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SMR.998a - 2

Research Workshop on Condensed Matter Physics
30 June - 22 August 1997
MINIWORKSHOP ON
QUANTUM MONTE CARLO SIMULATIONS OF LIQUIDS AND SOLIDS
30 JUNE - 11 JULY 1997
and
CONFERENCE ON
QUANTUM SOLIDS AND POLARIZED SYSTEMS
3 - 5 JULY 1997

"Magnetic Ordering in High-Density Solid ^{3}He"

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

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Magnetic Ordering in High-Density Solid ^{3}He

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Microkelvin Laboratory

Outline

1. Background

2. Exchange in bcc and hcp ^{3}He

3. Prior results, comparison of T & E

4. Cascade demagnetization (Cu, ^{3}He)

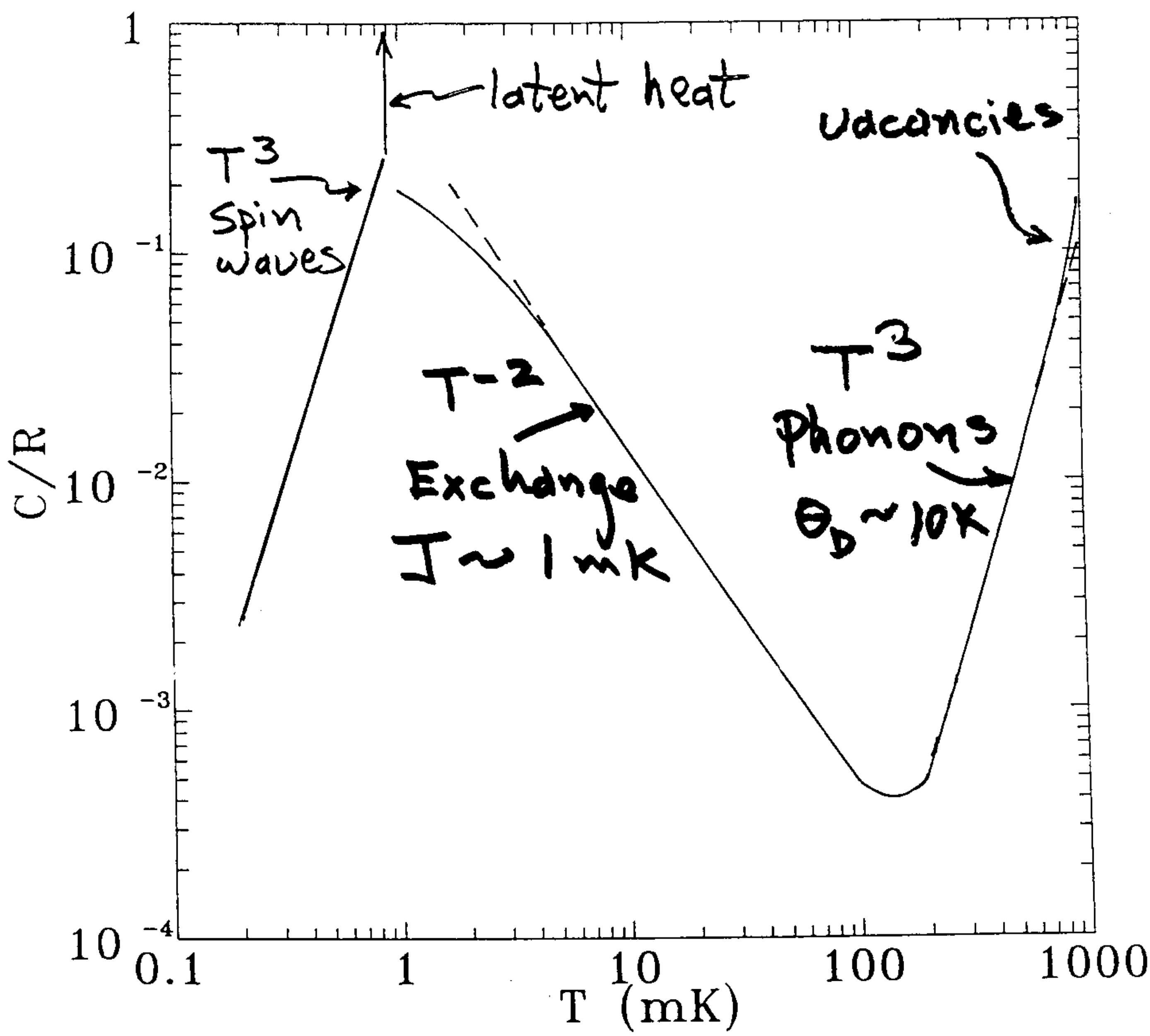
5. bcc results

6. hcp results

7. Conclusions

Supported by National Science Foundation

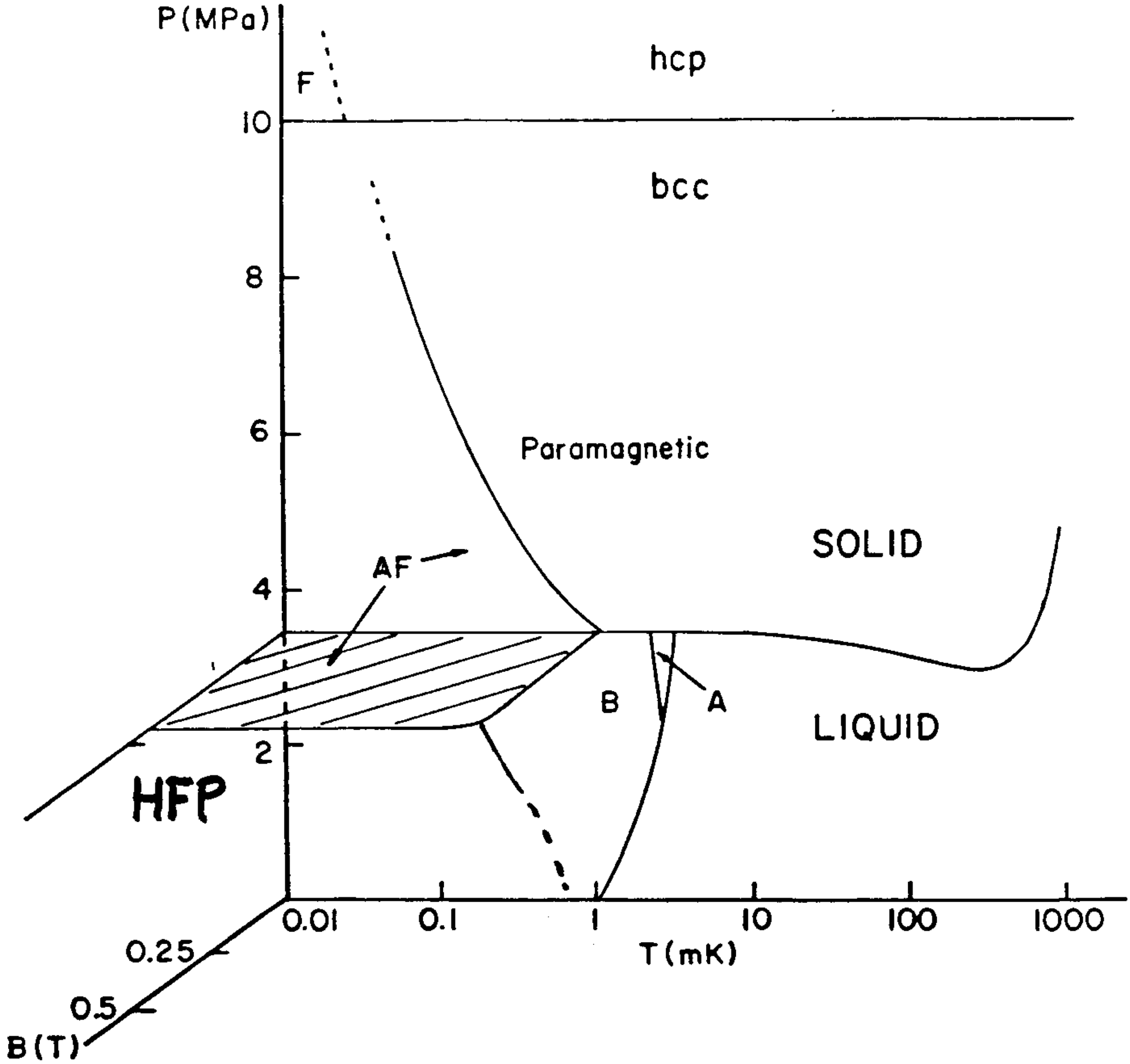
Excitation in Solid ^{3}He



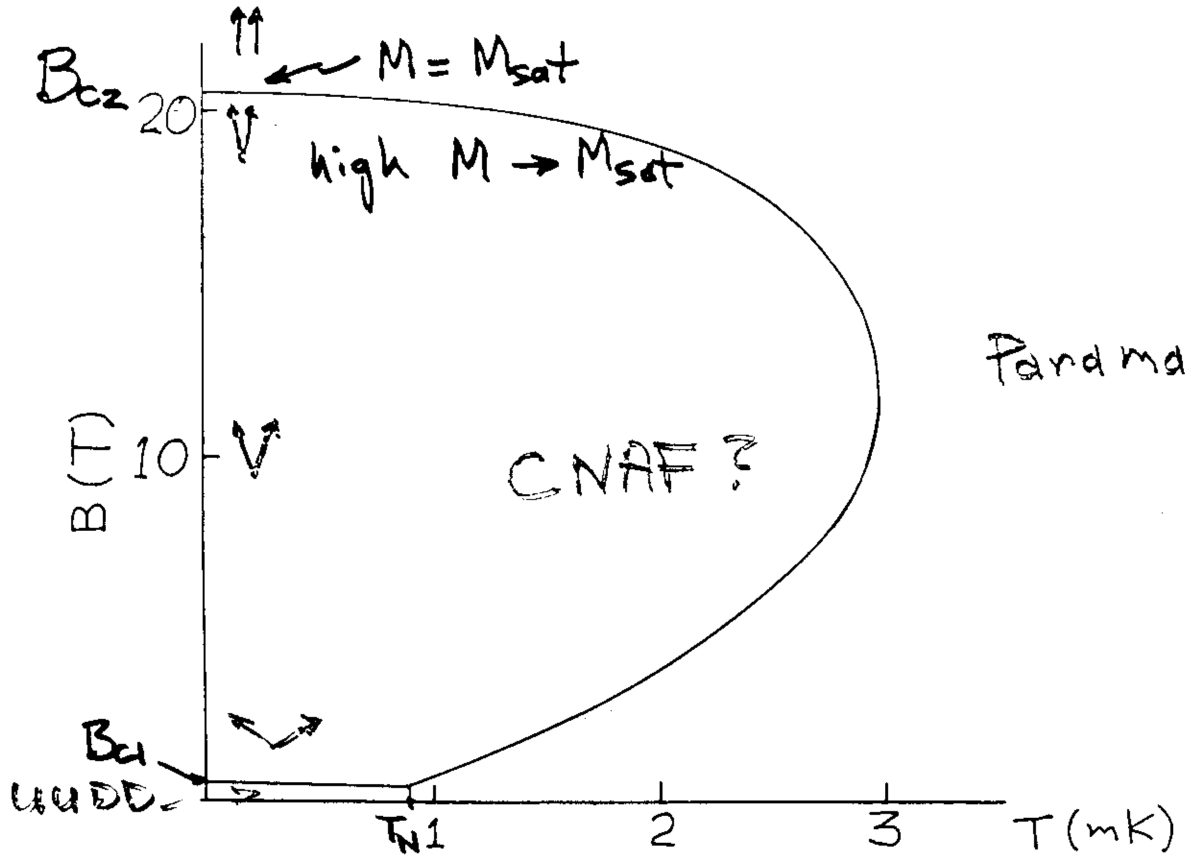
$$\mathcal{H} = \mathcal{H}_{ph} + \mathcal{H}_{ex} + \mathcal{H}_{Zm} + \mathcal{H}_d$$

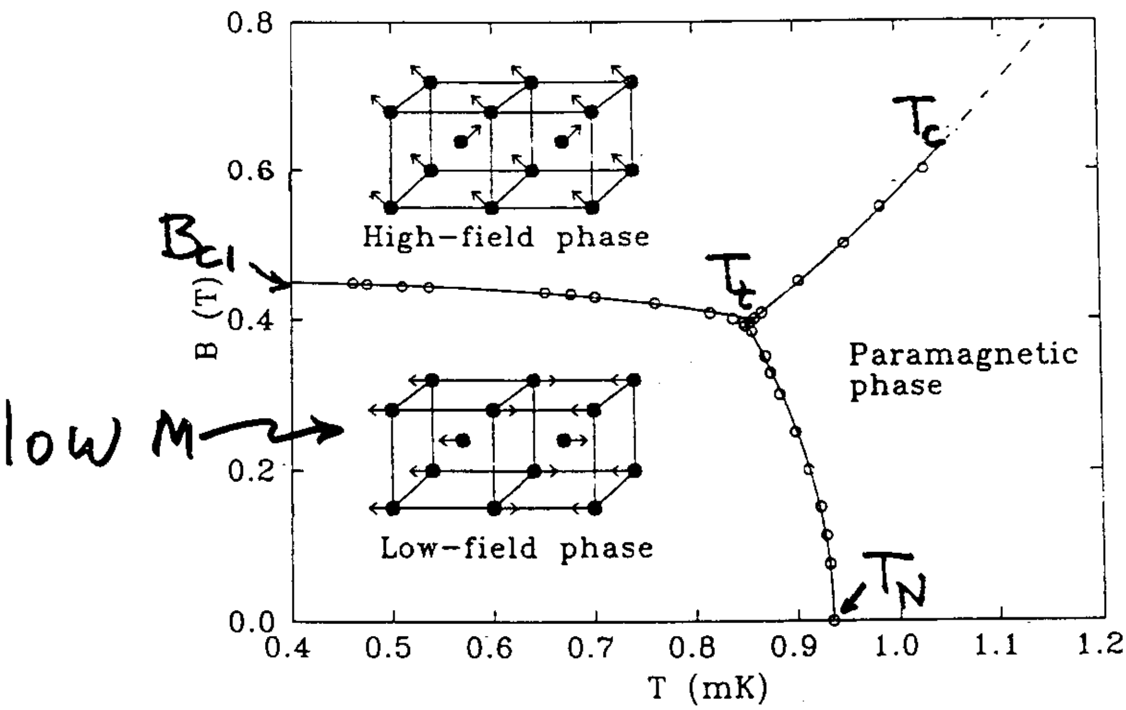
10K 1 mK 0.7 mK (B = 1 T) 100 nK

P-T-B Phases of ^{3}He



B-T Phases of Solid ^{3}He ($v = 24.2$ cm^3/mole)

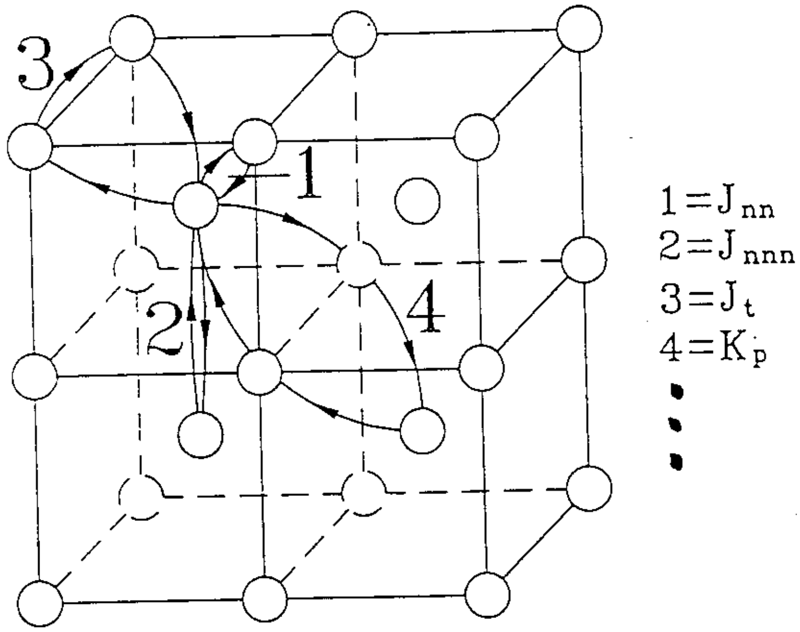


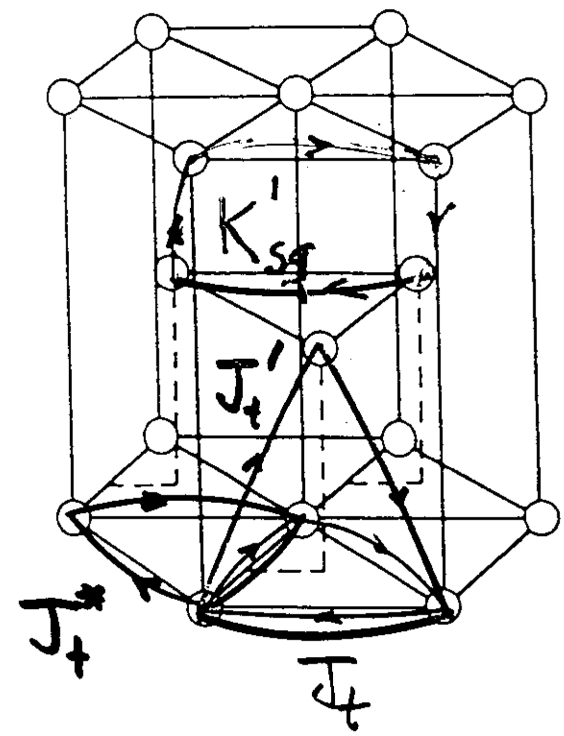


$$\frac{\partial \ln T_N}{\partial \ln v} \approx \frac{\partial \ln B_{c2}}{\partial \ln v} \approx 18, \quad \frac{\partial \ln B_{c1}}{\partial \ln v} \approx 16$$

Multiple Exchange in ^{3}He

bcc:
antiferro.
$0.9\,mK > T_N > 30\,\mu K$





hcp:
ferromagnetic
(expected)
$T_c \gtrsim 20\,\mu K$
not shown:
$J_{nn}, J'_{nn} \cdots$

Exchange Hamiltonian, High-T Expansion

$$H_{exchange} = \tilde{J}_1 \sum_{i<j}^{(1)} P_{ij} + \tilde{J}_2 \sum_{i<j}^{(2)} P_{ij} + K \sum_{i<j<k<l} (P_{ijkl} + P_{ijkl}^{-1}) + \cdots$$

bcc	hcp
$\tilde{J}_1 = J_{nn} - 6J_t$	$\tilde{J}_1 = J_{nn} - J_t - 2J_t'$
$\tilde{J}_2 = J_{nnn} - 4J_t$	$\tilde{J}_2 = J_{nn}' - 4J_t'$
$K = K_p$	$K = K_{sq}'$

Susc: $\chi = C/(T - \theta_w + B/T + \cdots)$

$$\text{where } k_B\theta_w = \begin{cases} 4\tilde{J}_1 + 3\tilde{J}_2 + 18K_p & \text{bcc} \\ 3\tilde{J}_1 + 3\tilde{J}_2 + 9K_{sq}' & \text{hcp} \end{cases}$$

$$\text{Pressure: } P = R\left(\frac{\partial\theta_w}{\partial v} \frac{p^2}{2} + \frac{\partial K}{k_B \partial v} \frac{3p^4}{2} \right) + \cdots$$

where $p = \tanh x$, $x = \hbar\gamma B / 2k_B T$

Entrophy: $S = R\,[\ln(2\cosh x) - x\tanh x]$

Calculated Exchange Parameters
(Ceperley and Jacucci, Monte Carlo)

bcc, v = 24.22 cm^3/mole

Type of exchange	Exchange frequency (mK)
J_{1N}	-0.487±0.015
J_{2N}	-0.067±0.005
T_1	-0.193±0.010
T_2	-0.0057±0.0009
K_P	-0.269±0.016
K_F	-0.034±0.004
K_A	-0.0065±0.0016
K_B	-0.00054±0.00025
K_L	-0.012±0.0035
K_S	-0.0020±0.0006
F	-0.0016±0.0002
S_1	-0.037±0.008
S_2	-0.0108±0.0011

hcp, v = 19.4 cm^3/mole

Type of exchange	Exchange Frequency (μK)
J_{nn}	- 2.4
J'_{nn}	- 3.3
J_T	- 4.8
J'_T	- 2.4
J^*_T	- 0.5
K'_{sq}	- 1.4

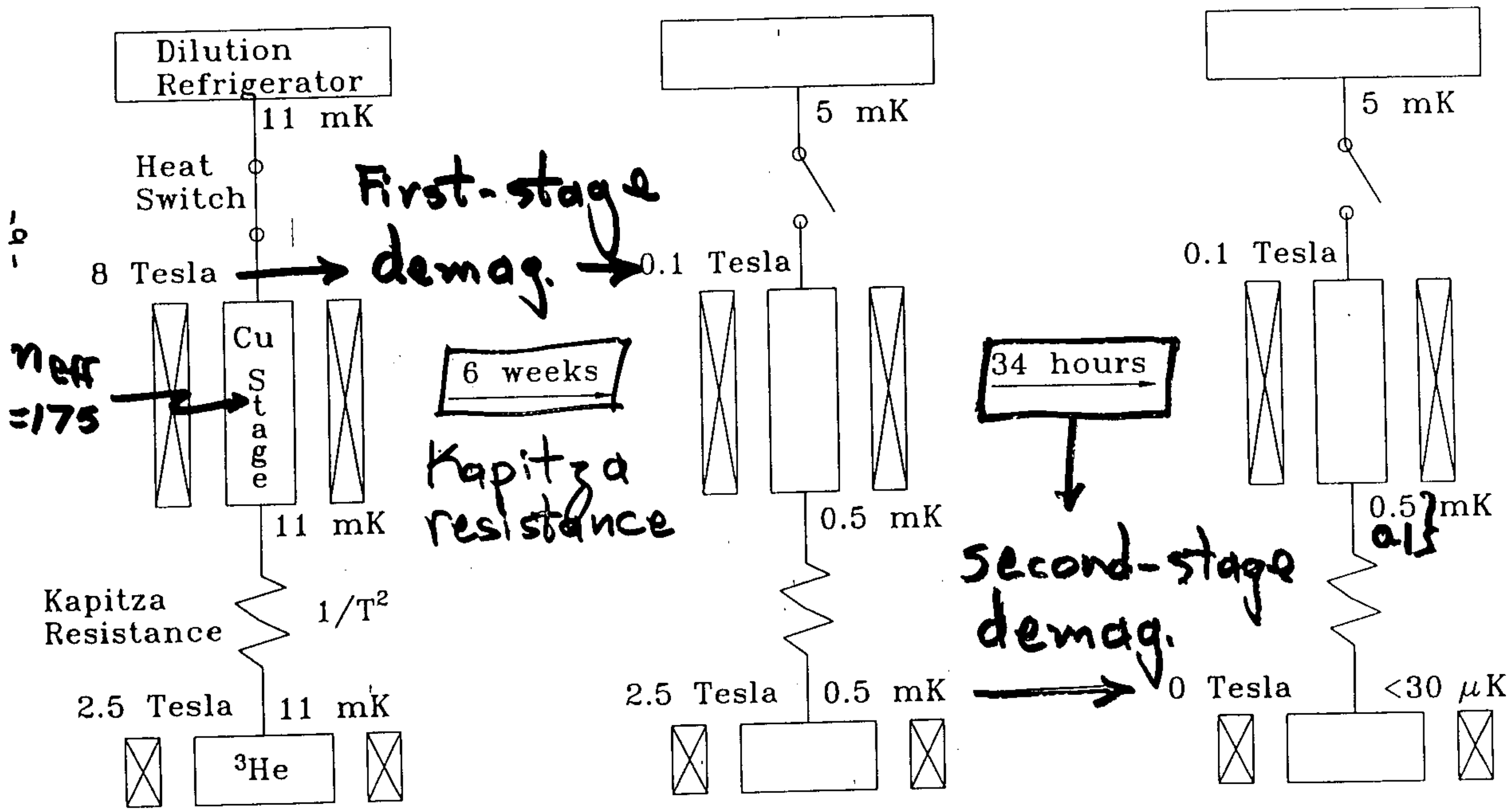
Comparison between Experiment and Theory
(bcc, v = 24.22)

Physical quantities	Experiment	Fit to[a] e_2, B_{C1}, T_N	Calculation[b] $J_{NN} \cdots S$
θ_w	-1.8±0.1	-2.17	-1.81
$e_2(C)$	6.8	6.80	
c_{spin}	7.8±0.4	7.80	8.05
$C_1/\chi_\perp$	3.84	4.61	4.06
T_N	0.934	(1.03)	1.2
T_t	0.850	0.994	
B_{C1}	0.452	0.436	0.76
B_t	0.390	0.376	
B_{C2}	(22.3)	14.66	21.2
T_C	1.15	1.062	
B_C	0.6	0.479	11

a - Stipdonk and Hetherington: 3-param, MF

b - Roger and Hetherington: 6-spin, CCA
Sun and Hetherington
Godfrin and Osheroff

Cascade Demagnetization: copper, Solid ^{3}He



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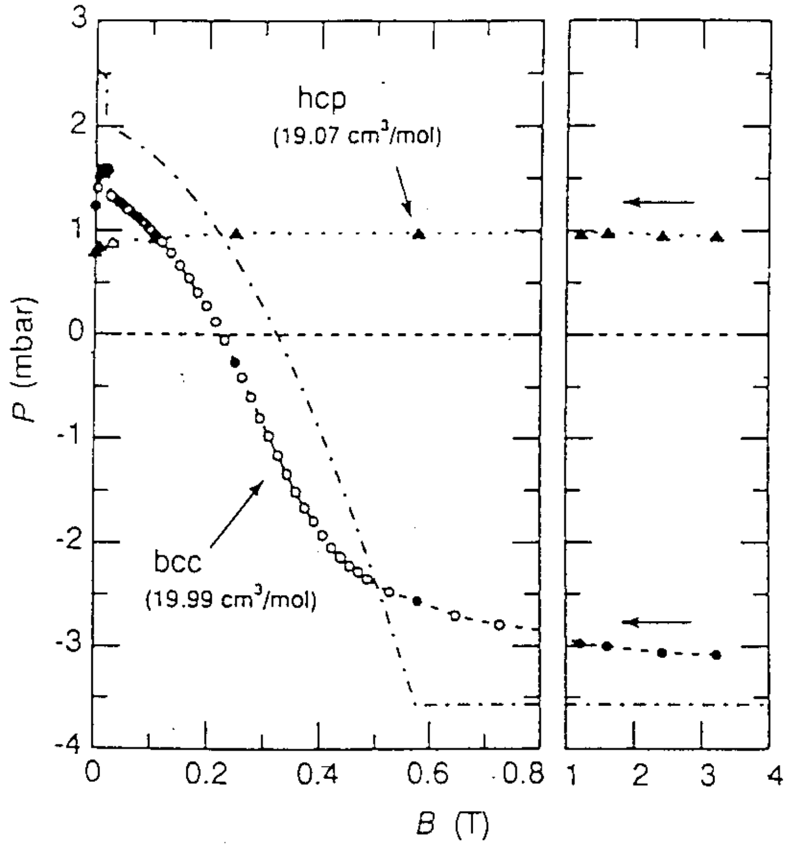
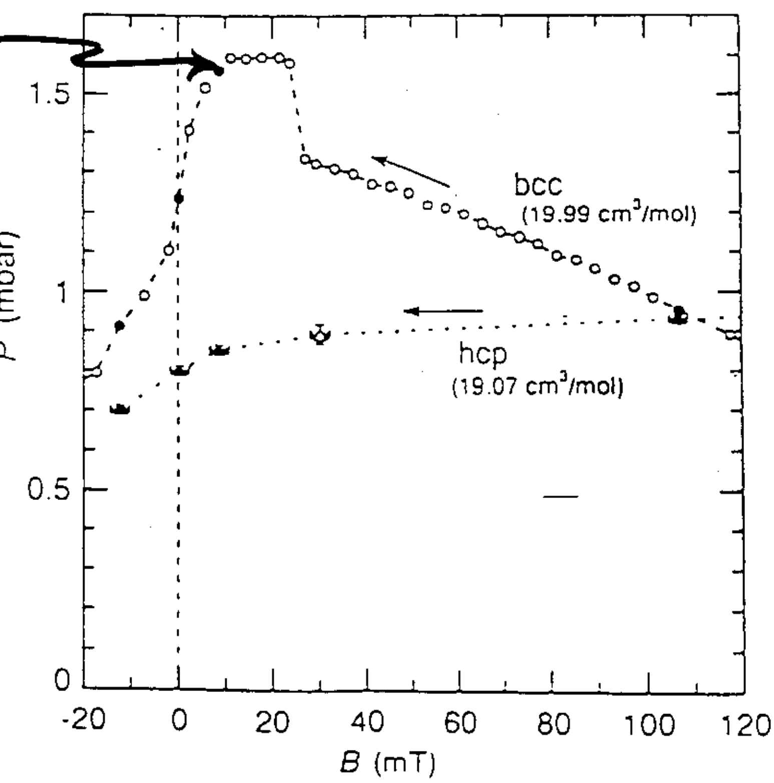
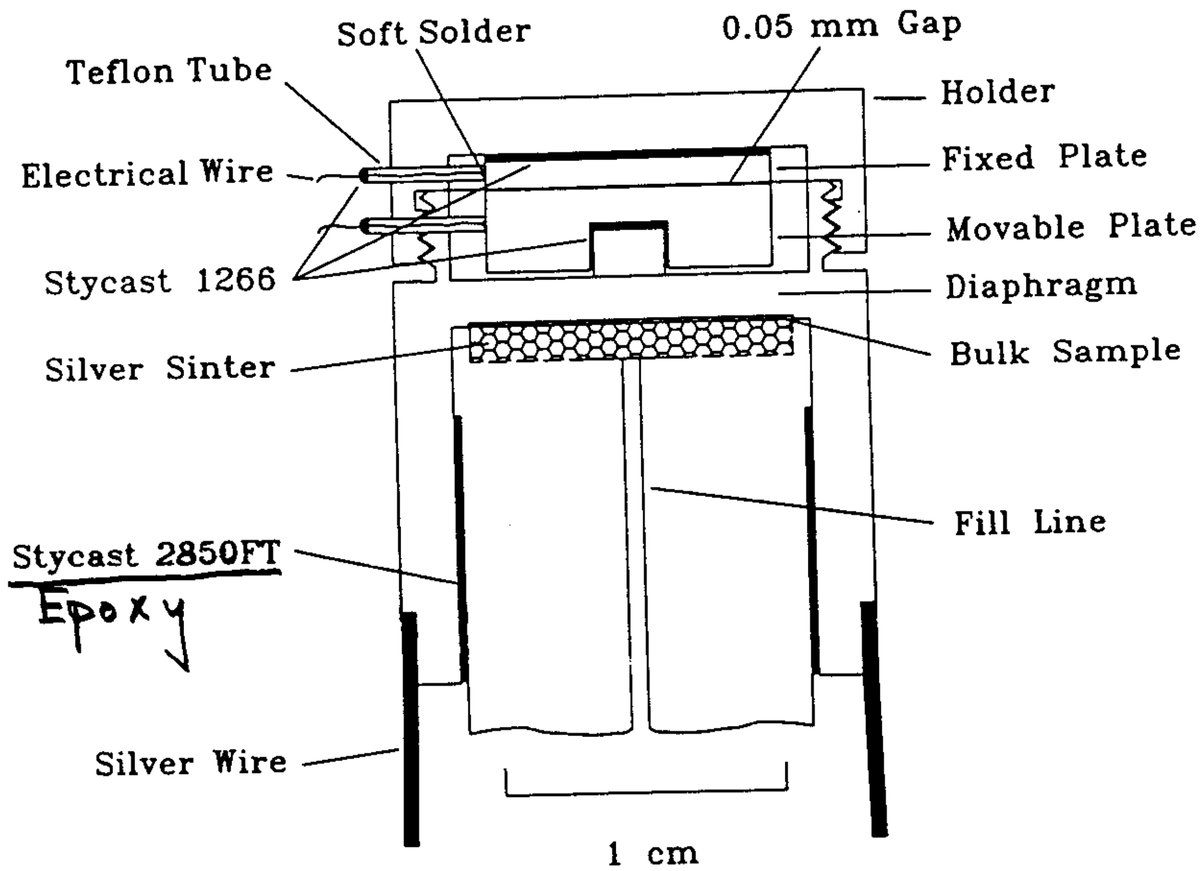
Demagnetization of Okamoto et al.



heating
when In
O-ring
became
normal

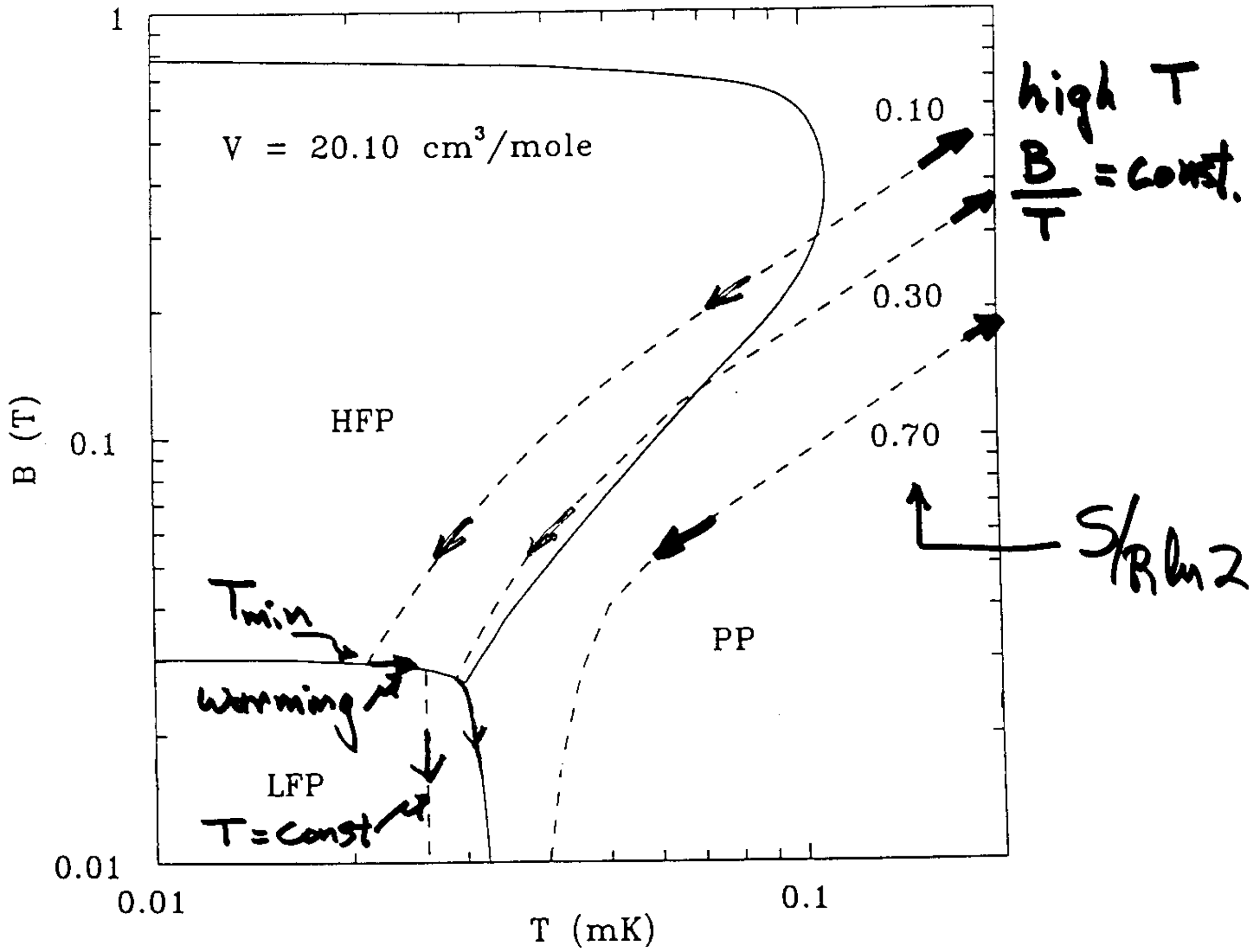


Cell for Pressure Measurement



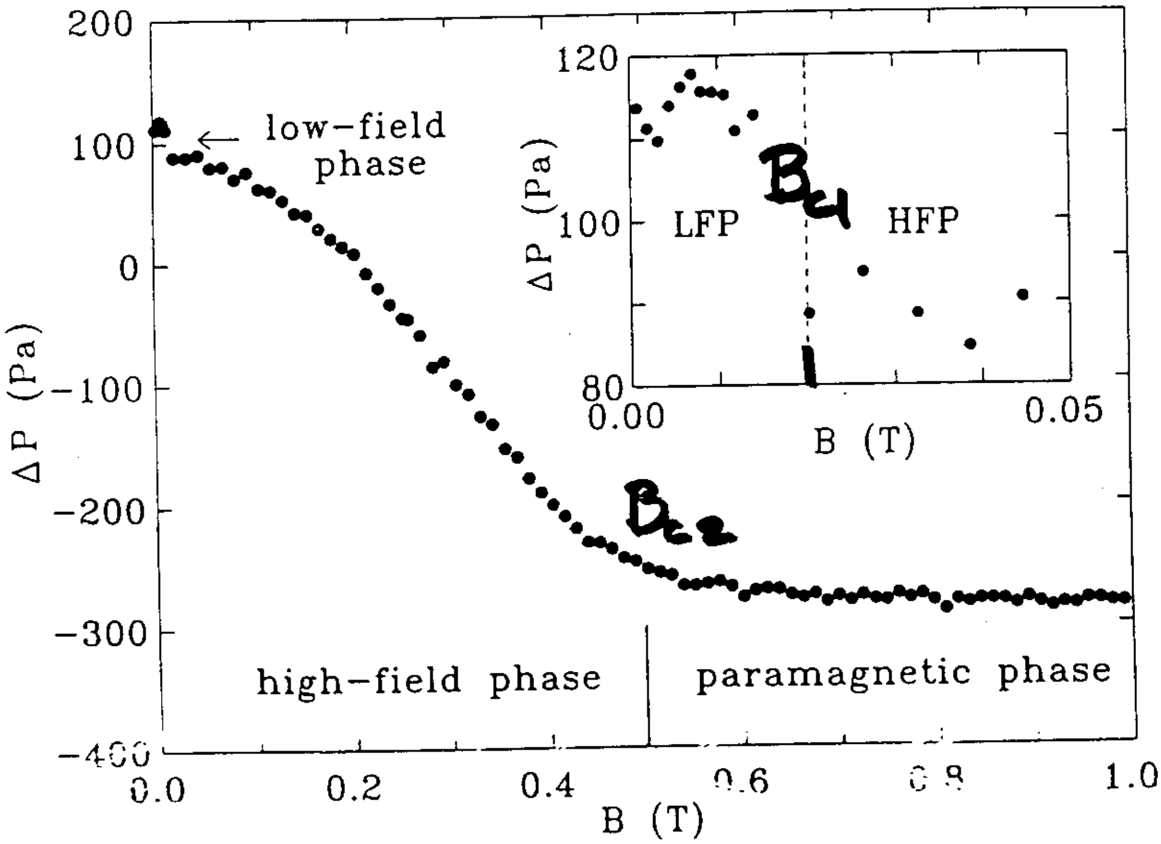
To minimize heating during demag:
no O-ring, bridge excitation
2 V_{pp}, 90 sec every 10 min (5 min)
1st stage → 100 μK, slots
in silver parts.

bcc Demagnetization (Calculated)



No ordering for $S/R\ln 2 \gtrsim 0.5$

bcc Demagnetization ($v = 20.10\ cm^3/mole$)



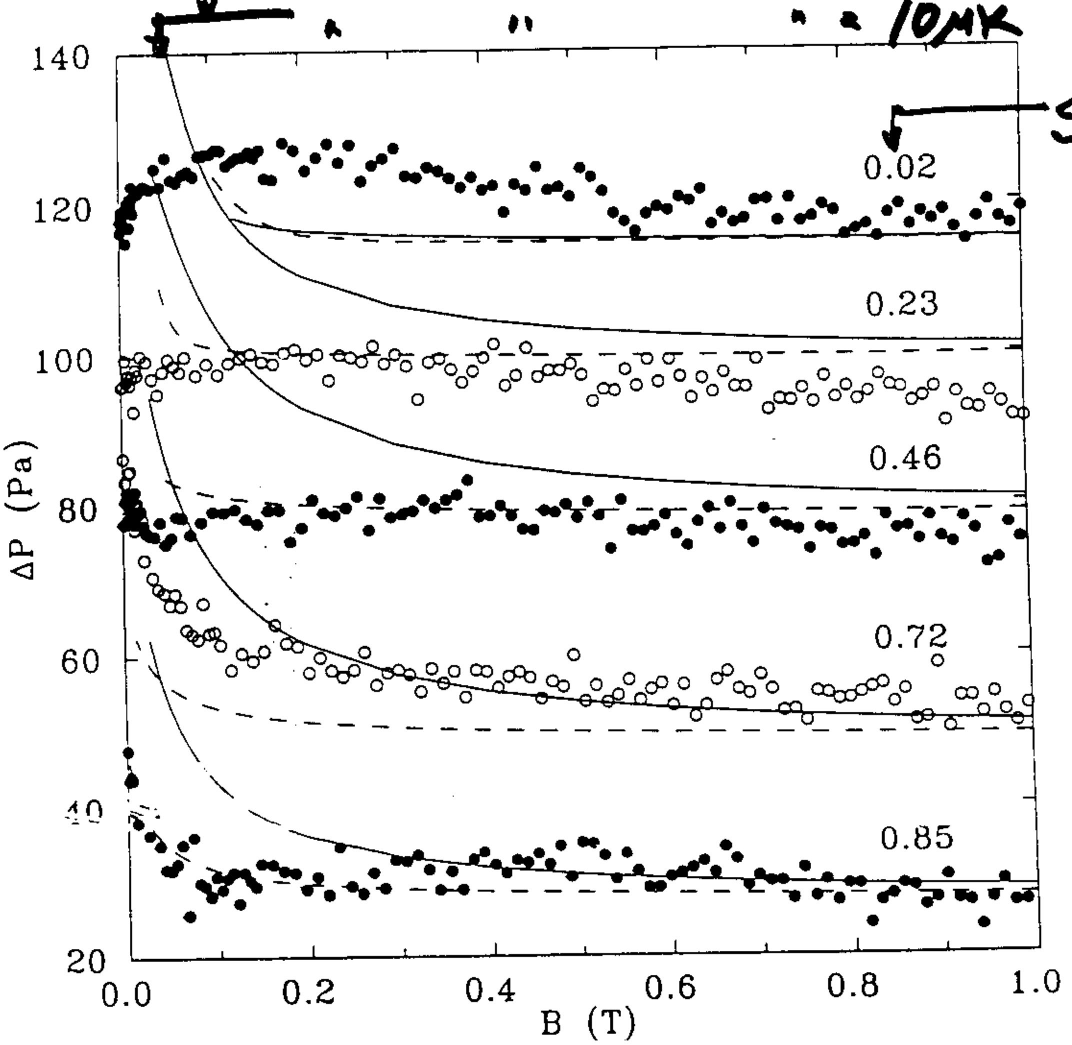
$T_{final} \approx 26\ \mu K$
(based on B_{c1})

hcp Demagnetization (v = 19.6 cm^3/mole)

B/T = const. → T = 20 μK for

" " " " 10 μK 0.02

S/R ln 2



--- Heisenberg (1 J), high-T, 10 terms

—— 3 par. exch, high-T, 4th order

Valid only for $T > T_c$

Conclusions and Questions

- bcc demagnetized to antiferromagnetically ordered state

- hcp: $S \gtrsim 0.46$ R ln 2, pressure increase, no ordering;
  $S \lesssim 0.23$ R ln 2, pressure decrease, ordered state

- Pressure decrease signature of ferromagnetic state (calculations needed)

- Ferromagnetism not proven, T_C not measured, ~ 17 μK

- Warm up time not measured
  $\Delta Q = T\Delta S = 10^{-6}$ J,
  for $\dot{Q} = 1$ nW, $\Delta T = 1000$ sec.

- Future work (in ordered state): magnetization, ferromagnetic resonance, calculations, etc.

- Needed: time, money