ABNORMAL NORMAL STATE of the HIGH-Tc's
(and WHY USE HIGH MAGNETIC FIELDS ?)

LOW - DIMENSIONAL TRANSPORT
and QUASI-PARTICLE CONFINEMENT

REVEALING QUANTUM CRITICAL POINTS
in the HIGH-Tc PHASE DIAGRAM

SCIENCE, Correlated Electron Systems, 21 April 2000
"Advances in the Physics of High-Temperature Superconductivity"
"Quantum Criticality: Competing Ground States in Low Dimensions"
Subir Sachdev Science 288 (2000) 475
"Sources of Quantum Protection in High-Tc Superconductivity"

THE Theory of SUPERCONDUCTIVITY in the High-Tc Cuprates,
ANISOTROPIC, UNIVERSALLY-BIZARRE RESISTIVITY

Optimally-doped Bi-2212, Martin, et al

- $\rho_{ab}$ **LINEAR**... with small residual resistivity
- $\rho_{ab}$ is featureless... no energy scale other than temperature
- $\rho_{c}$ is insulating

Compilation by Batlogg, et al

$\rho_{ab} / \rho_0 = \frac{m^*}{ne^2c}$

$\rho_{ab}/\rho_0 = \frac{h}{e^2}\left(\frac{1}{kT}\right)$

Figure 3.2b. Planar resistivity vs. $T$ for a variety of materials. (b) Anisotropic resistivity of Bi2201.

Figure 1. Illustration of Independence of Planar Properties and $T_c$.

Figure 3.2d. Generalized Phase Diagram (CuO$_2$ planes).
WE EXPECT A LARGE RESIDUAL RESISTIVITY
10% - 20% Doping... Within Austenite or Plates
Very Little Screeing in Dopants... Since #Carriers is #Dopants

No Hint of Scattering

Optimally-doped BL-2212, Martin et al

Scaling and Feature-less Scattering Rate
THE TWO-DIMENSIONAL STRANGE METAL

<table>
<thead>
<tr>
<th>SUPERCONDUCTORS IN THE NORMAL STATE</th>
<th>Experiment</th>
<th>Cuprates</th>
<th>BCS Superconductors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical conductivity</td>
<td>Metallic in C-O plane</td>
<td>Metallic in all directions</td>
<td></td>
</tr>
<tr>
<td>Resistivity</td>
<td>Increases linearly with temperature</td>
<td>Linear increase with temp. at high temp. Faster at low temp.</td>
<td></td>
</tr>
<tr>
<td>Hall effect</td>
<td>Temperature-dependent</td>
<td>Non-temperature-dependent</td>
<td></td>
</tr>
<tr>
<td>Neutron scattering</td>
<td>Temperature-dependent magnetic signature</td>
<td>Non-temperature-dependent</td>
<td></td>
</tr>
<tr>
<td>NMR spin relaxation rate</td>
<td>Increases nonlinearly with temp. above Tc</td>
<td>Increases linearly with temp. above Tc</td>
<td></td>
</tr>
<tr>
<td>NMR spin susceptibility</td>
<td>Pseudogap</td>
<td>No pseudogap</td>
<td></td>
</tr>
<tr>
<td>Specific heat</td>
<td>Pseudogap</td>
<td>No pseudogap</td>
<td></td>
</tr>
<tr>
<td>Photoemission</td>
<td>D-wave pseudogap</td>
<td>No pseudogap</td>
<td></td>
</tr>
<tr>
<td>Electron tunneling</td>
<td>Pseudogap, superconducting gap same size</td>
<td>No pseudogap</td>
<td></td>
</tr>
<tr>
<td>Electronic Raman scattering</td>
<td>Pseudogap</td>
<td>No pseudogap</td>
<td></td>
</tr>
<tr>
<td>Phonon frequency shift</td>
<td>Pseudogap</td>
<td>No pseudogap</td>
<td></td>
</tr>
</tbody>
</table>

Figure 3.26. "Generalized Phase Diagram" as seen (roughly) in (La-Sr)CuO4.

Anderson, Science 256, 1526 (1992)

ALSO:
Research News Science 278 (12 Dec 1997) 1879

\[ V_{\text{HALL}} = \frac{1}{ne}\text{B} \]

HALL EFFECT: EVIDENCES TWO SCATTERING RATES?

\[ T^{\text{Hall}} = T^{\text{Cuprate}} \]

YBCO, Ong, et al

\[
\begin{align*}
\text{From } & \rho_{\text{H}} \rightarrow \tau_{\text{H}}^{-1} \sim T \\
\text{From } & \rho_{\text{HALL}} \rightarrow \tau_{\text{HALL}}^{-1} \sim \frac{1}{T}
\end{align*}
\]

\[ \cot \theta_{\text{H}} = \frac{\rho_{\text{HALL}}}{\rho_{\text{H}}} \sim \frac{T}{T^2} \text{ (conventional)} \]

Figure 3.7. Earliest data on the Hall effect, showing confusing picture in terms of \(\rho_{\text{H}}\).

Figure 3.9. \(\theta_{\text{H}}^{-1} \propto T^2\) for a single crystal, from Ginsberg.

Optimally-doped YBCO, Ginsberg, et al

\[ \cot \theta_{\text{H}} = \frac{\rho_{\text{HALL}}}{\rho_{\text{H}}} \sim \frac{T}{T^2} \text{ (looks conventional)} \]
La$_{2-x}$Sr$_x$CuO$_4$

- Variable range hopping
- Metallic $\rho_{ab}$
- Insulating $\rho_e$
- Insulator: variable range hopping
- Metal: Fermi liquid
- $k_F l \sim 1$
- $k_F l \sim 100$

\[ x = 0.08 \]
\[ x = 0.15 \]
\[ x = 0.22 \]

Logarithmic $\rho_{ab}$ or $\rho_{ab}^*$

- Karpinska et al. PRL 72 (1994)
- Prayer et al. PRB 44 (1991)
- Jing et al. PRL 67 761 (1991)
Transport studies of Lu$_{1-x}$Sr$_x$CuO$_4$ near the insulator-metal-superconductor transition

A. S. Cooper and G. P. Espinosa
AT&T Bell Laboratories, Murray Hill, New Jersey 07974

Received 27 October 1988

Resistivity of Lu$_{1-x}$Sr$_x$CuO$_4$, for all measured concentrations. Curves A, B, C, D, E, and F are the data from the $x = 0.02, 0.05, 0.055, 0.065, 0.075$, and 0.10 samples, respectively. Superconductivity in the $x = 0.055$ sample coincides with a drop in normal-state resistivity

$\rho = \exp \left( \frac{4T}{T_c} \right)$

T$_c$ = 20 (K)

3D VARIABLE RANGE HOPPING

Tl$_2$Ba$_2$CuO$_{6+\delta}$ (single crystal)
Low temperature mean free path 500-1000 Å

Tl$_2$Ba$_2$CuO$_{6+\delta}$ (polycrystalline)

Resistivity (10$^{-3}$ Ω cm)

Temperature (K)

Work on sintered material by Kubo et al. (Proc M$^2$-HTSC II Stanford, 1989)
\[ k_F l = \frac{k_c}{\rho_{ab}} \]

**LSCO single crystals**  
**ab-plane**

- \( x = 0.06 \)
- \( x = 0.08 \)
- \( x = 0.15 \)
- \( x = 0.22 \)

Graph showing the relation between \( \rho_{ab} \) (mΩ-cm) and \( T(K) \) for different values of \( x \).
SUPERCONDUCTOR-INSULATOR TRANSITION in BISMUTH THIN-FILMS

Haviland, Liu, Goldman, PRL 62 (1989) 2180
Low-Temperature Normal State of High-Temperature Superconductors

Using 60 Tesla to reveal the normal-spike phase diagram.

Using 60 Tesla to suppress the superconducting state
Samples for in-plane resistivity measurement

\[ \rho_{ab} \]

Samples for out-of-plane resistivity measurement

\[ \rho_c \]

For \text{LSCO},

\[ \frac{\rho_c}{\rho_{ab}} \approx 10^3 \]
MAGNET PULSE PROFILE
- 73T PEAK FIELD
- 1400 PULSES OF 60T
- 19 MINUTES BETWEEN PULSES OF 60T

$\text{La}_{(2-x)}\text{Sr}_x\text{CuO}_4 \quad x=0.08$

$T=1.5K$
$B \perp c-axis$

$c-\text{axis} : f = 30 - 150 \text{ kHz}$
$\tau = 10 - 30 \text{ msec}$

72 TESLA
INSULATOR--TO--METAL Crossover
IN THE NORMAL STATE OF A HIGH-Tc SUPERCONDUCTOR

(a) LSCO single crystals

$\rho_{ab}$ (m$\Omega$-cm)

$k_f=1$

$T$ (K)

$x = 0.08$

$x = 0.15$

$x = 0.17$

$x = 0.22$

(b) $x = 0.15$

$x = 0.17$

$x = 0.22$

Localization in the high-Tc cuprates:
Same animal or completely different zoo?

Sixty teslas suppresses the superconducting phase
in many different cuprates to reveal....
NORMAL STATE AT LOW TEMPERATURES

GSB
Fedor Balakirev
Bell Labs and Los Alamos National Lab
Yoichi Ando
Al Passner
Bell Labs

YBCO
Yoichi Ando
Kouji Segawa
CRIEPI, Tokyo

Bi-2201
Nan Lin Wang
Christoph Geibel
Frank Steglich
TH Darmstadt

LSCO
Masayuki Okuya
Tsuyoshi Kimura
Jun-ichi Shimoyama
Kohji Kishio
Appl. Chemistry, U. of Tokyo

Bi-2201
CRIEPI, Tokyo

LSCO
Kenji Tamasaku
Noriya Ichikawa
Shin-ichi Uchida
SRC, U. of Tokyo

Bi-2201
TH Darmstadt

LSCO, Nd-doped LSCO, and (SrCa)14 Cu24 O41
Naoki Motoyama
Hiroshi Eisaki
Department of Superconductivity, U. of Tokyo

Kenji Tamasaku
Noriya Ichikawa
Shin-ichi Uchida
La_{2-x}Sr_xCuO_4, x=0.08, H // c

$\rho_{ab}(T) = \rho_0 \ln \left( \frac{T_0}{T} \right)$

Ando, Nat. Phys. 25, 1117 (2009)
**La$_{2-x}$Sr$_x$CuO$_4$**

**PHASE DIAGRAM**

WITH SUPERCONDUCTIVITY SUPPRESSED
THE UNDERDOPED NORMAL STATE IS A STRANGE INSULATOR

\[ \rho_{ab} \sim \rho_\perp \log(1/T) \]

La_{2-x}Sr_xCO_4 single crystals, \( x = 0.08 \)


INSULATING BEHAVIOR IN THE UNDERDOPED NORMAL STATE
ARISES FROM LOCALIZATION - Beschoten, et al,
PRL 78, 1938 (1997)

Comparing Bi_2Sr_{2-x}La_xCuO_{6+y} and La_{2-x}Sr_xCuO_4

Similarities between BSLCO and LSCO:
Insulator Behavior exhibits Log-T divergence.
Insulator-to-Metal Crossover occurs at \( k_F a \sim 15 \).

Differences between BSLCO and LSCO:
Insulator-to-Metal Crossover occurs gradually in BSLCO.
BSLCO data suggests the underdoped regime contains
a metallic state exhibiting unusual localization behavior.
WHAT IT IS NOT

Kondo effect

3D \ln(1/T) dependence in \rho from Spin-flip scattering

\times No spin-flip below \kB T \approx g\mu_B B.

60-T magnetic field \Rightarrow \kB T < 40 K

\textit{Expect saturated }\rho\textit{ at low }T

Weak Anderson Localization

\ln(1/T) dependence in \sigma

\times No coherent back scattering in 60 T
\times Plot of \sigma vs \ln T is not linear
\times Same \ln(1/T) behavior for \rho_c

Ong's group also finds inconsistencies with

conventional 2D weak localization in Bi-2201.

[ T. W. Jang et al., PRL 67, 761 (1991) ]
Electron-electron Interaction Effect

Electron-electron interaction in 2D system also leads to

$$\sigma = \sigma_0 + \alpha' \sigma_1 \ln(T/T_0),$$

where $\alpha'$ is a constant of order 1 and $\sigma_1 = e^2 / nh$.

Origin of this correction: modification of 2D DOS

$\Rightarrow$ If $\rho_c$ is determined by tunneling between 2D systems, $\rho_c$ may show the same T-dependence as $\rho_{ab}$.

• For our data, the plot of $\sigma$ vs $\ln T$ is not linear.

(Not known if this is a problem.)

THIS LOG-(1/T) IS NOT...

...CONVENTIONAL WEAK LOCALIZATION
No coherent backscattering would survive 60 teslas
Log-(1/T) divergence is large and in resistivity
Log-(1/T) divergence occurs also in c-axis resistivity
PRL 75 4662 (1995)

...DISORDER-ENHANCED e⁻⁻e⁻⁻ INTERACTIONS
Log-(1/T) divergence is large and in resistivity
First-order perturbation finds a small correction
Log-(1/T) divergence not observed in Hall coefficient
PRB 56 R8530 (1997)

...SPIN-FLIP KONDO SCATTERING
No spin-flip scattering in 60 teslas for $T<60K$
Ando et al. PRB 56 R8530 (1997)

$R_H$ becomes nearly $T$-independent at low-$T$ REGARDLESS of whether $\rho_{ab}$ is insulating or not
Modulated Spin and Charge Densities in Cuprate Superconductors


Fig. 1 A model of spin and charge stripes in the CuO$_2$ planes corresponding to $\varepsilon = 1/8$. The Cu ions are represented by circles (not shown are the oxygen ions). The holes occupy every other Cu site on the charge stripe which separates regions of the AF ordered spin domains. A possible stacking of the stripe ordered CuO$_2$ planes is also shown.

Evidence that Charges Move Along Stripes

SCIENCE Oct 8, 1999
- By Photoemission, Shen Group
- By Hall Effect, Uchida Group

PRL Oct 4, 1999
- By Angle-Dependent Magneto-Resistance, Ando Group
SUMMARY

NORMAL STATE TRANSPORT IN LSCO

- 60-TESLA PULSED MAGNETIC FIELDS
  provide the "gentlest" way to reveal
  the normal state phase diagram

- INCREASING CARRIER CONCENTRATION....
  FROM ANTI-FERROMAGNETIC INSULATOR....
  Strong localization regime
  "Log-T" localization regime
  "Linear-T" metallic regime
  ....TOWARD FERMI LIQUID METAL
Building World-Record Magnets

MAGNETIC FIELDS----HOW BIG IS BIG?

PERMANENT MAGNETS

0.4 gauss EARTH'S FIELD

600 gauss REFRIGERATOR MAGNET (Iron--oxide)

4000 gauss STRONGEST PERMANENT (Neodymium--Iron--Boron)

730,000 gauss OUR PULSED MAGNETS
PRESSURES—-HOW BIG IS BIG?

UNDER WATER

<table>
<thead>
<tr>
<th>Depth</th>
<th>Object</th>
<th>Pressure (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 meters</td>
<td>EARS</td>
<td>6</td>
</tr>
<tr>
<td>700 meters</td>
<td>SUBMARINE</td>
<td>1000</td>
</tr>
<tr>
<td>4000 meters</td>
<td>OCEAN FLOOR</td>
<td>6000</td>
</tr>
</tbody>
</table>

OUR PULSED MAGNETS 200,000 psi
NUCLEATION of DISLOCATION PAIR

SIMPLE MOTION of ONE DISLOCATION

PROPAGATION to the SURFACES
CONDUCTORS

Cu Nb
(layers 2-7)
70% IACS
expensive

CuNiBe
(layer 1)
65% IACS

Cu-Alumina
(layers 8-14)
85% IACS
inexpensive

STRESS (ksi) (145ksi = 1GPa)

PERCENT ELONGATION
MAGNET TRAINING

MAGNET INDUCTANCE MONITORED WHILE SLOWLY INCREASING PEAK MAGNETIC FIELD

MAGNET CN93-1
- B vs Vcap
- (L/L) vs Vcap

MAGNET CN93-2
- B vs Vcap
- (L/L) vs Vcap

71.8T

72.6T
Resistivity of the 2-leg ladder compound Sr₂Ca₁₂Cu₂₄O₄₁...

in high magnetic fields (up to 400 mG)

Fedor Balakirev, Bell Labs and LANL

Jon Betts, LANL

Naoki Motoyama

Hiroshi Eisaki

Shin-Ichi Uchida

cond-mat/9308234

FIG. 1. a, The crystal structure for (Sr,Ca)₁₄Cu₂₄O₄₁, including b, the plane containing CuO₂ chains and c, the plane containing Cu₃O₃ ladders.
Fig. 1 A model of spin and charge stripes in the CuO$_2$ planes corresponding to $\epsilon = 1/8$. The Cu ions are represented by circles (not shown are the oxygen ions). The holes occupy every other Cu site on the charge stripe which separates regions of the AF ordered spin domains. A possible stacking of the stripe ordered CuO$_2$ planes is also shown.
Observation of a Well Defined Transition from Weak to Strong Localization in Two Dimensions

Cu/Ge, Ag/Ge, and Au/Ge thin films

Weak localization......log-(1/T) divergence
Strong localization......variable range hopping (exponential divergence)

Crossover occurs at \[ \rho = \pi h/e^2 \] \( (k_f^* = 1/\pi) \)
marked by magneto-resistance changing sign

FIG. 3. Variable range hopping (dashed lines) in the lowest temperature range for both samples.
FIG. 1. (a) Sheet conductance in units of $G_{0} = e^{2}/2π^{2}$ versus temperature with $T_{0} = 1$ K on logarithmic scales for Cu/Ge (circles), Ag/Ge (triangles), and Au/Ge (diamonds) films with thicknesses in the range 0.3 < $r$ < 3 nm. The solid curve and points on it were obtained by adjusting $T_{0}$ for each film described in Ref. [7]. (b) Semilogarithmic plot of $G_{0}/G_{0}$ vs $F^{-1}$ for the recorded data. The line is a fit to the low $G$ limit. (c) $G_{0}/G_{0}$ vs In(T) for the recorded data. The line is a fit to the high $G$ limit.

Sr$_{2}$Ca$_{12}$Cu$_{24}$O$_{41}$

Fit to VRH for $T < 0.6$K
Transport measurements in granular niobium nitride cermet films

We have studied normal-state and superconducting transport properties in a granular cermet consisting of NbN grains in a boron nitride insulating matrix. By varying the volume fraction of the two components we produced films (20-70 nm thick) that exhibited transport behavior in either of two distinct and mutually exclusive classes: "insulating" films with \( \rho \propto \exp(-x/T_\alpha) \) which never went superconducting, and "superconducting" films with \( \rho \sim \exp(-x/T_\alpha) \) from room temperature down to the superconducting transition. This linear logarithmic temperature dependence for the resistivity is also observed at low temperature when superconductivity is suppressed by high magnetic fields. Broad superconducting transitions are observed with a strong compositional dependence of the zero-field critical temperature, \( T_c \). The Kosterlitz-Thouless two-dimensional (2D) topological phase transition at \( T_c \) is observed in the superconducting samples both by the power-law behavior in current-voltage characteristics and by pure flux flow transport in high magnetic fields.
SUMMARY

60-TELESA PULSED MAGNETIC FIELDS REVEAL THE NORMAL STATE PHASE DIAGRAM
Log-(1/T) divergence is large and in resistivity

IN THE UPSTATE
FROM ANTI-FERROMAGNETIC INSULATOR....
Strong localization regime
"Log-T" localization regime
"Linear-T" metallic regime near optimal doping

....TOWARD FERMI LIQUID METAL

SIMILAR BEHAVIOR HAS BEEN FOUND
IN THE LADDER COMPOUND, Sr2 Ca12 Cu24 O41

The strongly-localized behavior may look familiar.....
but we still can't see the forest amidst the logs