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

LOW - DIMENSIONAL TRANSPORT
and QUASI-PARTICLE CONFINEMENT

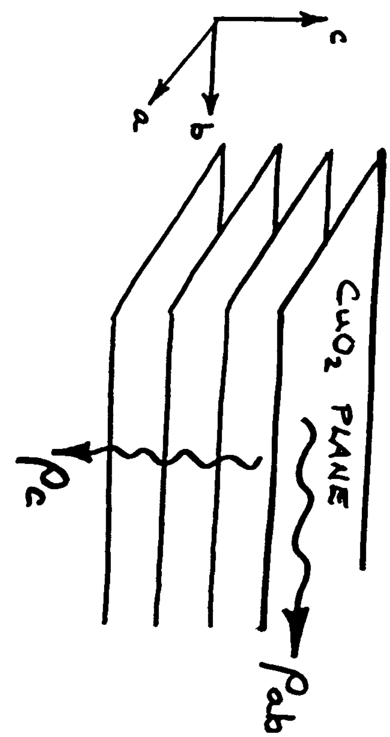
REVEALING QUANTUM CRITICAL POINTS
in the HIGH-Tc PHASE DIAGRAM

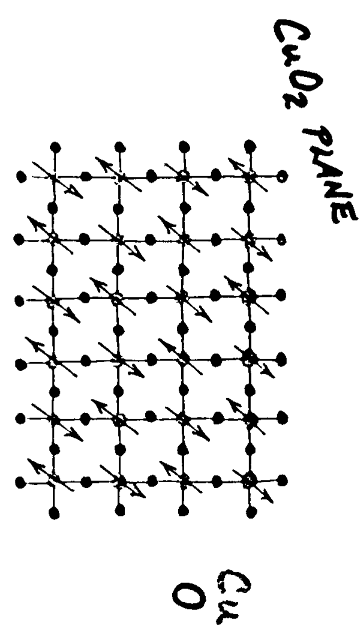
SCIENCE, Correlated Electron Systems, 21 April 2000
"Advances in the Physics of High-Temperature Superconductivity"
J. Orenstein and A.J. Millis, Science 288 (2000) 468
"Quantum Criticality: Competing Ground States in Low Dimensions"
Subir Sachdev, Science 288 (2000) 475
"Sources of Quantum Protection in High-Tc Superconductivity"
Philip W. Anderson, Science 288 (2000) 480

THE Theory of SUPERCONDUCTIVITY in the High-Tc Cuprates,
P.W. Anderson (Princeton Univ. Press, 1997) ISBN 0-691-04365-5

Boebinger
Lecture 1

1





2D HEISENBERG ANTIFERROMAGNET

2

ANISOTROPIC, UNIVERSALLY-BIZARRE RESISTIVITY

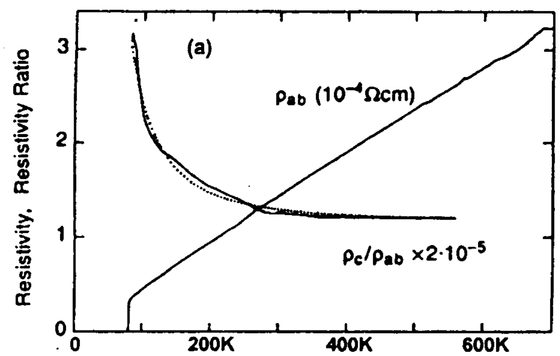


Figure 3.2b. Planar resistivity vs. T for a variety of materials. (b) Anisotropic resistivity of BISCO.

Optimally-doped Bi-2212, Martin, et al

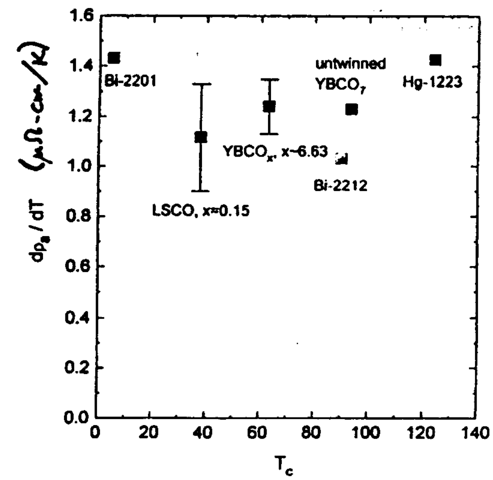


Figure 1. Illustration of Independence of Planar Properties and T_c

Compilation by Batlogg, et al

- ρ_{ab} LINEAR.... WITH SMALL RESIDUAL RESISTIVITY
- ρ_{ab} IS FEATURELESS... NO ENERGY SCALE OTHER THAN TEMPERATURE
- ρ_c IS INSULATING

IN 2D

$$\frac{\rho_{ab}}{c_0} = \frac{m^*}{ne^2\tau}$$

$$\frac{\rho_{ab}}{c_0} = \frac{h}{e^2}\left(\frac{1}{k_F \ell}\right)$$

(3)

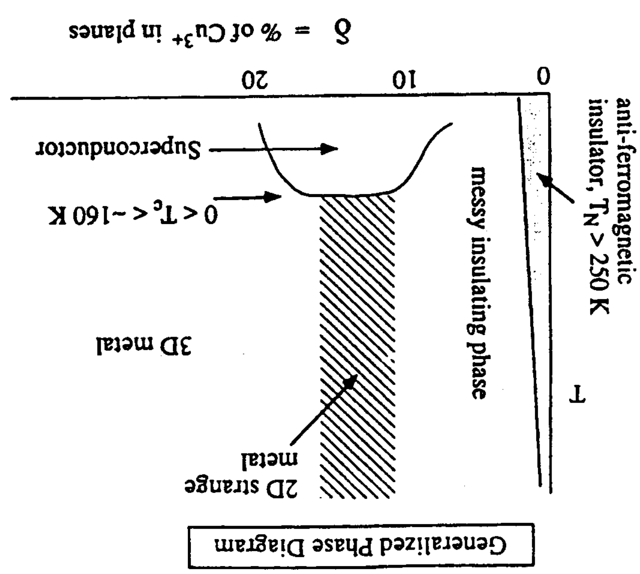
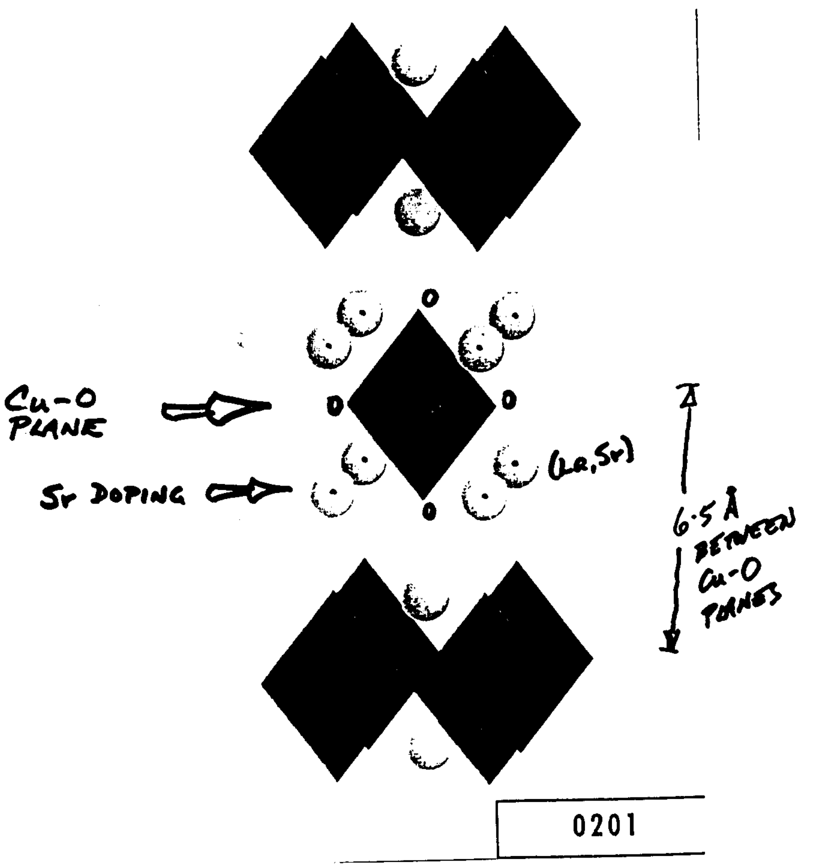


Figure 3.26. "Generalized Phase Diagram" as seen (roughly) in $(La-Sr)CuO_4$.

(4)

$La_{2-x}Sr_xCuO_4$



WE EXPECT A LARGE RESIDUAL RESISTIVITY

10% – 20% DOPING.... WITHIN ANGSTROMS OF Cu-O PLANES

VERY LITTLE SCREENING OF DOPANTS....

.... SINCE #CARRIERS ≈ #DOPANTS

SCALE-LESS and FEATURE-LESS SCATTERING RATE

dc resistivity

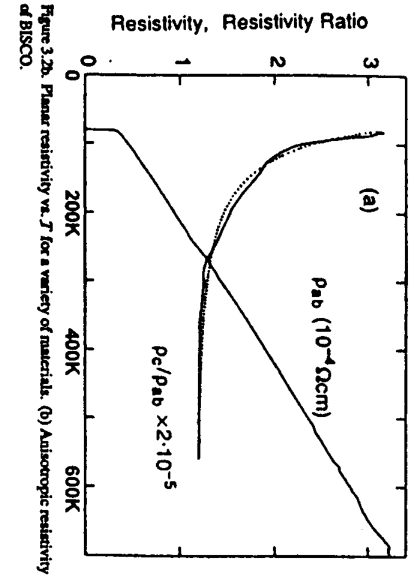
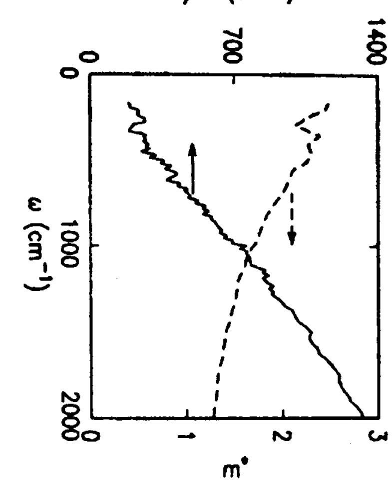


Figure 3.2b. Planar resistivity vs. T for a variety of materials. (b) Anisotropic resistivity of BISCO.

Optimally-doped Bi-2212, Martin, et al

optical conductivity



Optimally-doped YBCO, Schlesinger, et al

$$\frac{\hbar}{\tau} \sim \max \begin{Bmatrix} kT \\ \hbar\omega \end{Bmatrix}$$

$\tau \sim \tau_{INELASTIC}$

NO HINT OF ELASTIC SCATTERING

THE TWO-DIMENSIONAL STRANGE METAL

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

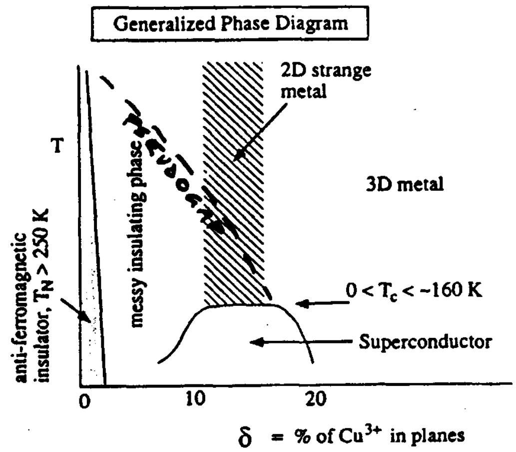


Figure 3.26. "Generalized Phase Diagram" as seen (roughly) in $(La-Sr)CuO_4$.

ANDERSON, SCIENCE 256, 1526 (1992)

ALSO: RESEARCH NEWS SCIENCE 278 (12 Dec 1997) 1879

(7)

$V_{HALL} = \frac{1}{nec} B$

HALL EFFECT: EVIDENCES TWO SCATTERING RATES ?

TEMPERATURE-DEPENDENT HALL VOLTAGE

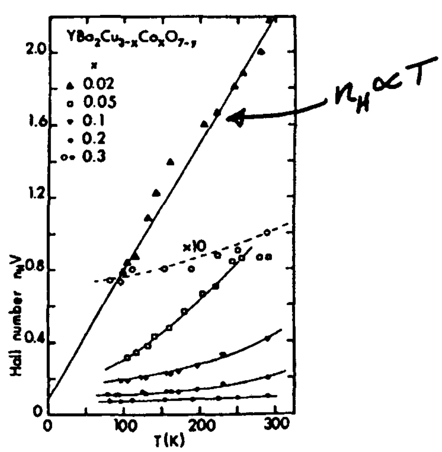


Figure 3.7. Earliest data on the Hall effect, showing confusing picture in terms of R_H.

YBCO, Ong, et al

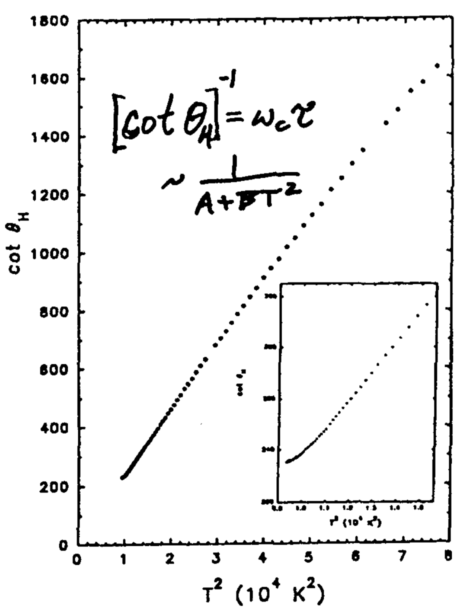


Figure 3.9. Θ_H^{-1} vs T^2 for a single crystal, from Ginsberg.

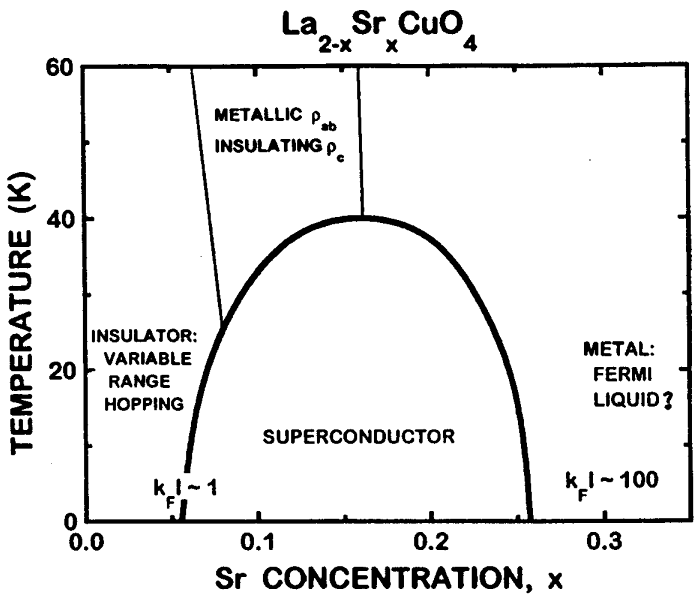
Optimally-doped YBCO, Ginsberg, et al

FROM $\rho_{ab} \rightarrow \tau_{ab}^{-1} \sim T$

FROM $\rho_{HALL} \rightarrow \tau_{HALL}^{-1} \sim 1/T$

$\cot \theta_H = \frac{\rho_{ab}}{\rho_{HALL}} \sim \frac{T}{(1/T)} \sim T^2$ (LOOKS CONVENTIONAL)

(8)



↑

VARIABLE RANGE HOPPING

Ellman et al PRB 39 (1989)

Karpinska et al PRL 77 (1996)

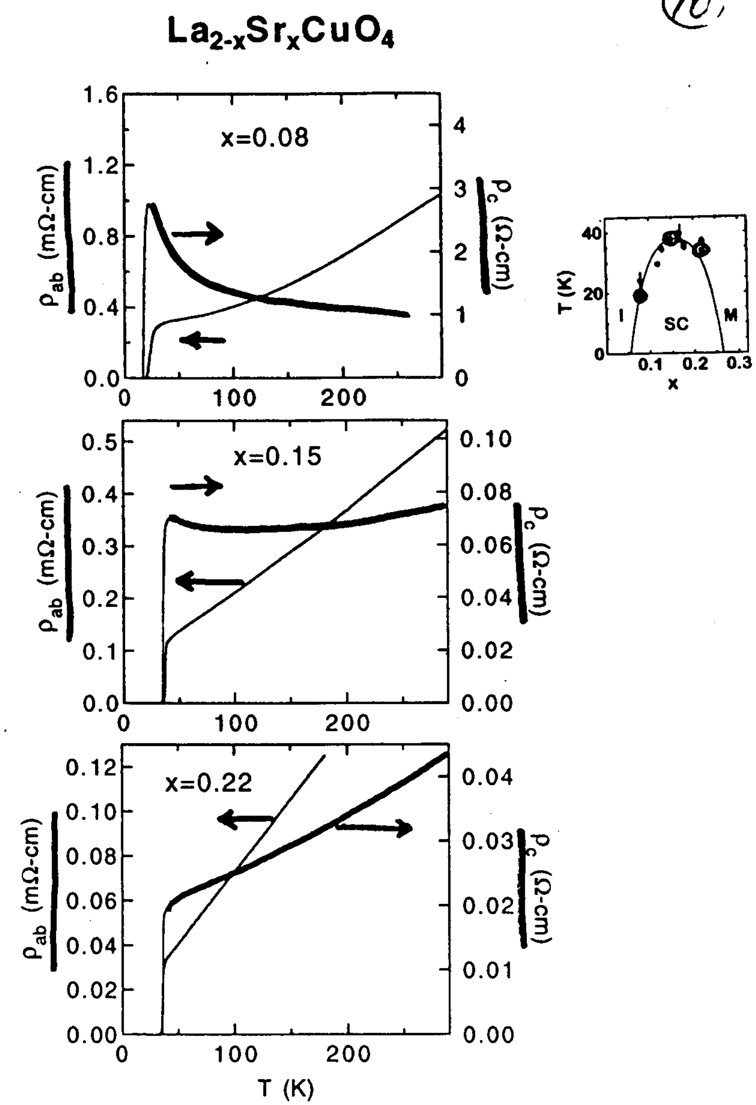
↑

LOGARITHMIC ρ_{ab} OR σ_{ab}

Preyer et al PRB 44 (1991)

Jing et al PRL 67 761 (1991)

→ TOWARD FERMI LIQUID



NONSUPERCONDUCTING UNDERDOPED LSCO

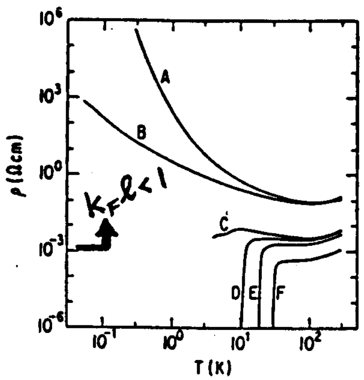
PHYSICAL REVIEW B VOLUME 39, NUMBER 13 1 MAY 1989

Transport studies of $La_{2-x}Sr_xCuO_4$ near the insulator-metal-superconductor transition

B. Ellman, H. M. Jaeger, D. P. Katz, and T. F. Rosenbaum
The James Franck Institute and Department of Physics, The University of Chicago, Chicago, Illinois 60637

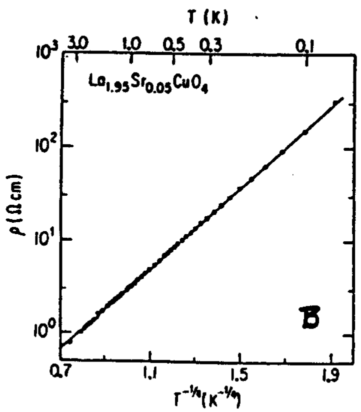
A. S. Cooper and G. P. Espinosa
AT&T Bell Laboratories, Murray Hill, New Jersey 07974

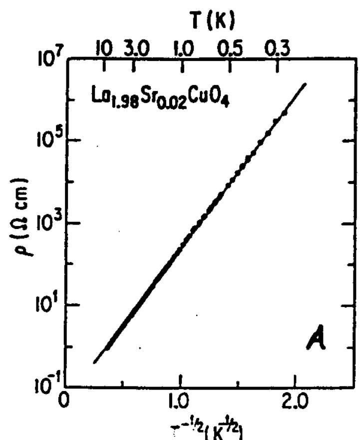
(Received 27 October 1988)



Resistivity of $La_{2-x}Sr_xCuO_4$ 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 $x \geq 0.055$ samples coincides with a drop in normal-state resistivity

$$\rho \sim \exp\left[-\left\{\frac{T_0}{T}\right\}^{\beta}\right]$$

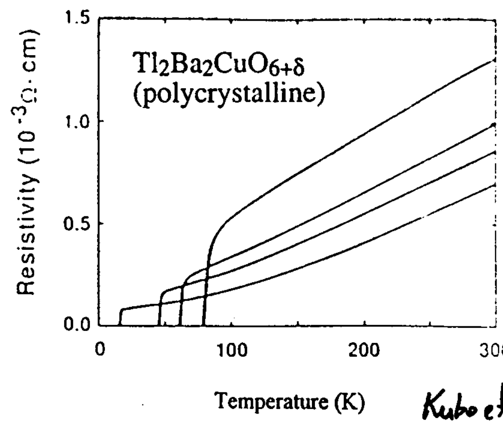




$T^{-1/4}$ $(K^{-1/4})$ $T^{-1/2}$ $(K^{-1/2})$

3D VARIABLE RANGE HOPPING

OVERDOPING → TOWARD FERMI LIQUID

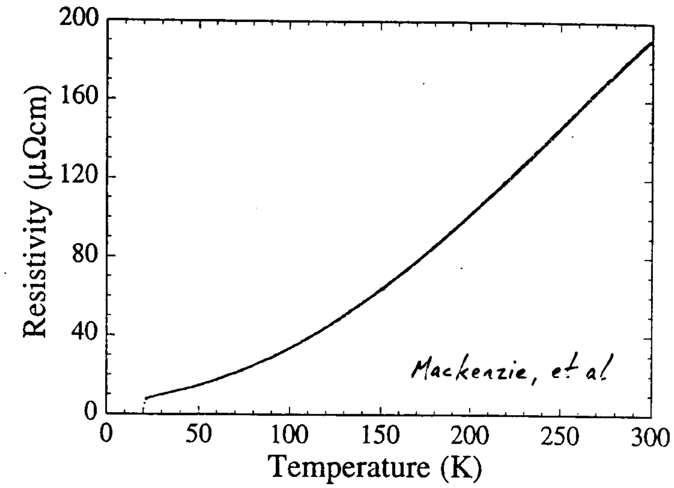


Kubo et al PRB 43 7875 (1991)

Work on sintered material by Kubo et al. (Proc M^2S-HTSC II Stanford, 1989)

$Tl_2Ba_2CuO_{6+\delta}$ (single crystal)

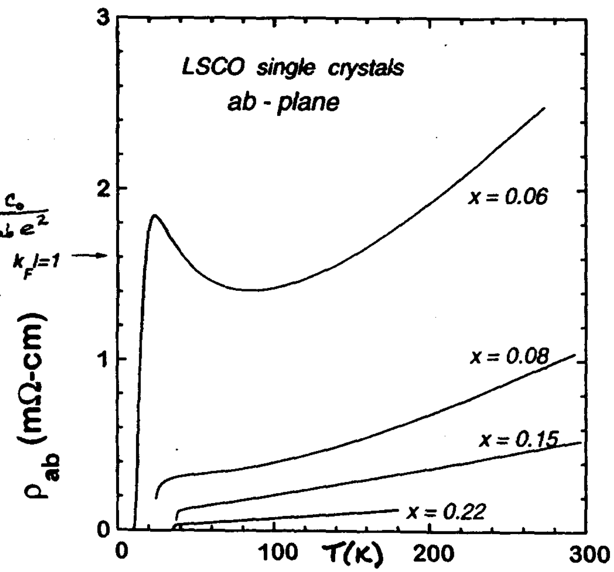
Low temperature mean free path 500-1000 Å

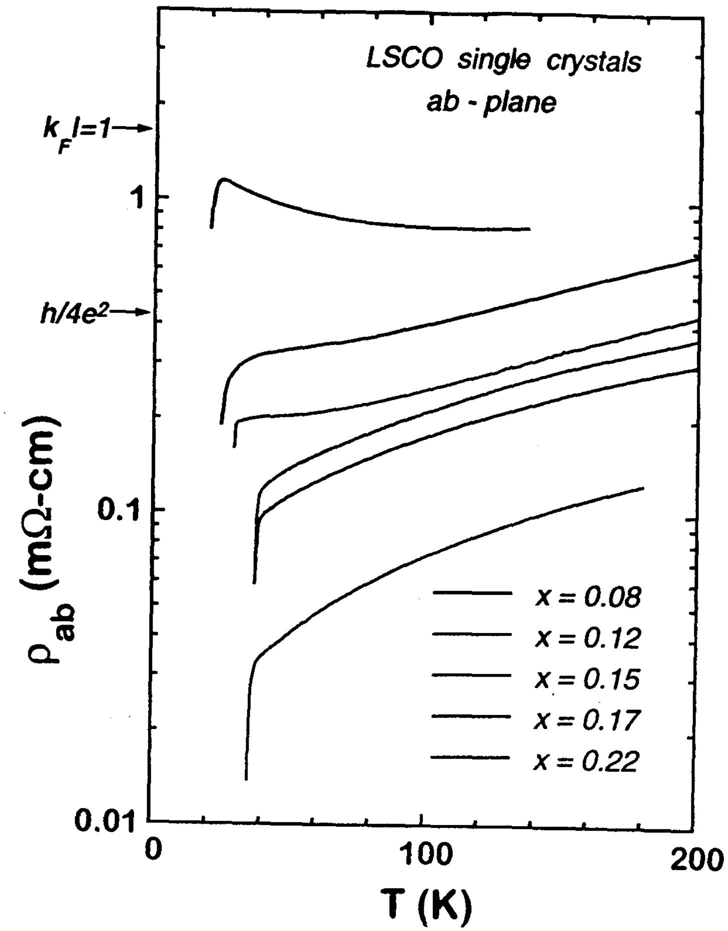


lsco_sum/xa-lin8.opj 19

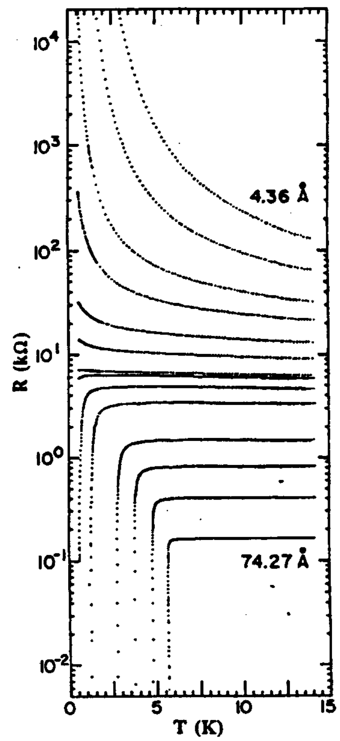
IN 2D,

$k_F \ell = \frac{h c_0}{\rho_{ab} e^2}$





SUPERCONDUCTOR-
INSULATOR TRANSITION
in BISMUTH THIN-FILMS

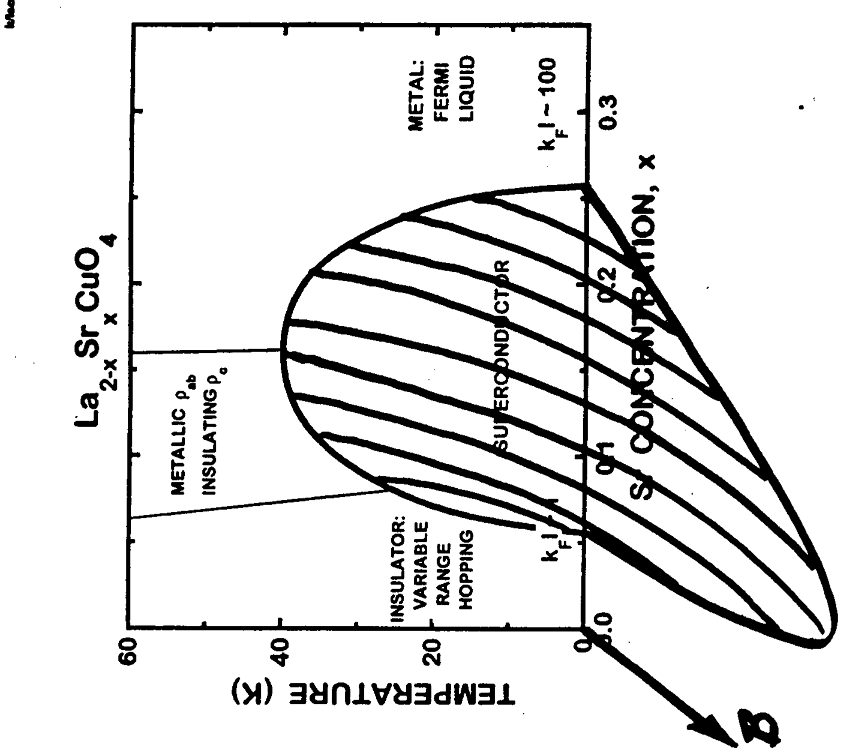


Haviland, Liu, Goldman, PRL 62 (1989) 2180

(15)

(16)

(18)



(17) DELICATELY UNVEILING THE....

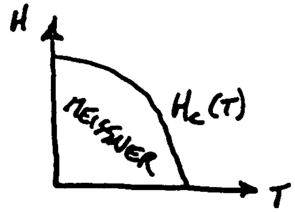
Low-Temperature Normal State of High-Temperature Superconductors

Using 60 teslas ....to suppress the superconducting state
....to reveal the normal-state phase diagram

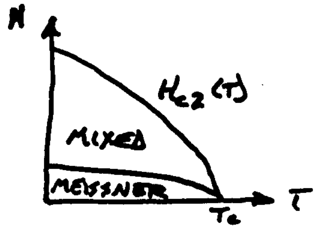
Greg Boebinger, Fedor Balakirev, Jon Betts
Bell Laboratories, Lucent Technologies
National Magnetic Field Laboratory at Los Alamos
Yoichi Ando, Shimpei Ono
CRIEPI, Tokyo
Kohji Kishio, Masayuki Okuya, Tsuyoshi Kimura, Jun-ichi Shimoyama
Applied Chemistry, University of Tokyo
Shin-ichi Uchida, Naoki Motoyama, Hiroshi Eisaki
Department of Superconductivity, University of Tokyo

PRL 75, (1995) 4662
PRL 77, (1996) 2065
PRL 77, (1996) 5417
condmat 9808284
PRL 85 (2000) 638

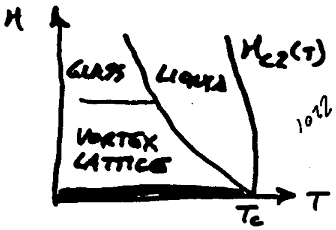
TYPE I



TYPE II BAD METALS = GOOD SUPERCONDUCTORS



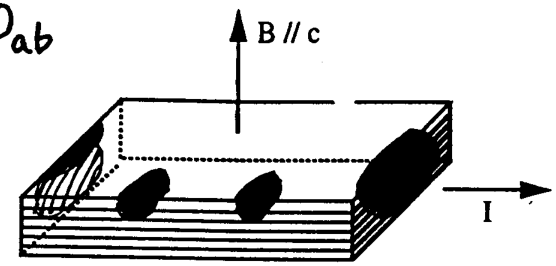
EXTREME TYPE II 2D STRANGE BAD METALS
= HIGH T_c SUPERCONDUCTORS



LSCO

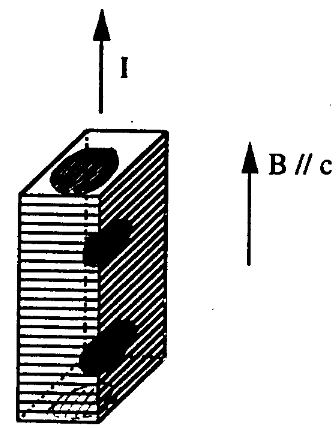
Samples for in-plane resistivity measurement

ρ_{ab}

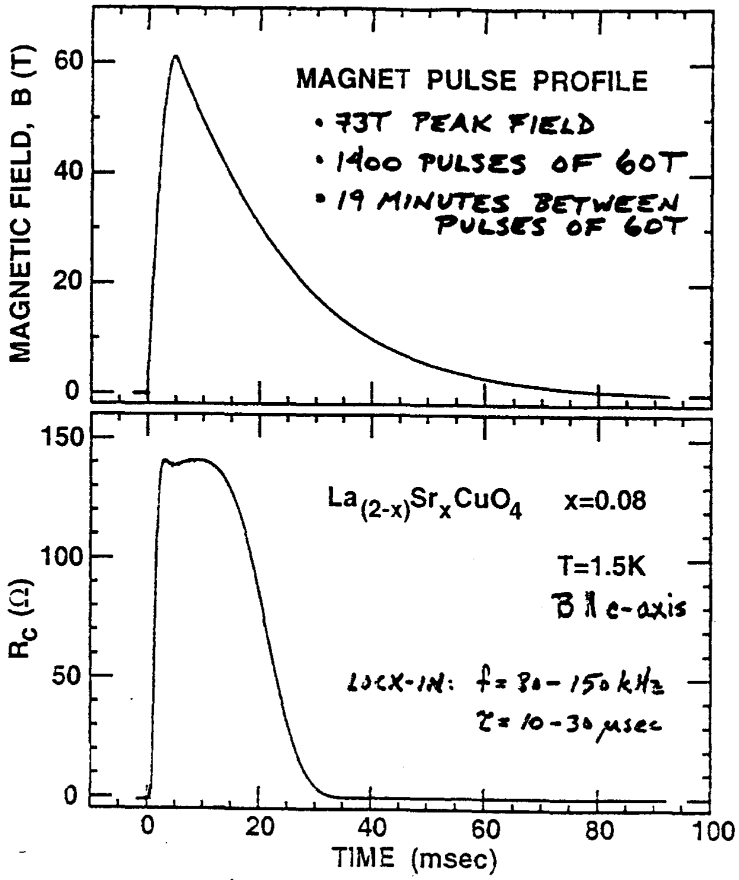


Samples for out-of-plane resistivity measurement

ρ_c

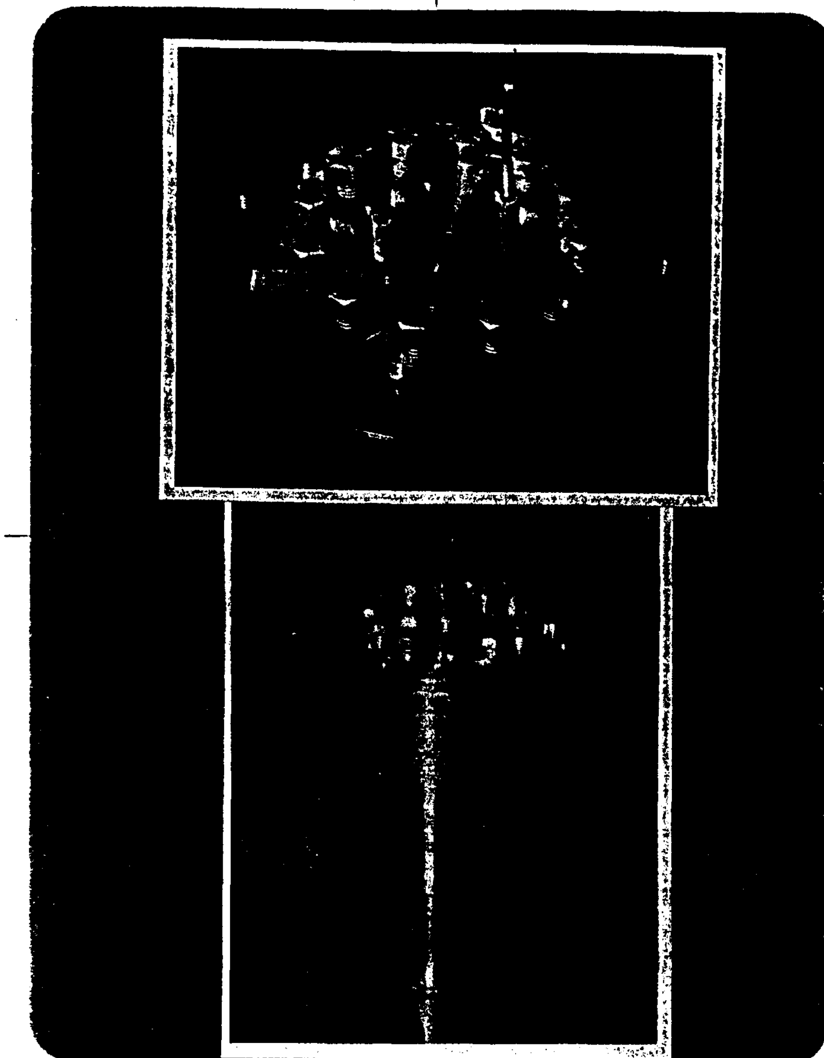


FOR LSCO, $\frac{\rho_c}{\rho_{ab}} \sim 10^3$



VG. NO.

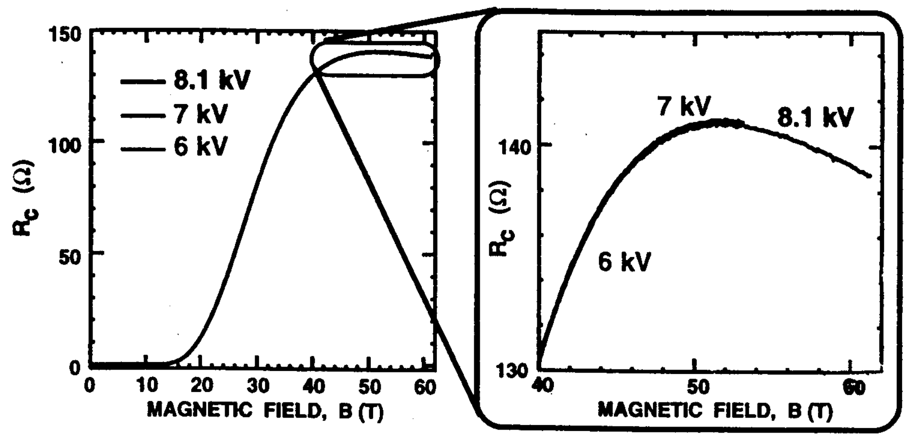
TOP
DO NOT AFFIX OVERLAYS ALONG THIS SURFACE



72 TESLA

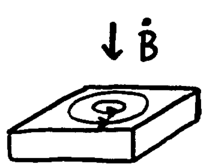
RULING OUT SAMPLE HEATING DURING THE MAGNET PULSE

$La_{(2-x)}Sr_xCuO_4$ (x = 0.08) at T = 1.5 K



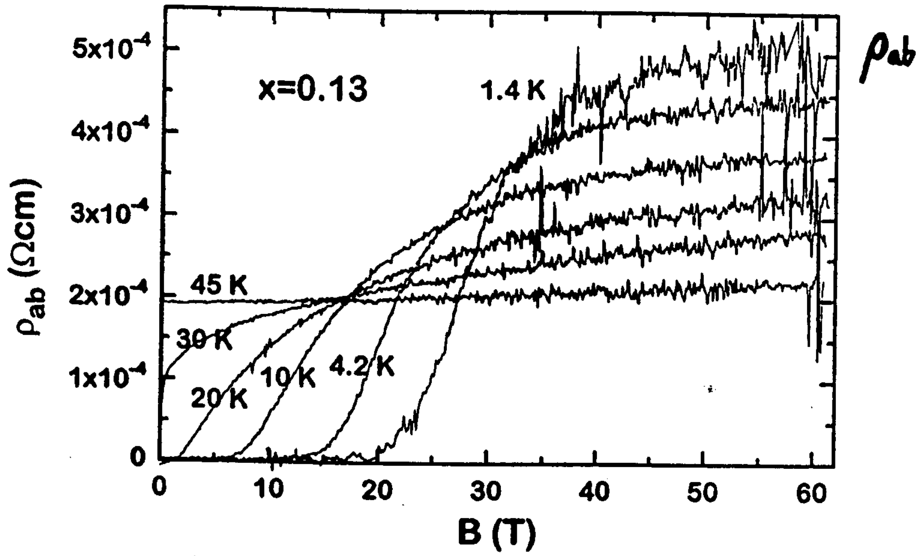
Eddy-current-heating is proportional to $(dB/dt)^2$

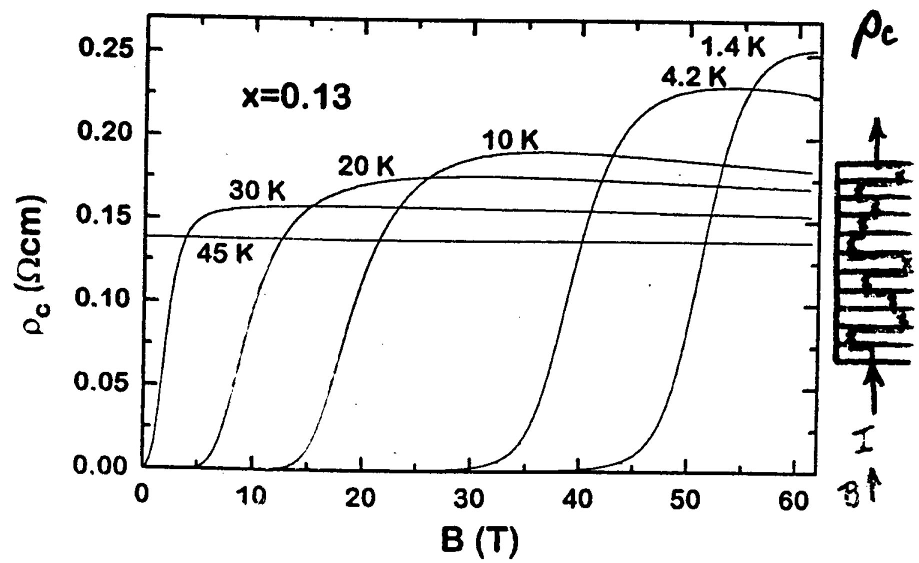
and therefore proportional to $(\text{peak field})^2$

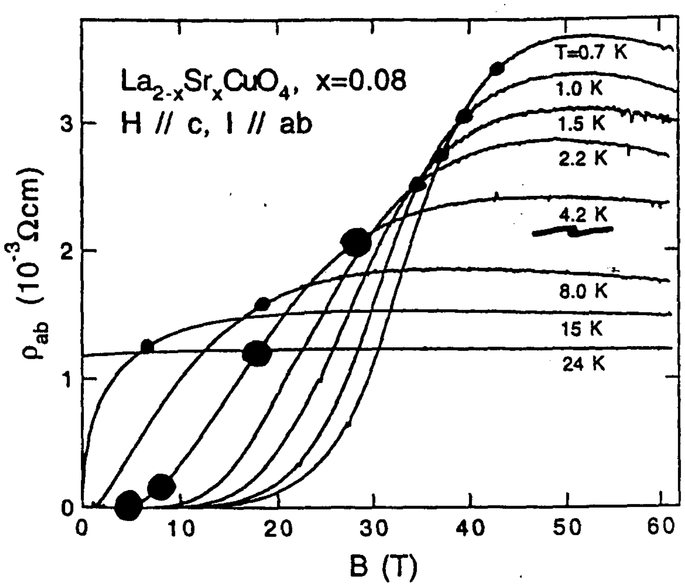


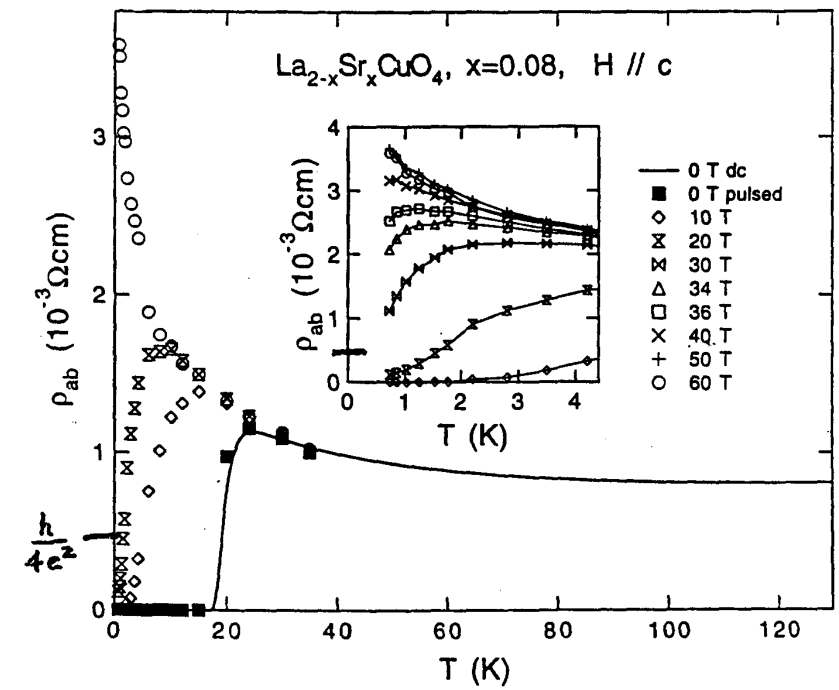
$\dot{Q} \propto \left(\frac{dB}{dt}\right)^2 \propto B_{max}^2$

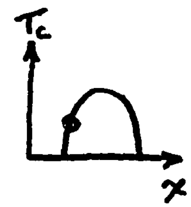
IS THE ρ_c GEOMETRY INADVERTANTLY MEASURING ρ_{ab}?



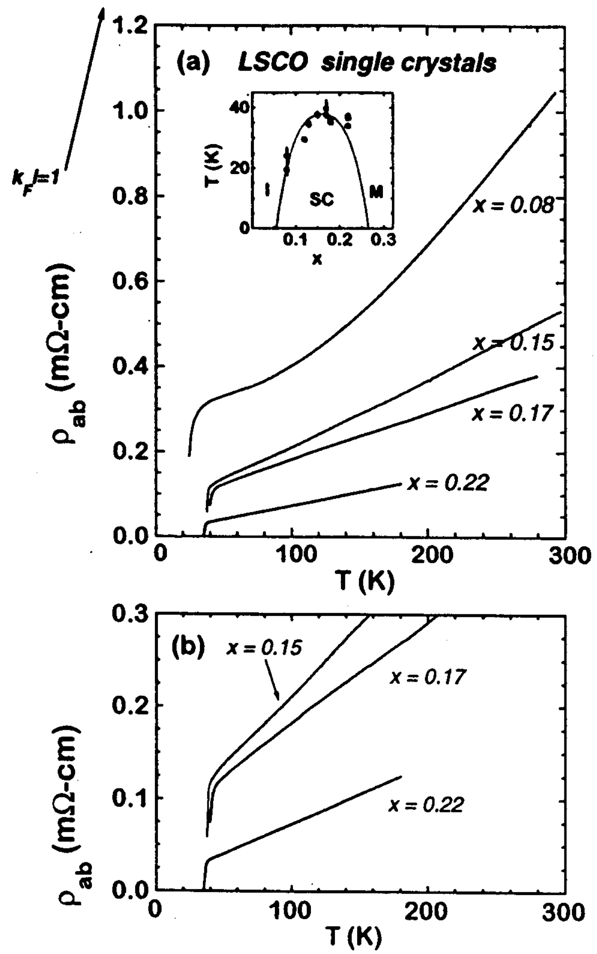



La$_{2-x}$Sr$_x$CuO$_4$, x=0.08
H // c, I // ab
T=0.7 K
1.0 K
1.5 K
2.2 K
4.2 K
8.0 K
15 K
24 K
ρ_{ab} ($10^{-3}\Omega$cm)
B (T)


La$_{2-x}$Sr$_x$CuO$_4$, x=0.08, H // c
ρ_{ab} ($10^{-3}\Omega$cm)
T (K)
0 T dc
0 T pulsed
10 T
20 T
30 T
34 T
36 T
40 T
50 T
60 T
$\frac{h}{4e^2}$

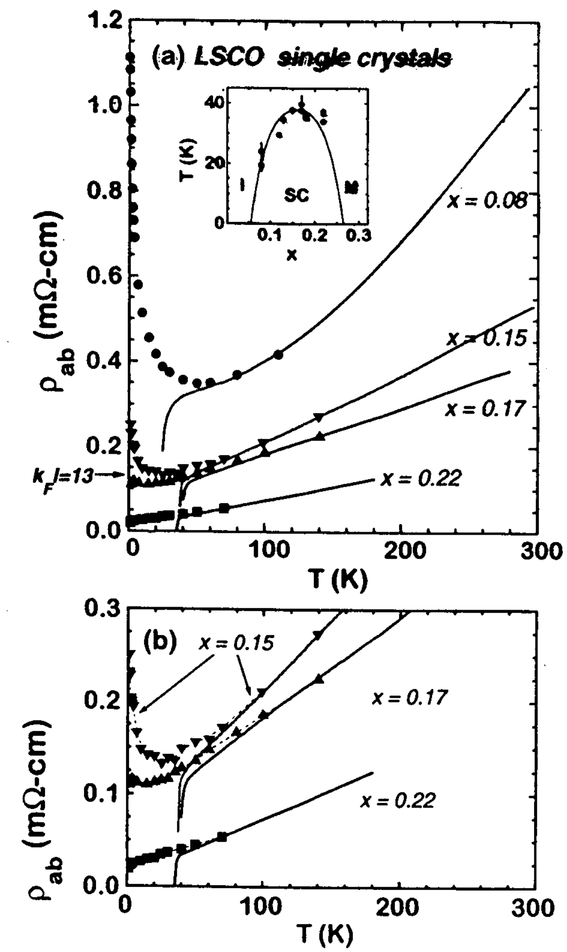

T_c
x

INSULATOR–TO–METAL CROSSOVER IN THE NORMAL STATE OF A HIGH-Tc SUPERCONDUCTOR



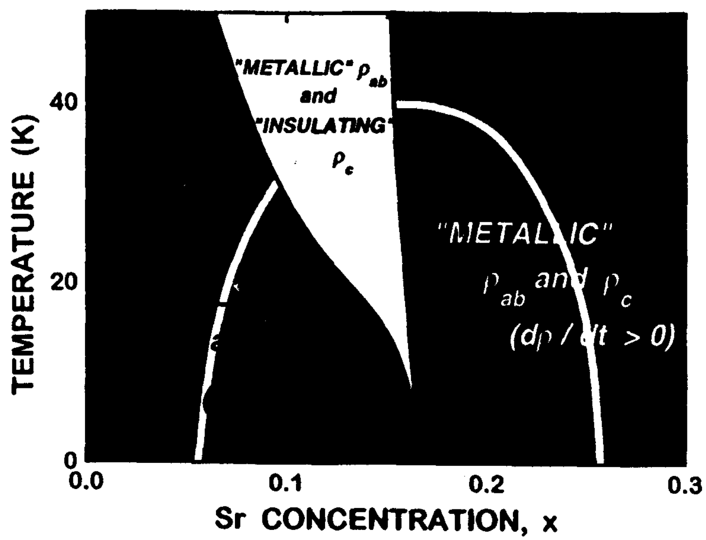
Boebinger, et al. PRL 77, 5417 (1996)

INSULATOR–TO–METAL CROSSOVER IN THE NORMAL STATE OF A HIGH-Tc SUPERCONDUCTOR



Boebinger, et al. PRL 77, 5417 (1996)

$La_{2-x}Sr_xCuO_4$



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

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

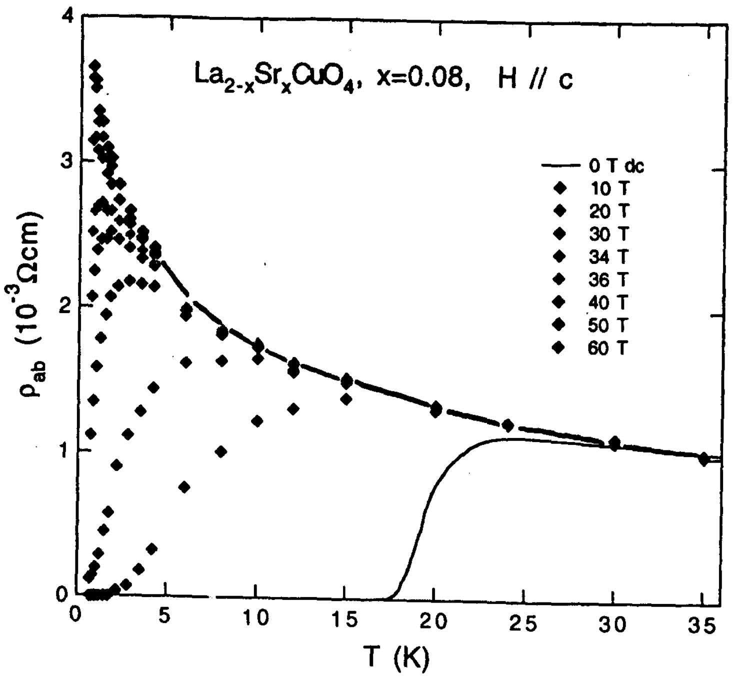
LSCO
Kenji Tamasaku
Noriya Ichikawa
Shin-ichi Uchida
SRC, U. of Tokyo

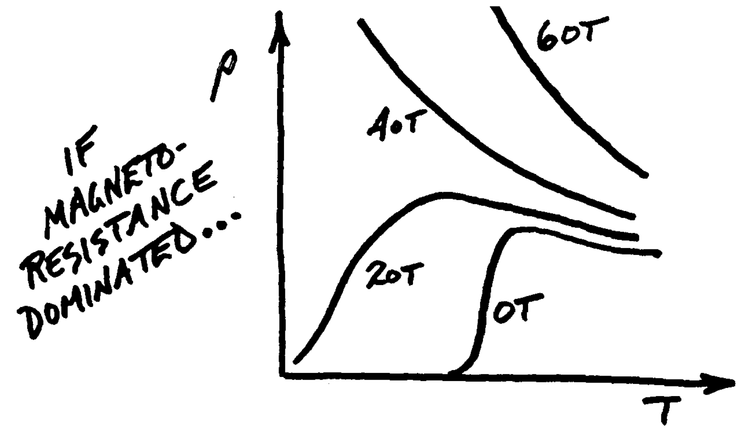
YBCO
Yoichi Ando
Kouji Segawa
CRIEPI, Tokyo

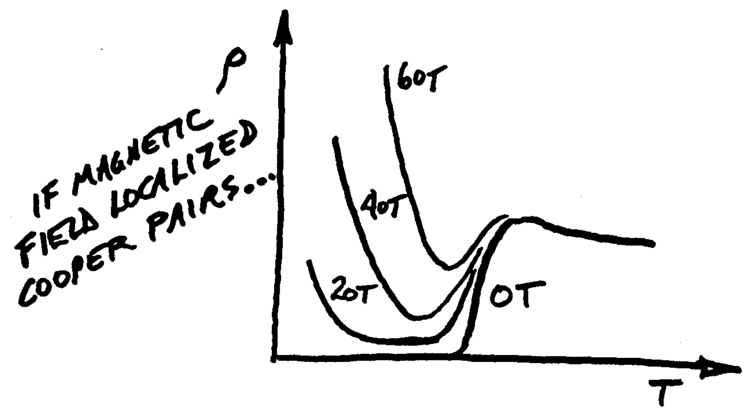
Bi-2201
Nan Lin Wang
Christoph Geibel
Frank Steglich
TH Darmstadt

Tl-2201
Andre Tyler
Andy Mackenzie
Birmingham University

LSCO, Nd-doped LSCO, and (SrCa)14 Cu24 O41
Naoki Motoyama
Hiroshi Eisaki
Kenji Tamasaku
Noriya Ichikawa
Shin-ichi Uchida
Department of Superconductivity, U. of Tokyo





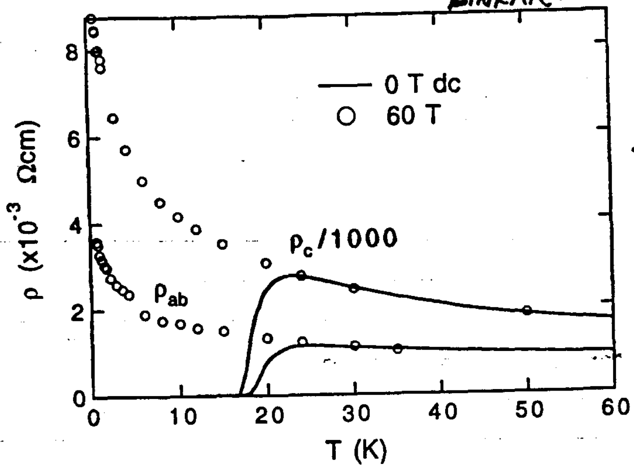


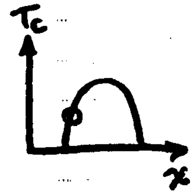
$$\rho_{ab}(T) = \rho_0 \ln\left(\frac{T_0}{T}\right)$$

ANDO, et al PRL 75 4... (1995)

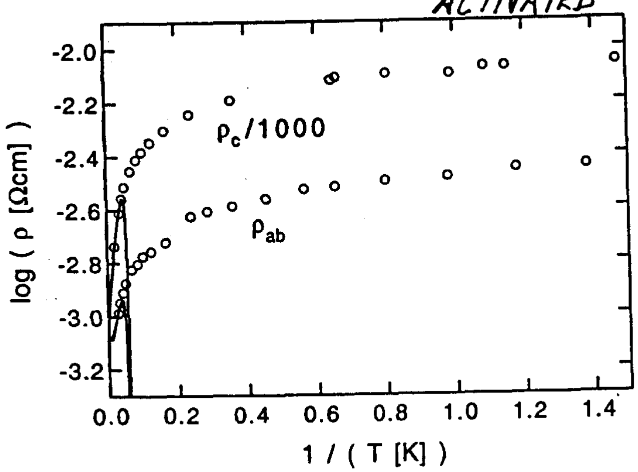
(33)

LINEAR



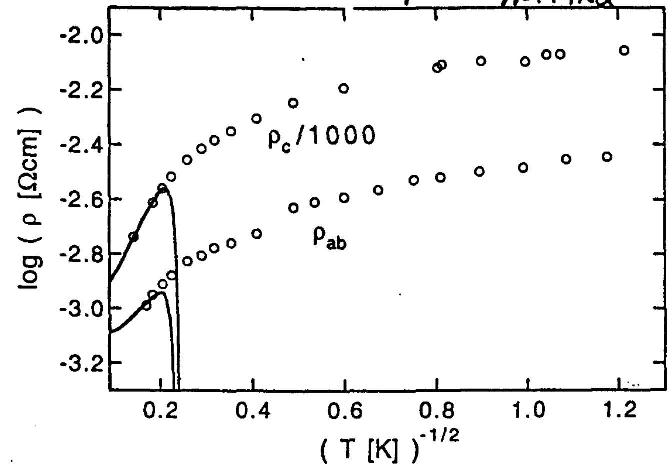


ACTIVATED

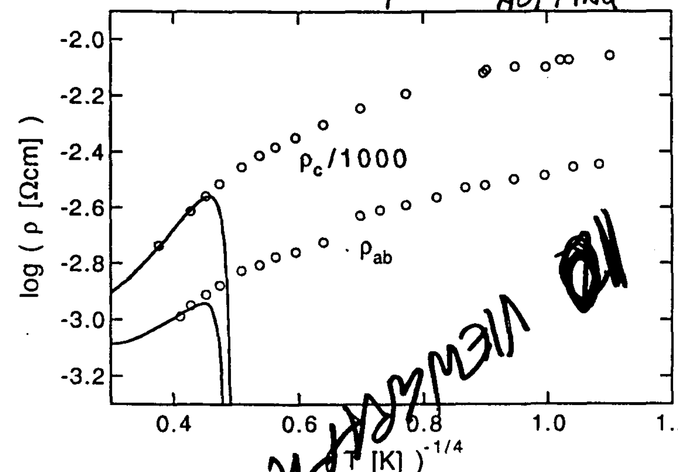


(34)

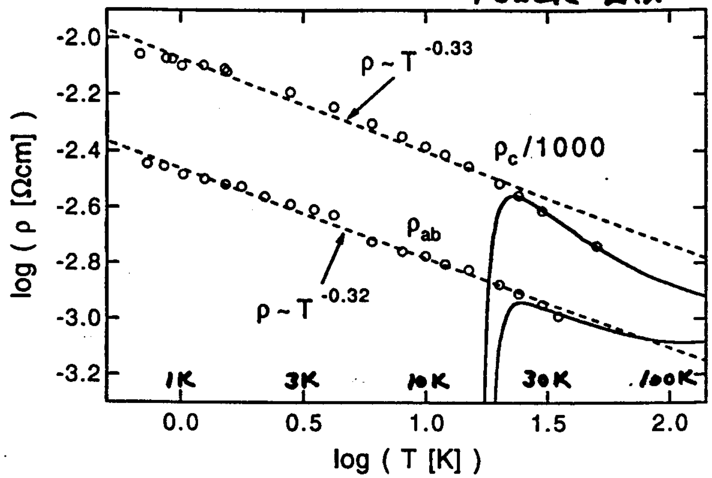
$T^{1/2}$ HOPPING



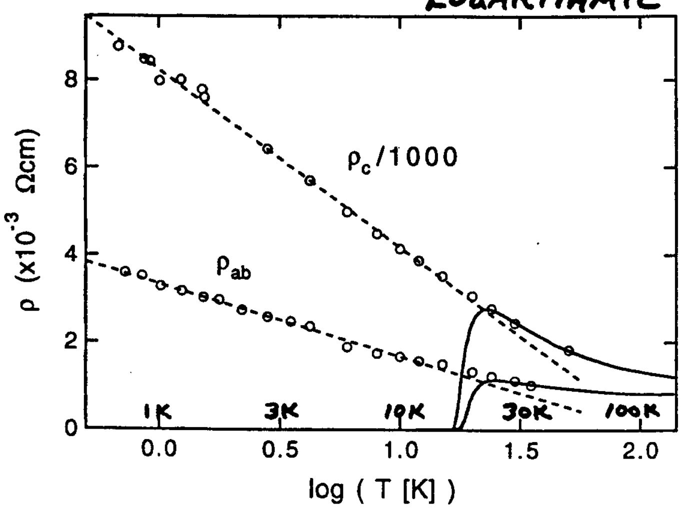
$T^{1/4}$ HOPPING

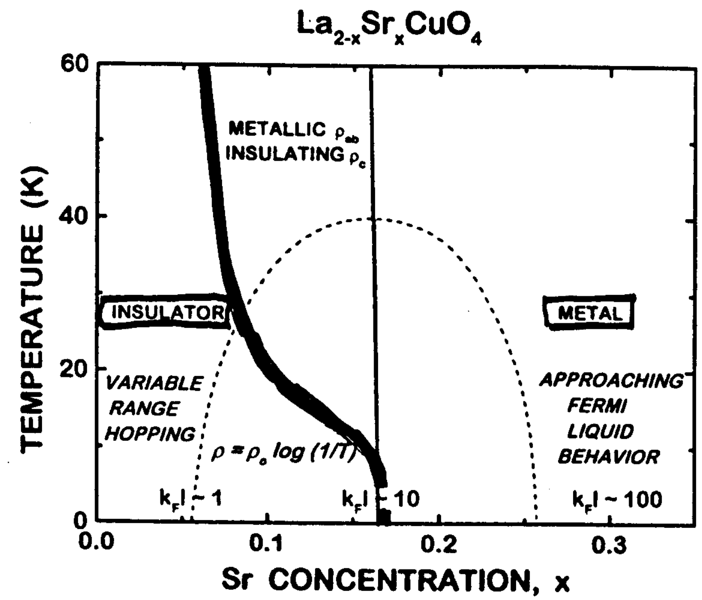


POWER LAW



LOGARITHMIC

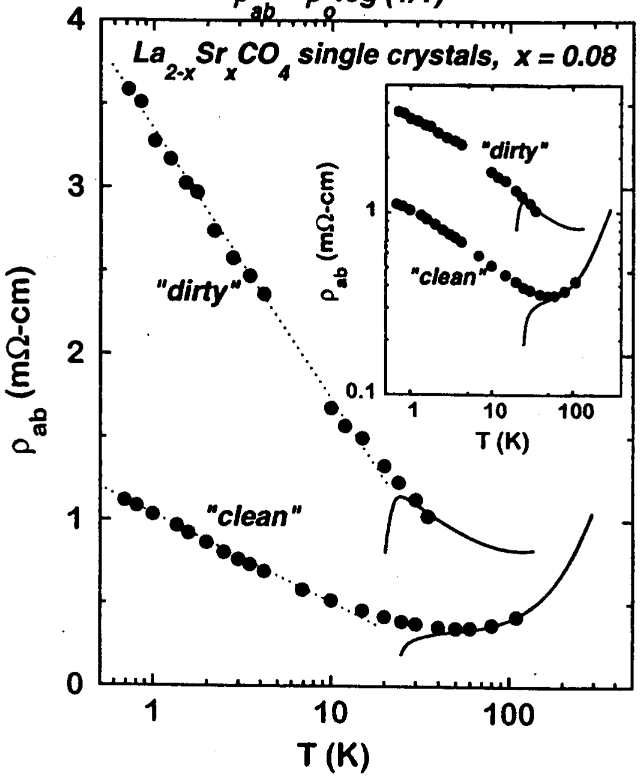




PHASE DIAGRAM WITH SUPERCONDUCTIVITY SUPPRESSED

THE UNDERDOPED NORMAL STATE IS A STRANGE INSULATOR

$\rho_{ab} \sim \rho_o \log(1/T)$

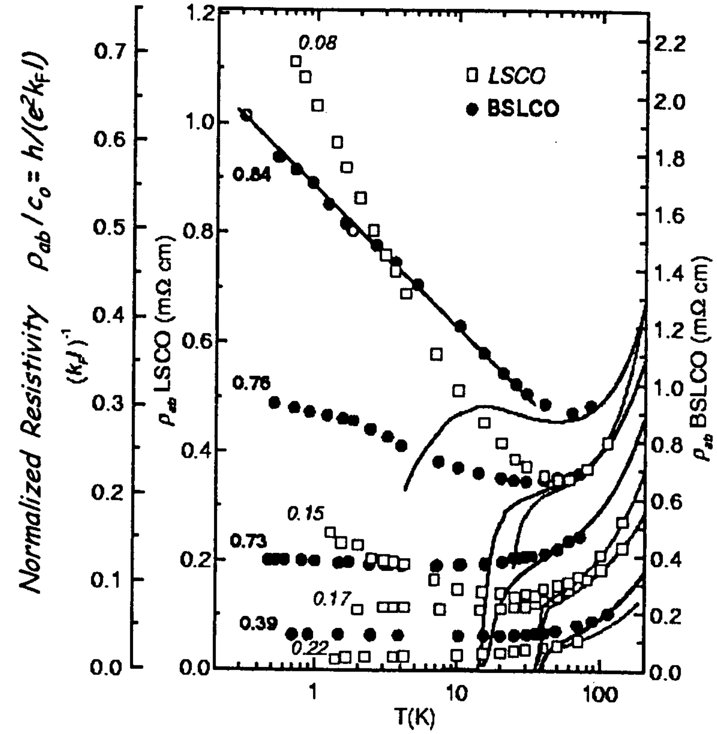


Ando, et al, PRL 75, 4662 (1995)
Ando, et al, Proc. of MOS Conf. (Karlsruhe, 1996)

INSULATING BEHAVIOR IN THE UNDERDOPED NORMAL STATE ARISES FROM LOCALIZATION – Beschoten, et al, PRL 77, 1837 (1996)

ONO, et al PRL 85 (2000) 638

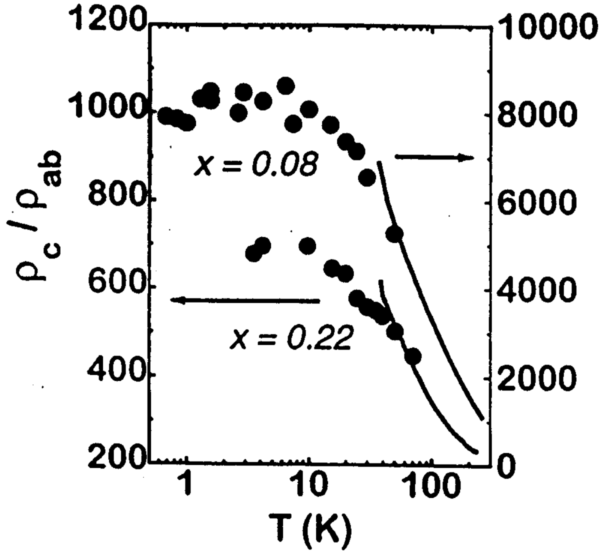
Comparing $Bi_2Sr_{2-x}La_xCuO_{6+\delta}$ and $La_{2-x}Sr_xCuO_4$



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

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.

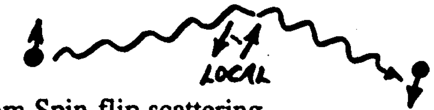
$\frac{\rho_c}{\rho_a} \rightarrow$ CONSTANT AS $T \rightarrow 0$



THE SAME LOGARITHMIC DEPENDENCE IN ρ_{ab} AND ρ_c

WHAT IT IS NOT

<u>Kondo effect</u>



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

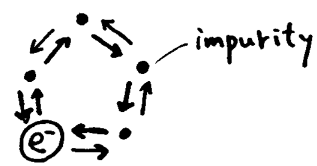
✗ No spin-flip below $k_BT \sim g\mu_B B$.

60-T magnetic field ⇒ $k_BT < 40$ K

EXPECT SATURATED ρ AT LOW T

<u>Weak Anderson Localization</u>

ln(1/T) dependence in σ



✗ No coherent back scattering in 60 T

✗ Plot of σ vs ln*T* is not linear

✗ Same ln(1/T) behavior for ρ_c

Ong's group also finds inconsistencies with conventional 2D weak localization in Bi-2201.
[T. W. Jiang et al., PRL 67, 761 (1991)]

Electron-electron Interaction Effect — Altshuler, et al PRL 44 1288 ('80)

Electron-electron interaction in 2D system also leads to

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

where α' is a constant of order 1 and $\sigma_1 = e^2/\pi h$.

Origin of this correction : modification of 2D DOS

⇒ If ρ_c is determined by tunneling between 2D systems, ρ_c may show the same T-dependence as ρ_{ab}.

- For our data, the plot of σ 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)

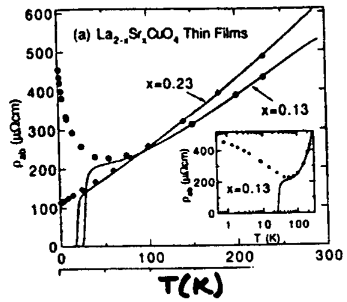
...DISORDER-ENHANCED e^--e^- INTERACTIONS

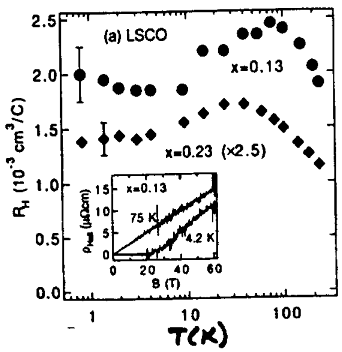
Log-(1/T) divergence is large and in resistivity
First-order perturbation finds a small correction
Log-(1/T) divergence not observed in Hall coefficient
PRB 56 R8530 (1997)

...SPIN-FLIP KONDO SCATTERING

No spin-flip scattering in 60 teslas for T<60K

(43)

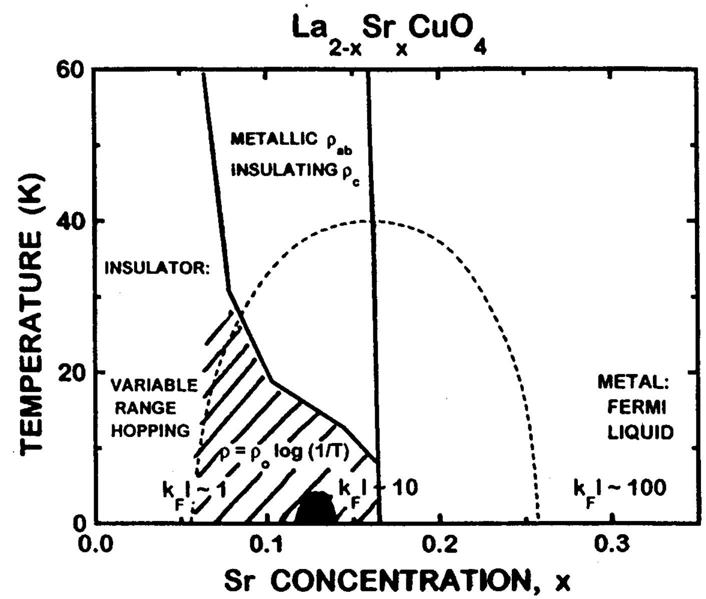




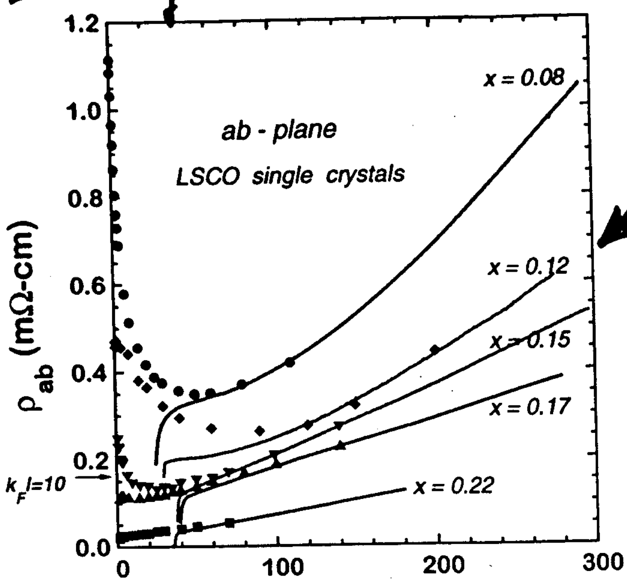
Ando, et al PRB 56 R8530 (1997)

R_H becomes nearly T-independent at low-T REGARDLESS of whether ρ_{ab} is insulating or not

(44)



//// = BOTH ρ_{ab} AND ρ_c FOLLOW LOG (1/T) BEHAVIOR log (1/T) IS NOT AN x = 1/8 ANOMALY



MODULATED SPIN AND CHARGE DENSITIES
IN CUPRATE SUPERCONDUCTORS

TRANQUADA, Physica B 241-243 (1998) 745

"STRIPES"

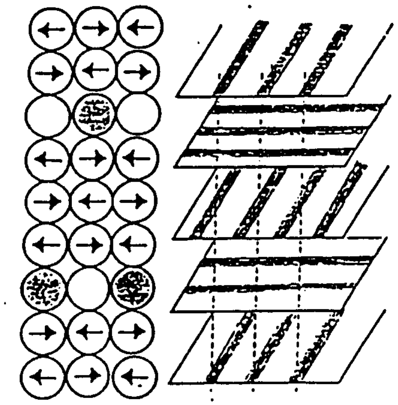
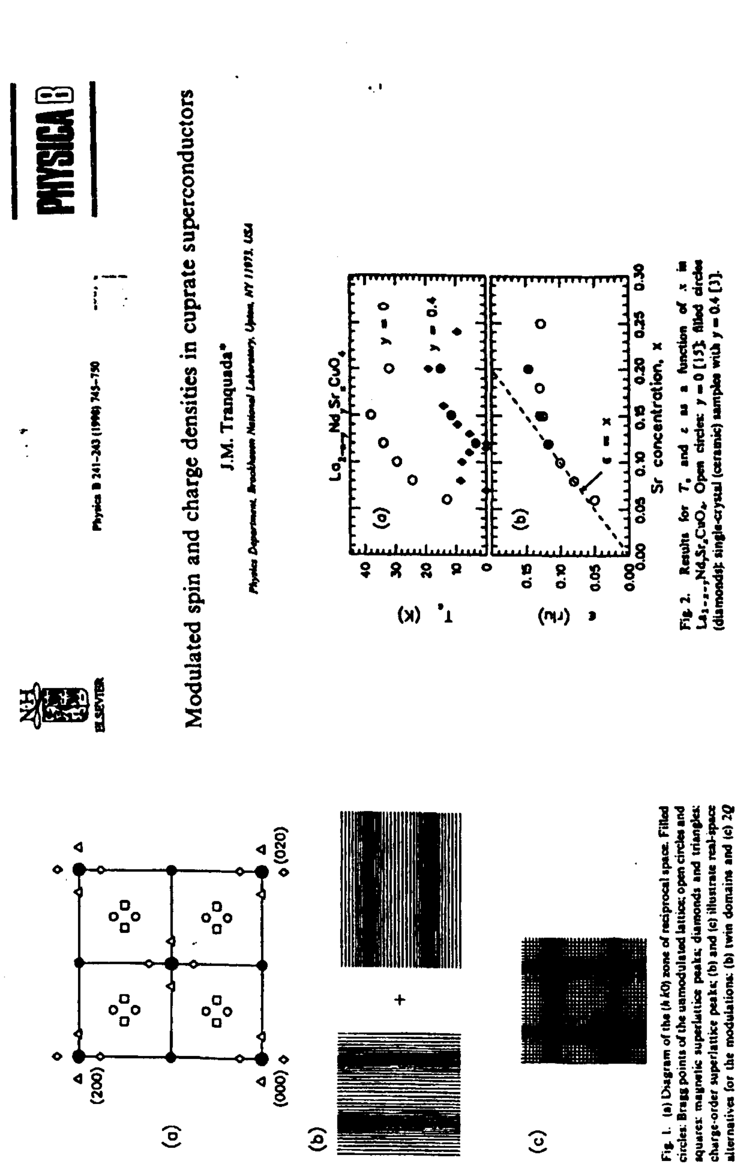


Fig.1 A model of spin and charge stripes in the CuO_2 planes corresponding to $\epsilon = 1/8$. The Cu ions are represented by circles (not shown are the oxygen ions). The holes occupy every other Cu site on the charge stripe which separates regions of the AF ordered spin domains. A possible stacking of the stripe ordered CuO_2 planes is also shown.

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


PHYSICA B

Physica B 241-243 (1998) 745-750

Modulated spin and charge densities in cuprate superconductors

J.M. Tranquada*

Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA

Fig. 1. (a) Diagram of the (h k0) zone of reciprocal space. Filled circles: Bragg points of the unmodulated lattice; open circles and squares: magnetic superlattice peaks; diamonds and triangles: charge-order superlattice peaks; (b) and (c) illustrate real-space alternatives for the modulations: (b) twin domains and (c) 2Q structure.

Fig. 2. Results for T_c and ϵ as a function of x in $La_{2-x-y}Nd_ySr_xCuO_4$. Open circles: $y = 0$ [15]; filled circles (diamonds): single-crystal (ceramic) samples with $y = 0.4$ [3].

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

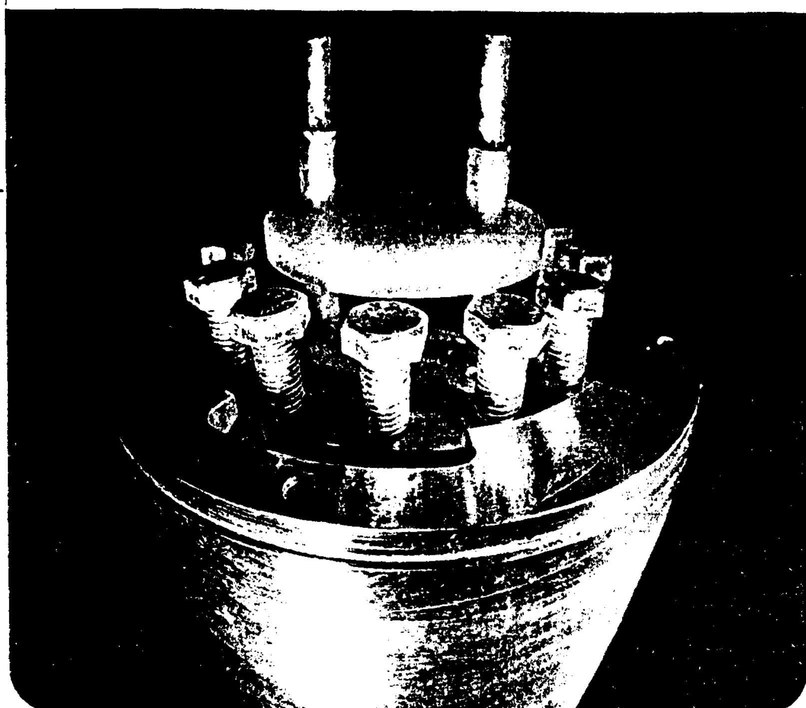
(49) X

Building World-Record Magnets

Packing the energy equivalent of a stick of dynamite, powerful electromagnets around the globe compete to advance our knowledge of materials science and physics

by Greg Boebinger, Al Passner and Joze Bevk

SCIENTIFIC AMERICAN, JUNE 1995



AT&T

E-9148 (6-85)
AT&T BELL LABORATORIES

(50)

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)

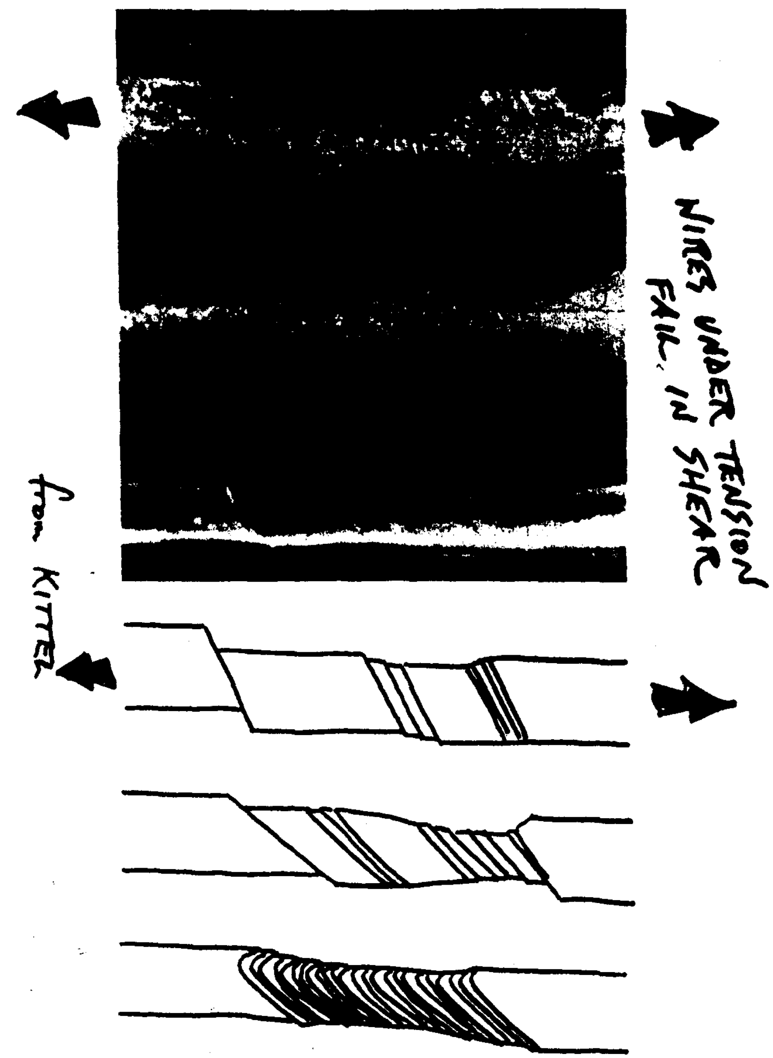
730,000 gauss OUR PULSED MAGNETS

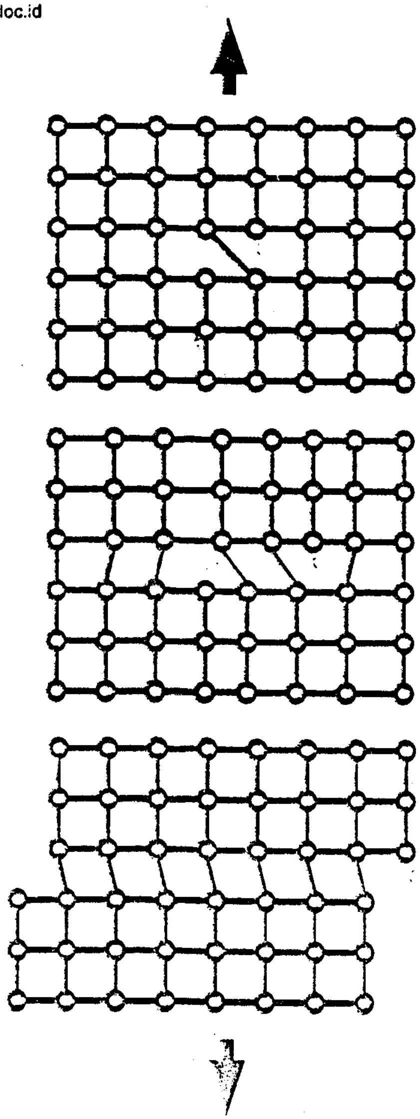
PRESSURES----HOW BIG IS BIG ?

UNDER WATER

4 meters	EARS	6 psi
700 meters	SUBMARINE	1000 psi
4000 meters	OCEAN FLOOR	6000 psi

OUR PULSED MAGNETS	200,000 psi

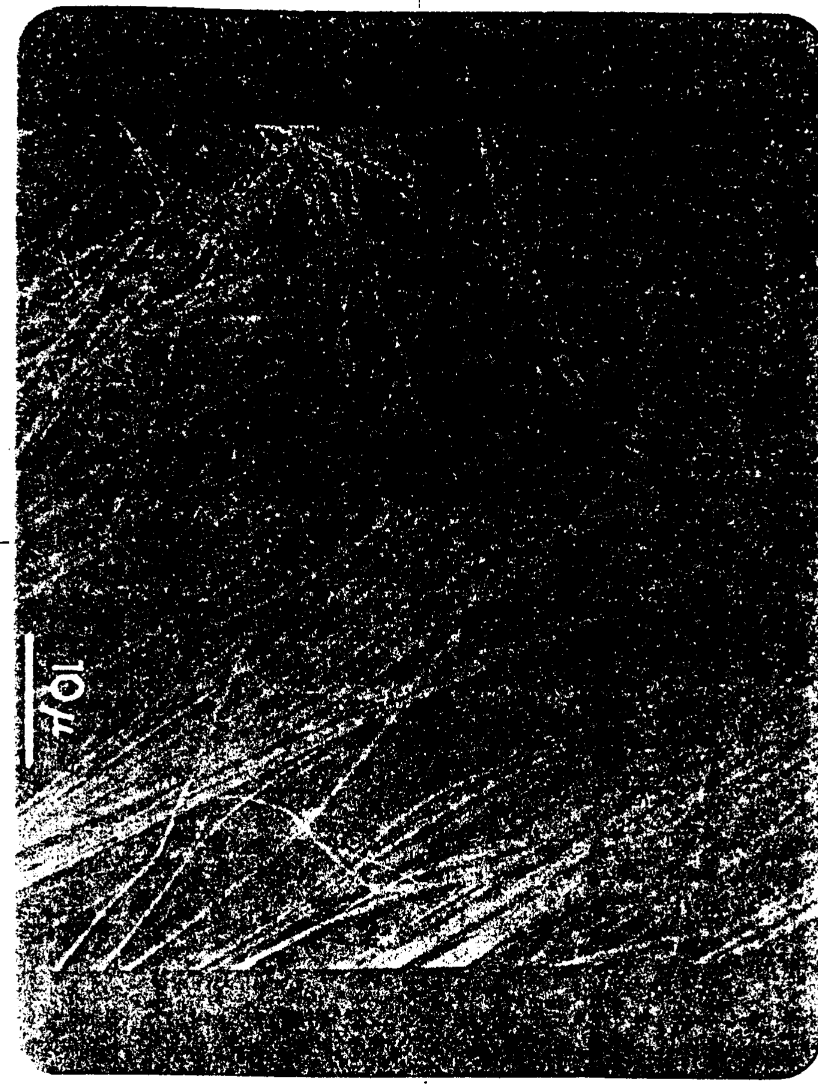




NUCLEATION of DISLOCATION PAIR

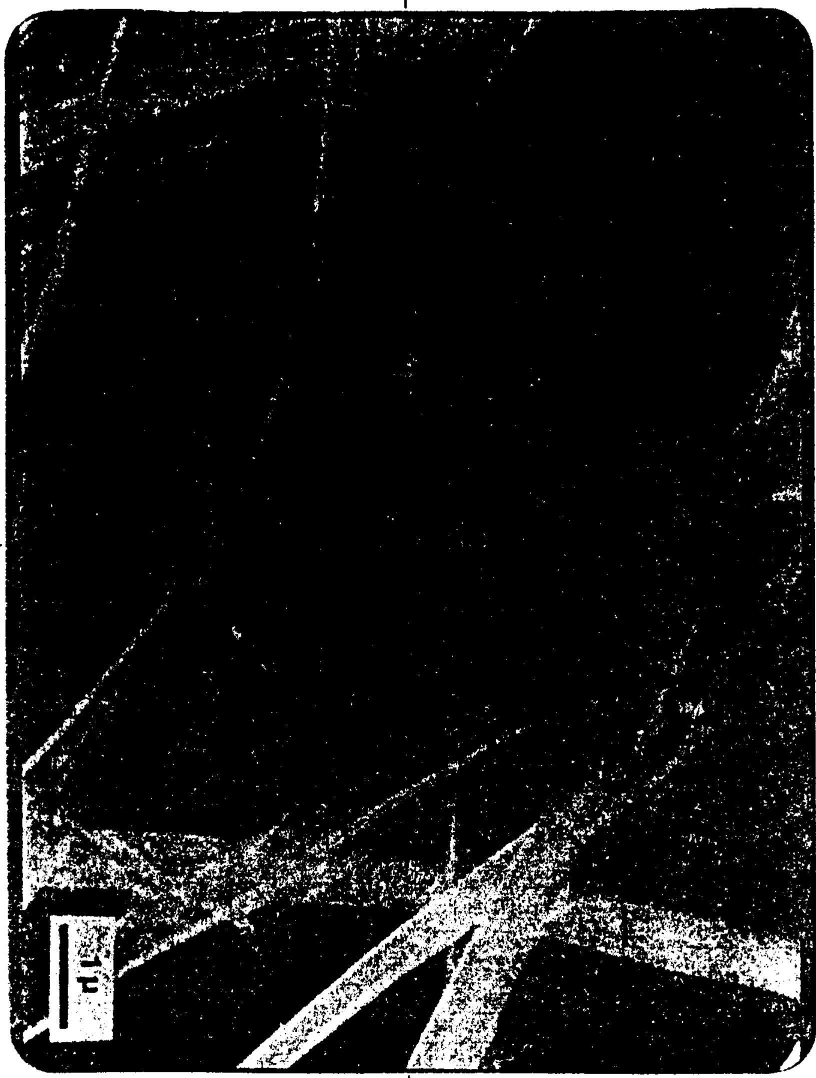
SIMPLE MOTION of ONE DISLOCATION

PROPAGATION to the SURFACES



(55)

E 9148 (6 85)
AT&T BELL LABORATORIES



TOP
DO NOT AFFIX OVERLAYS ALONG THIS SURFACE

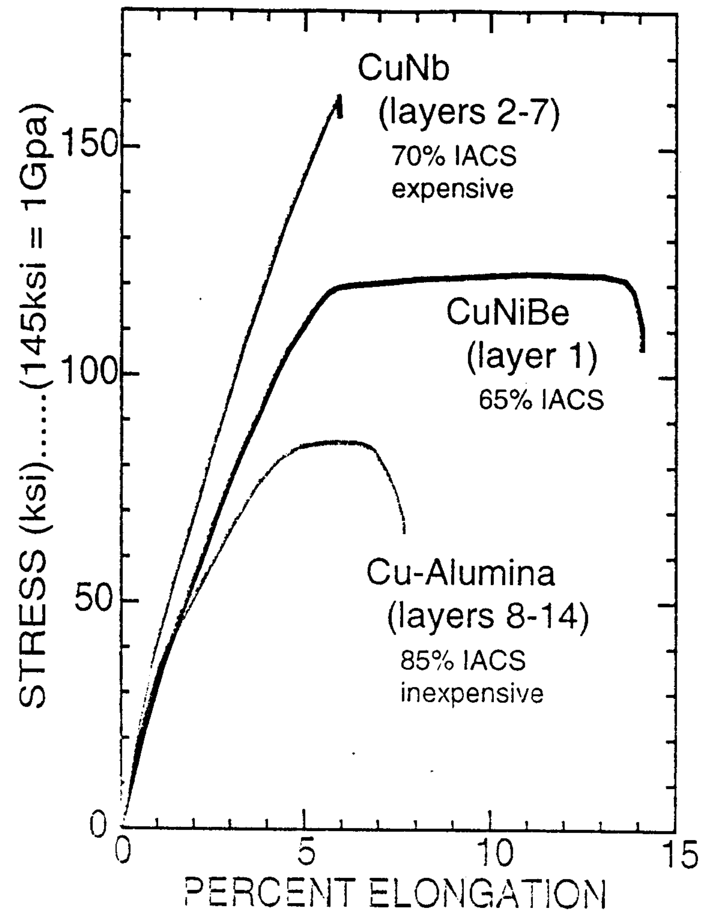
VG. NO.

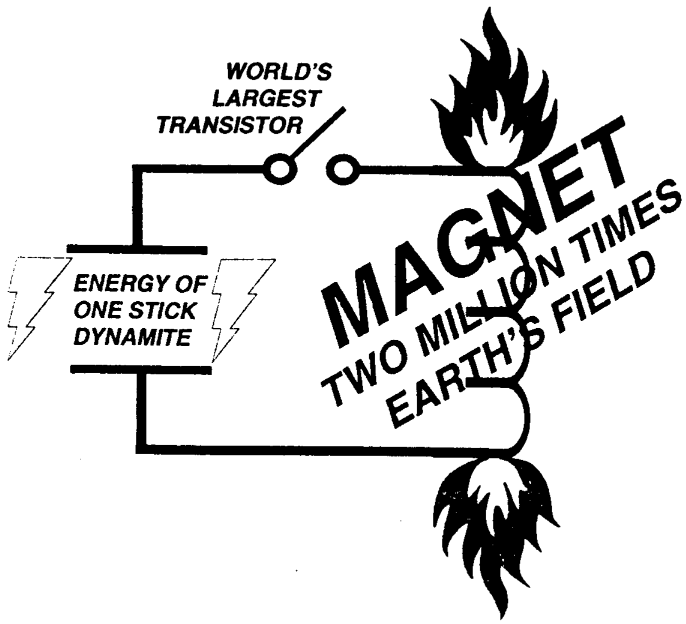
AT&T

wstress.id

(56)

CONDUCTORS

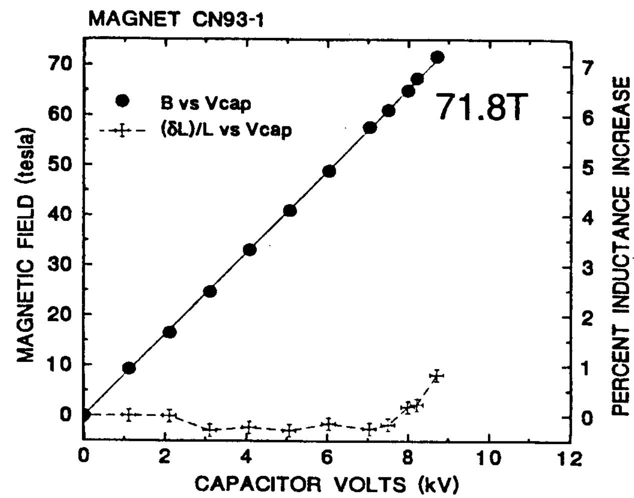


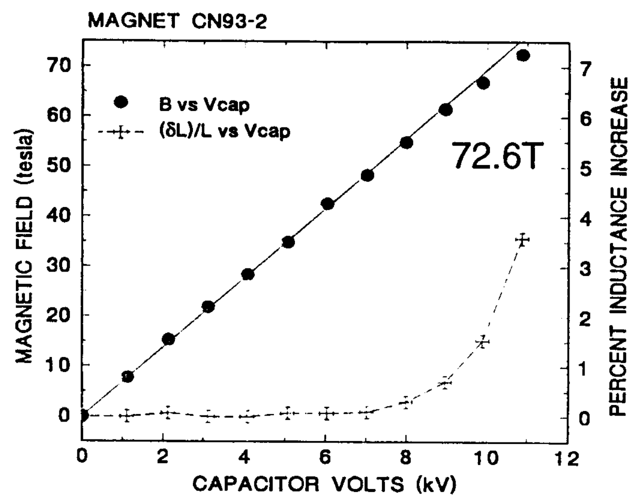


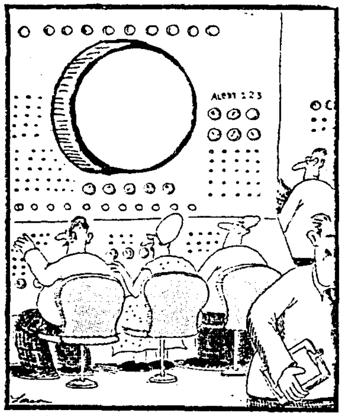
DETECT Ti 71T AT A FIELD -10% TO -15% FROM PEAK FIELD

MAGNET TRAINING

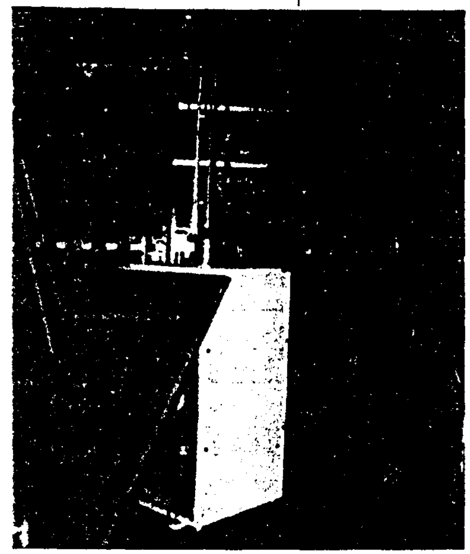
MAGNET INDUCTANCE MONITORED WHILE SLOWLY INCREASING PEAK MAGNETIC FIELD





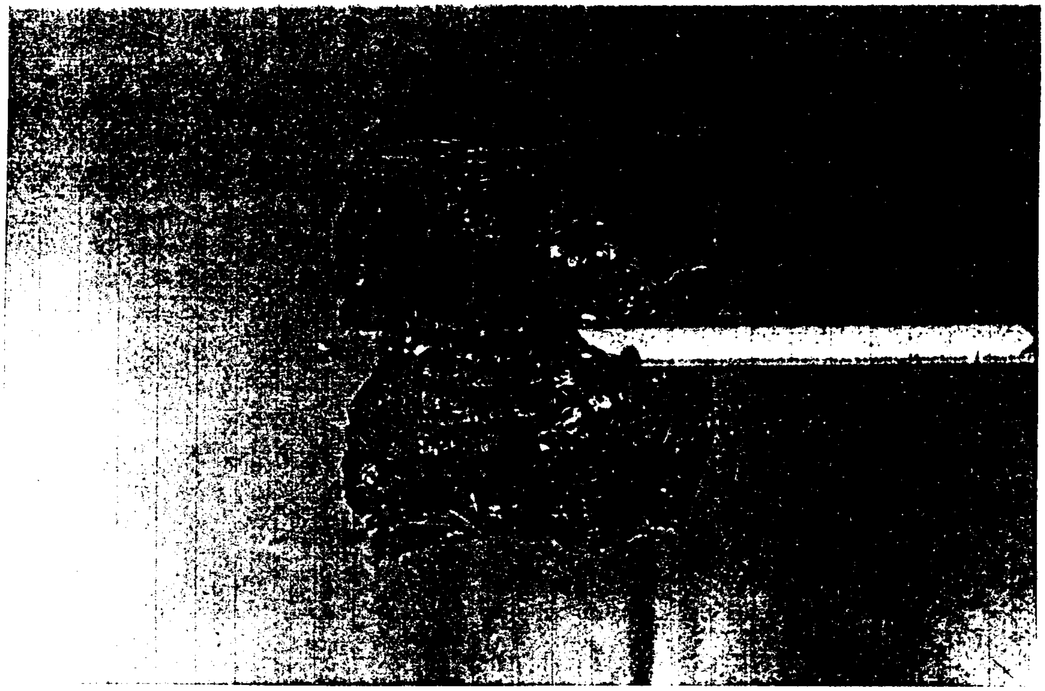


One day, Frank knew, he was just going to have to push that big button.



DO NOT AFFIX OVERLAYS ALONG THIS SURFACE

VG. NO.



(61)

E 9148 (6-85)
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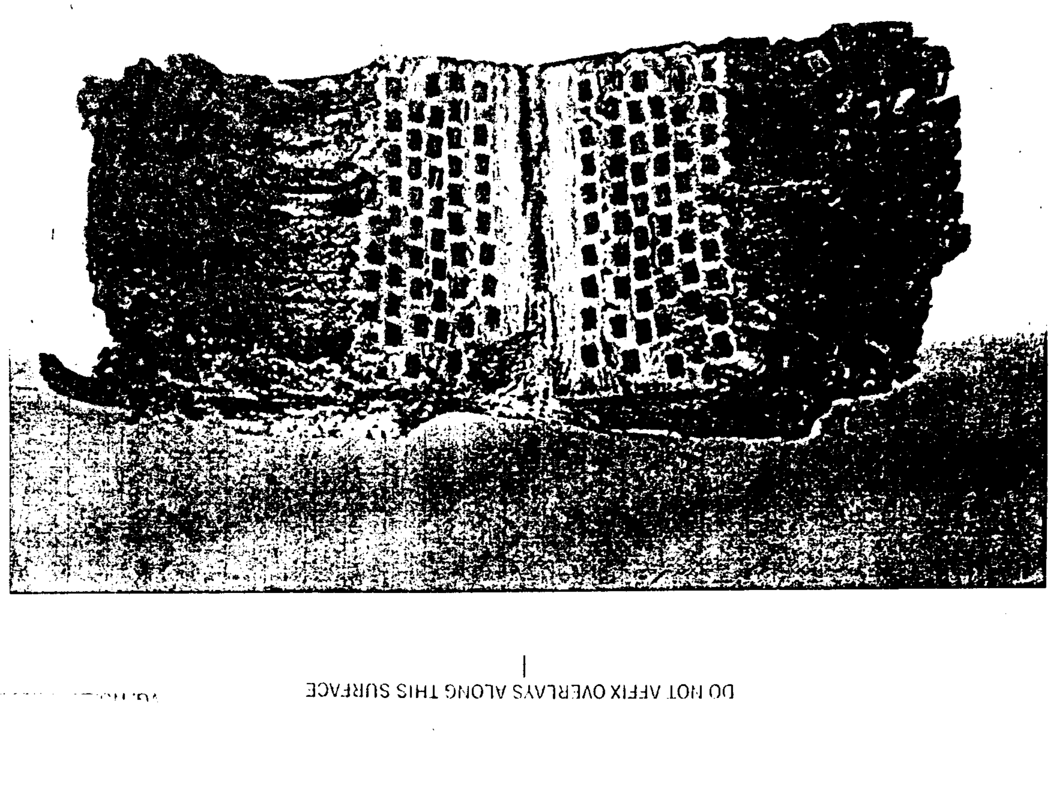


(62)

DO NOT AFFIX OVERLAYS ALONG THIS SURFACE

RESISTIVITY OF THE 2-LEG LADDER COMPOUND $Sr_2Ca_{12}Cu_{24}O_{41}$

... IN HIGH MAGNETIC FIELDS (UP TO 400mG)

FEDOR BALAKIREV, BELL LABS AND LANL

JON BETTS, LANL

NAOKI MOTOYAMA
HIROSHI EISAKI
SHIN-ICHI UCHIDA
} UNIV. OF TOKYO

cond mat 9808284

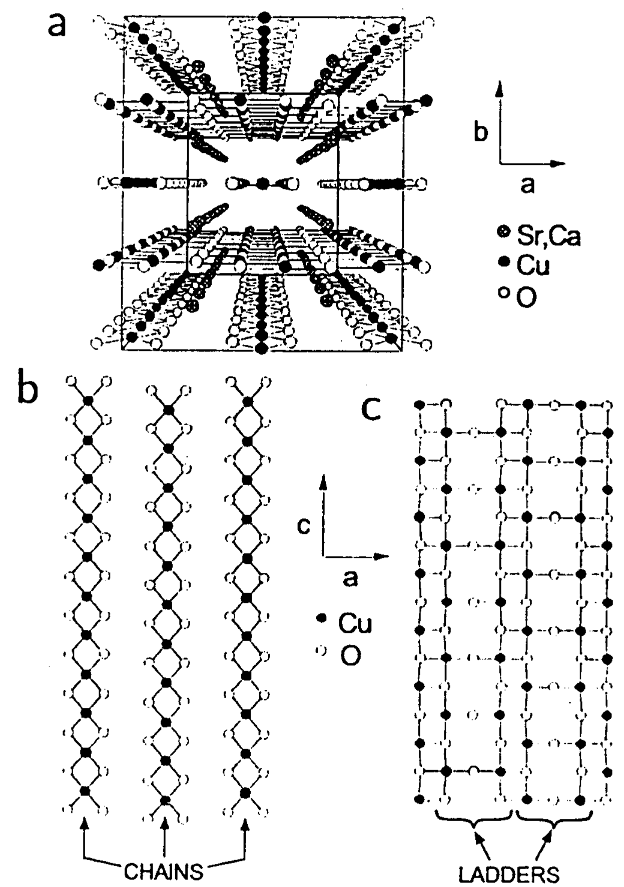


FIG. 1. a, The crystal structure for $(Sr,Ca)_{14}Cu_{24}O_{41}$, including b, the plane containing CuO_2 chains and c, the plane containing Cu_2O_3 ladders.

65

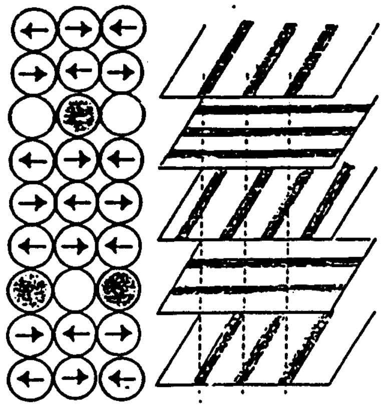
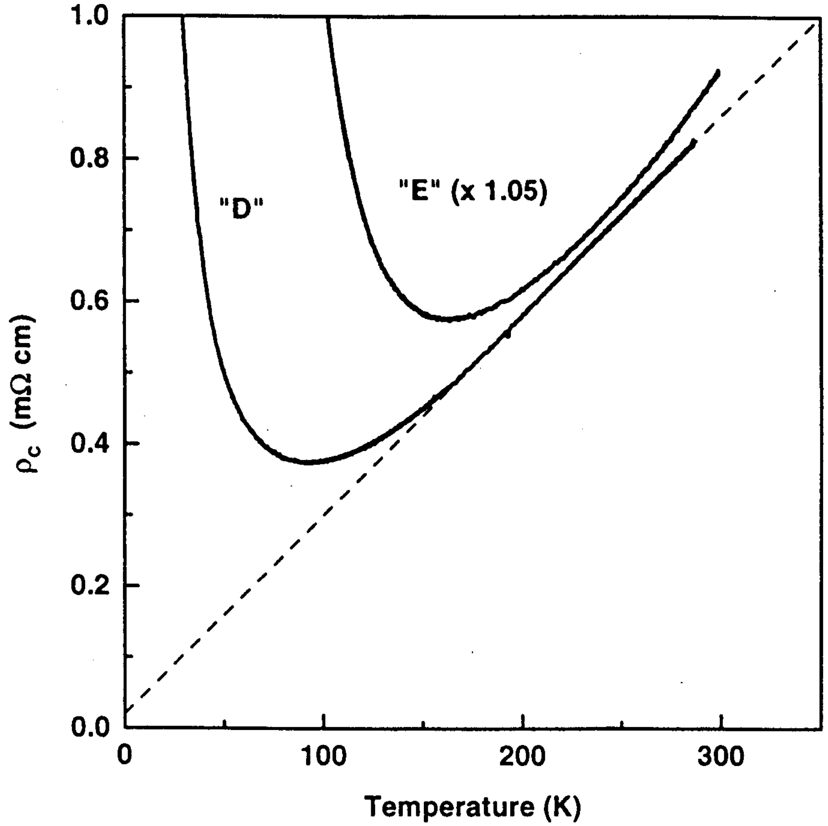


Fig.1 A model of spin and charge stripes in the CuO_2 planes corresponding to $\epsilon = 1/8$. The Cu ions are represented by circles (not shown are the oxygen ions). The holes occupy every other Cu site on the charge stripe which separates regions of the AF ordered spin domains. A possible stacking of the stripe ordered CuO_2 planes is also shown.

METALLIC BEHAVIOR $\rho \sim T$ 66

(JUST LIKE IN THE CUPRATES)



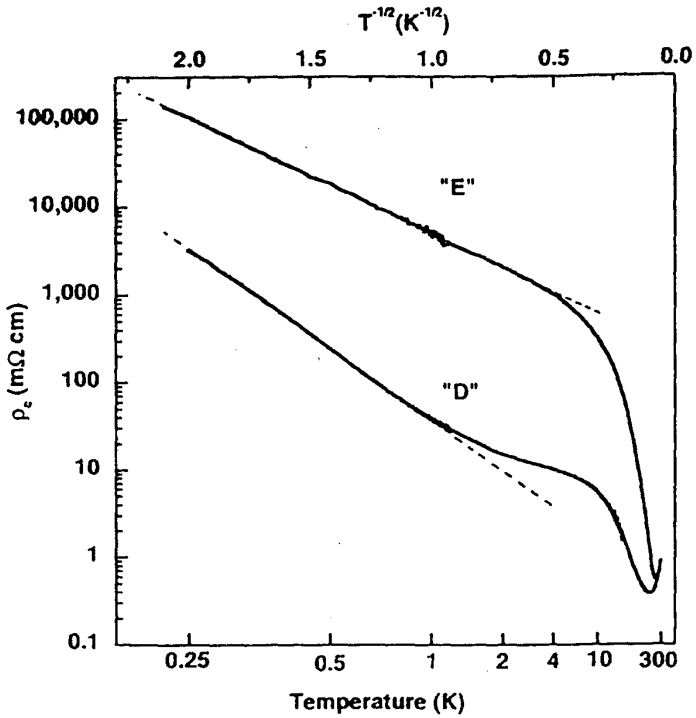


FIG. 3. Variable range hopping (dashed lines) in the lowest temperature range for both samples.

Observation of a Well Defined Transition from Weak to Strong Localization in Two Dimensions

S.-Y. Hsu and J.M. Valles, Jr, PRL <u>74</u> 2331 (1995)

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 $\rho = \pi h/e^2$ $(k_F l^* = 1/\pi)$
marked by magneto-resistance changing sign

VOLUME 74, NUMBER 12 PHYSICAL REV

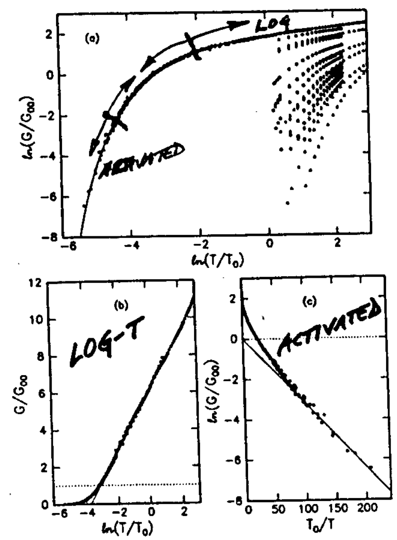
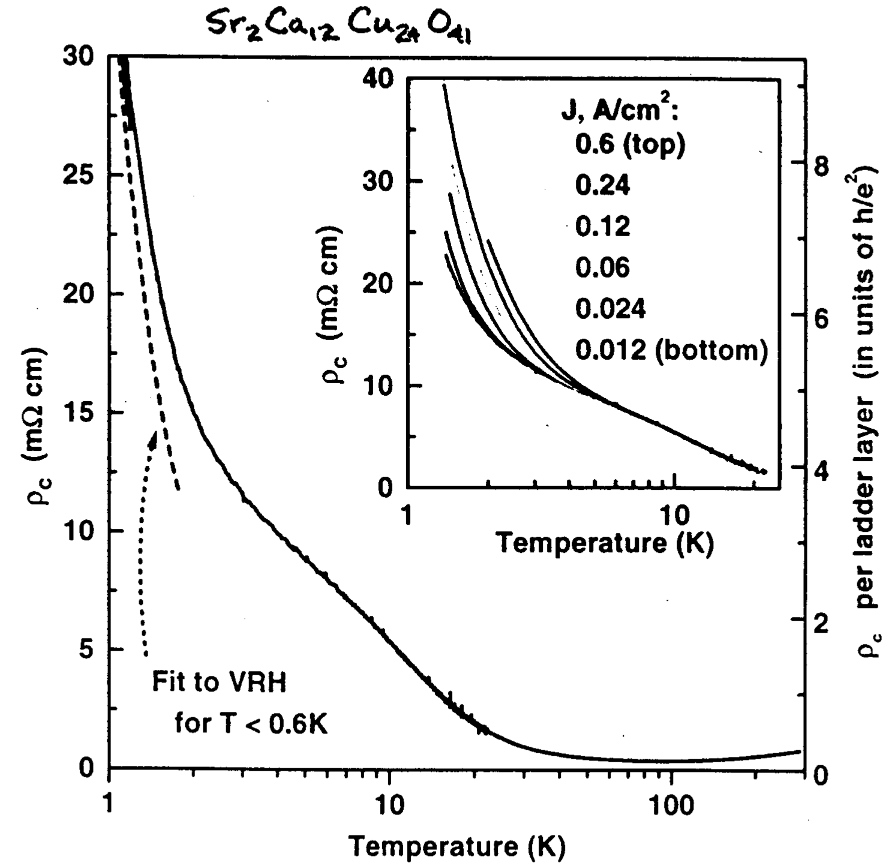


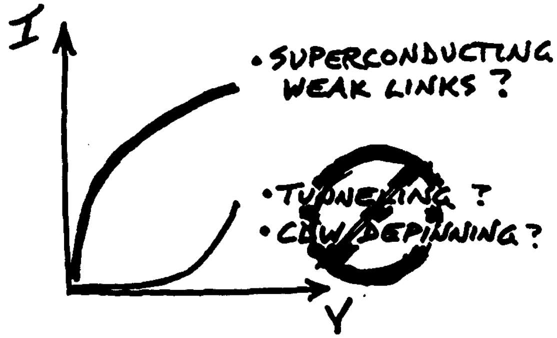
FIG. 1. (a) Sheet conductance in units of $G_{00} = e^2/2\pi^2\hbar$ versus temperature with $T_0 = 1$ K on logarithmic scales for Cu/Ge (circles), Ag/Ge (triangles), and Au/Ge (diamonds) films with thicknesses in the range $0.3 < t < 2$ nm. The solid curve and points on it were obtained by adjusting T_0 for each film described in Ref. [7]. (b) Semilogarithmic plot of G/G_{00} vs T^{-1} for the rescaled data. The line is a fit to the low G limit. (c) G/G_{00} vs $\ln(T)$ for the rescaled data. The line is a fit to the high G limit.

HSU & VALLES
PRL 74 2331 ('95)

SERIES OF THIN FILMS
Cu/Ge, Ag/Ge, Au/Ge



(71)



(72)

LOGARITHMIC DIVERGENCE IN GRANULAR SUPERCONDUCTOR

PHYSICAL REVIEW B VOLUME 36, NUMBER 4 1 AUGUST 1987

Transport measurements in granular niobium nitride cermet films

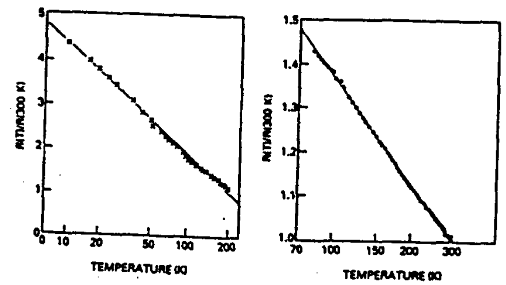
R. W. Simon,* B. J. Dalrymple,* D. Van Vechten, W. W. Fuller, and S. A. Wolf
Naval Research Laboratory, Washington, D.C. 20375

(Received 4 March 1987)

We have studied normal-state and superconducting transport properties in a granular cermet consisting of $B1$-structure NbN grains in a boron nitride insulating matrix. By varying the volume fraction of the two components we produced films (20–70 nm in thickness) that exhibited transport behavior in either of two distinct and mutually exclusive classes: "insulating" films with $\rho \sim \exp(-a/T^{1/2})$ which never went superconducting, and "superconducting" films with $\rho \sim \ln(T)$ from room temperature down to the superconducting transition. This latter logarithmic temperature dependence for the resistivity is also observed at low temperature when superconductivity is suppressed in high magnetic fields. Broad superconducting transitions are observed with a strong compositional dependence of the mean field critical temperature, T_{c0}. The Kosterlitz-Thouless two-dimensional (2D) topological phase transition at T_{2D} 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.

NbN GRAIN

INSULATING BORON NITRIDE MATRIX



← $R(T) \sim \log \frac{1}{T}$ TO 300 K

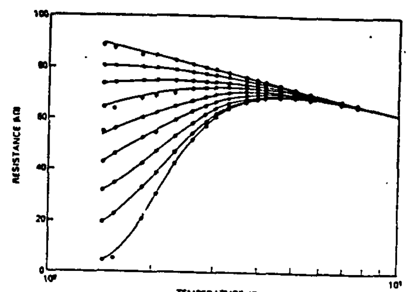
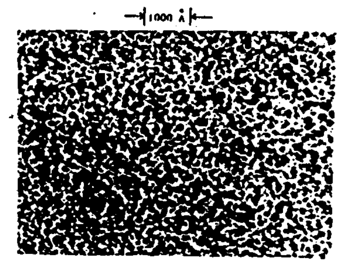


FIG. 11. The resistance as a function of temperature (plotted as $\ln T$) for a variety of magnetic fields with values of 0, 10, 20, 30, 40, 50, 60, 70, and 80 kG. Note that when the superconductivity has been quenched, the $\log_{10} T$ dependence seen at higher temperatures has been recovered. This sample had $R_{\square}(300\ K) = 2000\ \Omega/\square$.



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SUMMARY

60-TESLA PULSED MAGNETIC FIELDS
REVEAL THE NORMAL STATE PHASE DIAGRAM

Log-(1/T) divergence is large and in resistivity

IN THE CUPRATES
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