united nations
educational, scientific
and cultural
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international atomic
energy agency

the
abdus salam
international centre for theoretical physics

SMR 1232 - 31

XII WORKSHOP ON
STRONGLY CORRELATED ELECTRON SYSTEMS

17 - 28 July 2000

TRANSPORT MEASUREMENTS ON THE CUPRATES

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IRC in Superconductivity
University of Cambridge
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These are preliminary lecture notes, intended only for distribution to participants.

(SOME) TRANSPORT PROPERTIES OF CUPRATES

J. R. Cooper, IRC in Superconductivity
and Department of Physics, University of Cambridge.

PLAN

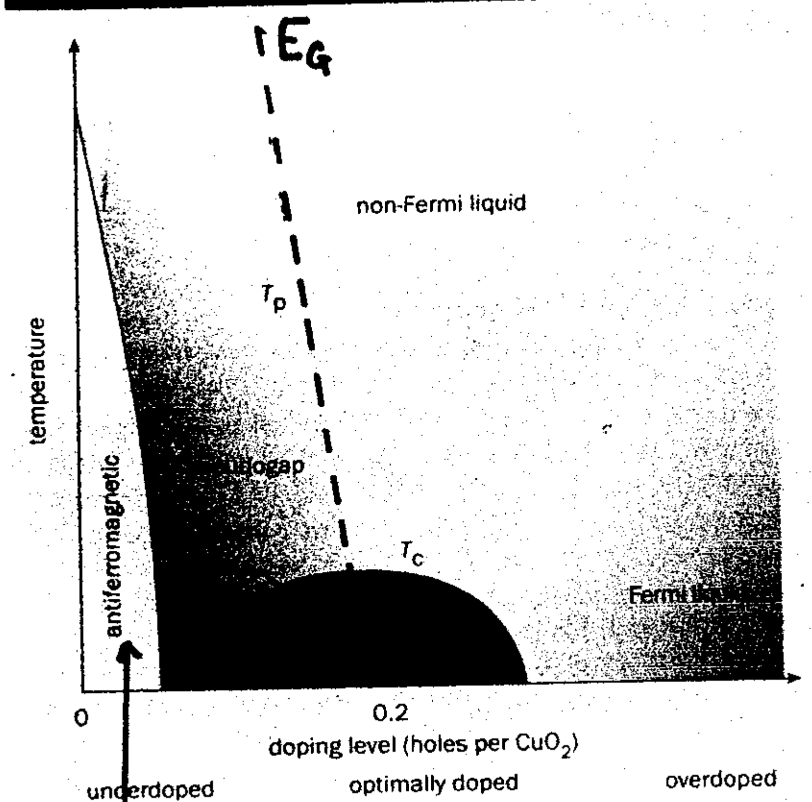
1. REMINDER OF MAIN SPECIFIC HEAT RESULTS AND J. LORAM'S EMPIRICAL MODEL FOR DOS.
2. THERMOELECTRIC POWER - SCALING, STRIPES
3. $\rho(T)$ SCALING Bi:2212, 2201, H. RAFFY'S GROUP (ORSAY) [Tunnelling model c-axis $\rho_c(T,H)$]
4. t-J MODEL CALCULATIONS, PRELOVŠEK ET AL. (HIGH T).
5. POSSIBLE ANALOGIES WITH KONDO EFFECT AND HEAVY FERMIONS
6. SUMMARY AND CONCLUSIONS.
7. A PAIR-BREAKING MODEL FOR THE NON-LINEAR MEISSNER EFFECT.
8. PRELIMINARY CONCLUSIONS. (NLME)

Acknowledgements

1-6 D. Babić, A.M. Campbell, N.E. Hussey, W.Y. Liang
K. A. Mirza, J.L. Tallon, J.W. Loram.

7-8. A. Carrington, R. Giannetta, W.N. Hardy, J.W. Loram, T.X
J.R. Waldram

1 Cuprate phase diagram mystery



Mott-Hubbard insulator Cu^{2+} d^9 $S = 1/2$

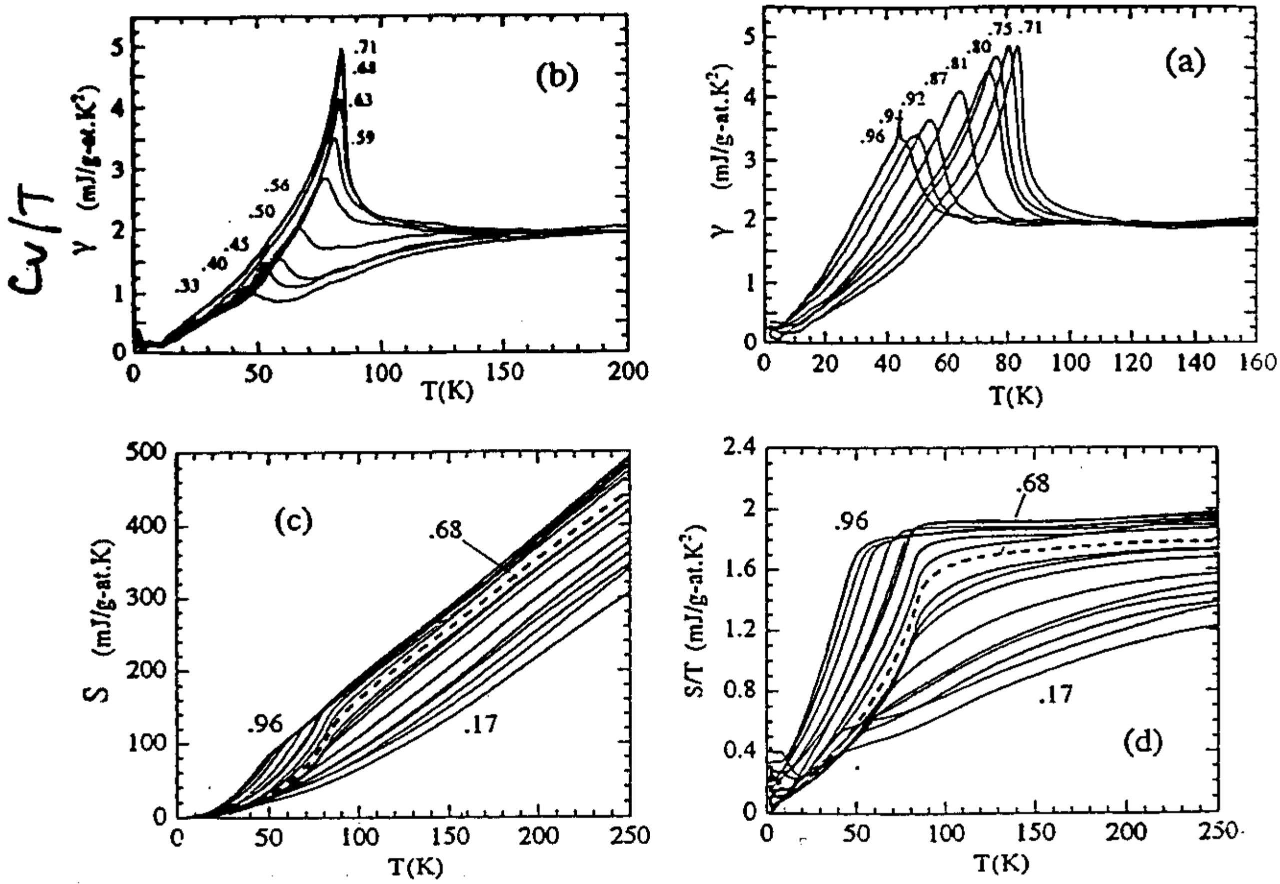
at what point does standard band theory apply?

small or large Fermi surface?

p , $1+p$ holes / CuO_2

Batlogg and Varma
Physics World (2000)

under-doped overdoped (3)



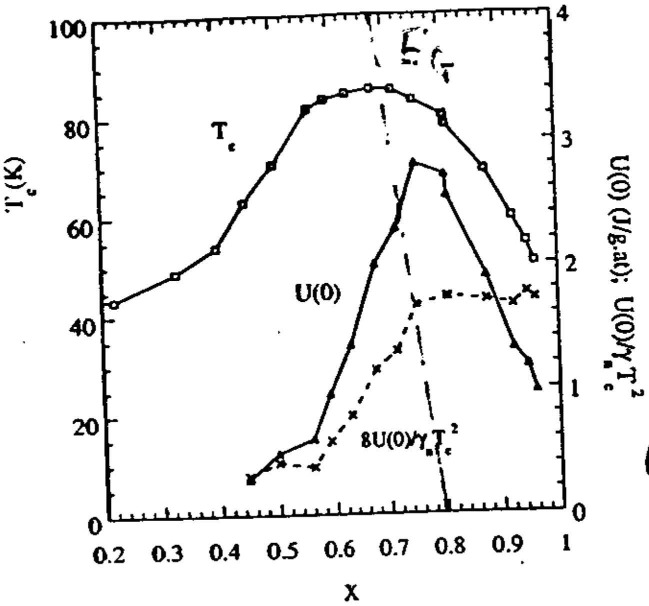
$Y_{0.8}Ca_{0.2}Ba_2Cu_3O_{6+x}$

Also YBCO LSCO Bi:2212

J. W. Loram et al

Physica C 282, 1287 (1997)

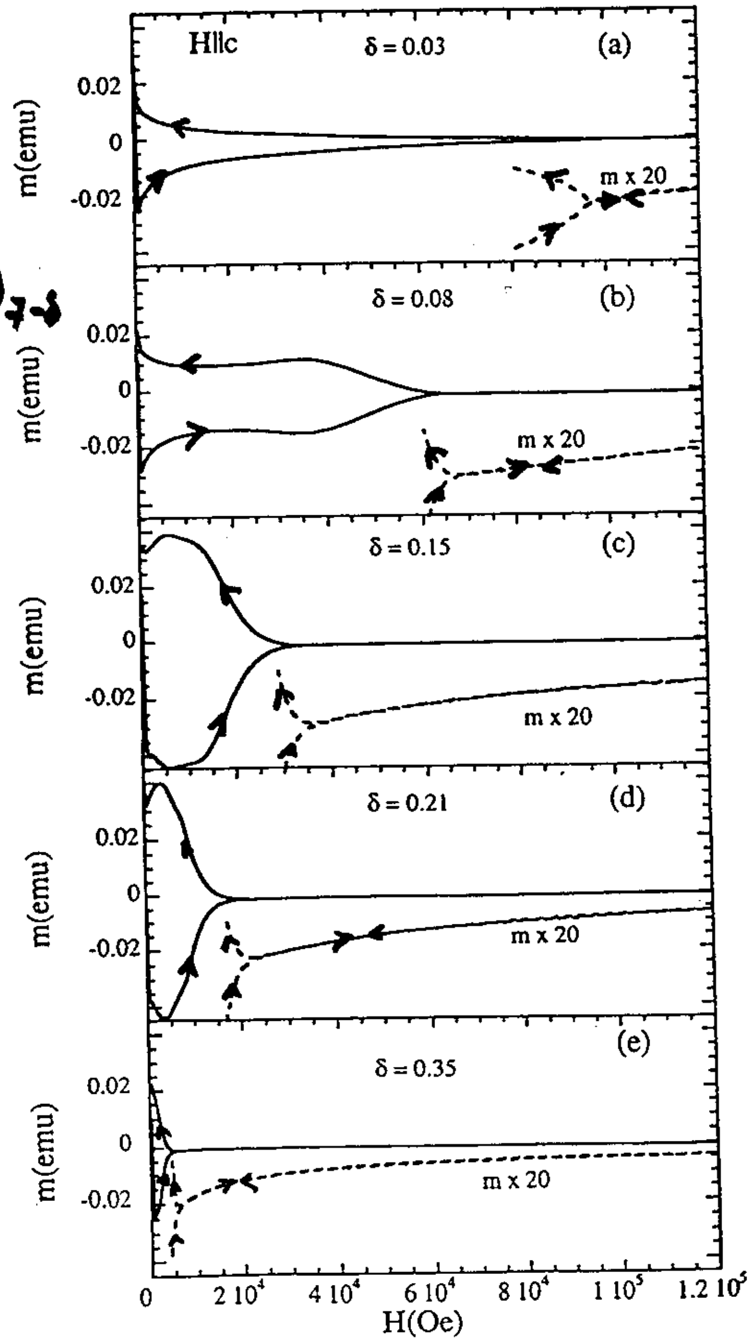
Representative specific heat results.



$Y_{0.8}Ca_{0.2}Ba_2Cu_3O_{6+x}$

J. W. Loram et al
Physica C, 282, 1287
(1997)

Condensation energy
$U(0) \equiv H_c(0)^2/8\pi$



Irreversibility
(Melting)
Line.

$YBa_2Cu_3O_{7-\delta}$
5mg
$H \perp CuO_2$
layers

$\frac{T}{T_c} = 0.8_3$

D. Babić
J.R.C. et al
Phys. Rev.
B60, 698
(1999)

4

(5)

Bi: 2212

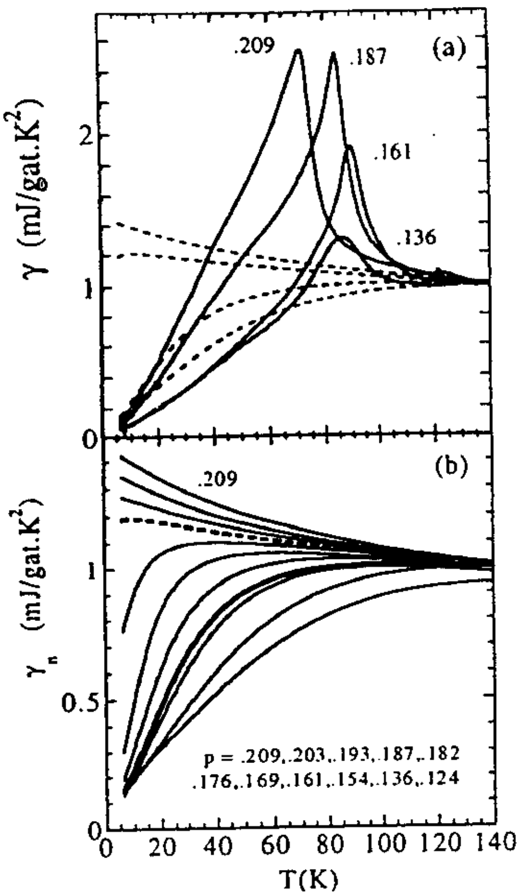


Fig. 6 (a) Broken curves show γ_n below T_c deduced from an extrapolation of S_n from above T_c. A NS pseudogap for $p < p_{crit} \sim 0.19$ and no pseudogap for $p > p_{crit}$ follow from the condition $S_n(T_c) = S_s(T_c)$. (b) γ_n for the undoped Bi2212 sample for all p.

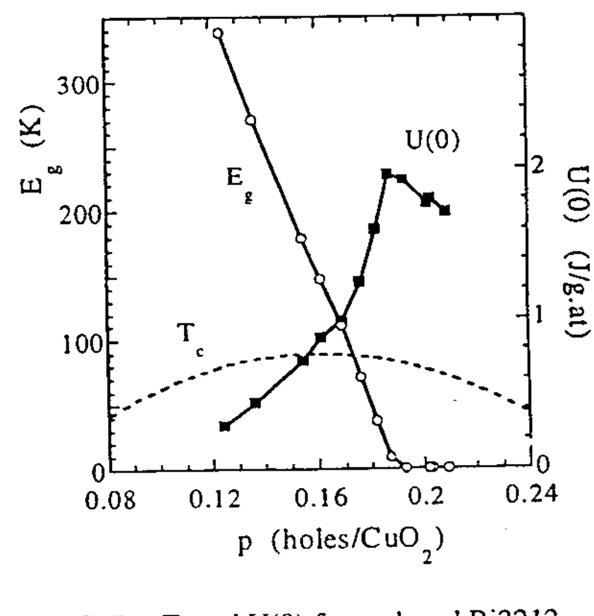
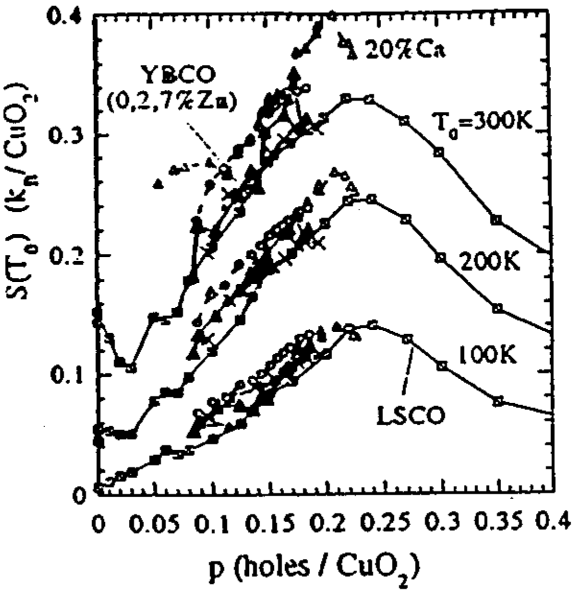


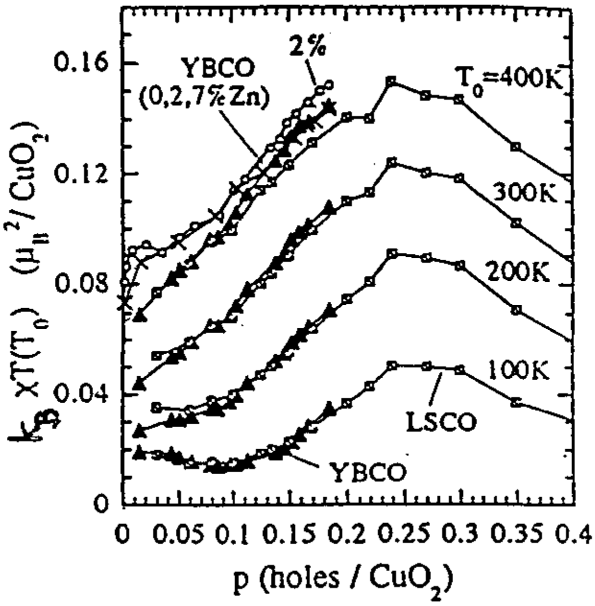
Fig. 5. E_g/k_B, T_c and U(0) for undoped Bi2212.

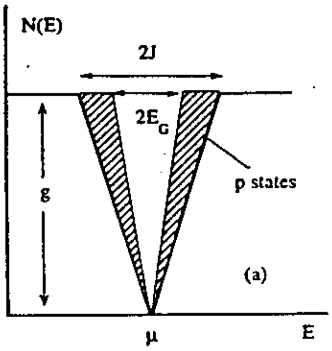
J. W. Loram et al.
Procs. Houston conf. Feb. (2000).

(6)

$\chi T/S$ = WILSON RATIO





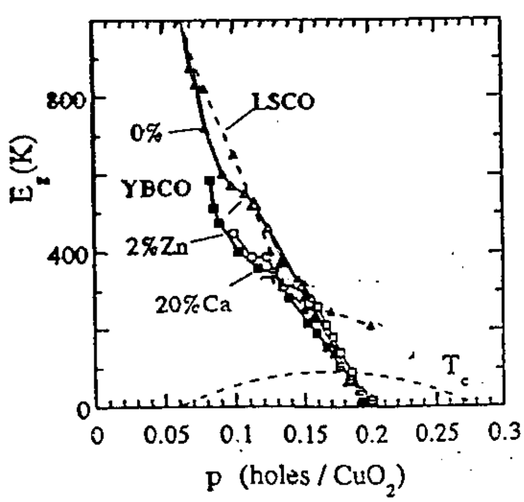


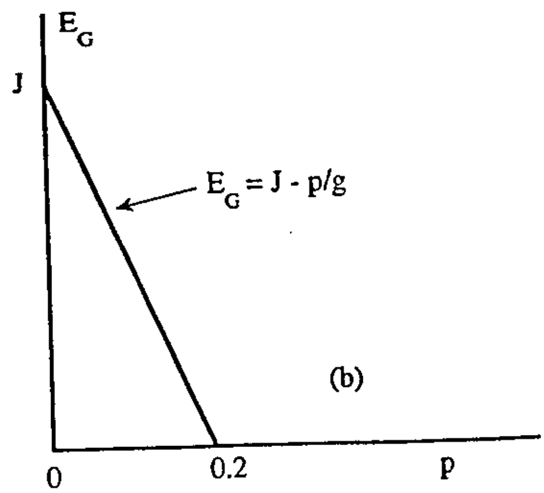
t - J type

Empirical description of correlated state - Fermion DOS.

J.W. Loram et al

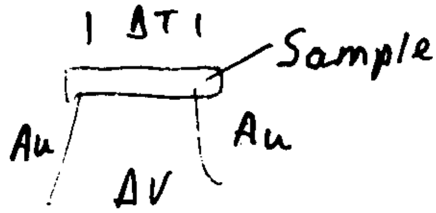
J. Phys. Chem. Solids 59, 2091 (1998)





Thermoelectric Power

Easy to measure



$$\left.\frac{\Delta V}{\Delta T}\right)_{\Delta T \to 0} \equiv \frac{dV}{dT} = S_{sample} - S_{Au}$$

for sintered ceramics measure S_{ab}.
TEP insensitive to grain boundaries.

Interpretation

1 el. theory $\quad S = \frac{1}{eT} \frac{\int (\varepsilon - \mu) \frac{\partial f}{\partial \varepsilon} \sigma(\varepsilon)\, d\varepsilon}{\int \sigma(\varepsilon) \frac{\partial f}{\partial \varepsilon}\, d\varepsilon}$

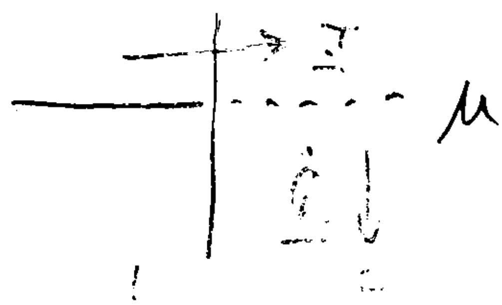
$$\sigma(\varepsilon) \propto N(\varepsilon)\, V(\varepsilon)^2\, \tau(\varepsilon)$$

more generally $\quad S = \frac{\Pi}{T} = \frac{\langle \varepsilon - \mu \rangle}{eT}$

$\langle \varepsilon - \mu \rangle$ mean energy / charge carrier relative to μ

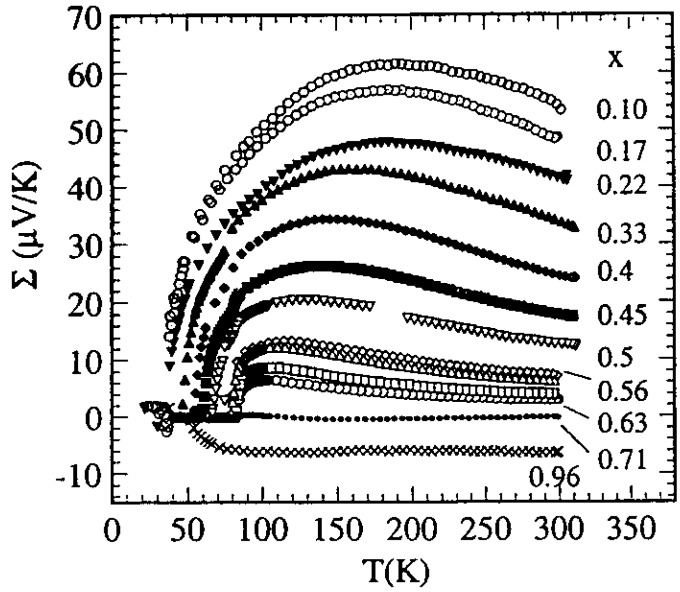
metal $\quad S = \frac{k_B}{e} \cdot \frac{T}{\varepsilon_F}$

1–10 $\mu V/K$ at R.T.



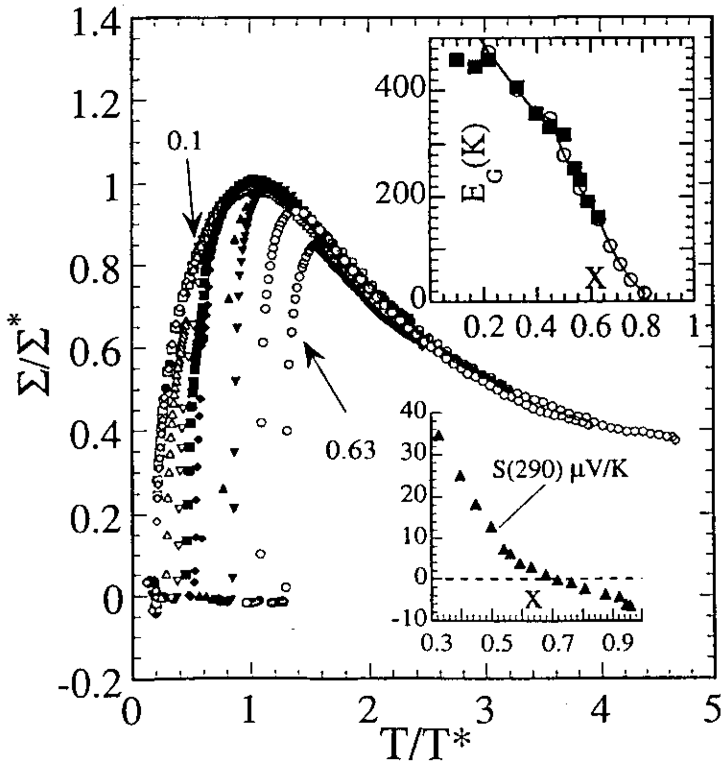
el. TEP very sensitive to higher order scattering processes.

Thermoelectric power



$Y_{0.8}Ca_{0.2}Ba_2Cu_3O_{6+x}$

J.R.C. and J.W. Loram J.Phys (France) (2000)
+ Procs. Houston conf. (2000)



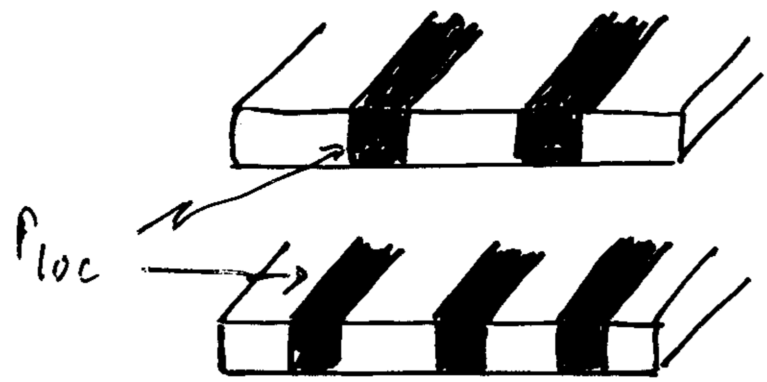
■ 2.5 T*
○ S(110K)

Also
LSCO
YBCO 0[?]
Bi:2212

Also similar scaling in R_H (Batlogg, Uchida) and $\rho(T)$ {Wuyts et al., Uchida et al.}

Stripes and the TEP

Several wires in parallel same TEP *



"rivers of charge"

So would not expect TEP to change if ρ_{loc} stays $\simeq$ constant.

(contrast ρ and R_H - both change a lot - depend on p_{av}. ρ/R_H depends on p_{loc})

Random arrangements of static stripe - still valid - TEP of ceramic = ab TEP × [illegible]

Dynamic stripes - would have to move on time scale of carrier scattering time...

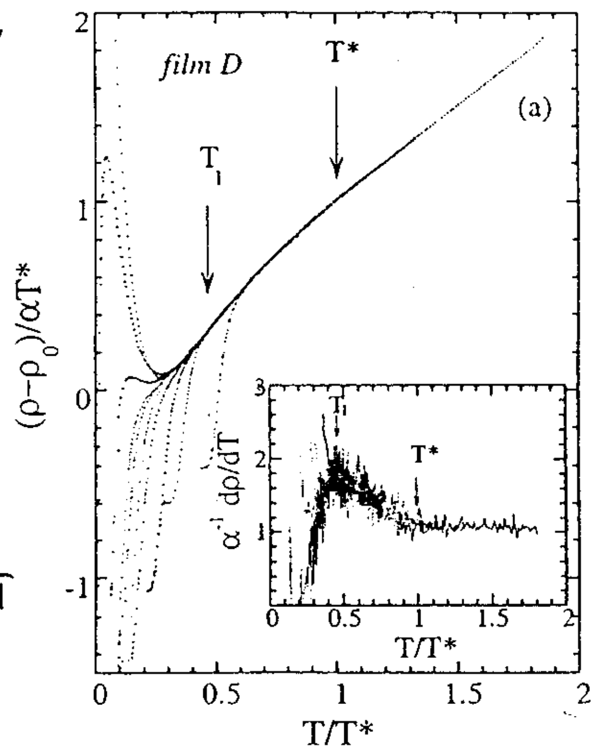
Or

* Voltage from non-conducting regions shorted out by conducting ones.

Scaling of resistivity (ab plane) for:

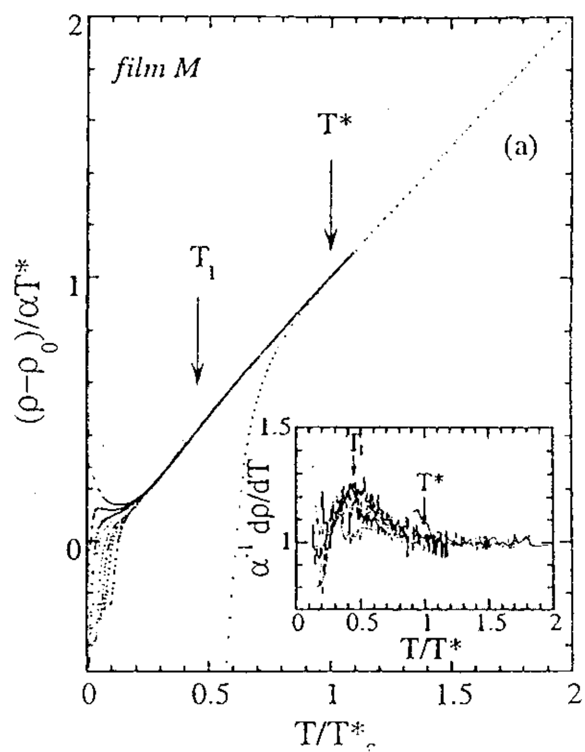
Bi2212

$$\alpha = \left.\frac{d\rho}{dT}\right)_{\mathrm{High}\,T}$$



H. Raffy et al.
Procs. Houston conference (Feb. 2000)
& Konstantinović
Ph. D. Thesis
(Orsay 2000)

Bi(La)2201



$$\frac{\rho-\rho_0}{\alpha T^*} \equiv \frac{\rho(T)-\rho_0}{\rho(T^*)-\rho_0}$$

E_G from $C_v(T)$

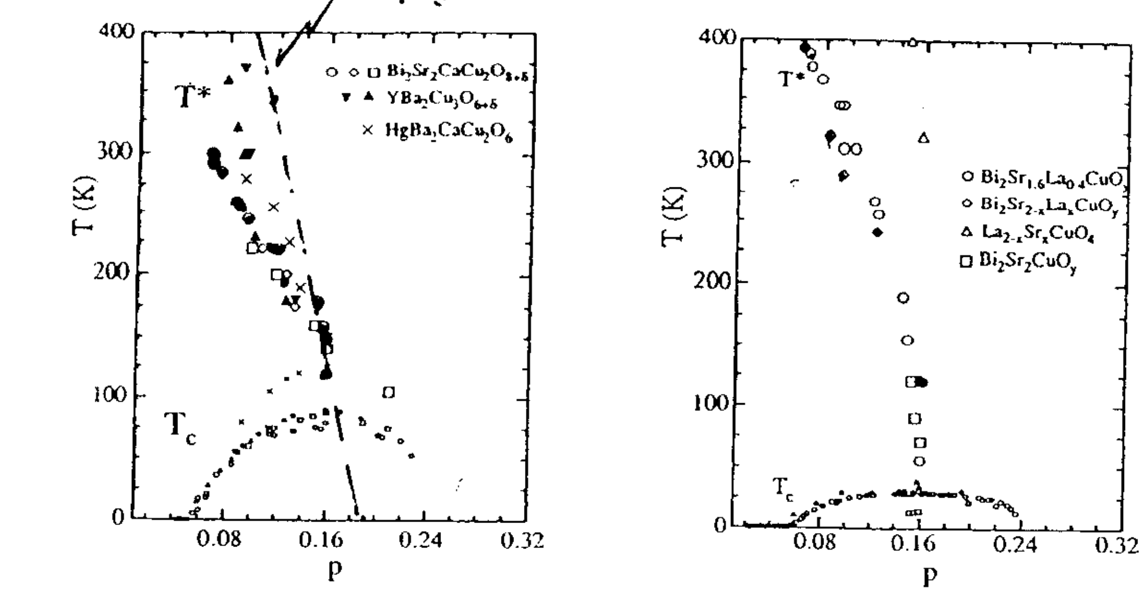


Figure 18 : Comparaison des nos valeurs de T (cercles vides) avec les différentes mesures (a) de transport Bi-2212 (diamants vides) [8], (carrés vides) [16], d'YBCO (triangles pointant vers le haut, pleins) [14], (triangles pointant vers le bas, pleins) [13] et (croix) Hg-1212 [24] des systèmes avec deux plans CuO_2 et (b) BiSrLaCuO (diamants) [9] et LSCO (triangles) [25] et Bi-2201 pur (carrés) [3] des systèmes avec un seul plan CuO_2.*

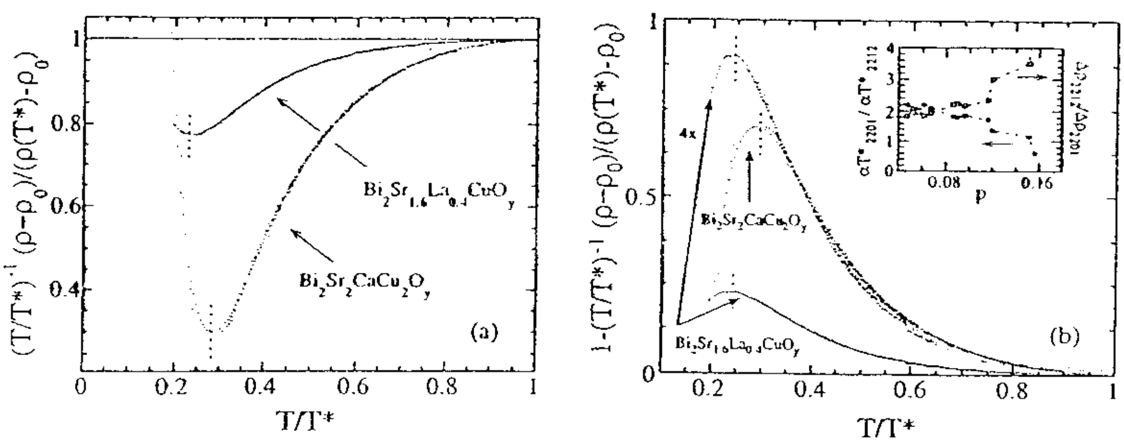


Figure 20 : L'effet de pseudogap sur $\rho(T)$ pour les phases Bi-2212 et Bi(La)-2201. La courbe unique obtenue pour Bi-2212 coïncide avec celle de Bi(La)-2201 après multiplication par un facteur 4 de la quantité A en fonction de la température réduite T/T. L'encart montre les rapports $(\alpha T^*)_{2201}/(\alpha T^*)_{2212}$ et $\Delta\rho_{2212}/\Delta\rho_{2201}$ en fonction de p.*

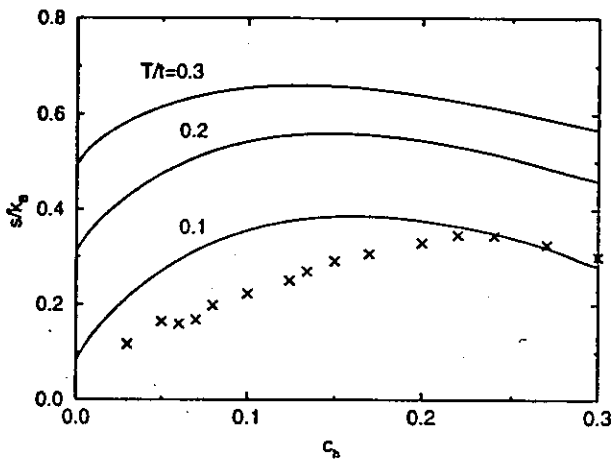
Z. Konstantinović Ph.D thesis Orsay (2000)

H. Raffy et al. Houston conf. Feb. 2000

Jaklič and Prelovšek Adv. Phys (2000) 1–95

$$H = -t \sum_{\langle ij \rangle s} (\tilde{c}^\dagger_{js} \tilde{c}_{is} + \text{H.c.}) + J \sum_{\langle ij \rangle} (\vec{S}_i \cdot \vec{S}_j - \frac{1}{4} n_i n_j),$$

describing fermions in a tight-binding band with the hopping parameter $t \propto t_{pd}^2/\Delta$. Here $\vec{S}_i = (1/2)\sum_{ss'} c^\dagger_{is} \vec{\sigma}_{ss'} c_{is'}$ are the local spin operators interacting with the exchange parameter $J \propto t_{pd}^4/U_d\Delta < t$. Due to the strong on-site repulsion states with doubly occupied sites are explicitly forbidden and we are dealing with projected fermion operators $\tilde{c}_{is} = c_{is}(1 - n_{i,-s})$.



doped holes reduce a-f order release spin entropy

Figure 4.4: s vs. c_h at several T, calculated in a system with $N = 20$ sites. We show for comparison also experimental results for LSCO by Loram *et al.* (1996) at highest $T = 320\ K \sim 0.07\ t$.

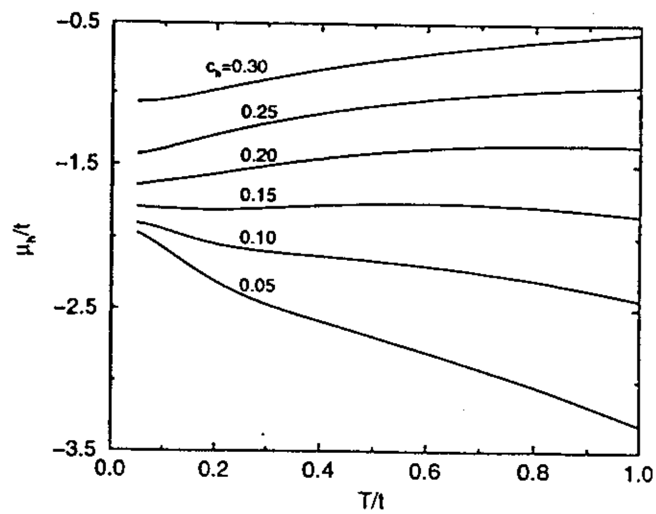


Figure 4.1: Hole chemical potential μ_h vs. T at several dopings c_h.

$$\left.\frac{\partial s}{\partial c_h}\right|_T = -\left.\frac{\partial \mu_h}{\partial T}\right|_{c_h}$$

$$\underset{TEP}{S} \sim \frac{1}{e_0 T}[\mu_h(T=0) - \mu_h(T)],$$

(12)

(13)

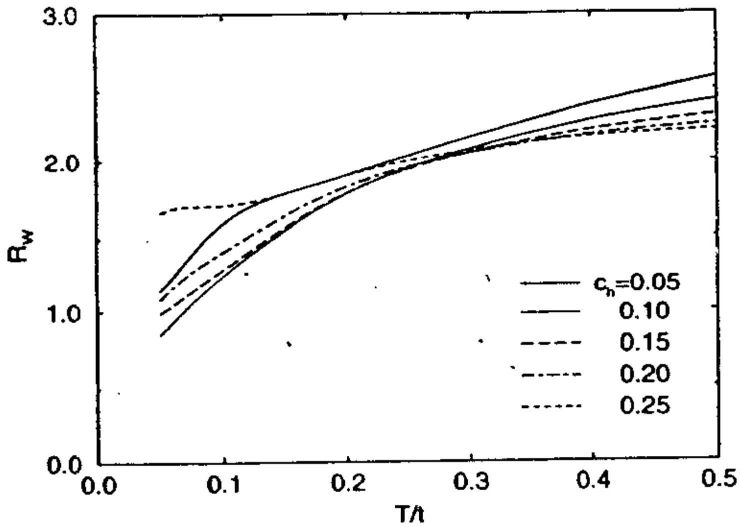
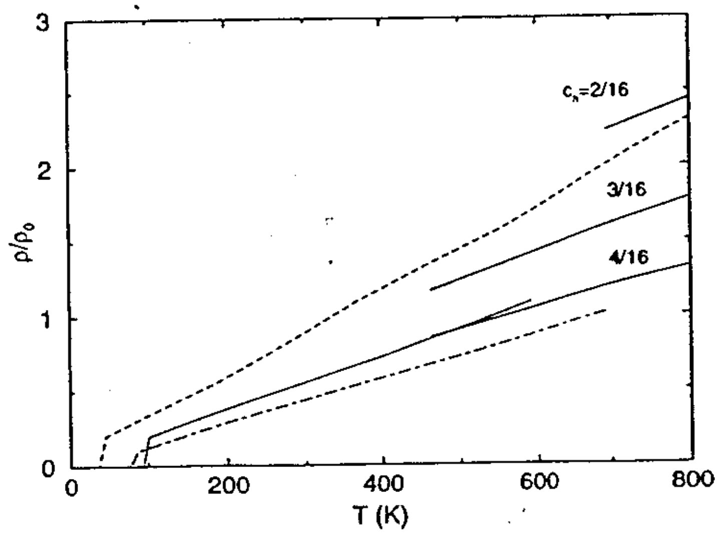


Figure 26. Wilson ratio R_W versus T at several c_h.



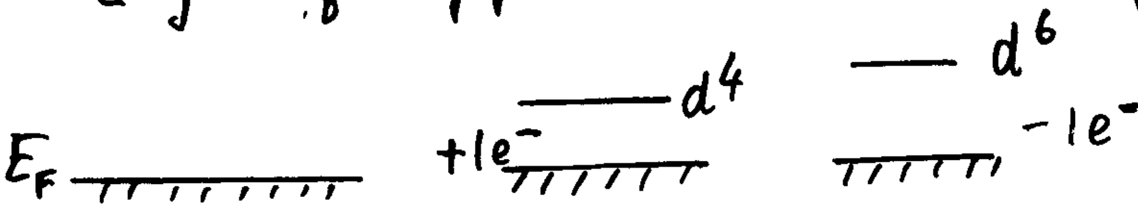
$\rho_0 = \frac{\hbar}{e^2}$ /layer

Figure 24. Sheet resistivities $\rho(T)$ for various dopings (full lines) in comparison with measurements in LSCO with $x = 0.15$ (dotted), BSCCO (dashed), and YBCO (dash-dotted).

Jaklič and Prelovšek
numerical studies of t-J model.
Adv. Phys. (2000) 1-85

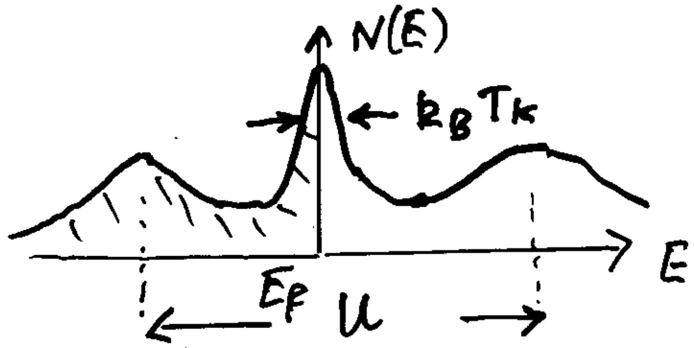
KONDO EFFECT

e.g. few ppm Mn (d^5) in Ag



Mn ↑↑↑↑↑ d^5

RESONANCE AT E_F – SPIN ENTROPY TRANSFERRED TO CONDUCTION ELECTRONS



$\Delta C_v \sim \frac{T}{T_K}$

Mn spin compensated by cond^n electron.

ALSO HAPPENS IN HEAVY FERMION COMPOUNDS E.G. $CeSn_3$

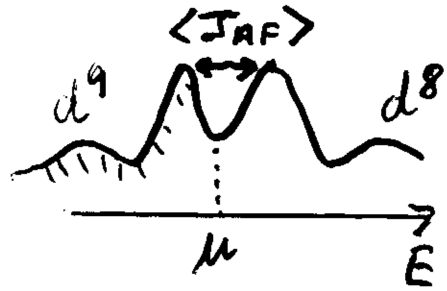
Ce^{4+} or Ce^{3+} f^0 or f^1

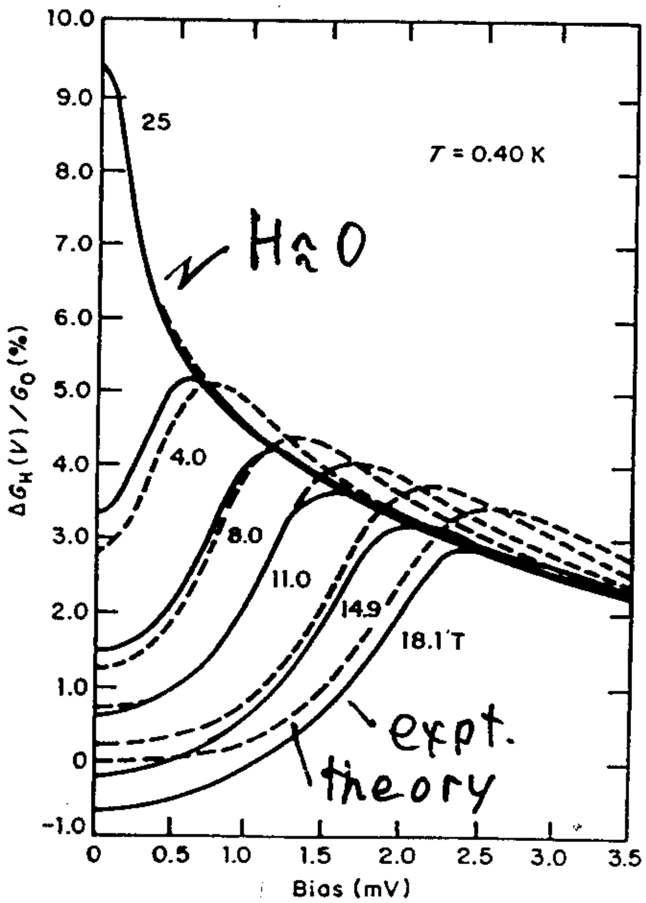
BUT (e.g. LONZARICH GROUP) LDA BAND STRUCTURE → SHAPE OF FERMI-SURFACE, NOT m^*.

IS THIS A USEFUL WAY OF LOOKING AT HTS? N.B. T_K LARGE

Cu d^9 spin interacting with more mobile O 2p holes.

MAGNETIC FIELD (OR IN THIS CASE J_{AF} - NEAREST NEIGHBOUR EXCHANGE INTERACTION) "DIGS HOLE" IN RESONANCE AT E_F. HOLE FILLS AS $\langle J_{AF} \rangle$ IS REDUCED BY DOPING.





Al | AlO$_x$ | Al Tunnel junction doped with Fe

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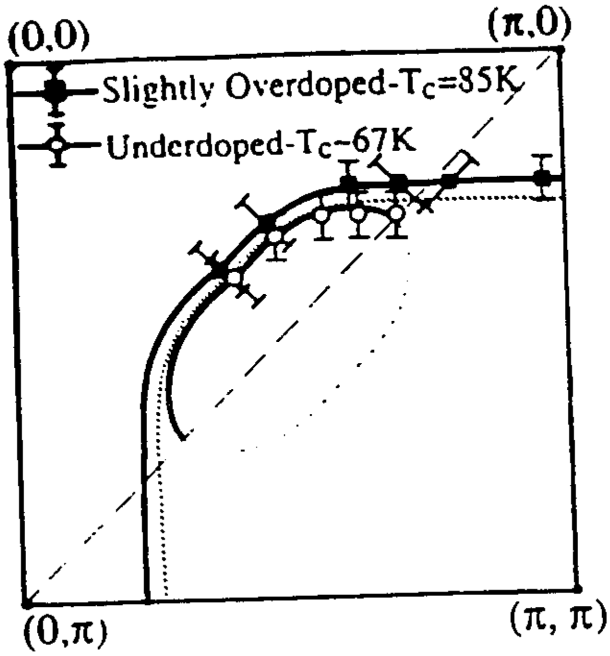
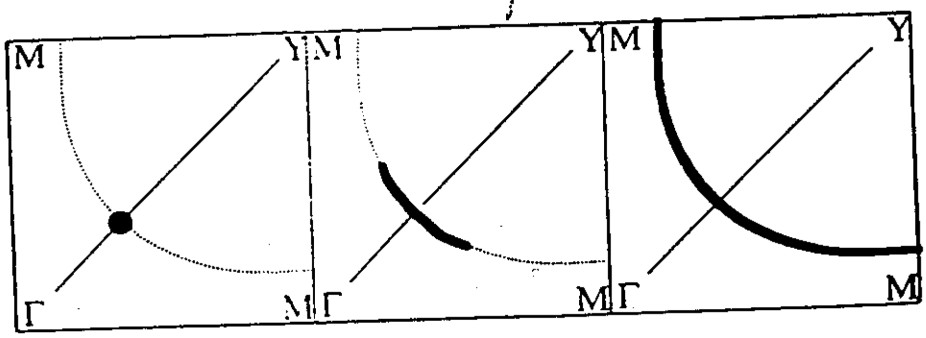
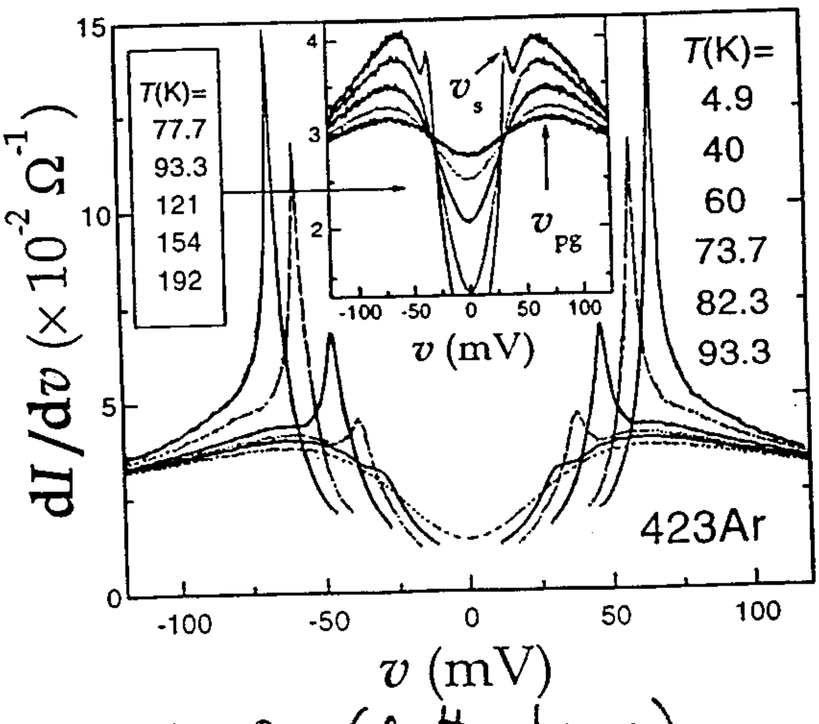


From
T. Timusk and B. Statt
Repts. Prog. Phys.
62 1-122 (1999)

Based on recent
ARPES data
(Argonne, Stanford...)



c-axis.
Intrinsic
Tunnelling
Bi: 2212
mesas.



Krasnov et al (Gothenburg)
cond-mat 0002172

Summary and Conclusions

The strange properties of the normal state pseudogap (E_G) suggest a new type of correlated electron system - a quasi-2D doped Mott-Hubbard insulator – not a usual metal or semiconductor.

- **For under- and optimal doping, E_G has strong** (weakening) **effect on superconducting properties.**
- **Unusual transport, but crucially, doping gives 1 state per hole near Fermi energy. $\Delta S/\Delta p \approx k_B$ (above about 100 K) and $\Delta\chi T/\Delta S = 3\mu_B^2/\pi^2 k_B^2$, Wilson ratio for weakly interacting Fermions.**
- **Variation of E_G (or T*) and T_c vs. p, like heavy Fermions under pressure – but no evidence for phase transition at T*.**
- **Numerical t-J model results agree with data at high T, but no clear picture for E_G. Give "marginal Fermi liquid" results, $\tau^{-1} \sim T^1$, ω^1. Can this account for empirical N(E)?**
- **Other possibilities for N(E) –**
  holes "dressed" by AF spin waves,
  2D equivalent of CH_x (P.Wiegmann),
  many-body effects e.g. spin fluctuations (Pines et al.), Umklapp el-el processes (Rice et al.)
- many-body resonance with structure near E_F induced by n.n. exchange interactions.

Non-linear Meissner Effect
(NLME)

$$\lambda(T,H) - \lambda(T,0) = \Delta\lambda(H)$$

$H \leq H_{c1}(T)$
$$= \alpha\,\lambda(T)\,\frac{|H|}{H_0(T)}$$

$H_0(T) \approx H_c(T)$ Thermodynamic critical field

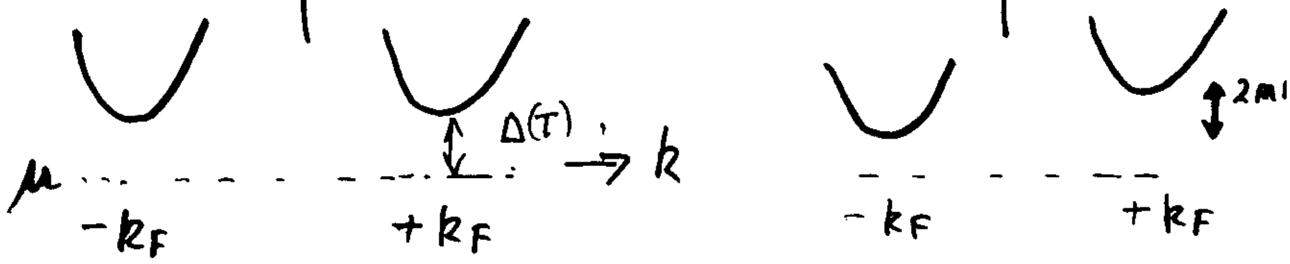
at low T
where Doppler shift $m v_s v_F > k_B T$

Predicted by S.K. Yip and J.A. Sauls
P.R.L. 69 2264 (1992)

Arises from enhanced back-flow of quasi-particles near the nodes of "non s-wave" superconductor

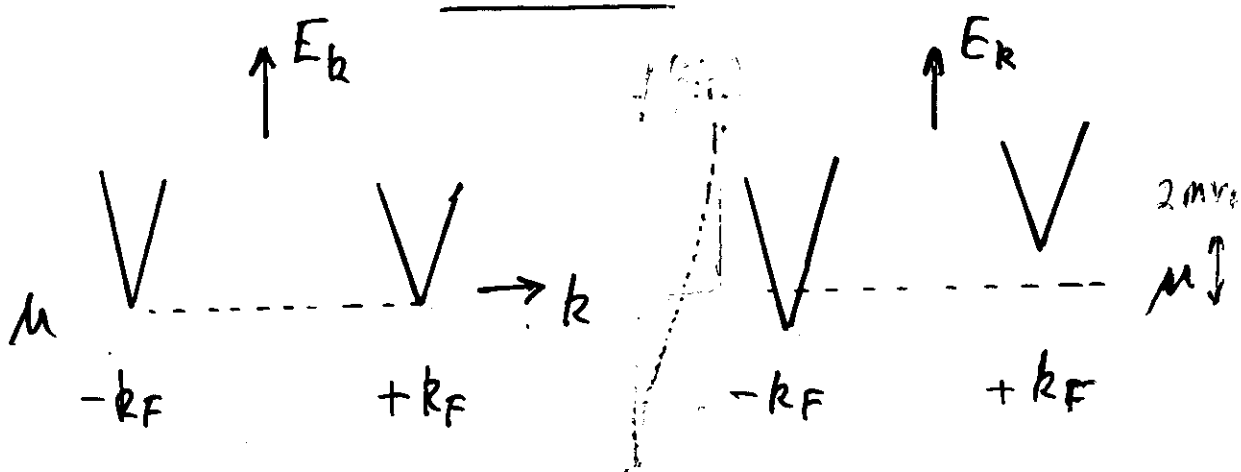
should be good test for nodes
<u>but</u> not really observed experimentally.
expect anisotropy of $\sqrt{2}$ and transverse moment: also not observed.

$$E_k^2 = \varepsilon_k^2 + \Delta_k^2$$



$V_s = 0$ $\qquad\qquad$ $V_s \neq 0$

<u>s- wave</u>



$V_s = 0$ $\qquad\qquad$ $V_s \neq 0$

<u>d- wave</u>

when $\quad m v_s v_F \lesssim k_B T$

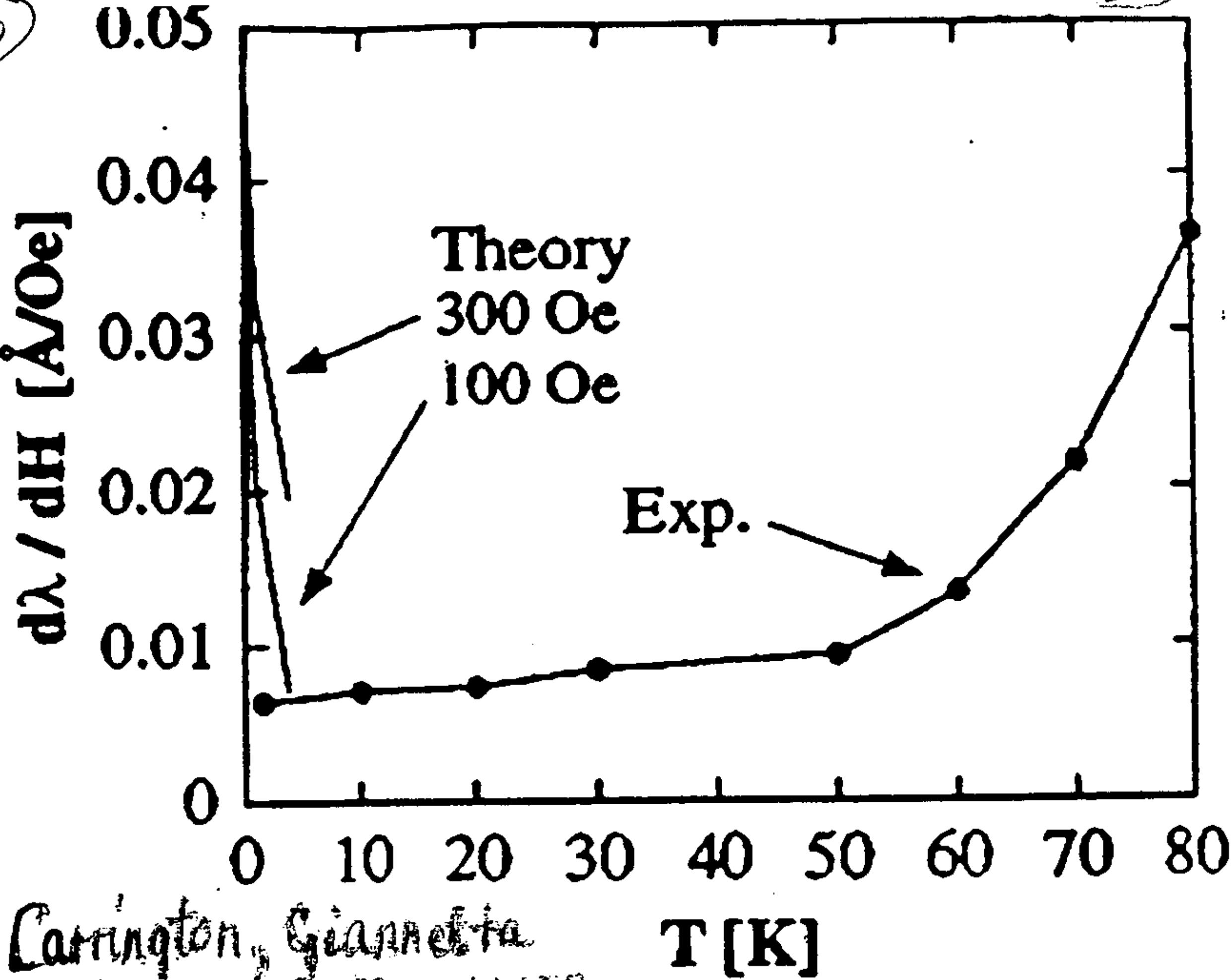
expect $\quad \delta\lambda = \frac{1}{24}\lambda(T)\,\frac{\Delta(0)}{T}\left(\frac{H}{H_0}\right)^2$

e.g.

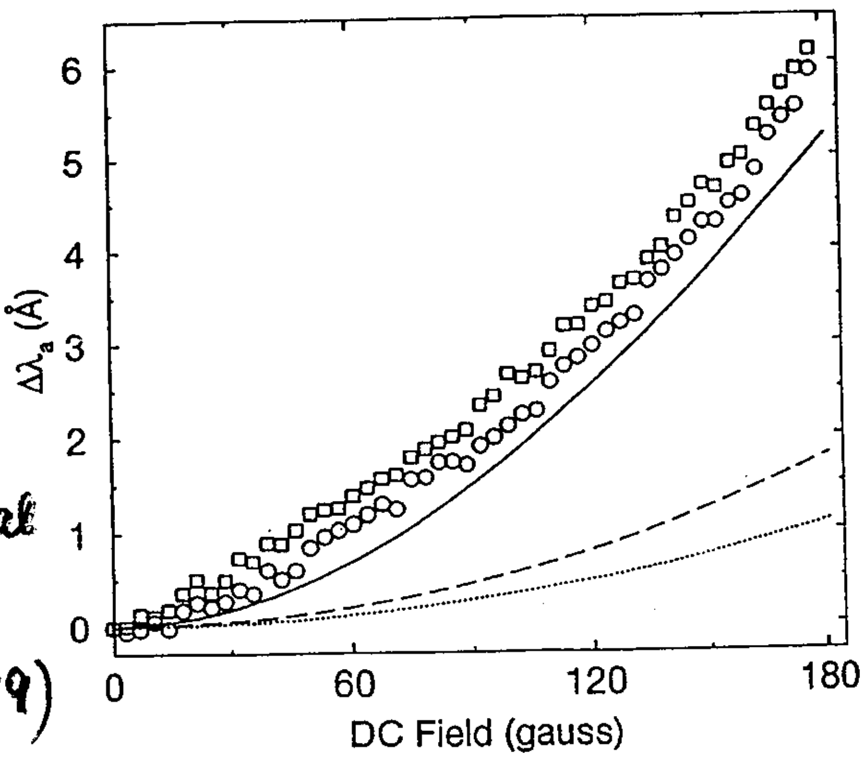
T. Dahm and D.J. Scalapino

Phys. Rev. B60, 13125 (1999)

20



Carrington, Giannetta et al P.R. B59 R14173 (1999)



Bidinosti, Hardy et al P.R.L. 83 3277 (1999)

FIG. 4. $\Delta\lambda_a$ as a function of H at various temperatures. Data: 4.2 K (circles), 7.0 K (squares). Theoretical curves: 1.2 K (solid line), 4.2 K (dashed line), 7.0 K (dotted line).

21

A. Maeda et al
P.R.L. 74 1202 (1995)

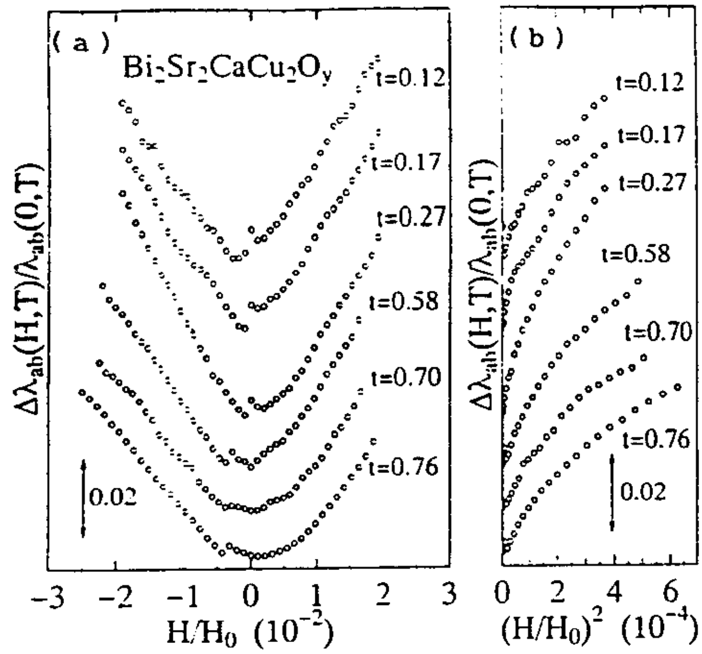


FIG. 2. (a) $\zeta \equiv \Delta\lambda_{ab}(H,T)/\lambda_{ab}(0,T)$ as a function of the normalized field $h \equiv H/H_0$ at various temperatures. Temperatures are also normalized to T_c; $t \equiv T/T_c$. (b) ζ as a function of h^2.

Bidinosti, Hardy et al. Cond. mat 9808231 $YBa_2Cu_3O_{6.95}$

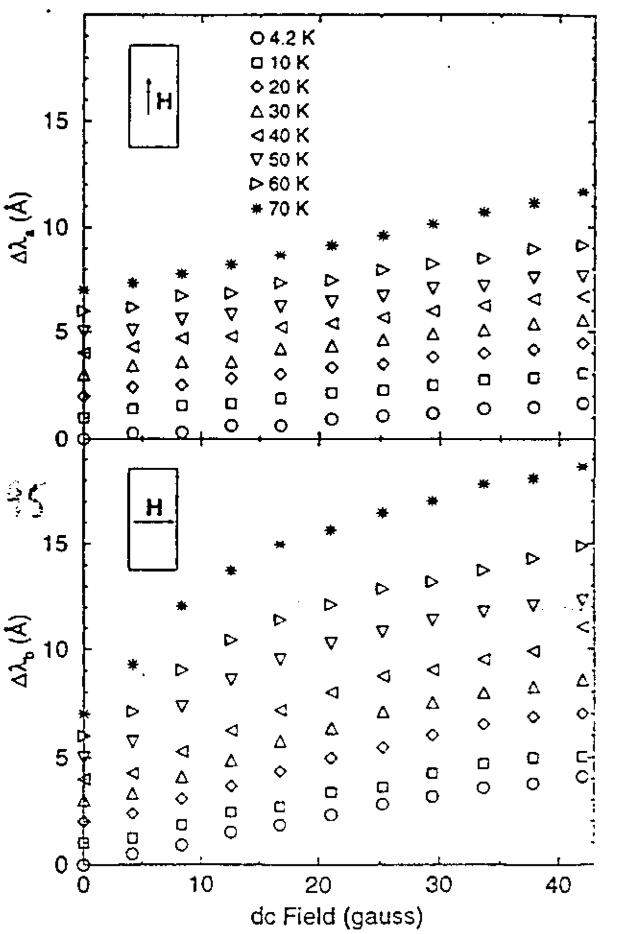
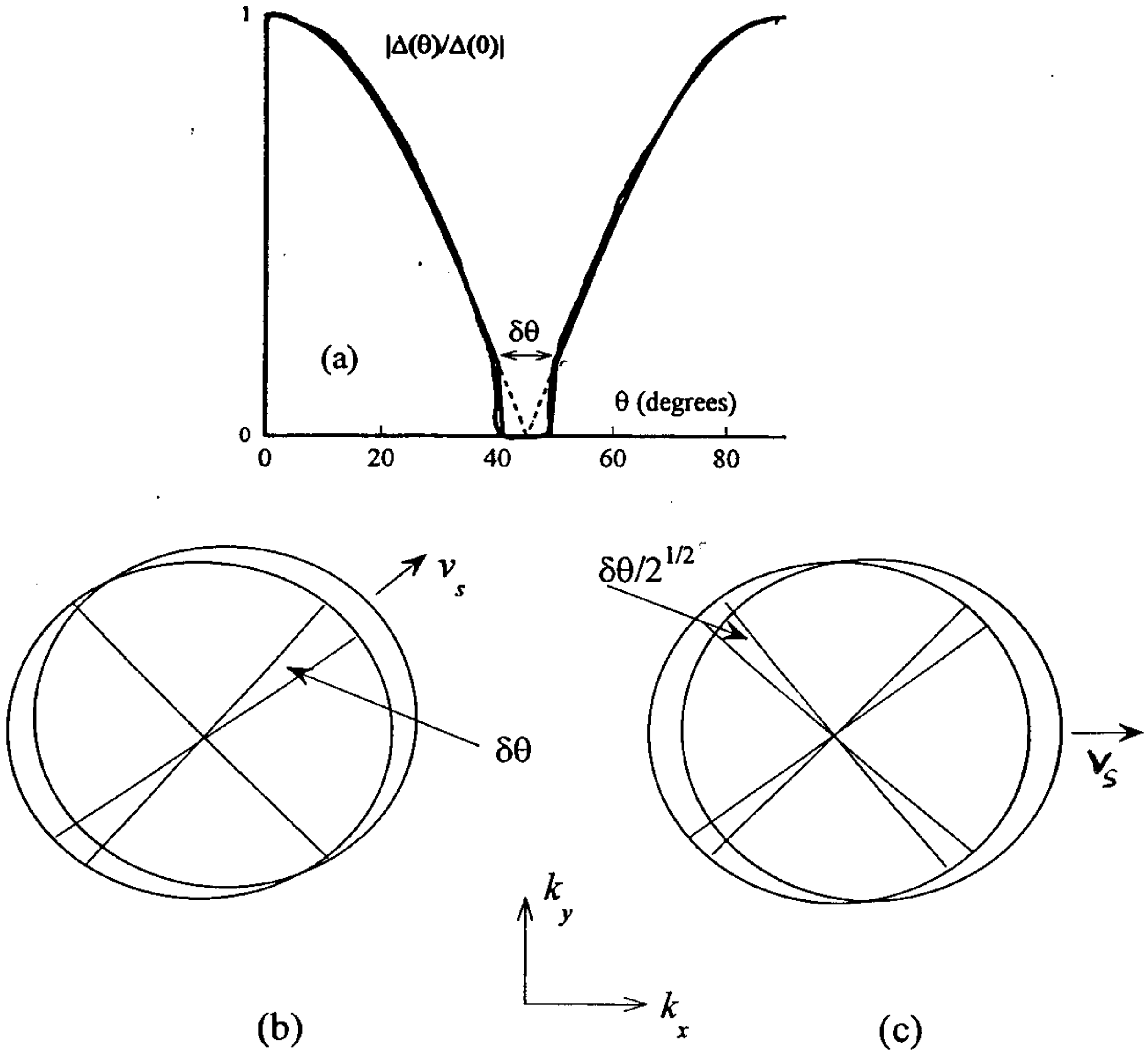


FIG. 3. $\Delta\lambda$ as a function of H for fields parallel (top) and perpendicular (bottom) to the crystal b-axis.

(22)

$$\Delta(\theta) = \Delta(T)\,|\cos 2\theta|$$

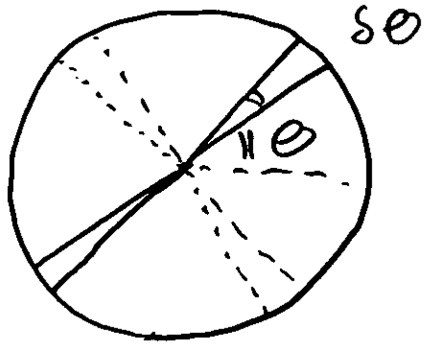


[illegible]
[illegible] superconducting [illegible]
[illegible]

J.R.C. preprint (June 2000)

Justification

weak coupling d-wave BCS theory



rest frame
$\underline{v}_s = 0$

Set $\Delta(T) = 0$ over small angle $\delta\theta$ near nodes

Calculate Free energy using BCS expression find $\Delta F = +\beta(T)(\delta\theta)^3$

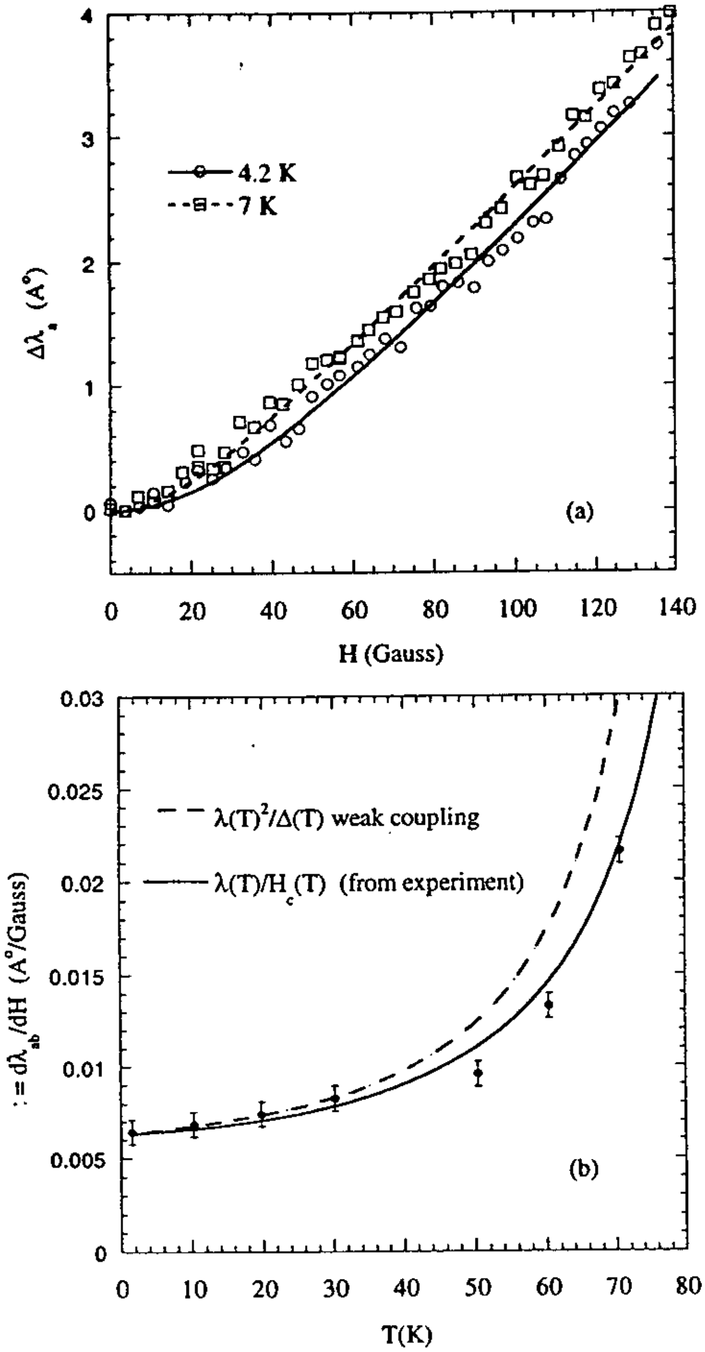
$(V_{kl} = -V\cos 2\theta_k \cos 2\theta_l)$

But for finite $\underline{v}_s$, K.E. is reduced by $\frac{1}{2} n m v_s^2 \cos^2\theta \, \frac{\delta\theta}{\pi}$ per node

minimise F gives:

$$\delta\theta = \frac{m v_F v_s}{\sqrt{2}\,\Delta(T)} \frac{1}{2.65} \text{ for } \underline{v}_s \parallel \hat{\underline{x}}, \hat{\underline{y}}$$

$$\delta\theta = \frac{m v_F v_s}{\Delta(T)} \frac{1}{2.65} \text{ for } \underline{v}_s \parallel \text{nodal dir}$$



J.R.C. preprint (2000)

○ □ } $YBa_2Cu_3O_{6.95}$ data Bidinosti et al.

- - - / ——— } pair breaking model.

$YBa_2Cu_3O_{6.95}$ Carrington et al

- - - / ——— } pair-breaking model

effect isotropic

	α
G.L.	0.353
BCS_A	0.226
BCS_B	0.182

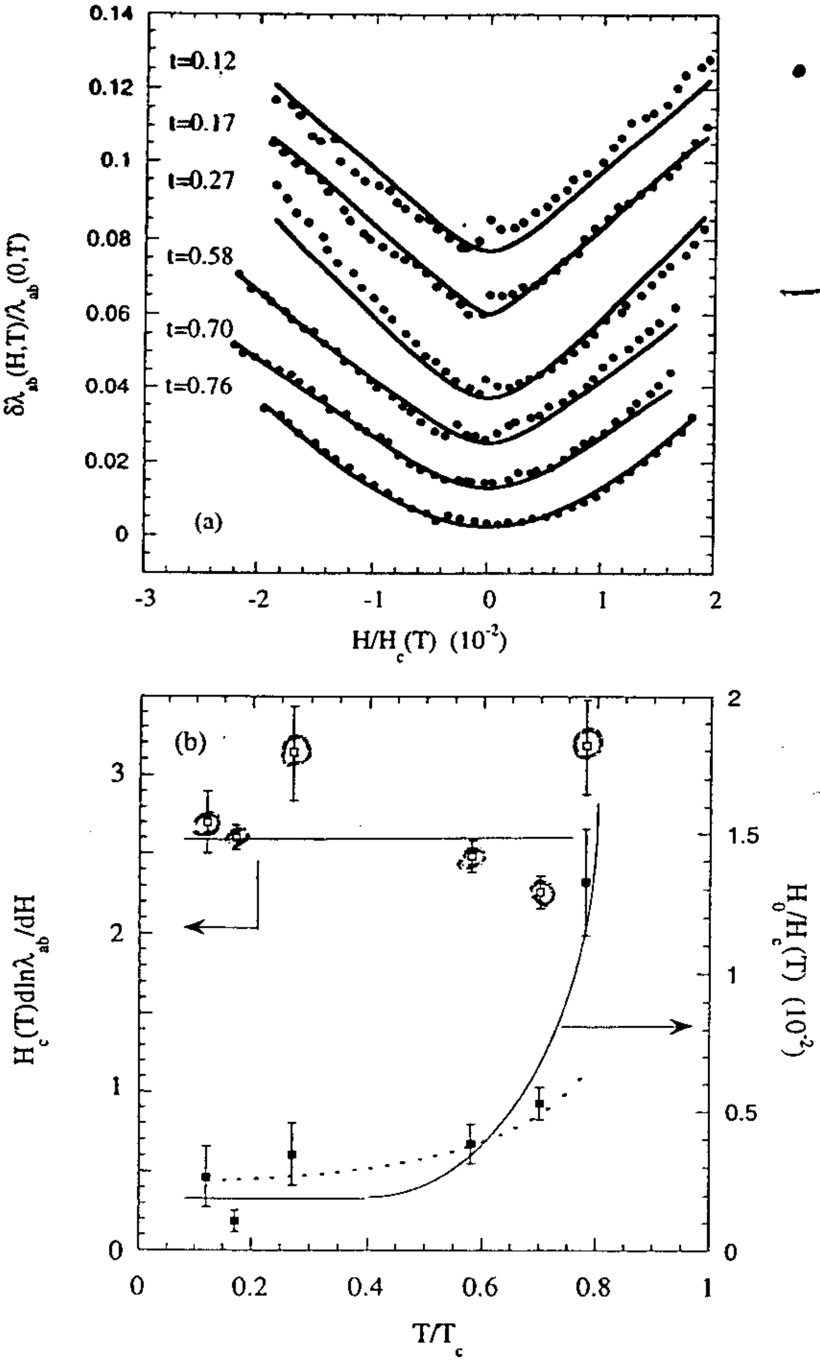
$$\frac{\delta\lambda}{\lambda} = \frac{m v_F v_s}{\pi \Delta(T)} = \frac{\alpha |H|}{H_c(T)}$$

$$\sigma = \frac{\alpha\sqrt{H^2 + H_{00}^2} - H_{00}}{H_c(T)}$$

H_{00} measure of pair breaking in zero field

25

Bi:2212



• Data of Maeda et al.

— pair-breaking model

PRELIMINARY CONCLUSIONS (NLME)

1. PAIR BREAKING MODEL GIVES BETTER DESCRIPTION OF DATA THAN "BACK FLOW" MODEL
2. COULD BE GENERAL PROPERTY OF "NON S-WAVE" SUPERCONDUCTORS
3. HAS SOME THEORETICAL BASIS (FREE ENERGY - BCS ARGUMENT)
4. WOULD GIVE SIMILAR RESULTS TO "BACK FLOW" MODEL IN HIGH FIELDS - SIMILAR NUMBERS OF SIMILAR QUASI-PARTICLES. BUT CONCEPTUALLY DIFFERENT - AND 'BACK-FLOW' EFFECTS SMALLER, (I.E. LESS IMBALANCE BETWEEN +ve and -ve BRANCHES OF E_k vs $\underline{k}$ CURVES).