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INTERNATIONAL ATOMIC ENERGY AGENCY
INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
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H4.SMR/1001-2

IX TRIESTE WORKSHOP ON
OPEN PROBLEMS IN
STRONGLY CORRELATED SYSTEMS

14 - 25 July 1997

A NEW PHASE TRANSITION IN THE SUPERCONDUCTING STATE OF Bi 2212 DETECTED BY THE QUASI-PARTICLE HEAT CURRENT

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These are preliminary lecture notes, intended only for distribution to participants.

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Quasi - Particle Heat Current in Field

K. Krishana, N.P.O. (Princeton)†
T. Kimura (U. of Tokyo, JRCAT)
Q. Li (Brookhaven Natl. Lab.)
G. Genda (U. New South Wales)

- Coherence

clean • Thermal Hall effect κ_{xy} in YBCO

dirty • κ_{xx} vs B in LaSrCuO

Decoherence

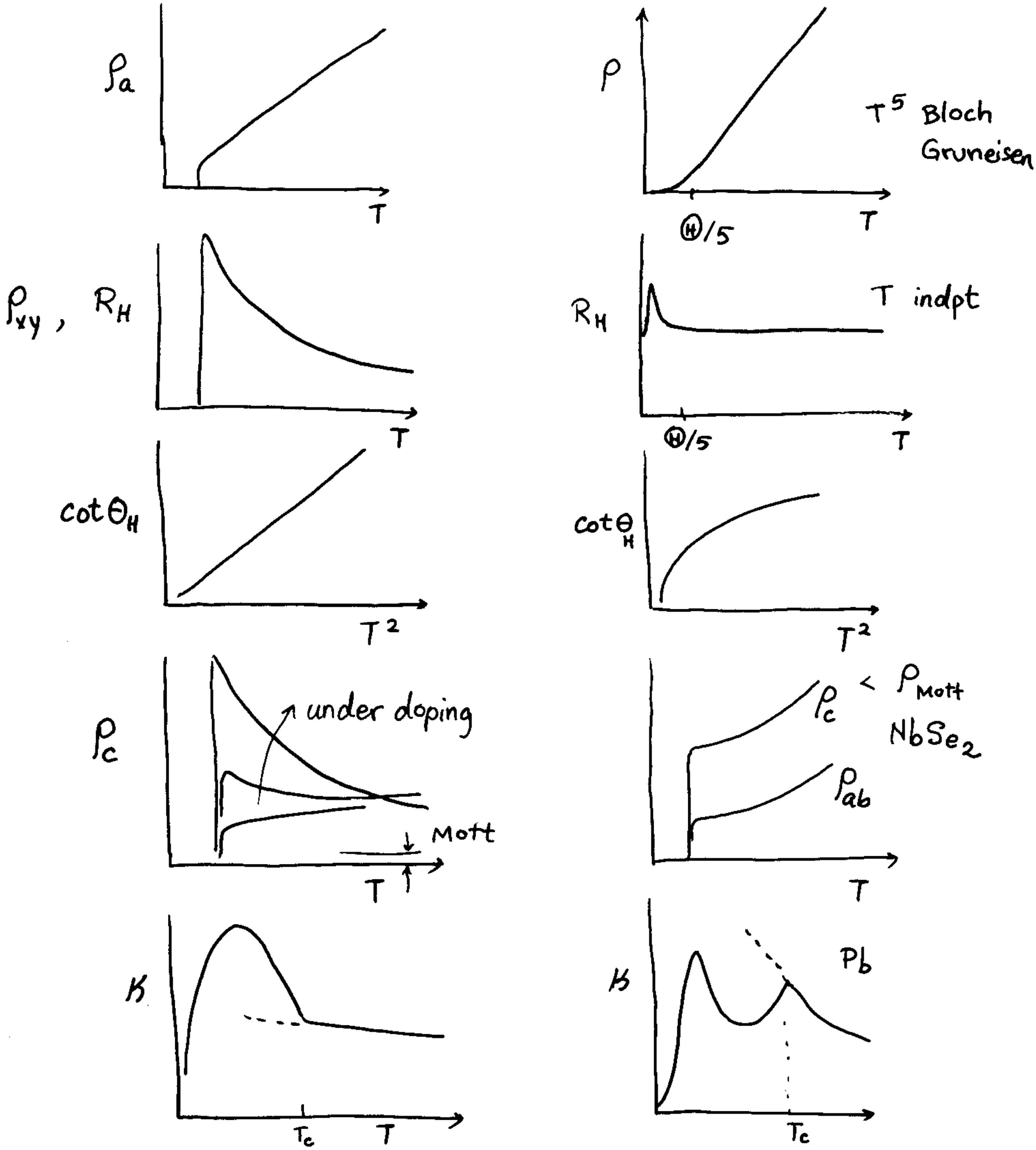
2D limit • κ_{xx} vs B in Bi 2212

Plateau ↔ a new state ?

† Supported by ONR, NSF

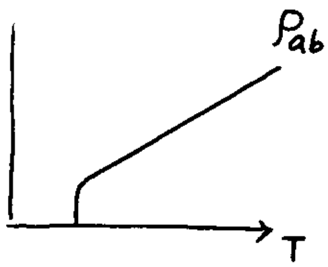
Transport Anomalies in Cuprates

Cuprates | Covent.^{n} Metals



Recovery of coherence

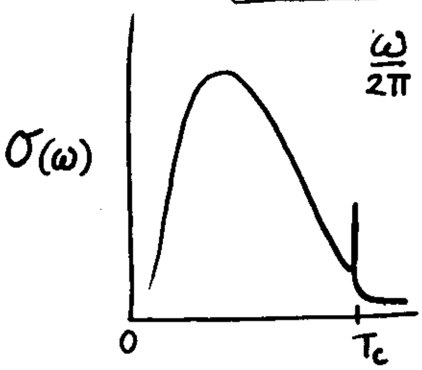
Above T_c, scattg. of charge is intense.



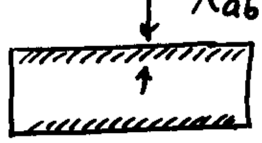
$\frac{\hbar}{\tau_{tr}} \sim 2kT$ $\quad \tau_{tr} \sim 25$ fs, $YBCO_7$

$k_F \ell \sim 35$, $\quad \ell \sim 60$ Å at 100K

① Microw. conductivity



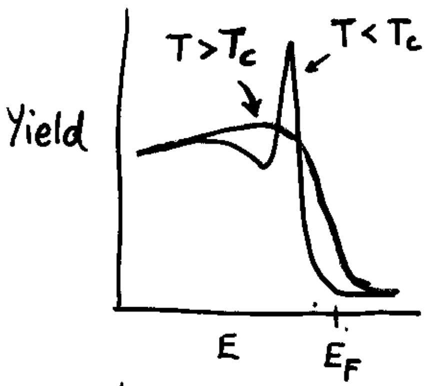
$\lambda_{ab} \sim 1500$ Å



Bonn, Hardy

Microwave abs. $\rightarrow$ $\sigma(\omega) = \frac{n_{qp}(T) e^2 \tau_{tr}}{m}$

est. $\tau_{tr} \sim 2$-4 ps at 4.2K

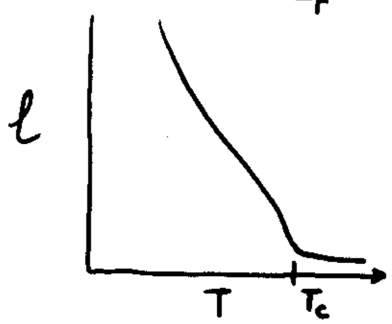


② ARPES spectrum

Bi 2212

Shen, Dessau..

Sharp QP peak at 20K

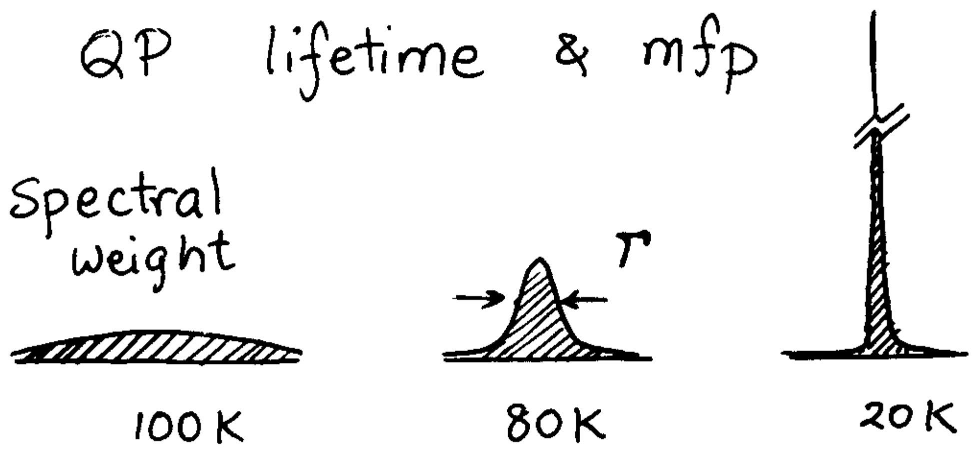


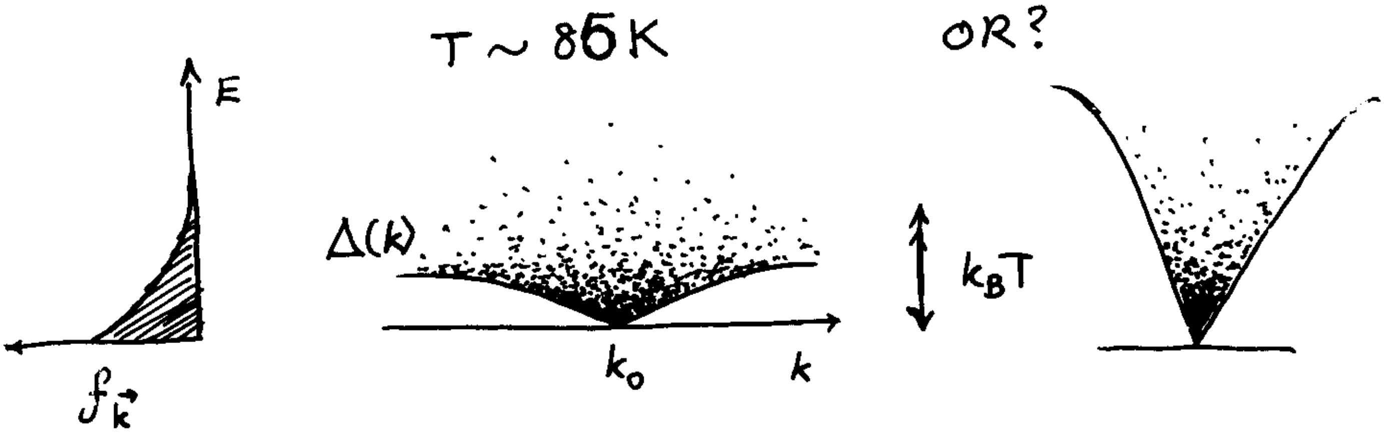
③ QP mean free path in $YBCO_7$

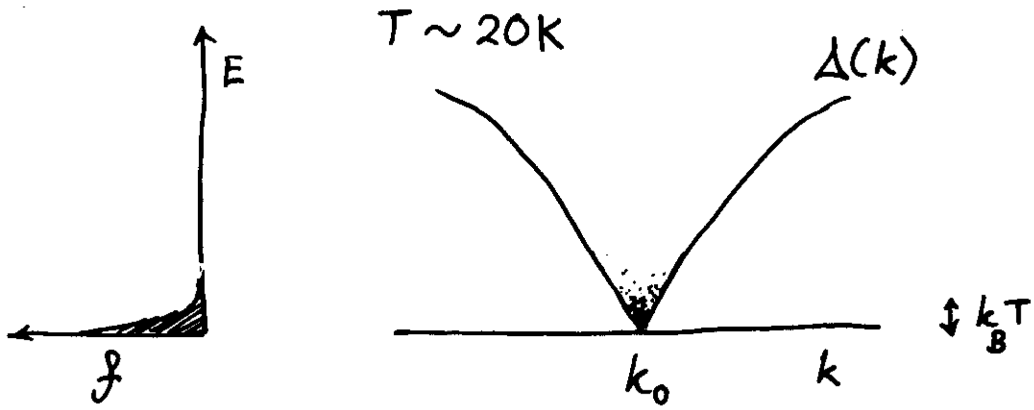
from thermal Hall $\quad$ Krishana

κ_{xy}

QP lifetime & mfp

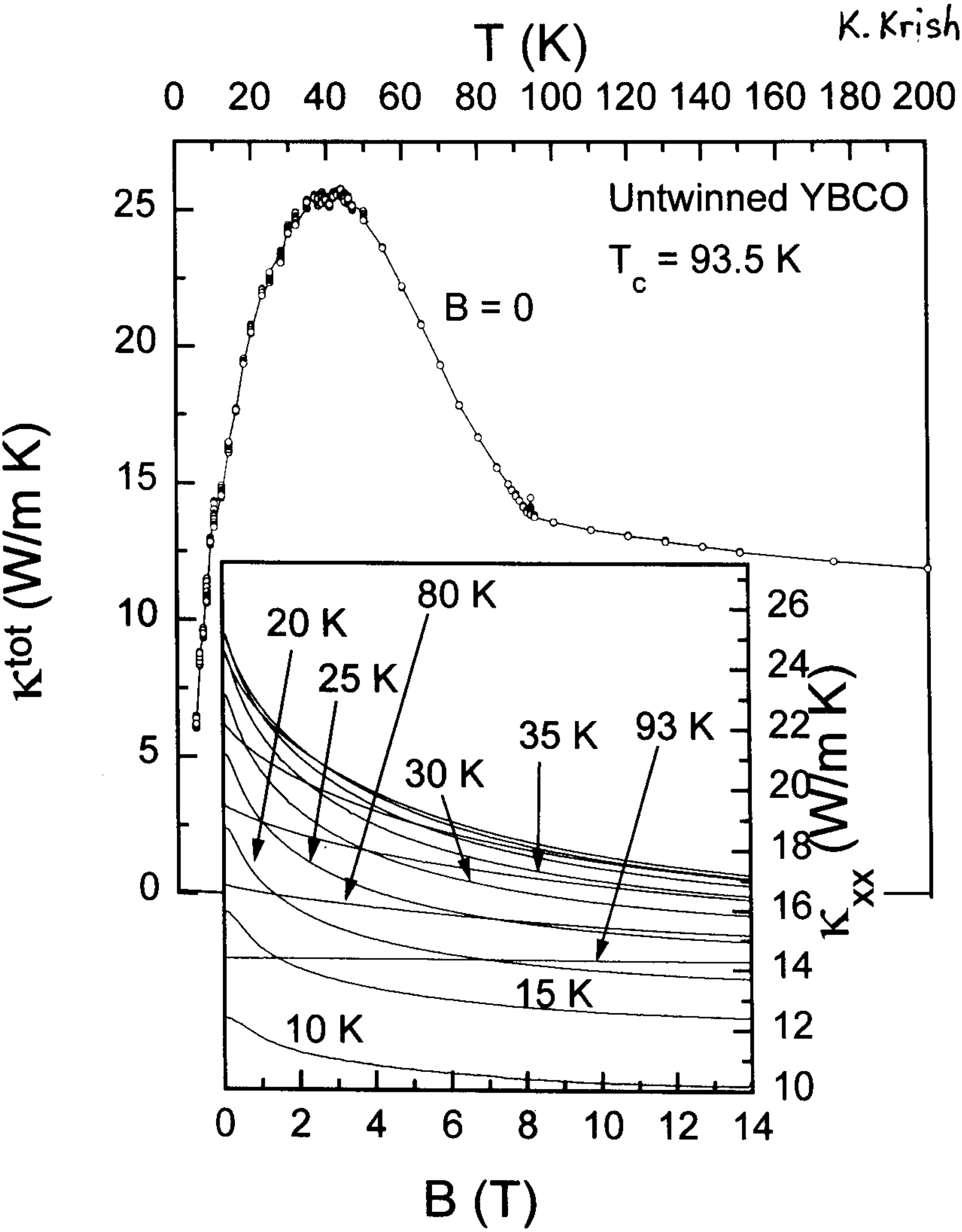






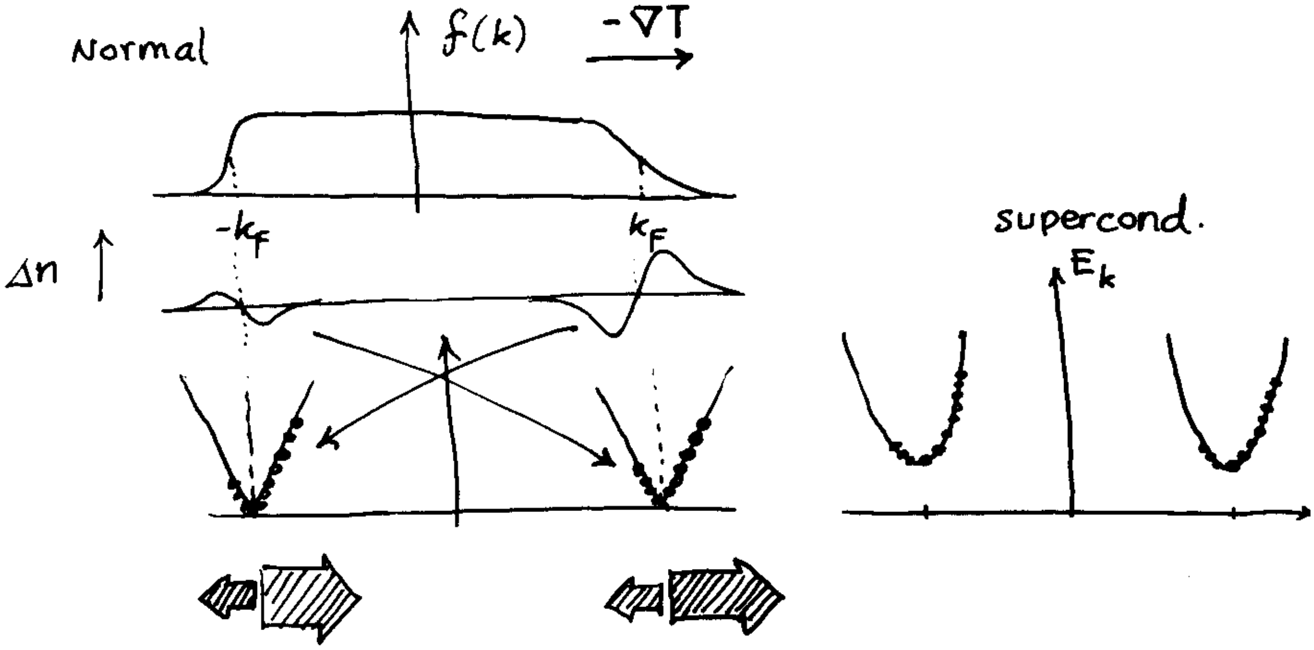
- Low-lying excitations of condensate
- Probe by microwave or thermal current

K. Krishana, N.P.O. Gagnon, Taillefer



Quasi Particle Heat Current

Excitation representation

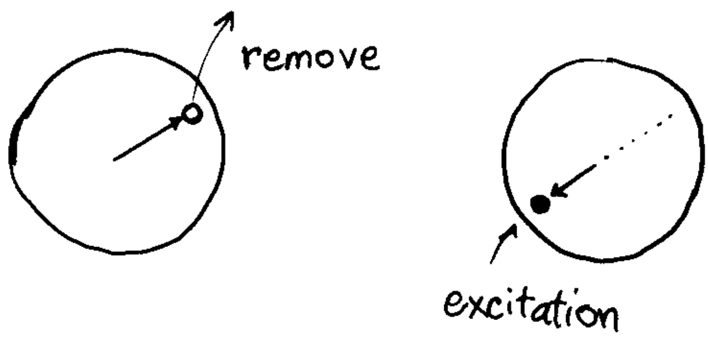


Neutral current

Absence of e^- at $\vec{k}\uparrow$, vel. $\vec{v}_e(\vec{k})$

= hole at $-\vec{k}\downarrow$, vel. $\vec{v}_h = \vec{v}_e(\vec{k})$

$$c_{k\uparrow}|0\rangle \longrightarrow d^{\dagger}_{-\vec{k}\downarrow}|0\rangle$$

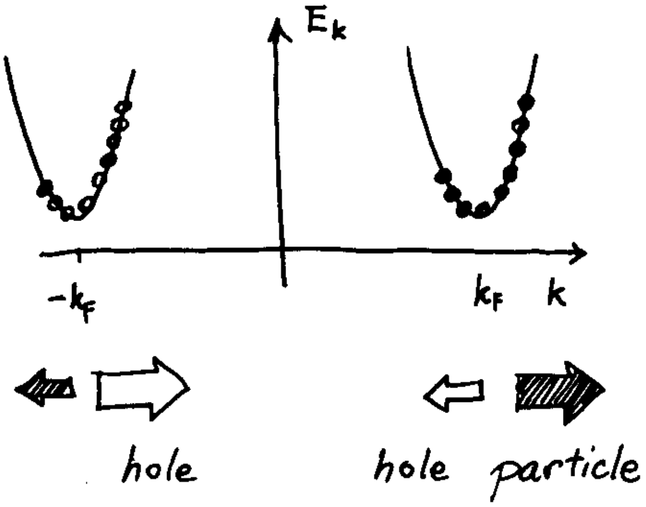


Bardeen Rickayzen Tewordt theory

Boltzmann

$$\vec{v}_k \cdot \frac{\partial f_k^0}{\partial \vec{x}} = -g_k \underset{\text{scattg. rate}}{\Gamma_k}$$

$-\nabla T$ $\longrightarrow$



QP energy

$$E_k = \sqrt{\Delta^2 + \xi_k^2}$$

$$\xi_k = \varepsilon_k^0 - \mu$$

J_e^Q is <u>electr. neutral</u>

$$\left(\hbar \vec{v}_k = \frac{\partial E_k}{\partial \vec{k}}\right) \qquad \vec{v}_k \cdot (-\nabla T)\left(\frac{-\partial f^0}{\partial E}\right)\frac{E_k}{T} = g_k \Gamma_k$$

$$J_e^Q = \sum_k g_k E_k v_k \cos\theta_k$$

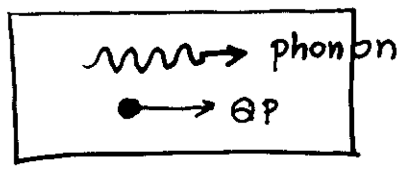
$$\kappa_{xx} = \frac{1}{T}\sum_k \left(\frac{-\partial f^0}{\partial E}\right) \frac{E_k^2}{\Gamma_k} v_k^2 \cos^2\theta_k$$

- $E_k v_k = \xi_k v_k^N$
- Impurity scattg. $\qquad \ell_N = \ell \rightarrow \frac{\tau_N}{\tau} = \frac{\xi_k}{E_k}$

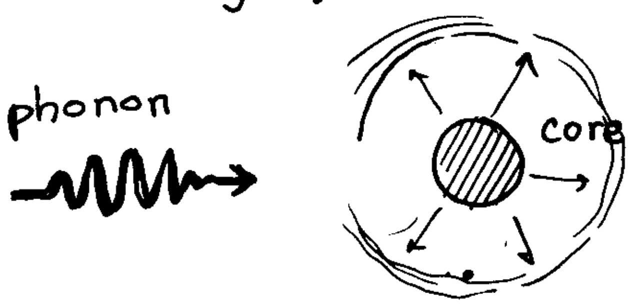
Heat current in low T_c supercond.

- Strong e^- – phonon scattg.

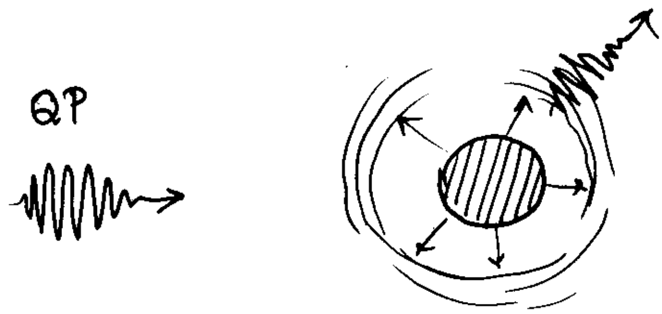
$$\kappa_{xx} = \kappa^{e}_{xx} + \kappa^{ph}_{xx}$$



Scattering from vortex core

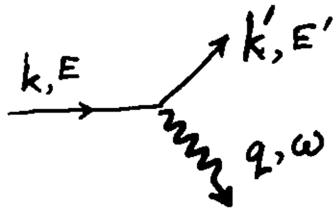


phonons scatter
el-phon. interactⁿ
in normal core



QP current also
scatters from core
(gap potential)

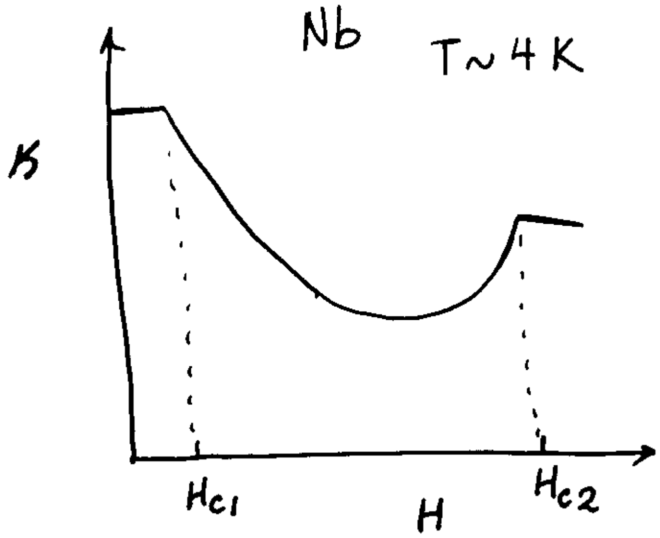
<u>Asymmetric</u>

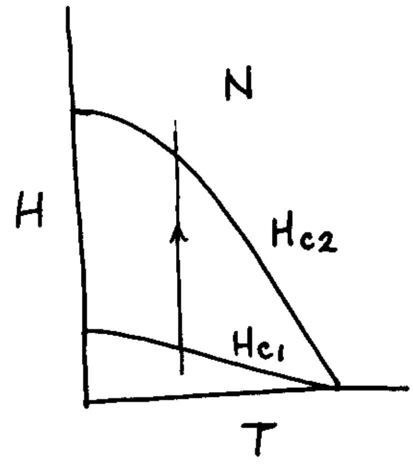


QP – phonon scattg.
in superfluid

Effect of H on κ (Nb, V)

Low T_c supercond.





① QP carries most of heat current

② Strong vortex - QP scattering decr. κ

③ $H \lesssim H_{c2}$ Sharp decr. of gap

→ incr. in QP population

→ incr. κ

④ Above H_{c2}, κ almost H indpt.

High purity Pb

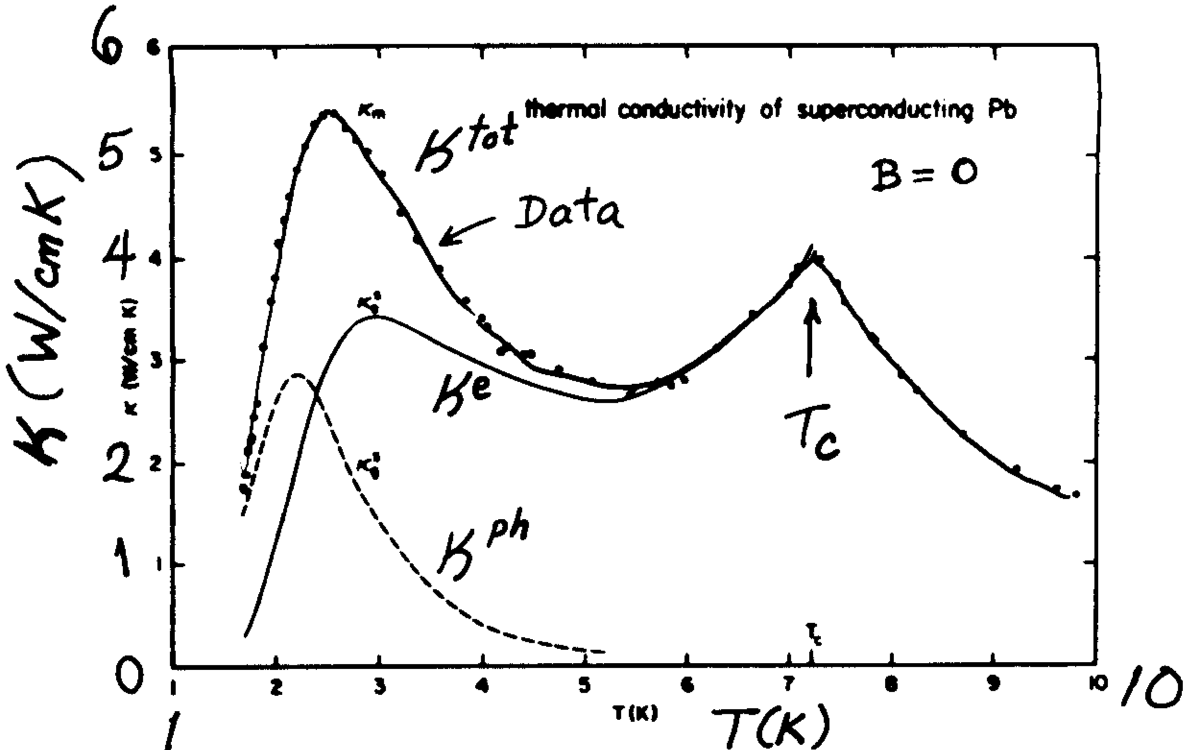


FIG. 1. Temperature dependence of the thermal conductivity of a high-purity lead crystal. κ_m, experimental data; κ_e^s, electronic component according to the theory of Ref. 9 with $c = 0.073$ and $\kappa_e(T_c) = 4.11$ W/cm K; κ_g^s, lattice thermal conductivity.

Jericho, Odani, Ott (1985)

Evidence for intense qp-phonon scattg.

5 K – 7 K $n_{qp} \searrow$ $n_{ph} \searrow$

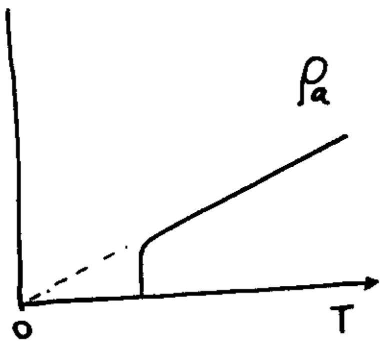
3 K – 5 K $\Gamma_{qp} \searrow$ $\Gamma_{ph} \searrow$ $\kappa^e \nearrow$, $\kappa^{ph} \nearrow$

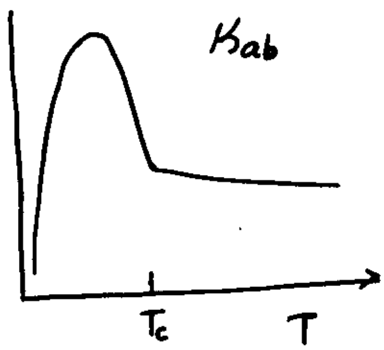
2 – 3 K $n_{qp} \searrow$ dominant, $\kappa^e \searrow$

< 2 K $n_{ph} \searrow$ " , $\kappa^{ph} \searrow$

Clean

$YBaCuO_7$



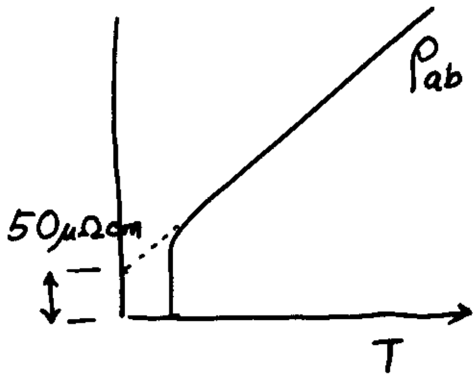


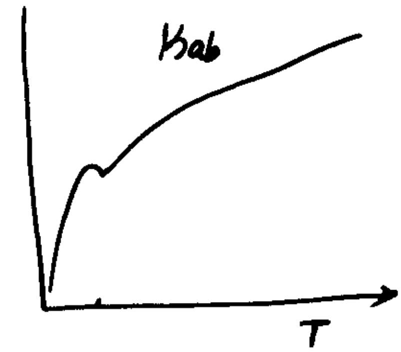
Negligible ρ_0

$l_0 \to \infty$

Dirty

LaSrCuO



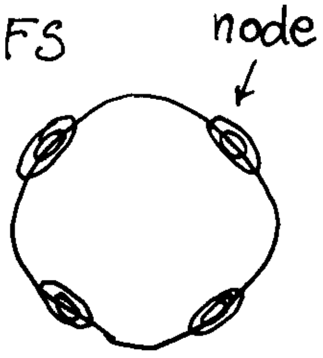


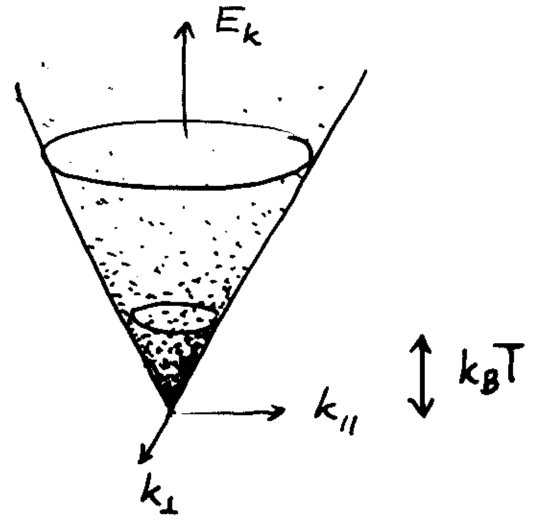
$\rho_0 \sim 50\,\mu\Omega cm$

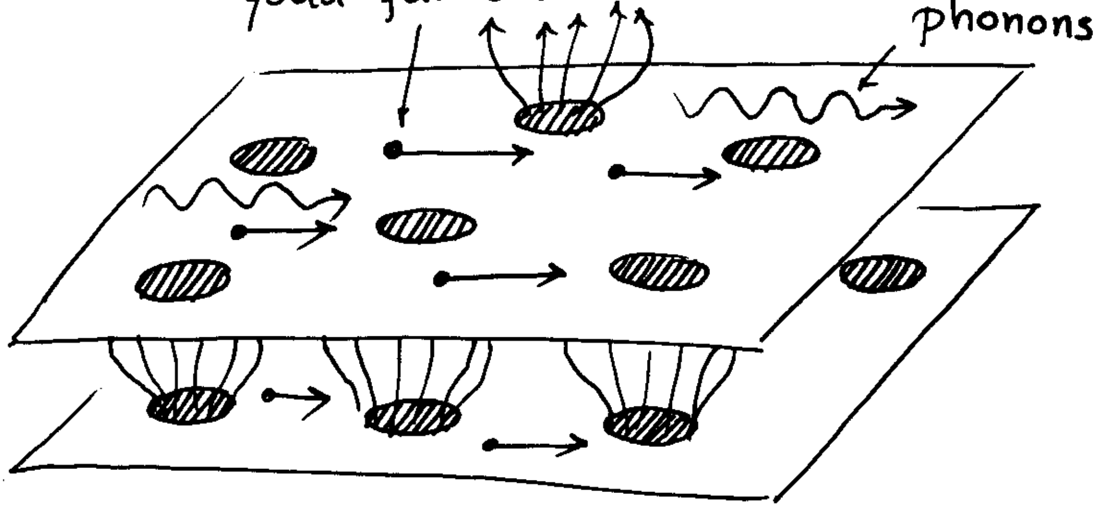
$\tau_0 \sim 86\ ps$

$l_0 \sim 113\ \text{Å}$

Cuprates

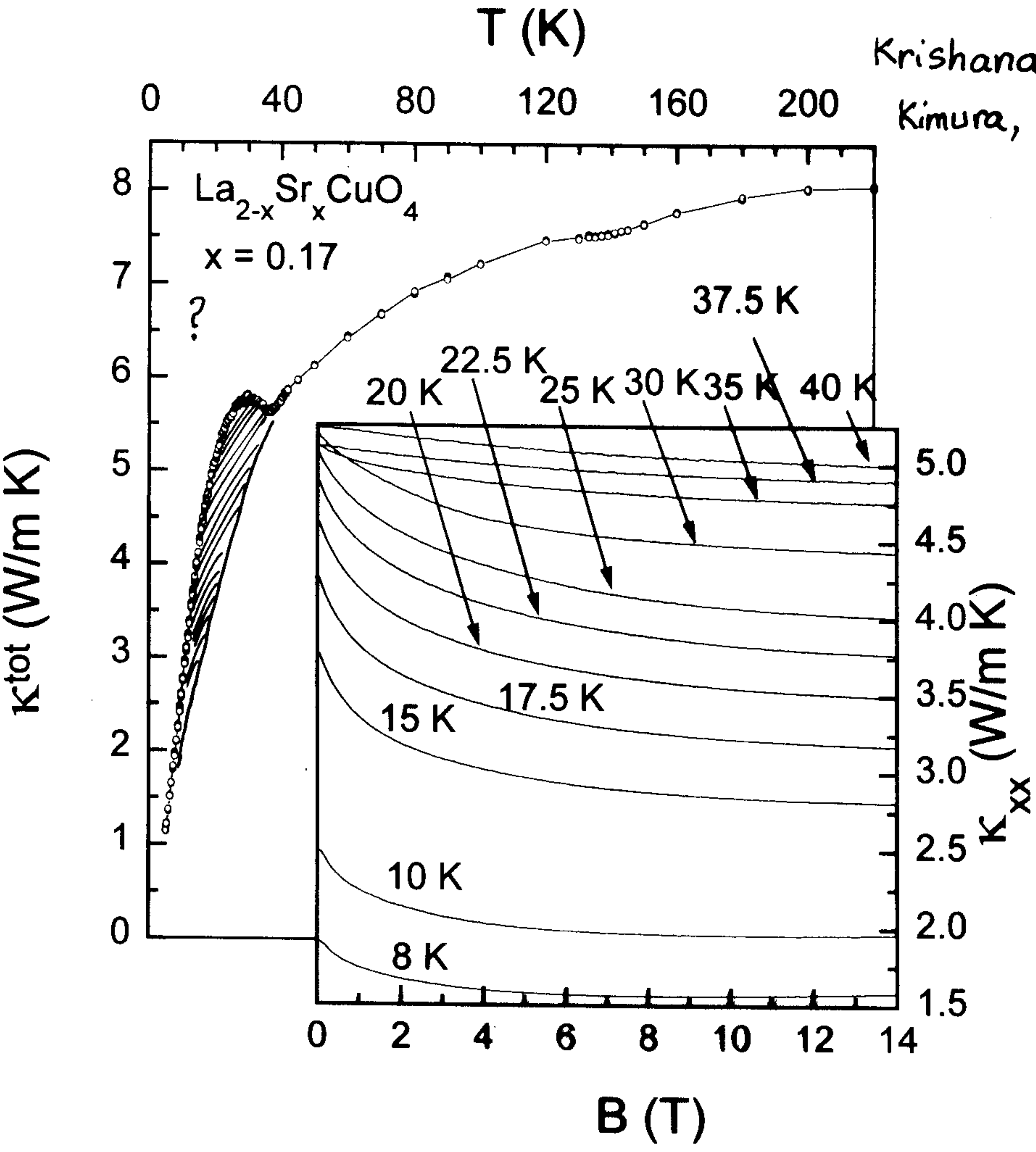






In-plane $\kappa = \kappa_{ph} + \kappa_e$

Krishana, Kimura, N.P.C



Absence of phonon scattering from vortex

At 10K, κ_{ph} dominates

$$\kappa_{ph} \gg \kappa_e$$

Total phonon scattg in field

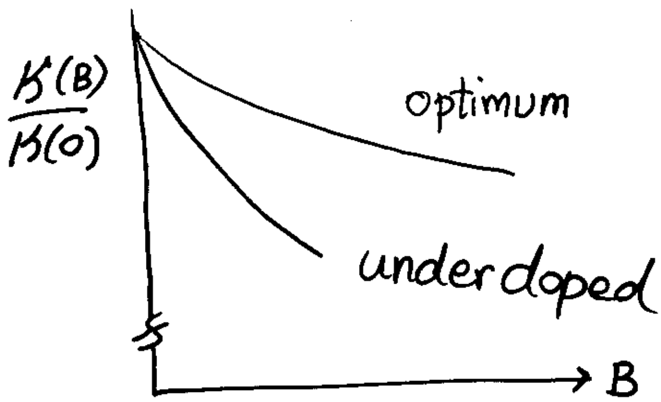
$$\frac{1}{\ell_{tot}} = \frac{1}{\ell_v} + \frac{1}{\ell(0)}$$

$$\kappa_{ph}(B) = \frac{\kappa_{ph}(0)}{1 + \frac{\ell(0)\sigma}{\Phi_0}|B|}$$

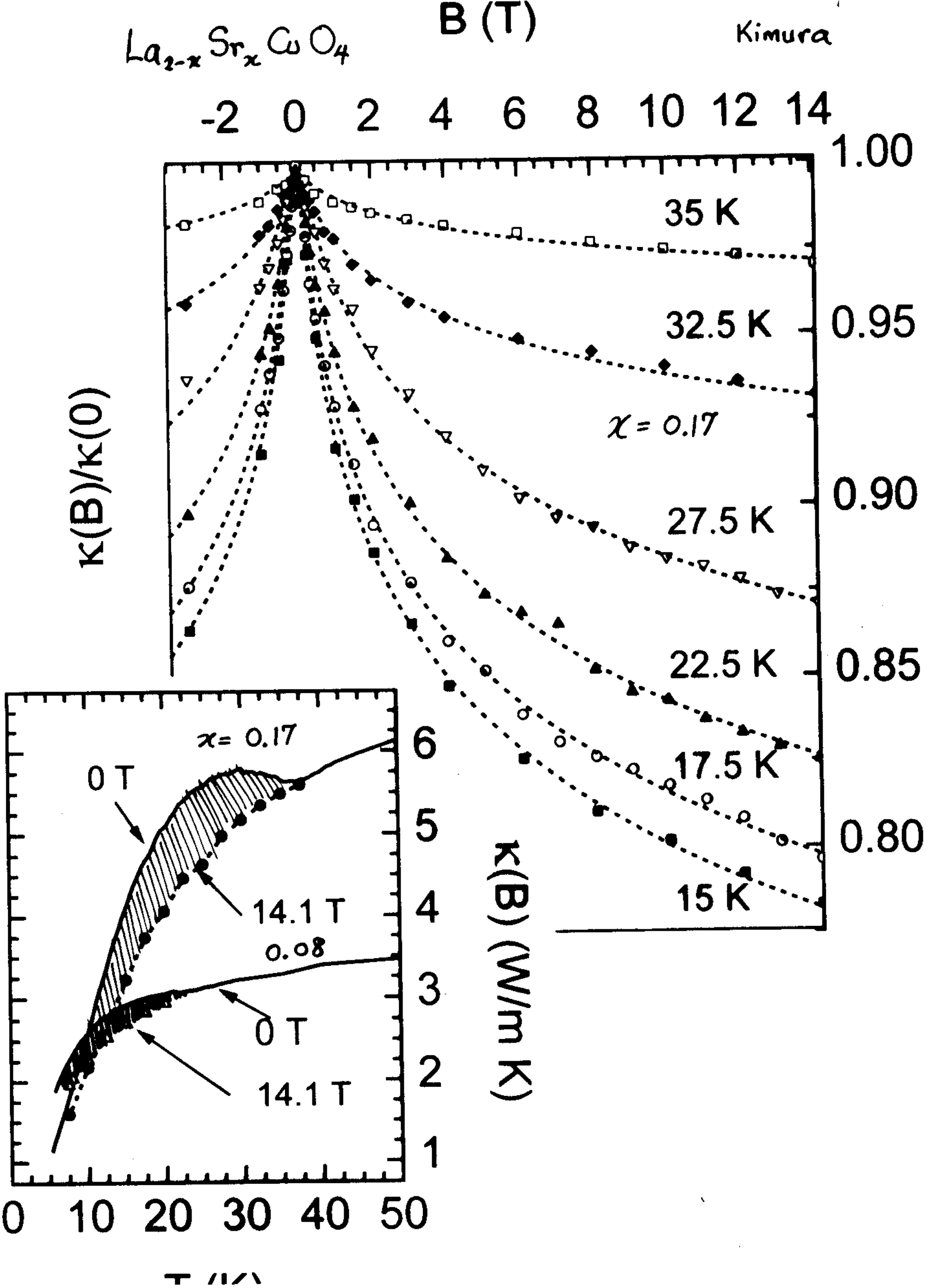
$$\frac{\Delta\kappa_{ph}(B)}{\kappa_{ph}(0)} = -\frac{\ell(0)\sigma}{\Phi_0}|B| \qquad (B \to 0)$$

$$= -\ell(0)\sigma n_v$$

Rate of decrease faster in underdoped. ?



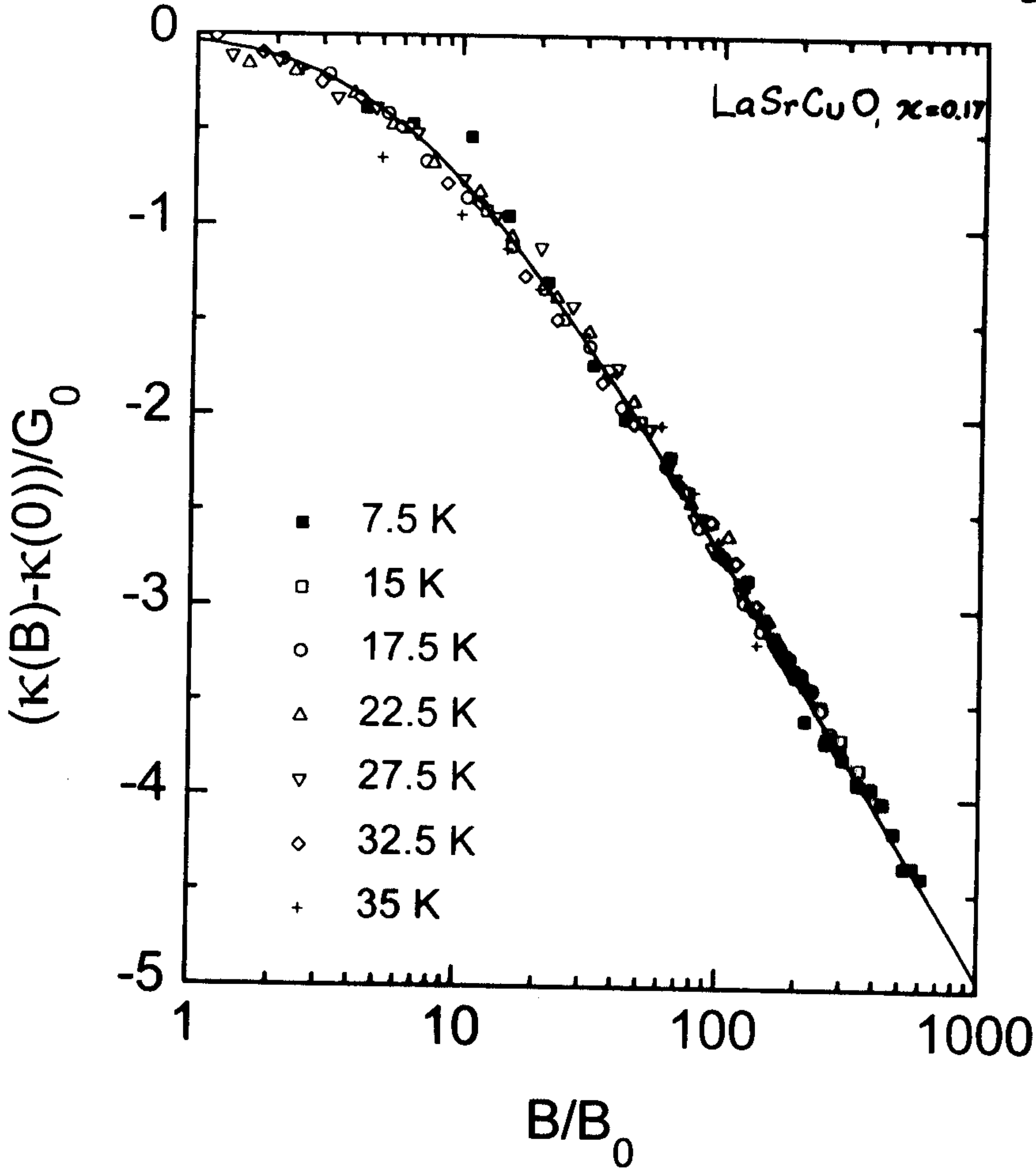
In conflict with expt.



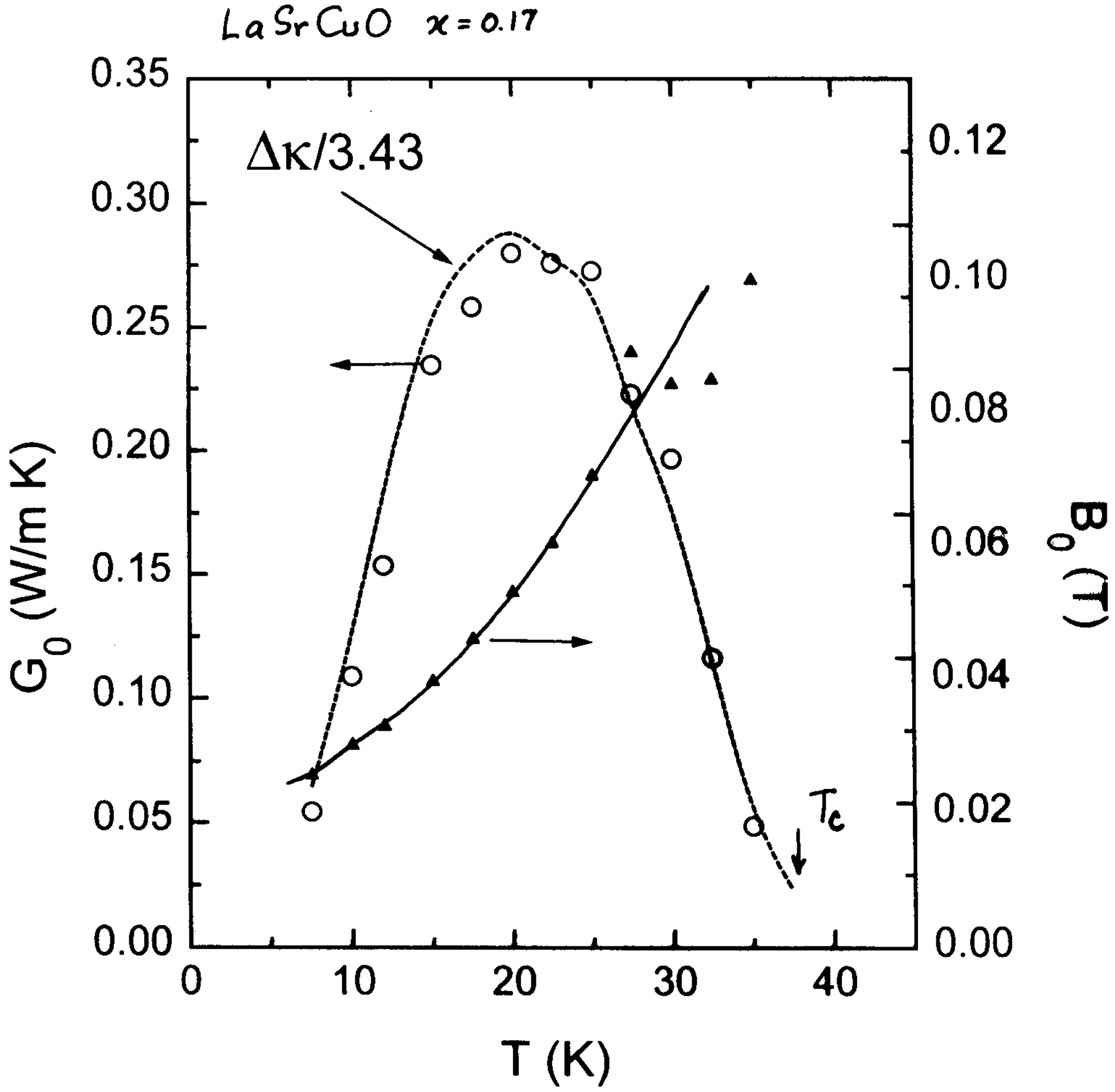
La$_{2-x}$Sr$_x$CuO$_4$
B (T)
Kimura
-2 0 2 4 6 8 10 12 14
1.00
0.95
0.90
0.85
0.80
35 K
32.5 K
x = 0.17
27.5 K
22.5 K
17.5 K
15 K
κ(B)/κ(0)
x = 0.17
0 T
14.1 T
0.08
0 T
14.1 T
6 5 4 3 2 1
κ(B) (W/m K)
0 10 20 30 40 50
T (K)

Krishana, NPO
Kimura

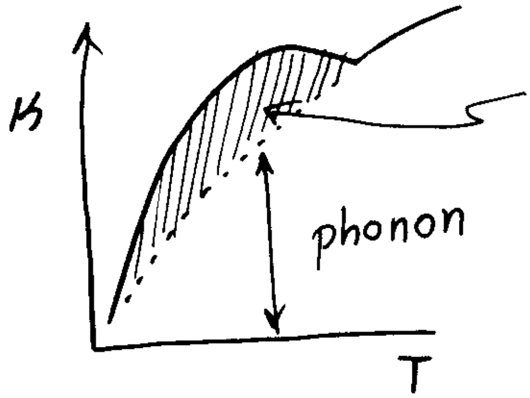
Fit to $Y(x) = \psi\left(\frac{1}{2} + \frac{1}{x}\right) + \ln x; \quad x = \frac{B}{B_0}$



Krishana, NPO
Kimura

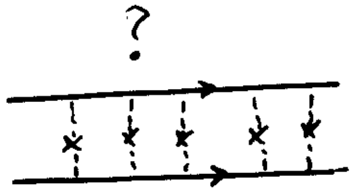


Picture



Enhancement entirely electronic

Extra heat current carried by



Ladder diagram

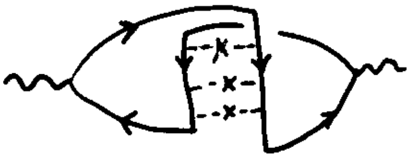
- NOT simple scattering fr. vortex
- Easily decohered by external field
- Suppression follows

$$\psi\left(\frac{1}{2} + \frac{B_0}{B}\right) + \ln\left(\frac{B}{B_0}\right)$$

- Specific to d-wave ?

Why $Y(x)$?

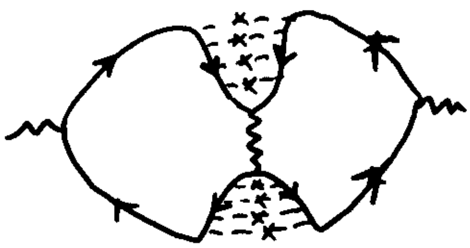
- Suppression of weak localization in 2D



$$\Delta\sigma = +\frac{e^2}{4\pi\hbar} Y\left(\frac{B}{B_0}\right)$$

$$Y(x) = \psi\left(\tfrac{1}{2}+\tfrac{1}{x}\right) + \ln x$$

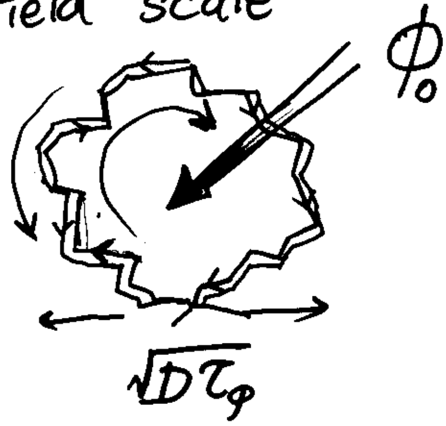
- Diffusion + Fluctuation (Larkin)



$$\Delta\sigma = -\frac{e^2}{4\pi\hbar}\beta(T)\, Y\left(\frac{B}{B_0}\right)$$

Field cuts off logarithmic divergence in particle-particle channel.

Field scale



e^- retains phase coherence in patch area $D\tau_\varphi$

B kills coherence if

$$B.D\tau_\varphi \sim \phi_0 = \frac{h}{e}$$

$$\boxed{B = \frac{\hbar}{4eD\tau_\varphi}}$$

$\boxed{\text{Conclusions}}$

1. Mean free path $\ell \rightarrow 6{,}000\,\mathring{A}$ in YBCO $\sim 20K$

2. Rapid growth $\lesssim T_c$ $\rightarrow$ Inelastic scattg. not from phonons
$\rightarrow$ Inelastic rate suppressed $T < T_c$.

3. In disordered cuprate LaSrCuO

$$\Delta \kappa_{xx} = - G_0 \left[\psi\left(\tfrac{1}{2} + \tfrac{B_0}{B}\right) + \ln \tfrac{B}{B_0} \right]$$

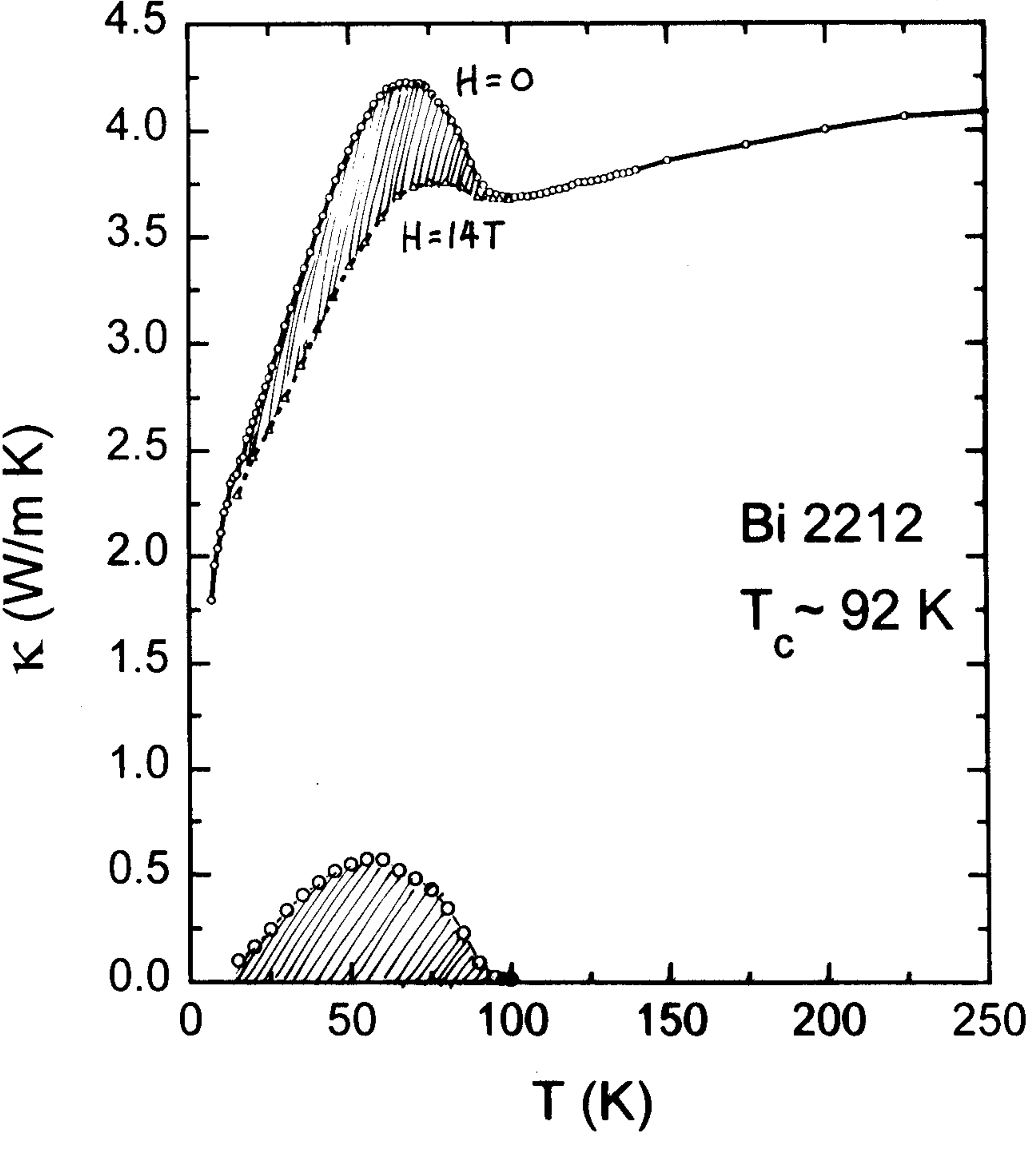
4. B field suppresses quantum coherence of diffusing qp.

5. Enhancement of κ entirely electronic.

6. Est. dephasing rate

$$\frac{\hbar}{\tau_\varphi} = 0.3 \frac{m_0}{m} k_B T$$

Krishana, NPO
Li, Genda Gu



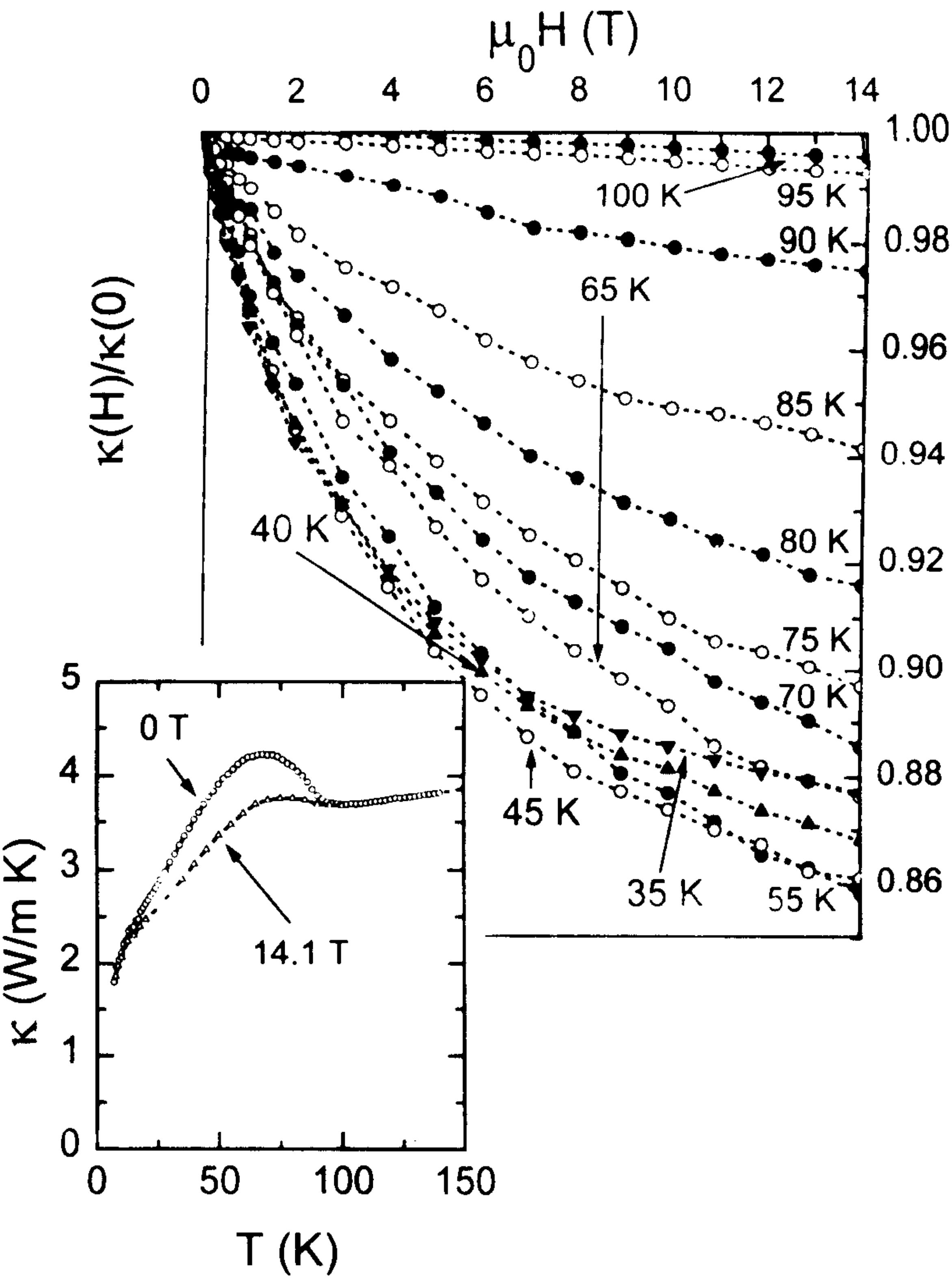
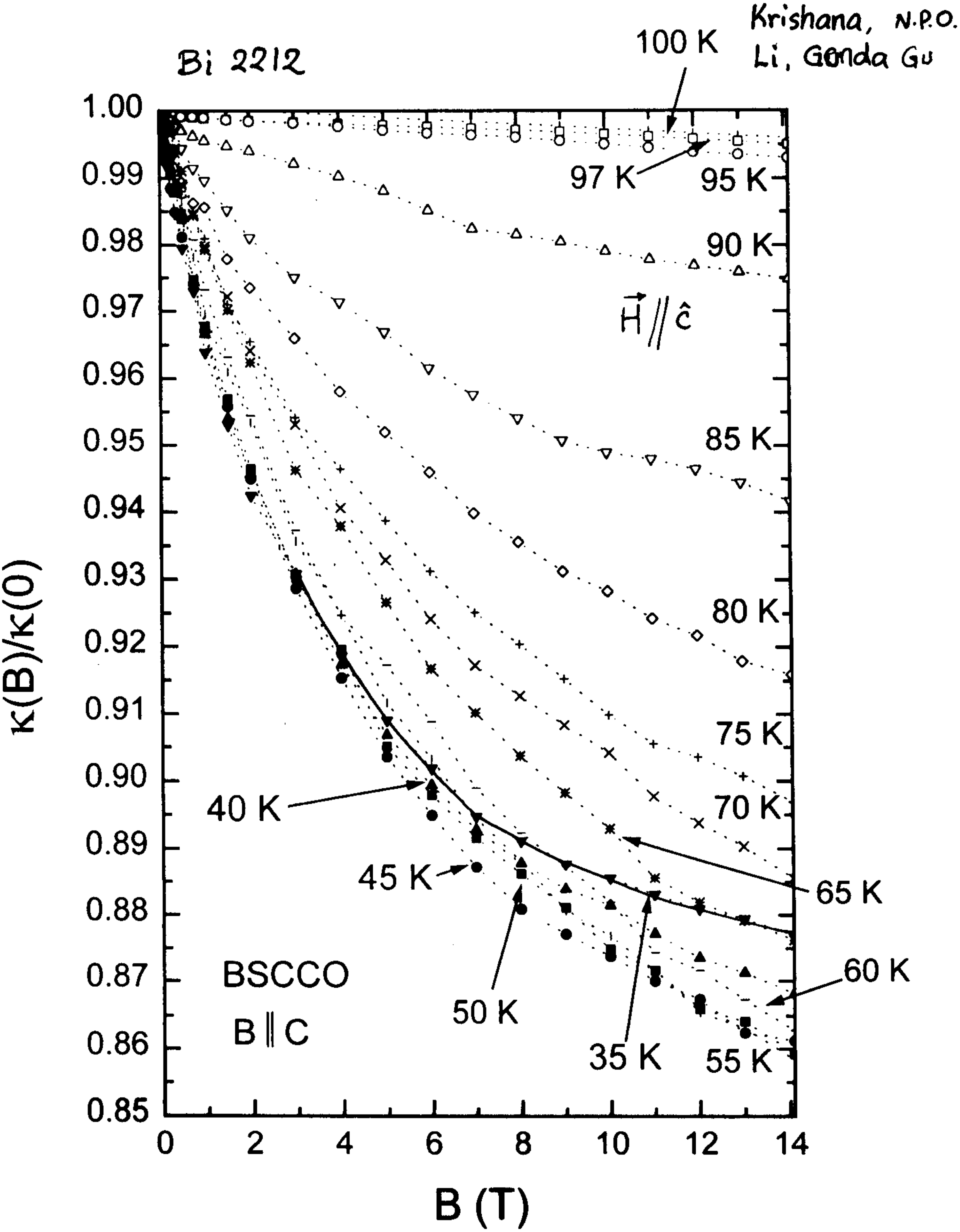
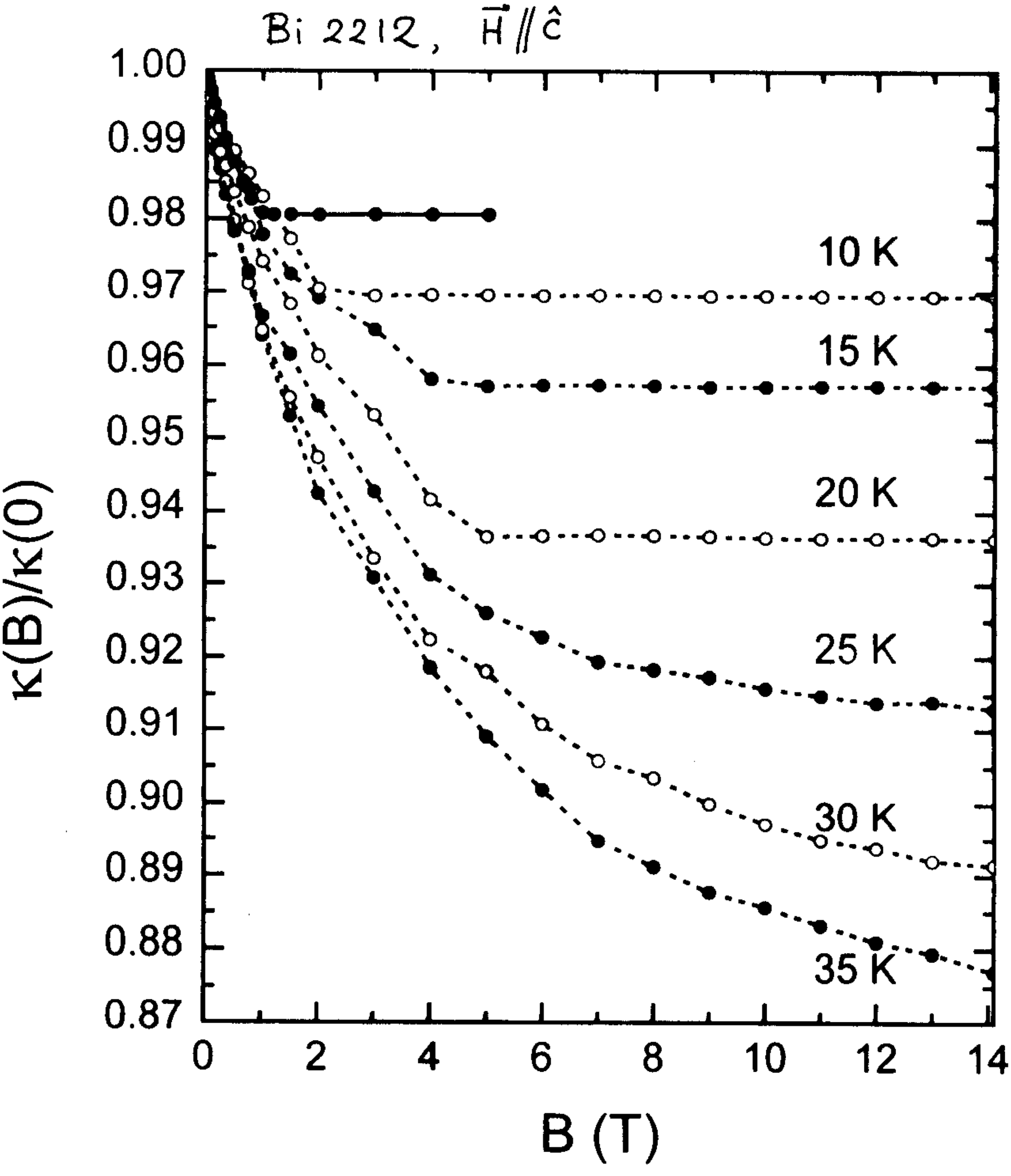


Fig. 1 Krishana


Bi 2212
Krishana, N.P.O.
Li, Gonda Gu
100 K
97 K
95 K
90 K
85 K
80 K
75 K
70 K
65 K
60 K
55 K
50 K
45 K
40 K
35 K
$\vec{H} \parallel \hat{c}$
BSCCO
B ∥ C
κ(B)/κ(0)
B (T)
1.00
0.99
0.98
0.97
0.96
0.95
0.94
0.93
0.92
0.91
0.90
0.89
0.88
0.87
0.86
0.85
0
2
4
6
8
10
12
14

See Krishana N10 6



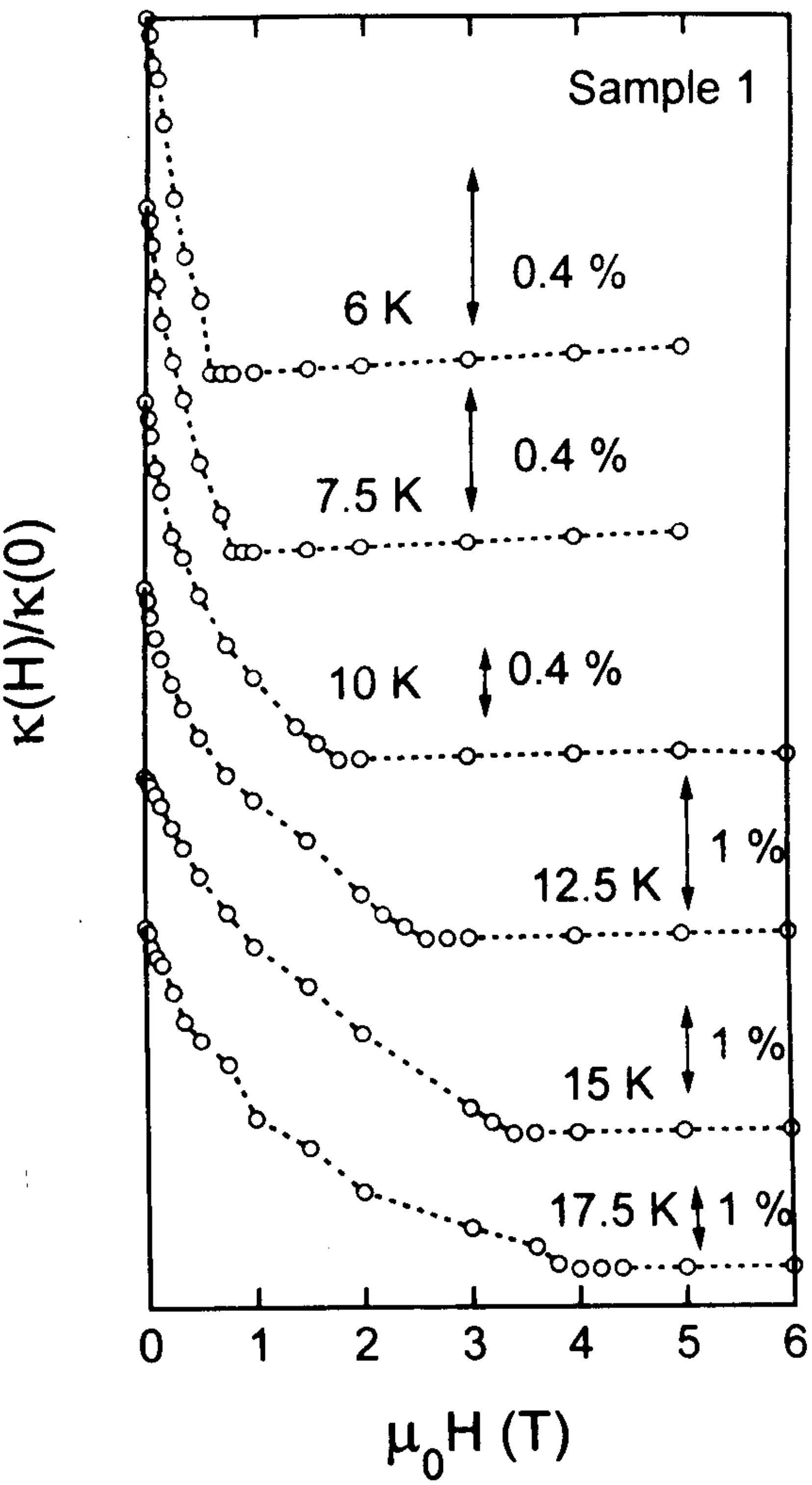
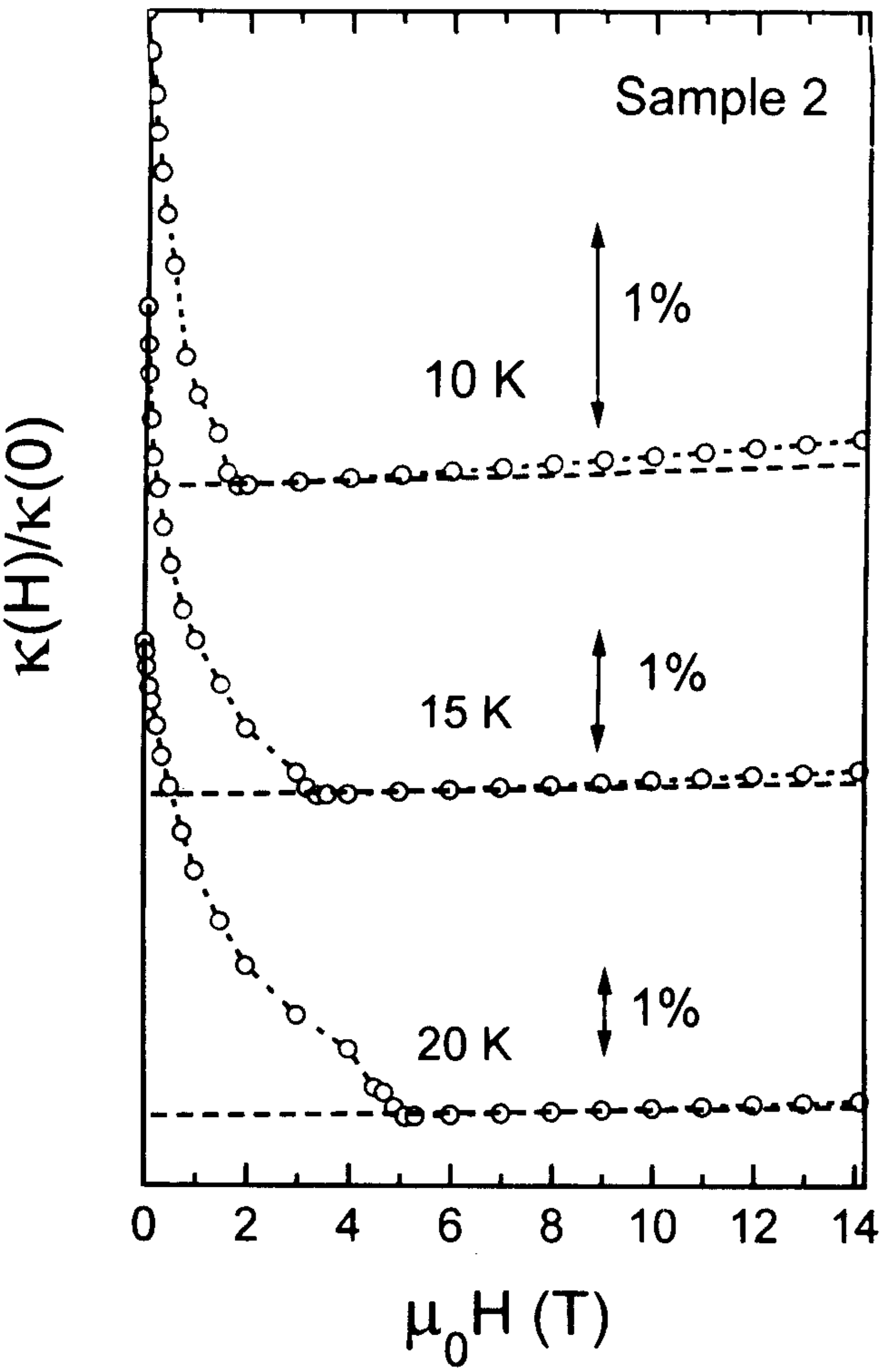


FIG 2 Krishana


Sample 2
1%
10 K
1%
15 K
1%
20 K
κ(H)/κ(0)
0
2
4
6
8
10
12
14
$\mu_0 H$ (T)

$\boxed{\Delta \kappa = 0}$ is a strong constraint

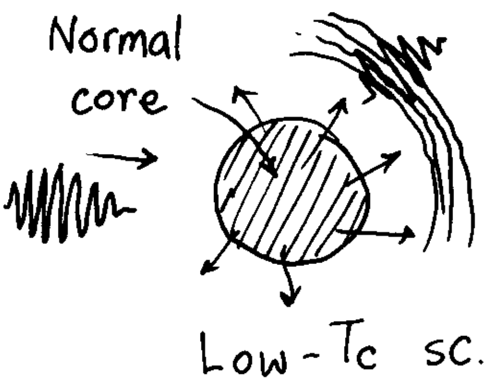
$$\kappa = \kappa_{ph} + \kappa_e$$

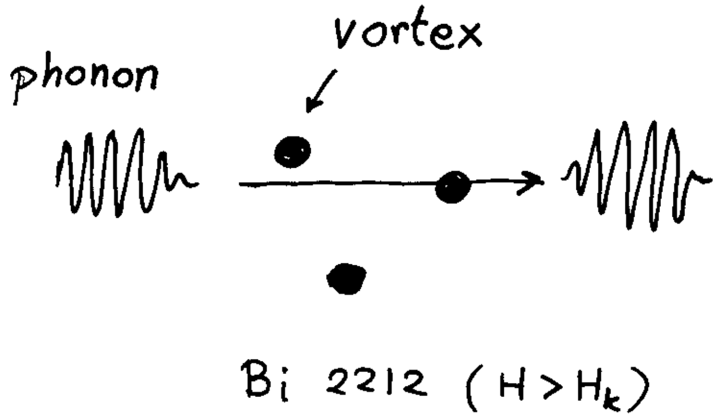
$H > H_k$, $\quad \Delta\kappa = 0 \quad \rightarrow \quad \Delta\kappa_{ph} = \Delta\kappa_e = 0$

Both currents constrained.

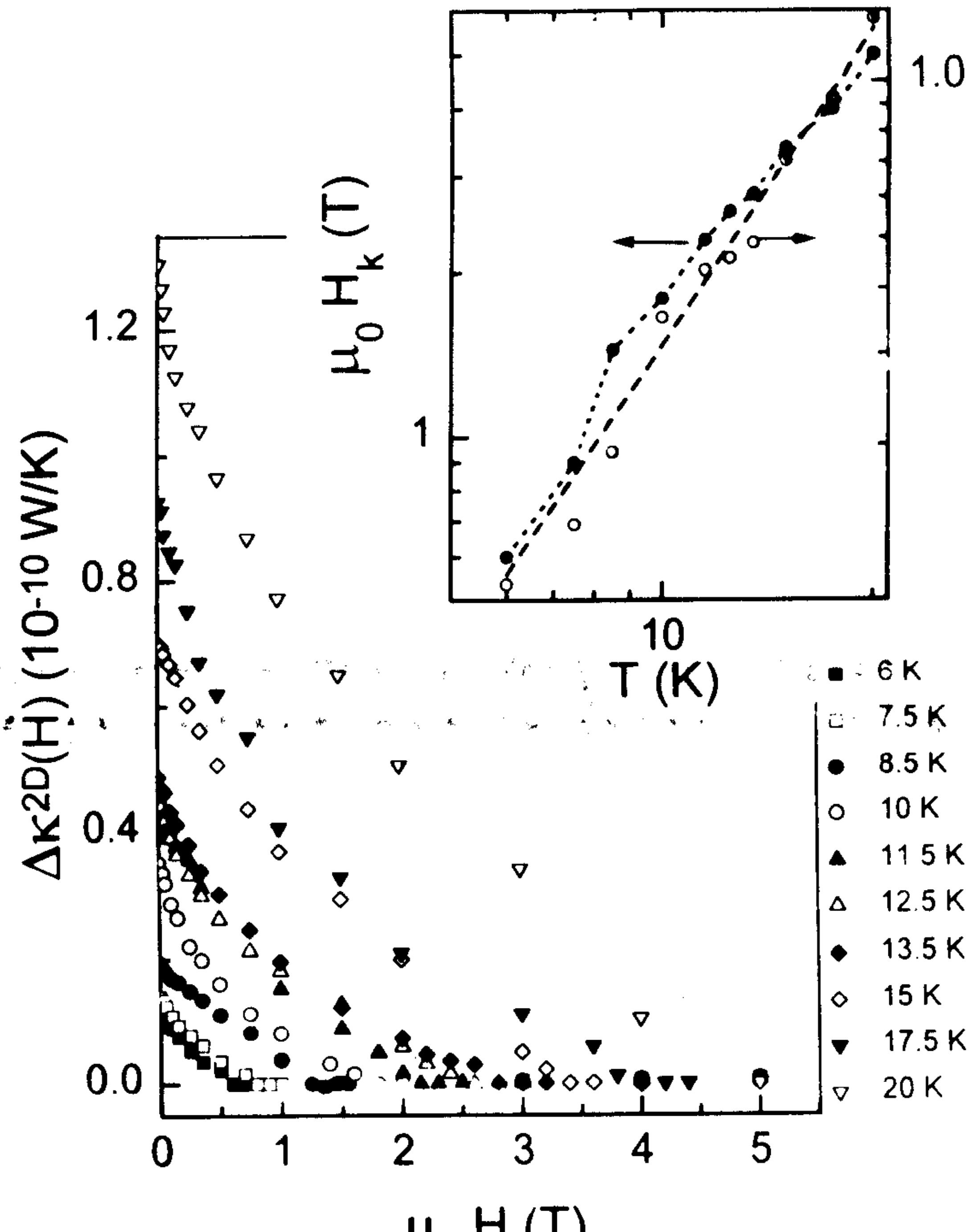
① $\boxed{\Delta \kappa_{ph} = 0}$

- Vortices transparent to phonons





- electron-phonon scattg ~ 0

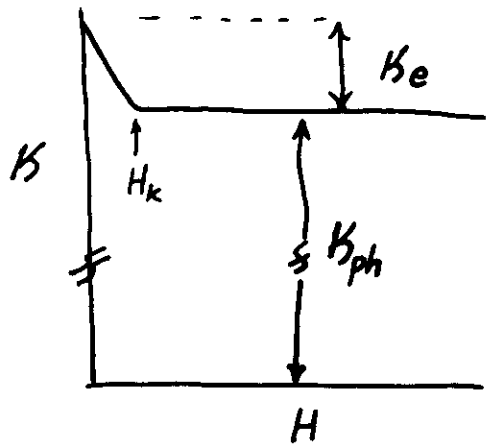


1.2
0.8
0.4
0.0
0
1
2
3
4
5
$\Delta\kappa^{2D}(H)$ (10^{-10} W/K)
μ_0 H (T)
6 K
7.5 K
8.5 K
10 K
11.5 K
12.5 K
13.5 K
15 K
17.5 K
20 K
$\mu_0 H_k$ (T)
1
10
T (K)
1.0
$\Delta\kappa^{2D}$ (10^{-10} W/K)

Fig 4 Kr...

② Constraint on κ_e

$$\frac{\partial \kappa_e}{\partial H} = 0, \qquad H > H_k$$



• Most direct interpretat^n:

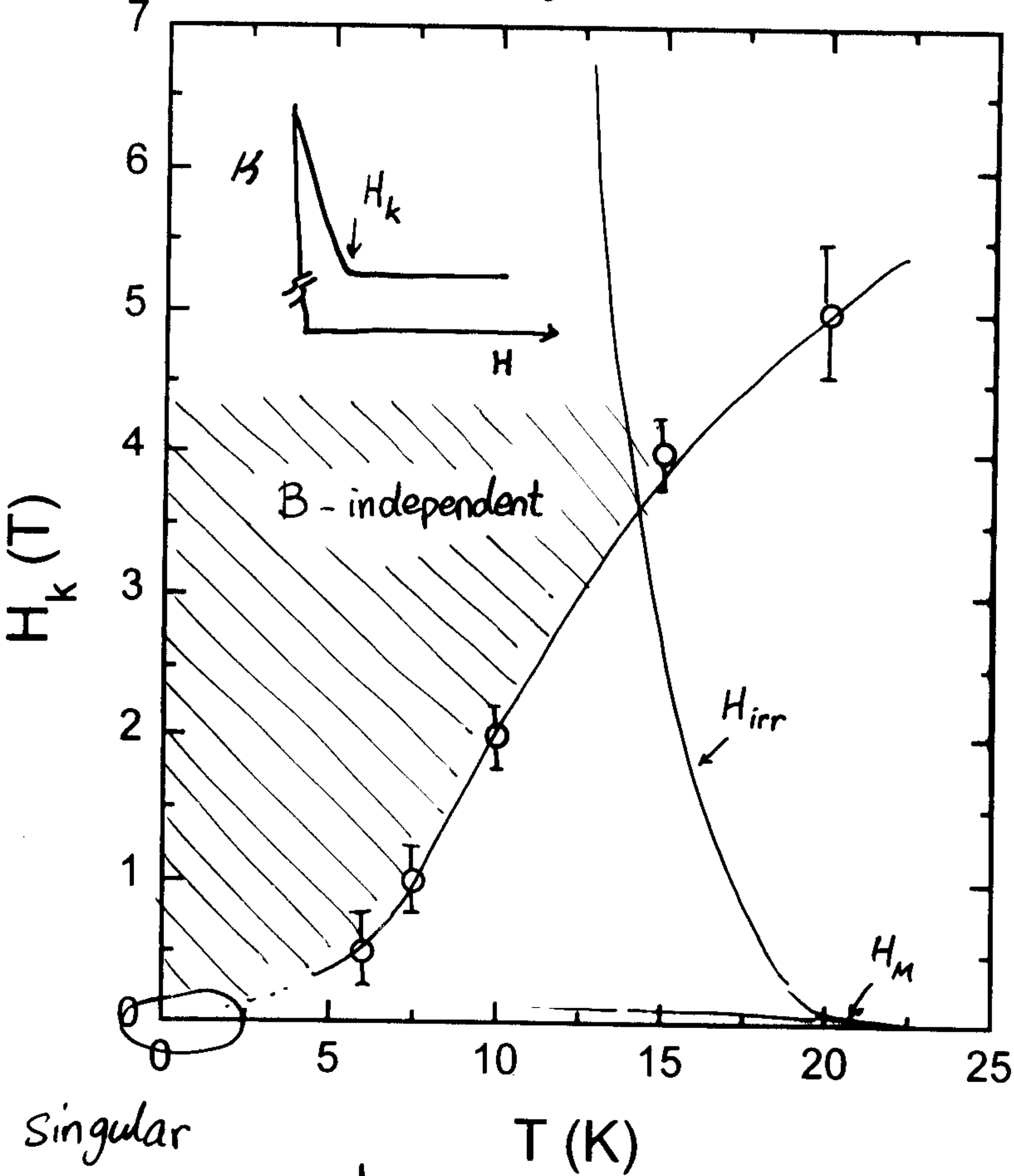
$$\boxed{n_{qp} = 0 \; ; \qquad H > H_k}$$

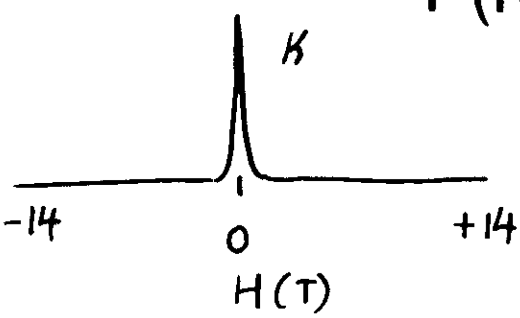
• Field causes abrupt transition at H_k

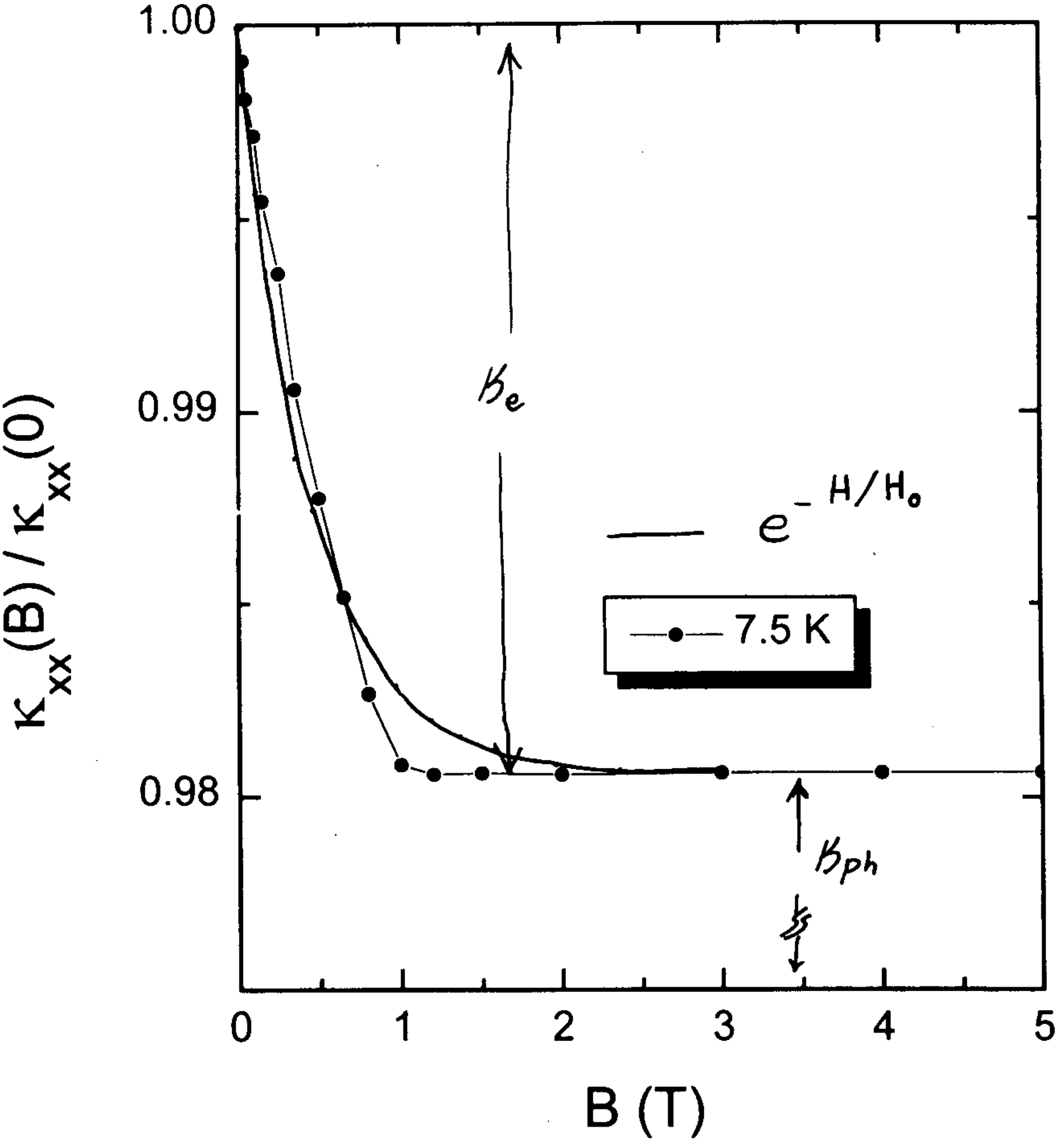
• n_{qp} abruptly $\to 0$

• step change $\Delta\kappa = \kappa_e(H=0)$

Phase diagram







1.00
0.99
0.98
$\kappa_{xx}(B) / \kappa_{xx}(0)$
κ_e
e^{-H/H_0}
7.5 K
κ_{ph}
0
1
2
3
4
5
B (T)

Constraint on QP current

$\boxed{\Delta K_e = 0}$ Either ① QP density $\to 0$

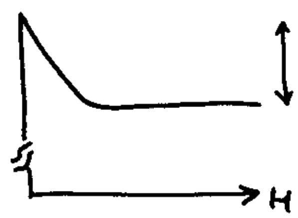
or ② A new state

QP current unaffected by $\vec{B}$.

Add^{l} info

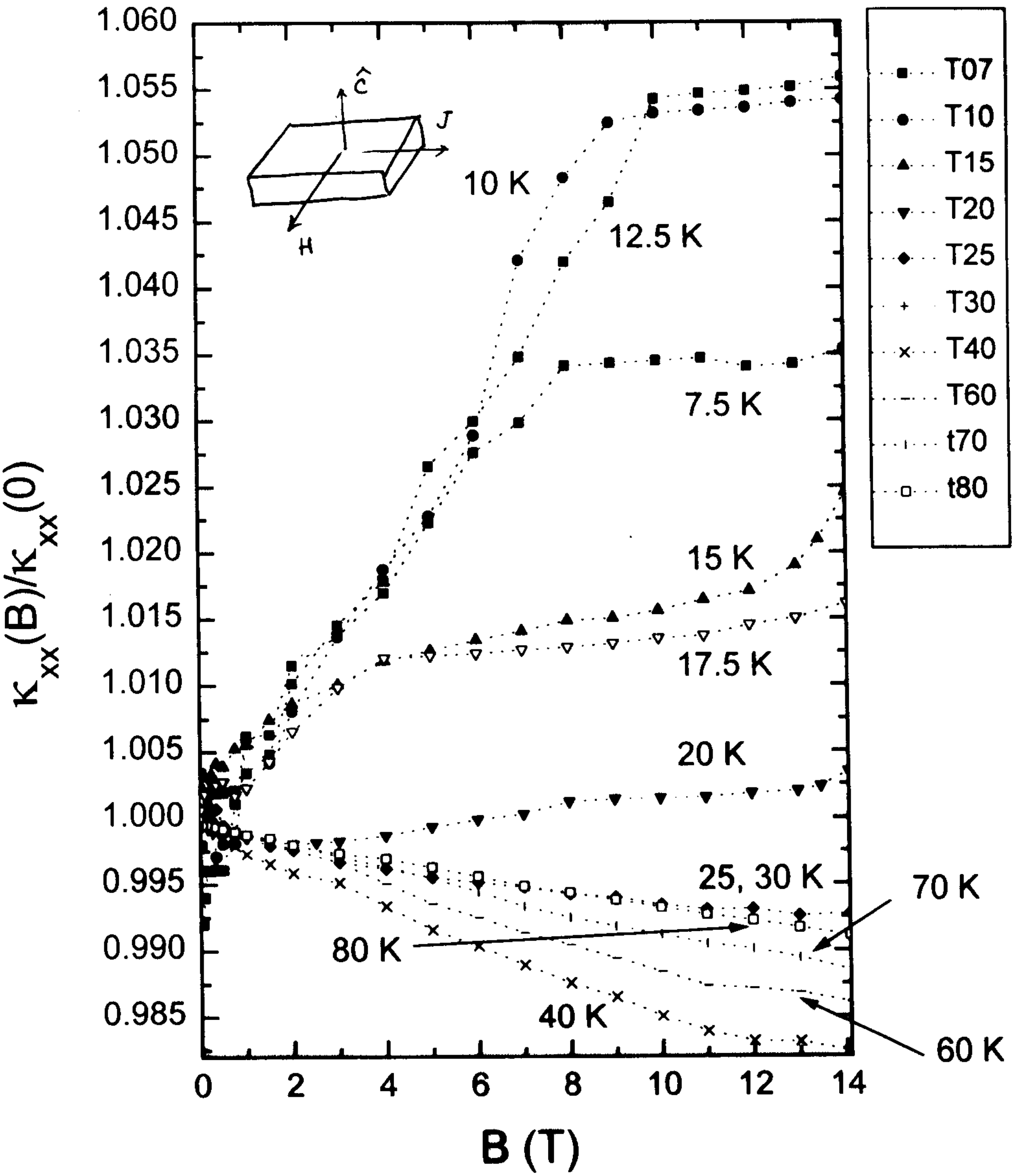
- Plateau effect is orbital (tilt expt.)

- $\frac{\Delta K}{T}$ is nominally $\sim T$



$\frac{\Delta K^{2D}}{T}$ has order of magnitude $\sim \frac{k_B^2}{\hbar} = 1.81 \times 10^{-12} \frac{W}{K^2}$

-


1.060
1.055
1.050
1.045
1.040
1.035
1.030
1.025
1.020
1.015
1.010
1.005
1.000
0.995
0.990
0.985
$\kappa_{xx}(B)/\kappa_{xx}(0)$
0
2
4
6
8
10
12
14
B (T)
ĉ
J
H
10 K
12.5 K
7.5 K
15 K
17.5 K
20 K
25, 30 K
70 K
80 K
40 K
60 K
T07
T10
T15
T20
T25
T30
T40
T60
t70
t80

Quasi Particle current

Bardeen
Rickayzon
Tewordt

$$\kappa_e = \frac{1}{T}\sum_k \xi_k^2 v_k^2 \cos^2\theta_k \left(-\frac{\partial f^0}{\partial E_k}\right)\tau$$

$$E_k = \sqrt{|\Delta_k|^2 + \xi_k^2}$$

2D, d-wave

$$\kappa^{2D} = \eta \cdot \frac{k_B^2 T}{\hbar} \cdot \frac{k_B T}{\Delta_0} \cdot \cancel{k_F l} \left(\frac{\hbar\Gamma}{\Delta_0}\right)^{-1}$$

$$\eta \sim 0.87$$

Wiedemann Franz

cpf $\sigma^{2D} = \dfrac{e^2}{2\pi\hbar} k_F l$

- $\kappa_e \sim T^2$ d-wave ✓

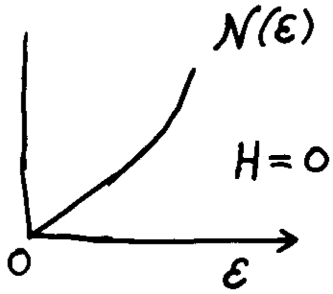
- $\kappa_e \sim \dfrac{T}{\Delta_0} \cdot \left(\dfrac{\hbar\Gamma}{\Delta_0}\right)^{-1}$ ✓

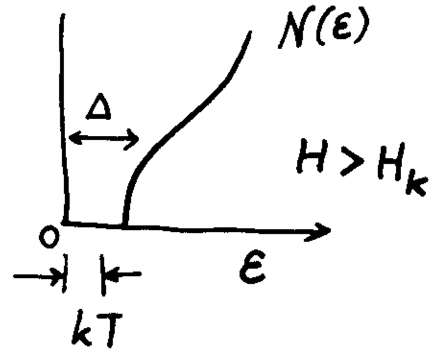
$$\tau \sim 0.4 \text{ ps}$$

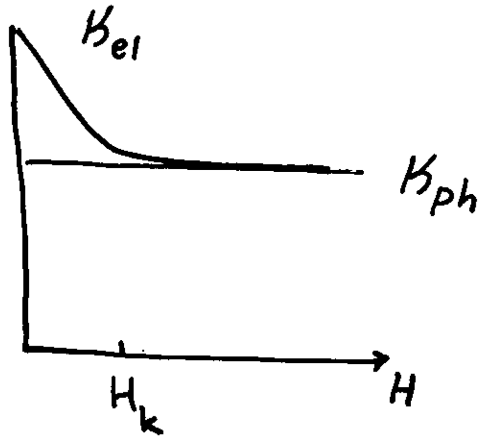
Scenario

① QP population driven $\to 0$?

$\vec{B}$ opens a gap Δ





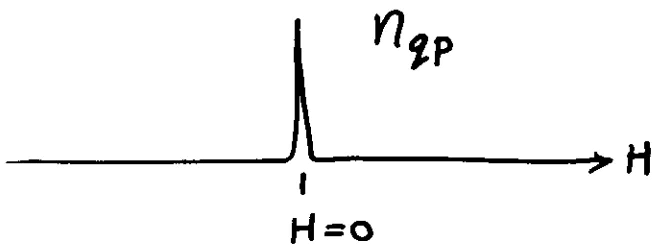


$H > H_k$

$\kappa \longrightarrow \kappa_{ph}$ (only)

- Transition seems too abrupt ? Not e^{-B}
- No known scenario ? $B\nearrow$ $n_{QP}\nearrow$ usually.
- Nodes fragile to field ? singular

$T \to 0$

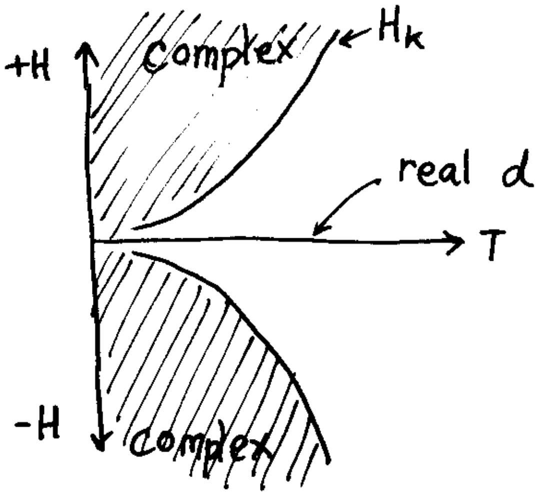


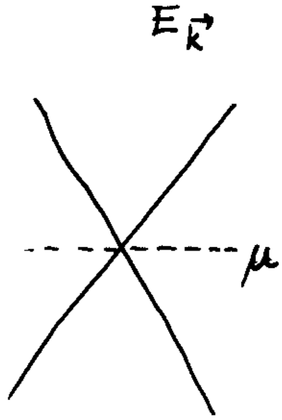
$\boxed{\text{Field-induced transition ?}}$ (Anderson, Haldane)

Real d-wave $\longrightarrow$ complex gap

s + id ?

d + id ?

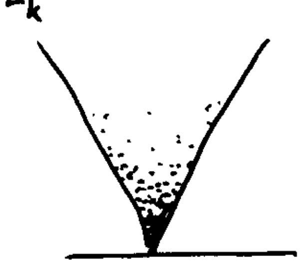




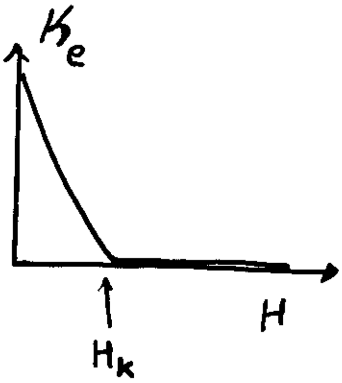
- Real d-wave

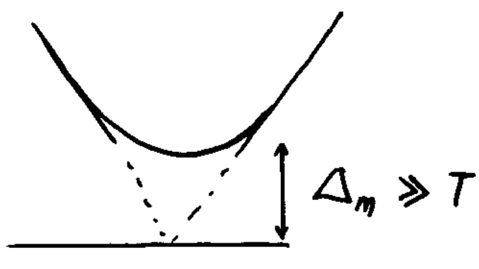
  Infrared sick

- $H_{ext} \longrightarrow \cancel{T}$



$H < H_k$

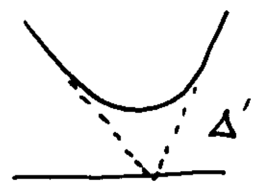




$H > H_k$

Laughlin

Field stabilizes new gap Δ'



$$F = -M_{orb} H + U_{QP}$$

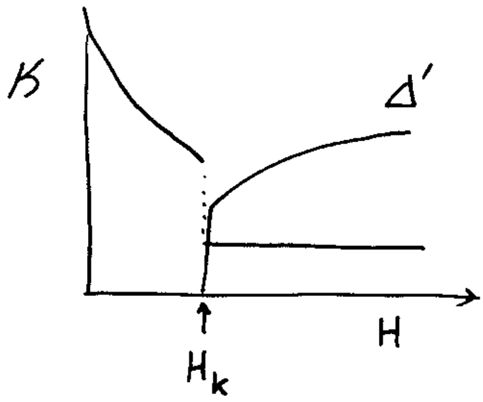
$$= -\alpha \Delta' H + \beta \Delta'^3$$

$$\frac{\partial F}{\partial \Delta'} = 0 \quad \rightarrow \quad H_k \sim \Delta'^2 \sim T^2$$

- magnitude of H_k about right
- Needs microscopic model for M_{orb}

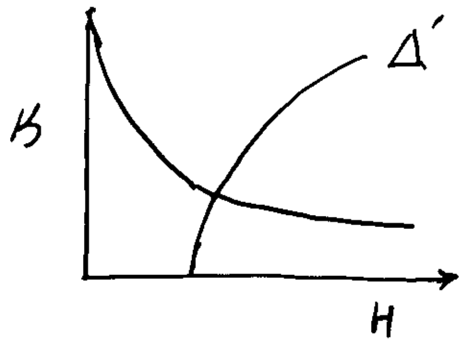
  Edge current ?

Is transition 1^{st} order ?



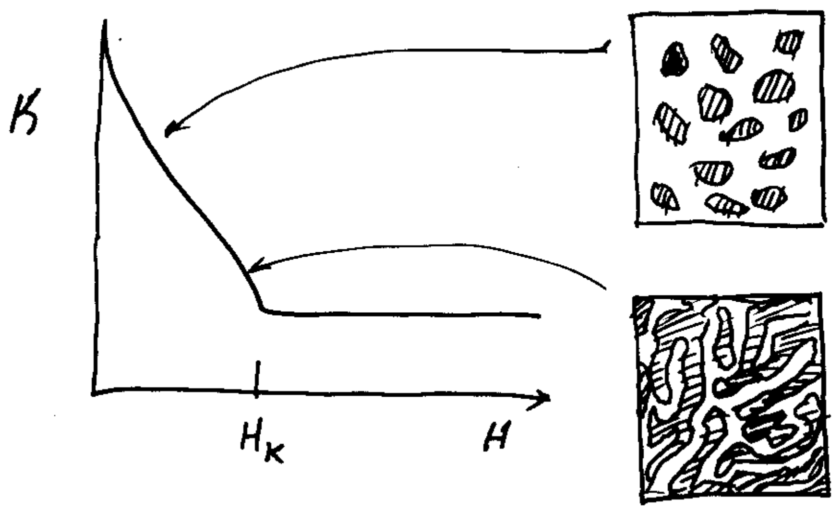
disconť. not seen.

2^{nd} order



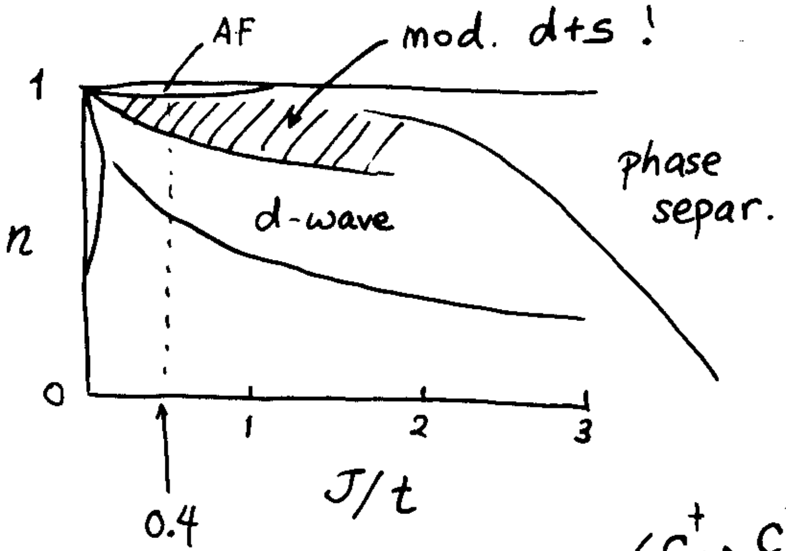
kink a problem.

Field nucleates new phase ?

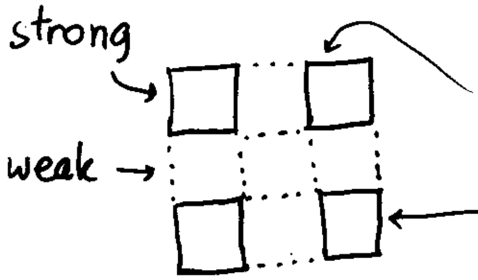


M. Ogata, Yokoyama

Ground state of tJ model

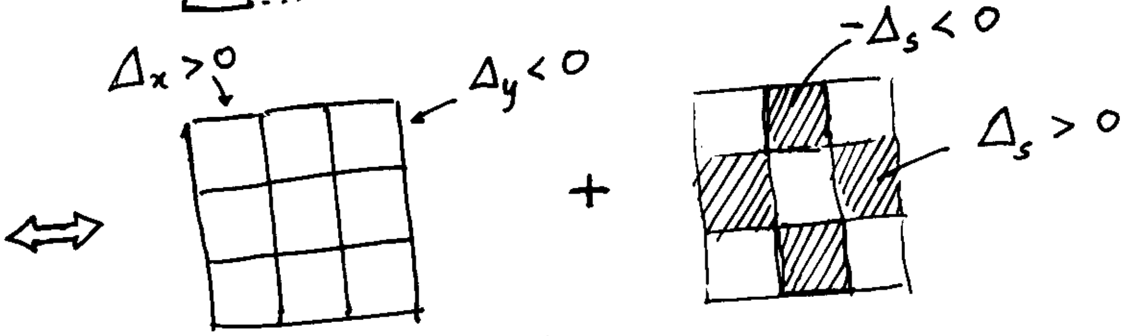


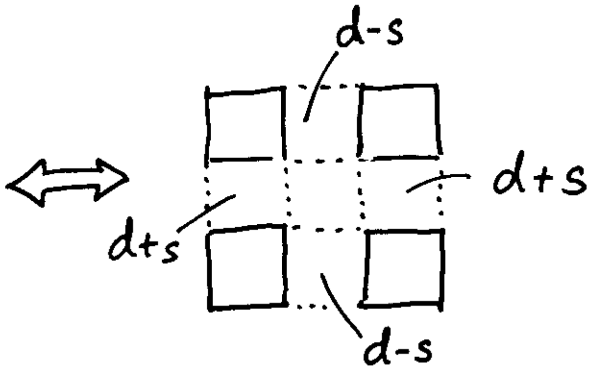
$$\Delta = \langle c^\dagger_{i\uparrow} c^\dagger_{j\downarrow} \rangle$$



$$\Delta_x = \Delta_d$$

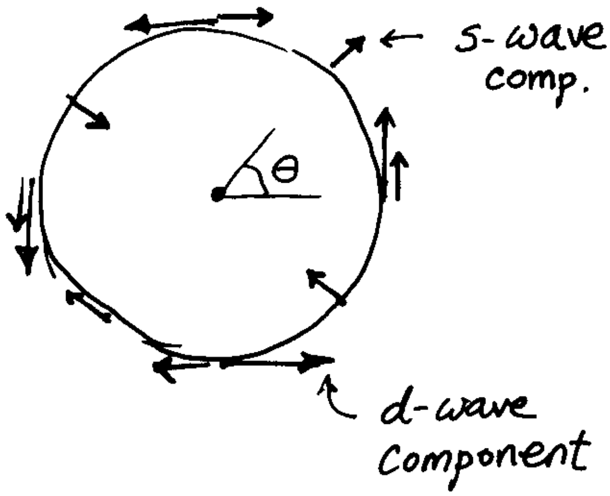
$$\Delta_y = -\Delta_d$$

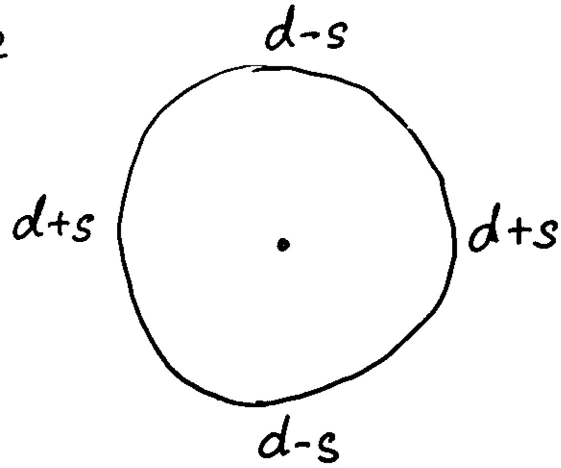


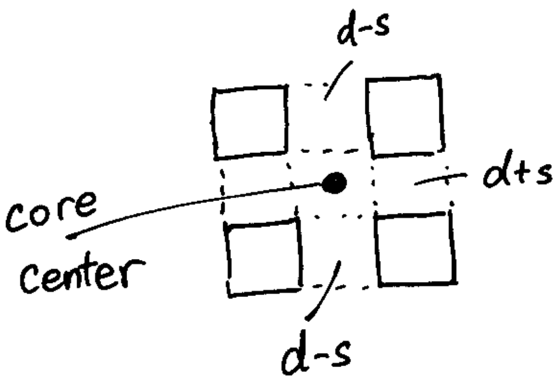


d-wave $\boxed{\text{Vortex core}}$ (Callin, Berlinsky Ren, Ting)

$$\psi \sim r(\alpha_d e^{i\theta} + \alpha_s e^{-i\theta}), \quad r < \xi$$

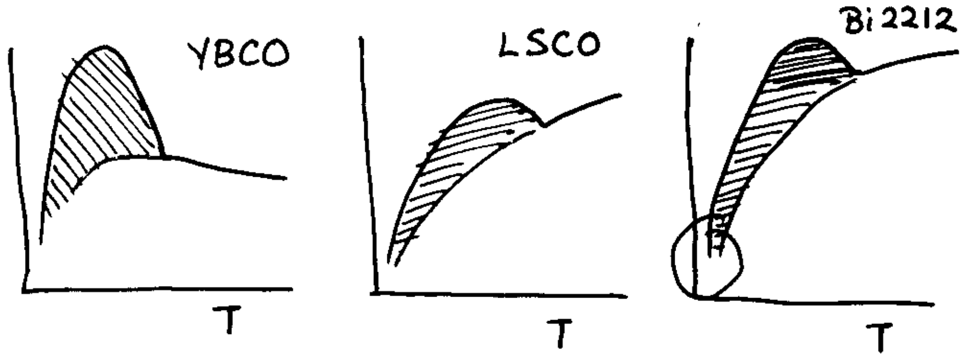






- Vortex favors mod. d+s state
- Acts as nucleation center ?

Summary



- Large anomaly in κ purely electronic.
  B dependence " "
- <u>Clean cuprate</u> Steep increase of $\frac{1}{\tau}$ or ℓ. below T_c.
  Large Hall current κ_{xy}
- <u>Dirty cuprate</u> Large enhancement of D
  Quantum interference effect?
  Rapid decoherence in B field.
- <u>2D cuprate</u> Additional feature at low T
  κ plateaus for $H > H_k$
  Either $n_{qp} \to 0$ Real d $\to$ complex
  or a novel state with
  B-indpt. current.
- Vortices do not scatter phonons.

See Krishana N/O 6