Lecture 2

Vortex phases in superconductors
with & without disorder

· Melting
· Amorphization - peak effect

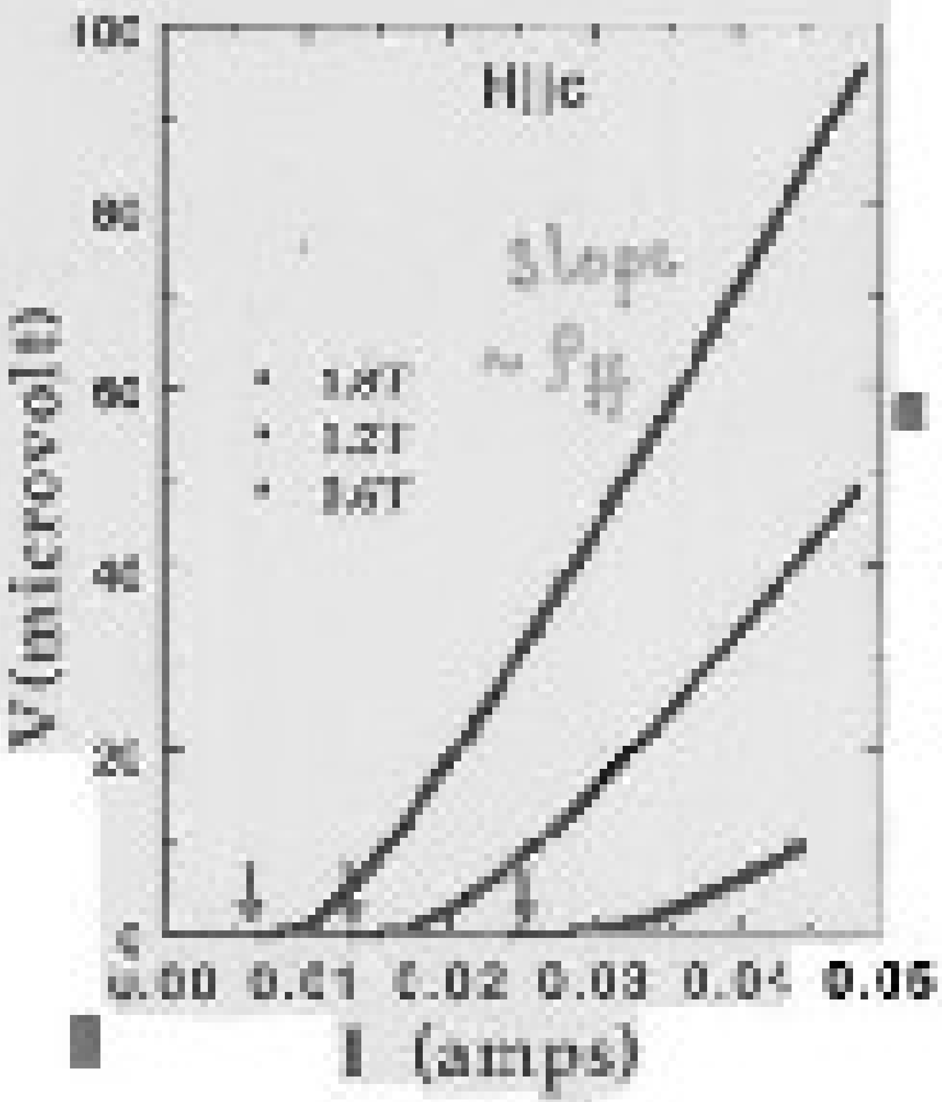
2. Motion of vortices - Moving Phases
   · Types of motion
   · Transitions among moving phases

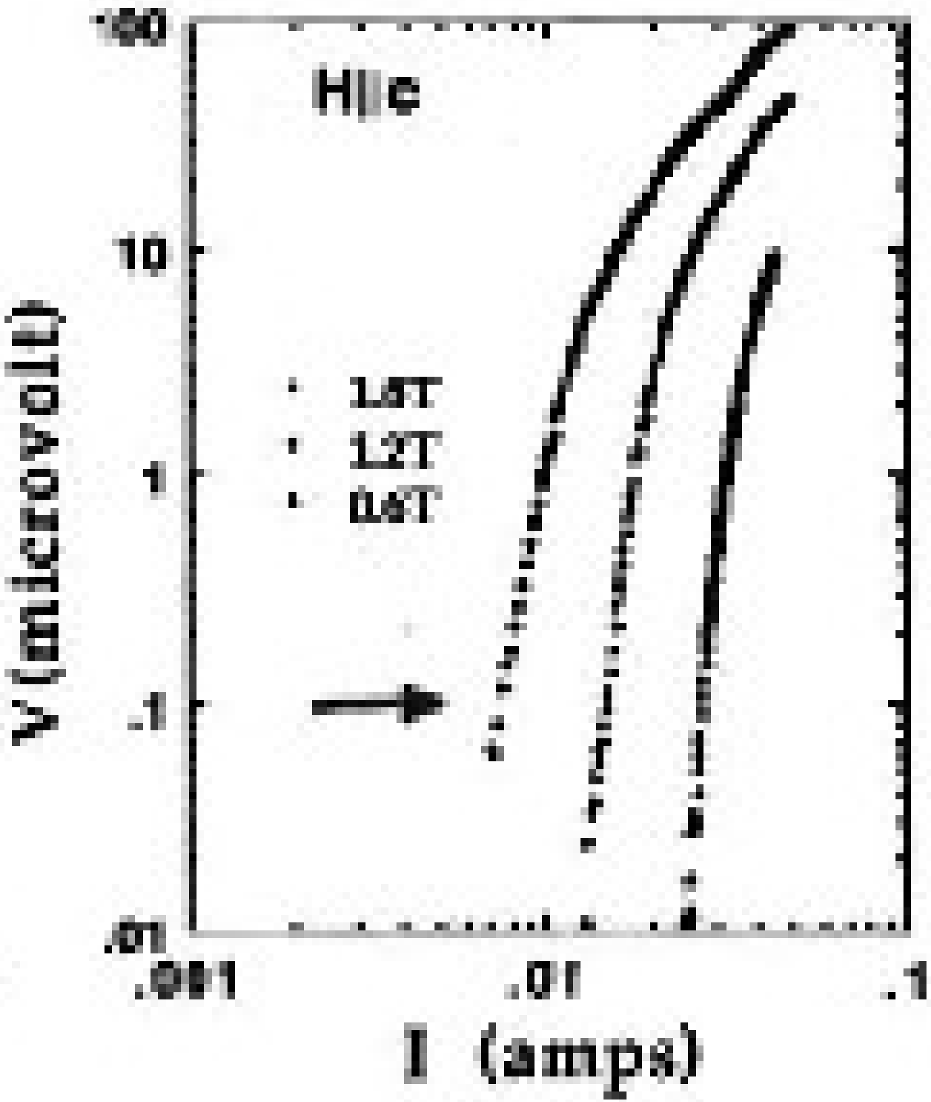
History Effects in "Equilibrium"

Imaging in "Meso-scale"

Intro. to Superconductivity - M. Tinkham [illegible]
Rev. [illegible] Phys. 6[illegible], 1125 ([illegible]) [illegible]

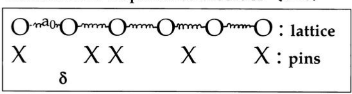
I-V curve in log and linear





LOFLIM

The generic problem :
Elastic media & quenched disorder (T = 0)



Competition between elasticity and pinning :

$$E_{el} \sim (R)^{d-2};\ E_{pin} \sim (R)^{d/2}$$

Minimize energy →
loss of long range order: correlation length [redacted]
[Larkin]

$$R_c \sim (K_{el}/V_{pin})^{2/(4-d)}$$

Threshold phenomena in dynamics : F_p

$$F_p \sim (R_c)^{-2}$$

(Soft things get stuck more)
Varying interaction or disorder changes the nature of threshold and dynamics

Interaction dominant :Weak pinning : $R_c \gg a_0, \delta$
Disorder dominant : Strong pinning : $R_c \sim \delta$

Question : how does the dynamics vary between the two extremes ?

In "Equilibrium"

Metastability and "glassiness"
History dependence

Relationship with other glasses

New "Phases" due to disorder ?
Nature of phase transition.

Role of thermal fluctuations

Away from Equilibrium in dynamics

Depinning as a critical phenomenon (Fisher)

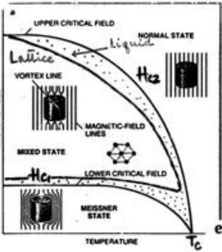
velocity force relation : $v \sim (F-F_c)^{\beta}$

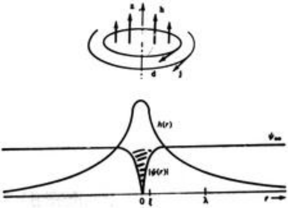
velocity correlation length : $L_v \sim (F-F_c)^{-\nu}$

Breakdown of purely elastic response
Role of plasticity

"Moving phases"

Phase diagram of a type-II superconductor





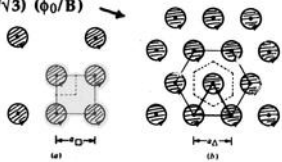
each flux line carries a flux quantum

: $\phi_0 = (ch/2e) = 2 \times 10^{-7}$ gauss.cm^2

Repulsion between flux lines
----> flux line lattice (FLL)

increasing H increases density of flux lines :

lattice spacing: $a_0^2 = (2/\sqrt{3})\ (\phi_0/B)$



* interaction in FLL is tunable by H *

Vortex Matter Phase Diagram

thout quenched Disorder

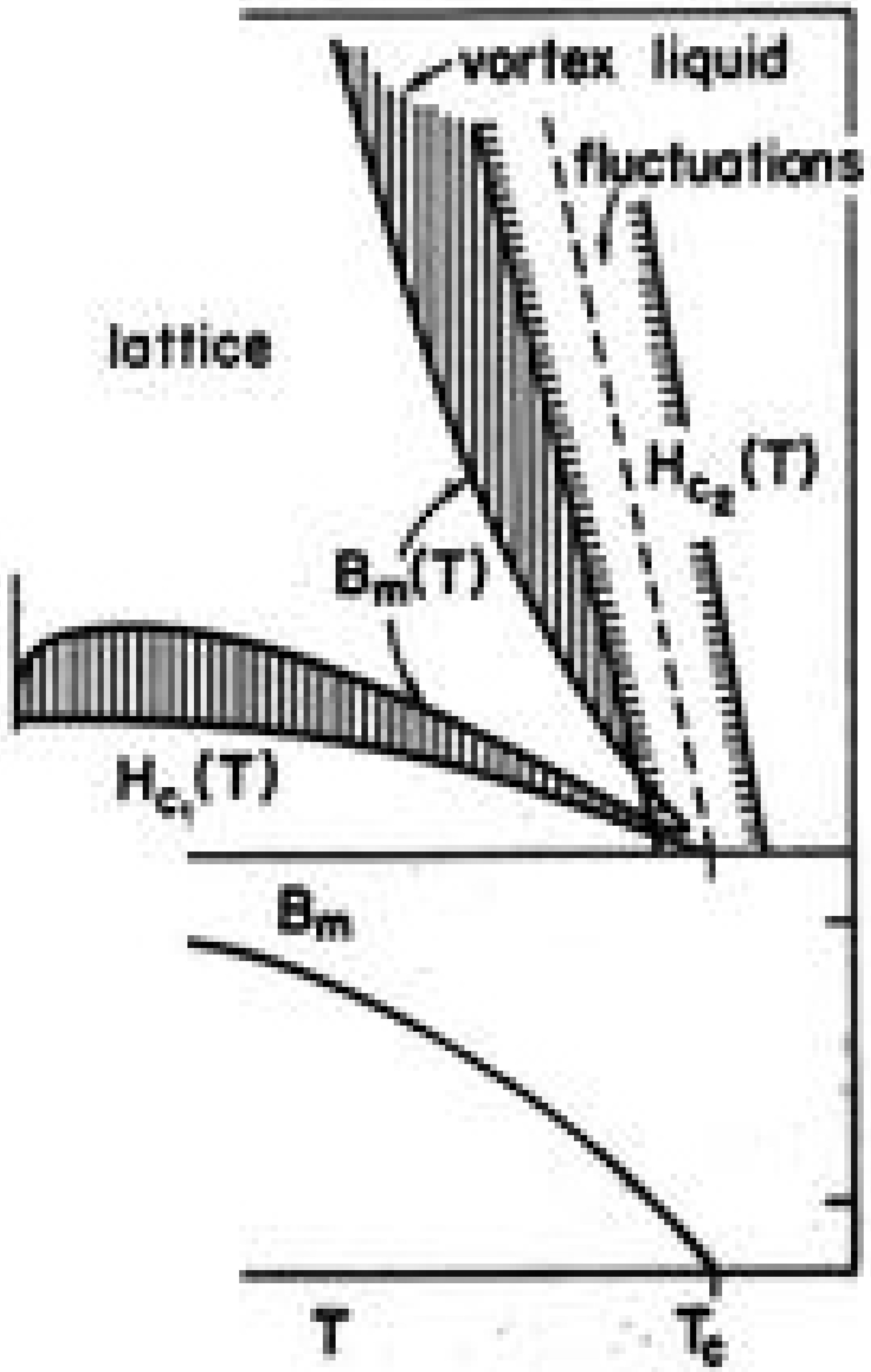


FIG. 2. Phenomenological phase diagram for the anisotropic high-temperature superconductors [parameters for YBCO,

With quenched Disorder

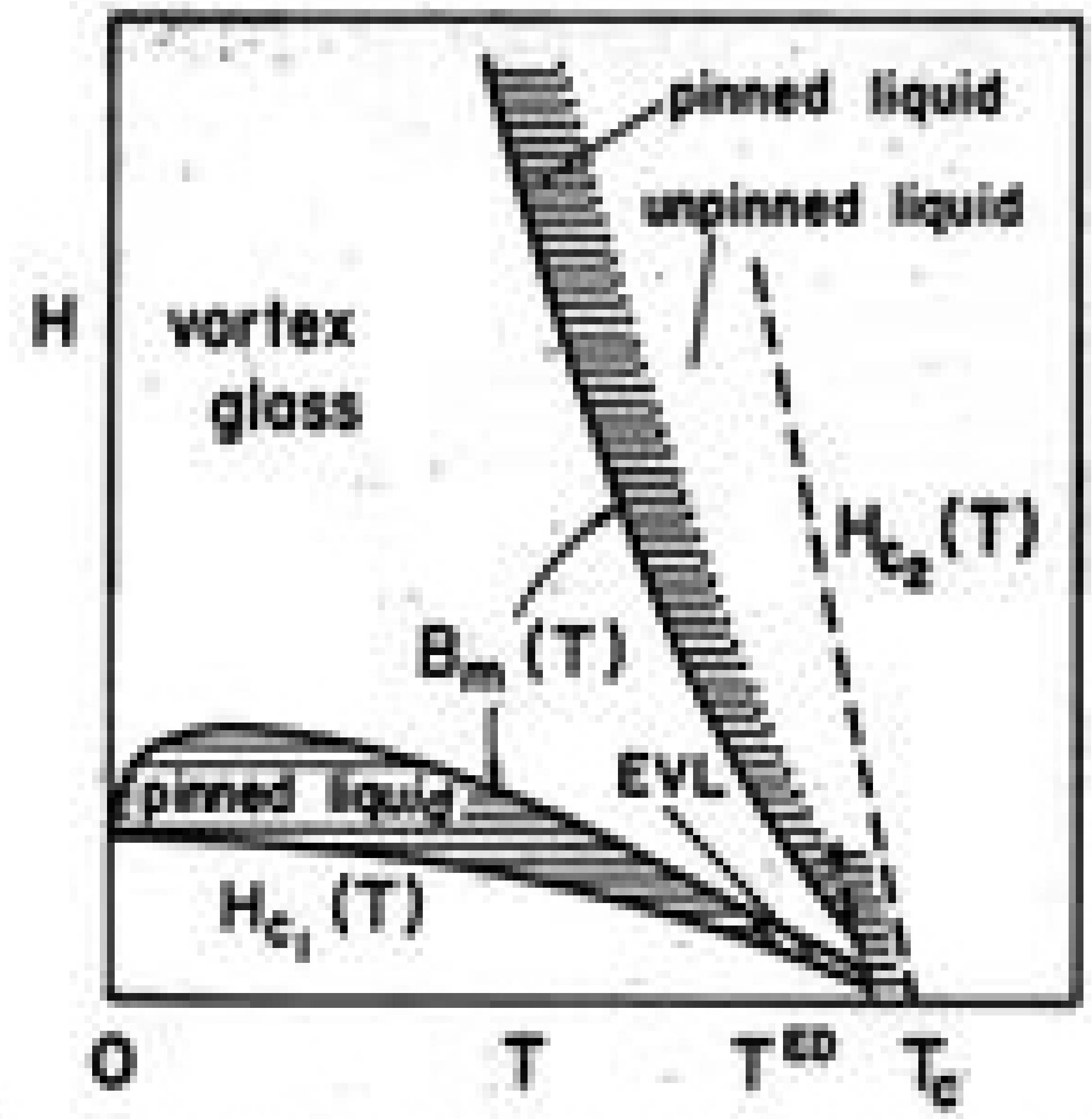


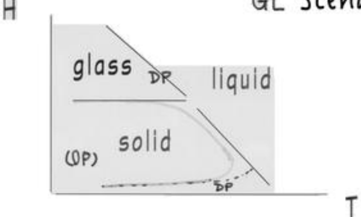
FIG. 6. Phenomenological phase diagram for the high-temperature superconductors including the effects of thermal fluctuations and of quenched disorder (pinning). For the vortex

elastic lattice
thermal liquid
pinning glass

weak disorder Bragg glass (Bragg peaks)
strong disorder Vortex glass (no Bragg peaks ?)
Vortex slush
Vortex molasses

correlated disorder Bose glass

"GL Scenario"



Structural glass/ "Supercooled" Liquids :

No quenched randomness

Falls out of equlibrium below

Viscosity diverges: $(T - T_k)]$

But no conventional transition at T_g ($\eta \sim 10^{13}$ poise)

$T_g >> T_k$

Cooling-rate dependent properties

Spin Glass

True transition at T_f : cusp in susceptibility

nonlinear susceptibility diverges

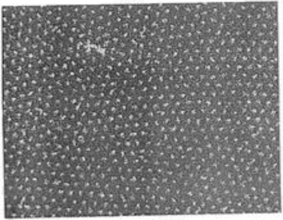
Strong History effects below T_f

anomalous time dependence...

Do glassy vortex matter resemble these ??

"Seeing Vortices" : erent methods

10^3

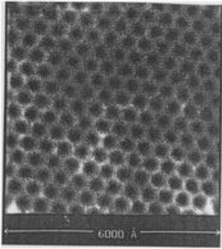


NbSe$_2$: H ~ 50G

magnetic decoration : few defects

Marchevsky et al

10^5



NbSe$_2$: H ~ 1T

STM : no defects

Hess et al.

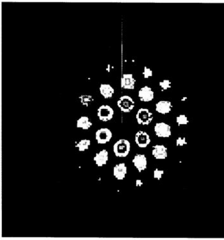
← 10^7

Fig.7.43. Lorentz micrograph of a fluxon lattice in a superconducting Nb film. Each spot with black and white contrast pair corresponds to a fluxon

Nb-film : Lorentz microscopy

Tonomura et. al

Vortex Solid in Nb (Sing

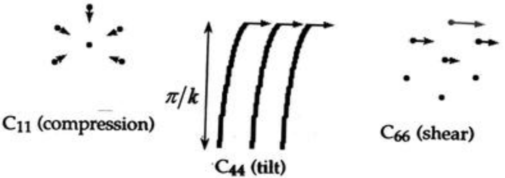


S.R. Park, B.A. McClain, X.S. Ling (Brown Univ.)
S.M. Choi, D.C. Dender, J.W. Lynn (NIST)
(May 30, 2000, unpublished)

of a

; Frie
arkin

ting or compressing the lattice costs energy;
lattice has finite elasticity



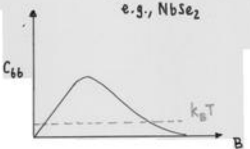
- $C_{66} \sim (B_{c2}^2/4\pi)(1 - 1/2\kappa^2)b(1 - b)^2(1 - 0.29b)/8\kappa^2$, $b \sim H/H_{c2}$
- $C_{11}(k) \sim (B^2/4\pi)(1 - 1/2\kappa^2)(1 + k^2\lambda'^2)^{-1}(1 + k^2\xi'^2)^{-1}$,
- $C_{44}(k) \sim (B^2/4\pi)[(1 + k^2\lambda'^2)^{-1} + 1/k_{BZ}^2\lambda'^2)^{-1}]$,

where $\lambda' = 1/k_h = \lambda/(1-b)^{1/2}$, $\xi' = 2\xi/(1 - b)^{1/2}$.

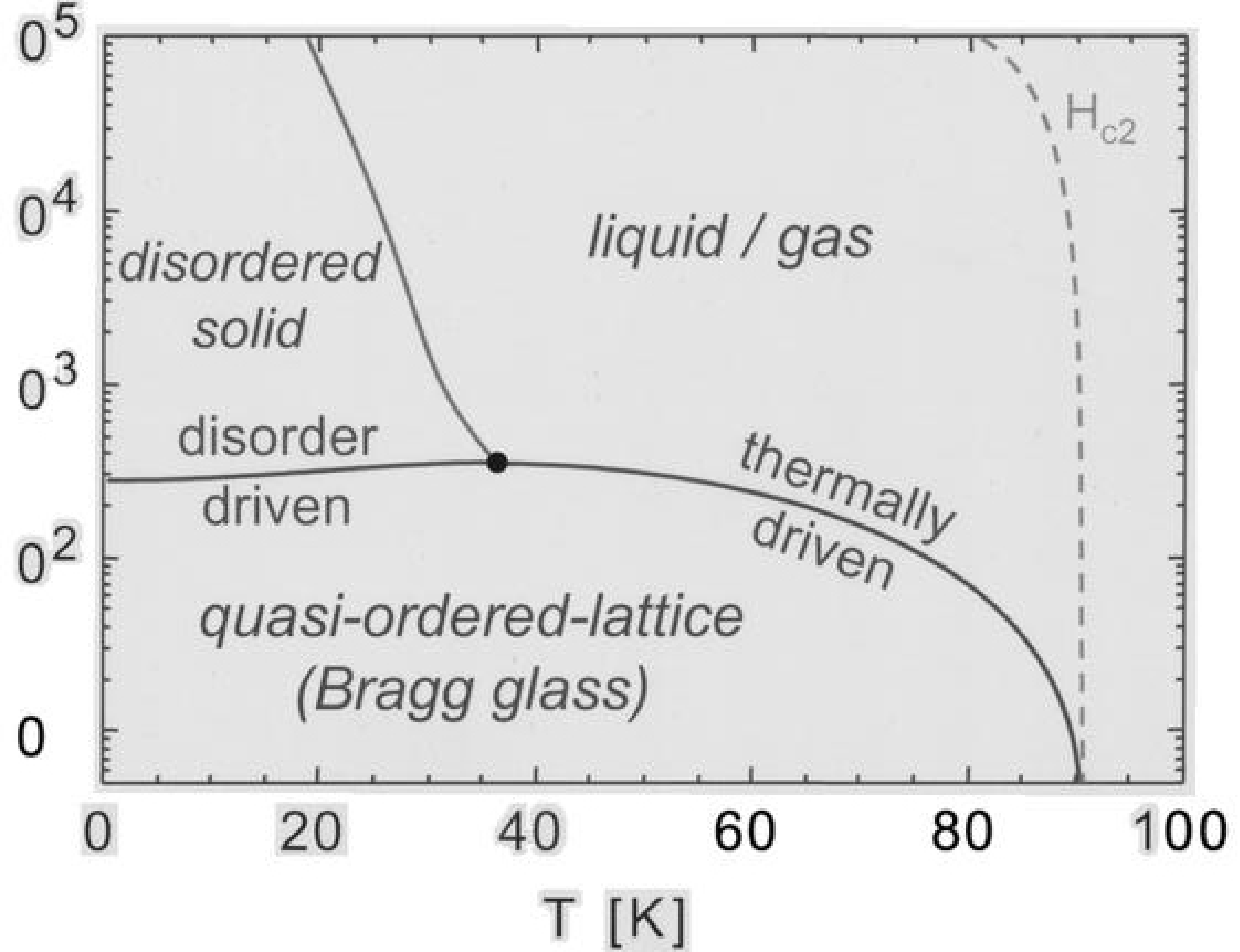
FLL is an extremely soft solid : H =1T, $C_{11} = 8 \times 10^6$ dynes/cm^2

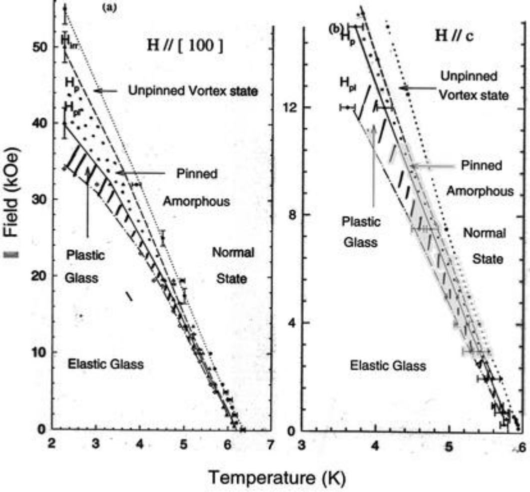
e.g., $NbSe_2$ $C_{66} \sim 5 \times 10^4$

$a_0 \sim 450$ Å



ex matter phase diagram in $Bi_2Sr_2CaCu_2O_8$

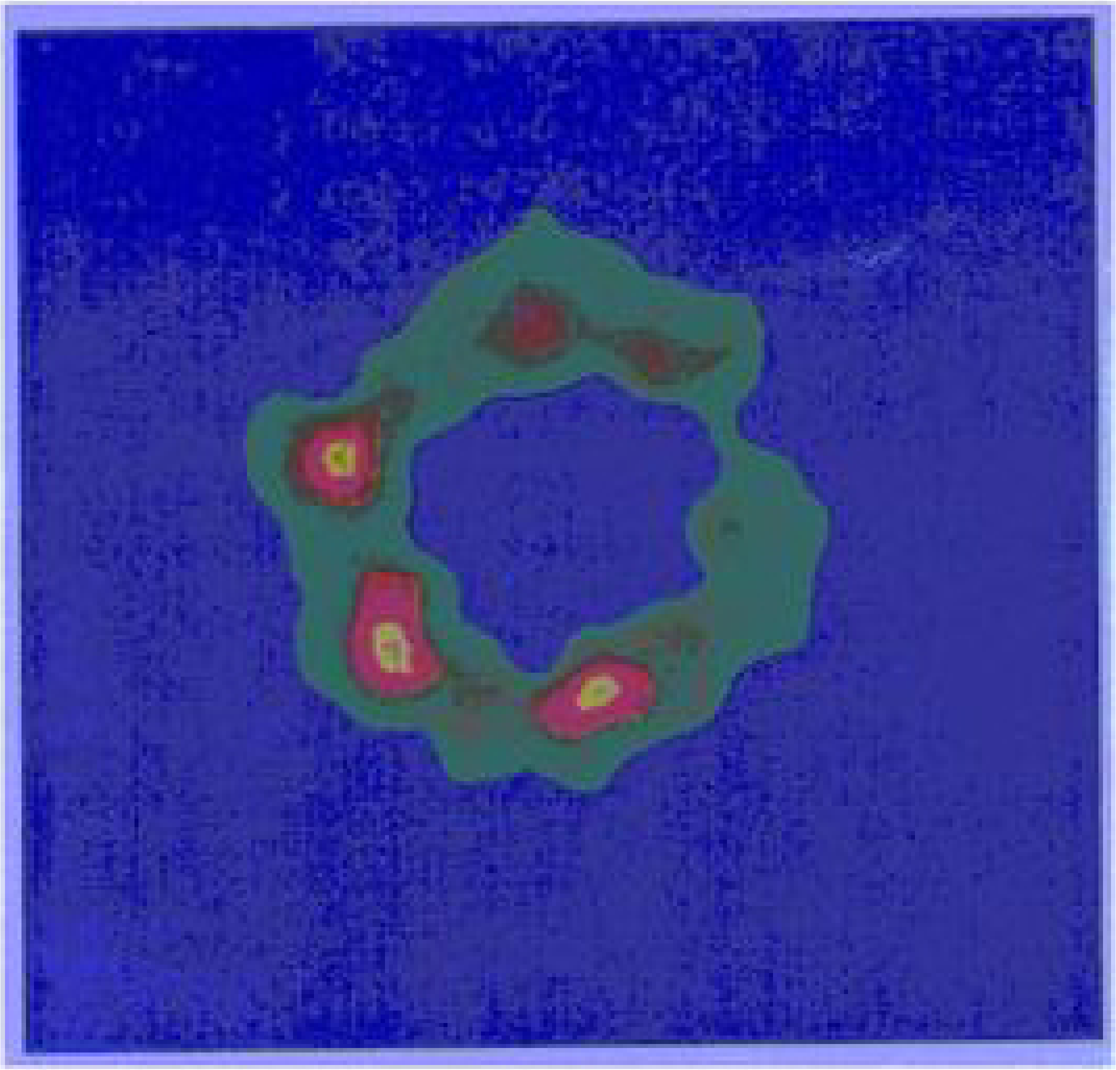




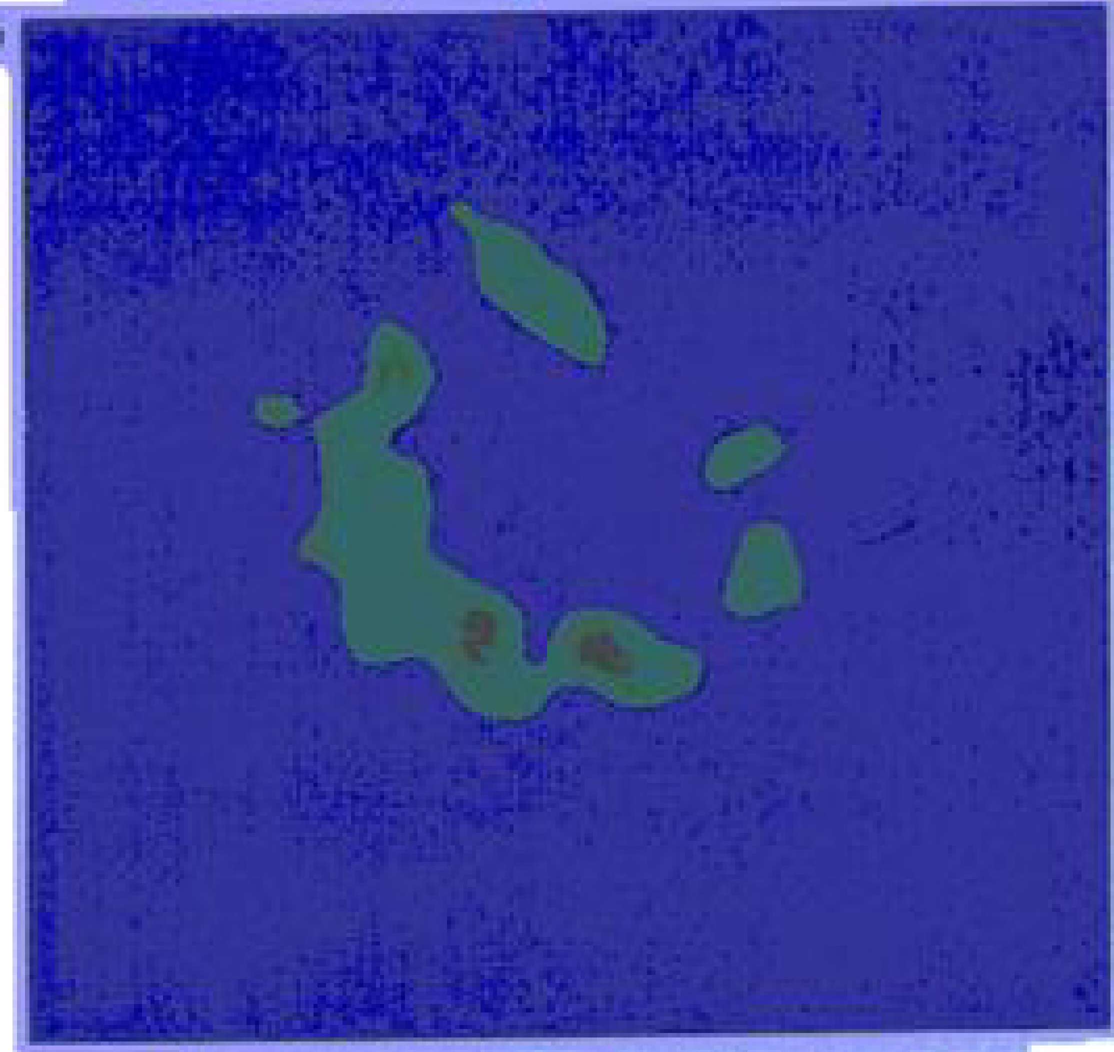
(a)
H // [100]
Unpinned Vortex state
Pinned
Amorphous
Normal
State
Plastic
Glass
Elastic Glass
(b)
H // c
Unpinned
Vortex state
Pinned
Amorphous
Plastic
Glass
Normal
State
Elastic Glass
Field (kOe)
Temperature (K)

T - dependence ~ peaks across melting
(Cubitt, Forgan et al)

a

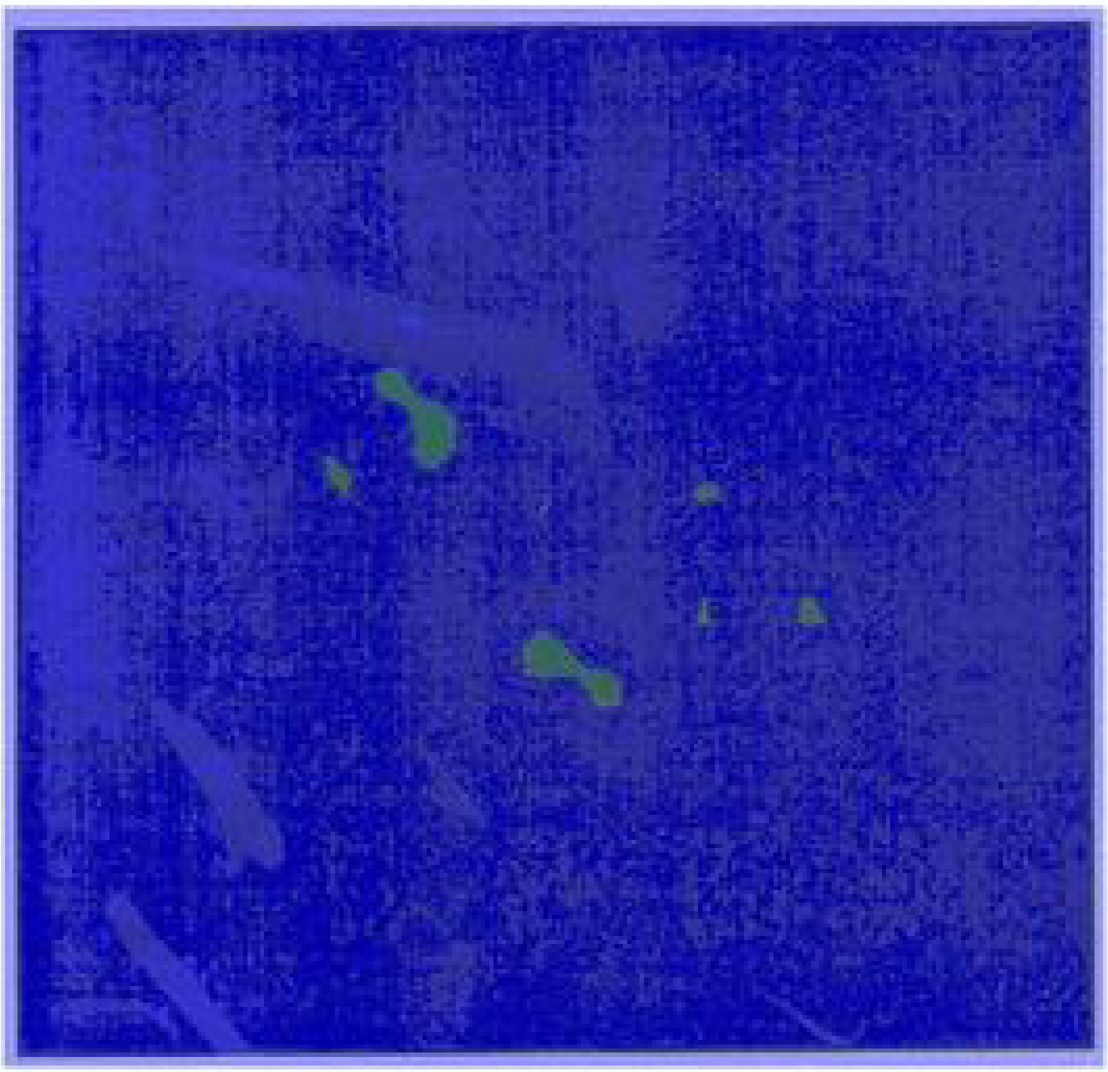


b



[redacted]endent of the presence of a lattice), and bearing in mind the shear modulus c_{66} is zero in the liquid state, we may

c



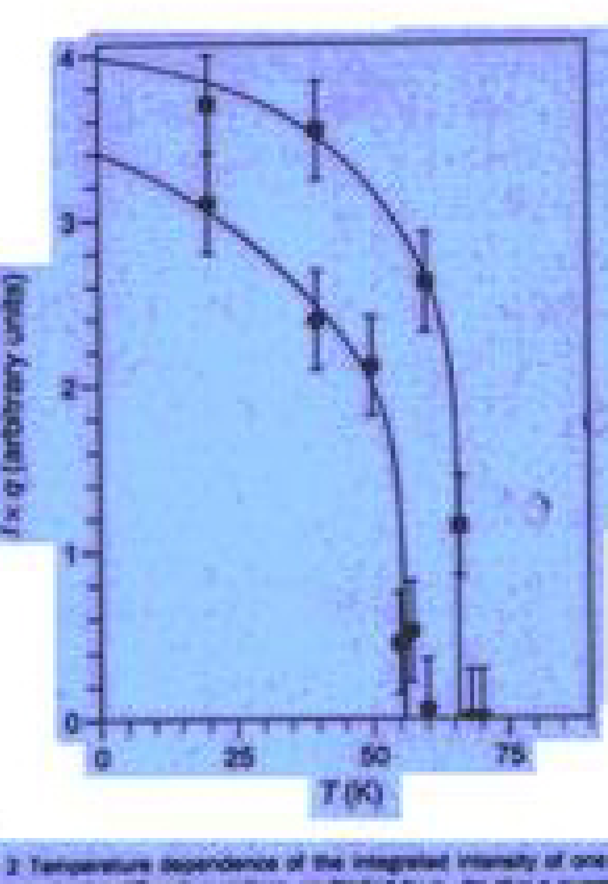
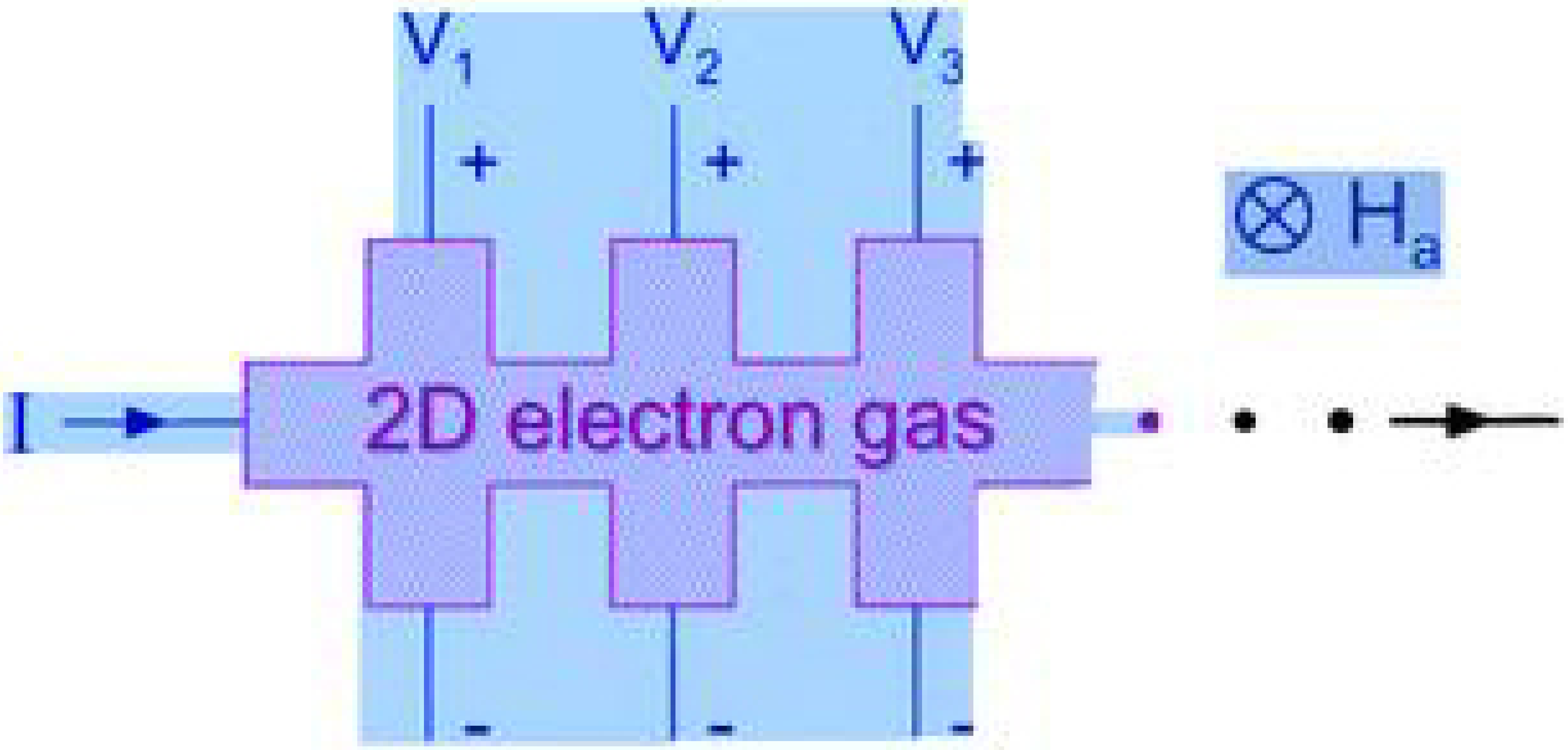
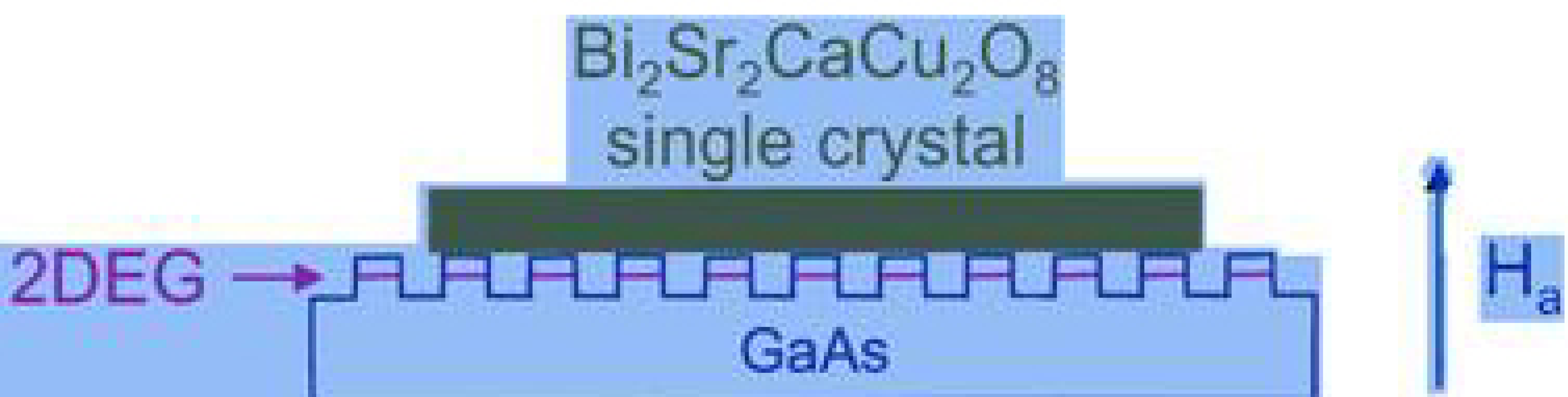


FIG. 2 Temperature dependence of the integrated intensity of one of the spots in the diffraction pattern, multiplied by q_{xx} (to give a quantity proportional to the form factor). Data is shown for 30 mT (squares) and 80 mT (crosses). The solid lines are a guide to the eye.

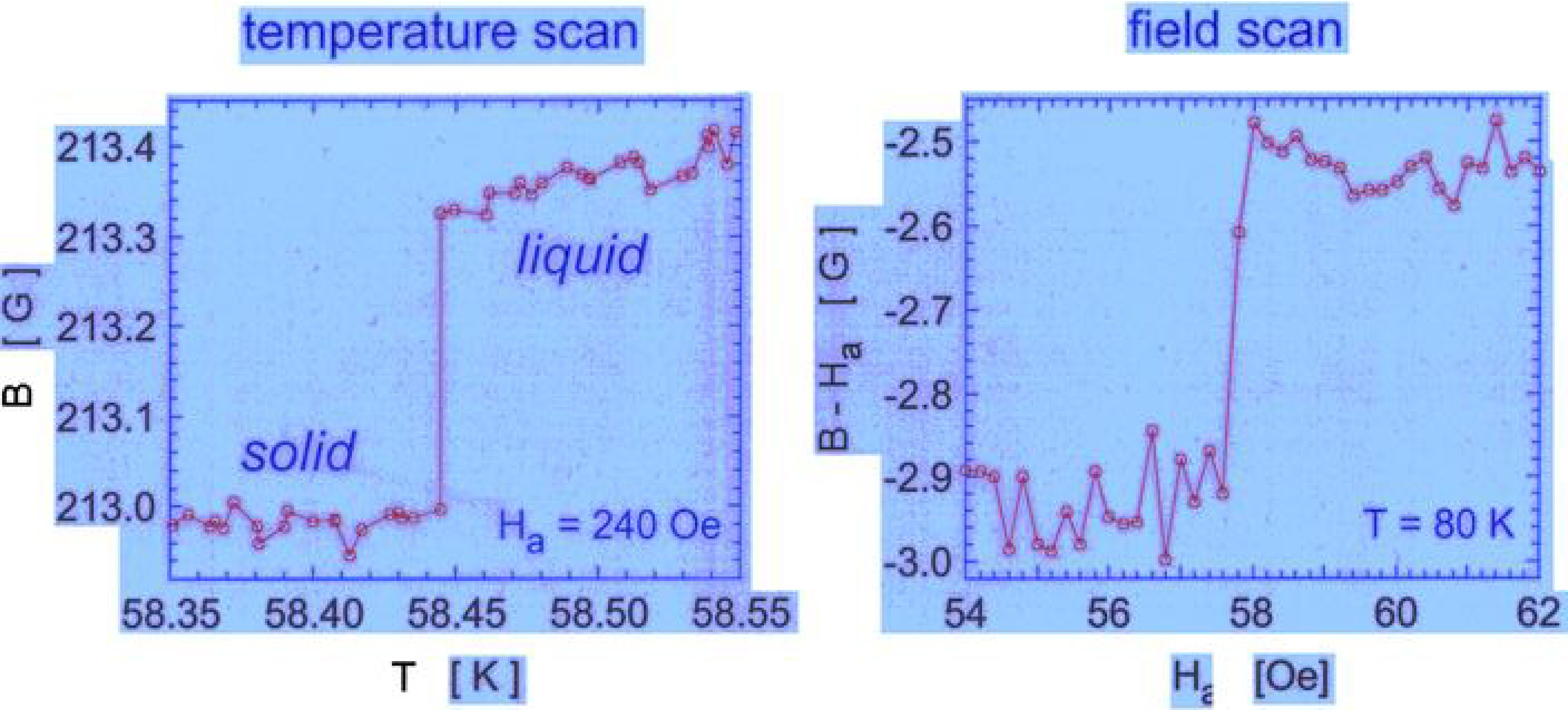
Zeldov et al
(Weizmann)

Hall-sensor arrays



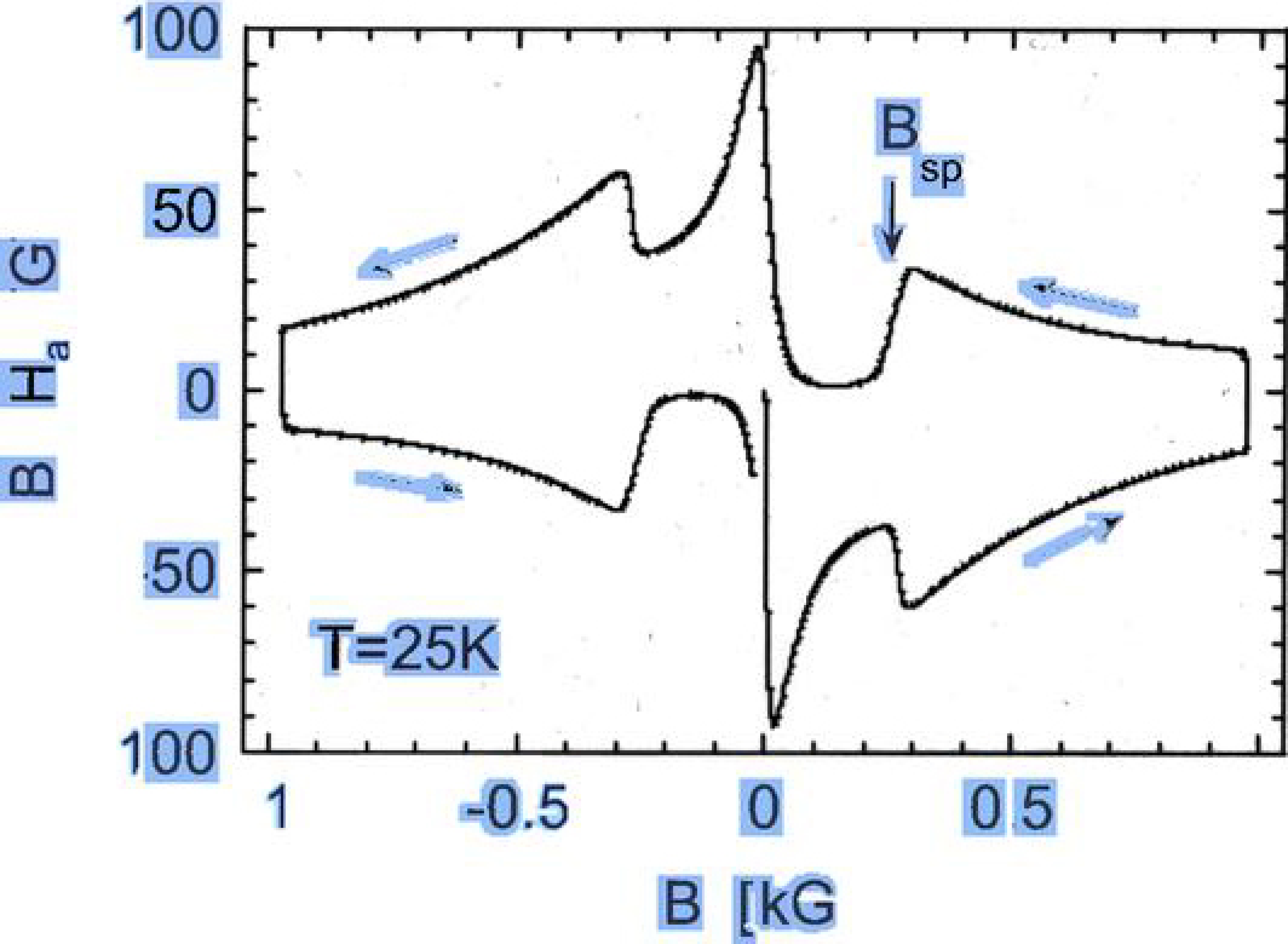


Magnetization step at the first-order transition



Clapeyron Eqn $$\frac{dH_m}{dt} = -\frac{\Delta S}{\Delta M}$$

Magnetization loop with second magnetization peak

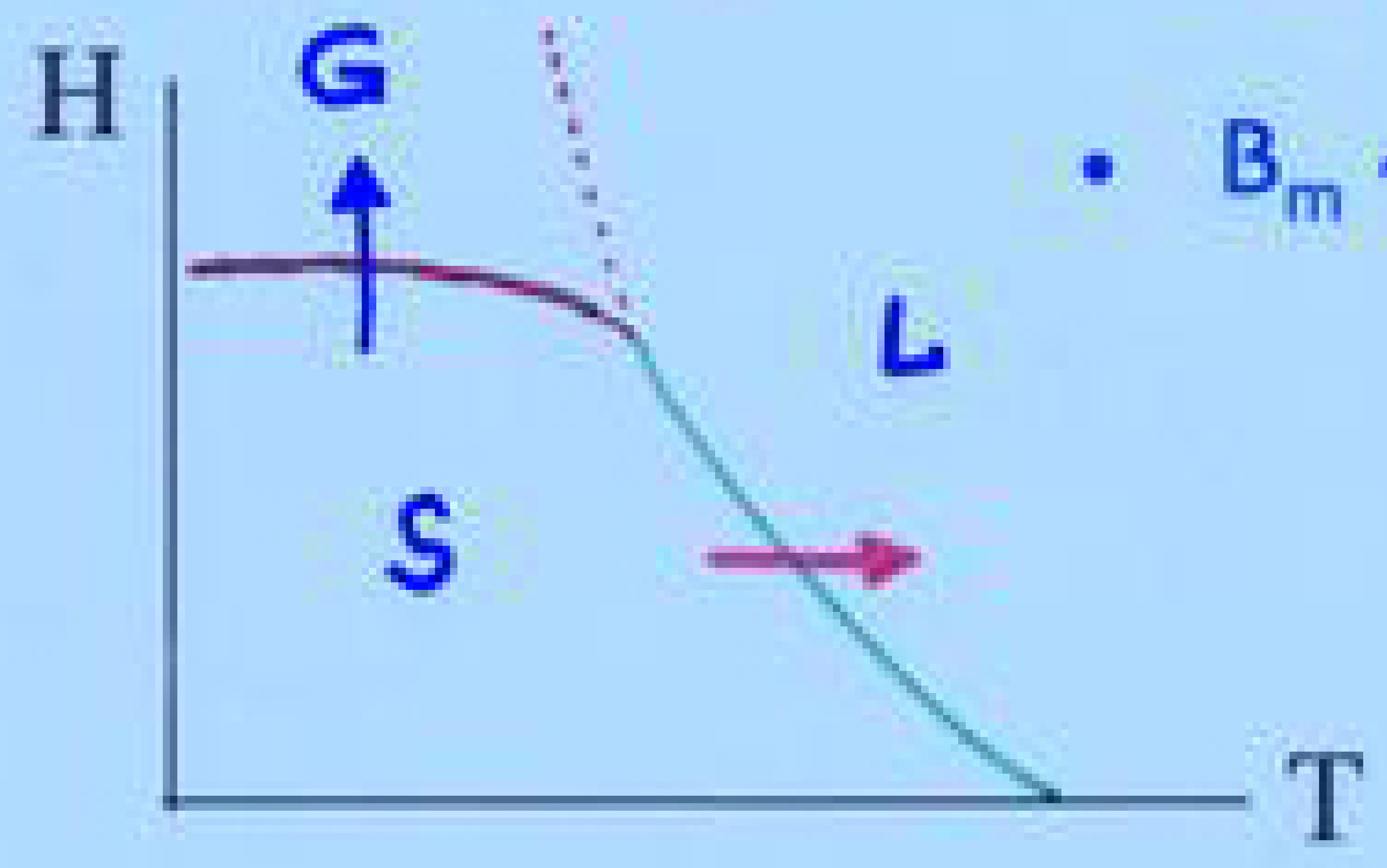


- Lindemann scenario of melting/amorphization :

RMS lattice fluctuations : $\langle u^2 \rangle^{1/2}$ too large for stable lattice

$\langle u^2 \rangle^{1/2}/a_0 \sim c_L$ (0.1-0.3 typically)

- Melting : fluctuations are thermal : lattice to liquid

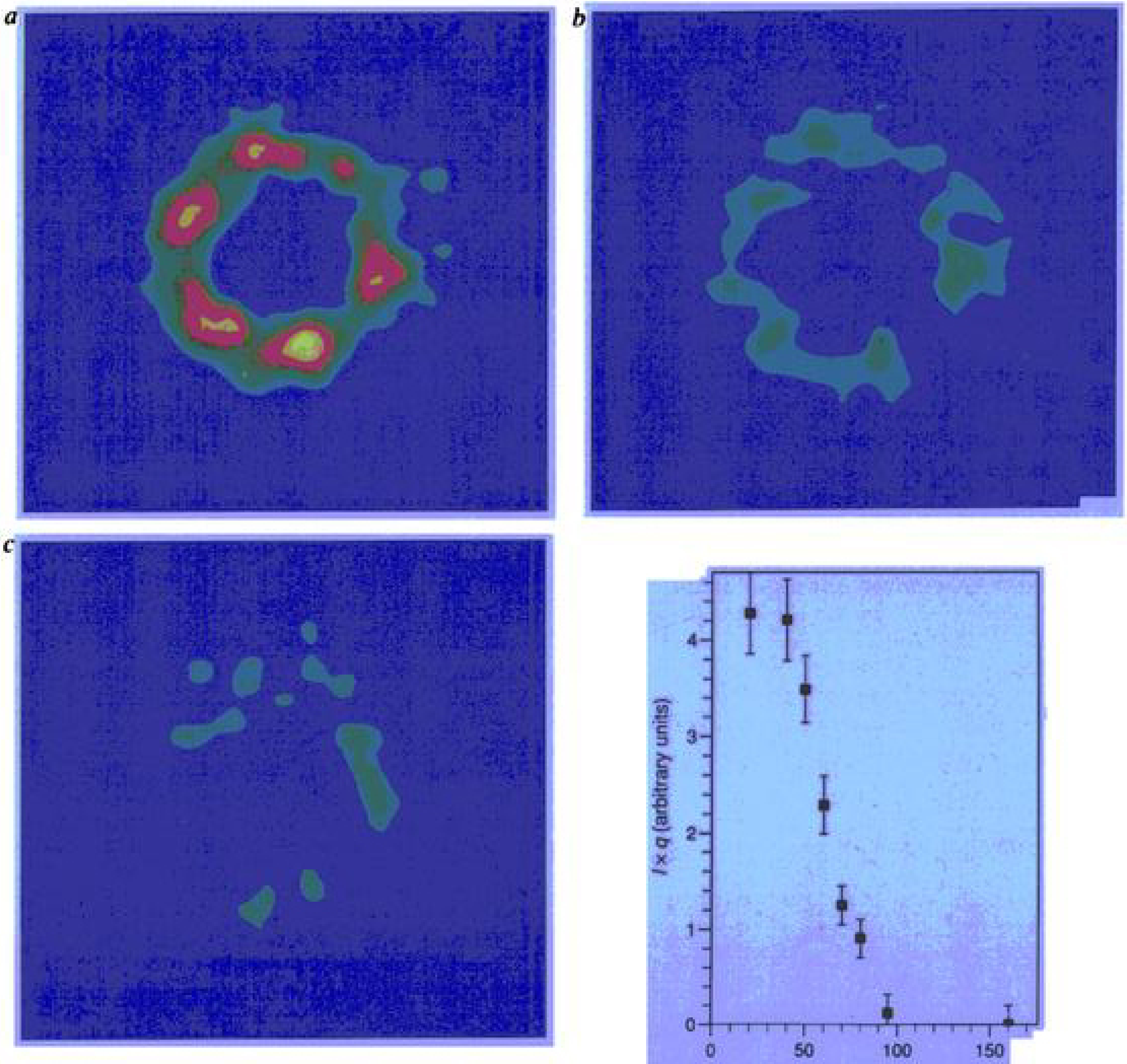


- $B_m \sim (c_L^4/Gi)\, H_{c2}[1-T/T_c]^2$

- Amorphization : fluctuations are due to quenched disorder

lattice to glass ?

H-dependence of neutron scattering intensity across solid-glass



High T_c phenomenology of solid, glass and fluid:

BSCCO and YBCO

Melting transition and second peak or peak effect ← BKBO

Low T_c phenomenology :

$NbSe_2$, Nb

Peak effect and "amorphization transition": **history effects**

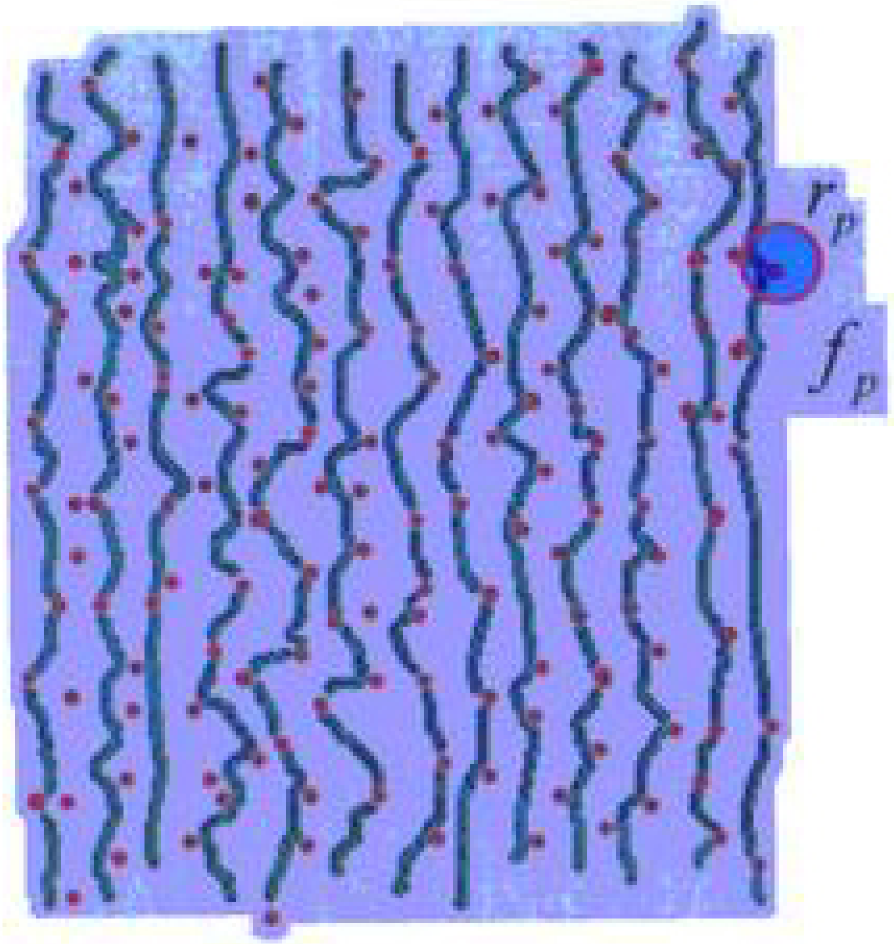
Dynamical phases and transitions :

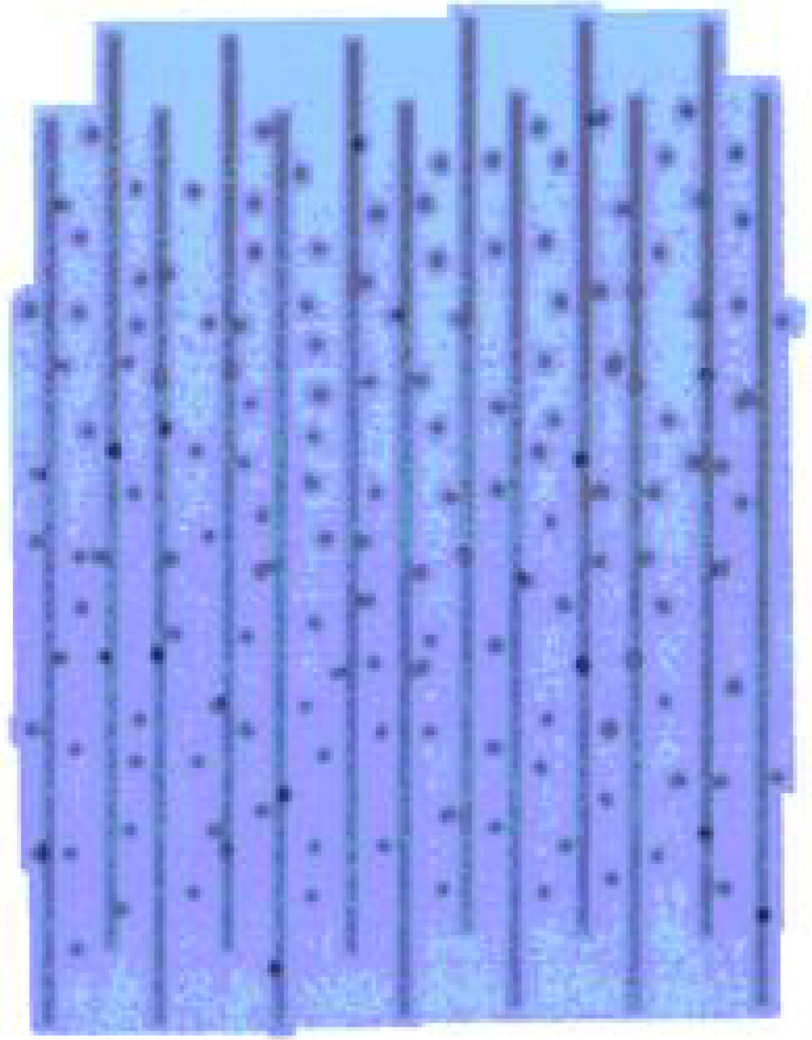
Elastic flow, plastic flow and fluid flow

Edge contamination and annealing scenario

Vortex pinning: individual and collective

strong pinning





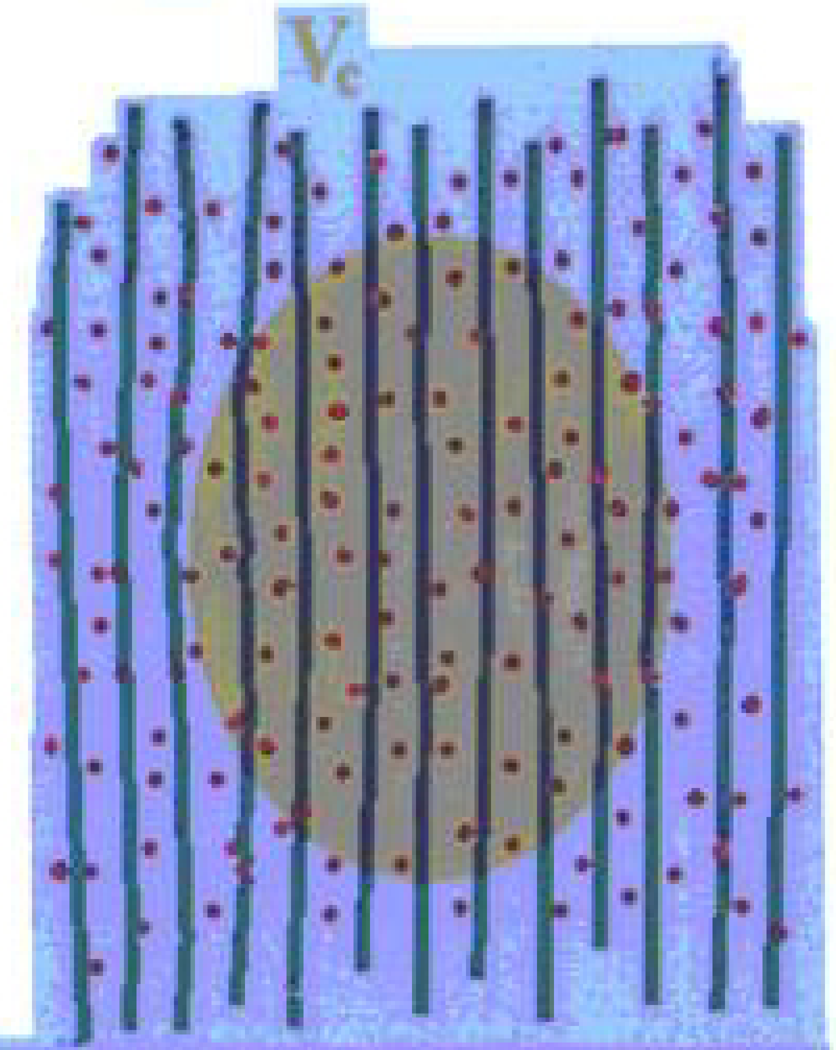
?

depinning:

$$F_p = J_c B$$

J_c - critical current

w



$$F_p = \left[\frac{1}{2} n_p f_p^2 \Big/ V_c \right]^{1/2}$$

$$V_c \sim c_{66}^2 c_{44}$$

Larkin and Ovchinnikov, 1979.

Anisotropic superconducting parameters for $2H\text{-}NbSe_2$

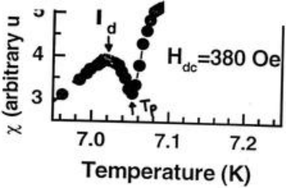
Parameter	$H \parallel c$	$H \perp c$
κ	9	30
ξ	77	23
λ	690	2300
J_c (1 T, 4.2 K)	1-30 amp/cm^2	10-200 amp/cm^2 H_{c2}

$2H\text{-}NbSe_2$ in comparison to other superconductors

Quantity	HTSC	LTSC	$2H\text{-}NbSe_2$
$G_i = [k_B T_c/(H_{c2}^2 \varepsilon \xi^3)]^2$	10^{-2}	10^{-8}	10^{-4}
$Q_u = (e^2/h)(\rho_n/\varepsilon\xi)$	10^{-1}	10^{-3}	10^{-3}
$j_c/j_0 = (\xi/R_c)^2$	10^{-2}	10^{-1}	10^{-6}

among the cleanest single-crystal systems;
i.e., longest Larkin lengths;

Ideally suited to test ideas relevant to clean systems such as melting;
But disorder is important even here

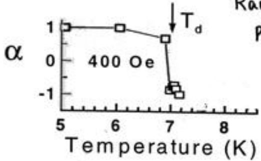


$$\chi' \sim -1 + \frac{\alpha h_{ac}}{J_c}$$

$$J_c \sim \frac{1}{B}\sqrt{\frac{n_p f^2}{V_c}}$$

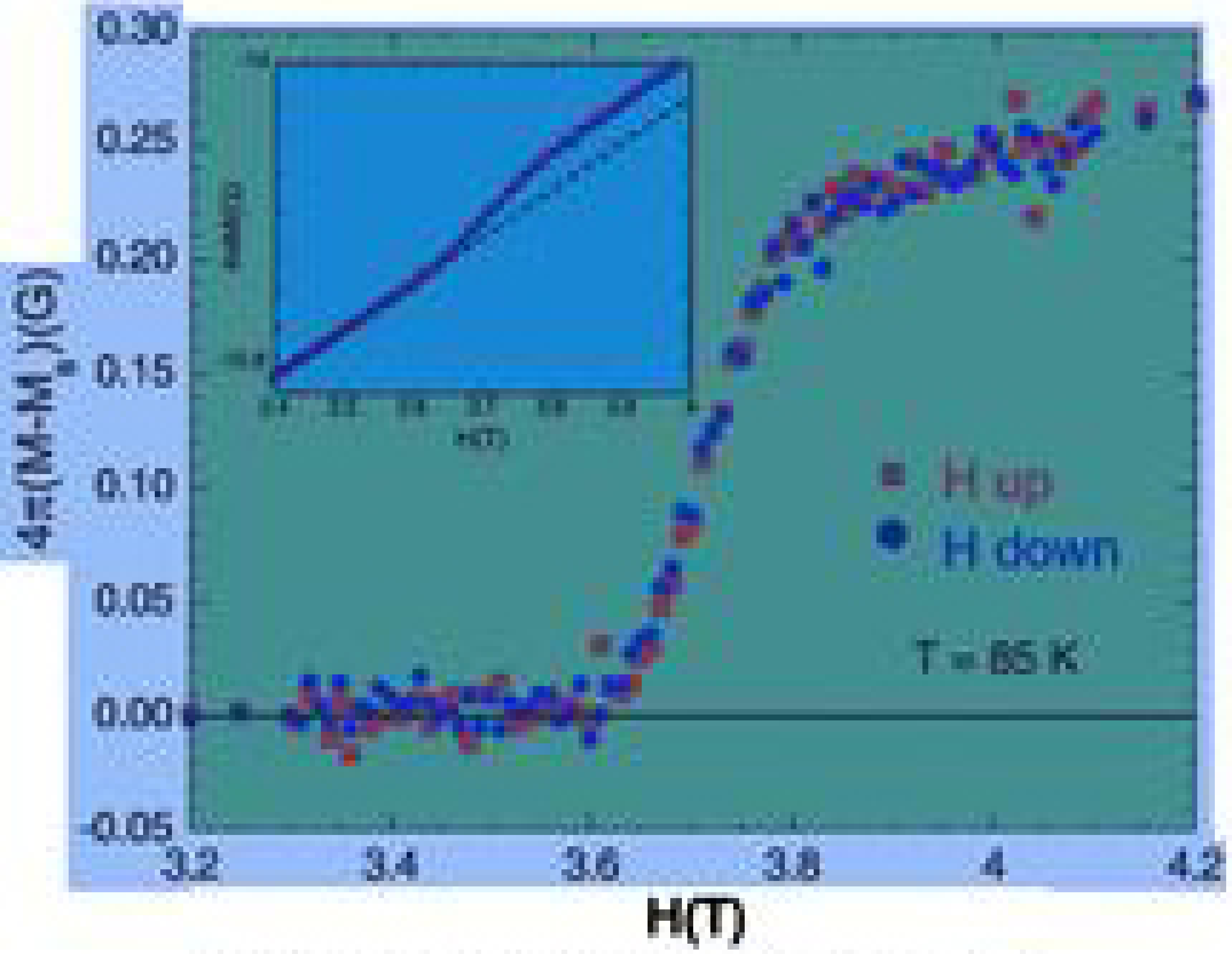
Temperature dependence of the in-phase ac magnetic susceptibility of a 2H-$NbSe_2$ single crystal, under a superposed dc field of 380 Oe. Note the onset of the peak effect at $T_d \approx$ 7.0K.

Rao et al. Physica C (98)

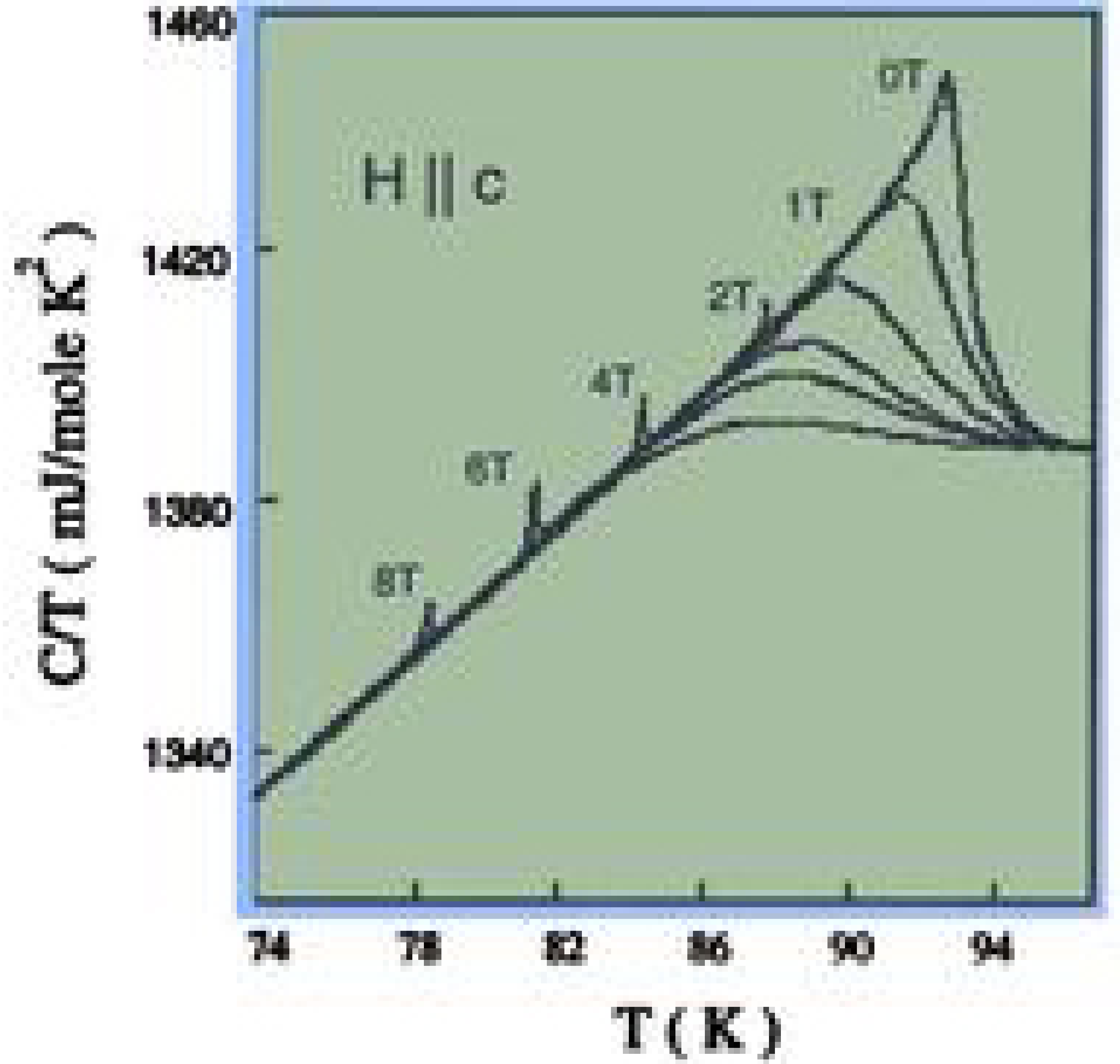


Temperature dependence of the line shape asymmetry parameter α', for a field of 400 Oe. Note the sharp change in α' at $T_d \approx$ 7.0K.

Amorphization of VL between the onset and the maximum, between T_d and T_p

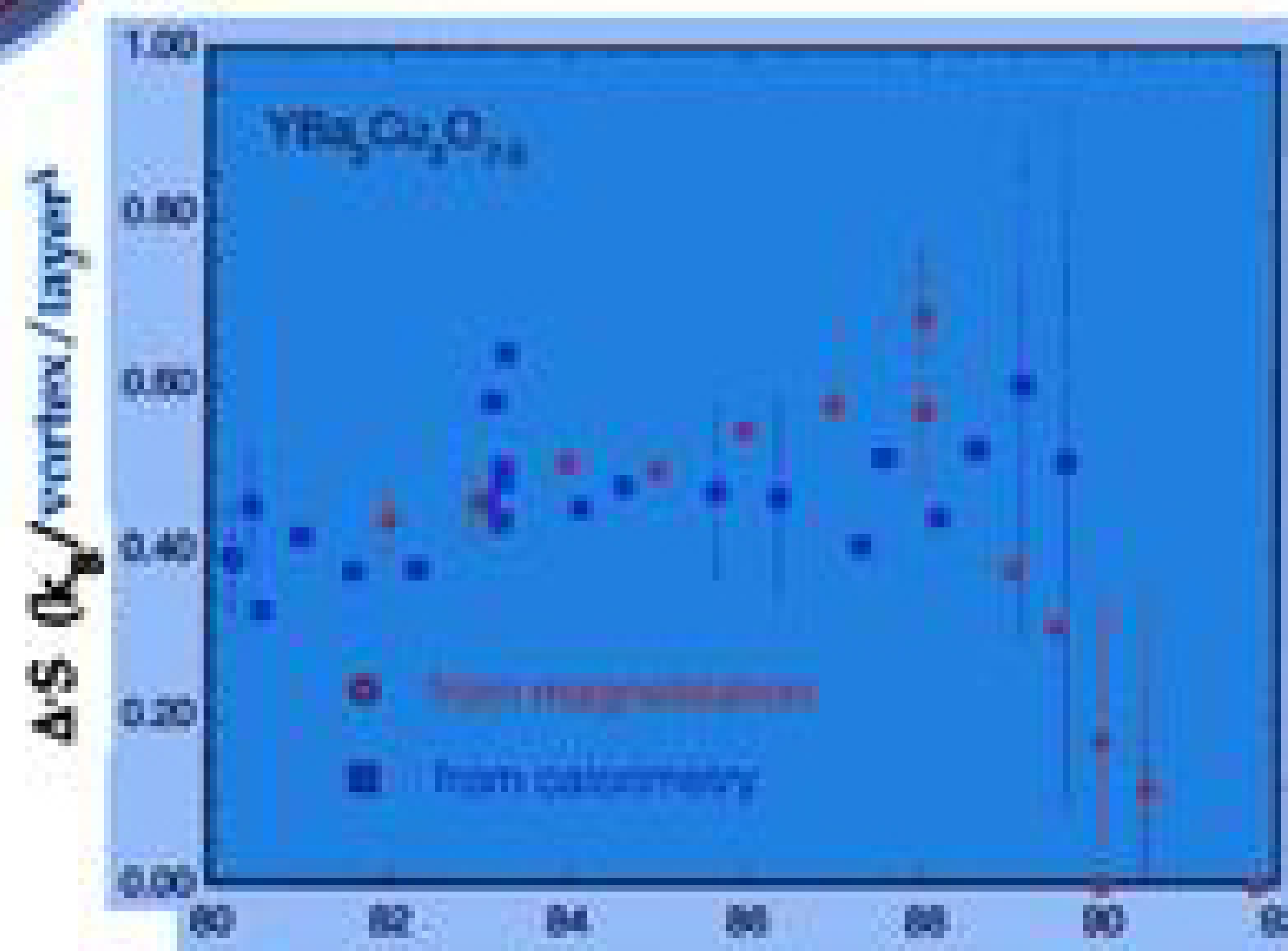


Welp, Fendrich, Kwok, Crabtree, Veal
PRL **76**, 4809 (1996)



Schilling, Phillips, Fisher, Welp, Kwok, Crabtr
Nature **382**, 791 (1996)

first order melting



$$\frac{dH_m}{dT} = - \frac{\Delta S}{\Delta M}$$

Clapeyron equation