(1)

# Interlayer Tunneling in Cuprate Superconductors

KAM July 5 2000

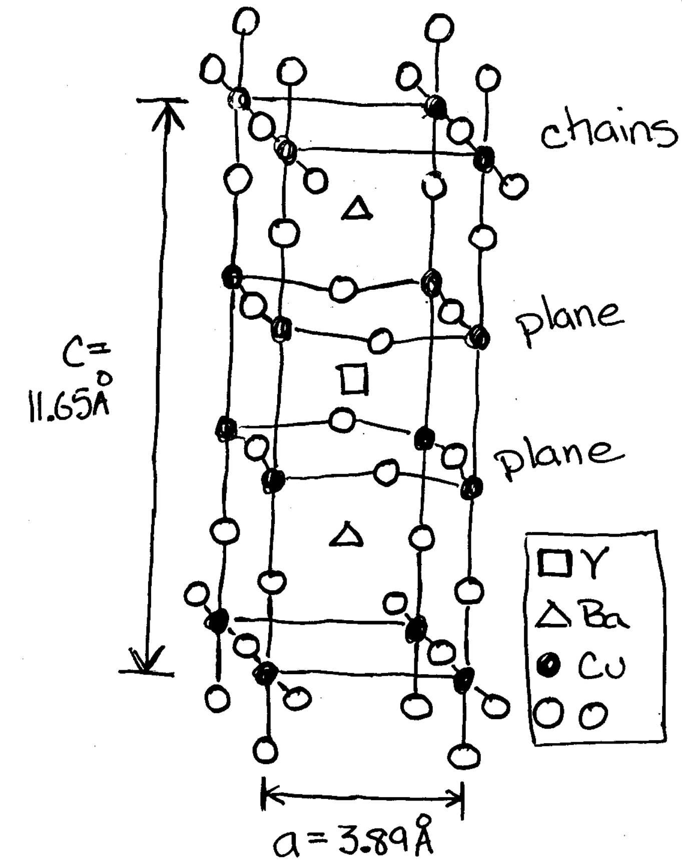
1. There is interlayering tunneling, and the Lawrence-Doniach model provides a pretty good phenomenological description.

2. The Inter-Layer Tunneling (ILT) model proposed as a <u>mechanism</u> for high-$T_c$ has testable experimental consequences.

(2)

$YBa_2Cu_3O_{7-\delta}$

drawn for $\delta=0$
(fully oxygenated)




$T_c \approx 90K$

Moler
Lecture 2

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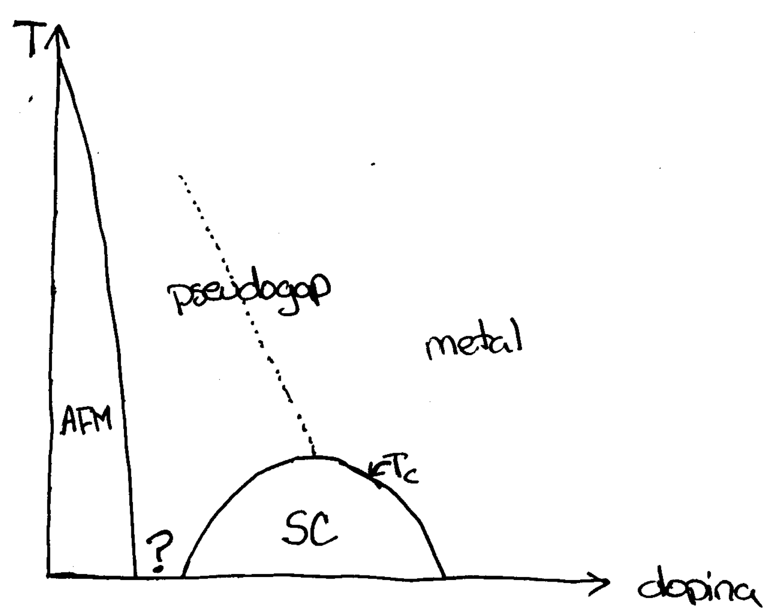
CARRIER DOPING HAS A RADICAL EFFECT ON THE PHYSICS

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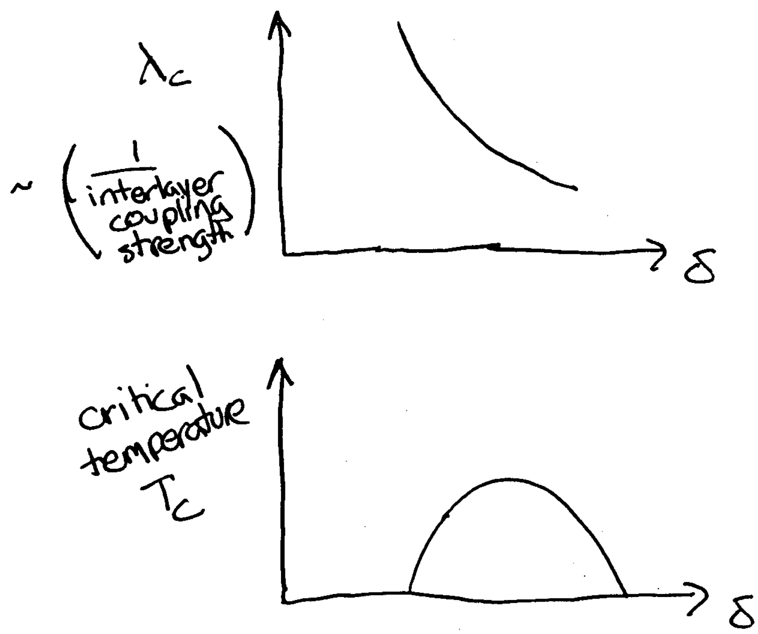
CARRIER DOPING ALSO HAS A RADICAL BUT DIFFERENT EFFECT ON THE INTERLAYER COUPLING:



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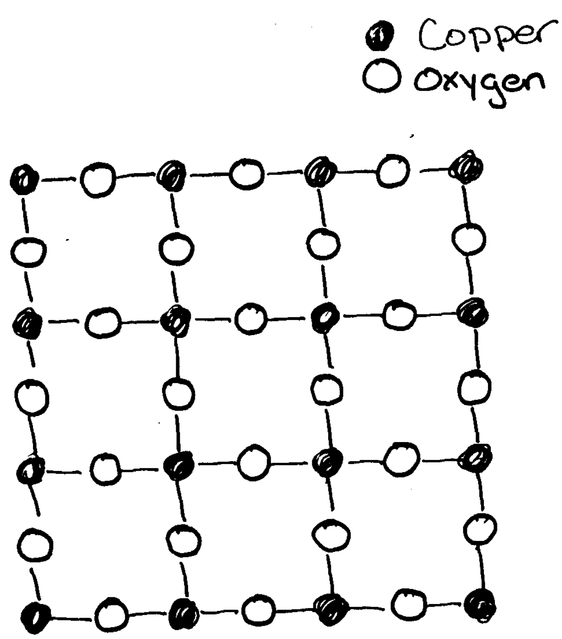
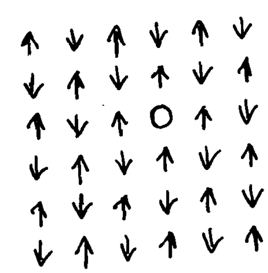
Popular School of Thought:

Superconductivity occurs because of an in-plane mechanism

but we don't need to know what it is to describe these materials quite well phenomenologically

5 Copper Oxide Planes



<u>t-J model</u>

antiferromagnetism (J)
plus hopping (t)

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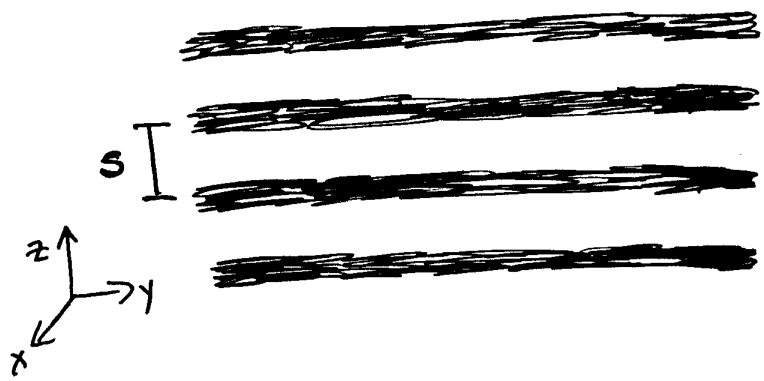
# Lawrence-Doniach Model 1971




(n) $\psi_n(x,y)$ in plane

$J_c \sin(\phi_n - \phi_{n-1})$
Josephson coupling between planes

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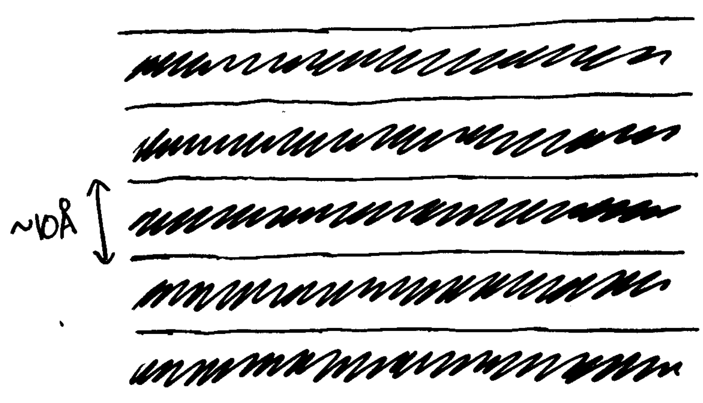
One way to look at cuprate superconductors:




copper oxide plane (superconducts)

stuff
- charge reservoir
- doesn't superconduct

Lawrence-Doniach equation:

$$\alpha\psi_n + \beta|\psi_n|^2\psi_n - \frac{\hbar^2}{2m_{ab}}\left(\vec{\nabla} - i\frac{2e}{\hbar c}\vec{A}\right)^2\psi_n$$

$$-\frac{\hbar^2}{2m_c s^2}\left(\psi_{n+1}e^{-2ieA_z s/\hbar c} - 2\psi_n + \psi_{n-1}e^{2ieA_z s/\hbar c}\right) = 0$$

$\vec{\nabla} = \hat{i}\frac{\partial}{\partial x} + \hat{j}\frac{\partial}{\partial y}$

$\vec{A} = A_x\hat{i} + A_z\hat{j}$

for smoothly varying $\psi$, this reduces to
Anisotropic Ginzburg-Landau:

$$\alpha\psi + \beta|\psi|^2\psi - \frac{\hbar^2}{2}\left(\vec{\nabla} - i\frac{2e}{\hbar c}\vec{A}\right)\cdot\frac{1}{m}\cdot\left(\vec{\nabla} - i\frac{2e}{\hbar c}\vec{A}\right)\psi = 0$$

$\vec{\nabla} = \hat{i}\frac{\partial}{\partial x} + \hat{j}\frac{\partial}{\partial y} + \hat{k}\frac{\partial}{\partial z}$

$\vec{A} = A_x\hat{i} + A_y\hat{j} + A_z\hat{k}$

$\frac{1}{m}$ reciprocal mass tensor

weak interlayer coupling $\Rightarrow$ $m_c \gg m_{ab}$

Ginzburg-Landau free energy in the absence of fields

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$$F = \int\left(\alpha|\psi|^2 + \frac{1}{2}\beta|\psi|^4 + \frac{1}{2m^*}\left|\frac{\hbar}{i}\vec{\nabla}\psi\right|^2\right)dx\,dy\,dz$$

Lawrence-Doniach free energy:

$$F = \sum_n \int\left[\alpha|\psi_n|^2 + \frac{1}{2}\beta|\psi_n|^4 + \frac{\hbar^2}{2m_{ab}}\left(\left|\frac{\partial\psi_n}{\partial x}\right|^2 + \left|\frac{\partial\psi_n}{\partial y}\right|^2\right)\right.$$

$$\left. + \frac{\hbar^2}{2m_c s^2}|\psi_n - \psi_{n-1}|^2\right]dx\,dy$$

aside: setting $\psi_n = |\psi_n|e^{-i\phi_n}$ and $\psi_{n-1} = |\psi_n|e^{-i\phi_{n-1}}$,
the last term becomes

$$\frac{\hbar^2}{m_c s^2}|\psi_n|^2\left[1 - \cos(\phi_n - \phi_{n-1})\right]$$

which looks like a Josephson coupling energy
(you can think of either $J_c$ or $m_c$ as being
the intrinsic parameter)

(12) Phenomenology of high-$T_c$ in LD model: $\perp$

anisotropic coherence length $\xi_i^2(T) = \dfrac{\hbar^2}{2m_i \cdot |\alpha(T)|}$

$$\boxed{\begin{array}{l} \xi_{ab} \sim 10\text{-}20\,\mathring{A} \\ \xi_c \lessapprox 1\,\mathring{A} \end{array}}$$

thermodynamic critical field $H_c(T) = \dfrac{\Phi_0}{2\sqrt{2}\pi\,\xi_i(T)\,\lambda_i(T)}$

cannot depend on $i$

penetration depth

$$\boxed{\begin{array}{l} \lambda_{ab} \sim 0.1\text{-}0.2\,\mu m \\ \lambda_c \sim 1\mu \rightarrow \text{larger than sample} \end{array}}$$

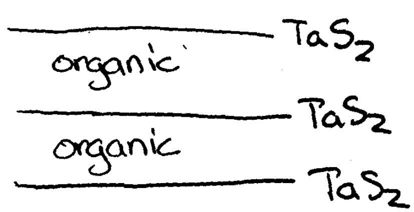
anisotropy parameter $\gamma \equiv \left(\dfrac{m_c}{m_{ab}}\right)^{1/2} = \dfrac{\lambda_c}{\lambda_{ab}} = \dfrac{\xi_{ab}}{\xi_c}$ $\sim 7$ YBCO

$>100$ BSCCO

both $T_c \approx 90K$

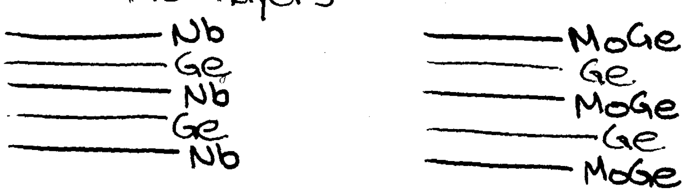
(11) Lawrence-Doniach model applied to:

- Transition-metal dichalcogenides

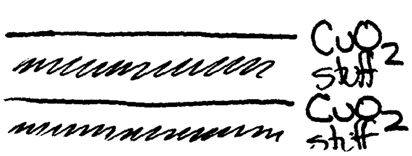



$T_c \sim 1K$

- Artificial multilayers

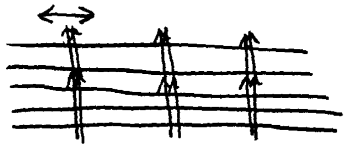



- Cuprate superconductors



(14) LD phenomenology in high-$T_c$ : 2

"pancake vortices" and 3D-2D behavior

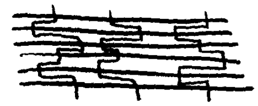


flux tubes or vortices parallel to c-axis

vortex core size: $\xi_{ab}$

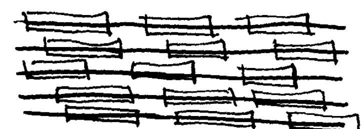
magnetic flux size: $\lambda_{ab}$

vortex spacing: $\sqrt{\Phi_0/B}$



thermal, quantum, and pinning effects

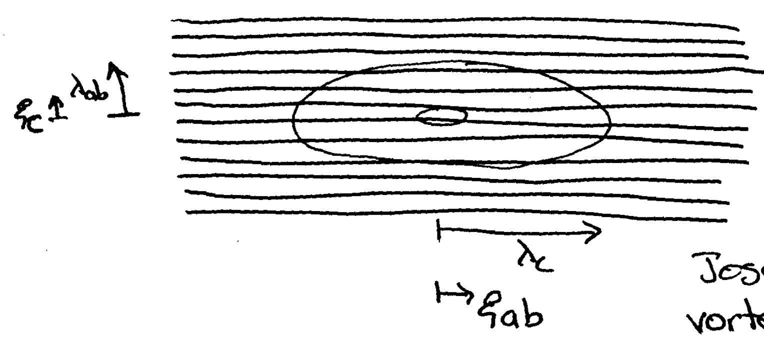
extreme 2D limit:



decoupled "pancake" vortices

(13) LD phenomenology in high-$T_c$ : 3

"interlayer Josephson vortex"




vortices parallel to a-axis

Josephson core: vortex core "fits between" layers

vortex in isotropic GL:

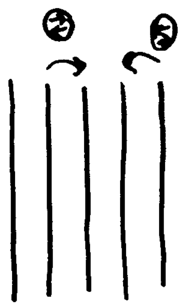
$$B(x,y) = \frac{\Phi_0}{2\pi\lambda^2} K_0\left(\sqrt{(\xi/\lambda)^2 + (x^2+y^2)/\lambda^2}\right)$$

vortex in LD:

$$B(x,y) = \frac{\Phi_0}{2\pi\lambda_a\lambda_c} K_0\left(\sqrt{\left(\frac{s}{2\lambda_a}\right)^2 + \left(\frac{x}{\lambda_c}\right)^2 + \left(\frac{y}{\lambda_a}\right)^2}\right)$$

LD phenomenology in high-$T_c$: 4

Josephson plasma resonance

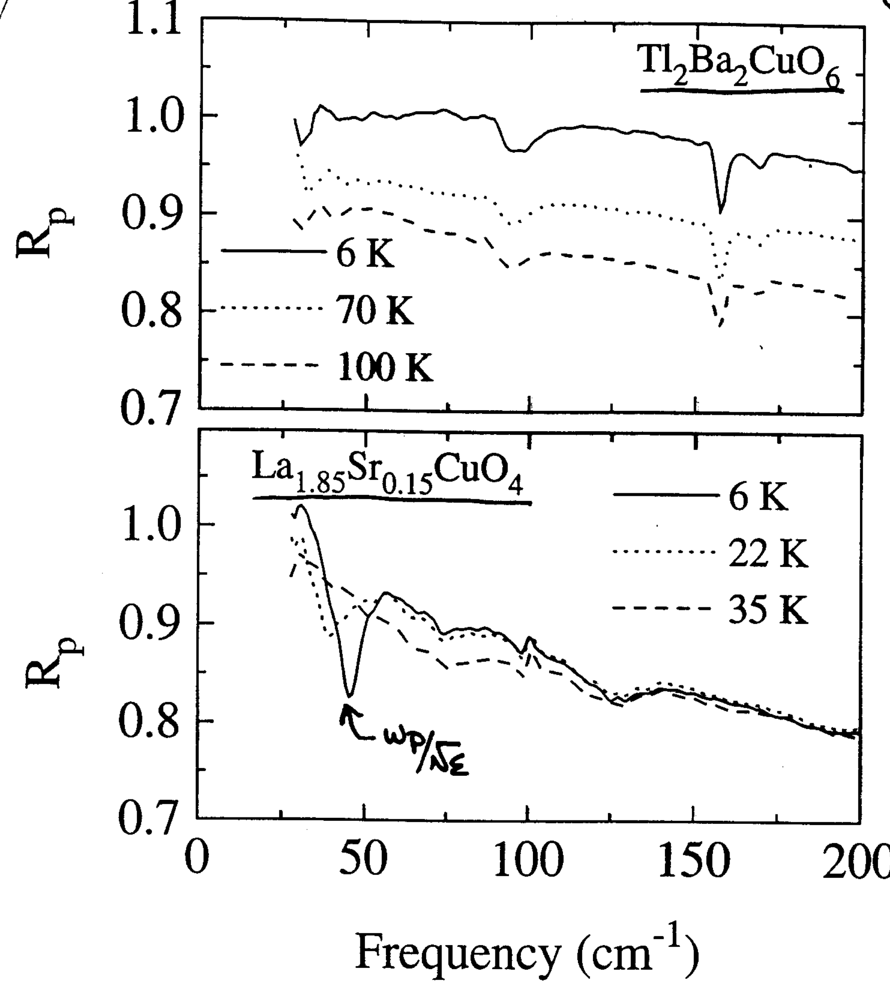


$\omega_p = \frac{1}{2\pi\sqrt{\varepsilon}\,\lambda_c}$

dielectric constant of interlayer medium

characteristic frequencies: far-infrared to microwave






Schützmann et al
Tl-2201 lower limit

$\frac{1}{(2\pi)\,100\,\text{cm}^{-1}} = 16\,\mu\text{m} < \lambda_c$

$\lambda_c = \frac{c}{2\pi f_p}$

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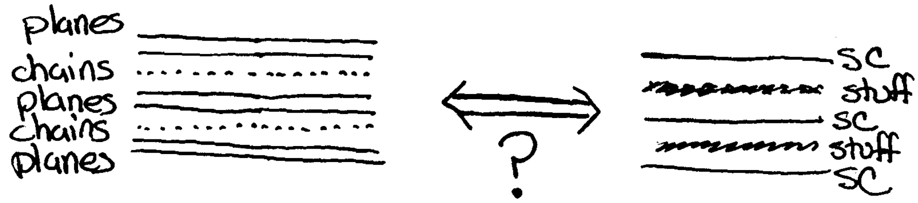
Qualitative fly in the ointment:

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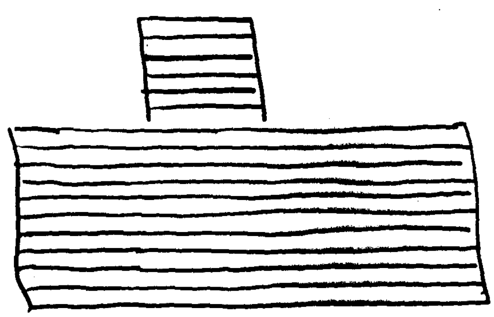
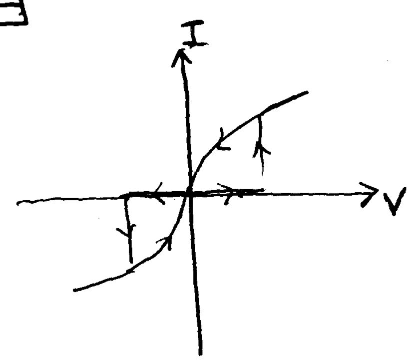
LD phenomenology: 5

direct observation of Josephson Junction behavior in BSCCO mesas



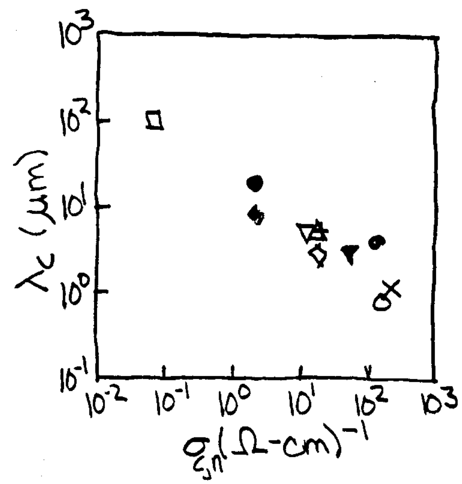


Naive model for c-axis tunneling:
Ambegaoker - Baratoff
(diffusive transfer of s-wave pairs)

$$J_0 = \frac{\pi \Delta_0}{2e\rho_{c,n}} \qquad \lambda_c = \sqrt{\frac{c\,\Phi_0}{8\pi^2 s J_0}}$$

problems:
- what's $\rho_{c,n}$ $(T=4K, H\approx 0)$?
- effective mass (Das Sarma)
- d-wave

$\lambda_c \cong 6\,\mu$ (Tl-2201)
$\lambda_c \cong 8\,\mu$ (Hg-1201)




adapted from Basov et al



Quantitative fly in the ointment:

LD gives a good description if $\lambda_{ab}$ and $\lambda_c$ are free parameters

but are they related to microscopic parameters in the way you'd expect for a stack of coupled Josephson junctions?

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"Convential" estimates for $\lambda_c$ in Tl-2201

| | |
|---|---|
| specular transmission (parallel momentum conserved) | $\lambda_c \approx 1\,\mu m$ |
| diffusive transmission (parallel momentum not conserved) | $\lambda_c \approx 1-6\,\mu m$ |
| diffusive + d-wave (or other anisotropic gap) | $\lambda_c > 1-6\,\mu m$ |
| Fertig & Das Sarma (microscopic tight binding) | $\lambda_c \approx 15-450\,\mu m$ |

Interlayer tunneling model $\lambda_c = 0.8-2\,\mu m$

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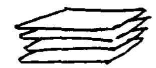
# Interlayer Tunneling (ILT) Model



tunneling inhibited in normal state
∴ c-axis kinetic energy saved in superconducting state

caution 1: ILT model ≠ interlayer tunneling
caution 2: ILT model ≠ Anderson-Chakravarty model

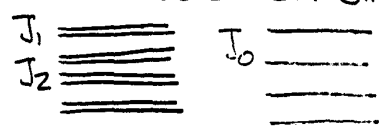
- non-observation of $\omega_p$ in Tl-2201 $\Rightarrow \lambda_c \gtrsim 15\mu$ (Groningen) $\omega_p \equiv \frac{c}{2\pi\lambda_c}$
- quantitative pre-requisite (Leggett)

$$\boxed{\lambda_c = \frac{\lambda_{ILT}}{2\eta^{1/2}}} \qquad \lambda_{ILT} = \frac{A}{(E_c)^{1/2}}$$

A: known geometrical factor; $E_c$: condensation energy

$\eta \approx$ fraction of condensation energy which could come from c-axis K.E. savings

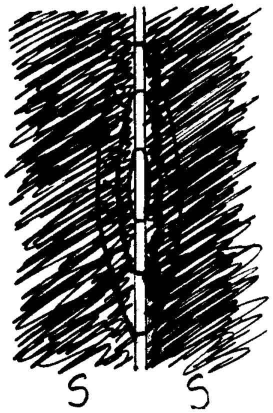
- best tested on single-layer high-$T_c$ material




| | |
|---|---|
| Tl-2201 | $\lambda_{ILT} \sim 1\mu$ |
| Hg-1201 | $\lambda_{ILT} \sim 1\mu$ |
| LSCO | $\lambda_{ILT} \sim 3\mu$ |

# Images of Interlayer Josephson Vortices

## Josephson vortex

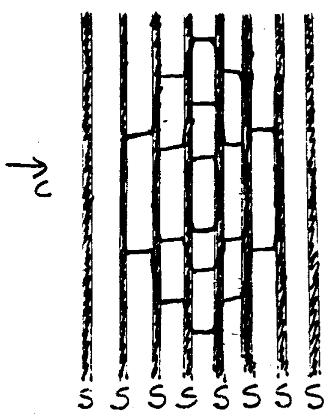



y
z → x

$$b_z(x,y) = \frac{\Phi_0}{2\pi\lambda_L\lambda_J}\,\mathrm{sech}(y/\lambda_J)\,e^{-|x|/\lambda_L}$$

$\lambda_L \sim 0.2\mu m$
$\lambda_J \sim$ microns

## Interlayer Josephson vortex



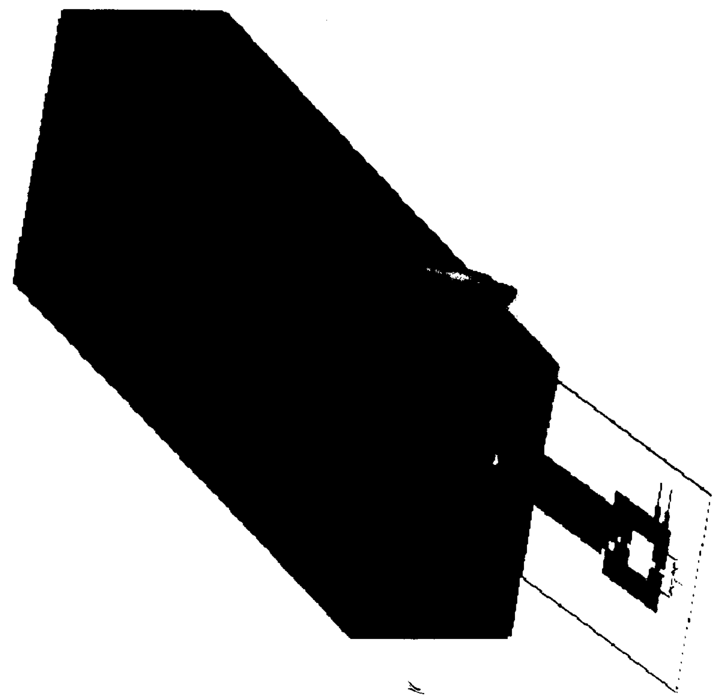

y
z → x

$$b_z(x,y) = \frac{\Phi_0}{2\pi\lambda_a\lambda_c}K_0\left(\left[\left(\frac{s}{2\lambda_a}\right)^2+\left(\frac{x}{\lambda_a}\right)^2+\left(\frac{y}{\lambda_c}\right)^2\right]^{1/2}\right)$$

$s \sim 10Å$
$\lambda_a \sim 0.2\mu$
$\lambda_c \sim$ microns



# Scanning SQUID microscopy of Josephson vortices



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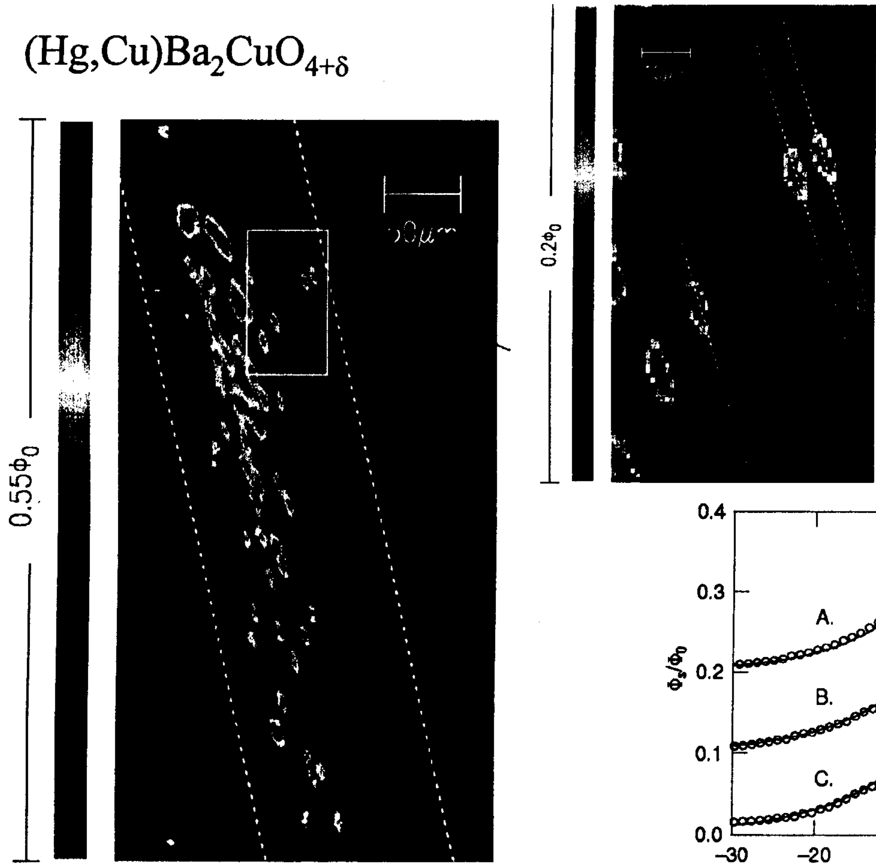
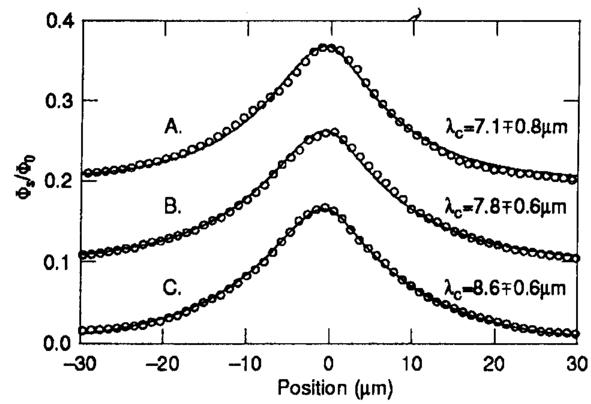
# $(Hg,Cu)Ba_2CuO_{4+\delta}$




$\lambda_c = 8 \pm 1 \mu m$




KAM APS 1999

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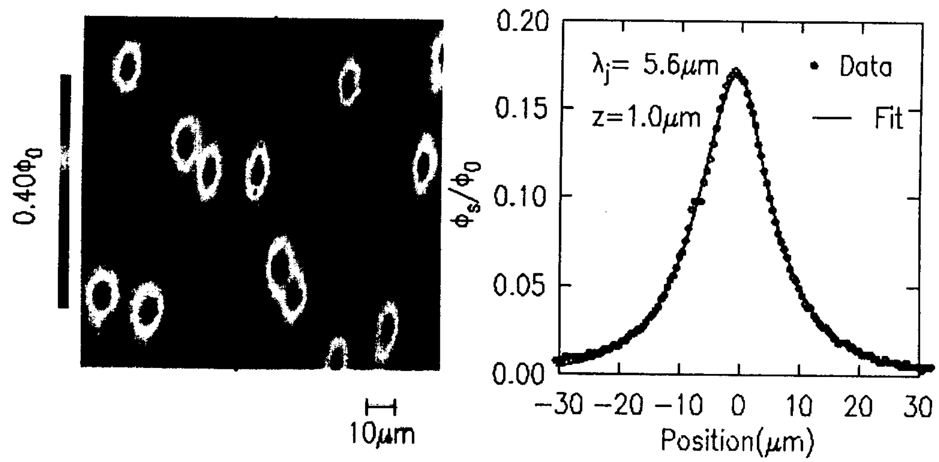
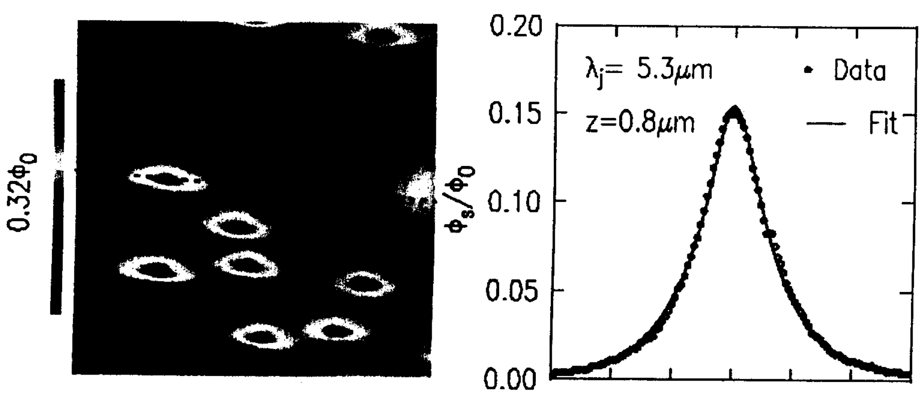
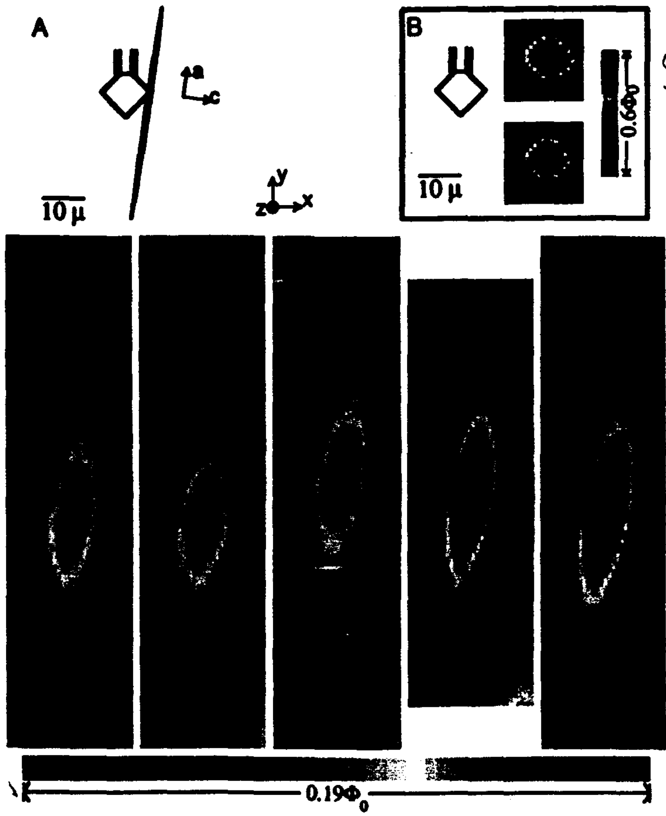
# $La_{2-x}Sr_xCuO_4$




$\lambda_c \approx 5 \pm 1\ \mu m$






$\lambda_c$

ab-plane vortices (UBC YBCO)

interlayer Josephson vortices (Argonne Tl-2201)

Tl-2201 Argonne onset $T_c$ 90K
midpoint $T_c$ 77-79K
width (10%-90%) 7-10K

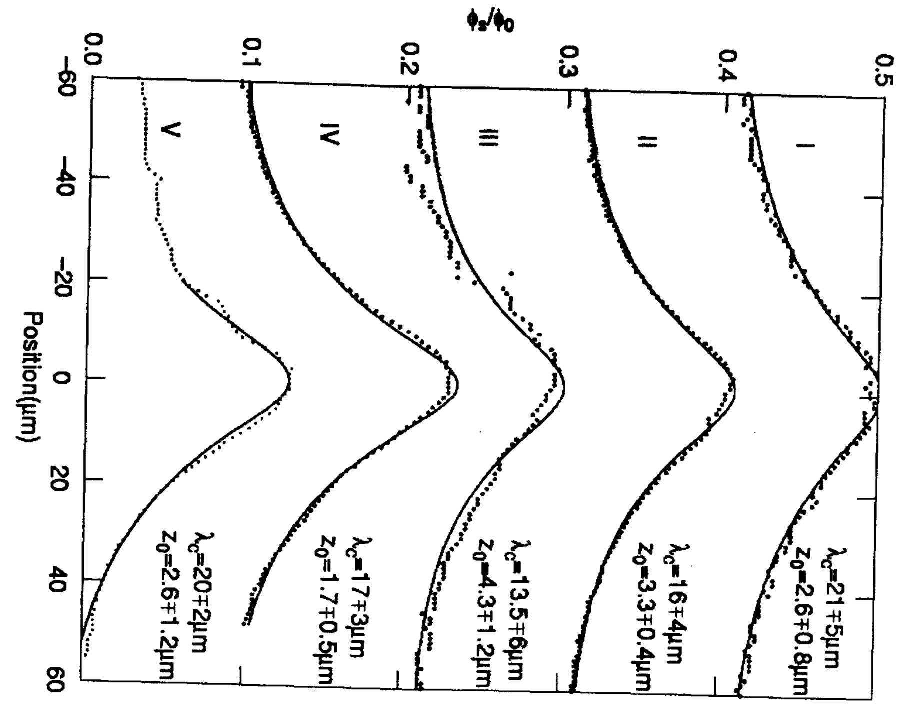


# Tl-2201 cross-section fits

FWHM ≈ 35 μm
$\lambda_c \approx 20$ μm

Spreading Neglected
$\lambda_c \approx 19 \pm 2$ μm

Anisotropic London model with interface
$\lambda_c \approx 18 \pm 3$ μm



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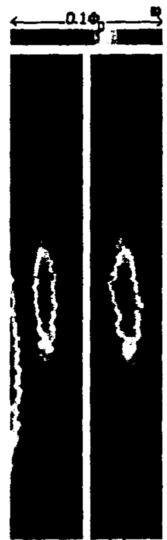
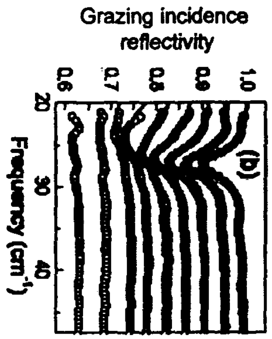
# Are we measuring the intrinsic penetration depth in Tl-2201?

Vortices in 3 crystals from 2 groups gives consistent results with scanning SQUID microscopy.



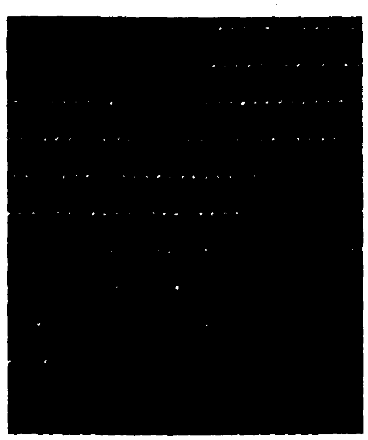

Optical techniques give consistent results.




λc = 17μm Tsvetkov et al 1998 (thin films from Ren's group)

λc = 12μm Basov et al 1999 (crystals from Hinks)

No evidence for stacking faults or superlattice structure in TEM or x-ray.



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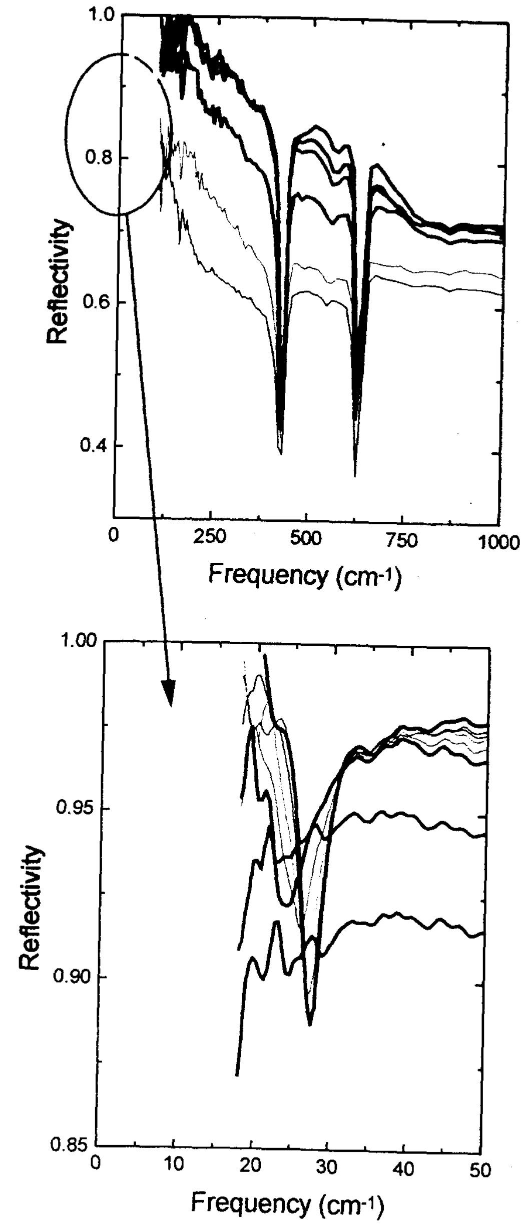
Single Crystal of Tl2B2aCuO6

300 K
200 K
**100 K**
**70 K**
**50 K**
**4 K**

Epitaxial Film of Tl2B2aCuO6

**90 K**
**75 K**

**50 K**
40 K
30 K
20 K
10 K
**4 K**




A. Tsvetkov et al, Gröningen

$\lambda_c$ in nominally optimally doped single-layer cuprates

| | LSCO | Hg-1201 | Tl-2201 |
|---|---|---|---|
| $\lambda_{ILT}$ | ~3μm [Anderson]* | ~1μm [Anderson]† | ~1μm [Anderson]* |
| vortex imaging | ~5μm | 8±1μm | 18±3μm |
| optical (1/ω) | | 6μm [Basov] | 12μm [Basov] |
| optical (sum rule) | 4½ μm [Uchida] | | |
| optical ($\omega_p$) | | | 17μm [van der Marel] |
| μwave | 4μm [Shibauchi] | | |
| oriented powder susceptibility | | 1.36±0.16μm [Panagopoulos] | |
| $\eta \cong \left(\frac{\lambda_{ILT}}{\lambda_c}\right)^2$ | $\eta \lesssim 1$ | $\eta \sim 10^{-2}$ | $\eta \sim 10^{-3}$ |

*C.p by Loram
†C.p by Charalambous



Summary:

- Lawrence-Doniach provides a good phenomenological model to describe the magnetic properties of the cuprates
(but leaves quantitative microscopic questions wide open)

- The Inter-Layer Tunneling (ILT) model proposed by P.W. Anderson and coworkers as a mechanism for superconductivity cannot supply all of the condensation energy
(but this model or conceptually similar models may still play some role).

talk to Michael Turlakov at this conference...