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EXPERIMENTAL WORKSHOP ON
"HIGH TEMPERATURE SUPERCONDUCTORS"
(30 March - 14 April 1989)

MAGNETIC AND TRANSPORT PROPERTIES

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TWO KEY PROPERTIES

$R = 0$ zero resistance

$B = 0$ Meissner effect

COMPLICATIONS EVEN IN CONVENTIONAL S/C:

two fluid model 

Type II s/c 

UNCONVENTIONAL BEHAVIOR IN HTSC:

anisotropy in m^* | anisotropy in H_{c1}, H_{c2}, etc

flux creep, flux flow | flux lattice melting

fluctuations | spin glass —

percolation, weak links
especially in ceramics,
films

THE ISSUE IS, DO THESE UNCONVENTIONAL BEHAVIORS REFLECT NEW PHYSICS?

ORGANIZATION

1. magnetostatics

   demagnetization, H_{c1}, Meissner effect, flux melting

2. dc transport zero field

   normal-state $\rho(T)$, ceramics, coarsening

3. resistive transition in a field

   flux motion, dissipation, phase boundary

4. critical currents

   transport : depinning, weak links, thin films

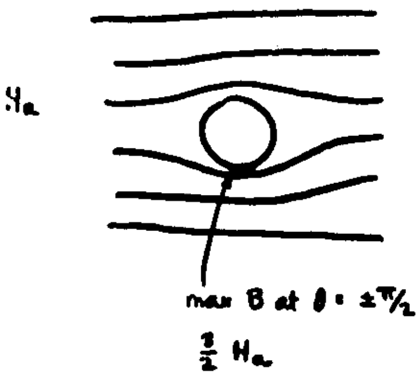
   magnetization : critical state, bean model, magnetization decay

MAGNETOSTATICS

demagnetization

superconducting sphere in a uniform applied field

$\underline{H}_a = H_a \cos\theta\, \hat{r} - H_a \sin\theta\, \hat{\theta}$



Meissner state $H < H_{c1}$

outside s/c $J = 0,\ M = 0$

$\Rightarrow \underline{\nabla} \cdot \underline{B} = 0$

$\underline{\nabla} \times \underline{B} = 0$

$\Rightarrow \underline{B} = \nabla V_m$ magnetic scalar potential

$\nabla^2 V_m = 0$

boundary condition

$B_r = 0$ at $r = a$

outside soln:

$$B_r = \left(H_a - H_a \frac{a^3}{r^3}\right) \cos\theta$$

$$B_\theta = -\left(H_a + H_a \frac{a^3}{2r^3}\right) \sin\theta$$

so $B_\theta(r, \pm\frac{\pi}{2}) = \underline{\frac{3}{2} H_a}$

inside $r < a$

$B = 0$

boundary condition H_θ continuous (because $J_{real} = 0$)

$\underline{H} = \underline{B}$ outside

$H_{\theta\, inside} = B_{\theta\, outside} = -\left(H_a + \frac{H_a a^3}{2r^3}\right) \sin\theta$

$\Rightarrow \underline{H}_{inside}$ is uniform

$\underline{H_{in} = \frac{3}{2} H_a}$ $\quad 4\pi M = -\frac{1}{2} H_a$

e.g. $H_{in} > H_{c1}$ for $H_a > \frac{2}{3} H_{c1}$

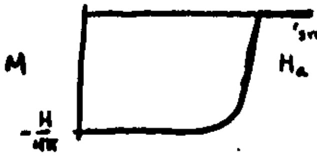
other geometries (demag factor well defined only for ellipsoids)

$H_{in} = H_a / 1-n$

cylinder, $H \parallel$ long axis	$n = 0$	
cylinder $H \perp$ long axis	$n = 1/2$	
sphere	$1/3$	
flat plate $H \perp \hat{n}$	0	
flat plate $H \parallel \hat{n}$	$1 - O(\frac{t}{a})$	

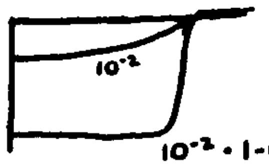
e.g. Chikazumi, Physics of Magnetism (Krieger) p19 ff.

demagnetization M(T) curves



'small' applied field
$H_a \sim 10^{-2} H_{c1}(0)$

demag $n = 0$



$\underbrace{10^{-2} \cdot 1-n}$

can be very small eg. xtal $1 \times 1 \times .01$mm

$1-n \simeq .0155$

for $H_{int} = 10$ Oe, must apply .015 Oe

furthermore n is not well defined for rectangular parallelpiped

demag $n \sim 1$

$(La,Sr)CuO_4$	$H_{c1}(0) = 200$ Oe	
$Ba_2YCu_3O_7$	1.2 kOe	$H \parallel \hat{c}$
$Bi_2Sr_2CaCu_2O_8$	1.1 kOe	"
$Tl_2Ba_2CaCu_2O_8$	350	ceramic
$Pb_2Sr_2YCu_3O_8$	?	

these values are very rough

use of 'meissner fraction' as a qualitative measure of superconducting volume fracti

empirical — not well-grounded theoretically

1. choose sample, orient it s.t. $n \sim 0$

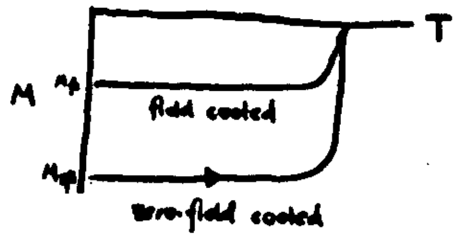
2. cool in zero field

   increase field to H_a

   measure $M(T)$

3. cool in H_a

   measure $M(T)$



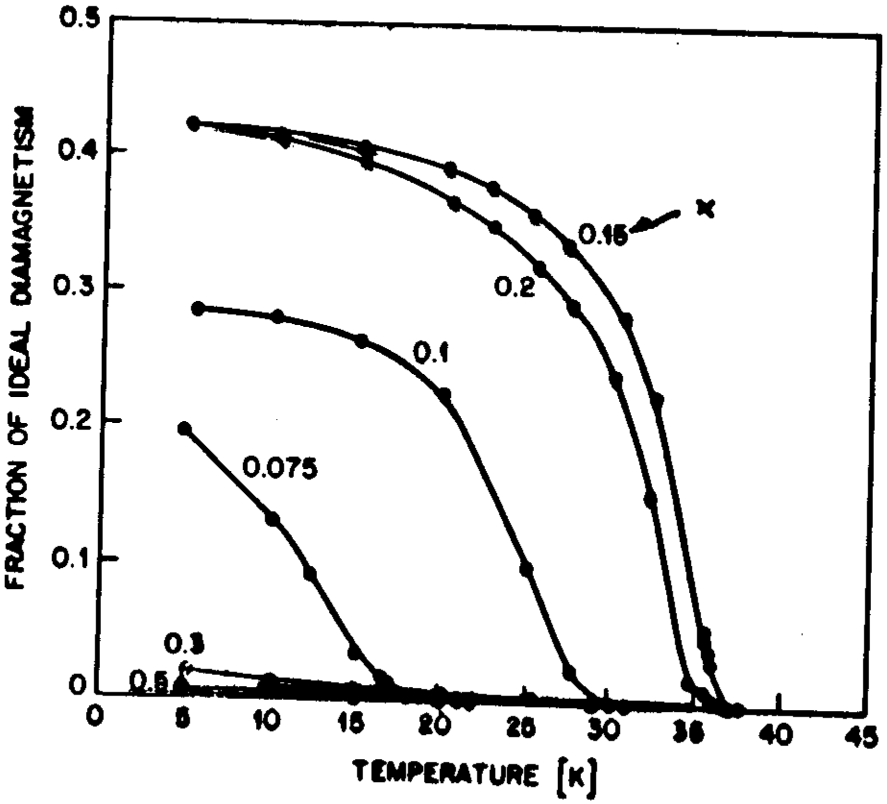
4. ratio $\frac{M_{fc}}{M_{zfc}}$

is indicative of sample quality

but not always: eg. 99.9999% Pb sphere, annealed

$\frac{M_{fc}}{M_{zfc}} = 0.3$ flux trapping

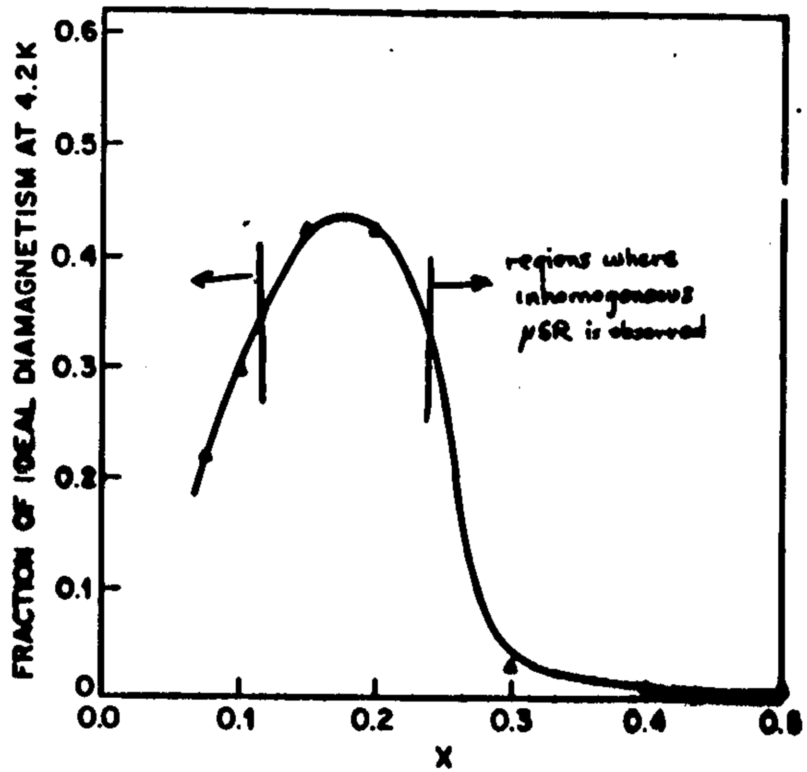
$La_{2-x}Sr_xCuO_4$ (ceramic)



van Dover et al. PR B35 (1987) 5337

COMPOSITION DEPENDENCE

$La_{2-x}Sr_xCuO_4$



μSR muon spin rotation
- local probe
- inhomogeneity for .1 < x < .2

van Dover et al. PR B35 (1987) 5337

quantitative measures of

superconducting volume fraction

heat capacity

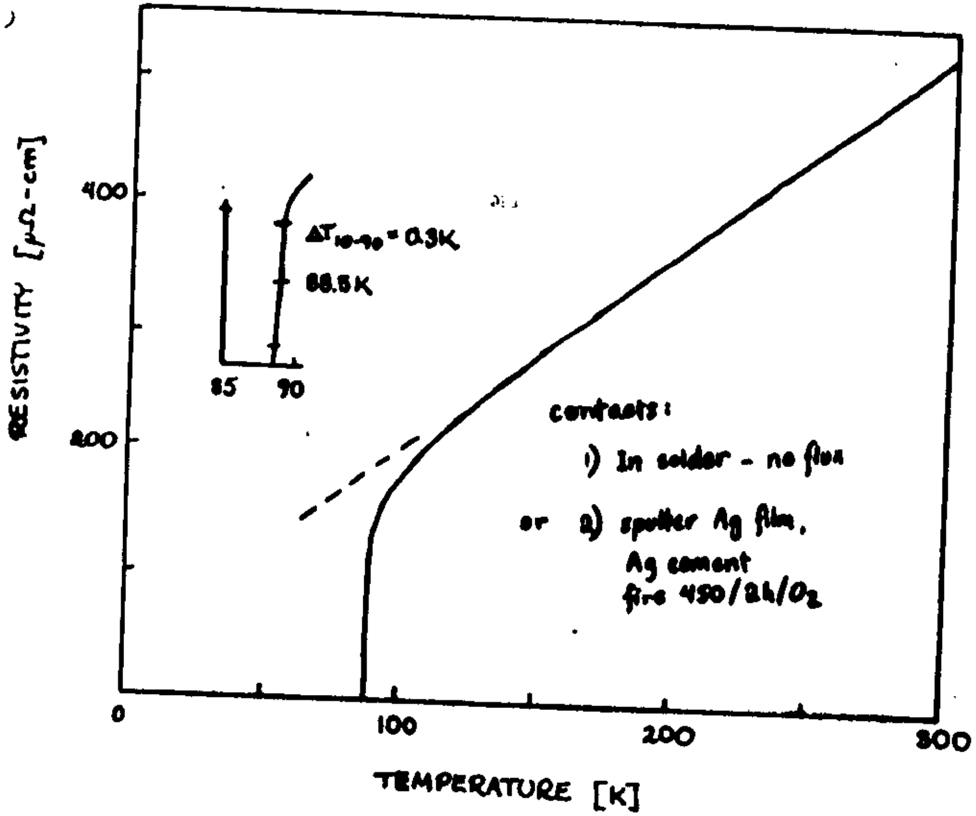
but need model to know what fractional ΔC_p jump is expected

ultrasonic attenuation

RESISTIVITY OF UNDOPED $Ba_2YCu_3O_7$

- narrow transition
- linear in T

$Ba_2YCu_3O_7$ - crystal



CONTACT RESISTIVITIES

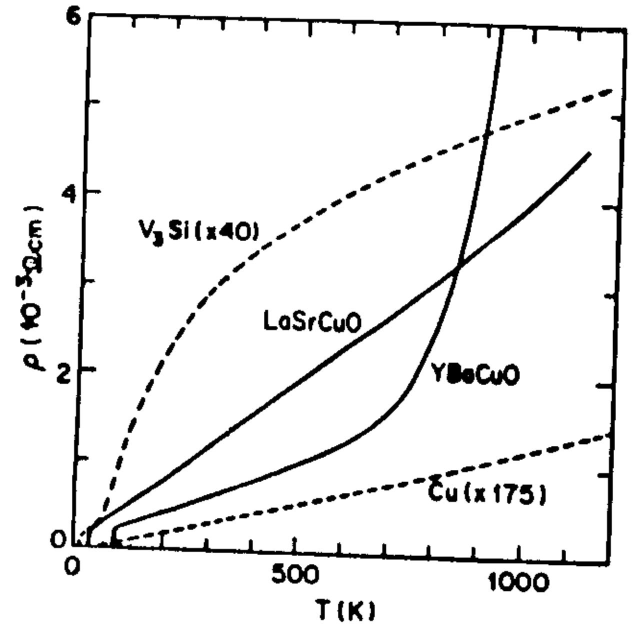
Table 6. Formation of contacts to the surfaces of YBCO films and sintered pellets.

Reference	Superconductor	Normal-Metal Contact	Processing Temperature	Measurement Temperature	ρ_c (Ω-cm^2)
50-52	YBCO films or pellets	Ag paste, In solder, direct wire bonds, pressure contacts	20-100°C	77K	10^{-2}-10
Iye et al.[53]	YBCO single crystal	spark-bonded Au wire	800°C	100K	10^{-4}
Kusaka et al.[50]	YBCO pellet	evaporated Pt film	~100°C	80K	3×10^{-4}
"	"	evaporated Au film	500°C	80K	2×10^{-5}
Caton et al.[51]	YBCO pellet	sputtered Au film	20°C	77K	2×10^{-3}
"	"	melted Au bead	1065°C	77K	5×10^{-7} ←
Wieck[54]	YBCO pellet	pressed and sintered Au bead	950°C	<20K	4×10^{-7} ←
van der Maas[55]	YBCO pellet	annealed Ag epoxy	900°C	77K	$<10^{-7}$ ←
Sugimoto et al.[56]	$ErBa_2Cu_3O_7$ pellet	evaporated Au film	300°C	77K	$<7 \times 10^{-8}$ ←
Tzeng et al.[57]	YBCO pellet	evaporated Ag film	~100°C	77K	6×10^{-6}
"	"	evaporated Ag film	500°C	77K	4×10^{-8} ←
Tzeng[58]	"	melted Ag bead	970°C	77K	$<10^{-8}$ ←
Ekin et al.[52]	sputter-etched YBCO pellet	sputtered Ag film	20°C	77K	10^{-5}
Ekin et al.[59]	"	sputtered Ag film	500°C	77K	$<2 \times 10^{-9}$ ←
"	"	sputtered Au film	600°C	77K	$<4 \times 10^{-10}$ ←
Mizushima et al.[60]	YBCO film	evaporated Au film	850°C	4.2K	$<10^{-8}$ ←
Gavaler et al.[61]	YBCO film	*ex-situ* evaporated Au film	20°C	10K	2×10^{-4}
"	"	*in-situ* evaporated Au film	20°C	10K	$<4 \times 10^{-10}$ ←
Jin (preprint, APL)	YBCO bulk	sintered Ag	900°C	77	$<2 \cdot 10^{-12}$ ←

the technology of making contacts is well established

Talvacchio IEEE Trans CHMT (1989)

high T resistivity of $Ba_2YCu_3O_7$, $La_{1.85}Sr_{.15}CuO_4$



no saturation at high T $\Rightarrow$ $l_{mfp} > a_0$ lattice spacing

$\Rightarrow$ $\lambda_{el\text{-}ph} < 0.21$ BYCO

< 0.1 LSCO (ceramic

similar to Cu, Au, Na, K, etc

<u>strong</u> argument against phononic mechanism

Gurvitch et al. PR B
Fiory et al.

linear $\rho(T)$ consistent with Bloch-Grüneisen:

Gottwick: BYCO $\rho(T)$ fitted with $\theta_D = 350$ K

Micnas: B-G curvature decreased for small Fermi surface

Martin: B-G curvature seen in $Ba_2YCu_4O_8$

$\Rightarrow$ linearity is striking but not exotic

however — Martin et al.: $\rho(T)$ $Bi_2Sr_2CuO_x$

linear down to <u>5 K</u>

$\Rightarrow$ can't be Bloch Grüneisen!

(?)

Gottwick et al. Europhys Lett 3 (1987) 1183.
Micnas et al PR B36 (1987) 4051.

ANISOTROPIC CONDUCTIVITY

van der Pauw Phillips Res. Rept. 16(1961)187
arbitrary shape 2D film can be mapped onto infinite half plane

Wasscher Philips Res Rept 16(1961)301
anisotropic mat'l can be mapped onto equivalent isotropic solid

Logan et al. JAP 42(1971)2975
calculate ρ for rectangular prism with contacts on corner of one face

Montgomery JAP 42(1971)2971
combine idea of Wasscher + calc'n of Logan to infer anisotropic ρ

real dimensions l_1' l_2' l_3'

resistivity ρ_{11} ρ_{22} ρ_{33} diagonal components of ρ tensor

mapped dimensions l_1 l_2 l_3, ρ

where $l_i = l_i' \cdot \left(\frac{\rho_i}{\rho}\right)^{1/2}$

$\rho \equiv (\rho_{11}\rho_{22}\rho_{33})^{1/3}$

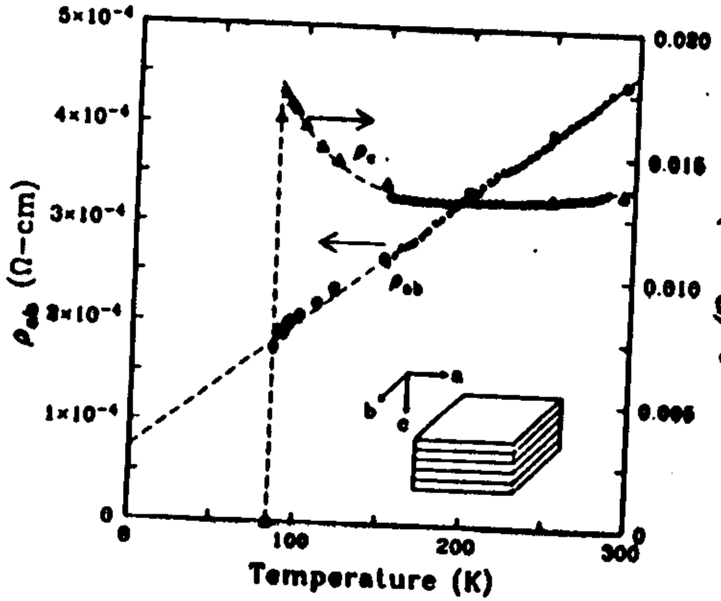
thus 1 × 1 × .05 mm $Ba_2YCu_3O_7$ ($\rho_{ab}/\rho_c = 10$)

maps to .68 × .68 × .11 mm

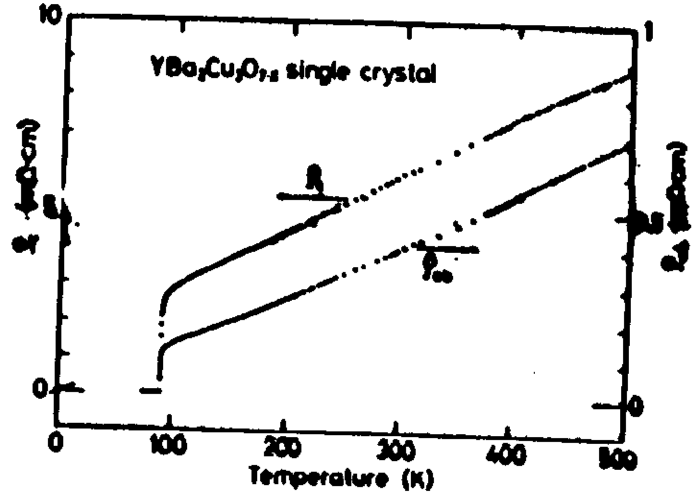
$Ba_2YCu_3O_7$

concensus on ρ_{ab}

controversy on ρ_c



Tozer et al
PRL 59(1987)1960



'typical of better crystals'

(longer O_2 anneal)

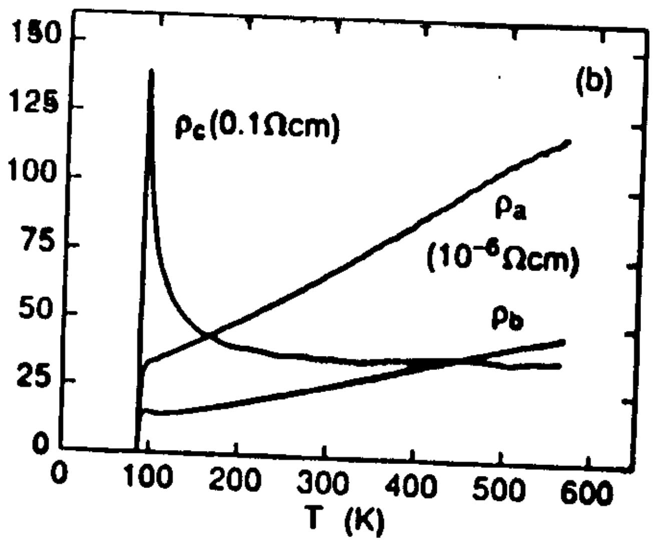
ρ_{ab} extrapolates to zero

Iye et al.
JJAP 27(1988)658

$Bi_{2.2}Sr_2Ca_{.8}Cu_2O_8$

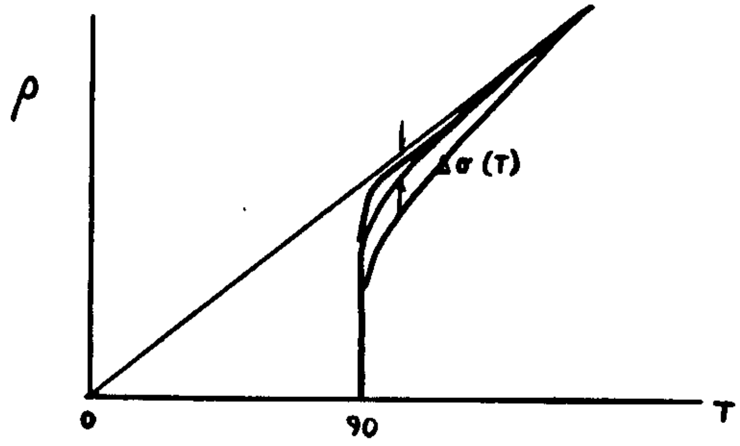
$$\frac{\rho_c}{\rho_a} \sim \underline{10^5} \quad \text{at } T = T_c$$

1 × 1 × .001 mm xtal maps to 1×1×.31 mm



Martin et al. APL 54(1989)72

FLUCTUATIONS



spontaneous fluctuations above T_c lead to enhanced conductivity (and decreased susceptibility)

2D or 3D ? depends on $\xi_c(T)$, coupling along $\hat{c}$

$\Delta\sigma(T)$ measurements $\underline{\text{not}}$ consistent

fitting to theory Aslamazov-Larkin + Maki-Thompson

+ Zeeman term ? Aronov et al. PRL 62(1989)965
(magnetoresistance)

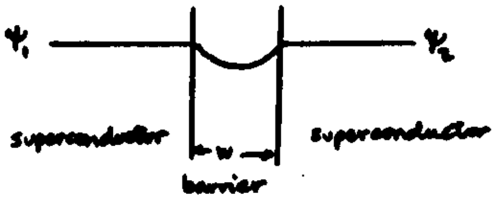
inhomogeneity ?

TRANSPORT MEASUREMENTS ON CERAMICS

- much easier to obtain than xtals or high-quality thin films
- although xtals & films are hard to vet, ceramics are much harder
- percolation, connectivity, cf Cu-Bi embrittlement

  B.T. Schlovskii + A.L. Efros
  Electronic Props. of Doped Semiconductors
  effective medium theory
- weak links

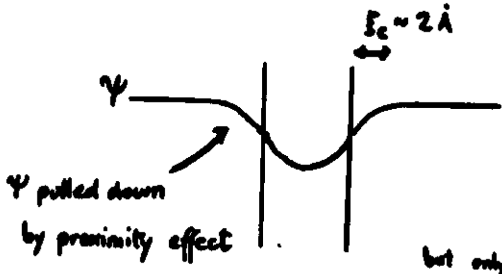
tunnel barriers



order parameter

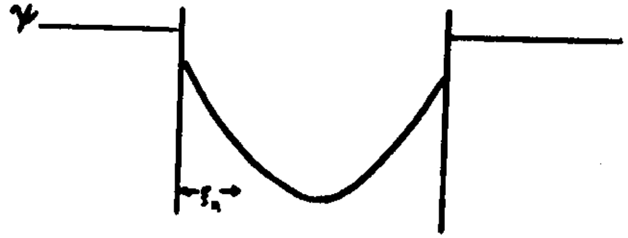
coupling ~ I_c ~ $e^{-w\kappa}$ length scale $\kappa = (2mE/\hbar)^{1/2}$ WKB

Ambegaokar - Baratoff $I_c R_n \sim \frac{\pi\Delta}{2e}$



Deutscher + Müller PRL 59 (1987), 1745
but only relevant for (001)-faced g.b.
at T=0

S - S' - S or S - N - S



length scale $\xi_{no} = \frac{\hbar v_F}{2\pi k(T-T_{cn})}$ clean

$\xi_n = \left[\frac{\hbar v_F \ell_{mfp}}{6\pi k(T-T_{cn})}\right]^{1/2}$ dirty limit

- granular superconductors
- more on this in discussion of j_c

ORIGIN OF WEAK COUPLING

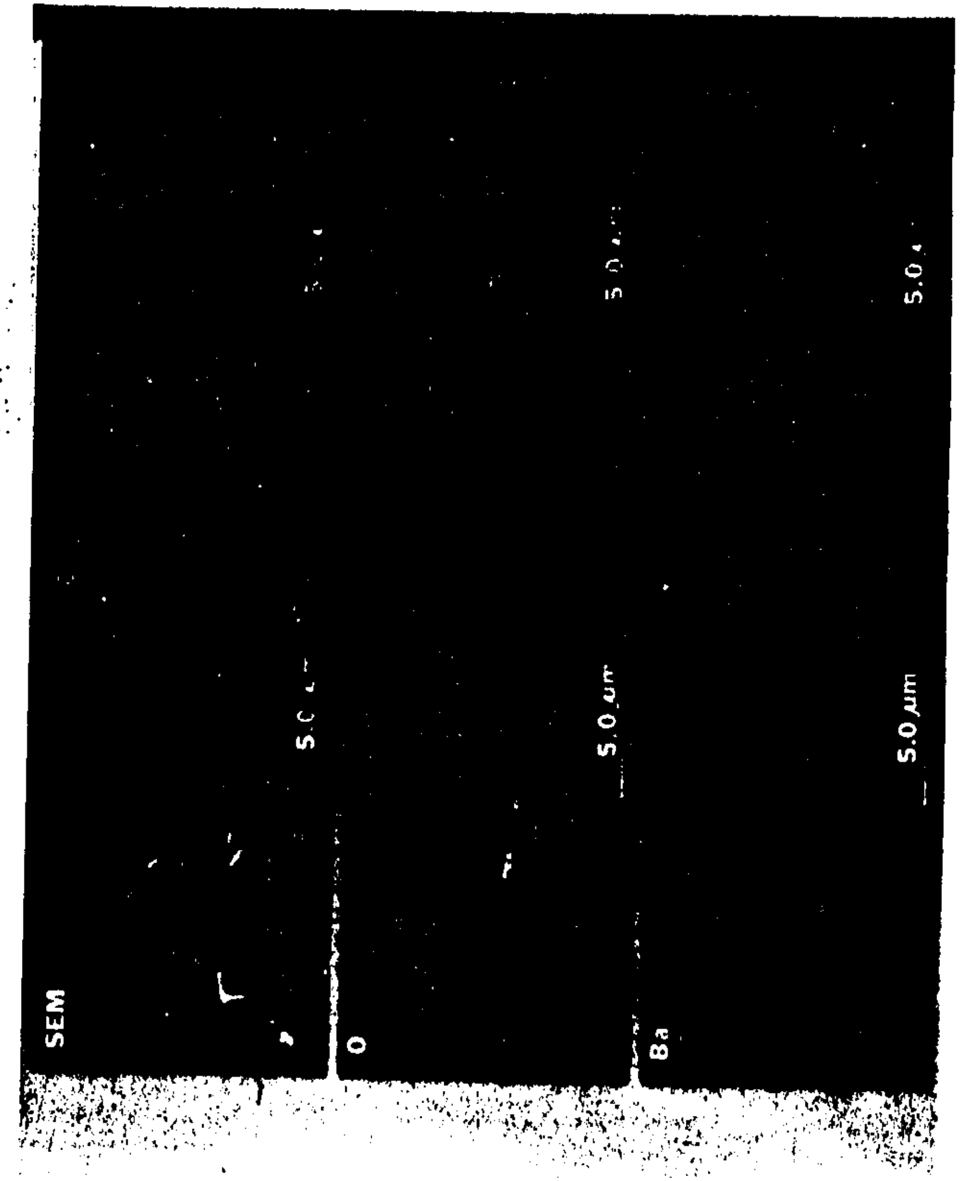
disorder

oxygen deficiency

intrinsic - due to anisotropy

extrinsic decoration ($Ba-CO_3$)

SCANNING AUGER



ac response

LONDON TWO-FLUID MODEL

- simple
- qualitatively correct for $\omega < 2\Delta/\hbar$ i.e. below gap frequency
- (no quantum mechanical aspect)

NORMAL STATE (Drude)

viscous charged fluid $q\ell \ll 1$ q = wavenumber of field, ℓ = mean free path

$$F = eE = m\frac{dv}{dt} + \frac{mv}{\tau} \qquad \tau = \text{scattering time}$$

$$\bar{E} = E_0 e^{i\omega t}$$

$$e\bar{E} = i\omega m v + \frac{mv}{\tau} \qquad \sigma = \frac{J}{E} = \frac{nev}{E} = \frac{ne^2\tau/m}{1+i\omega\tau} = \sigma_1 - i\sigma_2$$

$$\sigma_1 = \frac{ne^2\tau/m}{1+\omega^2\tau^2} \qquad \sigma_2 = \frac{(ne^2\tau/m)\,\omega\tau}{1+\omega^2\tau^2}$$

WHAT IF $\tau \to \infty$ $R \to 0$ (non viscous)

$$\sigma_s = \frac{\pi n e^2}{m}\delta(\omega) + \frac{ne^2}{im\omega}$$

TWO FLUID CONCEPT n_s, n_n

$$J = J_s + J_n \qquad \sigma = \frac{\pi n_s e^2}{m}\delta(\omega) + \frac{n_s e^2}{i\omega m} + \frac{n_n e^2\tau/m}{1+i\omega\tau}$$

equivalent circuit

NOTE: σ_n is <u>not</u> simply the normal-state resistivity extrapolated to the measurement temperature. it has a strong temperature dependence (at low T the 'normal' electrons, n_n, freeze out). σ_n must be measured for each mat'l individually.

response to ac magnetic field:

$$\frac{d}{dt}J_s = \frac{n e^2}{m}E \qquad \text{londons 1st eqn}$$

$$\nabla\times B = \frac{4\pi}{c}J$$
$$\nabla\times E = -\frac{1}{c}\frac{\partial B}{\partial t}$$

$$\frac{\partial}{\partial t}(\nabla\times B) = \frac{4\pi}{c}\frac{n_s e^2}{m}E$$

$$\nabla\times[\quad] = \nabla^2\dot{B} = \frac{1}{\lambda^2}\dot{B} \qquad \lambda = \frac{mc^2}{4\pi n_s e^2} \quad \text{london penetration depth}$$

only screens changes: NOT MEISSNER EFFECT

$$\nabla^2 \dot{B} = \frac{1}{\lambda^2}\dot{B}$$

screening changes in B

thus ac susceptibility measurements measure eddy current screening

χ' screening L_K or $\lambda \sim \mathrm{Im}\,\sigma$

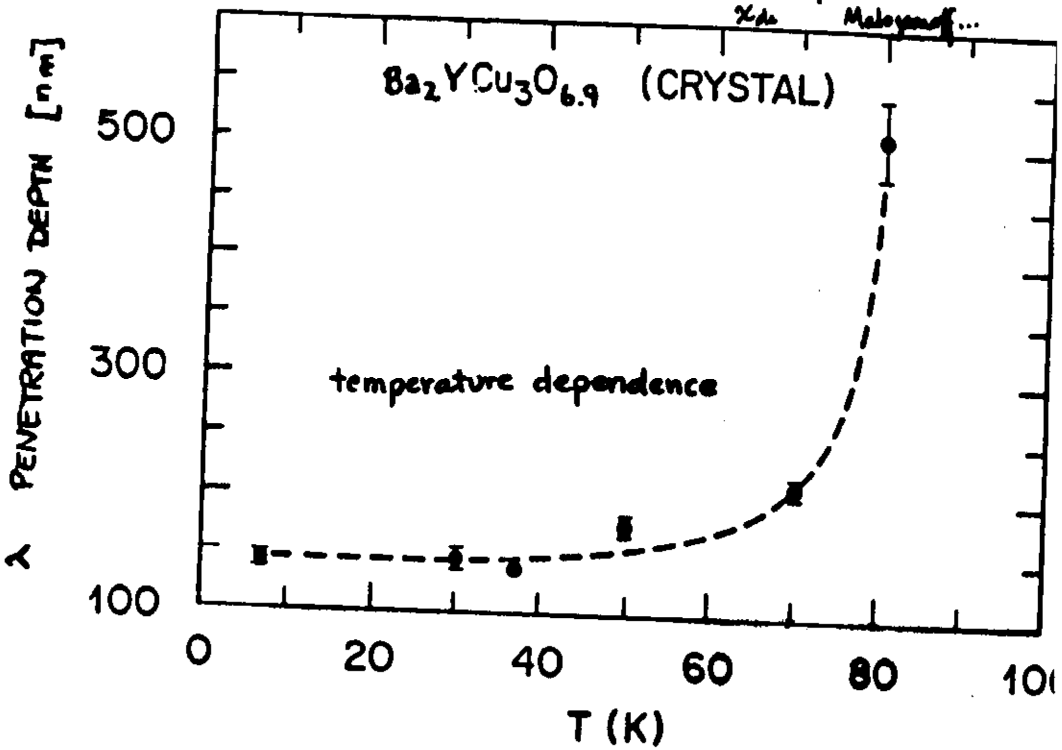
χ'' dissipation $R_n \sim \mathrm{Re}\,\sigma$

MAGNETIC PENETRATION DEPTH

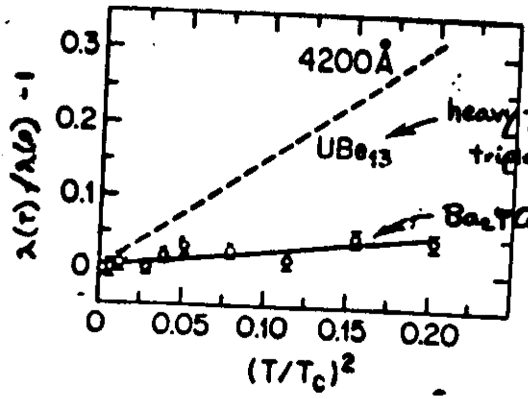
measure by μSR — Harshman

screening χ_{dc} — Hebard

Malozemoff...



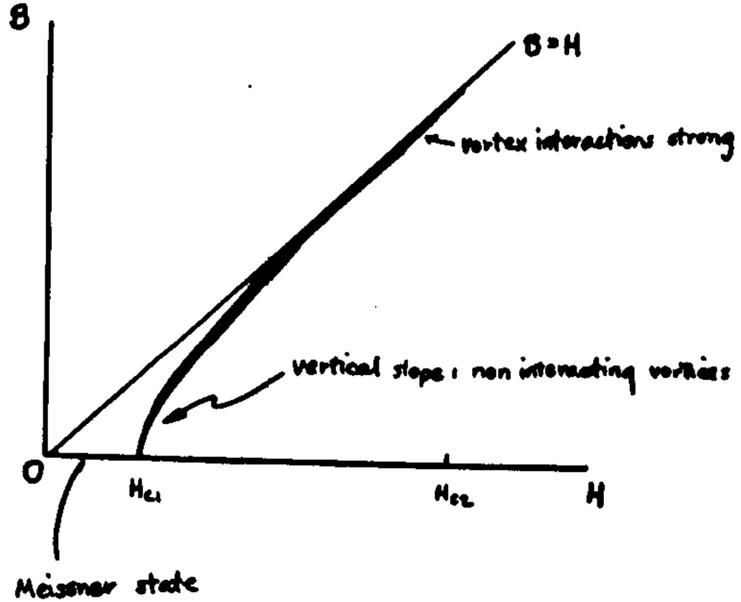
⇒ EVIDENCE FOR SINGLET PAIRING IN $Ba_2YCu_3O_7$



heavy fermion: triplet pairing?

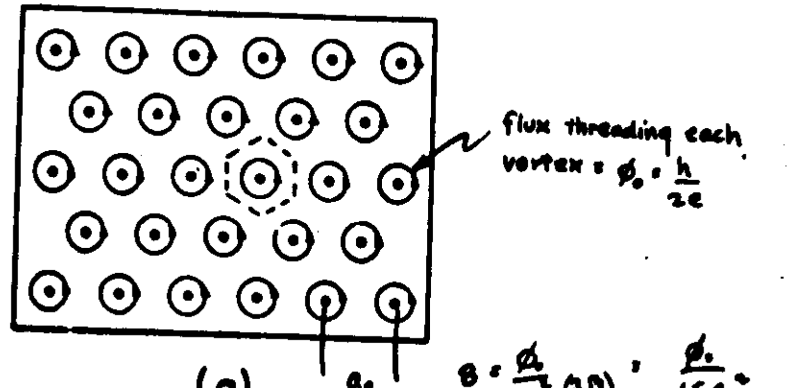
Harshman et al.

CONSTITUITIVE RELATION B(H)



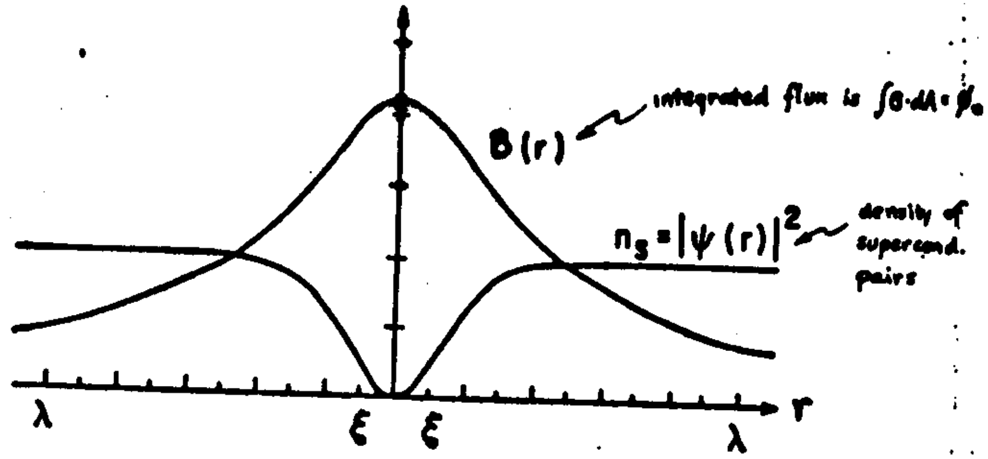
VORTEX STATE

CONVENTIONAL TYPE-II SUPERCONDUCTOR



(a)

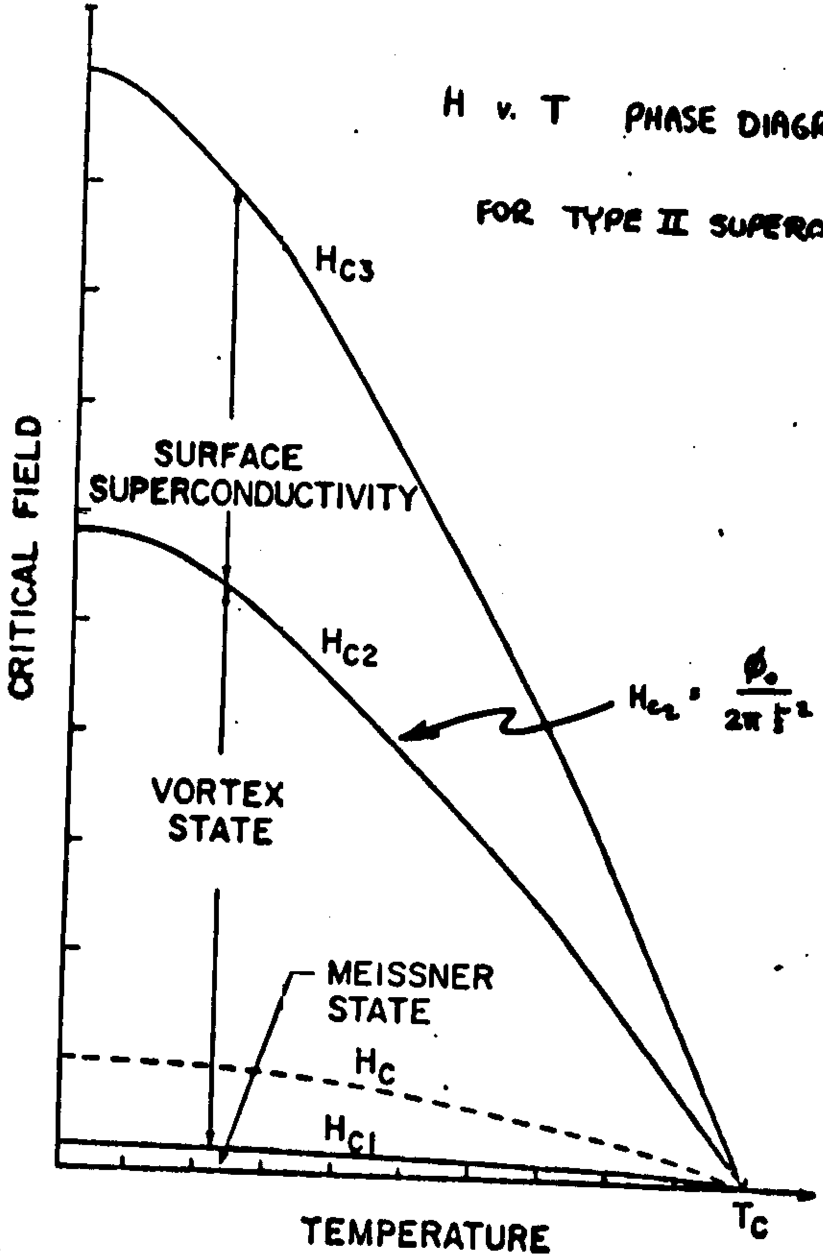
$B = \frac{\phi_0}{a_0^2}\left(\frac{3\sqrt{3}}{8}\right) = \frac{\phi_0}{.65\,a_0^2}$



(b)

H v. T PHASE DIAGRAM

FOR TYPE II SUPERCONDUCTO[RS]



VORTEX ENTANGLEMENT

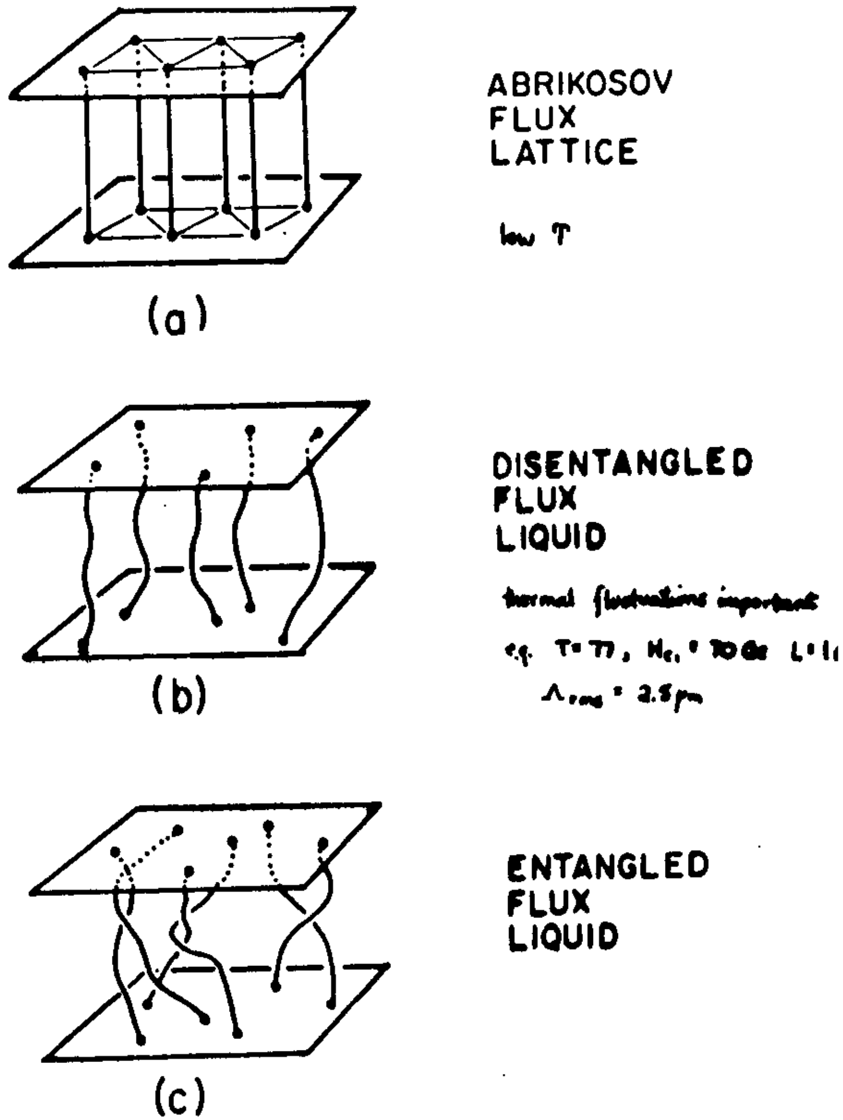
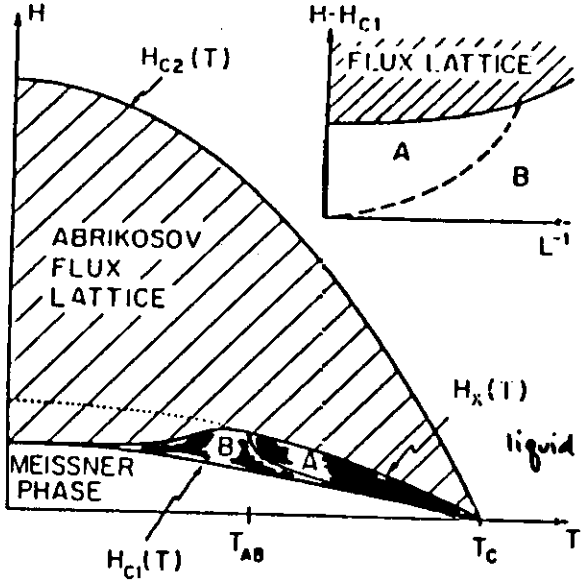


Figure 7

Nelson PRL 60 (1988) 1973

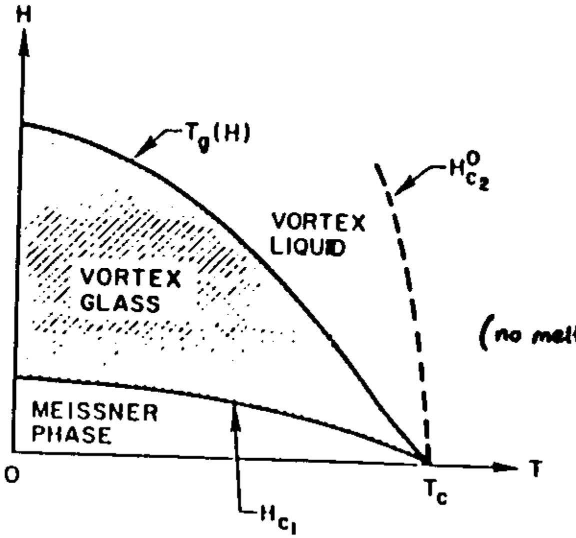
Nelson + Seung PRB (preprint



liquid phases

Nelson PRL 60 (1988) 1973

FIG. 1. Abrikosov flux lattice (shaded), entangled-flux liquid (A), and disentangled-flux liquid (B) phases as a function of H, T, and L^{-1}.



M.P.A. Fisher PRL 62 (1989) 1415

(no melting)

FIG. 1. Schematic phase diagram for a bulk dirty superconductor

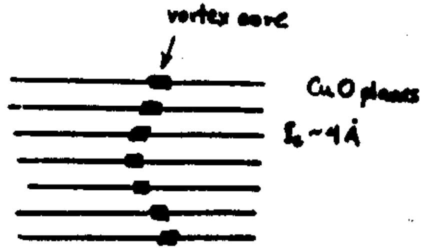
VORTEX ENTANGLEMENT + MELTED FLUX LATTICE

issues

boundary conditions (toroidal geometry)

strong sample thickness dependence $q \sim L^3$

effect of strong anisotropy



what is correlation length?

energy cost for lateral translation ↓ when anisotropy ↑ coupling ↓

EXPERIMENTAL ISSUES

distinguish between kinetic transition and phase transition

RESISTIVE TRANSITION IN A FIELD

COMPARE TO HIGH-T_c SUPERCONDUCTOR

H_{c2} phase boundary

Nb_3Sn: conventional superconductor.

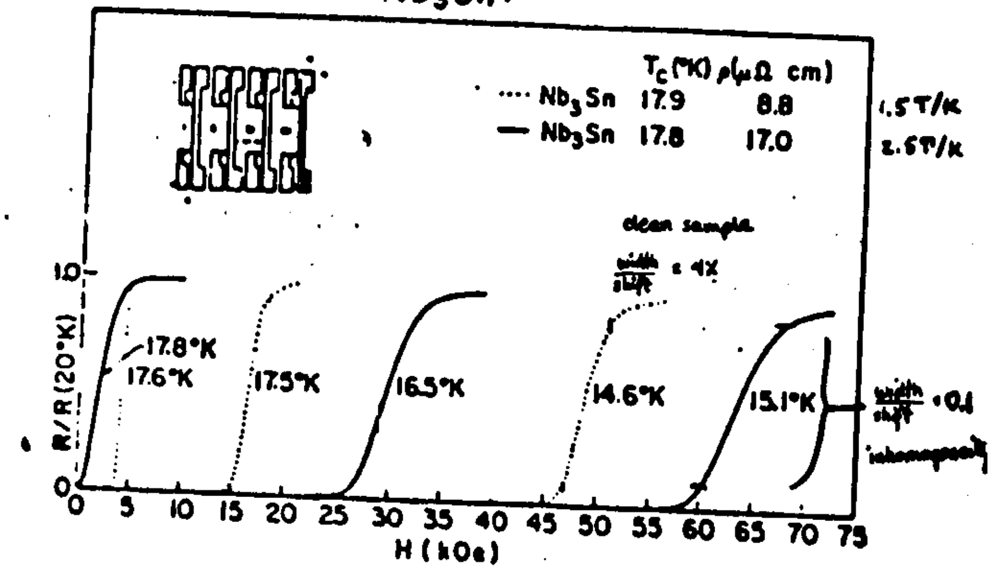
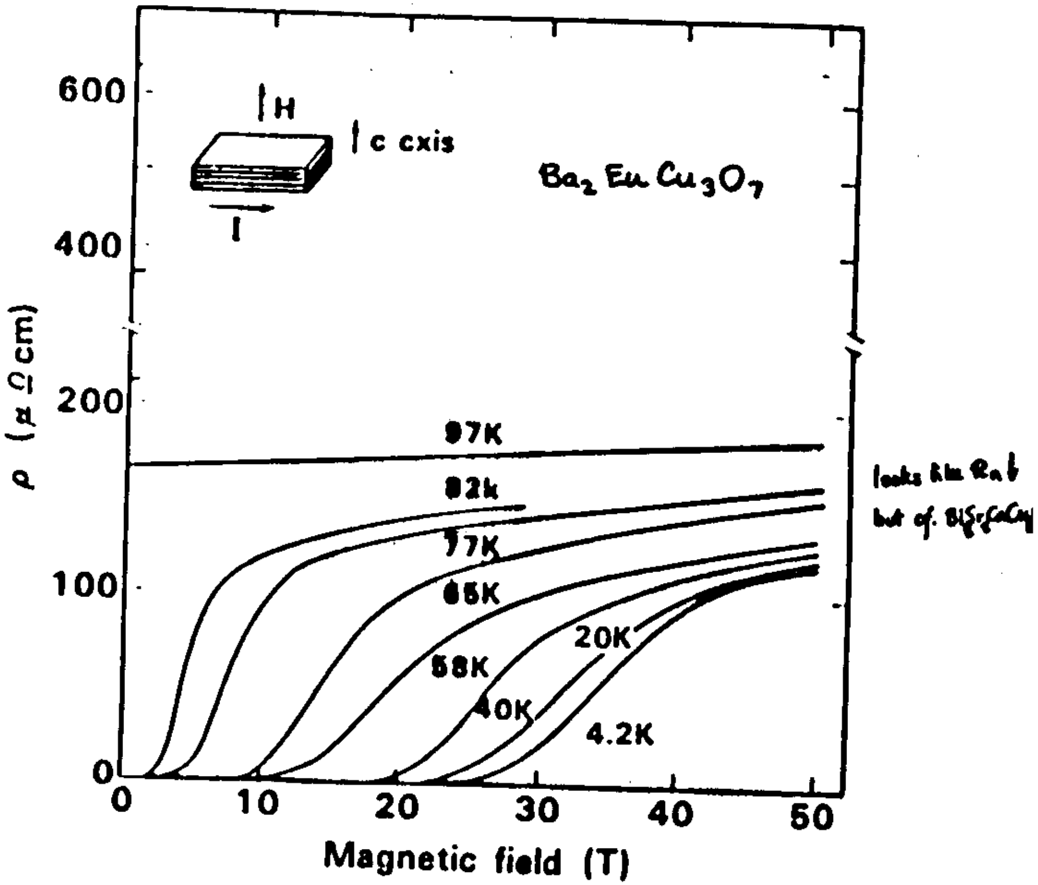


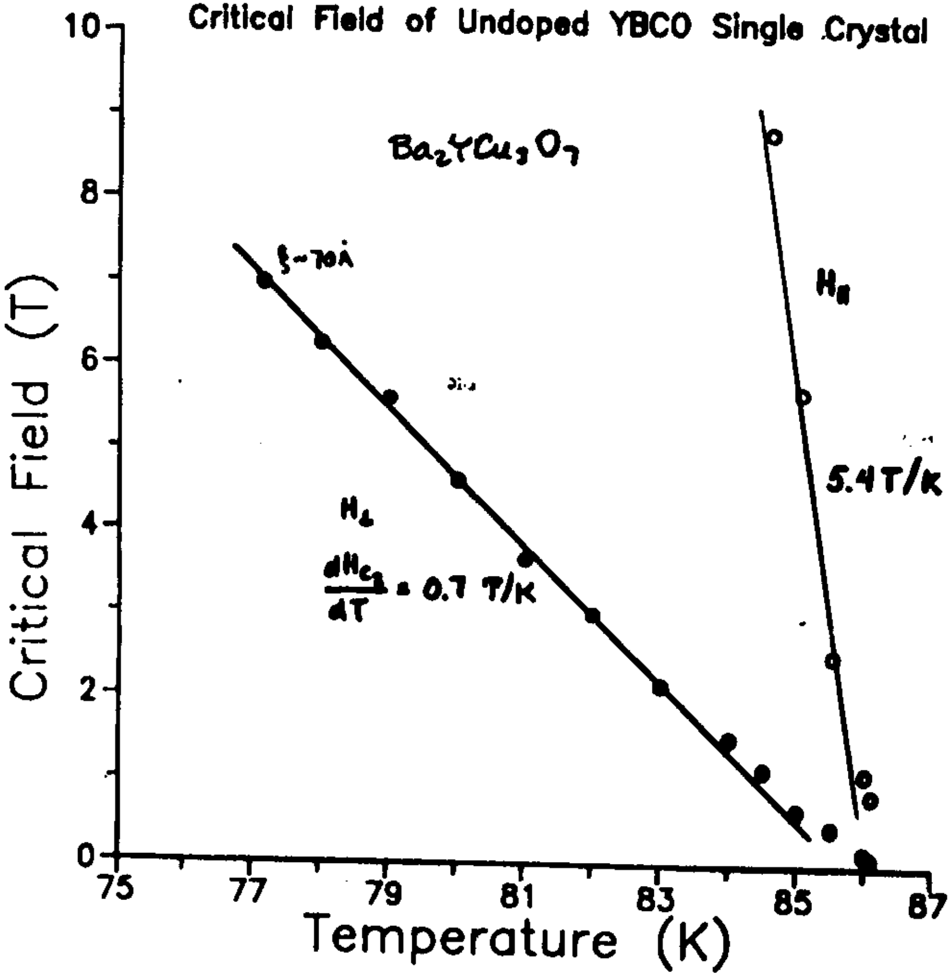
FIG. 1. Resistive transitions of Nb_3Sn thin films using field sweeps at constant temperatures. The sample (dotted



Orlando et al. PR B19 (1979) 4545

Tajima et al PR B37 (1988) 7956

using $\rho_n/2$ resistance criterion



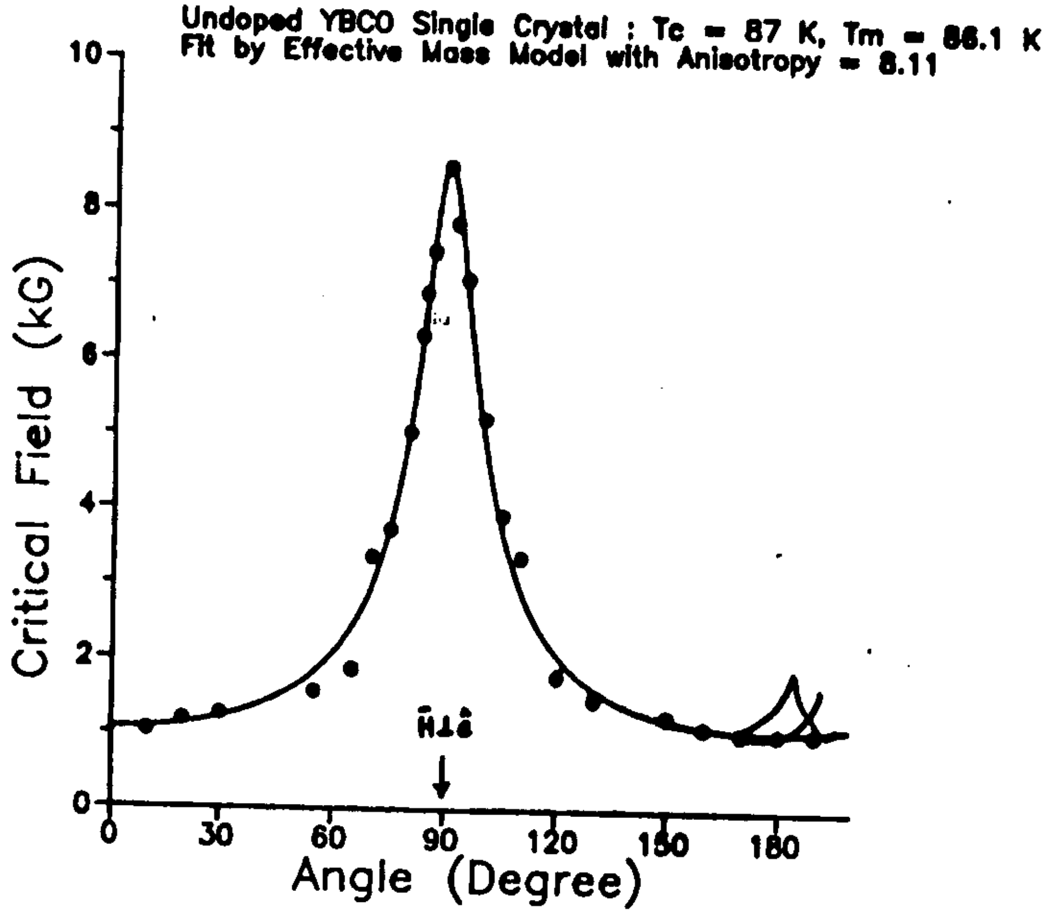
$$H_{c_2}(T) = \frac{\phi_0}{2\pi \xi_{ab}(T)}$$

van Dover et al. PR B39 (1989) 29

ANGULAR DEPENDENCE

fitted with GLAG-based effective mass model

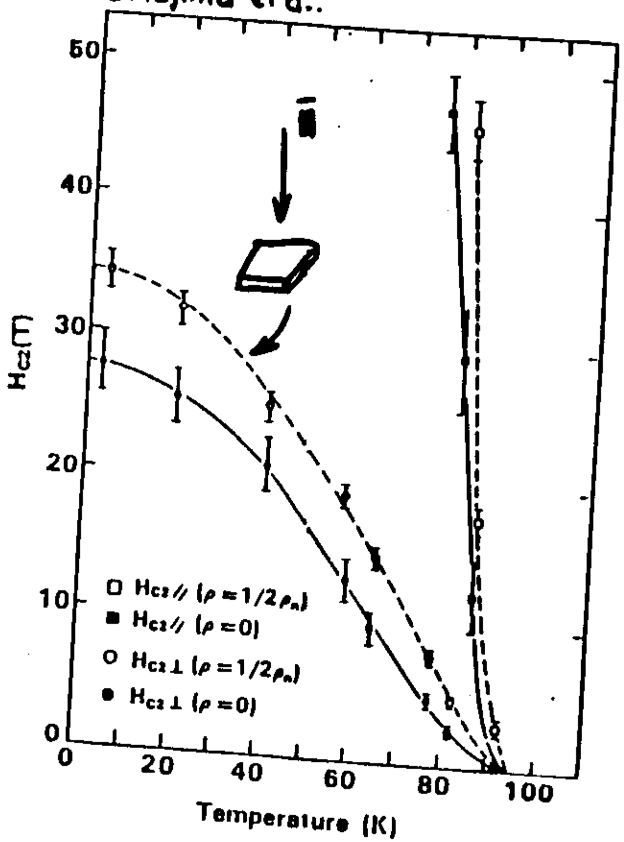
(doesn't fit 2D model – due to coupling in c direction)



van Dover et al. (unpublished)

Full $H_{c2}(T)$ $Ba_2EuCu_3O_7$

J. Tajima et al.

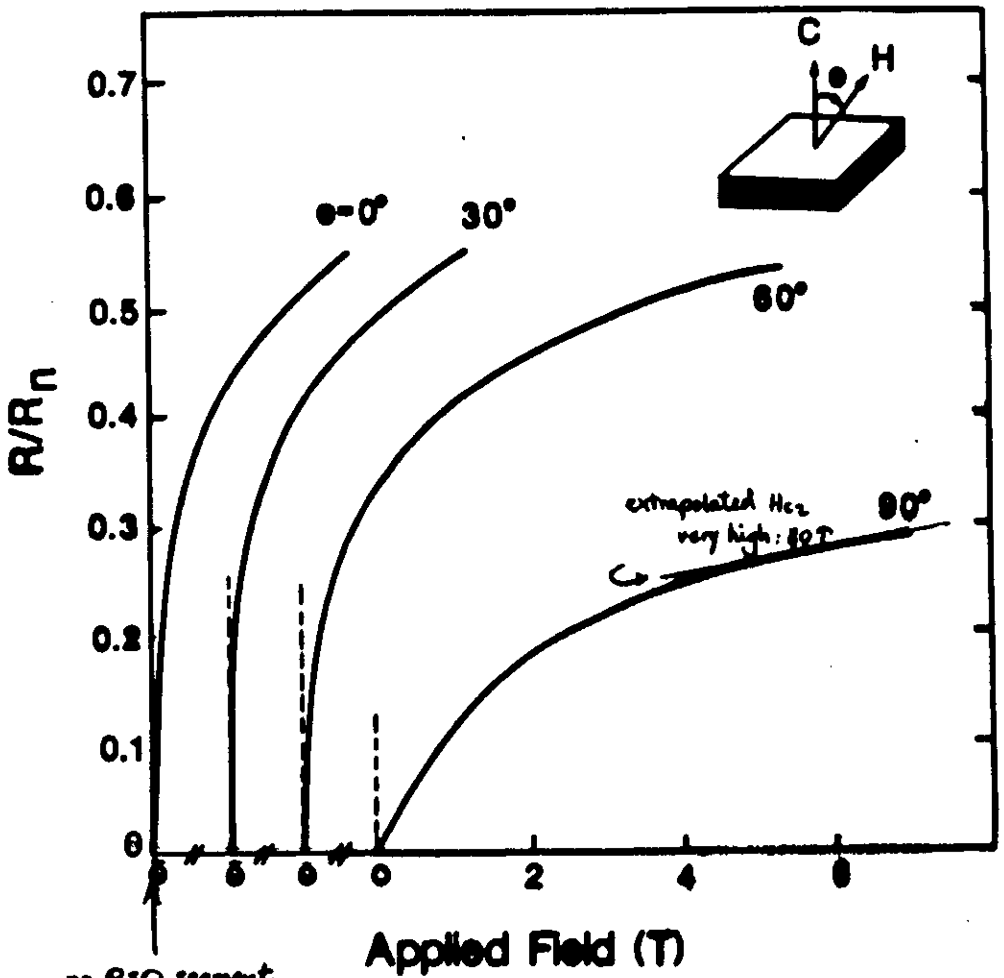


WHH ✓

Werthamer Helfand Hohenberg
PR 147(1966)295
Tajima et al. PR B37(1988)7956

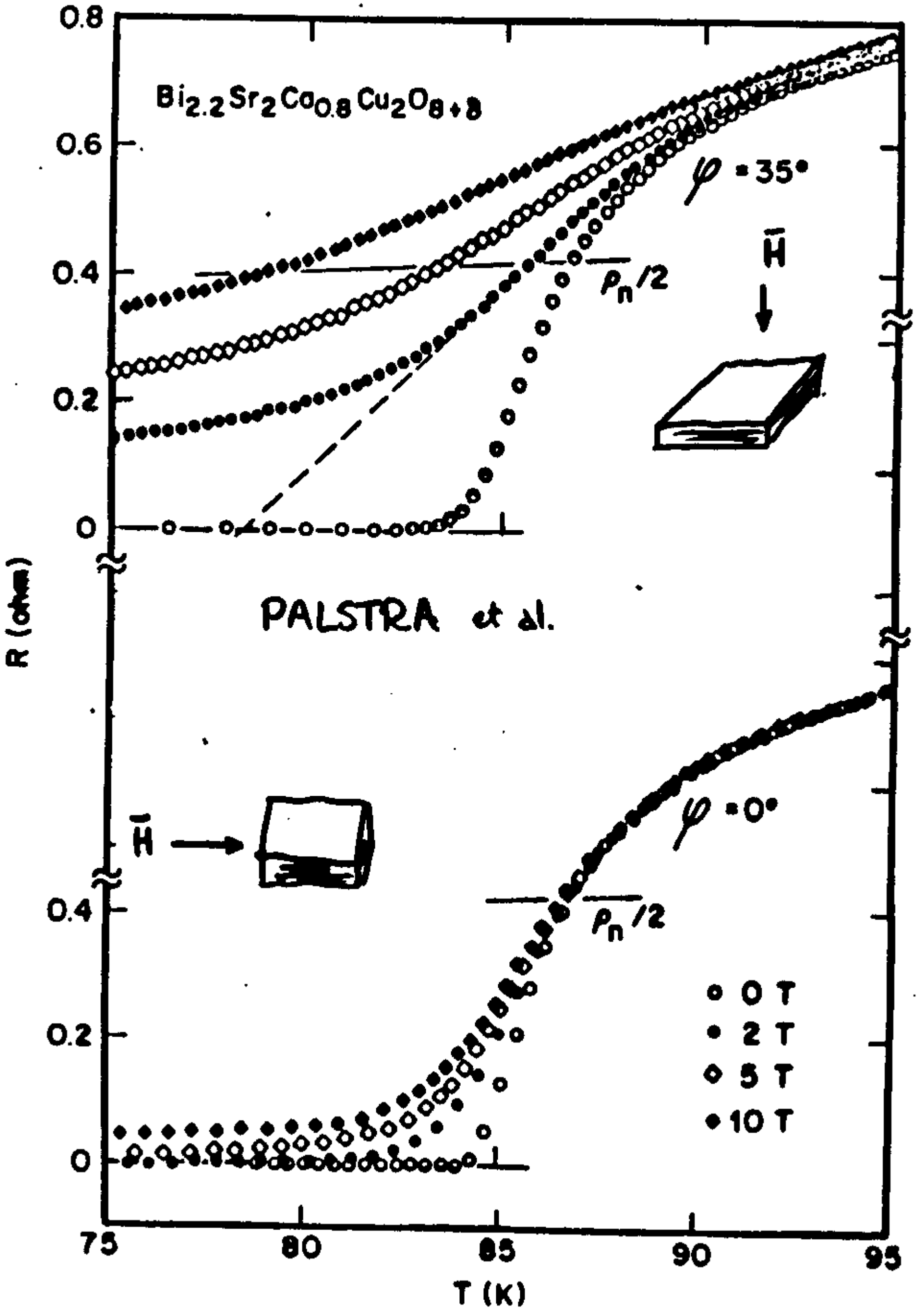
$Bi_2Sr_2Ca_1Cu_2O_8$ (2212)

T_c = 85
T_m = 83

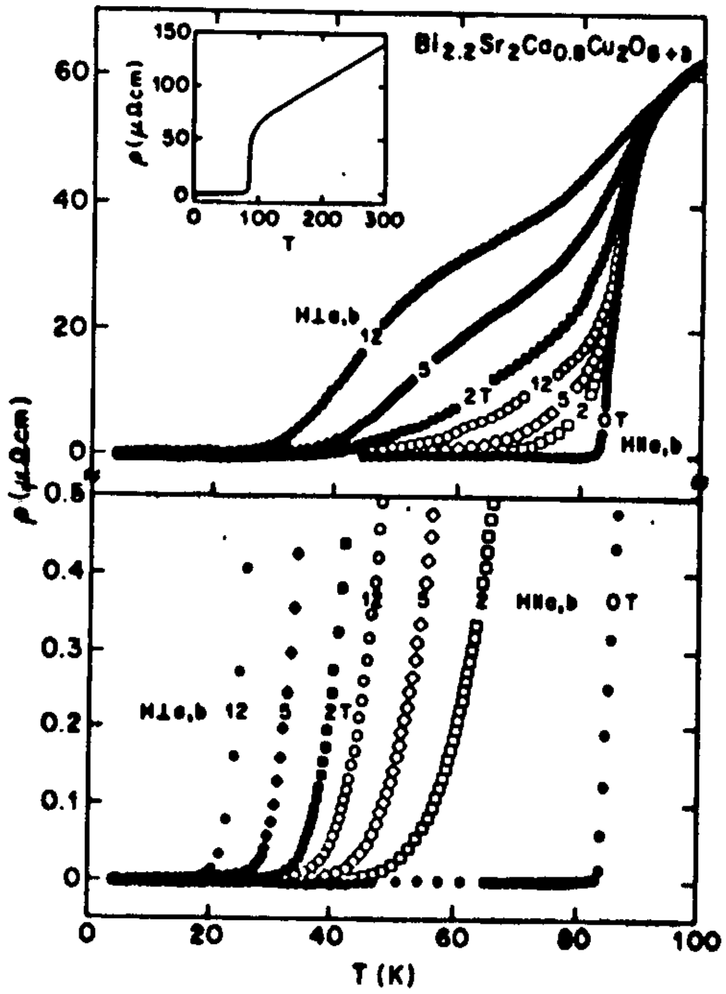


no R=0 segment
– flux creep

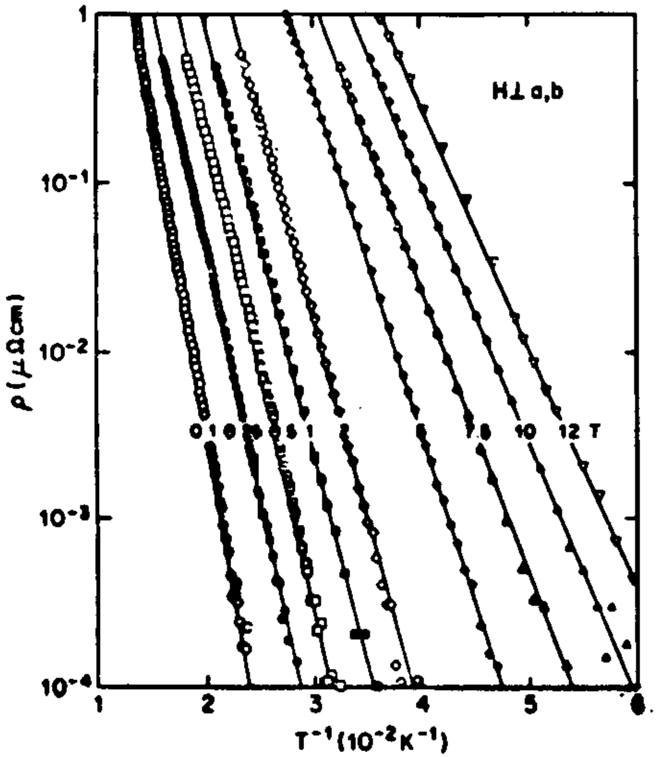
Juang et al. PR 38B(1988)



T.T.M. Palstra et al. PRL 61(1988)1662



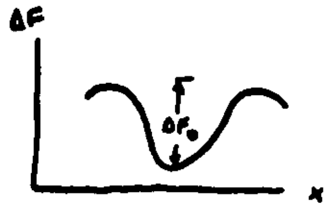
flux creep: Arrhenius law $\rho = \rho_0 e^{-u(H)/kT}$



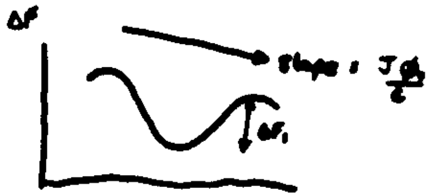
DISSIPATION LIMITED BY THERMALLY ACTIVATED HOPPING OUT OF FLUX PINNING CENTERS

FLUX CREEP

potential wall



$J = 0$



$$\Delta F_1 = \Delta F_0 - \frac{J\phi_0}{c}\,\Delta x$$ width of barrier

net prob. of jump — jump back

$$P \propto e^{-\frac{\Delta F_0}{kT}} \left(e^{\frac{J\phi_0}{c}\frac{\Delta x}{kT}} - e^{-\frac{J\phi_0}{c}\frac{\Delta x}{kT}} \right)$$

$$\frac{J\phi_0}{c} \rightarrow \frac{JBV}{c}$$ BV = flux bundle = $n\phi_0$

in MKS

attempt freq

$$\rho = \frac{2\nu_0 \Delta x\, B}{J} e^{-\Delta F_0/kT} \sinh\left(JBV\Delta x/kT\right)$$

for $\frac{JBV\Delta x}{kT} \ll 1$ $\quad \rho = 2\nu_0 B^2 V_0 \Delta x\, e^{-\Delta F_0/kT} / kT$

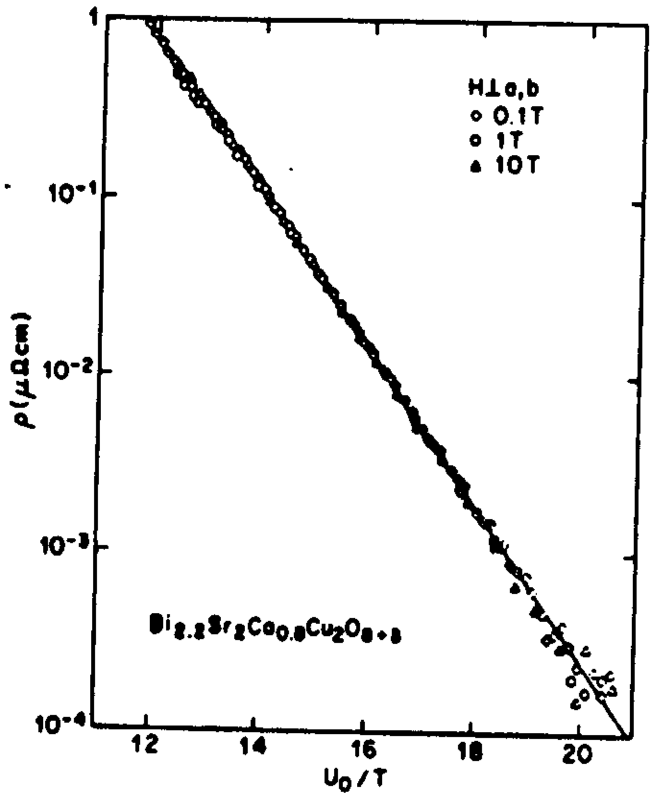


FIG. 3. Universal behavior of the thermally activated electrical resistivity for the data of Fig. 2 by use of a normalized temperature scale U_0/T.

i.e. ρ_0 independent of H

FIELD DEPENDENCE of ACTIVATION ENERGY

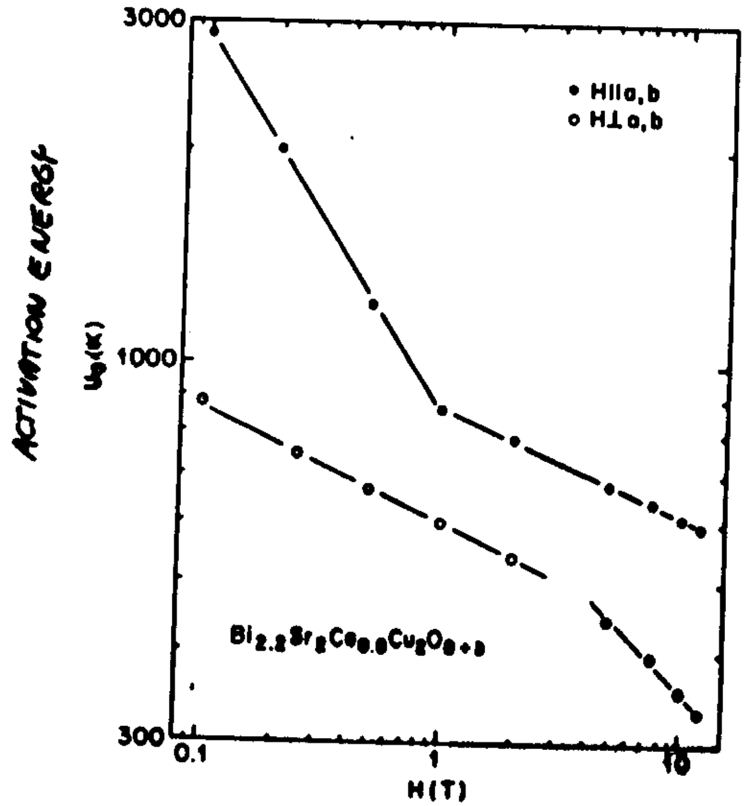
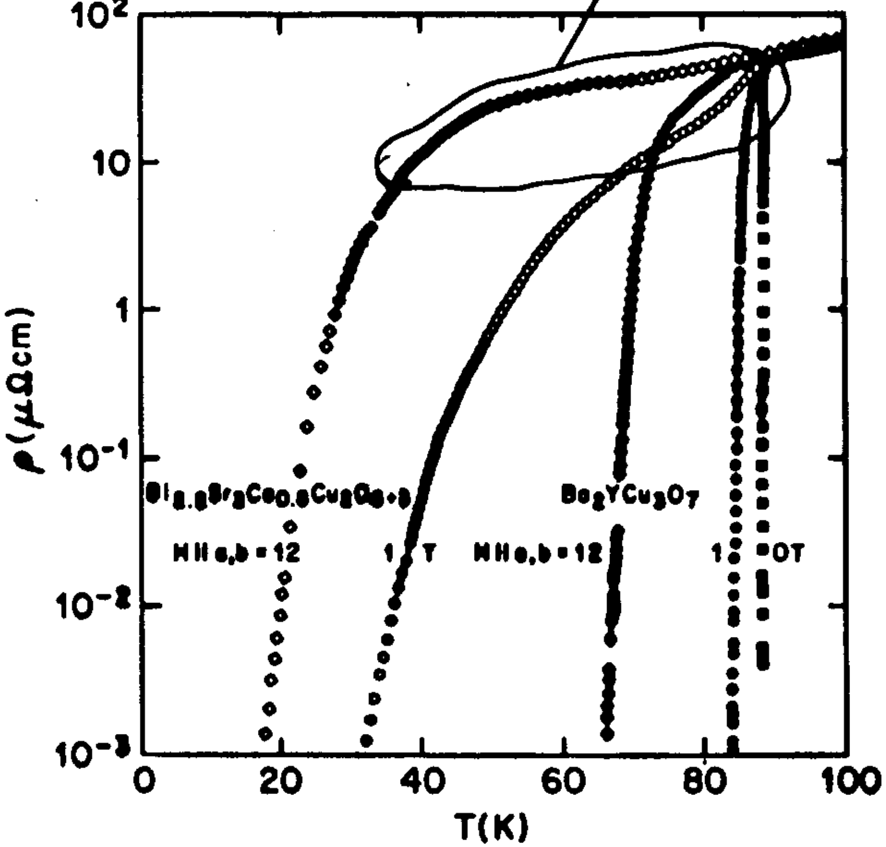


FIG. 4. Magnetic field dependence of the activation energy U_0 of $Bi_{2.2}Sr_2Ca_{0.8}Cu_2O_{8+\delta}$ in two orientations. The linear portions of the data suggest power laws $U_0 \sim H^{-\alpha}$ with $\alpha = \frac{1}{6}$ and $\frac{1}{2}$ for $H_\parallel$ and $\alpha = \frac{1}{6}$ and $\frac{1}{3}$ for $H_\perp$.

cf activation energy inferred by
Yeshurun + Malozemoff PRL 60 (1988) 1662

what is going on in the high dissipation regime?
FLUX FLOW



4

FLUX FLOW RESISTIVITY - THEORY

① Bardeen-Stephen — joule heating in core, Maxwell eqns

∃ low level excitations in core

$$\frac{\rho_f}{\rho_n} = \frac{B}{H_{c_2}}$$

② Tinkham

↓

Hu-Thompson — TDGL (gapless) — relaxation of order parameter

$$\frac{\rho_f}{\rho_n} = \alpha \cdot \frac{B}{H_{c_2}}$$

Gor'kov-Kopnin (dirty)

Eliashberg kinetic equation

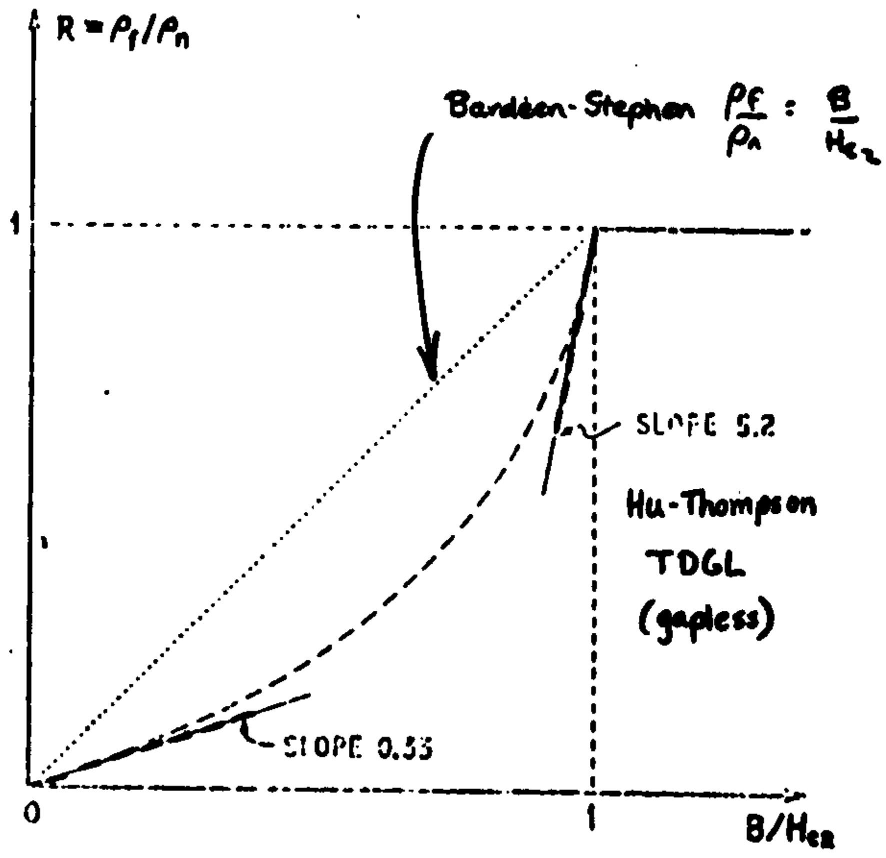
$$\frac{\rho_f}{\rho_n} = \frac{1}{\beta(T)}\,\frac{B}{H_{c_2}(T)}$$

$$\beta(T) = \frac{1.1}{(1-t)^{1/2}}$$

expts: Takayama $\beta(T) \sim (1-t)^{-1/2}$ $t<0.9$

$(1-t)^{1/2}$ $t>0.9$

FIELD DEPENDENCE



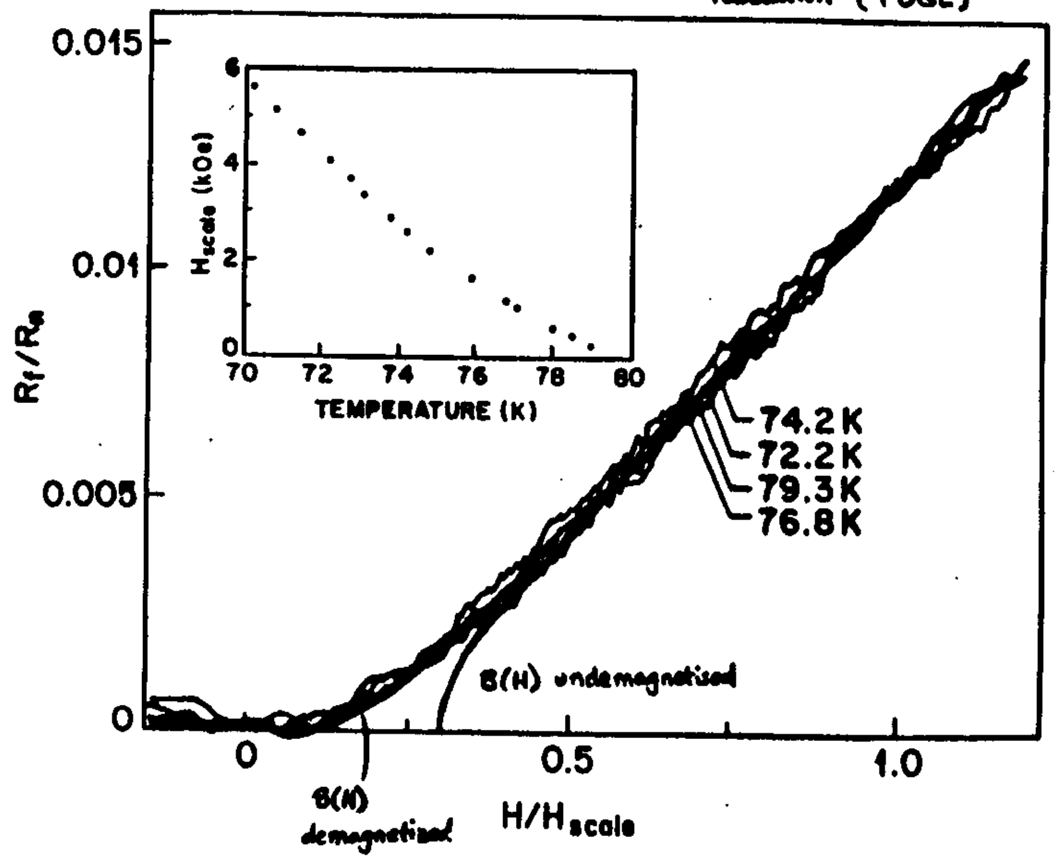
SINGLE CRYSTAL $Bi_2Sr_2CaCu_2O_8$

FLUX FLOW REGIME

i.e. viscosity-limited flow

$$\frac{R}{R_n} \sim \frac{B}{H_{c2}}$$

Bardeen-Stephan, depends on details of order-parameter relaxation (TDGL)



van Dover et al. PR B39 (1989) 4800

	this work	*Palstra, et al. (Ref. 10)*
$H'_{c1\parallel}$	100 Oe/K	⇒ $\lambda(0) \sim 300$ Å n.a.
$H'_{c2\parallel}$	14 kOe/K	7.5 kOe/K
$\kappa_{\parallel}$	13.5	n.a.
H'_{c}	740 Oe/K	280 Oe/K
$H'_{c1\perp}$	2.1 Oe/K (*)	2.1 Oe/K
$H'_{c2\perp}$	2000 kOe/K	450 kOe/K
$\kappa_{\perp}$	1900	1000

PINNING

total free energy depends on position of vortices due to local <u>fluctuations in material properties</u>

1. system seeks to sit at minimum total free energy
2. so it takes energy to move vortices out of position
3. moving vortices ⟷ dissipation
4. pinning ⟷ critical current

in a sample which is <u>perfectly uniform</u> (e.g. single xtal & no defects)

vortices are free to move ⇒ $\underline{j_c \to 0}$

examples of pinning

low field (vortices well-separated, non-interacting)

e.g. core pinning

e.g. normal core sitting on a void is lower energy than normal core where superconductor must be driven normal

e.g. magnetic pinning

image of vortex located at sc./non sc. boundary
$\Rightarrow$ attractive potential

high field – need to do a full G-L analysis

see Campbell + Evetts
Adv in Phys 21 (1972) 199

pinning of a single vortex

line energy of a fluxoid ($\kappa \gg 1/\sqrt{2}$)

$$F = \frac{\phi_0}{4\pi\lambda^2} \ln\kappa + \frac{H_c^2}{8\pi}\pi\xi^2 = \frac{H_c^2}{8\pi}\left(4\pi\xi^2 \ln\kappa + \pi\xi^2\right)$$

perturb $\frac{H_c^2}{8\pi}$ (condensation energy), ξ, $\ln\kappa$

$\Rightarrow$ perturbation in F

strength of pinning depends on subtleties

typical $\rho = \frac{\delta F}{F} \sim 10^{-3}$

NEED TO RELATE THE BASIC PINNING FORCE TO THE NET CRITICAL CURRENT:

" the summation problem "

see Campbell + Evetts

details of elasticity of flux line lattice are important

pinning by grain boundaries
in Nb_3Sn

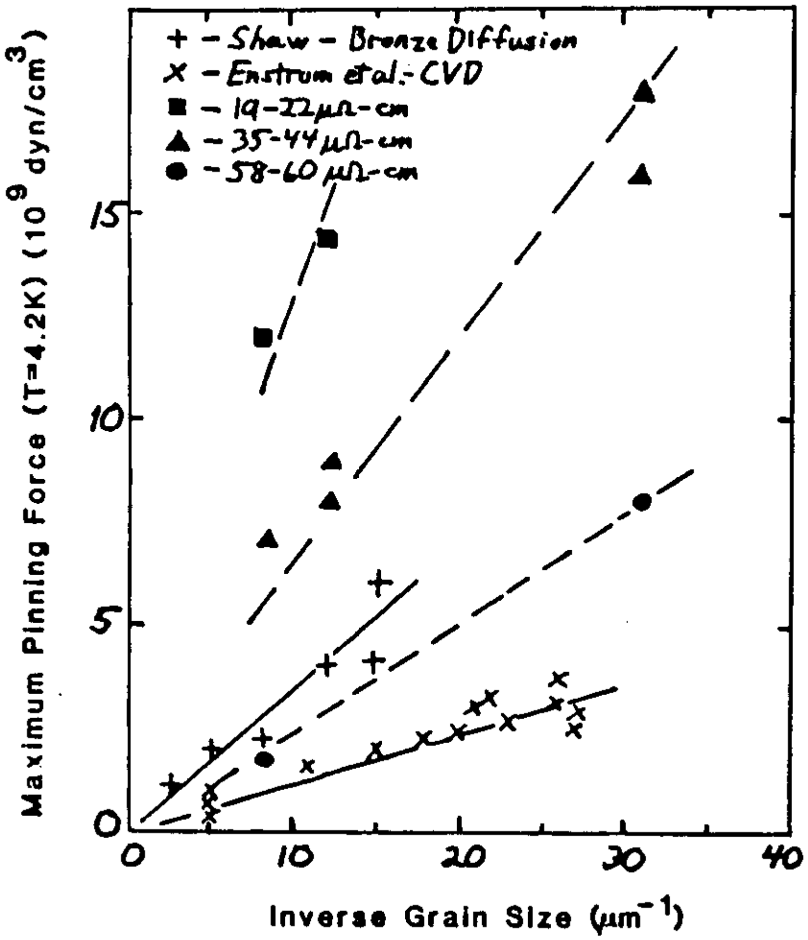


Figure 5.2: Maximum pinning force versus inverse grain size at 4.2K for samples grouped by their resistivity.

PINNING IN HIGH T_c MAT'LS

$Ba_2YCu_3O_7$ twins ?

o-vacancies ?

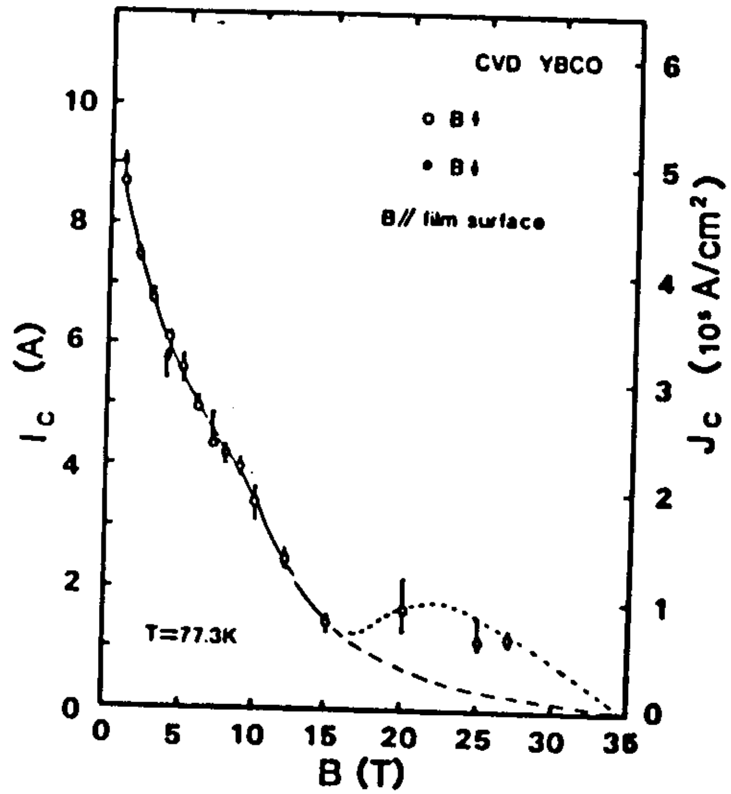
grain boundaries ?

$Bi_2Sr_2CaCu_2O_8$ no twins.

intergrowths ?

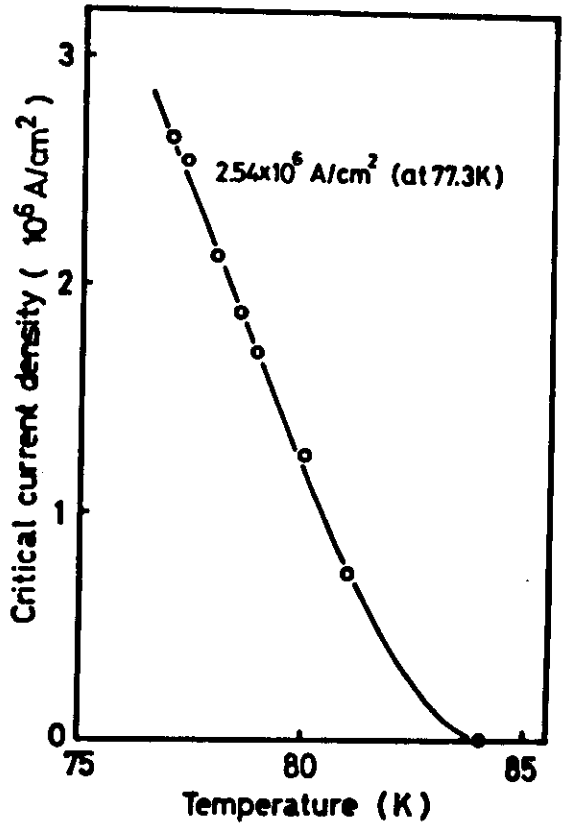
[illegible] pinning but [illegible]
high density of [illegible] boundaries

$Ba_2YCu_3O_7$ CVD



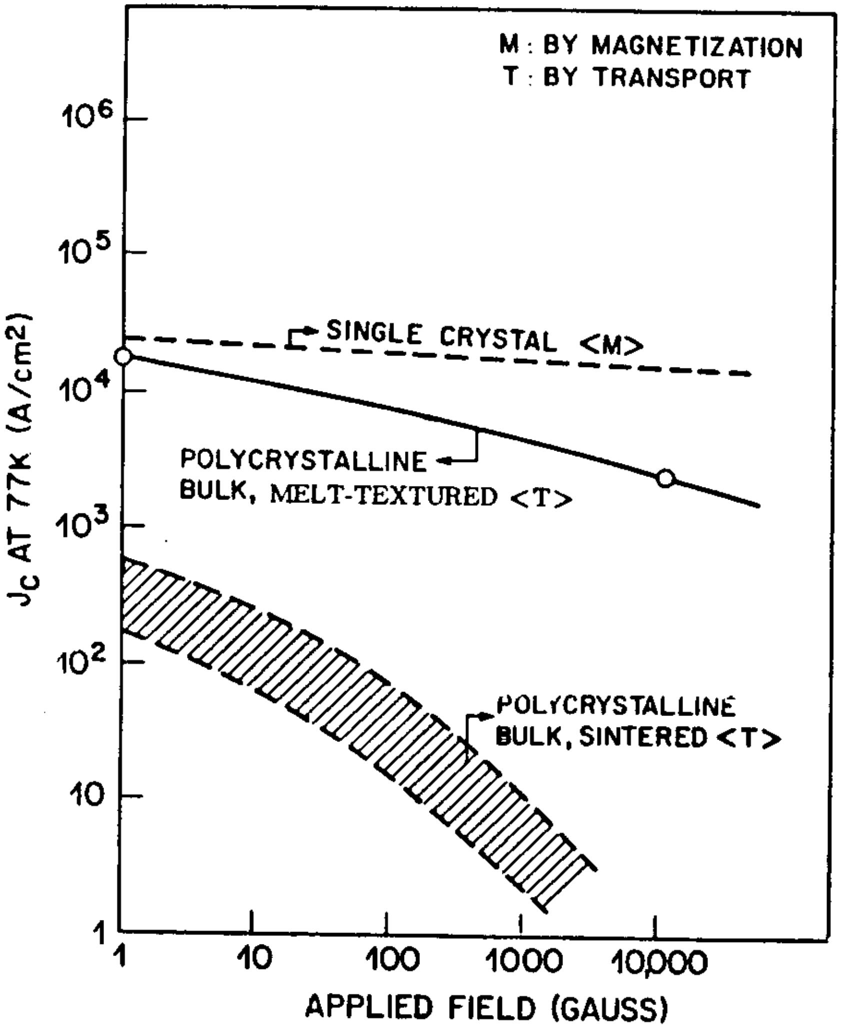
Watanabe et al APL 54 (1989) 576

$Ba_2HoCu_3O_7$ evap



Tanaka et al. JJAP 27 (1988) L622

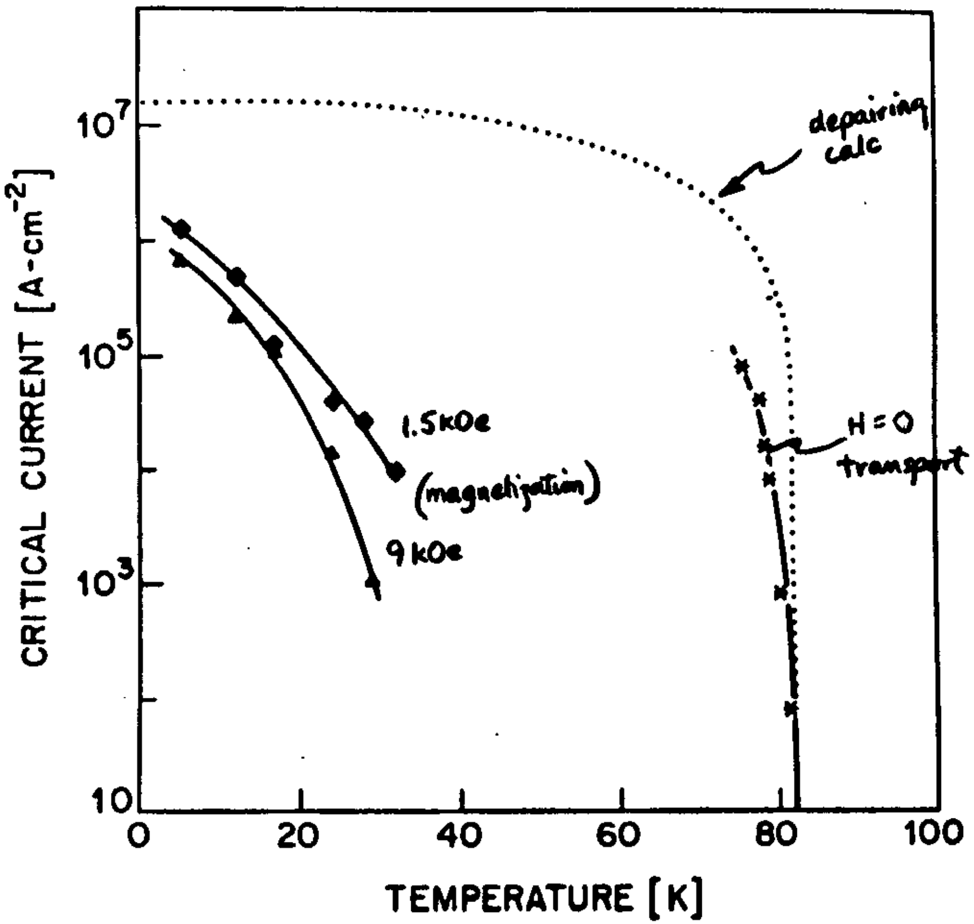
J_c OF $YBa_2Cu_3O_{7-\delta}$



SINGLE CRYSTAL

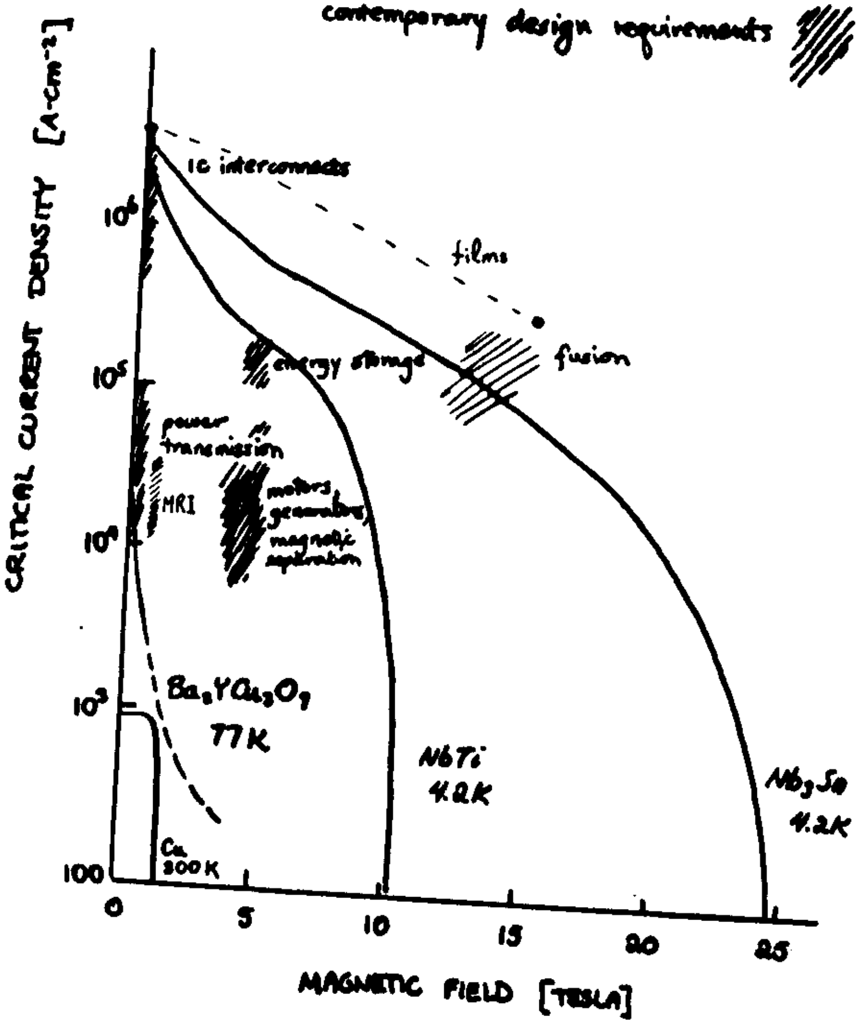
$Bi_2Sr_2CaCu_2O_8$

CRITICAL CURRENT



H=O silsbee law (H = H_{c1} on surface
— depends on demagnetization

PERFORMANCE REQUIREMENTS FOR APPLICATIONS



MAGNETIZATION LOOPS, CRITICAL STATE & THE BEAN MODEL

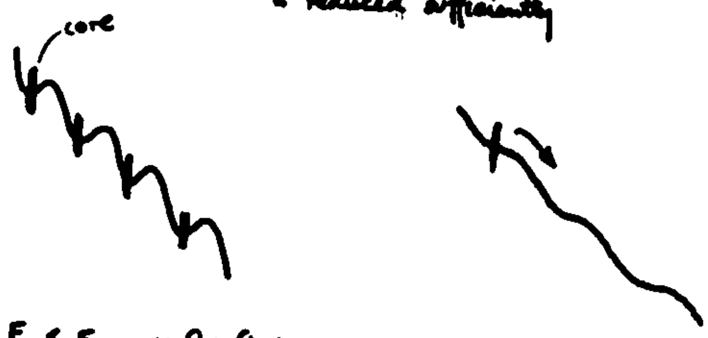
CRITICAL STATE MODEL

force on a single fluxoid $\quad F = \dfrac{\vec{J} \times \phi_0 \hat{z}}{c}$

driving force density $\quad F_v = \dfrac{\vec{J} \times \vec{B}}{c} \quad$ $\vec{J}$ & $\vec{B}$ are average over 'small' volume

critical state: balance pinning force density with driving force density

i.e. fluxoids will move until driving force density is reduced sufficiently



$F_v < F_p$ no flux flow $R = 0$

$F_v > F_p$ flux flow $R > 0$

critical current $\quad J_c = \dfrac{c F_p}{B}$ actually, use this to define F_p

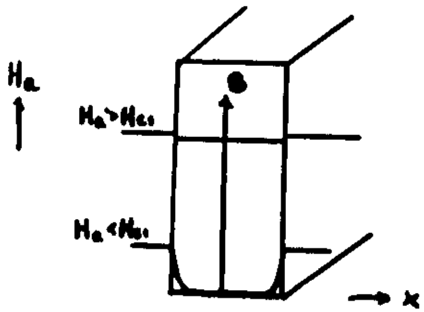
Bean model (use for calc'ns)

J_c = constant up to H_{c2} $\quad (\Rightarrow F_p \propto B)$

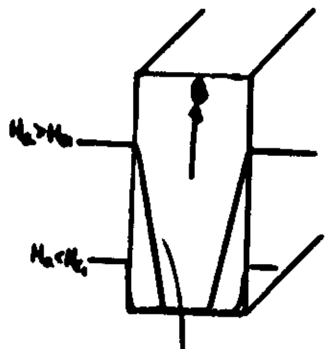
could also use Anderson Kim $\quad J_c = \dfrac{\alpha}{B + B_0} \quad$ (i.e. $F_p \sim$ const)

Ravi Kumar + Chaddah $\quad J_c = J_{c0}\, e^{-H/H_0}$

NO PINNING:



PINNING:



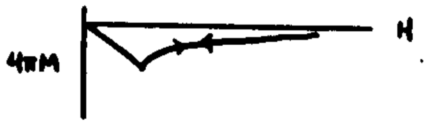
$\dfrac{dB}{dx} = \dfrac{4\pi}{c} J_c$

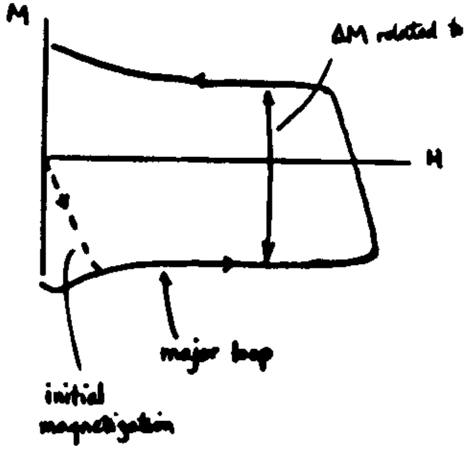
magnetization irreversible

M-H loops

NO PINNING:

reversible





ΔM a measure of J_c

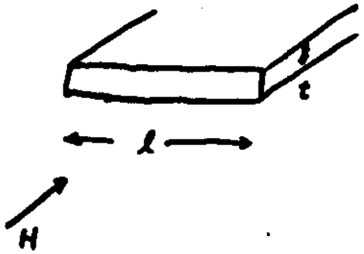
Bean model

analogous to piling sand on the surface under question

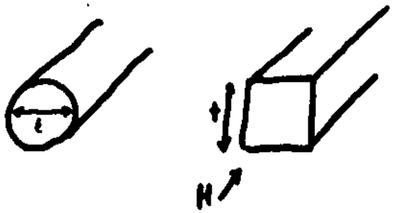
slope of sand ($\equiv$ angle of repose) $\sim J_c$

height of sand $\sim$ internal field resulting from current flow

$\dfrac{\text{volume of sand}}{\text{area of base}} \sim$ magnetization M from current flow examples

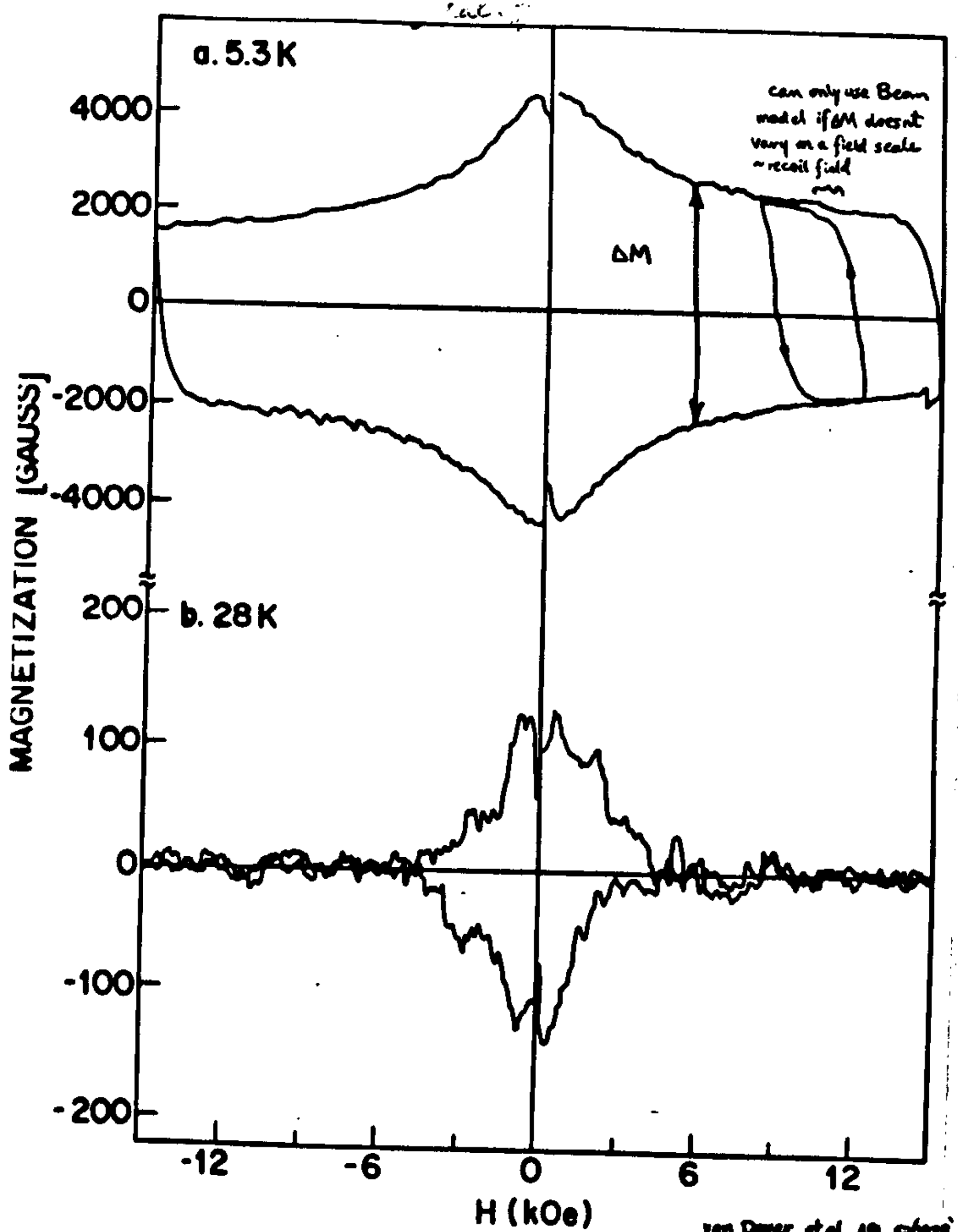


$$\Delta M = \frac{J_c t}{20} \qquad (\text{G},\ \text{A/cm}^2,\ \text{cm})$$

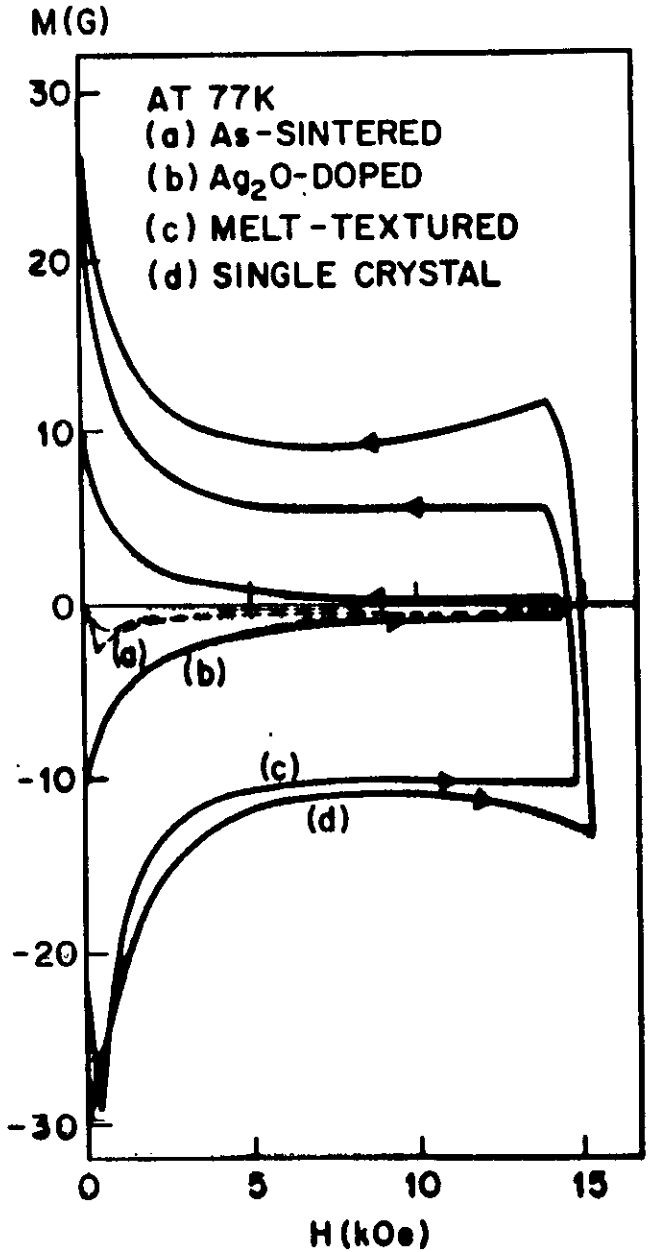


$$\Delta M = \frac{J_c t}{30}$$

Campbell + Evetts
Critical Currents in Superconductors
(Taylor + Francis, London)



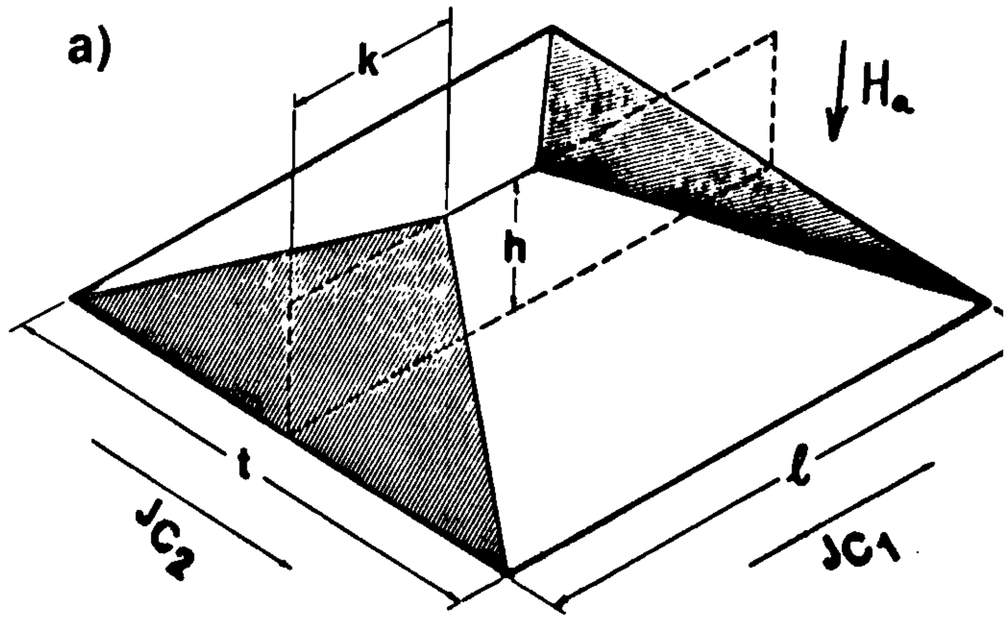
van Dover et al. APL 52(1988) 1910



Jin et al. APL 54(1989) 584

if J_c anisotropic, must use appropriate angle of repose for each direction

$$\Delta M = \frac{J_{c1}\, t}{20}\left(1 - \frac{t}{3l}\,\frac{J_{c1}}{J_{c2}}\right)$$



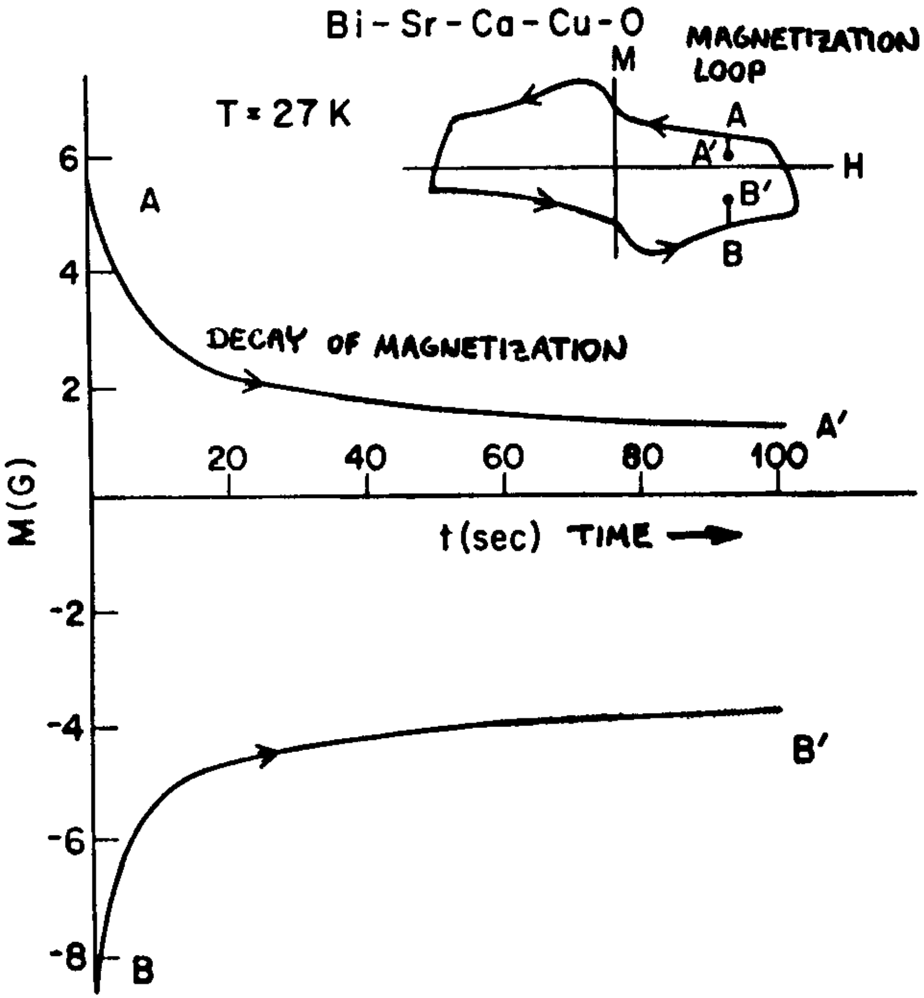
$Ba_2YCu_3O_7$:
result 30 K

$J_c^{ab} = 7.1 \cdot 10^5$ A/cm²

$J_c^{abc} = 4.9 \cdot 10^6$ — flux motion // to twins

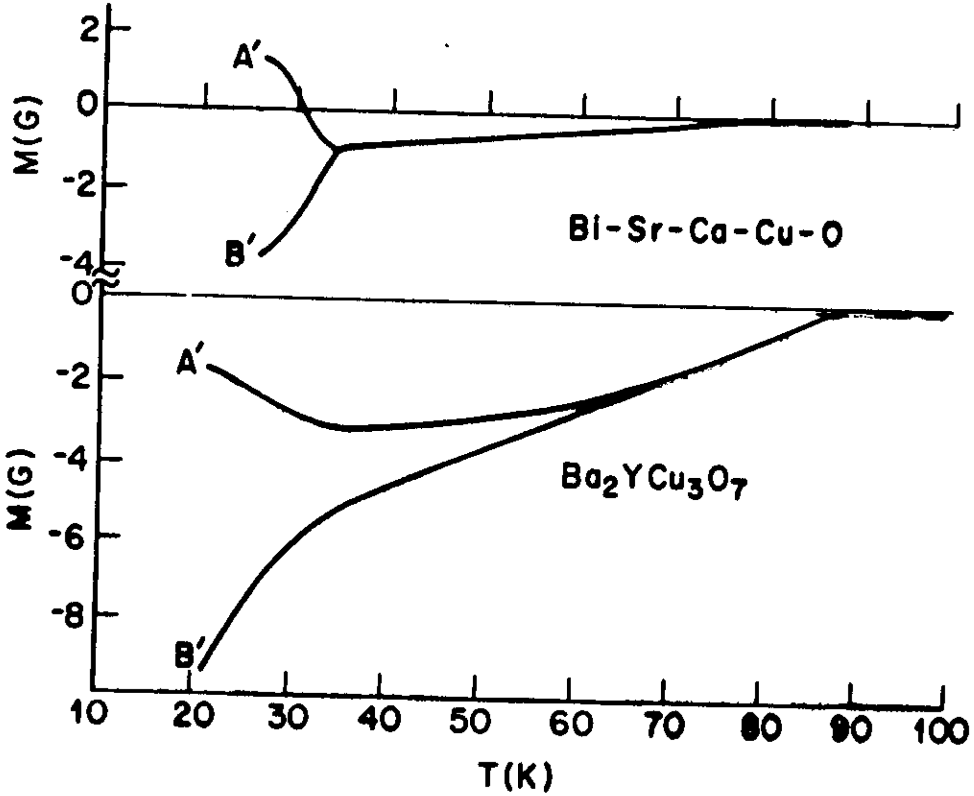
$J_c^{c} = 2.2 \cdot 10^4$ — Gyorgy et al. APL (preprint)

twins not important at 30 K!



Gyorgy et al. APL 52(1988)2223

MAGNETIZATION DECAY
AS A
FUNCTION OF TEMPERATURE



Gyorgy et al. APL 52(1988)2223

OUTSTANDING PROBLEMS

TRANSPORT + MAGNETICS

0. how do you vet ceramics + crystals
   case-by-case

1. normal-state transport   superconductivity thy must relate
   to n/s properties
   $\rho(T)$ perhaps perturb by doping
   $R_H(T)$ but how to interpret ?
   other magneto-galvanic, thermogalvanic, thermomagnetic...

2. H-T phase diagram   framework: FLUX CREEP
   what is V_c (flux bundle size, $< \xi_0$?)
   melted phases? entanglement? glassy phases? Kosterlitz-Thouless?
   → neutron scattering

3. nature of pinning sites
   relationship between F_p, U_0
   different pinning mechanism at different T
   intrinsic pinning ?
   engineering pin site density

4. dissipation
   possible insight into dynamics
   understand high dissipation regime ?