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SMR 1232 - 8

**XII WORKSHOP ON
STRONGLY CORRELATED ELECTRON SYSTEMS**

17 - 28 July 2000

Vortex-like excitations above Tc in LaSrCuO and YBaCuO (underdoped) obs. by Nernst effect

N.P. ONG
Princeton University, Dept. of Physics
Princeton, U.S.A.

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

strada costiera 11 - 34014 trieste italy - tel +39 0402240111 fax +39 040224163 - sci info@ictp.trieste.it - www.ictp.trieste.it

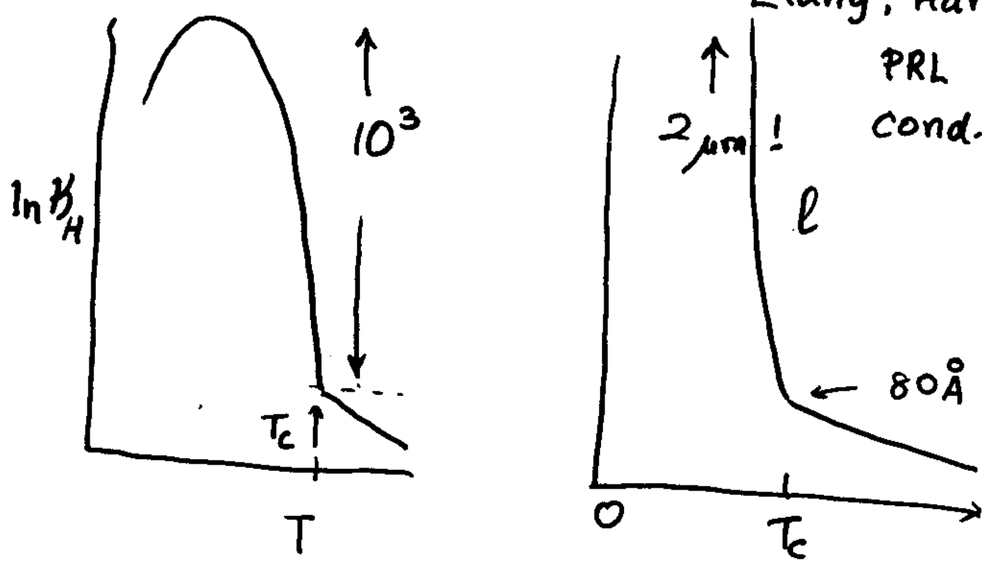
Vortex-like excitations above T_c in LaSrCuO and YBaCuO (underdoped) obs. by Nernst effect.

Z.A. Xu, Y. Wang, N.P. ONG
Princeton U
T. Kakeshita, S. Uchida
U. of Tokyo

- Phase stiffness
- Nernst effect of vortices
- " " carriers
- LaSrCuO $0.05 < x < 0.17$
- $YBaCuO_y$ $6.40 < y < 6.95$
  Zn_z $0 < z < 0.02$

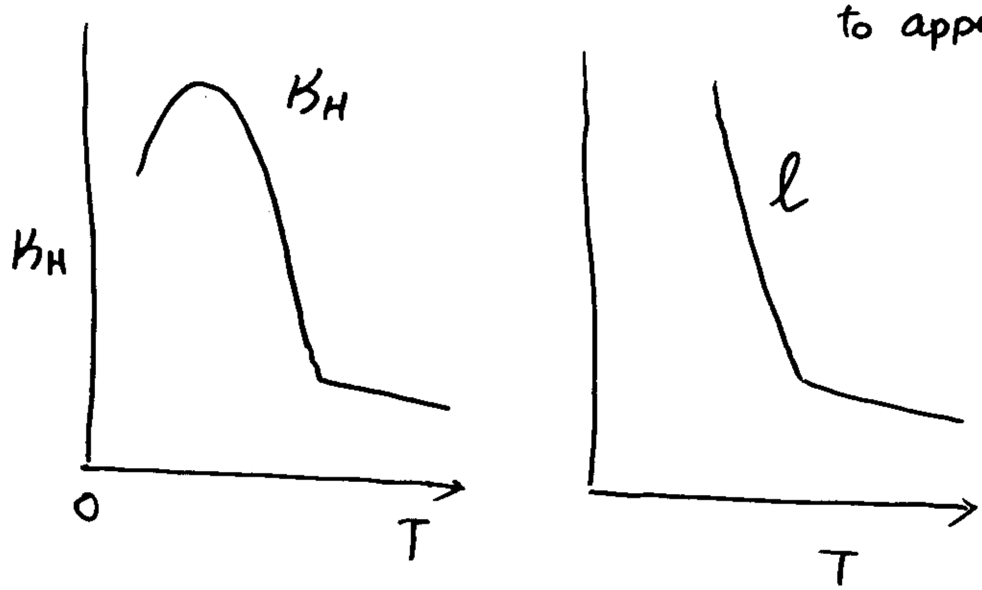
Thermal Hall Effect $YBCO_{6.95}$

Zhang, Ong, Bonn
Liang, Hardy
PRL submitted
cond. mat.



BSCCO

Zhang, Ong
to appear



Behavior of ℓ inconsistent with ARPES (Valla et al.)

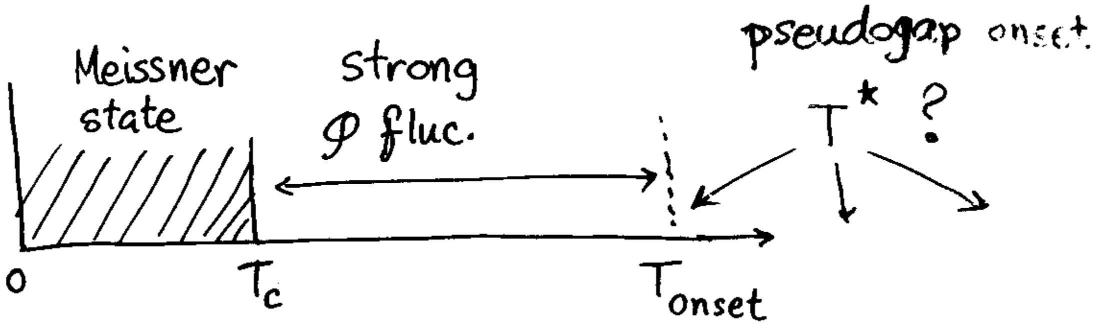
Pair formation above T_c in underdoped cuprates?

ARPES, STM tunneling

➡ pseudogap evolves smoothly from SC gap

Theory : Pair amplitude may survive above T_c
phase stiffness destroyed by fluct.

(Kivelson, Emery
Wen, Lee
Norman, Randeira ...)



➡ Phase stiffness estim. from teraHz expt.
in Bi2212

Corson, Mallozzi, Orenstein ...
Nature '99

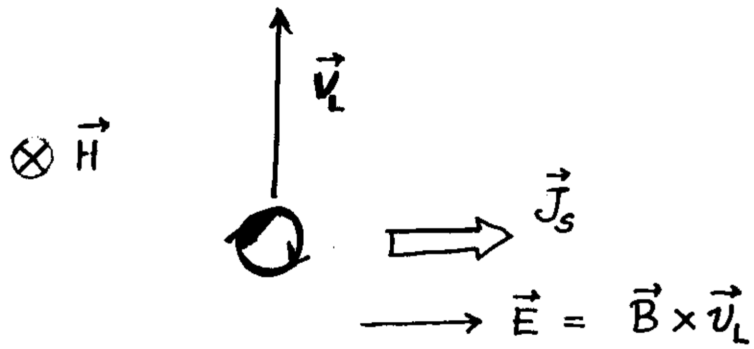
$T_{onset} < T^*$

timescale < 1 ps

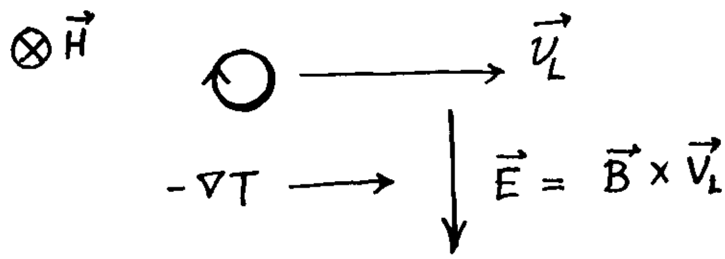
➡ DC probe of pairing amplitude ?

Search for vortices $T > T_c$

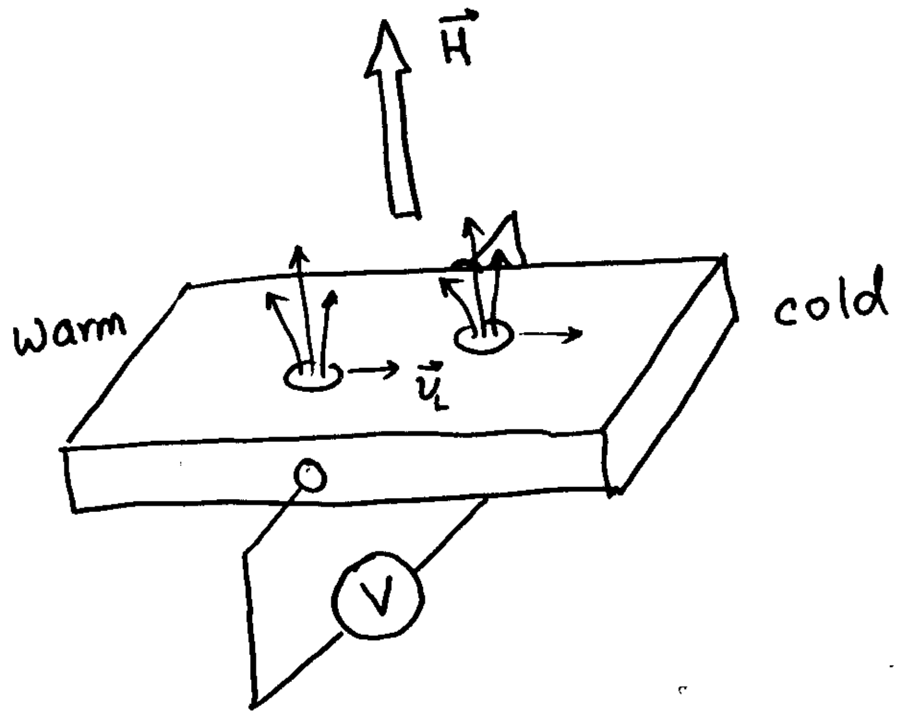
Xu et al. 2000



Response to applied $\vec{J}_s$



Response to applied $-\vec{\nabla} T$



Josephson $\quad eV = 2\pi \dot{n}_v \quad$ phase slip rate

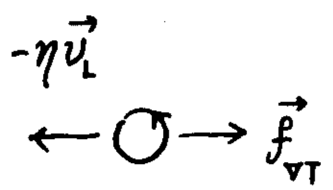
$$\rightarrow \quad \vec{E} = \vec{B} \times \vec{V}_L$$

- Distinct from Faraday effect

Vortex liquid state $\quad \vec{f}_{\nabla T} = -S_\phi \nabla T$

↑ entropy /cm

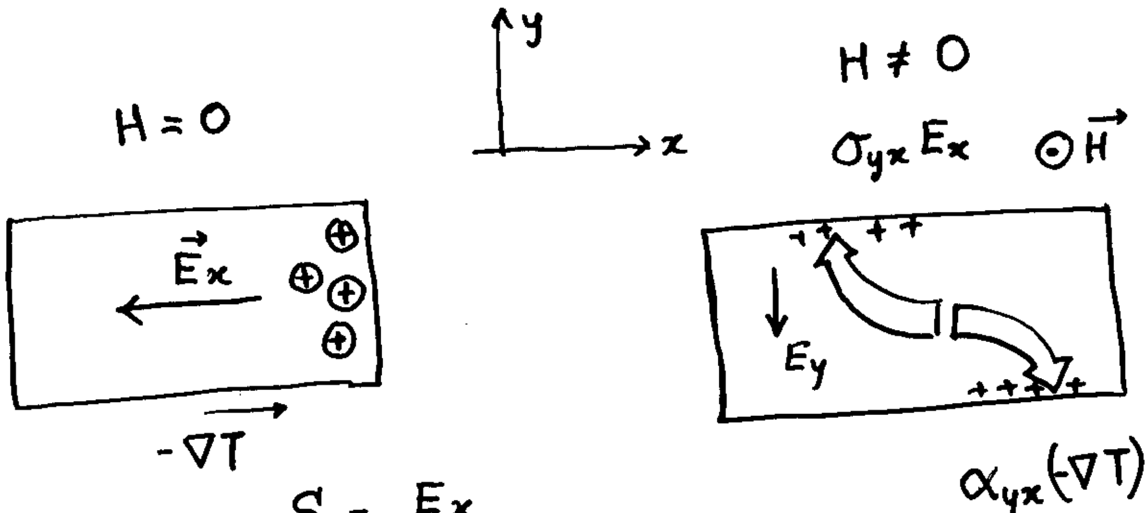
Damping $\quad \vec{f}_\eta = -\eta \vec{v}_L$



$$\eta v_L = S_\phi \nabla T$$

$$\nu \equiv \frac{E_y}{B|\nabla T|} = \frac{v_L}{\nabla T} = \frac{S_\phi}{\eta}$$

Nernst effect of normal charge carriers



Thermopower $S = \dfrac{E_x}{|\nabla T|}$

Nernst $E_y \approx 0$
because of cancellation

Total charge current along $\hat{y}$

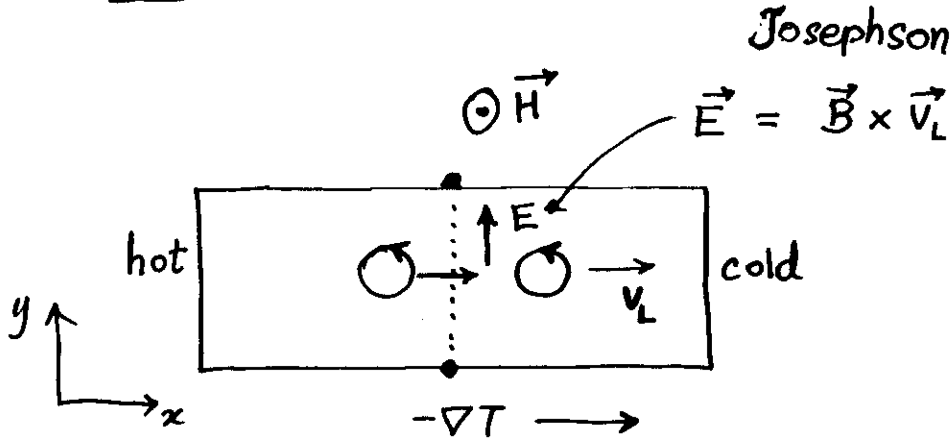
$$J_y = \sigma_{yx} E_x + \sigma E_y + \alpha_{yx}(-\nabla T)$$

bc: $J_y = 0$

$$E_y = -\left(\frac{\sigma_{yx}}{\sigma} E_x + \frac{\alpha_{yx}}{\sigma}(-\nabla T) \right)$$

Nernst $\nu = \dfrac{E_y}{B\,|\nabla T|}$

Vortex Nernst effect



- Vortex Nernst signal is a "large" effect

$$\nu_{Vortex} = \frac{E_y}{|\nabla T| H} \qquad \frac{\text{Volts}}{\text{Kelvin}} \cdot \frac{1}{\text{Tesla}}$$

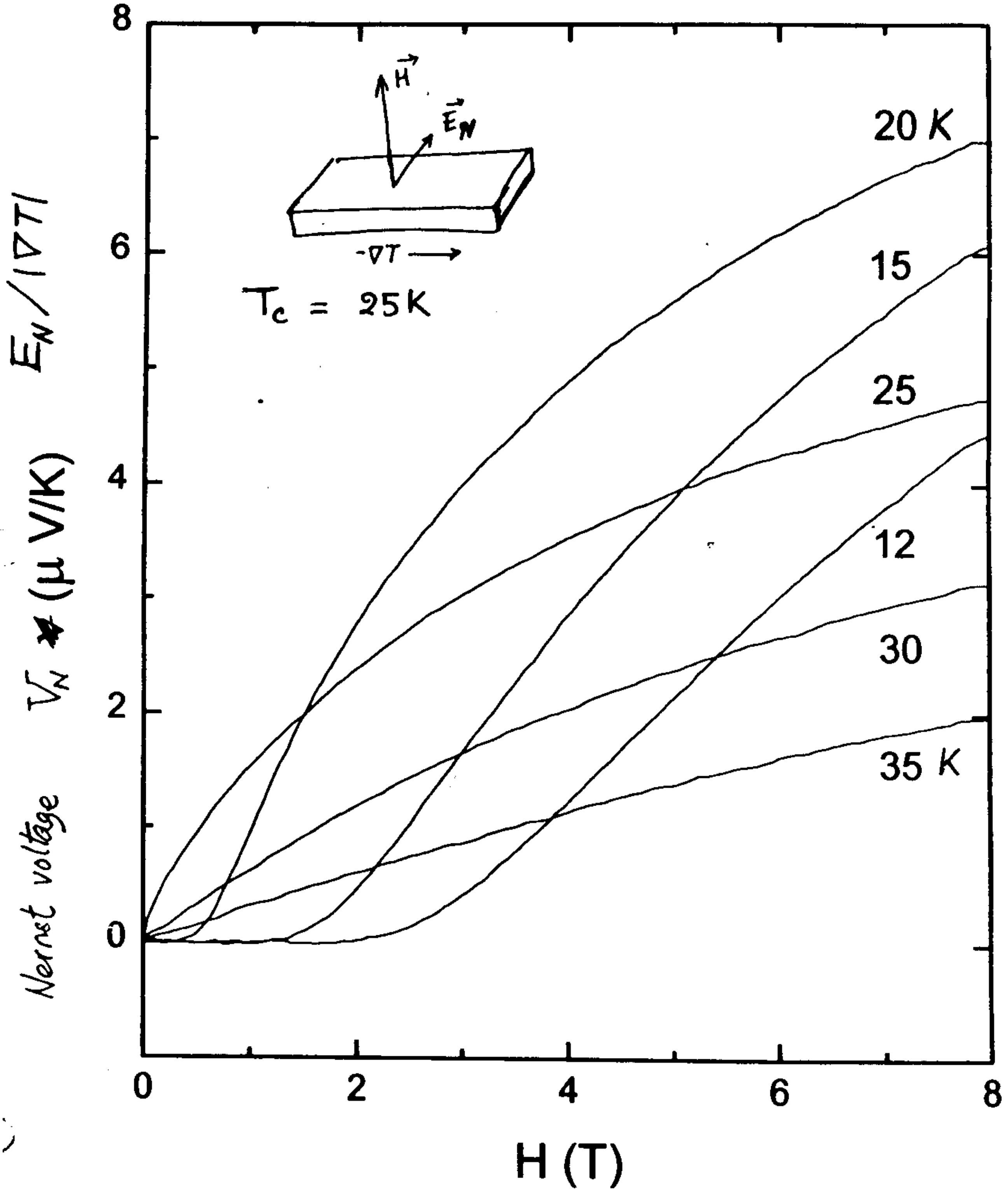
$$\sim 2-4 \ \frac{\mu V}{KT} \quad \text{in } 90K \text{ YBaCuO}$$

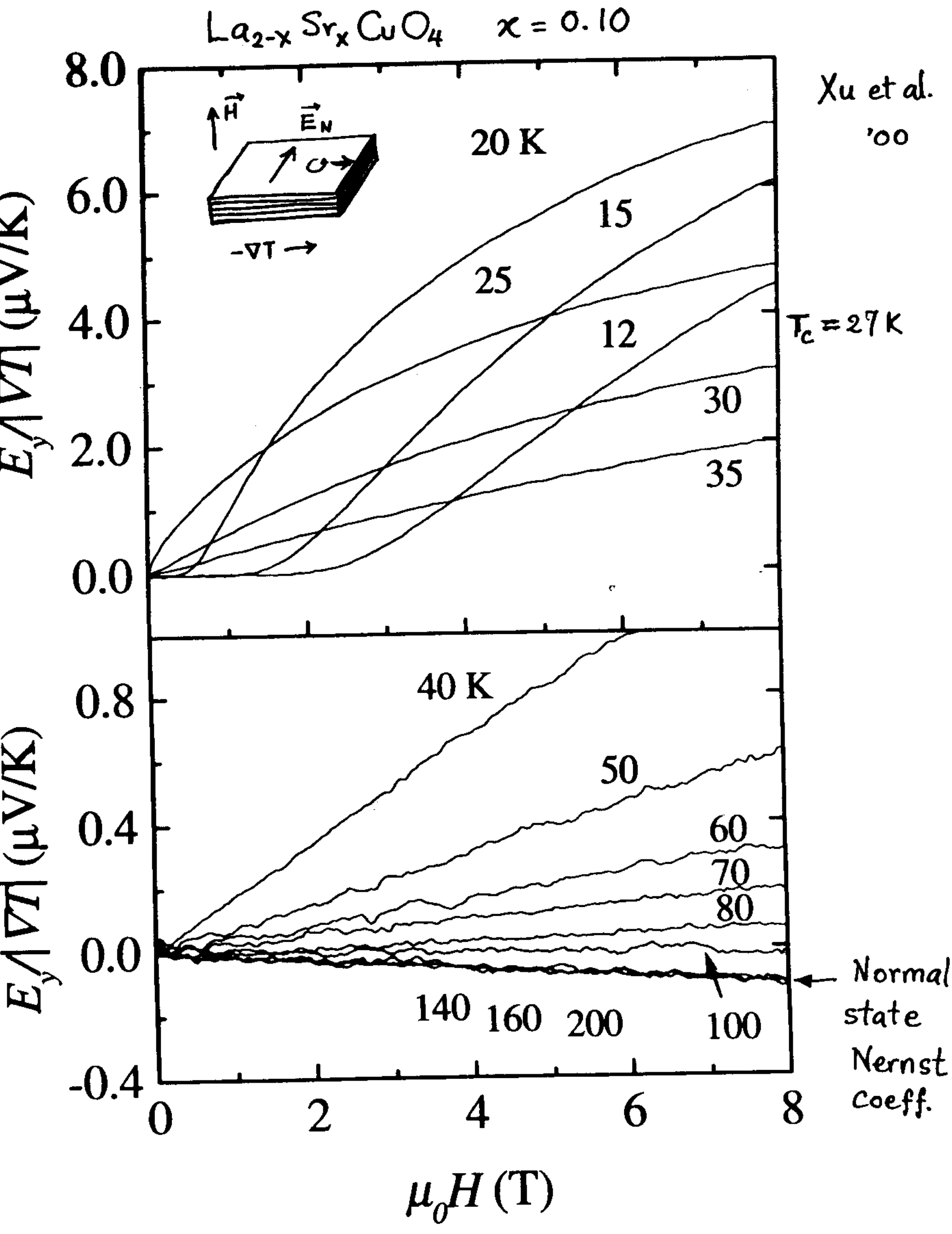
- Nernst contribution from charge carriers ν_N is a "small" effect if $\Theta_H \ll 1$.

$$\nu_{obs} = \nu_{vortex} + \nu_N$$

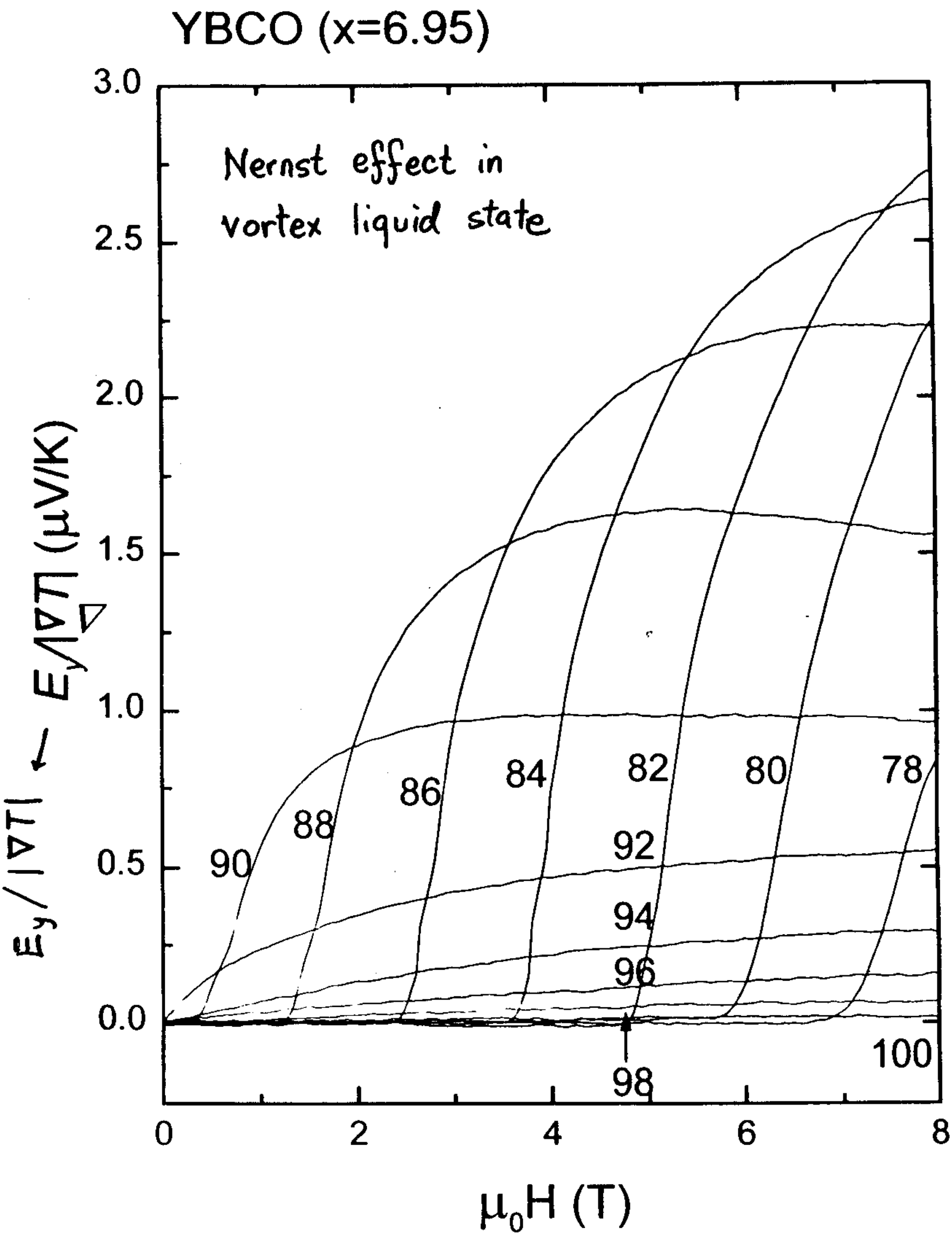
→ • ν_N further reduced by "Sondheimer cancellation."

$La_{2-x}Sr_xCuO_4$ (x=0.10)

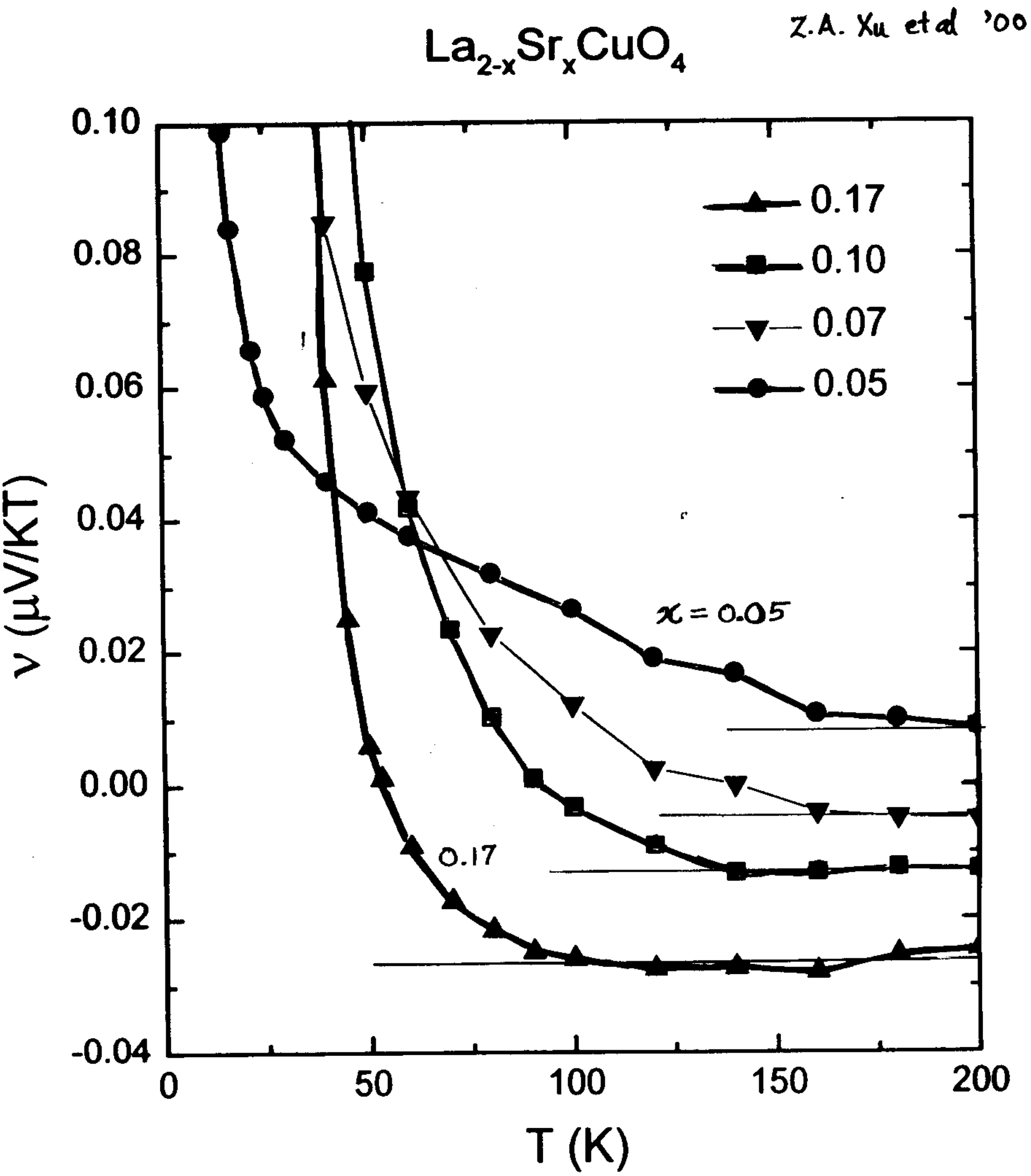




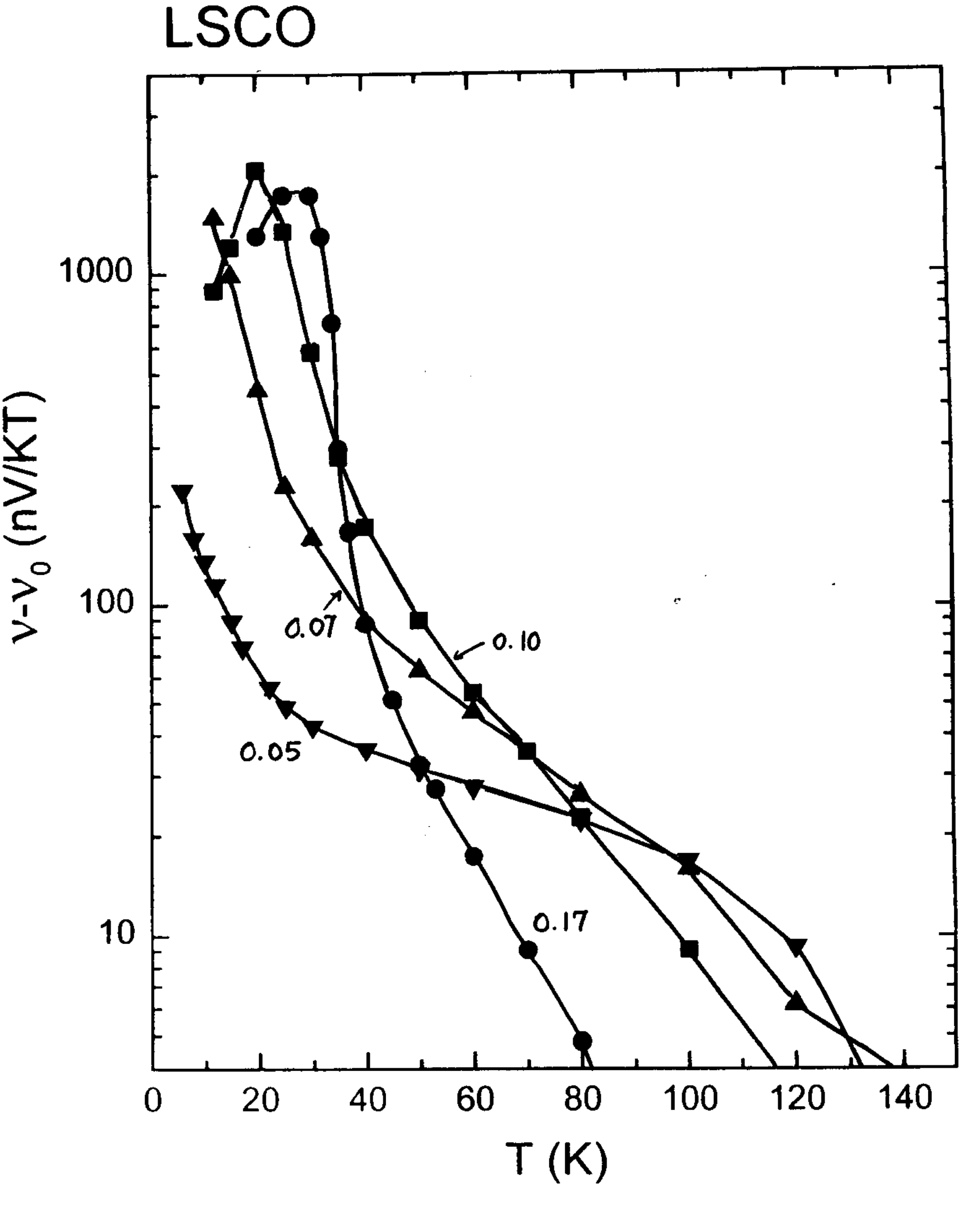
La$_{2-x}$Sr$_x$CuO$_4$ x = 0.10
Xu et al. '00
20 K
15
25
12
30
35
T_c = 27 K
40 K
50
60
70
80
140
160
200
100
Normal state Nernst coeff.
$E_y/|\nabla T|$ (μV/K)
$\mu_0 H$ (T)
-∇T



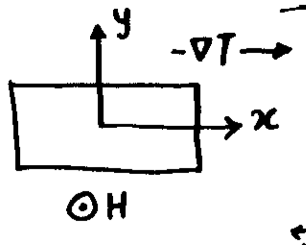
YBCO (x=6.95)
Nernst effect in vortex liquid state
$E_y/|\nabla T|$ (μV/K)
$\mu_0 H$ (T)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
2
4
6
8
90
88
86
84
82
80
78
92
94
96
98
100



Z.A. Xu et al '00
$La_{2-x}Sr_xCuO_4$
0.17
0.10
0.07
0.05
x = 0.05
0.17
ν (μV/KT)
T (K)
0.10
0.08
0.06
0.04
0.02
0.00
-0.02
-0.04
0
50
100
150
200


LSCO
ν-ν₀ (nV/KT)
T (K)
1000
100
10
0
20
40
60
80
100
120
140
0.07
0.10
0.05
0.17

Nernst effect of charge carriers



Peltier tensor

$$\vec{J} = \overleftrightarrow{\sigma}\cdot\vec{E} + \overleftrightarrow{\alpha}\cdot(-\vec{\nabla}T),$$

$$\overleftrightarrow{\sigma} = \begin{bmatrix} \sigma & \sigma_{xy} \\ \sigma_{yx} & \sigma \end{bmatrix}, \quad \overleftrightarrow{\alpha} = \begin{bmatrix} \alpha & \alpha_{xy} \\ \alpha_{yx} & \alpha \end{bmatrix}.$$

b.c. $J_x = 0 \quad \rightarrow \quad E_x = -S(-\partial_x T).$

Thermopower $\boxed{S = \frac{\alpha}{\sigma}}$

b.c. $0 = J_y = \sigma_{yx} E_x + \sigma E_y + \alpha_{yx}(-\partial_x T).$

$\sigma_{yx}E_x$ and $\alpha_{yx}(-\partial_x T)$: opposite in sign & equal in size if $\tau \neq \tau(\varepsilon)$!

σE_y: Nernst signal

Nernst coef. $\nu_N = \frac{E_y}{|\nabla T|}\frac{1}{H}$.

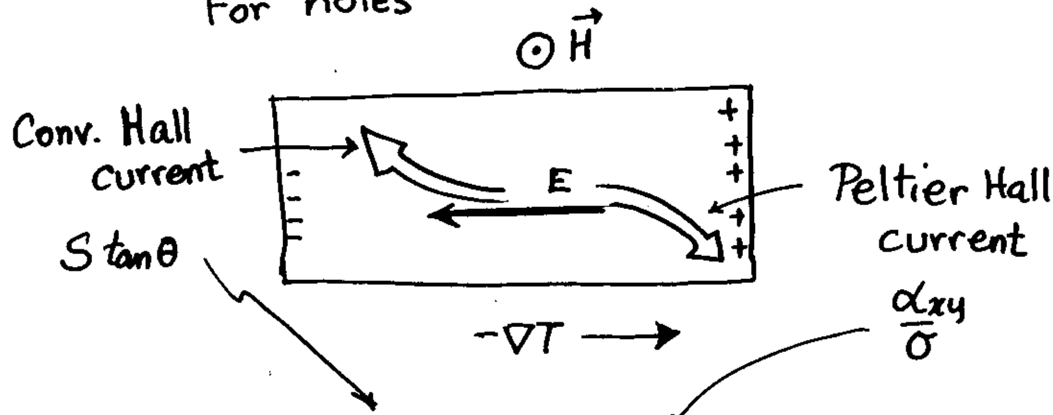
$$\boxed{\nu_N = -S\,\frac{\tan\theta}{H} + \frac{\alpha_{xy}}{\sigma H}}$$

Hall angle term — Peltier Hall term

SONDHEIMER CANCELLATION

Why 2 "large" terms cancel

For holes



$$0 = J_y = [-S\sigma_{xy} + \alpha_{yx}](-\partial_x T) + \sigma E_y$$

residual Nernst signal

Why 2 large terms are equal if $\tau \neq \tau(\varepsilon)$

Boltzmann theory

$$\alpha_{xy} = \frac{2e^2B}{T\hbar}\sum_k \left(-\frac{\partial f}{\partial \varepsilon}\right)(\varepsilon_k - \mu)\, \ell_y \frac{\partial \ell_x}{\partial s}$$

$$\simeq \frac{k_B^2 T}{e}\left(\frac{\partial \sigma_{xy}}{\partial \varepsilon}\right)_\mu$$

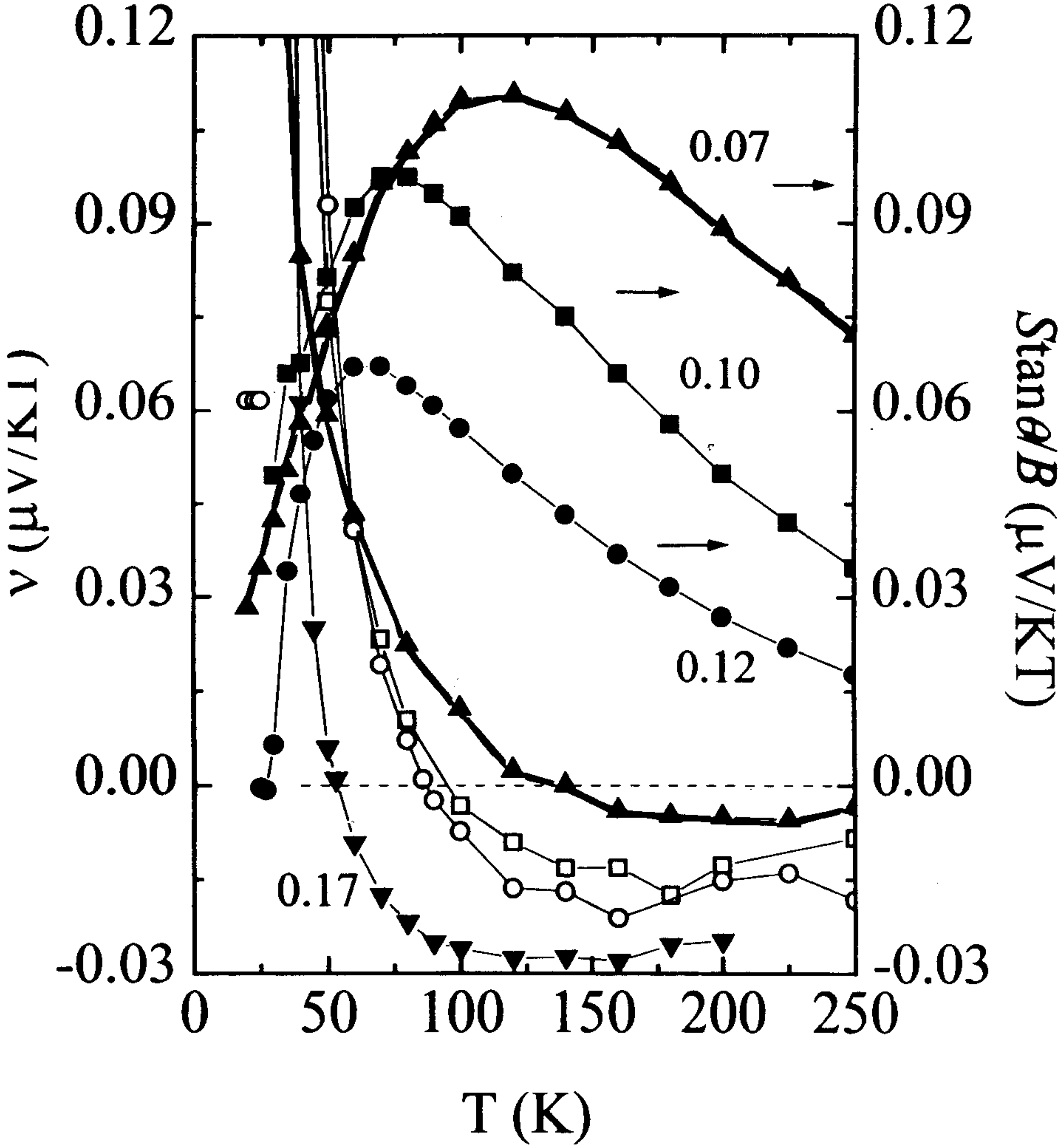
Analogous to $\alpha \sim \frac{k_B^2 T}{e}\left(\frac{\partial \sigma}{\partial \varepsilon}\right)_\mu$

$\tau \neq \tau(\varepsilon)$ $\quad S\sigma_{xy} = \alpha_{yx}$ (Sondheimer) 1949

$$\hookrightarrow \left(\frac{\partial \ln \sigma}{\partial \varepsilon}\right)_\mu = \left(\frac{\partial \ln \sigma_{xy}}{\partial \varepsilon}\right)_\mu$$

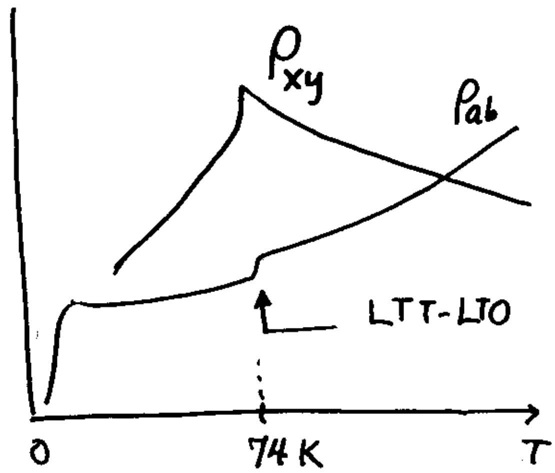
Sondheimer cancellation

$$\nu_{obs} = \nu_{Vortex} + \frac{1}{H}\left[\frac{\alpha_{xy}}{\sigma} - S\tan\theta_H\right]$$

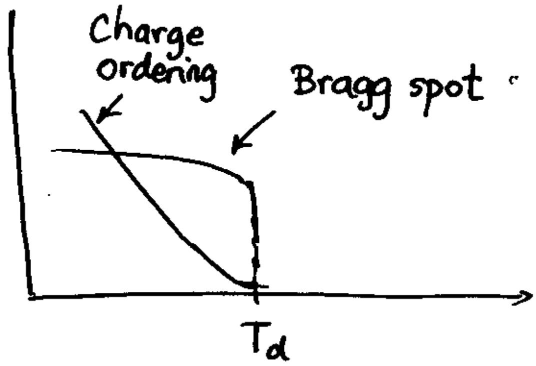


$La_{2-y-x}Nd_ySr_xCuO_4$

Nd impurities trigger LTT-LTO transition



Nakamura, Uchida

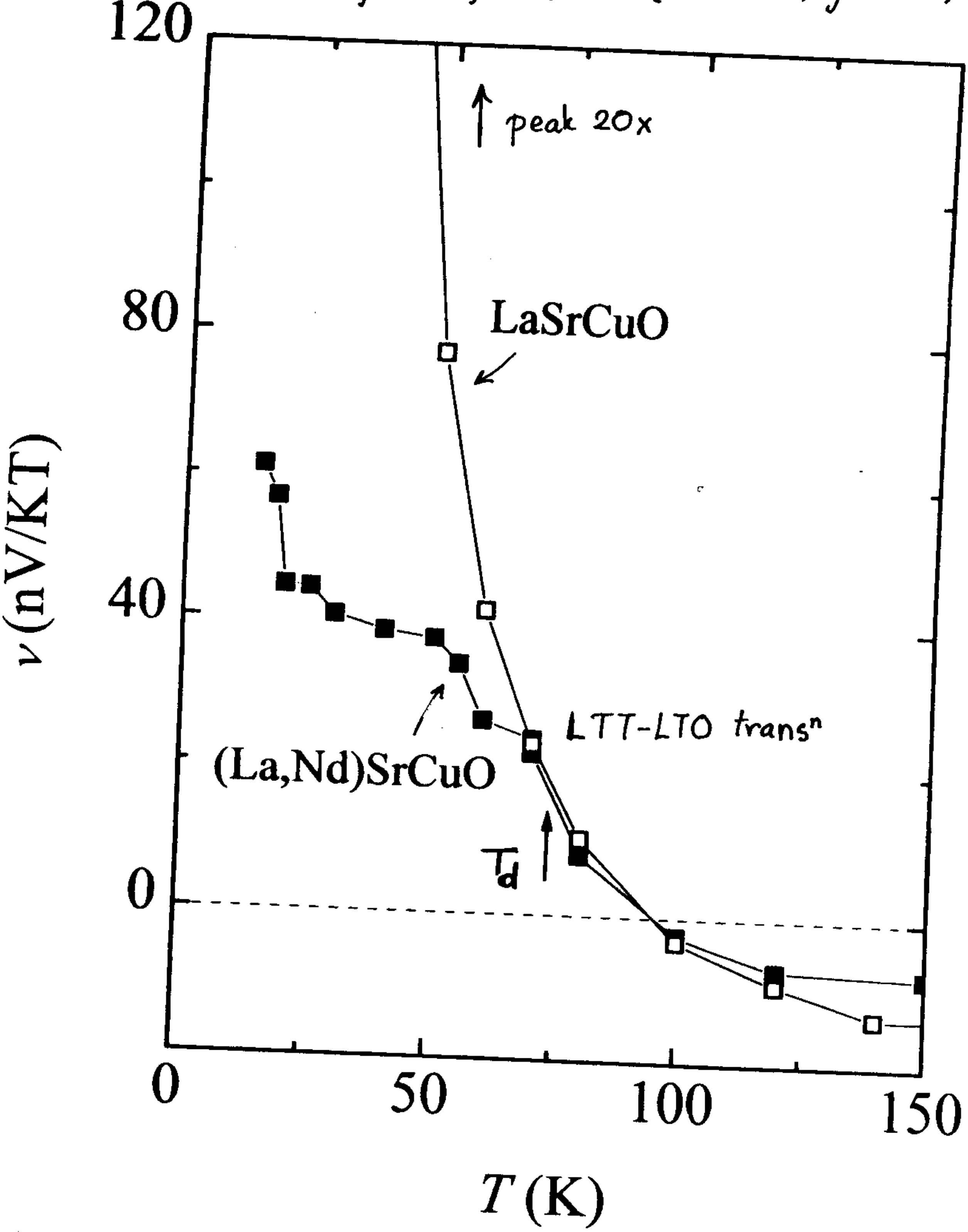


Tranquada et al.

- Charge ordering (stripe formation) stabilized below T_d
- T_c strongly suppressed cpf. LaSrCuO

  $x = 0.10$ 25 K $\longrightarrow$ ~8 K

Compare Nernst effect in $La_{2-x}Sr_xCuO_4$ &
$La_{2-y-x}Nd_ySr_xO_4$ ($x = 0.10$, $y = 0.6$)



Nature of excitation observed

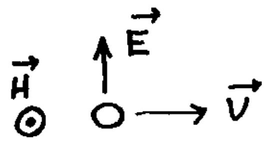
- Diffuses down $-\nabla T \,/\!/\, \hat{x}$

  $\vec{v} \,/\!/\, \hat{x}$

- Must carry a fluxoid $(\vec{E} = \vec{B} \times \vec{v})$

  or be bound to a fluxoid.

- Most likely a vortex

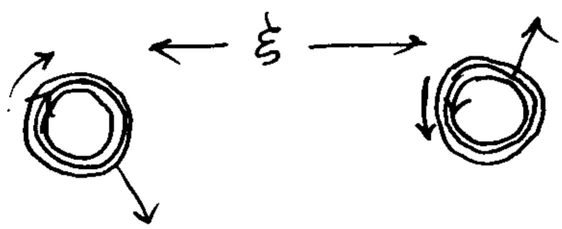


Scenario Order param. $|\Delta| e^{i\theta(\vec{r})}$

$$\langle e^{i\theta(r)} e^{-i\theta(r')} \rangle \sim e^{-\frac{|\vec{r}-\vec{r}'|}{\xi}}$$

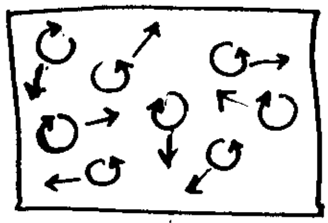
Corr. length ξ too short to support Meissner response

but long enough to wrap fluxoids.



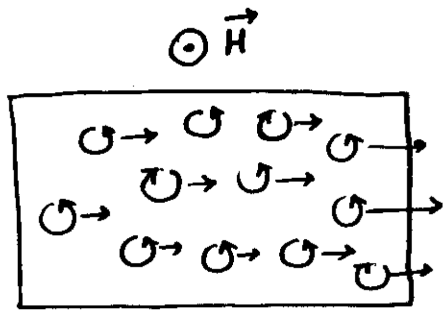
Diffusing vortices destroy phase rigidity

Physical Picture $T_c < T < T_{onset}$



$H = 0$; $\nabla T = 0$

- Equal No. up- down-vortices (unpinned)
- Phase rigidity ξ short
- No Meissner response



$H > 0$

$\nabla T > 0$

$N_+ - N_-$ increases linearly with H.

- Vortices coexist with nodal QP's ($\vec{J}_e$ is 'normal'; paraconduct. weak) No ↑AL terms
- Gap amplitude $|\Delta|$ survives in high fields $\sim 8T$.

Contour plots of $\nu - \nu_N$ in LaSrCuO

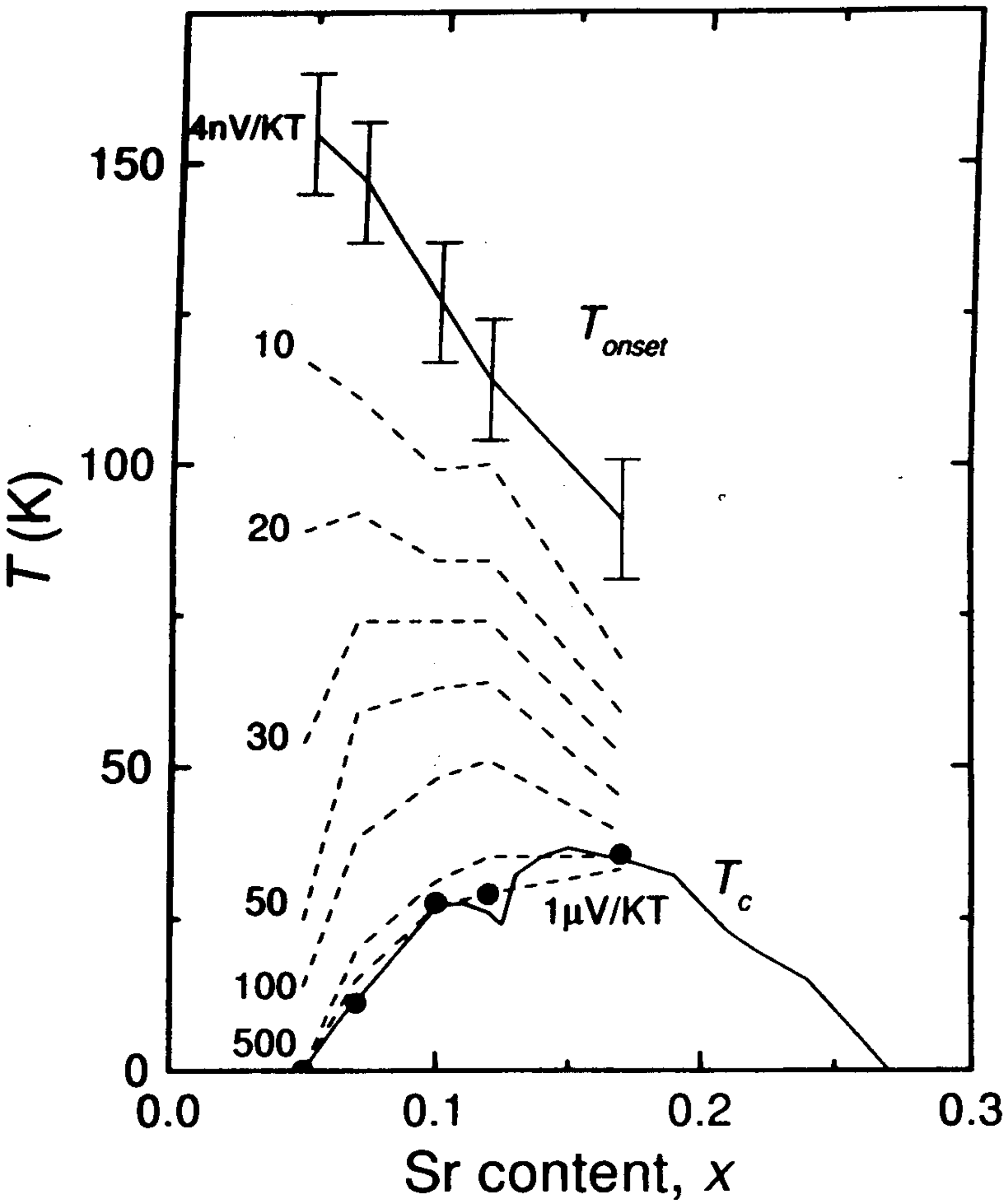
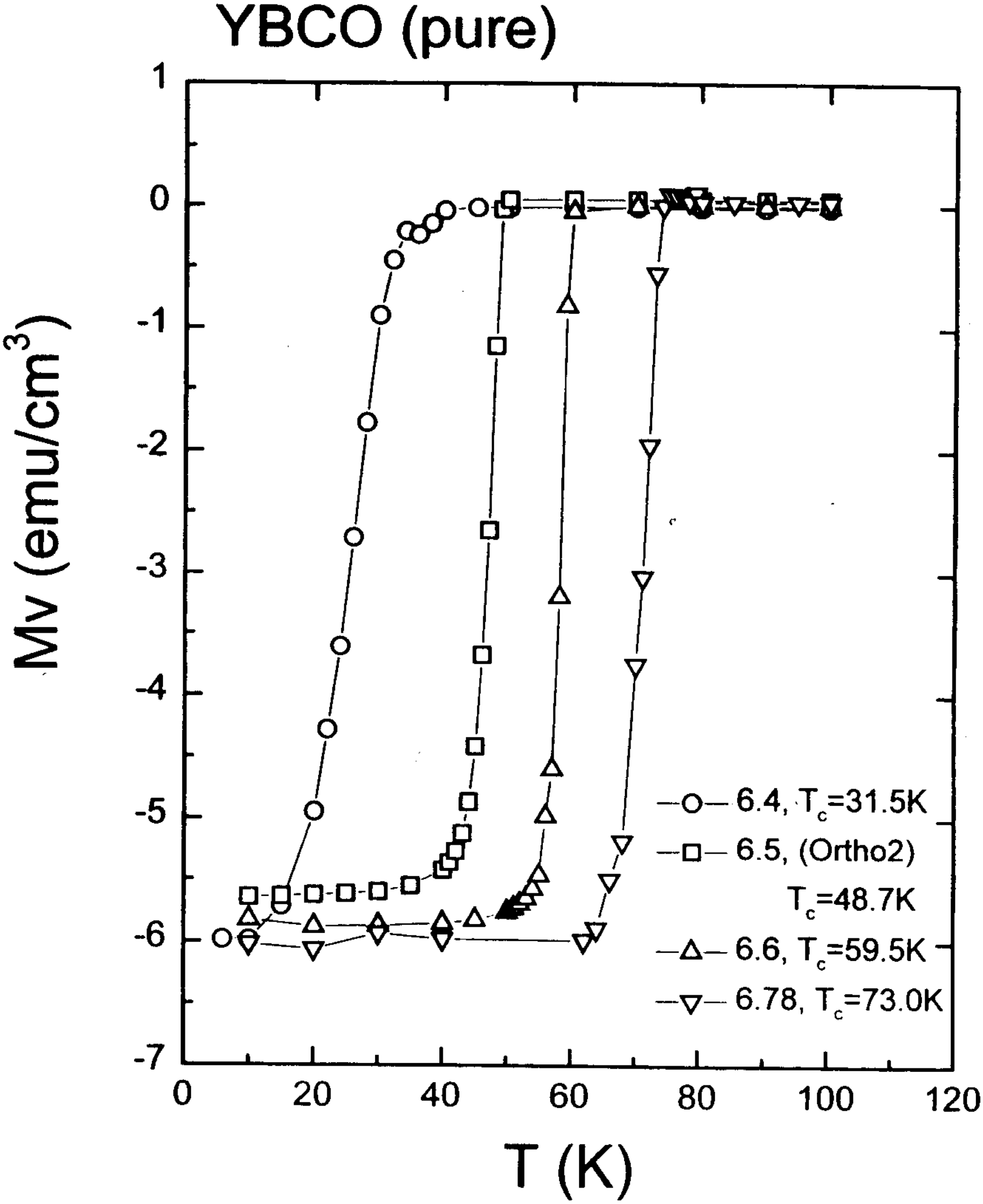
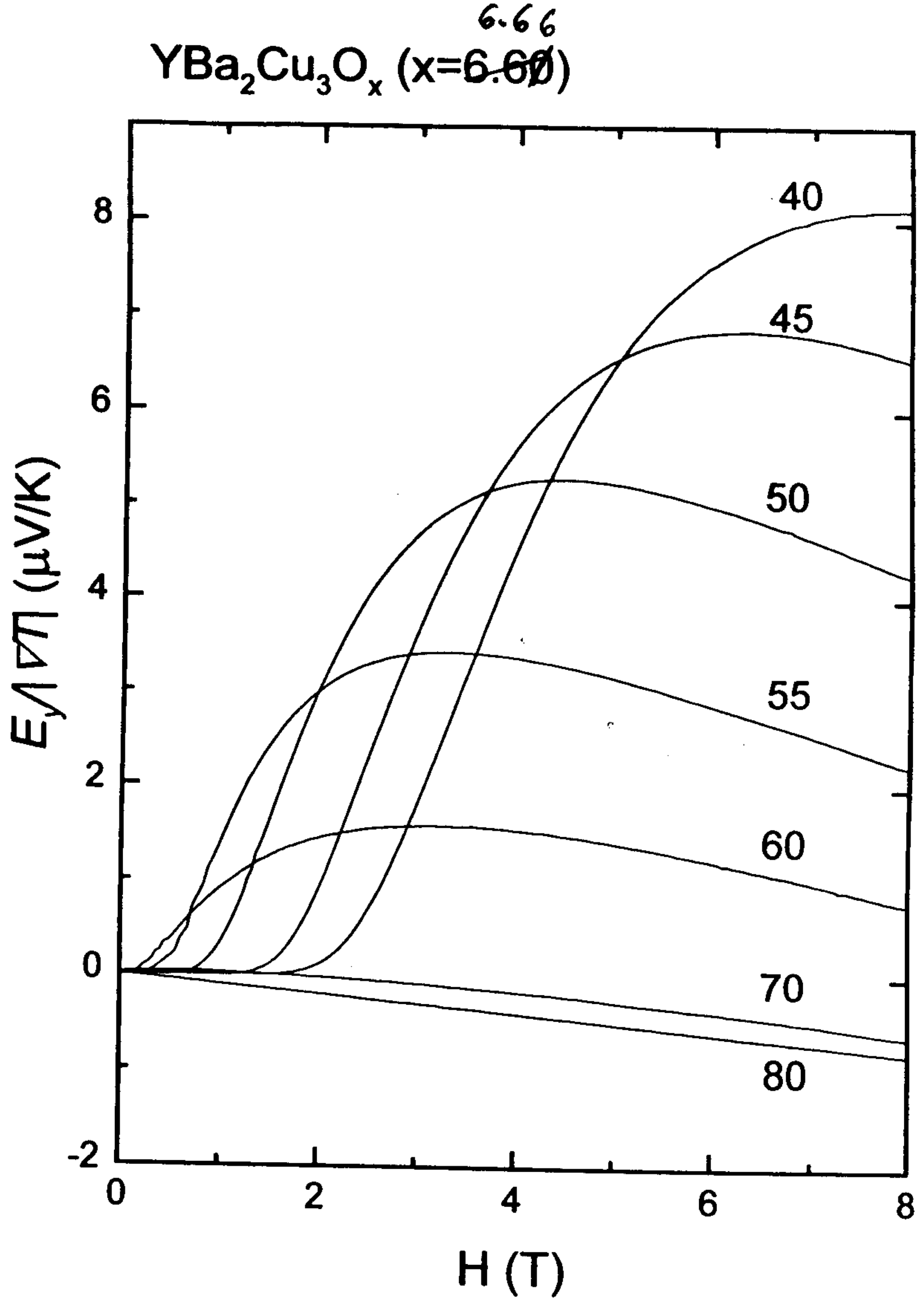
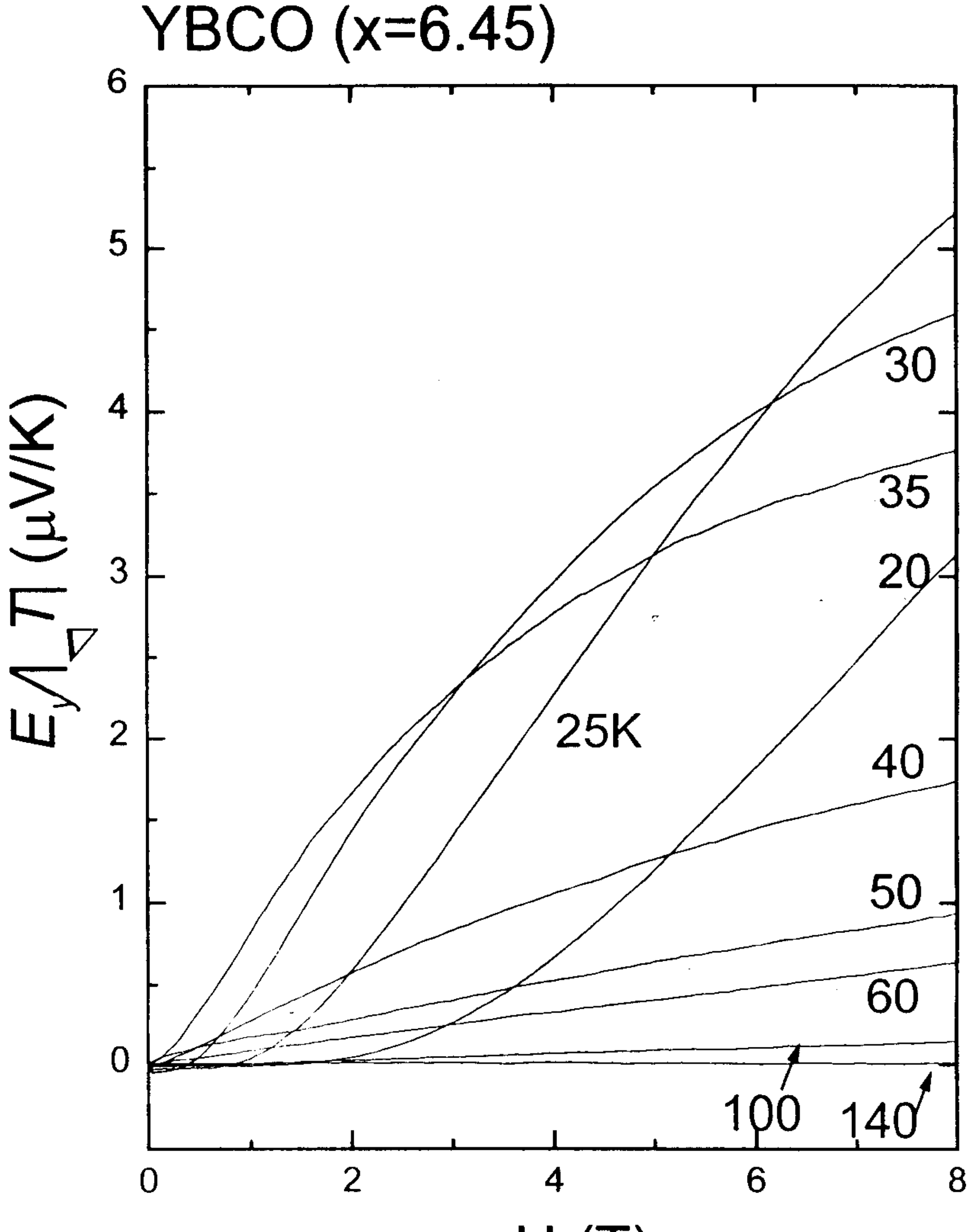


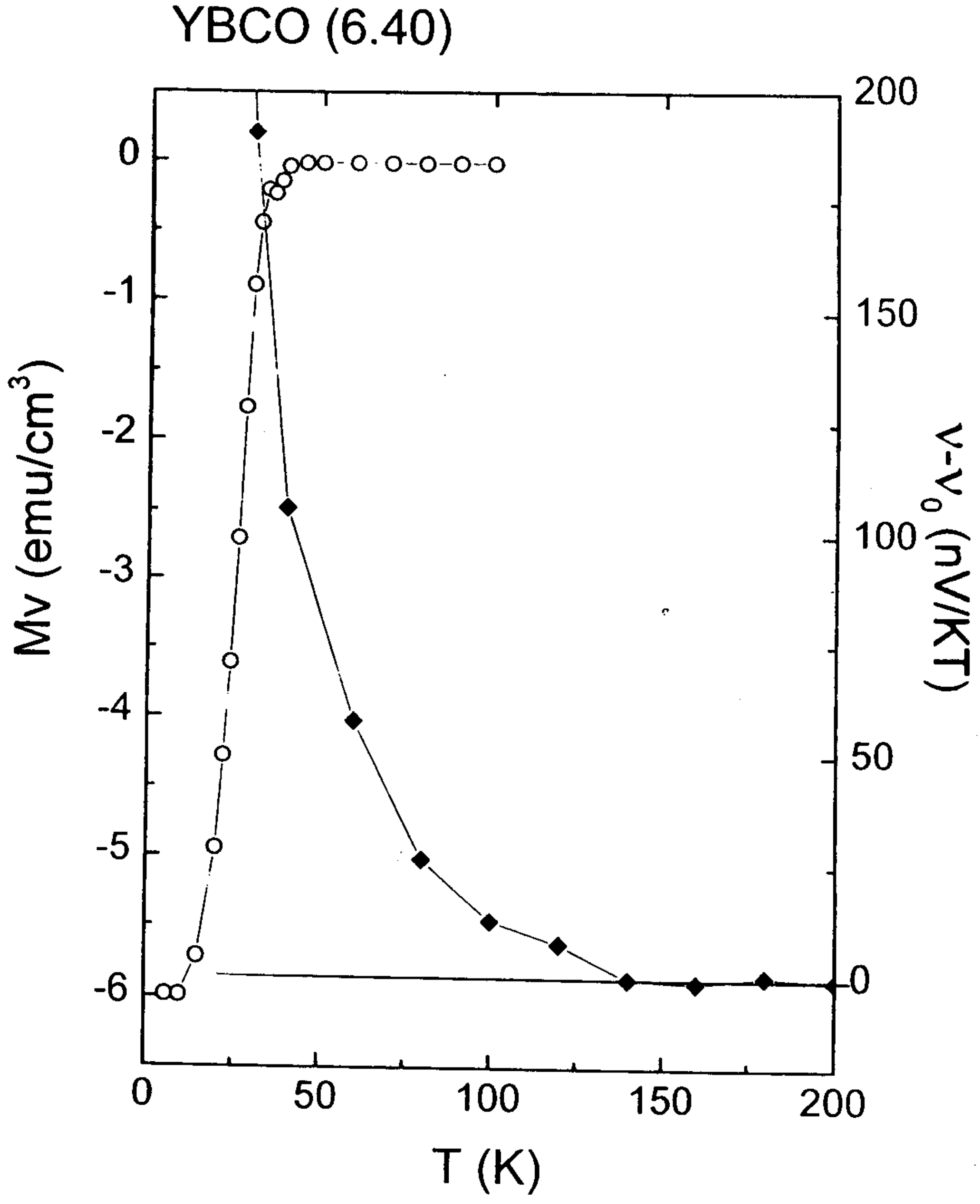
FIG 4


YBCO (pure)
Mv (emu/cm^3)
T (K)
1
0
-1
-2
-3
-4
-5
-6
-7
0
20
40
60
80
100
120
6.4, T_c=31.5K
6.5, (Ortho2)
T_c=48.7K
6.6, T_c=59.5K
6.78, T_c=73.0K

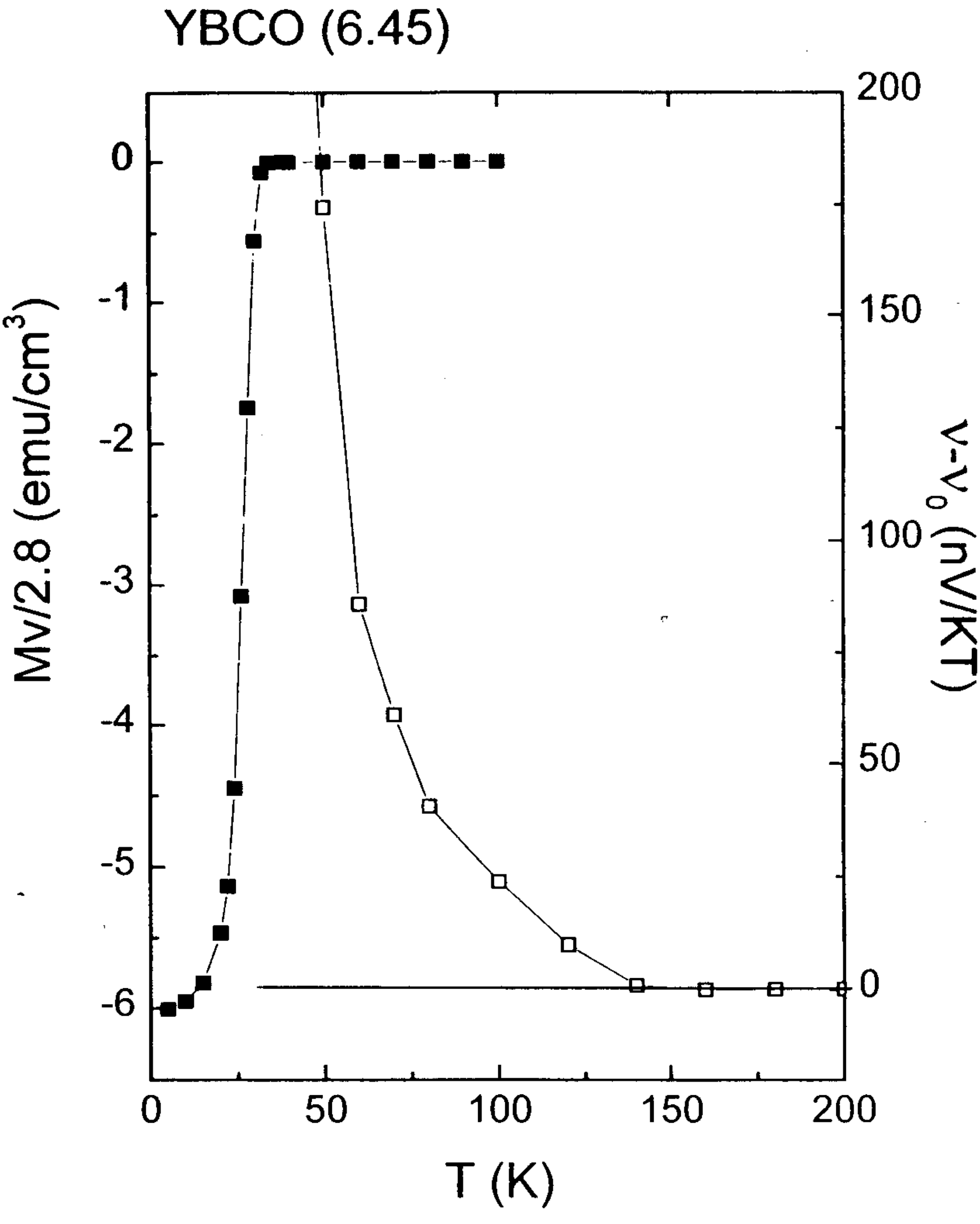

6.66
YBa2Cu3Ox (x=6.60)
40
45
50
55
60
70
80
8
6
4
2
0
-2
0
2
4
6
8
Ey/∇T (μV/K)
H (T)



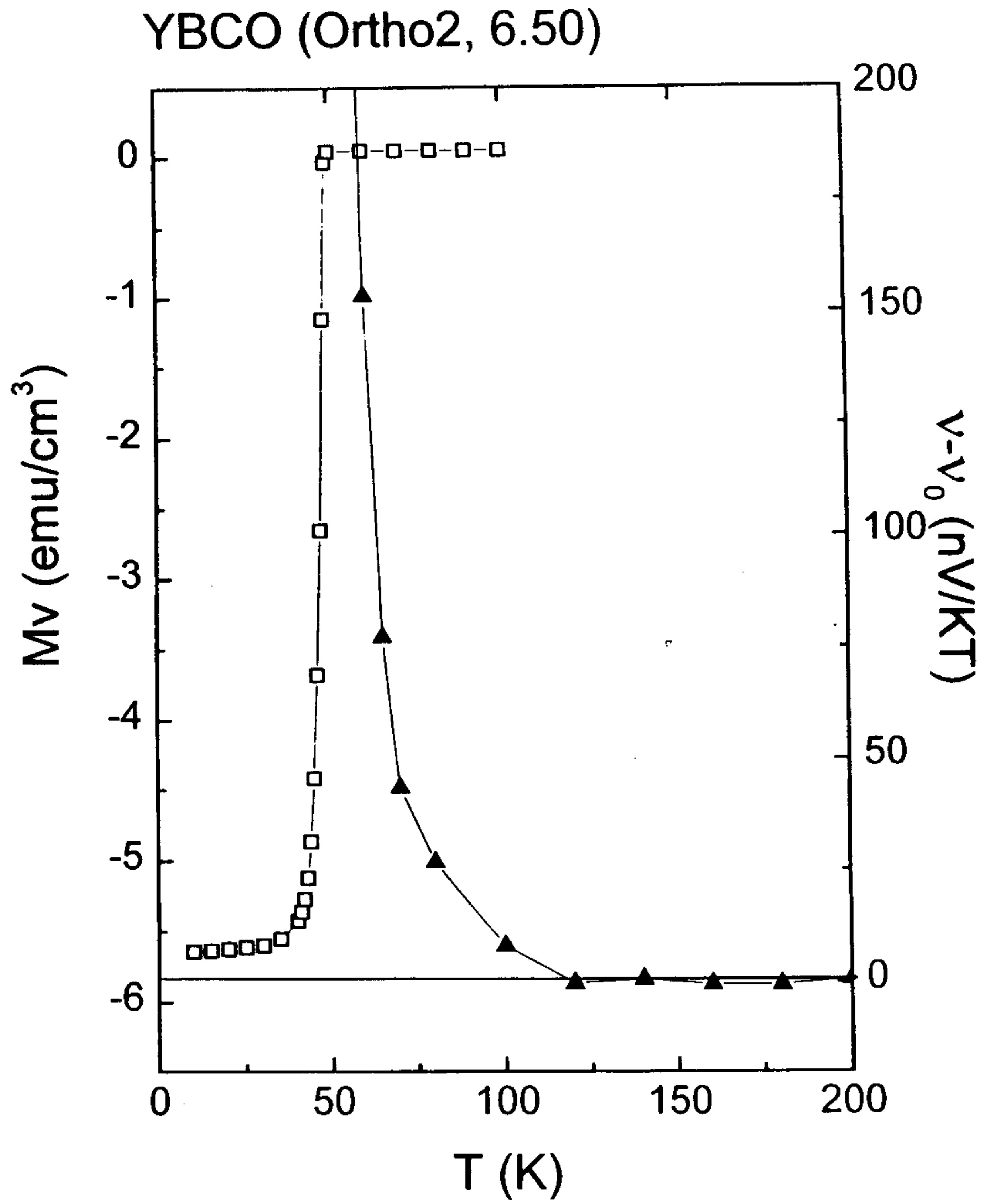
YBCO (x=6.45)
$E_y/|\nabla T|$ (μV/K)
μ_0H (T)
25K
30
35
20
40
50
60
100
140
0
1
2
3
4
5
6
0
2
4
6
8



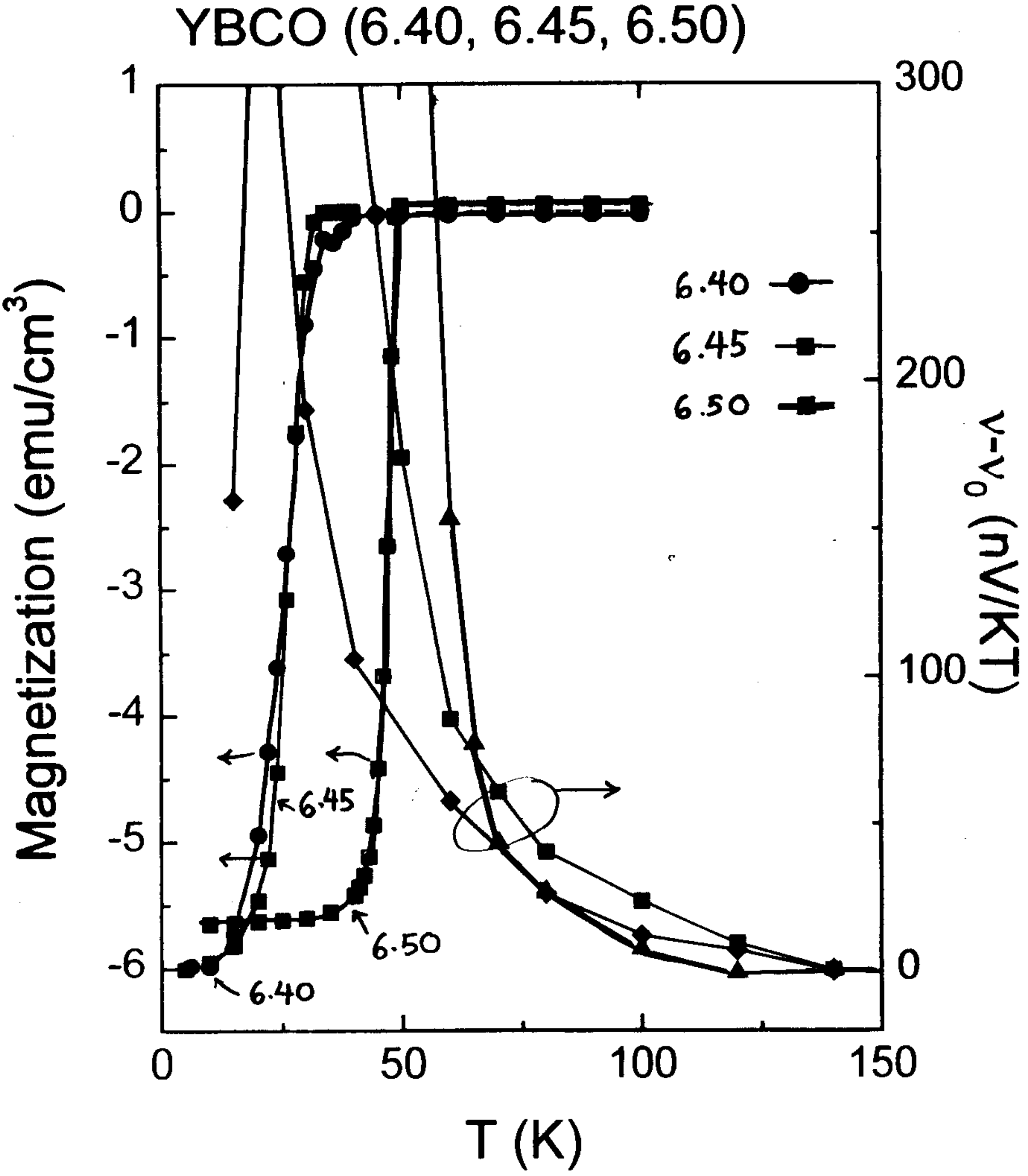
YBCO (6.40)
Mv (emu/cm3)
ν-ν0 (nV/KT)
T (K)
0
-1
-2
-3
-4
-5
-6
200
150
100
50
0
0
50
100
150
200



YBCO (6.45)
Mv/2.8 (emu/cm^3)
ν-ν_0 (nV/KT)
T (K)
0
-1
-2
-3
-4
-5
-6
200
150
100
50
0
0
50
100
150
200

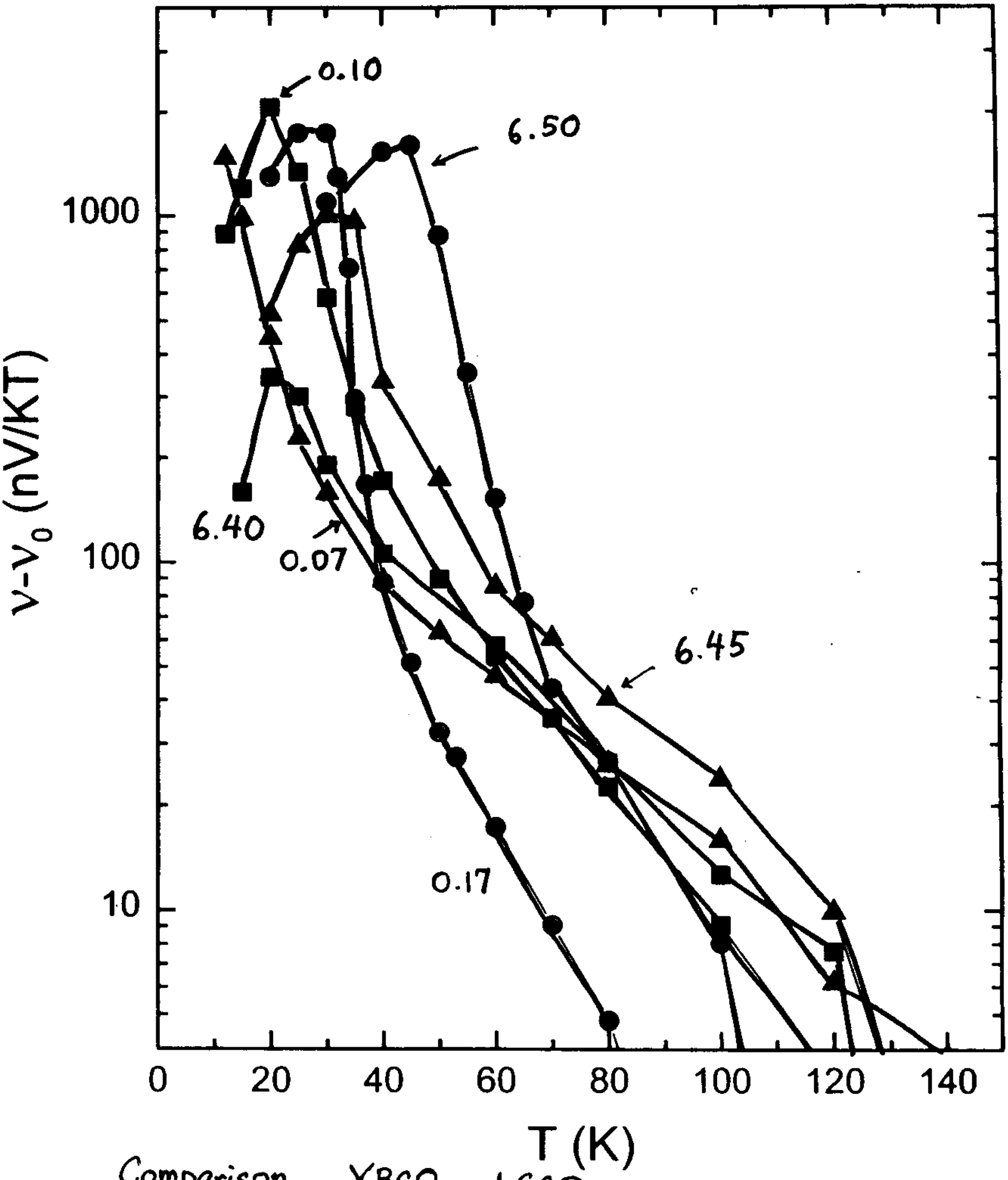


YBCO (Ortho2, 6.50)
Mv (emu/cm^3)
$\nu-\nu_0$ (nV/KT)
T (K)
0
-1
-2
-3
-4
-5
-6
200
150
100
50
0
0
50
100
150
200

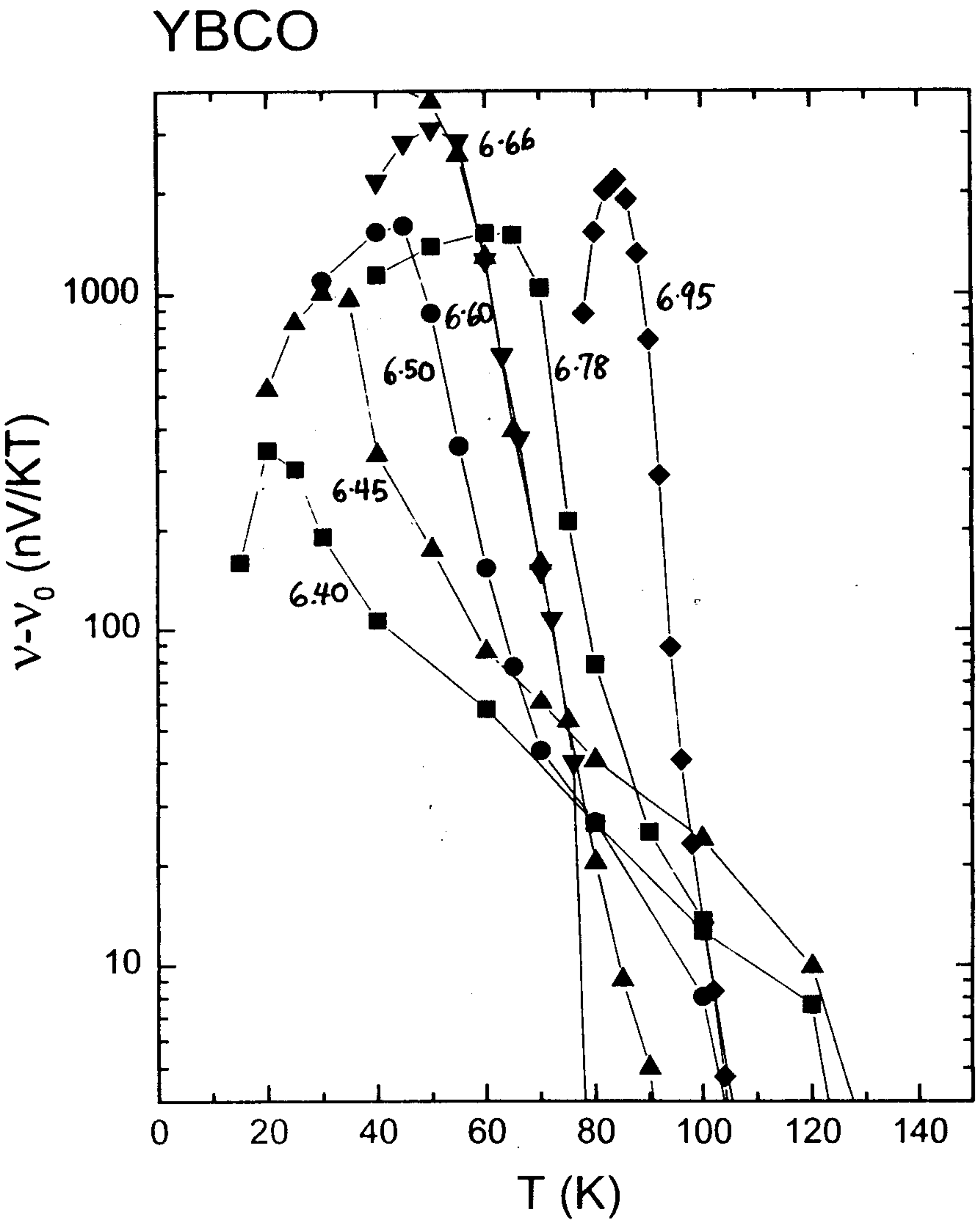


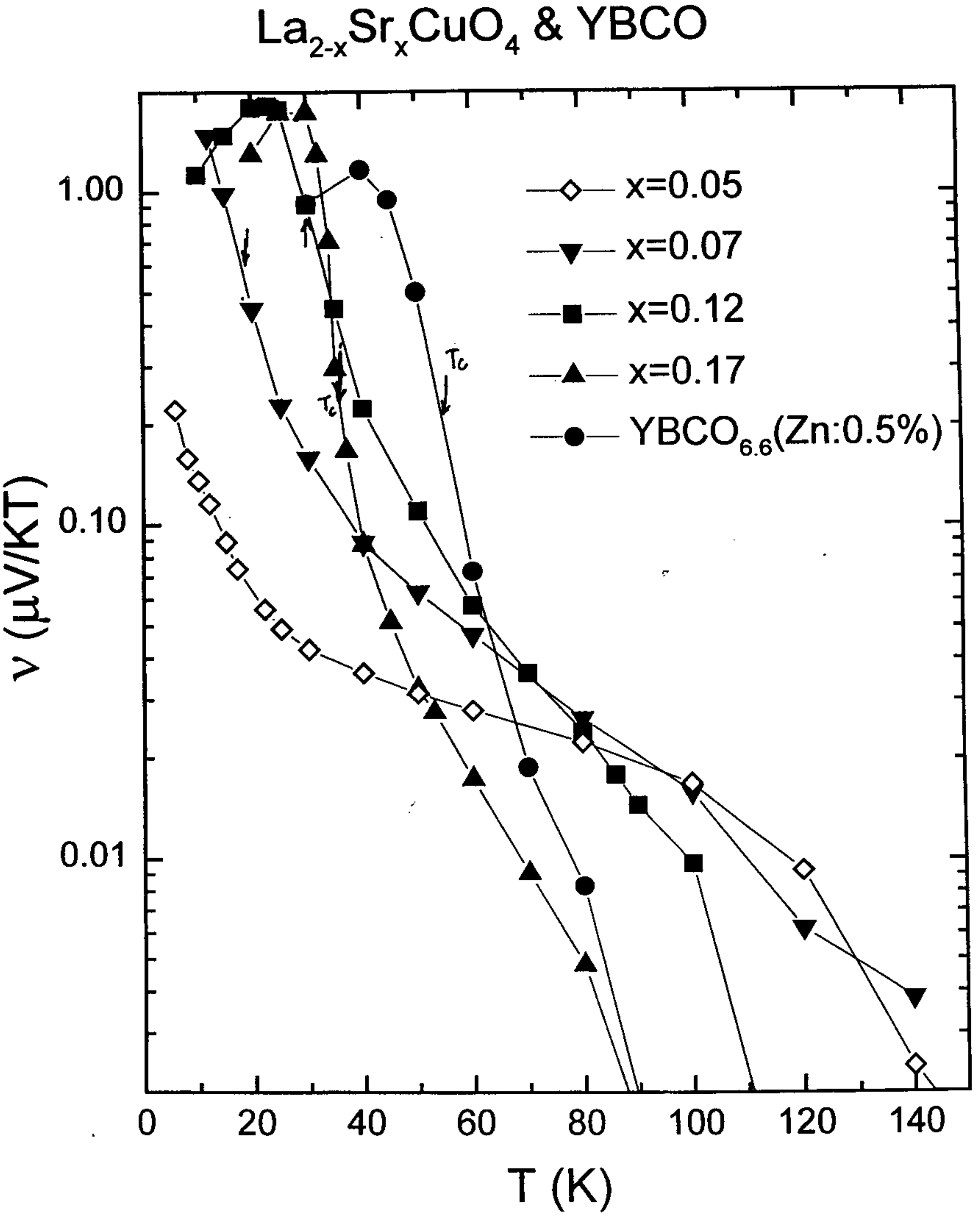
YBCO (6.40, 6.45, 6.50)
Magnetization (emu/cm^3)
ν-ν_0 (nV/KT)
T (K)
6.40
6.45
6.50
6.45
6.50
6.40
0
50
100
150
1
0
-1
-2
-3
-4
-5
-6
300
200
100
0

YBCO & LSCO



Comparison	YBCO	LSCO
	6.40	0.07
	6.45	0.10

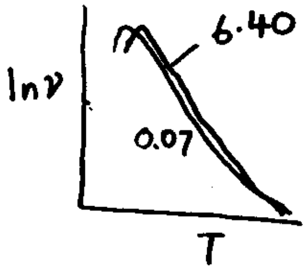

YBCO
6·66
6·95
6·60
6·50
6·78
6·45
6.40
1000
100
10
ν-ν$_0$ (nV/KT)
0
20
40
60
80
100
120
140
T (K)

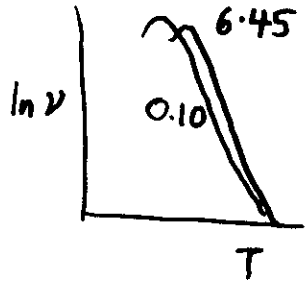


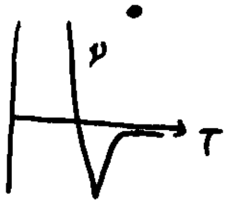
$La_{2-x}Sr_xCuO_4$ & YBCO
1.00
0.10
0.01
ν (μV/KT)
0
20
40
60
80
100
120
140
T (K)
x=0.05
x=0.07
x=0.12
x=0.17
$YBCO_{6.6}$(Zn:0.5%)
Tc
Tc

Comparison of fluct. ν in YBCO & LSCO

- Strong similarities $x < 6.60$



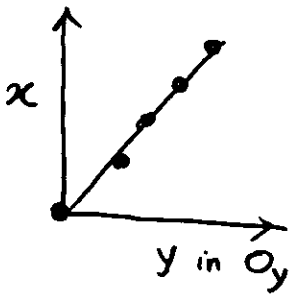




- Above $x = 6.60$ fluct. ν <u>suppressed</u>

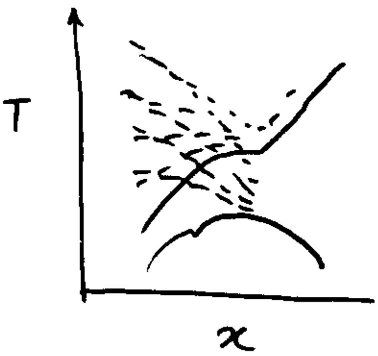
  Negative anomaly appears

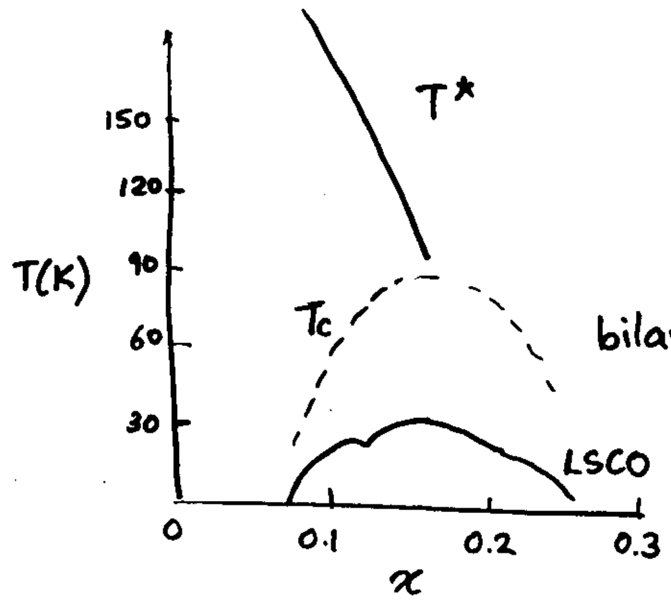
- New calibration of hole density x in $YBCO_y$



x	y in O_y
0	6.25
0.125	6.53
0.18	6.66
?	6.95

- Accounts for similarities in phase diagr. (contour plot)





Old phase diag.

Proposed p.d.