order noise statistic)

\[
S_2 \propto \frac{1}{f^2} \quad 1-\beta
\]

1- \( \beta = 0 \) \quad Gaussian (uncorrelated)
1- \( \beta > 0 \) \quad non-Gaussian (correlated)

Increase of correlations as \( T \to 0 \)

- Noise statistics independent of both \( B \) and magnetic history (unlike conventional spin glasses, but like a spin-polarized 2DES)

\( \Rightarrow \) Charge glass transition \( T_{cg} = 0 \)
Scaling of the second spectra

Measure of correlations

- can distinguish between different models (Weissman):
  - interacting droplet model
  - hierarchical, tree-like model

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

Competing interactions on different length scales

Charge cluster glass

\[ \text{La}_{2-x}\text{Sr}_x\text{CuO}_4, x=0.03 \]

\[ T = 0.118 \text{ K, } B = 6 \text{ T, } l \parallel ab \]

(Schmalian and Wolynes, PRL 85, 836 (2000): “stripe” glass in a model with competing interactions on different length scales, NO disorder)

Different from metallic spin glasses and a 2D Coulomb glass – systems with long-range interactions: hierarchical!
Hysteretic behavior of the low-T positive MR

LSCO; $R_c$

B||c axis

$T=0.450\,\text{K}$

Memory in $R$ erased for $T \geq 1\,\text{K}$, $T_{SG} \approx 7\,\text{K}$: holes do not merely “follow” the spins

$(R_c, R_{ab}; B||c \text{ and } B||ab)$

Difference between field-cooled and zero-field cooled resistance $R(B=0)$

History dependence in transport in non-SC samples: $T_{onset} \ll T_{sg}$

Use these effects as “easy tools” for detecting charge glassiness as a function of doping.
Temperature dependence of the in-plane resistivity

\( x = 0.03 \) and \( x = 0.05 \): 2D variable-range hopping
\( x = 0.055 \) and \( x = 0.06 \): non-SC; \( \rho(T) \) cannot be fitted to any simple form
\( x \geq 0.065 \): SC

\[ R = \frac{\rho}{d}, \]
\[ R_{\square/layer} = \frac{\rho}{l}, \]
\( d \) – sample thickness (~100 nm);
\( d = n l \); \( n \) - # of layers;
\( l = 6.6 \, \text{Å} \) – thickness of one layer

<table>
<thead>
<tr>
<th>( x )</th>
<th>( T_c ) (K) (midpoint)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.065</td>
<td>6 ± 1</td>
</tr>
<tr>
<td>0.07</td>
<td>9 ± 1</td>
</tr>
<tr>
<td>0.08</td>
<td>12 ± 1</td>
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</tbody>
</table>
High-field magnetoresistance and superconducting fluctuations

Normal-state resistivity (dashed lines) at low fields:
\[ \rho_n(H) = \rho_n(H=0) + \alpha H^2 \]

\((\text{Max } \omega_c \tau \approx 0.01 \text{ at } \sim 10 \text{ T})\)

\(H_c'(T)\) – field above which SCFs are suppressed and normal state is restored

Contribution to conductivity from SCFs:
\[ \Delta \sigma_{\text{SCF}}(T,H) = \rho^{-1}(T,H) - \rho_n^{-1}(T,H) \]

**LSCO:** Harris et al., PRL 75, 1391 (1995), Rourke et al., Nature Phys. 7, 455 (2011);

**YBCO:** Rullier-Albenque et al., PRL 99, 027003 (2007); PRB 84, 014522 (2011)
Doping-driven superconductor-insulator transition in \( \text{La}_{2-x}\text{Sr}_x\text{CuO}_4 \)

- Charge glass in the insulating regime at low doping

- Suppression of charge glassiness with doping

- Coexistence and competition of charge glass with superconducting fluctuations (SCFs) on the insulating side of the superconductor-insulator transition (SIT)

[Onset of SIT influenced by charge glass order]

[X. Shi et al., Nature Mater. 12, 47 (2013)]
**$H$-field-driven superconductor-insulator transition in cuprates**

- **Questions:**
  - Zero-temperature $H$-field-driven superconductor-insulator transition (SIT) in 2D? Quantum criticality? (scaling)
    (See “Conductor-Insulator Quantum Phase Transitions”, ed. by Dobrosavljević, Trivedi, Valles; Oxford University Press, 2012, for review and open questions)
  - Nature of the field-induced resistive state?
  - Interplay of quantum criticality and vortex matter physics?

- **Experiments:**
  - Magnetoresistance over a wide range of $H$ and $T$ (down to 0.09 K)
  - Low-$T_c$ ($\sim 4$ K) $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$ samples grown using different methods

- **Conclusions:**
  - **Three** distinct phases as $T \to 0$; **two** quantum critical points
Sketch of the \((T, H)\) phase diagram in underdoped \(\text{La}_{2-x}\text{Sr}_x\text{CuO}_4\)

Interplay of vortex physics and quantum critical behavior

\[
\begin{align*}
T_1^* &\sim |\delta|^{z_v}, \quad z_v \sim 0.7 \\
T_2^* &\sim |\delta|^{z_v}, \quad z_v \approx 1.15
\end{align*}
\]

2D SIT in the clean limit

\((R_{\square/\text{layer}} \approx 18 \text{ k}\Omega)\)

Bose glass

\([X. \text{ Shi et al.}, \text{Nature Phys. 10, 437 (2014)}]\)
Sketch of the \((T, H)\) phase diagram in underdoped \(\text{La}_{2-x}\text{Sr}_x\text{CuO}_4\): Interplay of vortex physics and quantum critical behavior

[X. Shi et al., Nature Phys. 10, 437 (2014)]
$H=0$ thermally-driven superconducting transition in a highly underdoped La$_{2-x}$Sr$_x$CuO$_4$

Extent of SCFs from MR:

$x=0.07$

$T_{R=0} \approx 4$ K

Fermi liquid behavior above $\sim 15$ K

$[\rho_n(H) - \rho_n(0)]/\rho_n(0) = \alpha_{\text{trans}} H^2$

[X. Shi et al. (unpublished)]
$H=0$ thermally-driven superconducting transition in a highly underdoped La$_{2-x}$Sr$_x$CuO$_4$

- **Signatures of the 2D, Berezinskii-Kosterlitz-Thouless (BKT) transition** (thermal unbinding of vortex-antivortex pairs) in bulk samples: paraconductivity, current-voltage characteristics
- **Good agreement with theory** by Benfatto, Castellani, Giamarchi (PRLs, PRBs since 2007) [P. Baity et al. (unpublished)]
Time-domain spectroscopy of the BKT transition in a highly underdoped La$_{2-x}$Sr$_x$CuO$_4$

Power spectral density:

\[ \frac{S_R}{R^2} \propto \frac{1}{f^\alpha} \]

Noise measured in this region

Arm size: 20 µm x 200 µm

\[ T_{c} \sim 11.3 \text{ K} \]

\[ T_{BKT} \sim 9.7 \text{ K} \]

\[ 9.82 \text{ K} \]

\[ 10.32 \text{ K} \]

\[ 10.86 \text{ K} \]

\[ 12.07 \text{ K} \]

\[ 10.20 \text{ K} \]

\[ 12.56 \text{ K} \]

\[ 13.81 \text{ K} \]

\[ x=0.08 \]
Normalized power spectral density increases by several orders of magnitude as $T \to T_{BKT}$

Below $\sim 14$ K, $\alpha$ increases from $\sim 1.0$ and reaches $\sim 1.4$ at $\sim 12$ K: slowing down of the dynamics
Time-domain spectroscopy of the BKT transition in a highly underdoped La$_{2-x}$Sr$_x$CuO$_4$

Magnitude of the resistance noise

In the BKT regime ($T_{\text{BKT}} < T < T_c$):

- Exponential increase of noise as $T \to T_{\text{BKT}}$
- Slow, correlated dynamics for $T < T_c$
- Interacting domains/clusters
- Non-Gaussian noise suppressed in $x=0.07$ sample $\rightarrow$ not due to disorder

[Z. Shi et al. (unpublished)]
Time-domain spectroscopy of the BKT transition in a highly underdoped La$_{2-x}$Sr$_x$CuO$_4$

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Cluster/stripe glass: competing interactions on different length scales?

Intermediate, bad metal phase?

[Z. Shi et al. (unpublished)]
Conclusions

1) Nature of the insulating ground state in La$_{2-x}$Sr$_x$CuO$_4$ at low doping
   • Doped holes form charge cluster glass (dynamic charge heterogeneities) in CuO$_2$ planes

2) Doping-driven SIT ($H=0$) in LSCO
   • Formation of localized Cooper pairs within the insulating, charge glass state
   • Onset of SIT influenced by a competing charge order

3) Thermally-driven ($H=0$) SC transition
   • BKT transition
   • Fluctuating, interacting clusters/domains; dynamical heterogeneities

4) $H$-field-driven SIT
   • Three distinct phases at $T=0$ in underdoped La$_{2-x}$Sr$_x$CuO$_4$:
     o superconductor with $T_c(H) \neq 0$ (pinned vortex solid/Bragg glass)
     o superconductor with $T_c = 0$ (vortex glass)
     o high-field insulator (Mott hopping)