Nuclear Spin Ordering in Solid ^3He

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PSM 2010 Symposium

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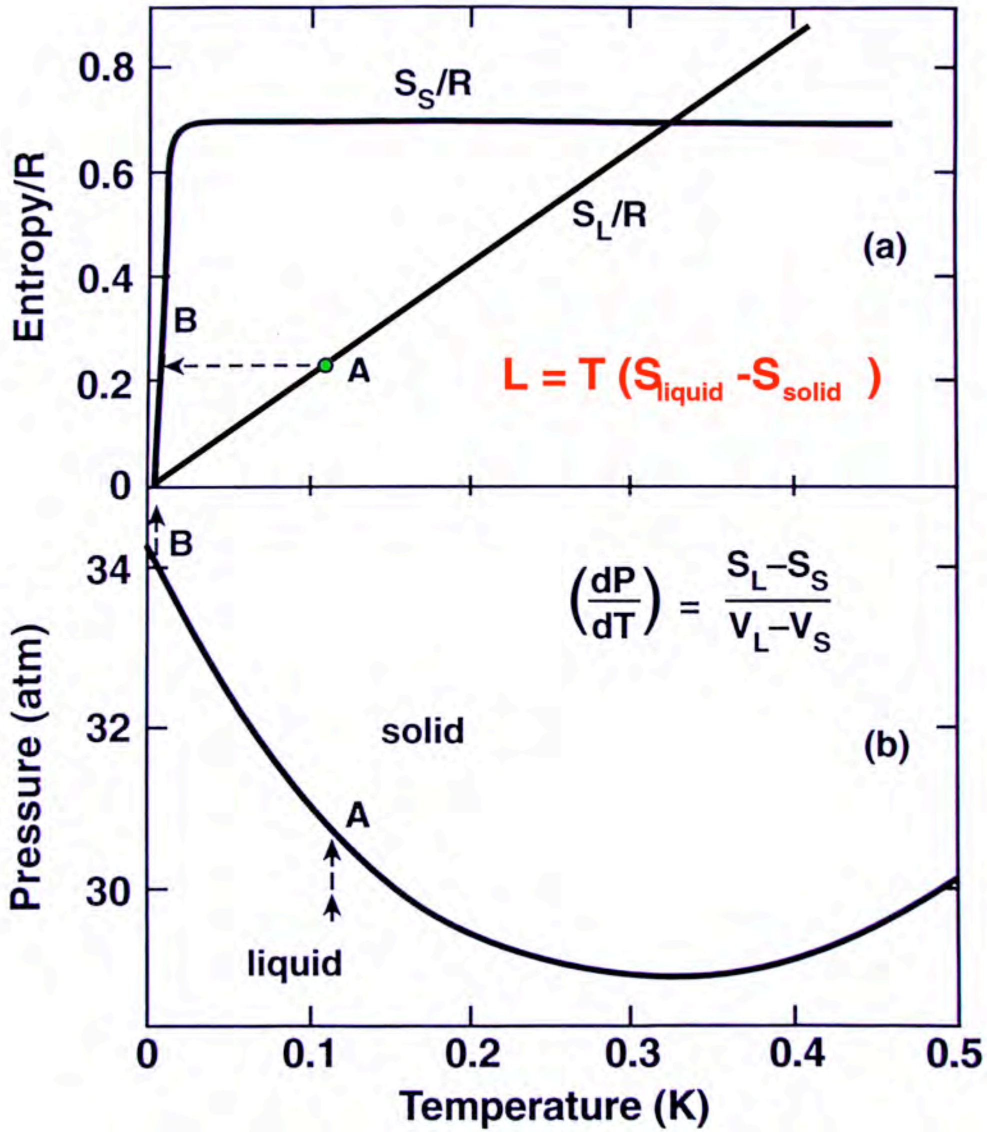
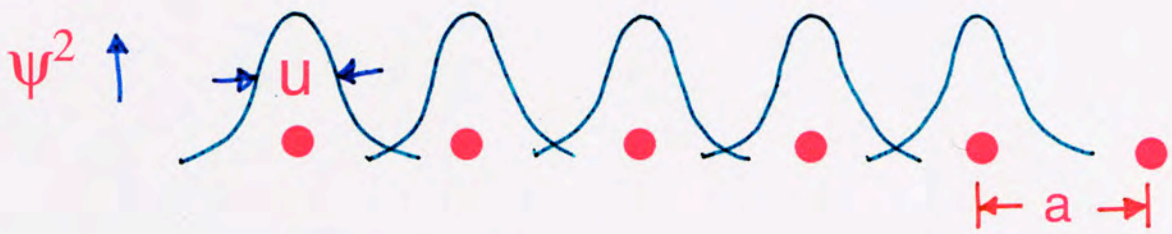
Pomeranchuk's Conjecture: *1950*



Fermi-Particle Exchange Spin Interactions:

a) Large zero point energy:



$u = a/3$

b) Atoms exchange lattice sites once in every $\sim 10^4$ zero point oscillations.

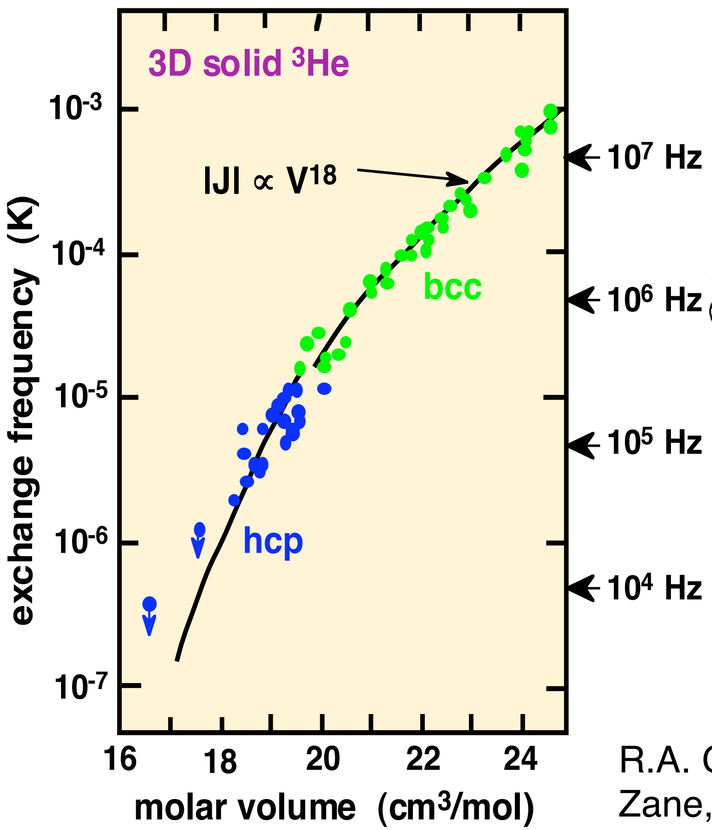
c) Lowest energy for two-particle exchange

— Symmetric orbital wave function

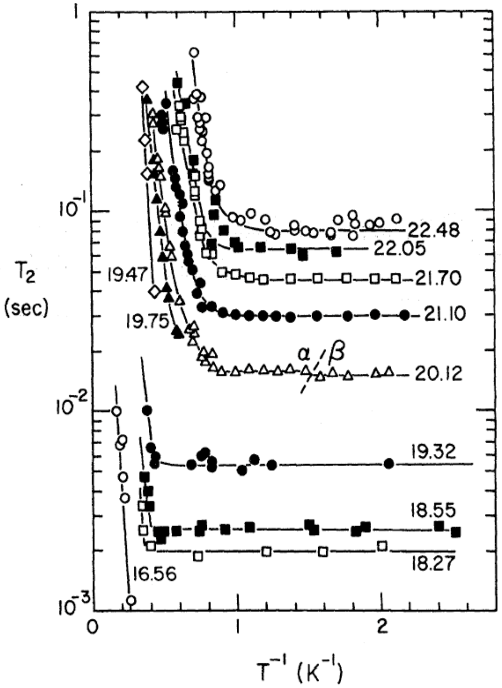
— Antisymmetric spin wave function

Early studies of exchange interactions in solid ^{3}He (1960s)

Volume dependence of *J*

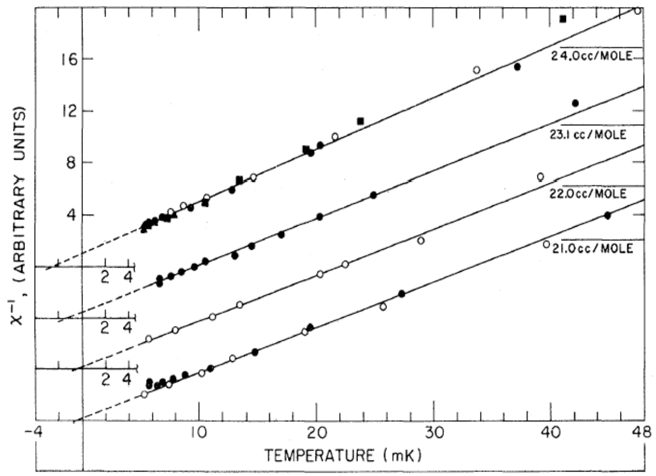


T_2 in NMR



R.A. Guyer, R.C. Richardson and L.I. Zane,
Rev. Mod. Phys. **43**, 532 (1971)

Magnetic susceptibility



W.P. Kirk et al., PRL **23**, 833 (1969)

antiferromagnetic

θ_W (= -4J) < 0

strong volume dependence

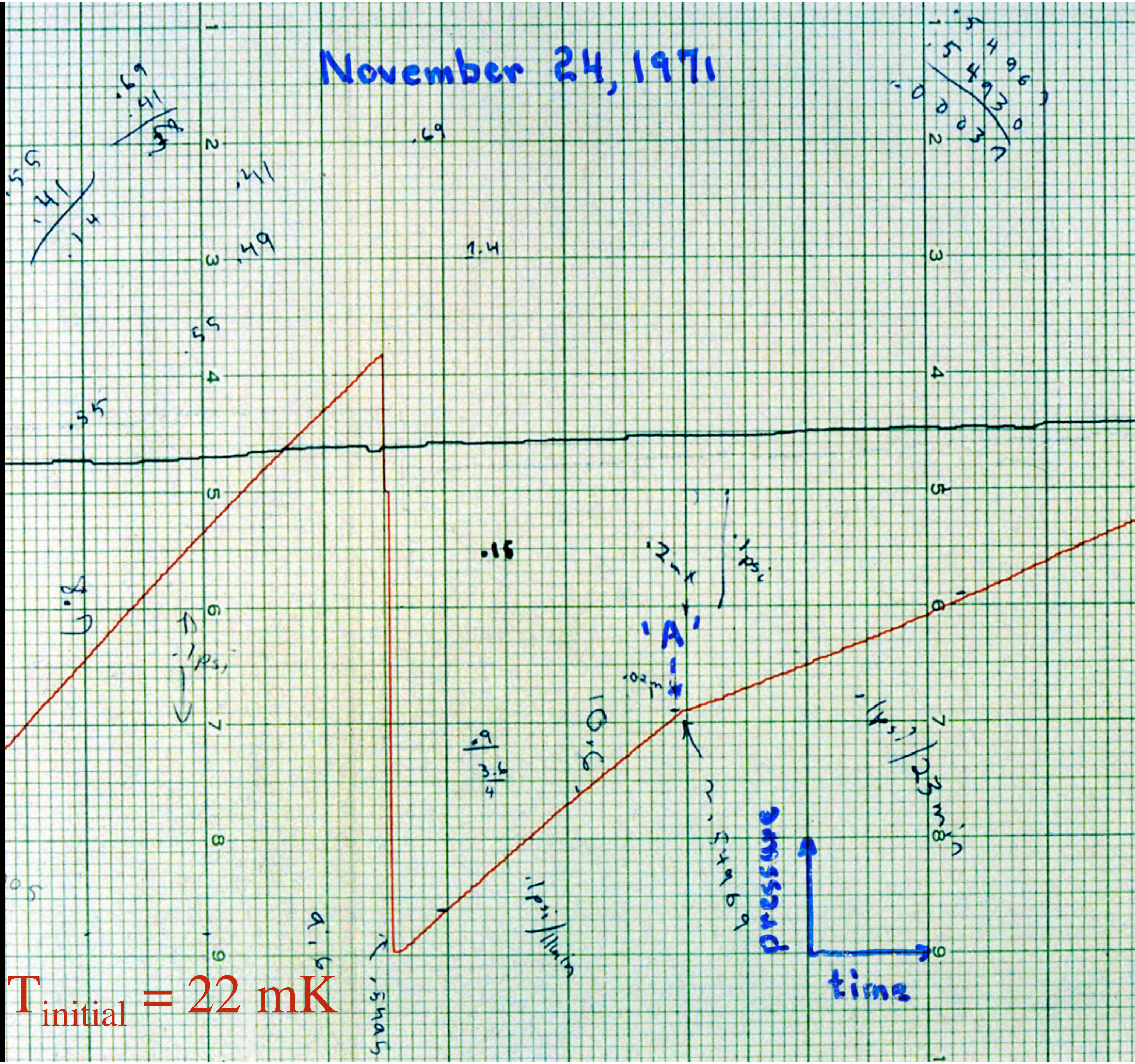
$|J| \propto V^{18}$

$J \approx$ -1 mK at melting pressure

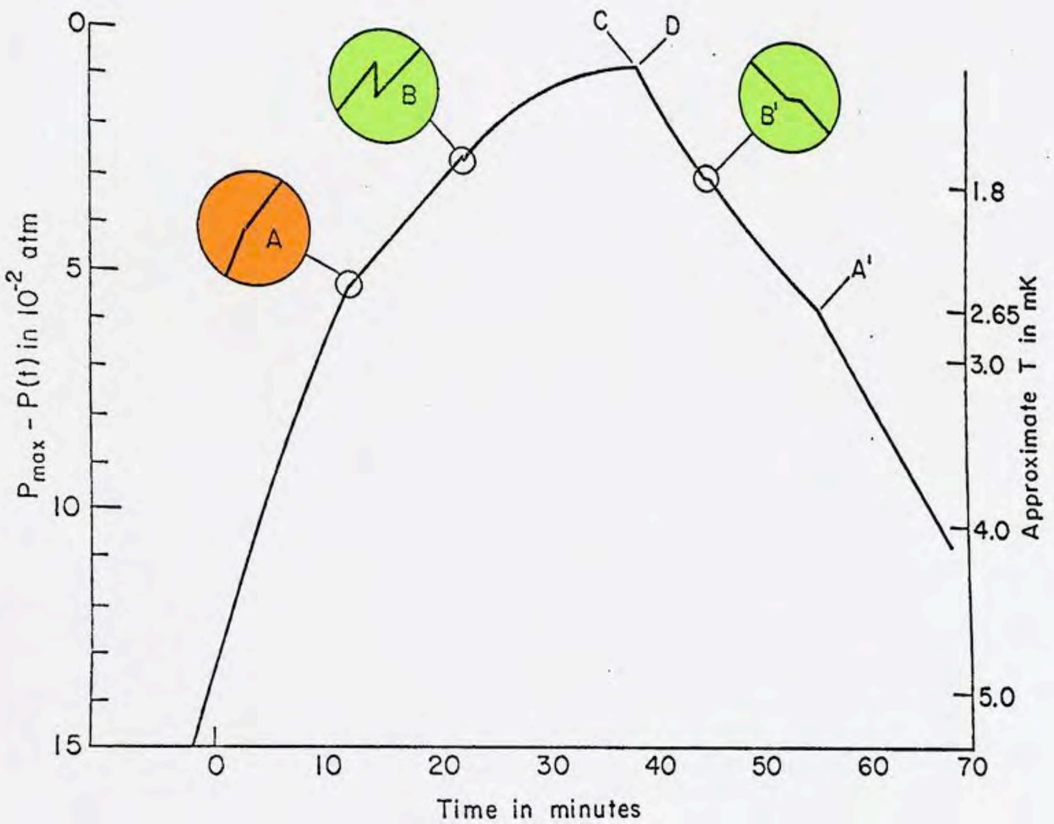
exchange narrowing

$T_2 \propto |J|$

Thanks to Hiroshi Fukuyama

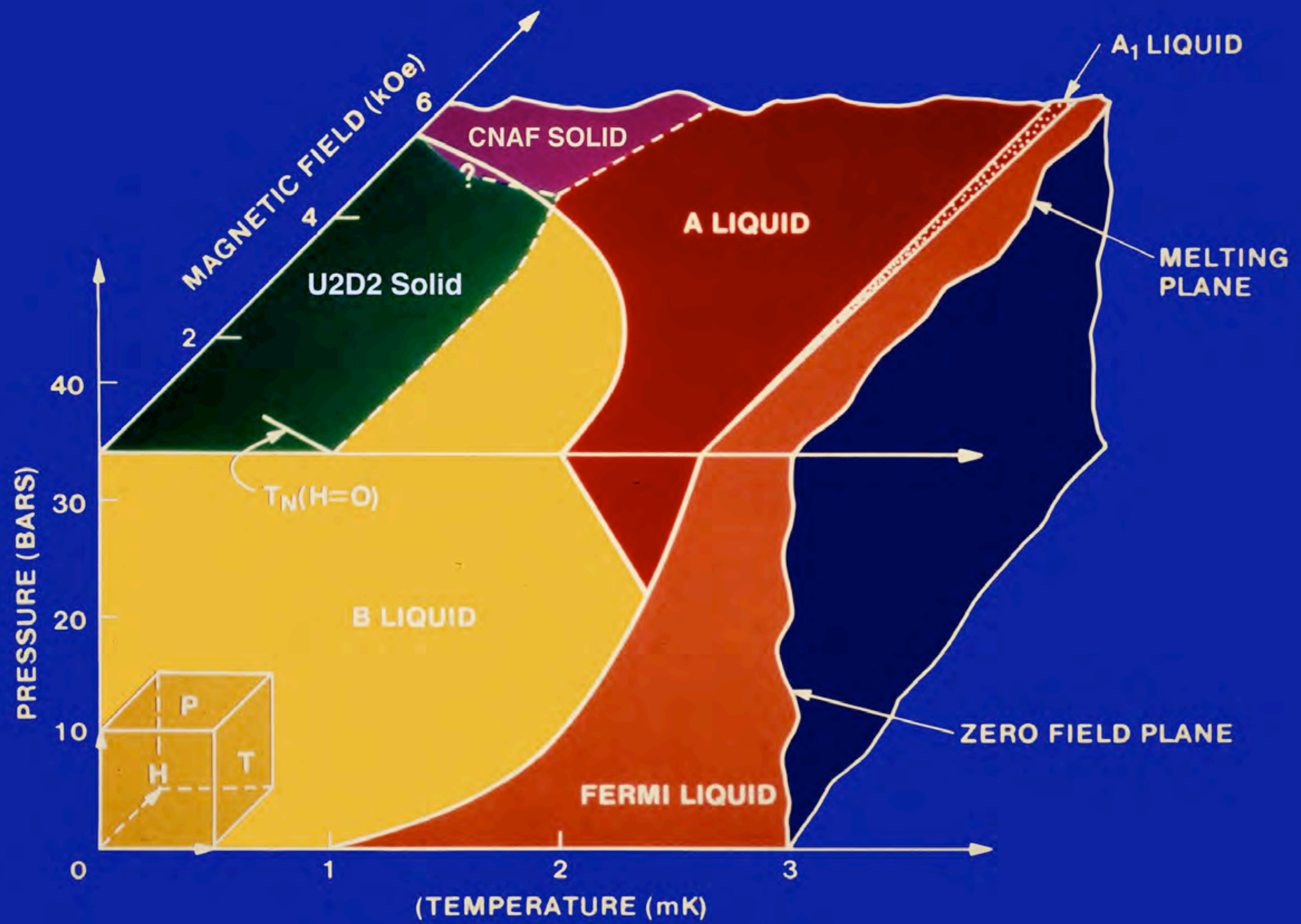

November 24, 1971
'A'
pressure
time
$T_{initial}$ = 22 mK

Full Pressurization Curve

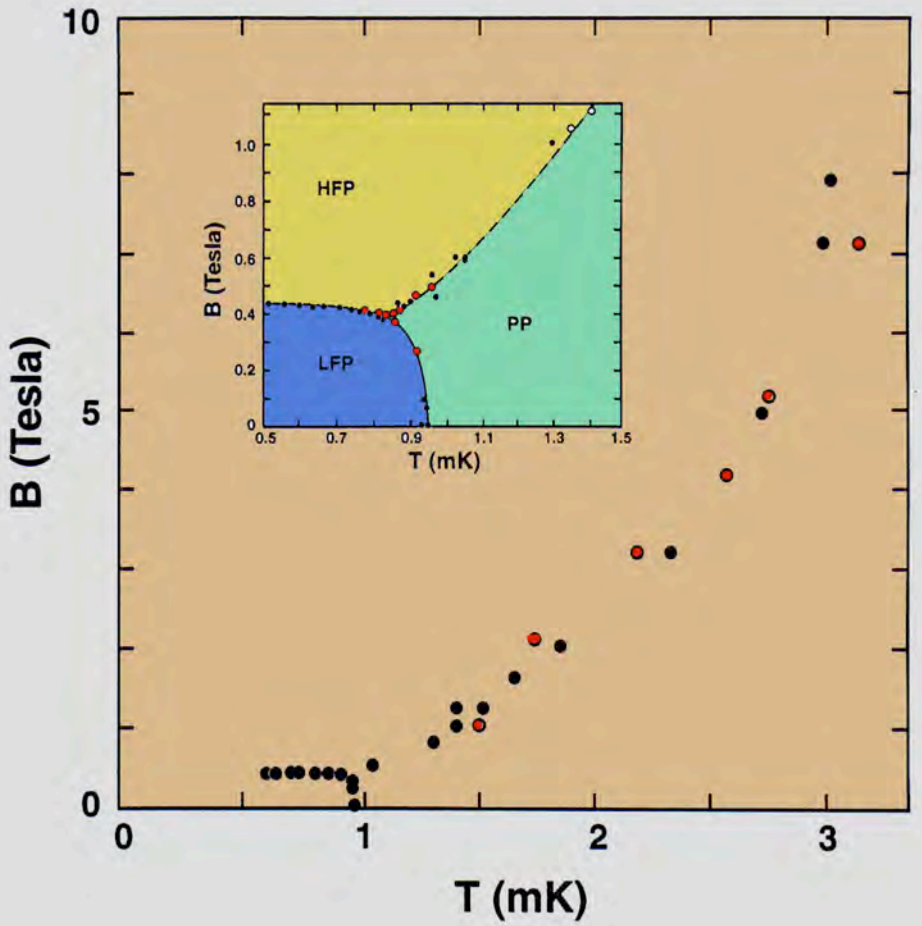


$$\Delta P \sim (1/\Delta V) \int_{T_i}^{T_f} S_{solid}(T)\,dT$$

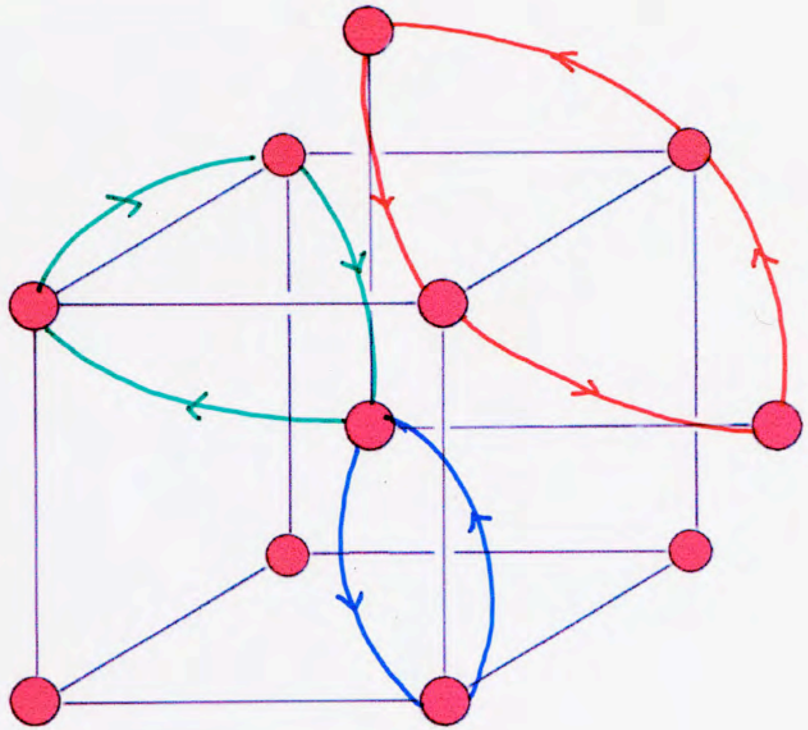
Ordered Helium Three Phase Diagram



Helium Three Magnetic Phase Diagram



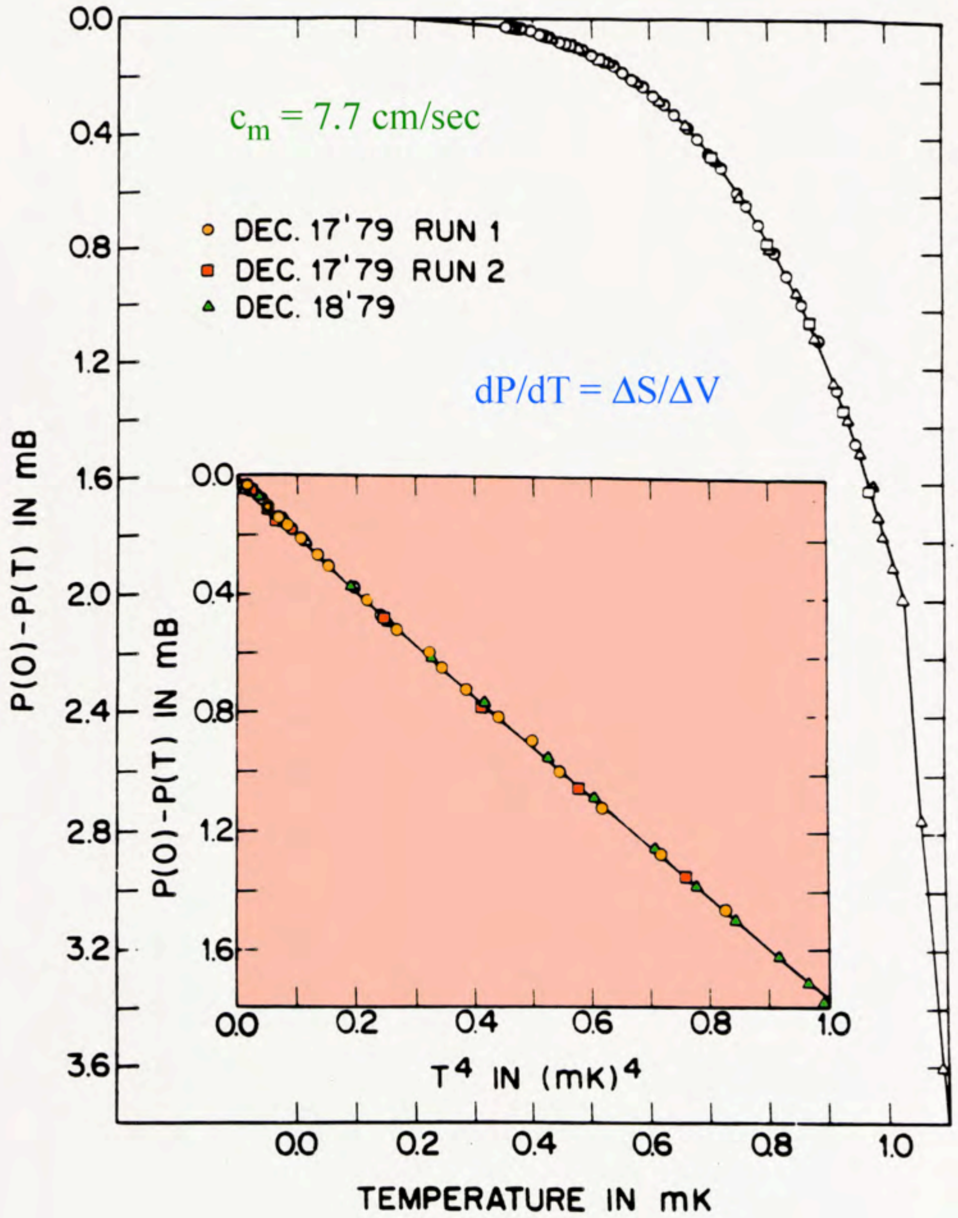
Multiple Exchange Hamiltonian



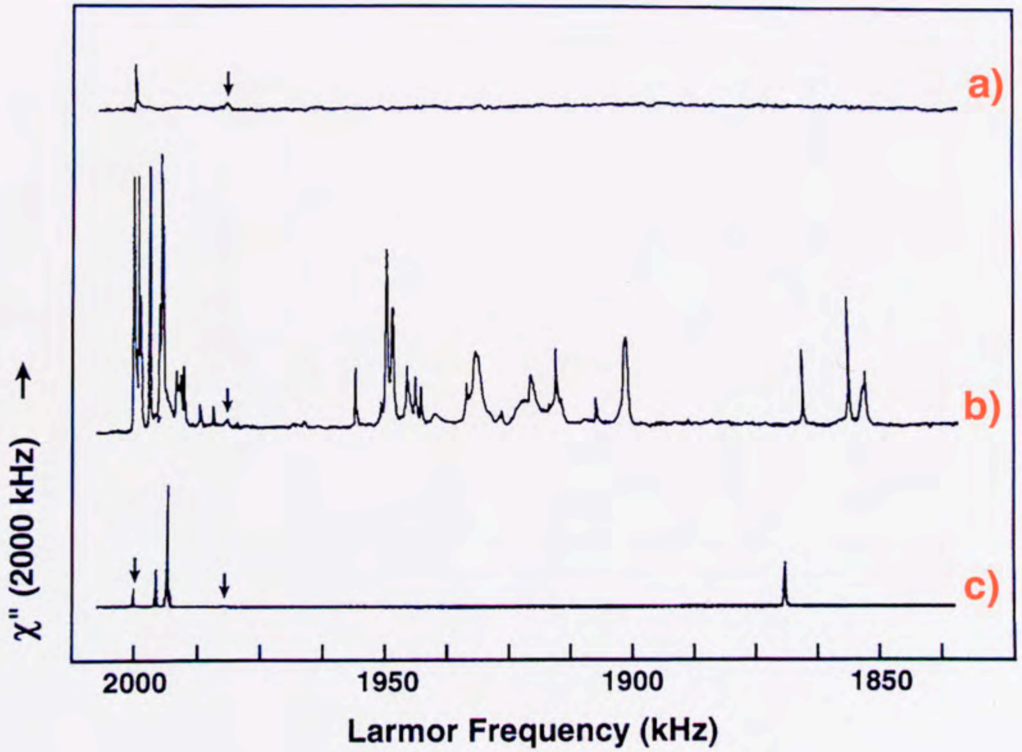
Even # exchanges antiferromagnetic,
odd # exchanges promote ferromagnetism.

Frustration

Osheroff and Yu, Phys. Letts. 77A, 458 (1980)



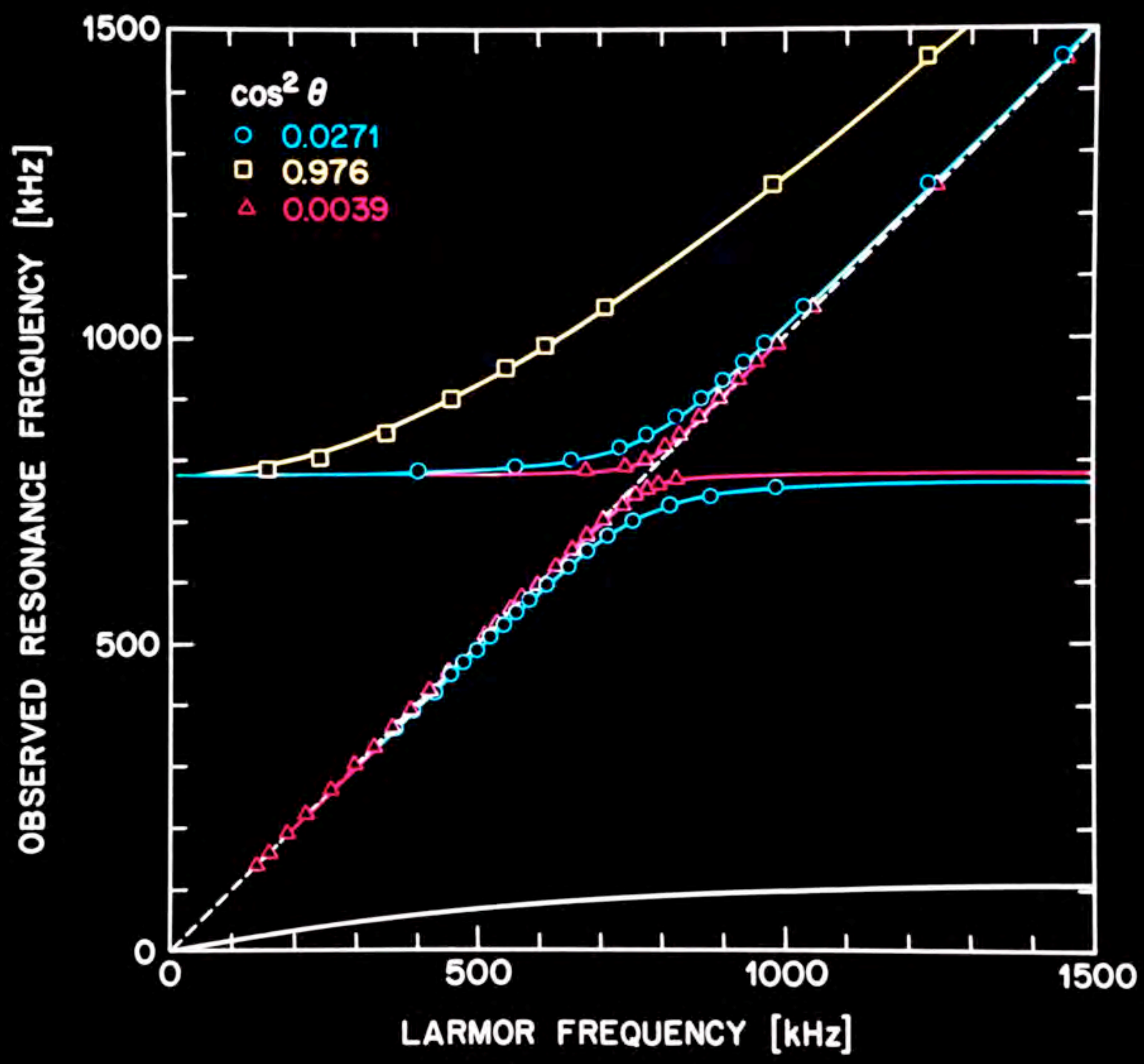
Growth of Single Crystals of Solid 3He



a) All-liquid NMR signal

b) Heat pulse growth pattern

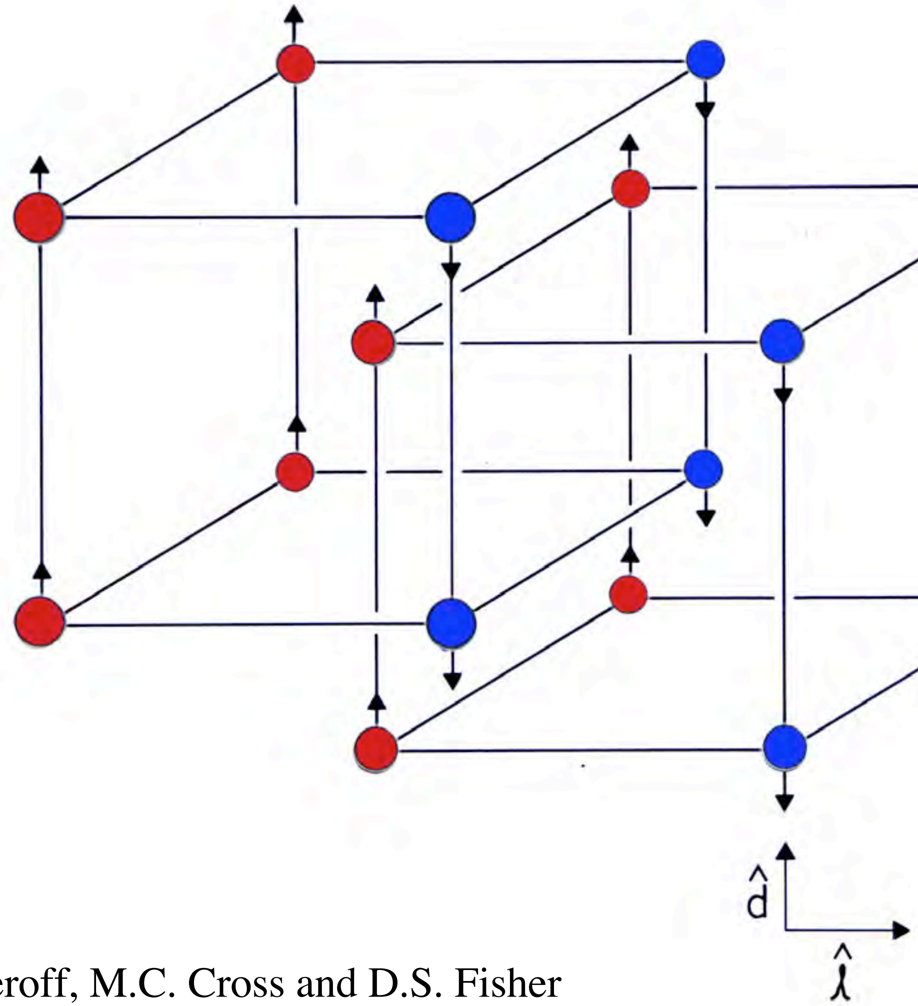
c) Seed Xl re-growth pattern



$$\left(\nu_i^{\pm}\right)^2 = \frac{1}{2}\left\{\nu_L^2 + \Omega_0^2 \pm \sqrt{\left(\nu_L^2 - \Omega_0^2\right)^2 + 4\,\nu_L^2\,\Omega_0^2\,\cos^2\Gamma_i}\right\}$$

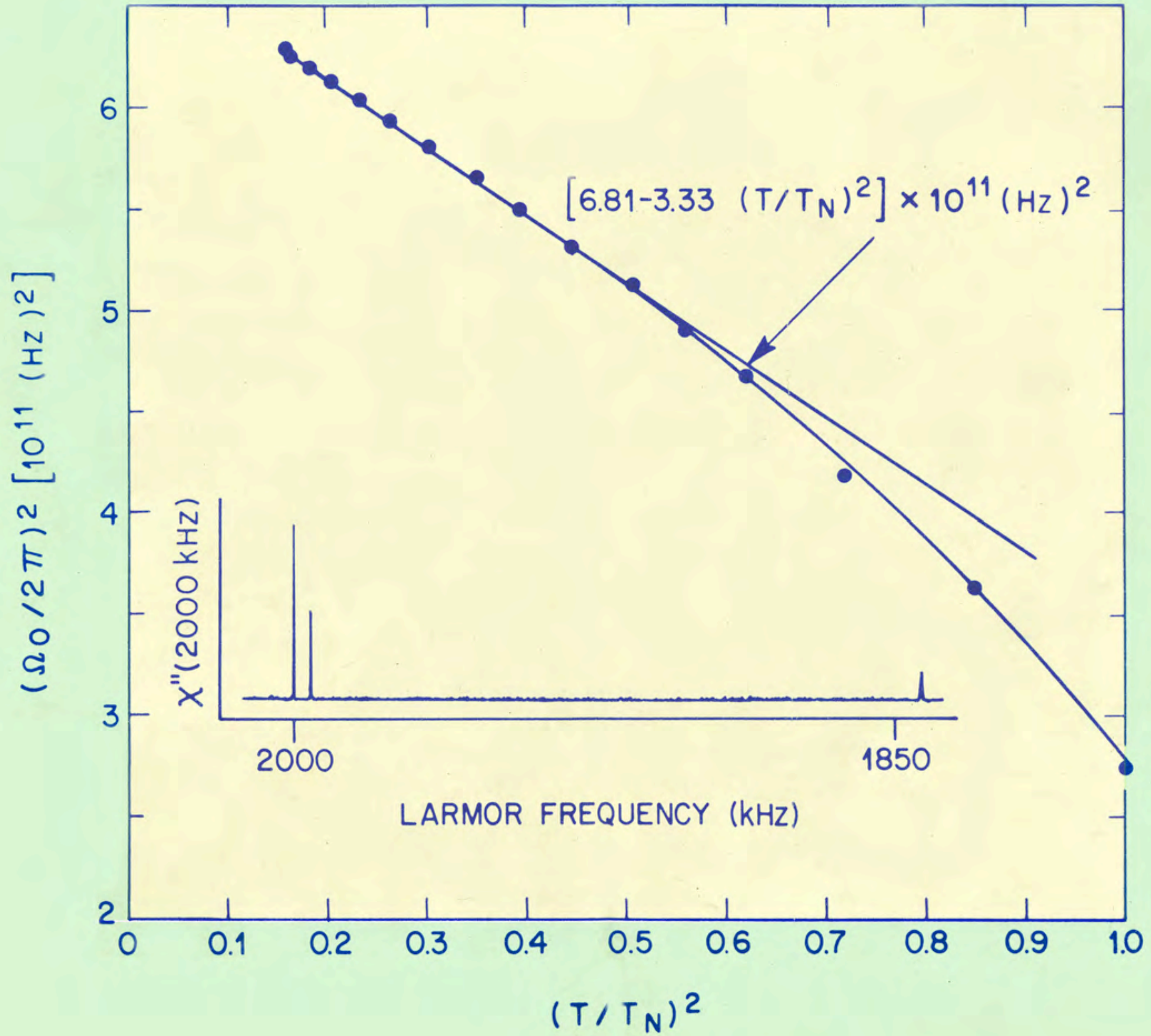
The U2D2 Phase of Solid ^{3}He

(after Star Wars' R2D2)



D.D. Osheroff, M.C. Cross and D.S. Fisher
Phys. Rev. Letts. 44, 792 (1980).


California
HE3 U2D2
CIVIC
HYBRID
GASOLINE-ELECTRIC



[6.81-3.33 (T/T_N)^2] × 10^11 (Hz)^2
(Ω0/2π)^2 [10^11 (Hz)^2]
χ''(2000 kHz)
2000
1850
LARMOR FREQUENCY (kHz)
2
3
4
5
6
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
(T/T_N)^2

$$\Omega_0 = \left(\frac{\sum_{i=1}^{3} v_i^4 - v_L^2 \sum_{i=1}^{3} v_i^2}{\sum_{i=1}^{3} v_i^2 - 2\, v_L^2} \right)^{1/2}$$

$$\cos^2 \Gamma_i = \frac{\left(v_i^2 - \Omega_0^2\right)\left(v_i^2 - v_L^2\right)}{\Omega_0^2\, v_L^2}$$

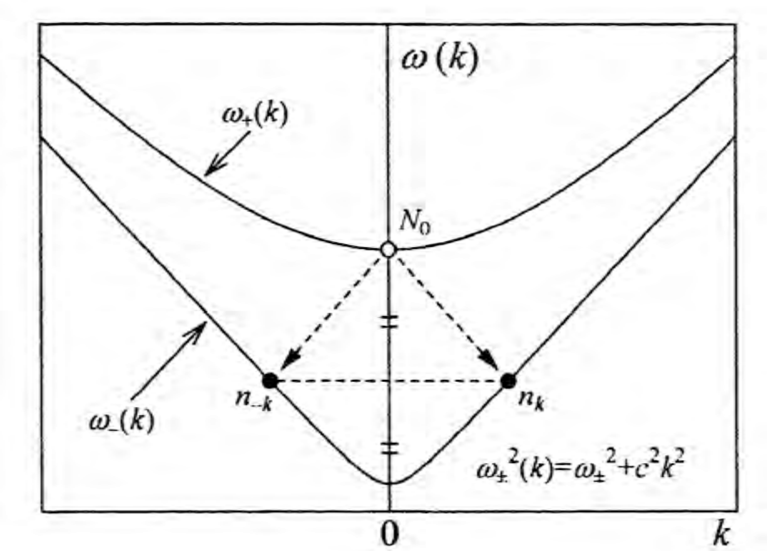
$$\Omega_0 = \left(\frac{v_i^2 \left(v_i^2 - v_L^2\right)}{v_i^2 - v_L^2 \left(1 - \cos^2 \Gamma_i\right)} \right)^{1/2}$$

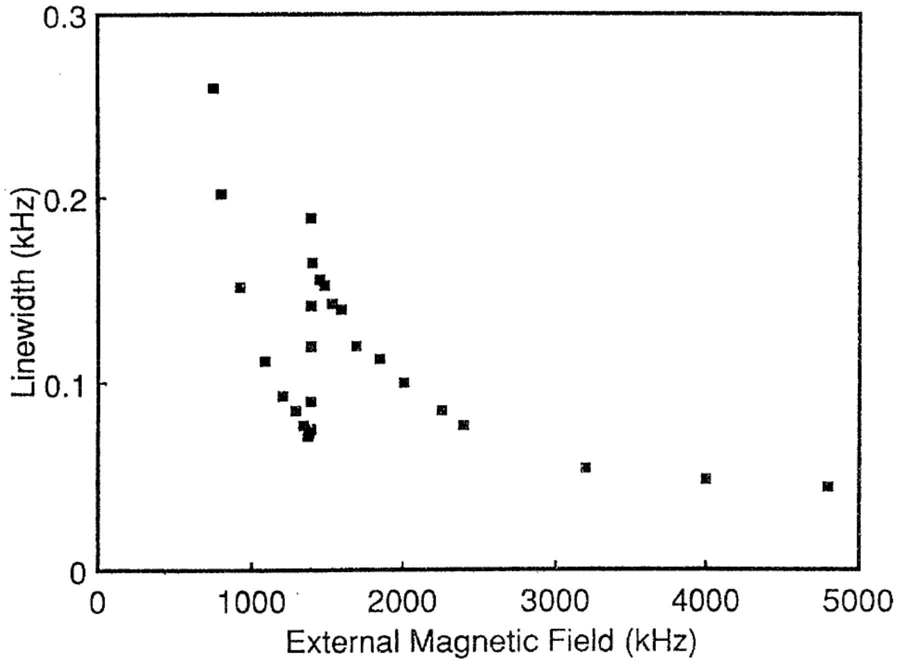
Three Magnon Decay Processes

- A magnon from the upper branch ($\omega > \gamma H$) can decay into two magnons in the lower branch provided energy and quasi-momentum can be conserved.

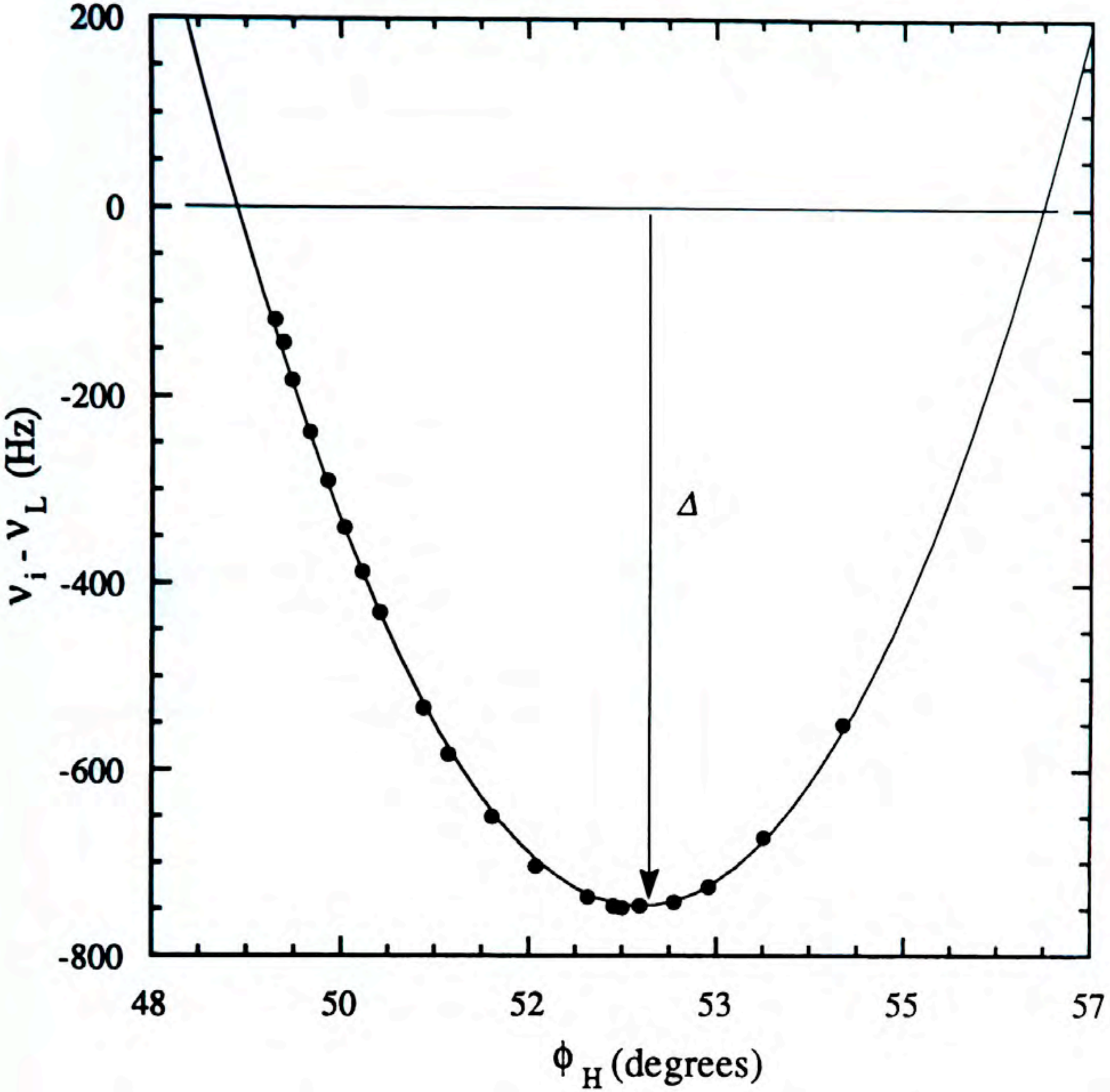
- For uniform spin precession in the upper branch, this loss is manifested by an abrupt broadening of the NMR line as shown.

$$\begin{cases} \dot{\boldsymbol{S}} = \gamma \boldsymbol{S} \times \boldsymbol{H} - \lambda(\boldsymbol{d} \bullet \boldsymbol{l})(\boldsymbol{d} \times \boldsymbol{l}) \\ \dot{\boldsymbol{d}} = \boldsymbol{d} \times \left(\gamma \boldsymbol{H} - \dfrac{\gamma^2}{\chi_\perp} \boldsymbol{S} \right) \end{cases}$$





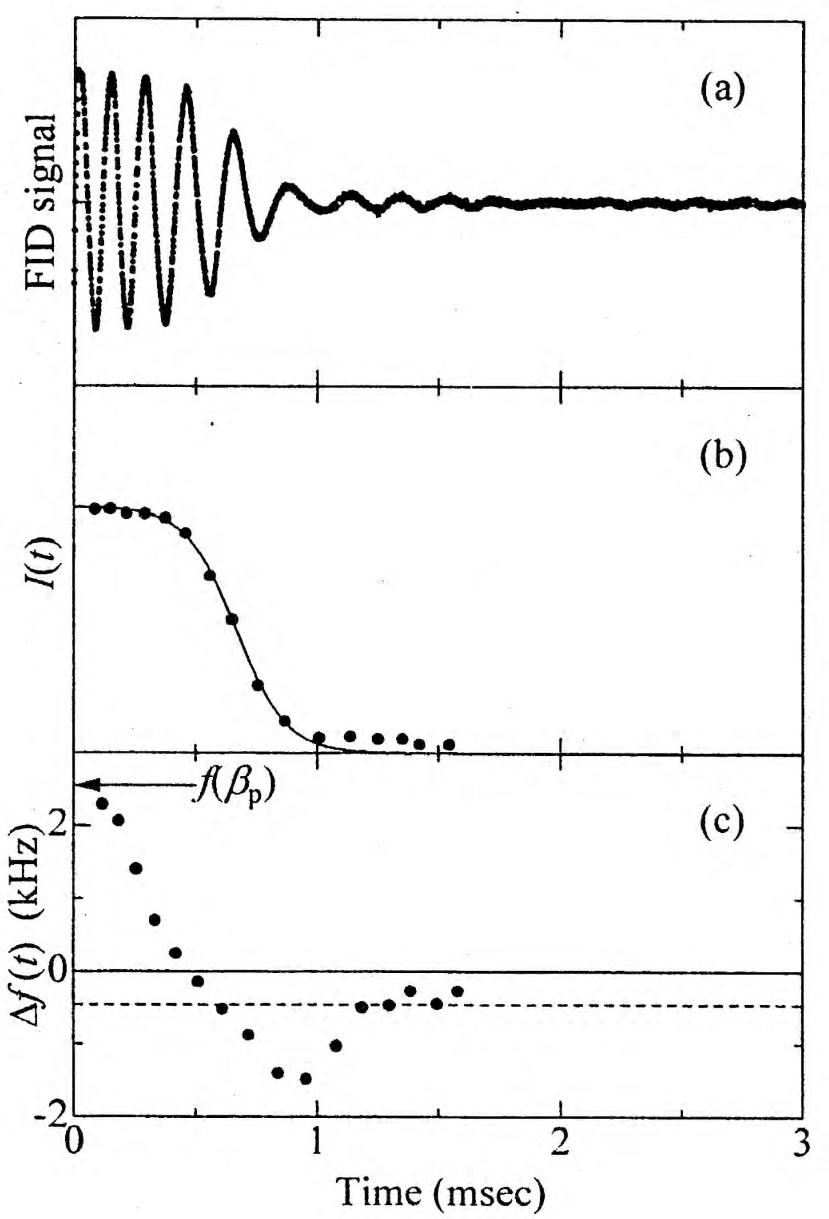
Thanks to Takao Mizusaki



200
0
-200
-400
-600
-800
$\nu_i - \nu_L$ (Hz)
Δ
48
50
52
53
55
57
ϕ_H (degrees)

Three Magnon Decay Processes

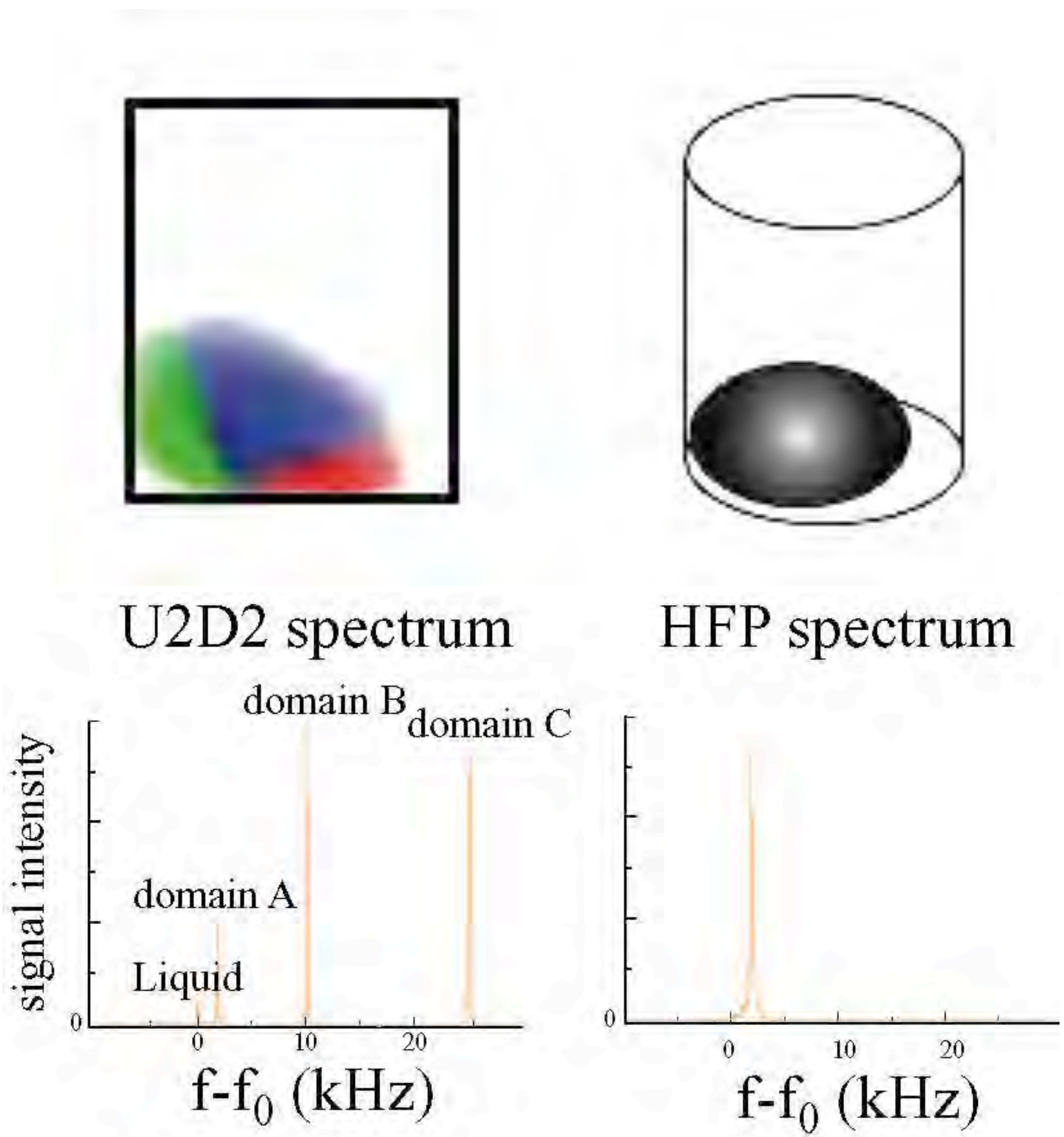
- Rapid three magnon decay from the upper frequency mode due to stimulated emission.
- Ohmi and Fomin showed that population of lower magnon mode produces a negative frequency shift in the upper mode.
- Non-linear spin dynamics in the U2D2 phase are complex but based on simple Hamiltonian.



Mizusaki et al: J. Low Temp. Phys. **89** 365-373 (1992)

Thanks to Takao Mizusaki

Domain Memory Between U2D2 and CNAF Phases

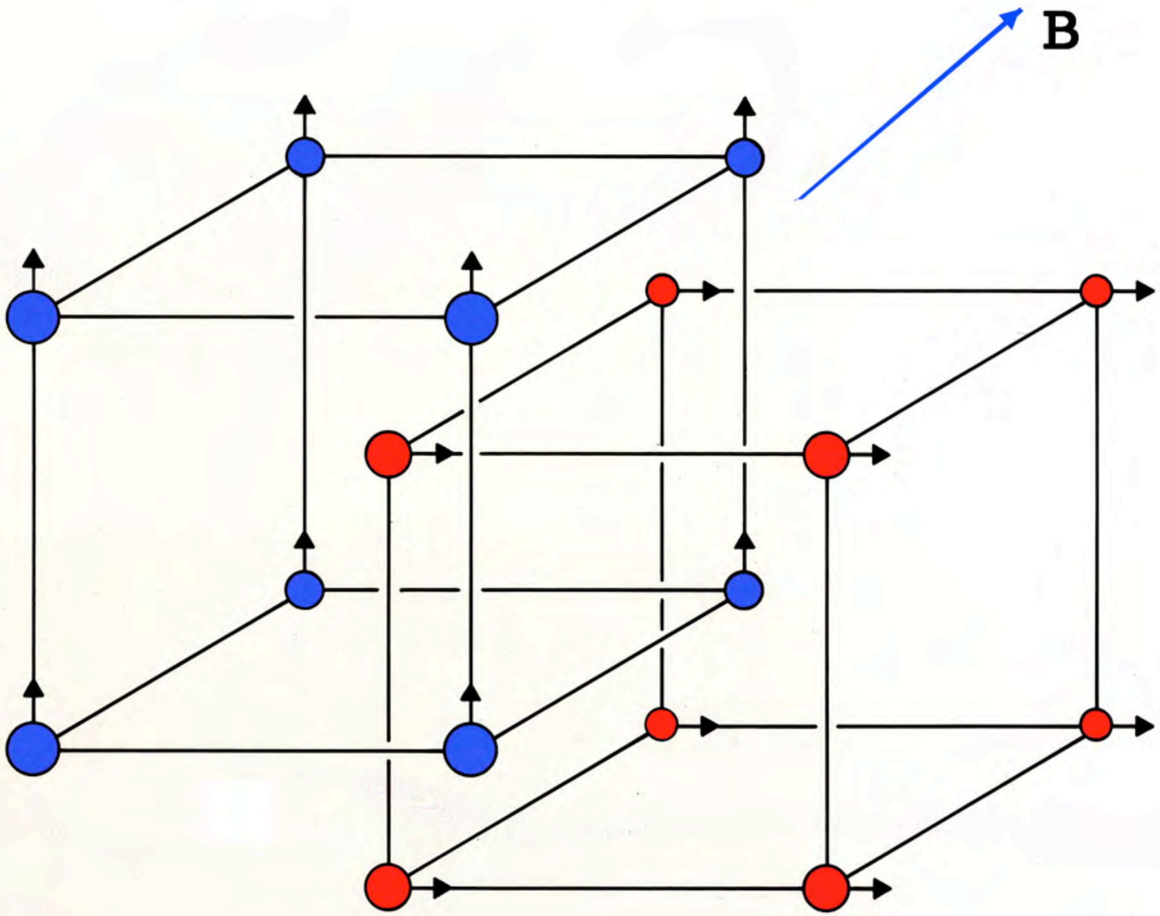


- Grow a 3-domain U2D2 sample near lower critical field.
- Measure the intensity from the three domains.
- Slowly raise magnetic field into the CNAF field Region, wait, and then lower the field back.
- Measure the intensity in the three domains again.
- For constrained xls domains are the same. For unconstrained samples, they are very different.

Mizusaki et al. (J. Low Temp. Phys. **127**, 1-10 (2002)

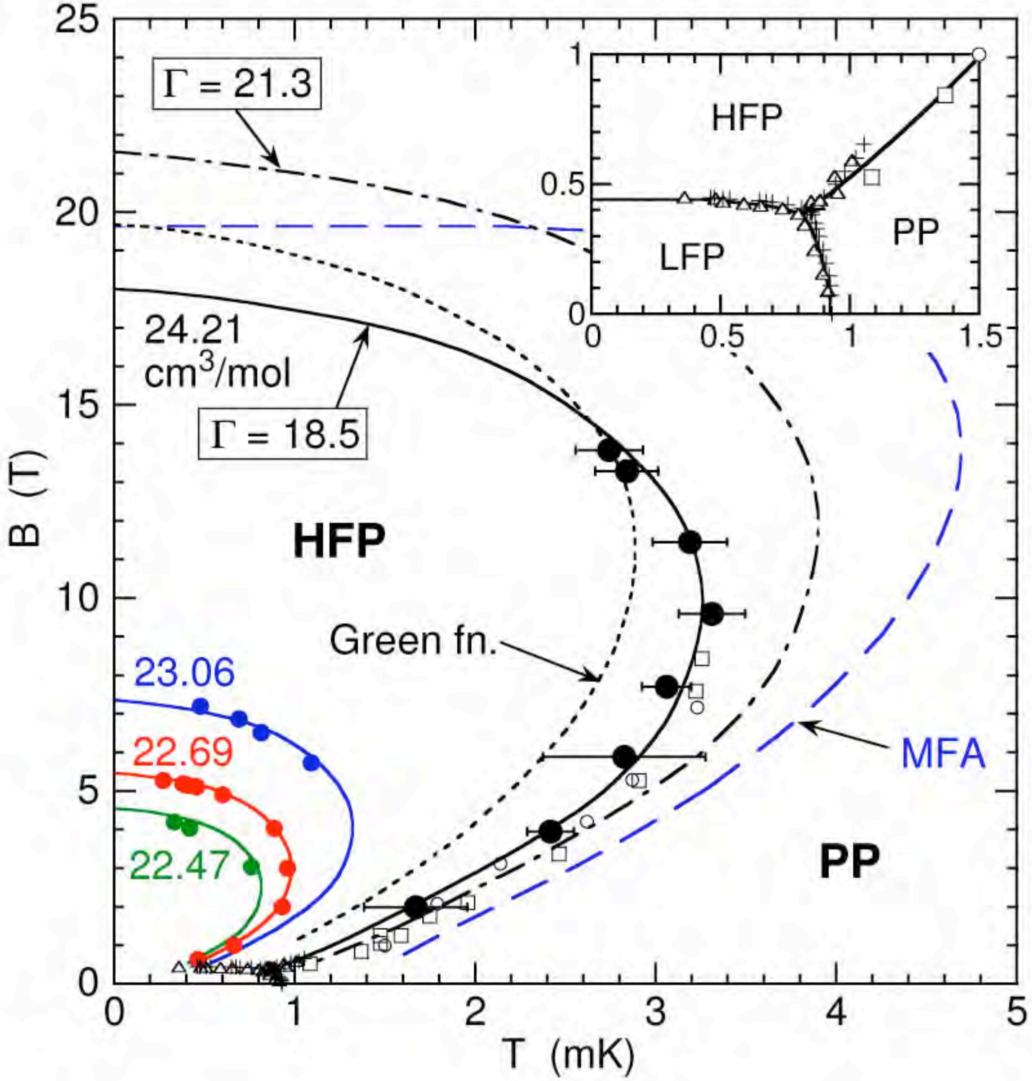
Thanks to Takao Mizusaki

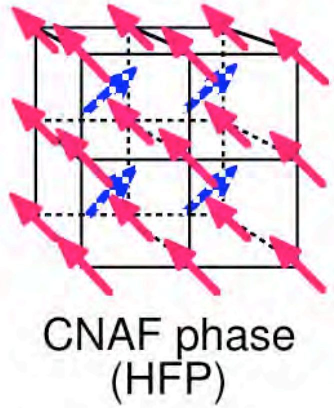
The CNAF Phase of Solid ^{3}He

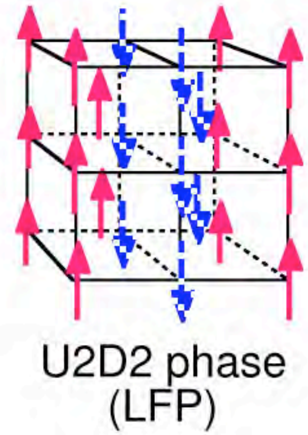


Jack Hetherington

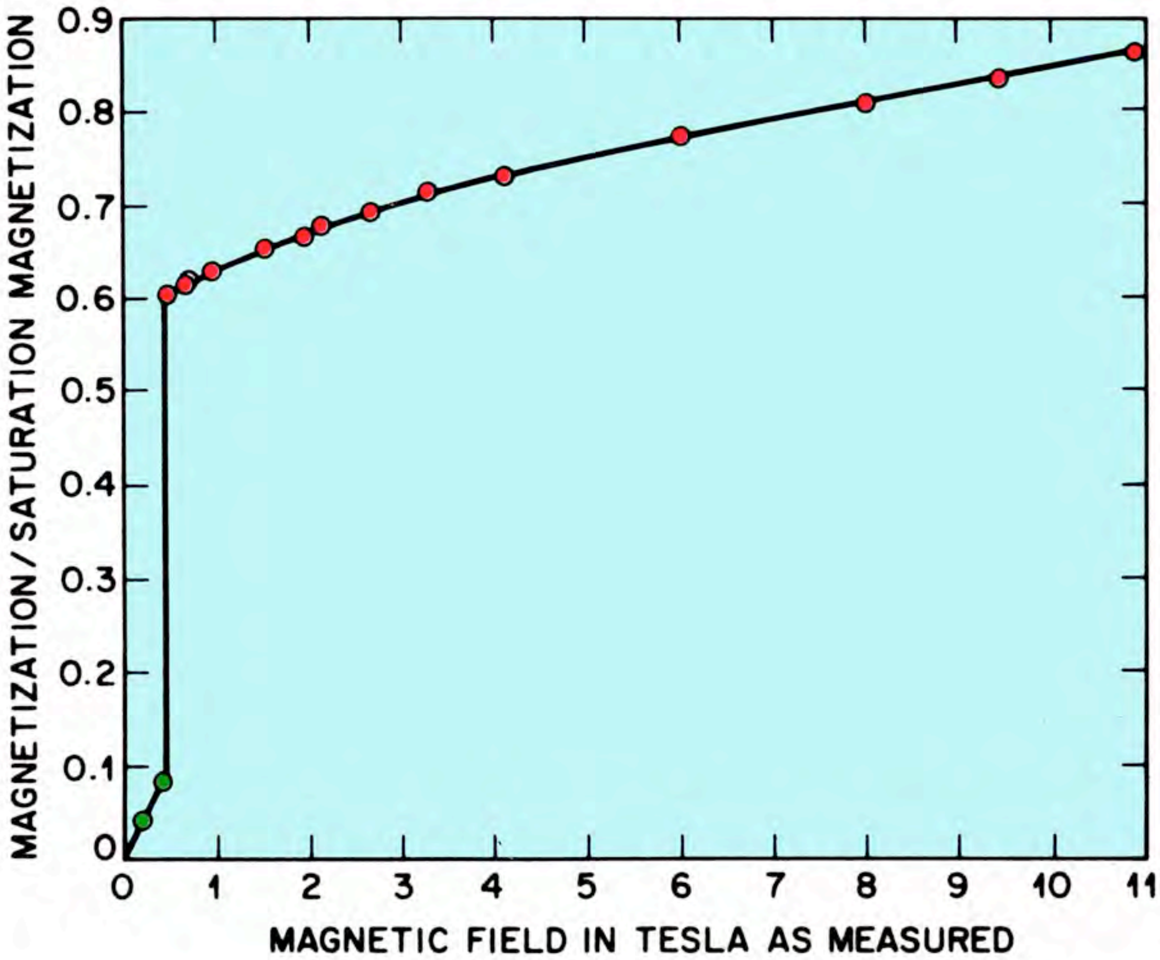
Thanks to Hiroshi Fukuyama





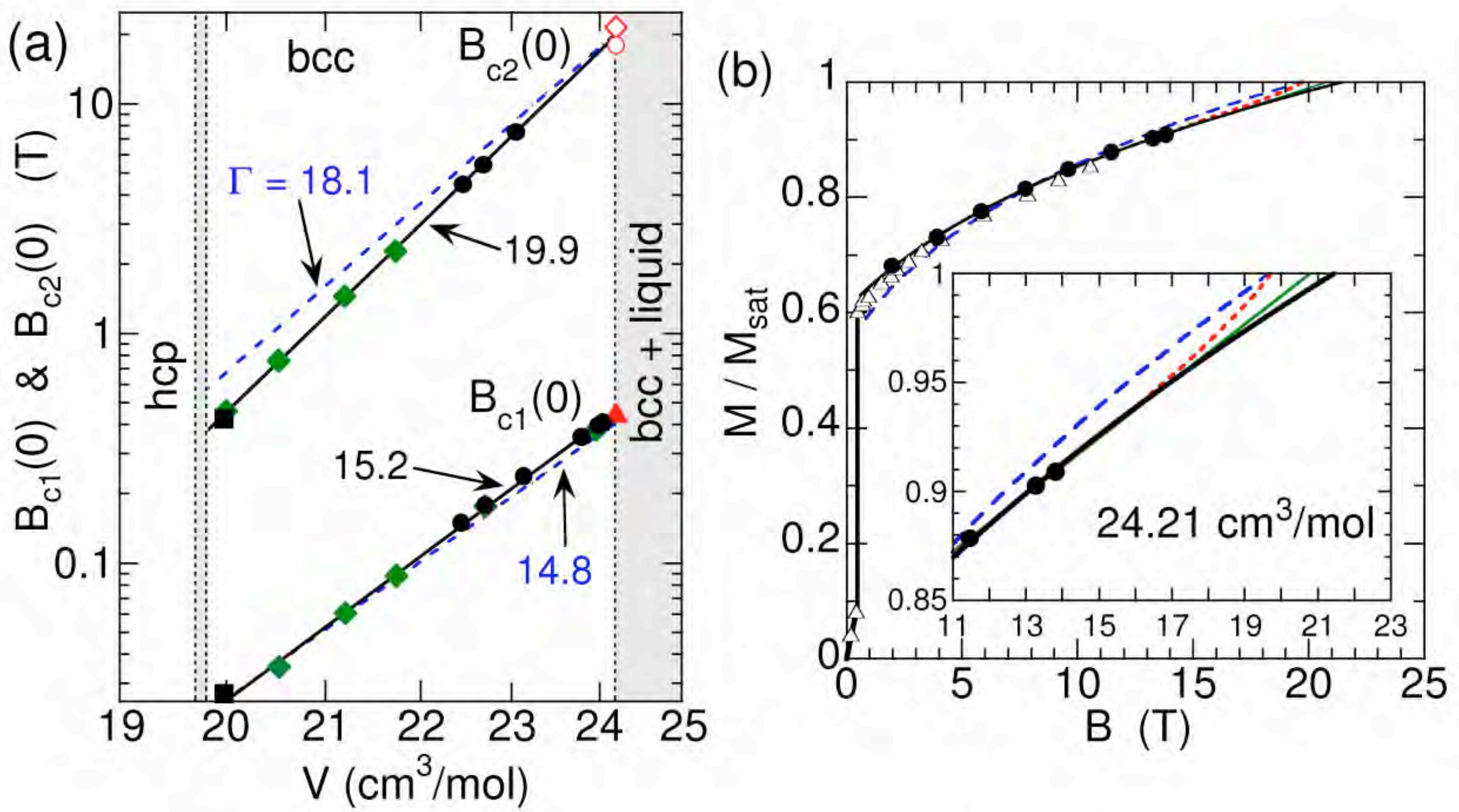


T=0 Solid ^{3}He Magnetization



Henri Godfrin and David Ceperley and later Hiroshi Fukuyama

Thanks to Hiroshi Fukuyama



- Change magnetic field by a small well known amount.
- Change in melting pressure just compensates for the change in liquid and solid free energies.

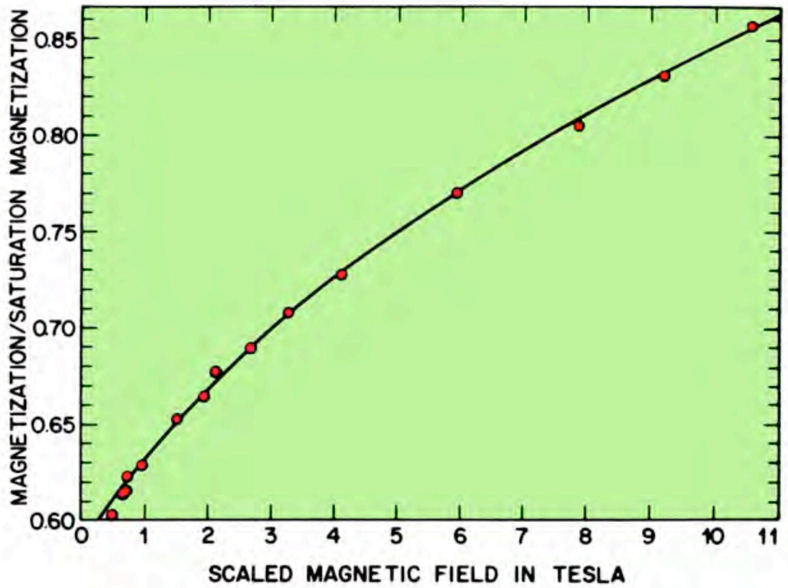
- Calculate solid magnetization

- Express magnetization in terms of magnetic field scaled to change in molar volume from change in P.

- Express magnetiation in terms of exchange frequencies.

D.D. Osheroff, H. Godfrin and R. Ruel
Phys. Rev. Letts. 58, 2458 (1987).

CNAF Magnetization Fit



$$H = -(9.1 \pm .6)m + (23.8 \pm 2)m^3 + (7.6 \pm 2)m^5$$

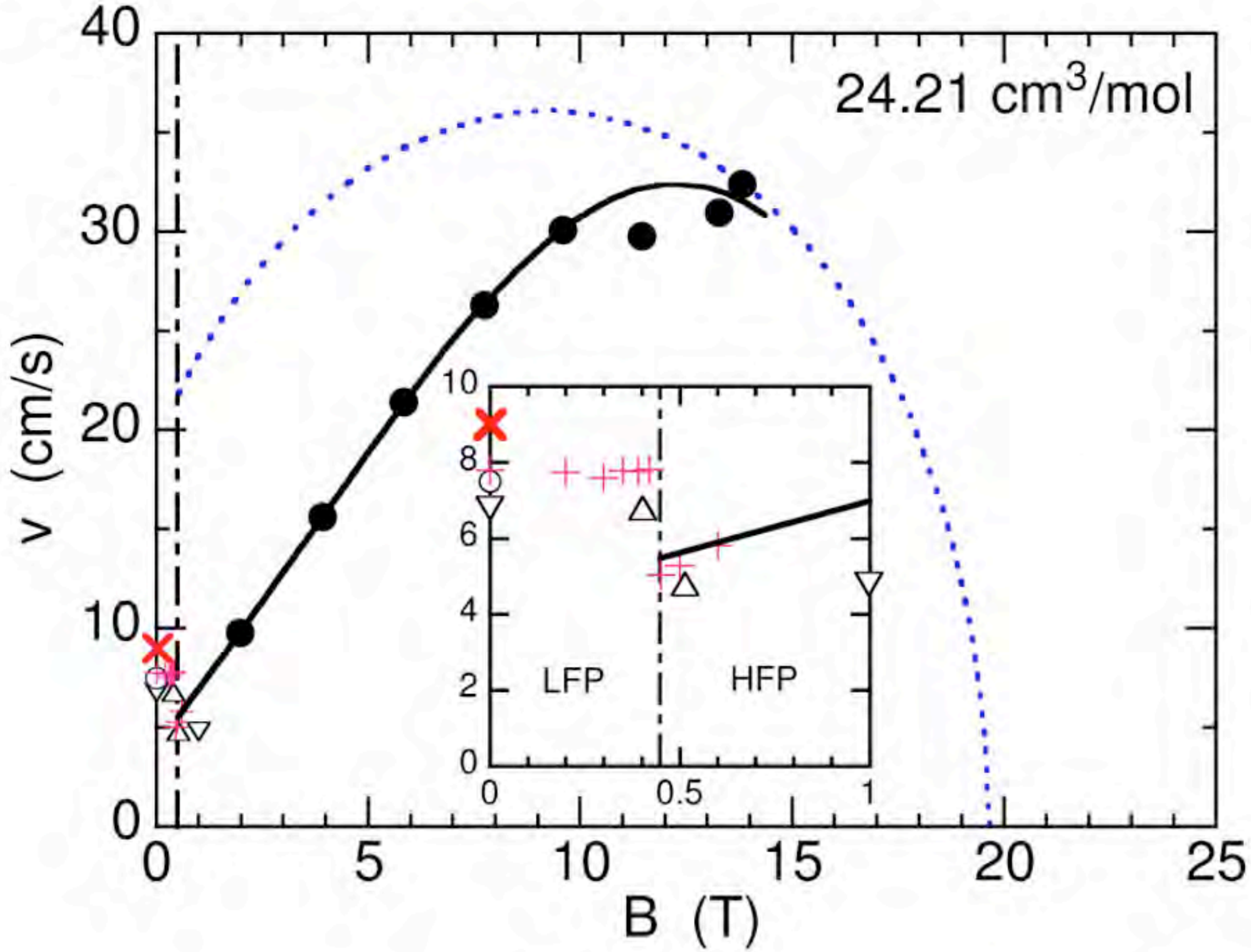
$H_{C2} = 22.3$ T

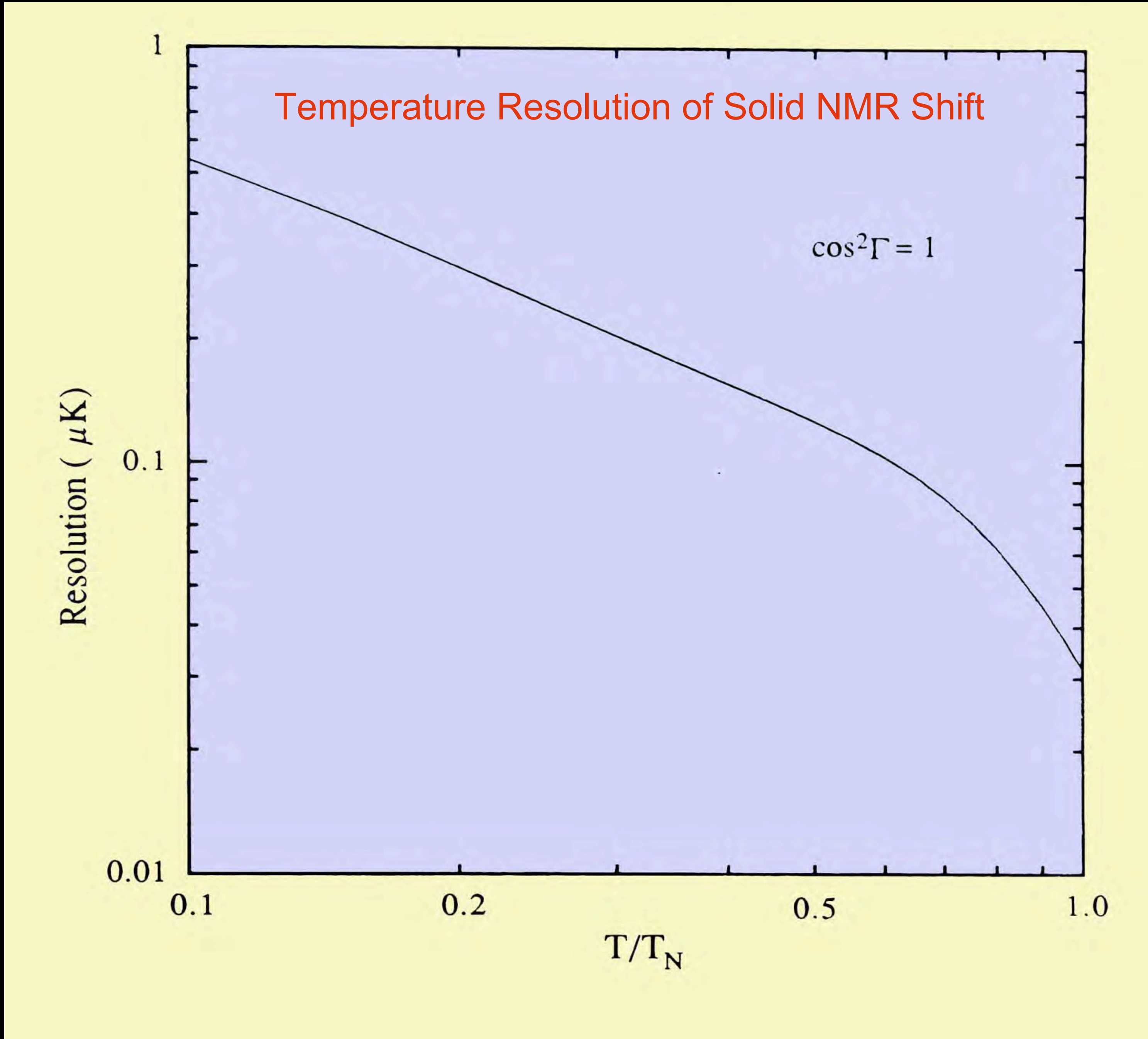
From Ceperley-Jacucci exchange terms:

$H_{C2} = 20.5$ T

$$H = -(6.0 \pm 1.4)m + (19.7 \pm 2)m^3 + (6.8 \pm 2)m^5$$

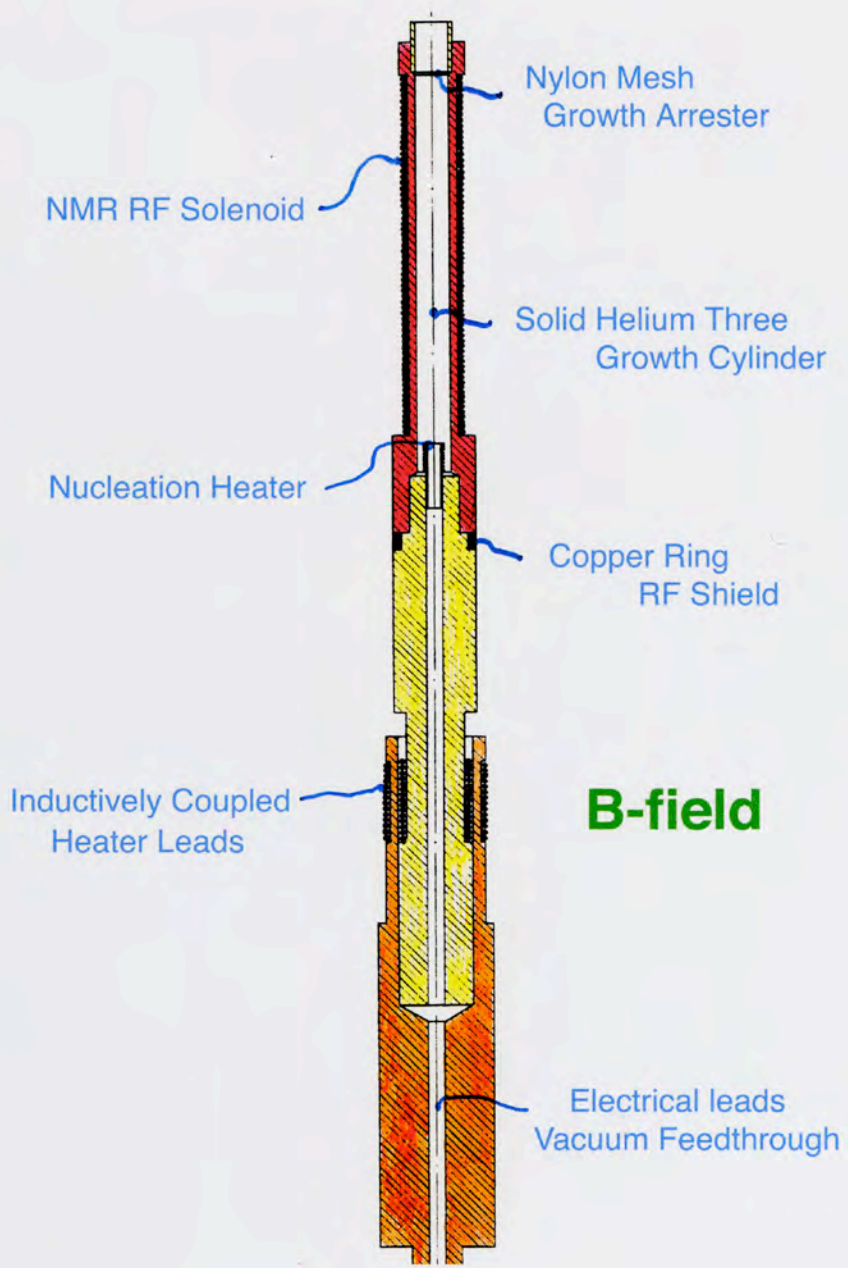
Thanks to Hiroshi Fukuyama

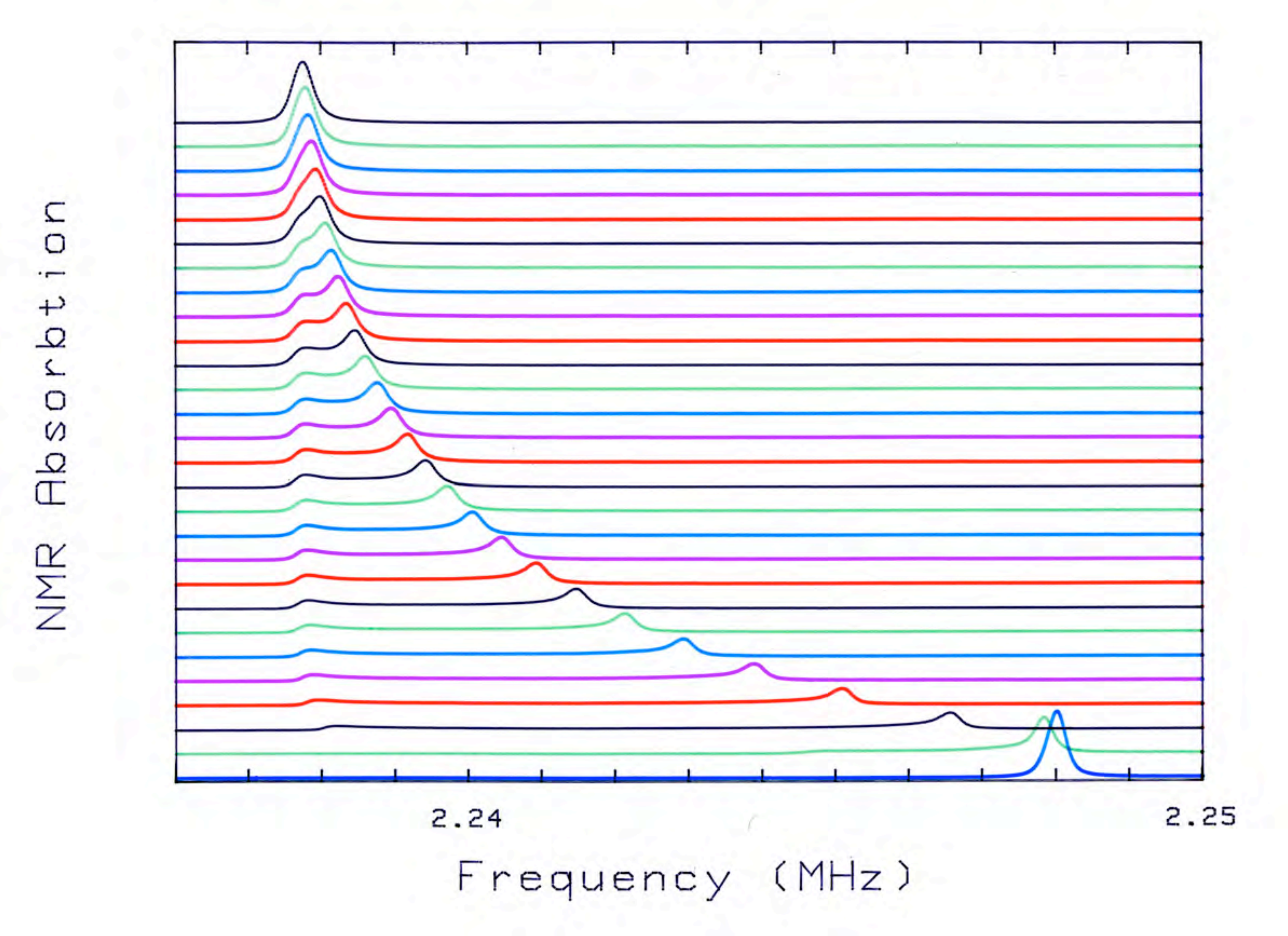


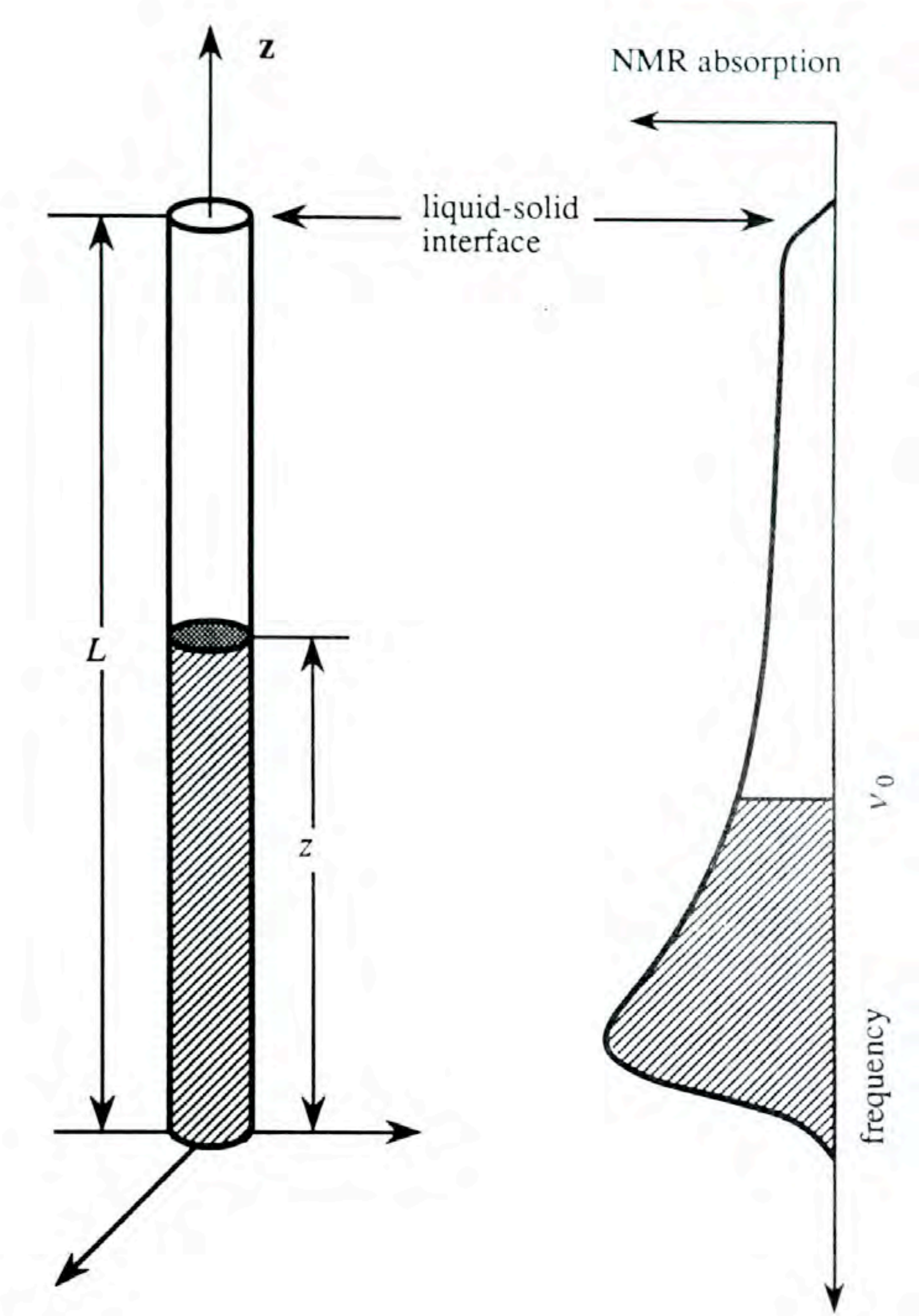


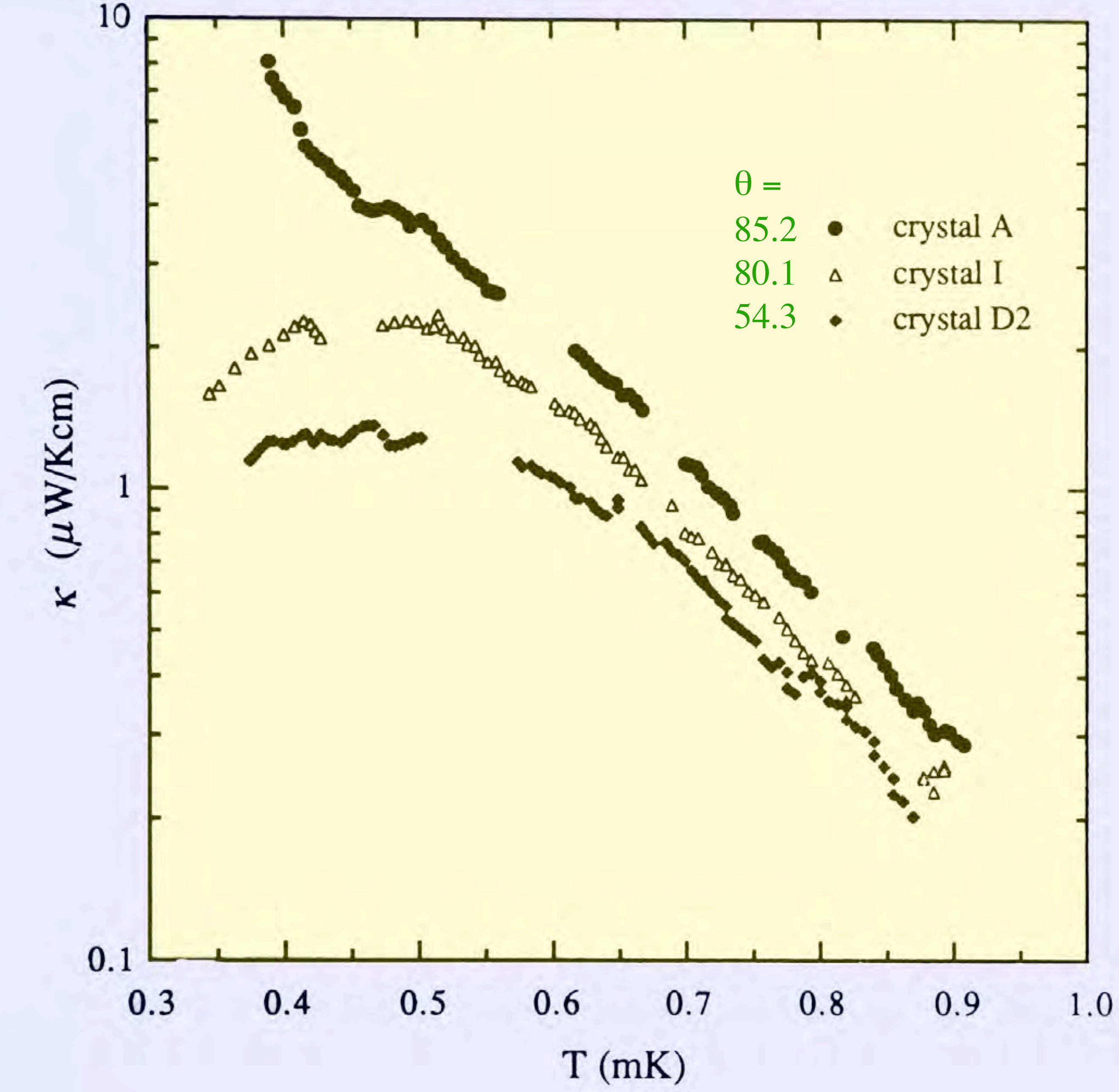
Temperature Resolution of Solid NMR Shift
cos²Γ = 1
Resolution (μK)
1
0.1
0.01
0.1
0.2
0.5
1.0
T/T_N

Magnon Diffusivity Cell

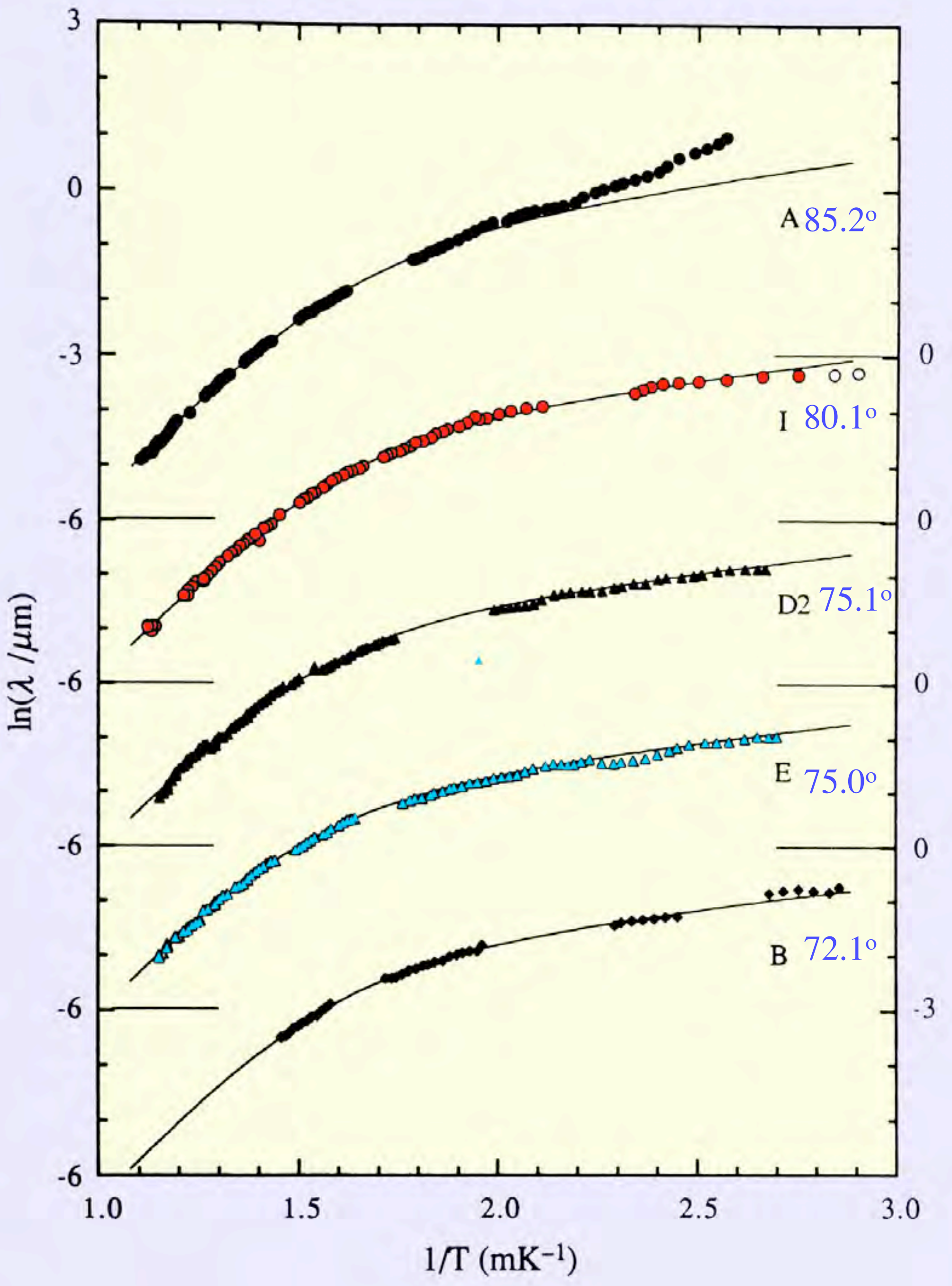



NMR Absorbtion
2.24
2.25
Frequency (MHz)


z
NMR absorption
liquid-solid
interface
L
z
ν_0
frequency



10
1
0.1
κ (μW/Kcm)
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
T (mK)
θ =
85.2 crystal A
80.1 crystal I
54.3 crystal D2



3
0
-3
-6
-6
-6
-6
-6
ln(λ /μm)
0
0
0
0
-3
A 85.2°
I 80.1°
D2 75.1°
E 75.0°
B 72.1°
1.0
1.5
2.0
2.5
3.0
1/T (mK⁻¹)

Conclusions:

BCC solid ^{3}He has been a remarkably fruitful system for understanding spin ordering due to particle exchange. Two very different nuclear spin ordered phases coexist over a narrow range of magnetic field. One phase exhibits rich antiferromagnetic resonance spectra while the other allows us to rather directly determine the importance of various ring exchange

Thank You for your attention!