Magnetism and crystal control in quantum solid

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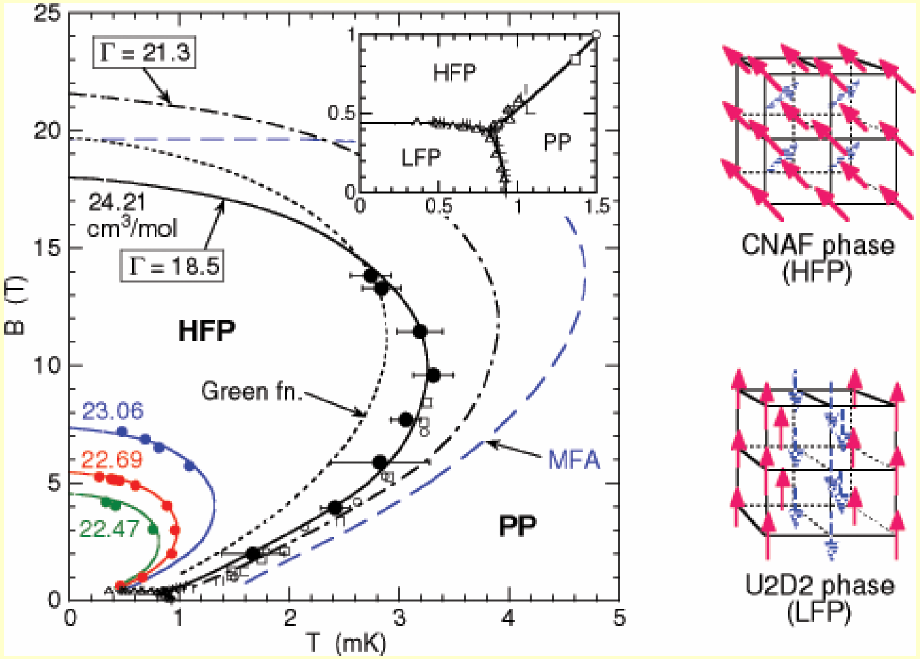
1. Overview of the whole group activity
2. ISSP activity
    - 2D solid ^{3}He on graphite

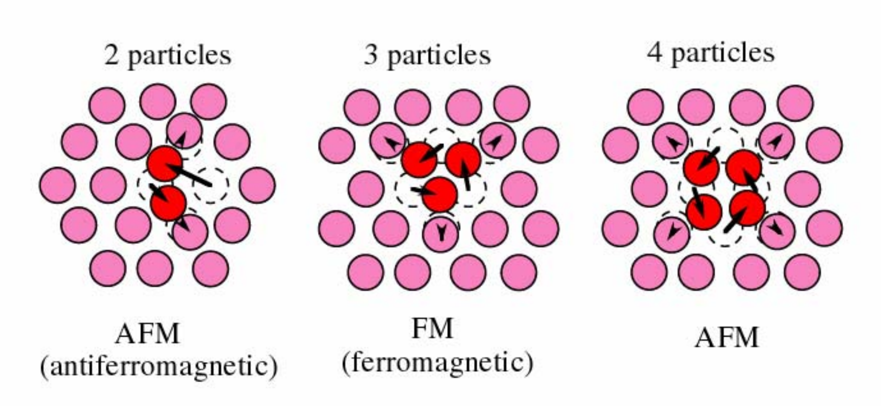
1. Magnetism of solid ^{3}He

Magnetic phase diagram



Ring exchange (MSE) model

$J_2, J_3, J_4, \cdots\cdots J_n$



(1) 3D solid ^{3}He on melting curve

clean and good quality single crystal

(single domain)

a) Sound experiment in the ordered state (Kyoto)

i) U2D2 phase

Δv and α : T and B dependence

ii) CNAF phase

observation of optical mode

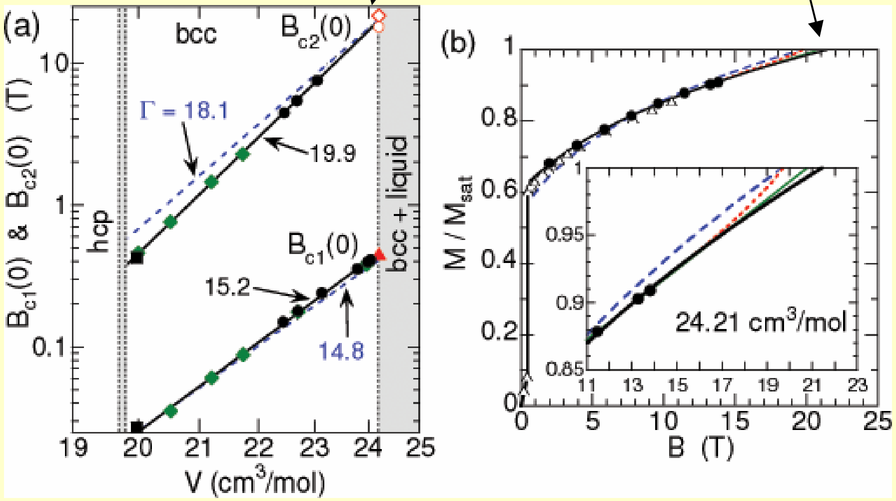
b) magnetic phase diagram (ISSP)

B_{c2} ?

melting pressure

in high fields (>15 T)

$dP/dT = (S_L - S_S) / (V_L - V_S)$



19.7 T

21.5 T

(2) 2D solid ^{3}He adsorbed on graphite （ISSP)

Frustration due to MSE in the triangular lattice

2D AFM solid ^{3}He on graphite: 4/7 phase

what is the ground state ? : gapless spin liquid

How is the magnetization curve ? : plateau ?

What is anomalous liquid phase just before Mott transition ?

heat capacity measurement

at a tens of mK in high fields (P05)

2. Crystal growth

coexistence of solid and superfluid down to 0 K

1) ^{4}He: optical method, ultrasound (TIT)

2) ^{3}He

a) nucleation and growth between U2D2 and CNAF (Kyoto)

b) spatial magnetic structure in the ordered state (MRI)（Kyoto)

domain wall, texture effect on crystal growth

big ΔM between liquid and solid :

M controlled crystal growth--- crystalization wave ?

$T < 0.1$ mK ?

B phase to U2D2, A phase to CNAF

Two-Dimensional Antiferromagnetic Solid ^{3}He on graphite

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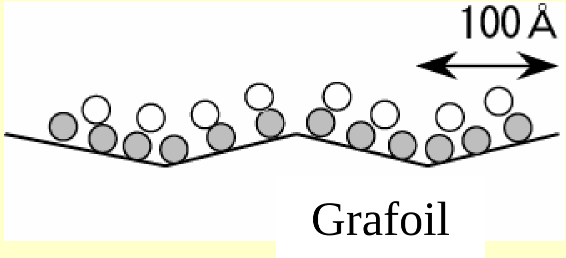
1. Introduction
2. Theoretical & Experimental background
3. Experiment I
4. Experiment II
5. Conclusion

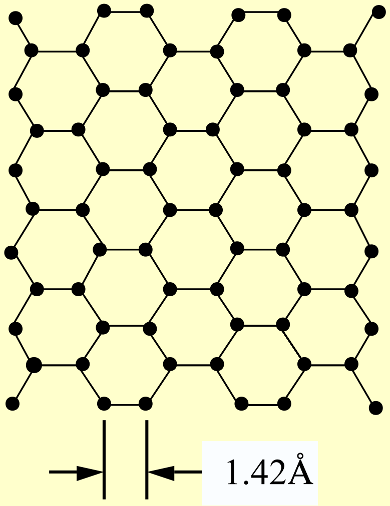
1. Solid ^{3}He on graphite

Properties of exfoliated graphite substrate

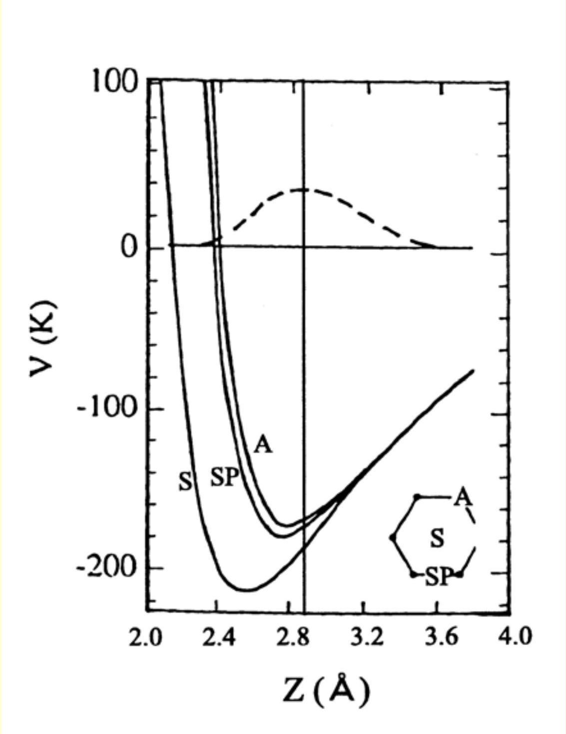
- Atomically flat surface
- Good thermal conductance
- Large surface area (Grafoil : 20 m^2/g)

platelet



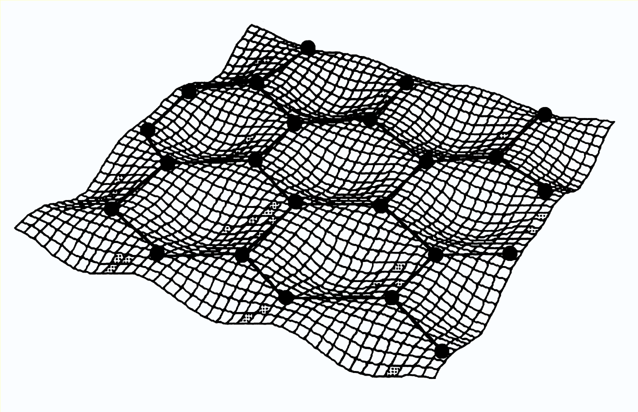


Adsorption potential



M.W.Cole et al,
Rev. Mod. Phys. **53** 199 (1981)

Corrugation potential



Phase Diagram of ^{3}He

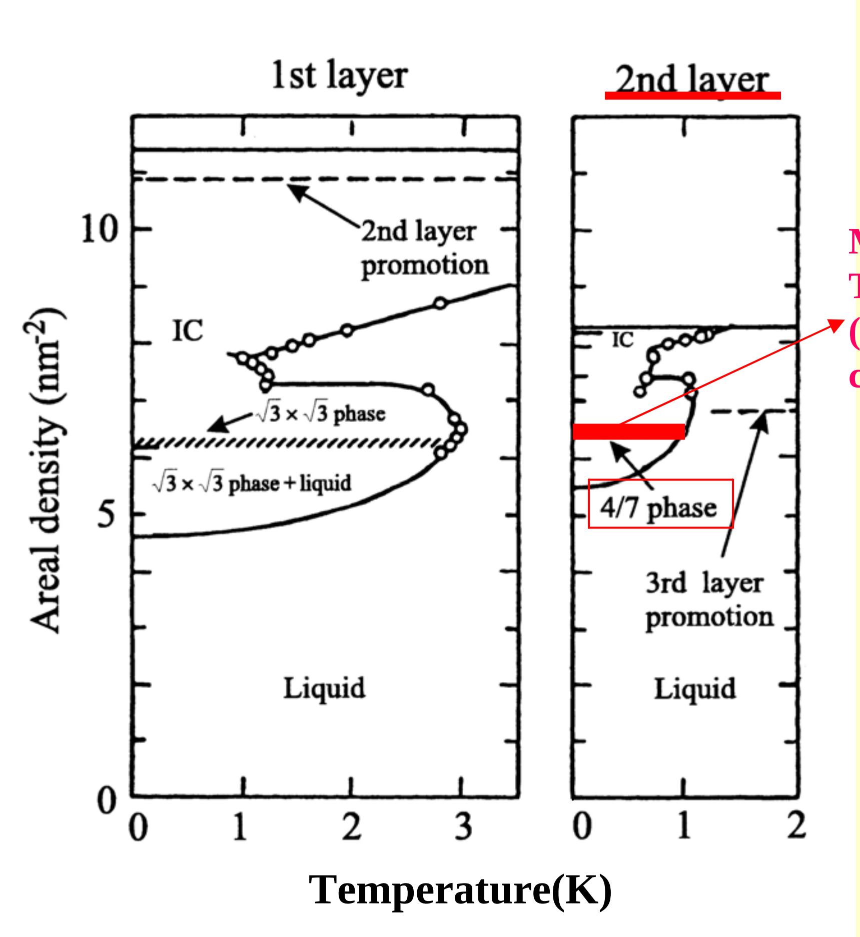
Ideal 2D : extremely small inter layer interaction

Clean

Quantum (S=1/2)

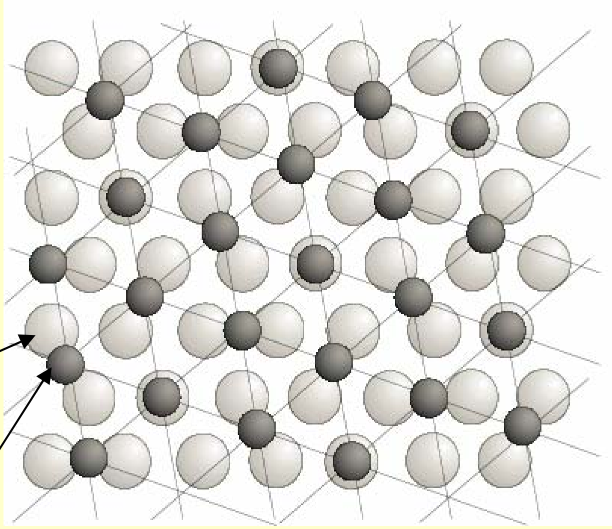
Easily controllable interaction

Second layer（^{3}He/^{3}He/Gr）



Mott Hubbard Transition (filling control)

IC first layer



second layer

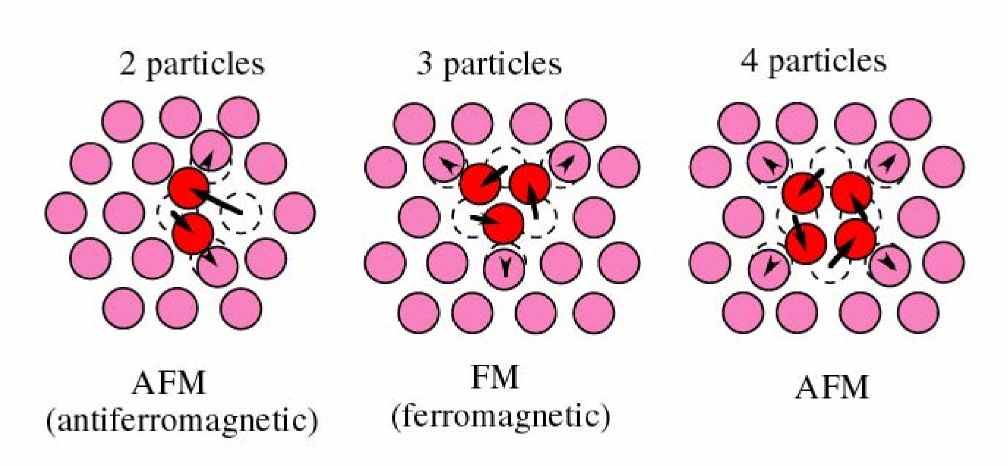
4/7 phase ($\sqrt{7}$ x $\sqrt{7}$)

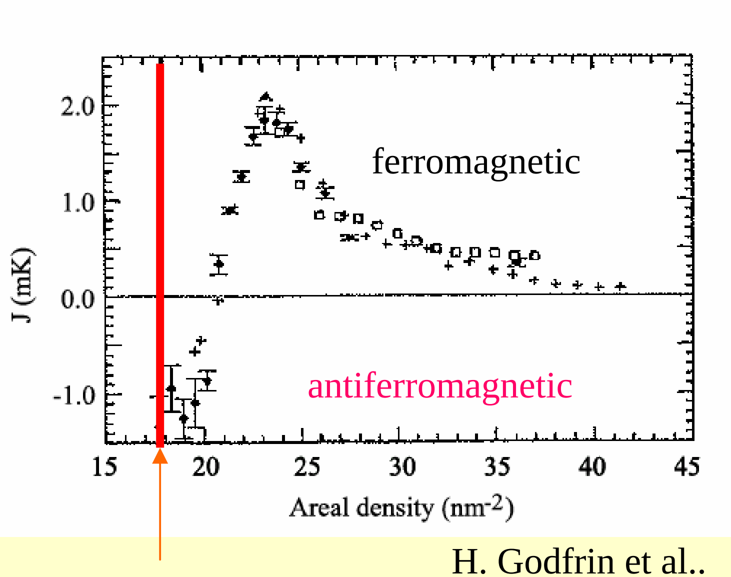
(6.4 nm^{-2})

Antiferromagnetic triangular lattice

1) Multiple exchange : J_n

Second layer (^{3}He/^{3}He/Gr)





H. Godfrin et al..

4/7 phase

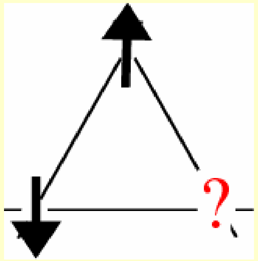
Competition between AFM and FM

different and strong density dependence of J_n ⟶ tunable frustration

Pre-plating of ^{4}He or HD ⟶ variable J_n

2) 4/7 phase
2D triangular lattice
effectively AFM

Geometrical frustration



What is the ground state ?
RVB liquid ?

2. Theo. and Exp. background

Multiple Spin Exchange

$$H = \sum_n J_n (-1)^n P_n^{(\sigma)}, \quad (P_n^{(\sigma)} : n-\text{particle permutation operators}) \quad J_n > 0$$

$$P\,ij = (1 + \sigma_i \cdot \sigma_j)/2\,, \quad P\,ijk + (P\,ijk)^{-1} = (1 + \sigma_i \cdot \sigma_j + \sigma_j \cdot \sigma_k + \sigma_k \cdot \sigma_i)/2$$

$$= (J_2^{eff}/2)\,\Sigma\,(\sigma_\iota \cdot \sigma_j) + J_4\,\Sigma\,h_p + \cdots\cdots$$

$$J_2^{eff} = (J_2 - 2J_3)\,, \quad h_p = \Sigma\,(\sigma_\mu \cdot \sigma_\nu + G_{ijkl})$$

$$G_{ijkl} = (\sigma_\iota \cdot \sigma_j)(\sigma_k \cdot \sigma_l) + (\sigma_\iota \cdot \sigma_l)(\sigma_j \cdot \sigma_k) - (\sigma_\iota \cdot \sigma_k)(\sigma_j \cdot \sigma_l)$$

High temperature series Expansion

$$J_\chi = \theta/3 = -(J_2^{eff} + 3J_4 - 5J_5 + 5J_6/8),$$

$$J_c^2 = \left(J_2^{eff} + \frac{5}{2}J_4 - \frac{7}{2}J_5 + \frac{1}{4}J_6\right)^2 + 2\left(J_4 - 2J_5 + \frac{1}{16}J_6\right)^2 + \frac{23}{8}J_5^2 - J_5J_6 + \frac{359}{384}J_6^2$$

Exp. results

$\chi = C/(T - \theta)\,, \quad \theta = 3J\chi$

$C = (9/4)N\,k_B\,(J_c/T)^2$

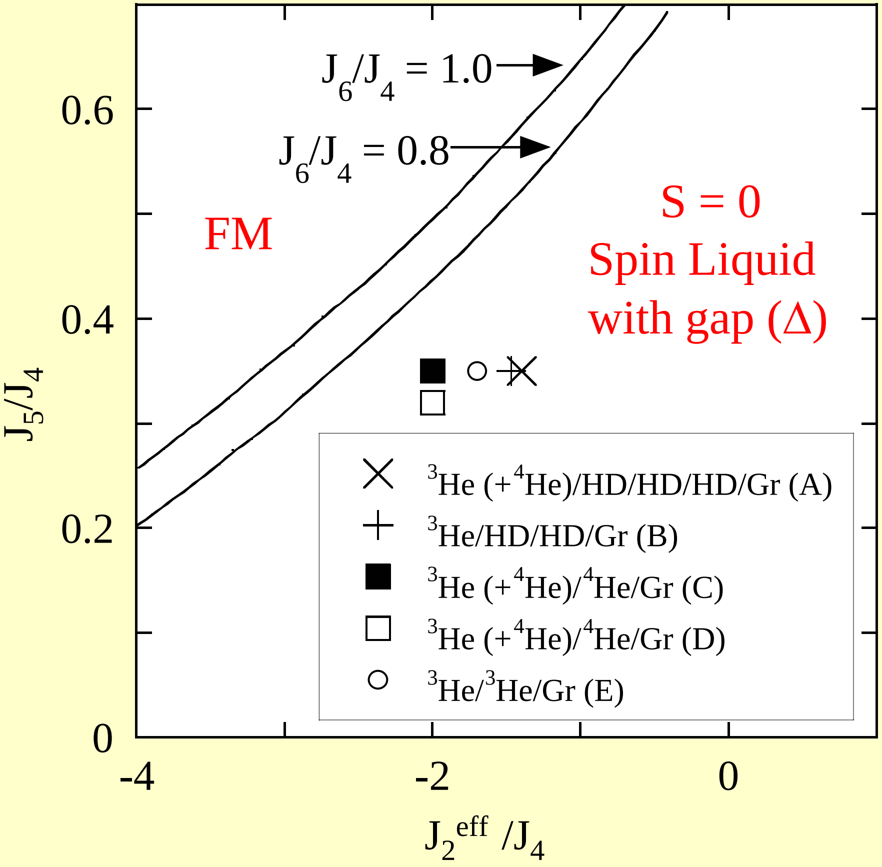
for 4/7 phase, ^{3}He/ ^{4}He/ Gr

$J_2^{eff} = J_2 - 2J_3 = -2.8$ mK, $J_4 = 1.4$ mK

MSE model (exact diagonalization for 24 atoms : J_2 to J_6)

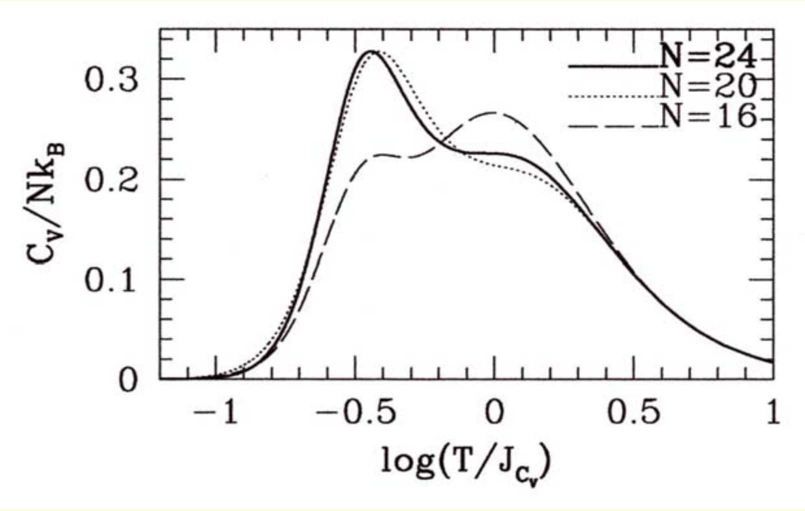
(G. Misguich et al.)

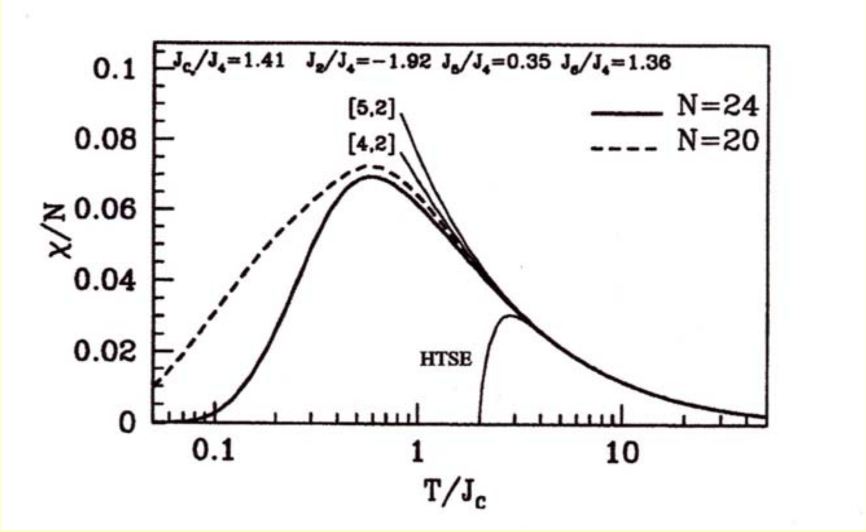
Phase diagram



$J_2^{eff} = J_2 - 2J_3 < 0, \quad J_4 > 0$

$J_2^{eff} / J_4 = -2, J_5 / J_4 = 0.2, J_6 / J_4 = 0.08$



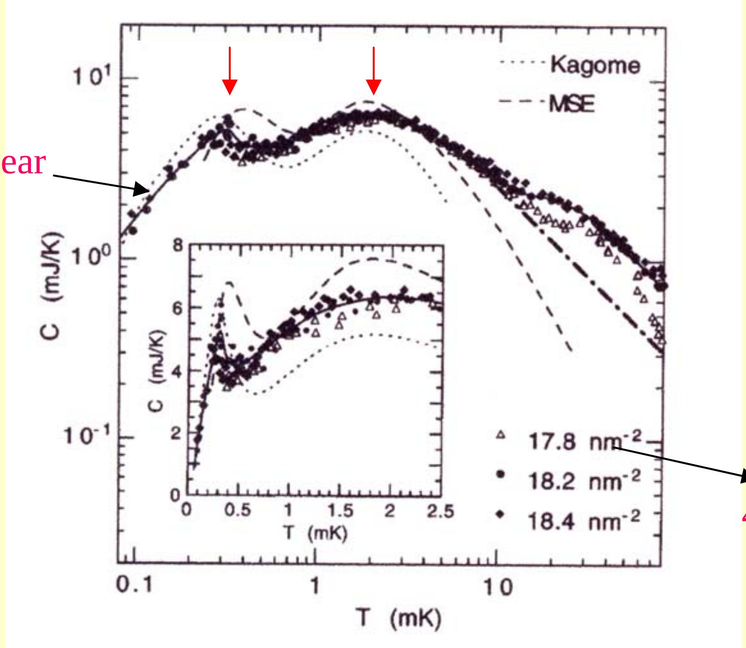


$\chi \approx e^{-\Delta / T}, C \approx e^{-\Delta / T}$

Previous experimental results for second layer solid ^{3}He

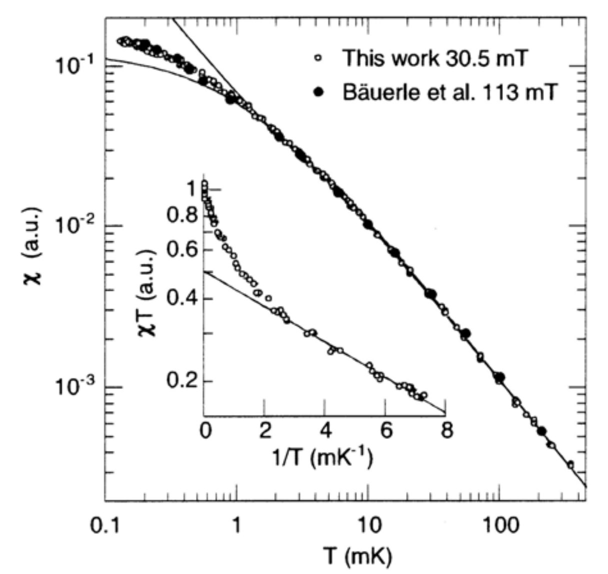
(A) heat capacity ^{3}He/^{3}He/Gr

(B) susceptibility ^{3}He/^{4}He/Gr



T linear

4/7 phase



Two peaks

T linear dependence below 2 nd peak

Disorderd ground state ?

4/7 phase

$$\chi \propto \frac{1}{T} e^{-\Delta/T}$$

$$\Delta \approx 70\,\mu K$$

(A) K.Ishida et al, Phys. Rev. Lett. **79**, 3451 (1997).

(B) E. Collin et al, Phys. Rev. Lett. **86**, 2447 (2001).

3. Experiment I

I. Two methods

1) Pre-plating of HD

lower density of 4/7 phase → enhancement of J_n

Lower effective temperature T / J_χ

2) Double stage nuclear demagnetization

direct demagnetization of the sample itself $T \rightarrow 10\ \mu\mathrm{K}$

II. Prepared sample

	underlying layer	2nd layer (4/7 phase)	J_χ ($=\theta/3$)
a) ^{3}He/^{4}He/Gr	12.4 atoms/nm^2	6.8 atoms/nm^2	0.3-0.4 mK
b) ^{3}He/HD/HD/Gr	9.2	5.26	3-4

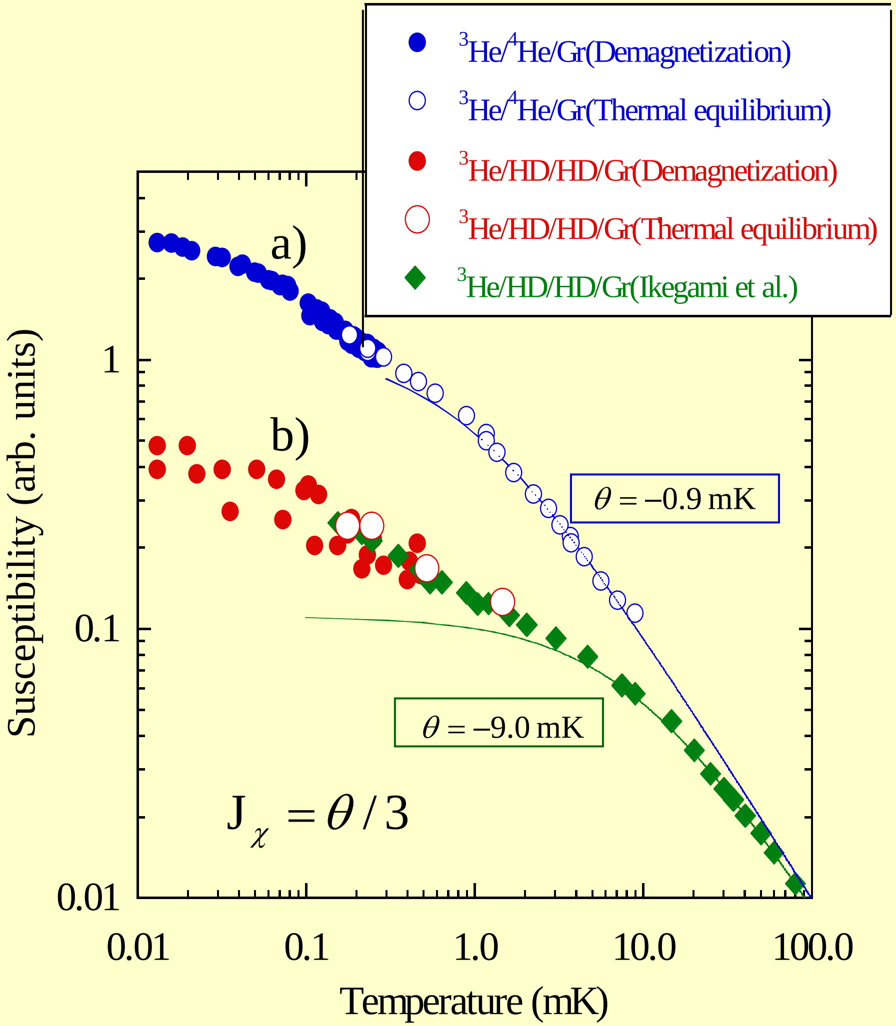
III. Detection

cw NMR (^{3}He, Cu, D, H, ^{13}C) at low field (2.5 or 5 mT : $\mu B < kT$)

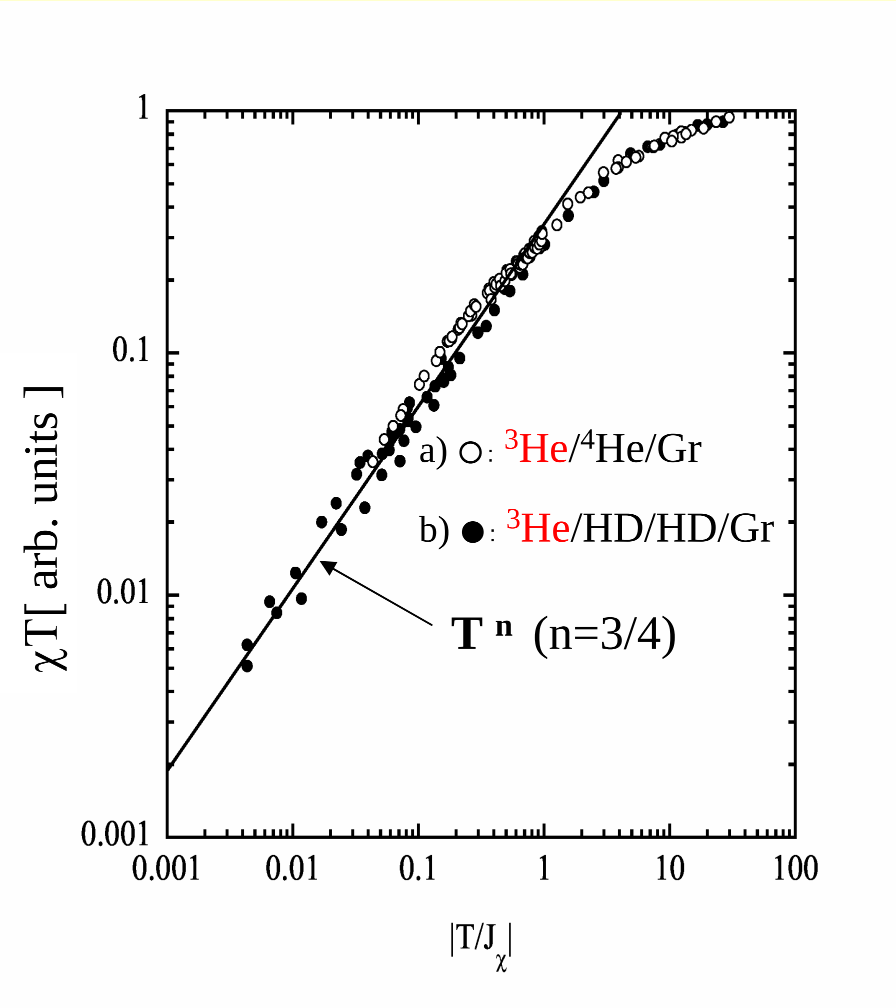
Results

4/7 phase

a) ^{3}He/^{4}He/Gr
b) ^{3}He/HD/HD/Gr



R.Masutomi et al, Phys. Rev. Lett. **92**, 025301 (2004).

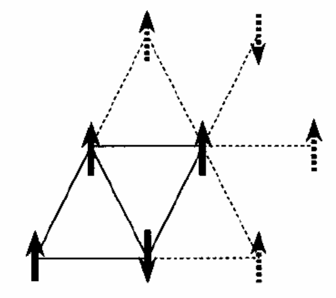


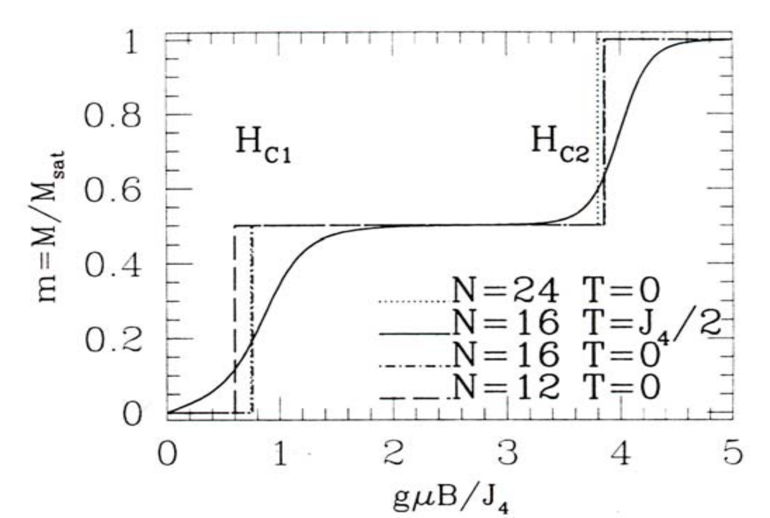
Gapless spin liquid ground State

4. Experiment II

Magnetization under high magnetic fields

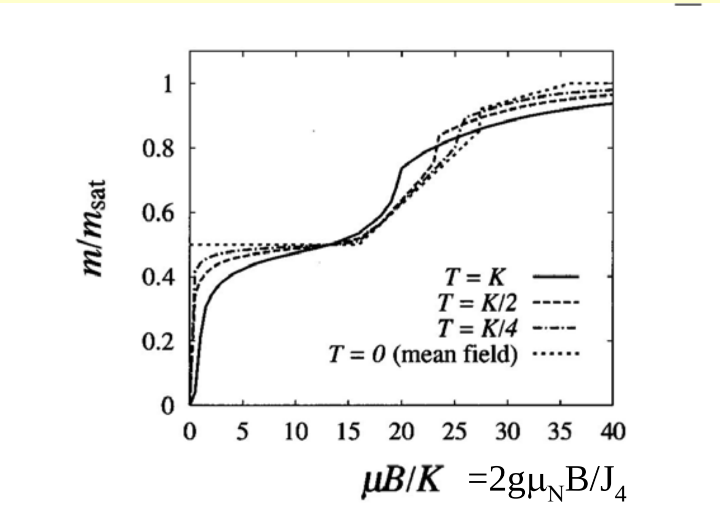
uuud state





$J_2^{eff}/J_4=-2.0,\ J_5/J_4=0.2,\ J_6/J_4=0.08$

Exact diagonalization (G. Misguich et al.)



$=2g\mu_N B/J_4$

$J_2^{eff}/J_4=-2.0,\ J_5=J_6=0$

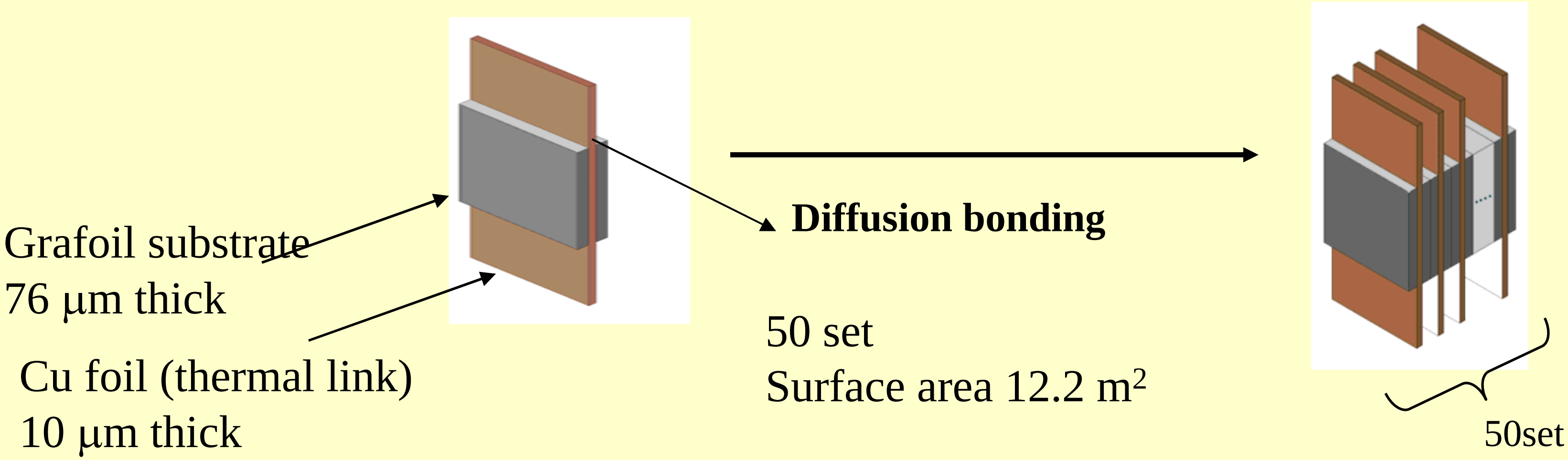
Semi classical (T.Momoi et al.)

~~NMR (>100 MHz)~~ → Faraday method

rf shielding and heating

$F = M_Z \cdot (dB/dz)$

Grafoil – Copper sandwiches



Grafoil substrate
76 μm thick

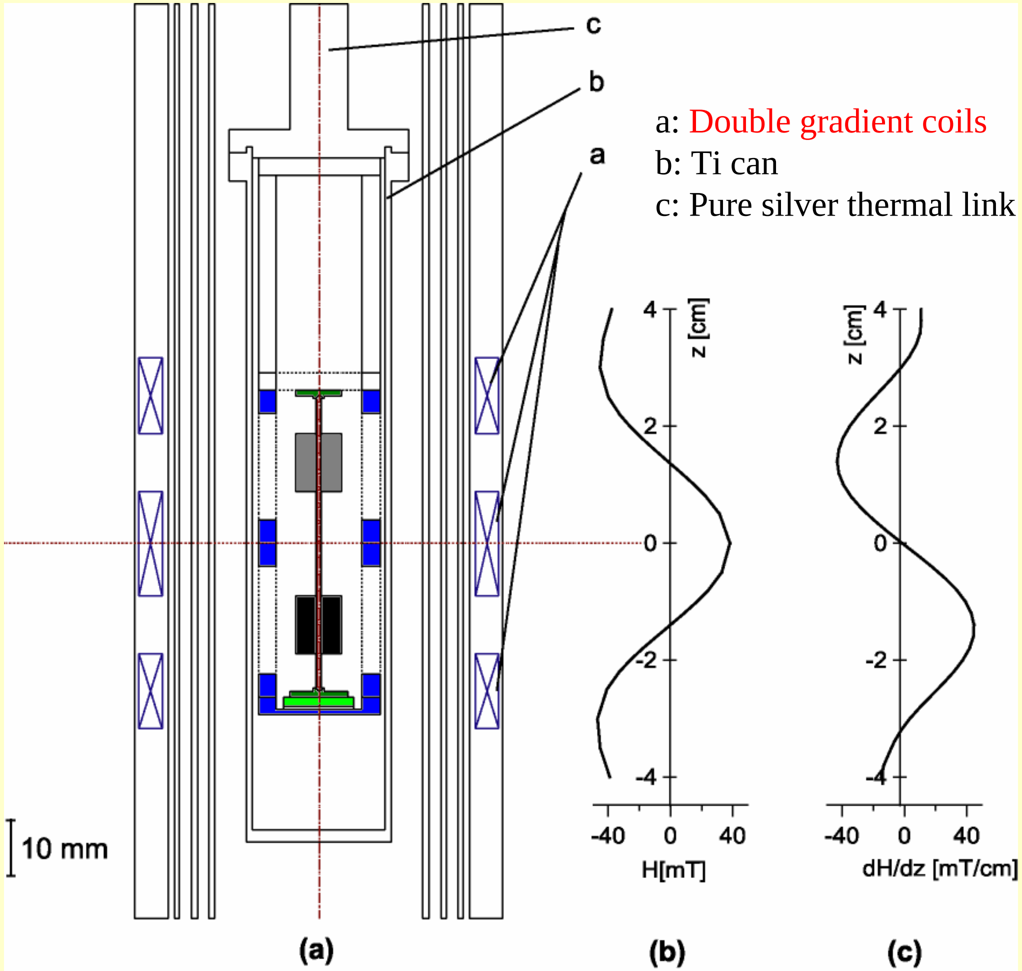
Cu foil (thermal link)
10 μm thick

Diffusion bonding

50 set
Surface area 12.2 m²

Material	Amount	Saturated nuclear moment	Diamagnetism
Solid ^{3}He (4/7 phase)	0.24 mmol	7.5 x10^{-4} emu 1	-3.4 x10^{-6} emu/T 0.02 (at 5T)
Graphite sheets	60.4 mmol	1.42 x10^{-3} emu 2 (^{13}C)	-2.3 x10^{-2} emu/T 150
Cu foils	35 mmol	0.24 emu 320	-1.9 x10^{-3} emu/T 13

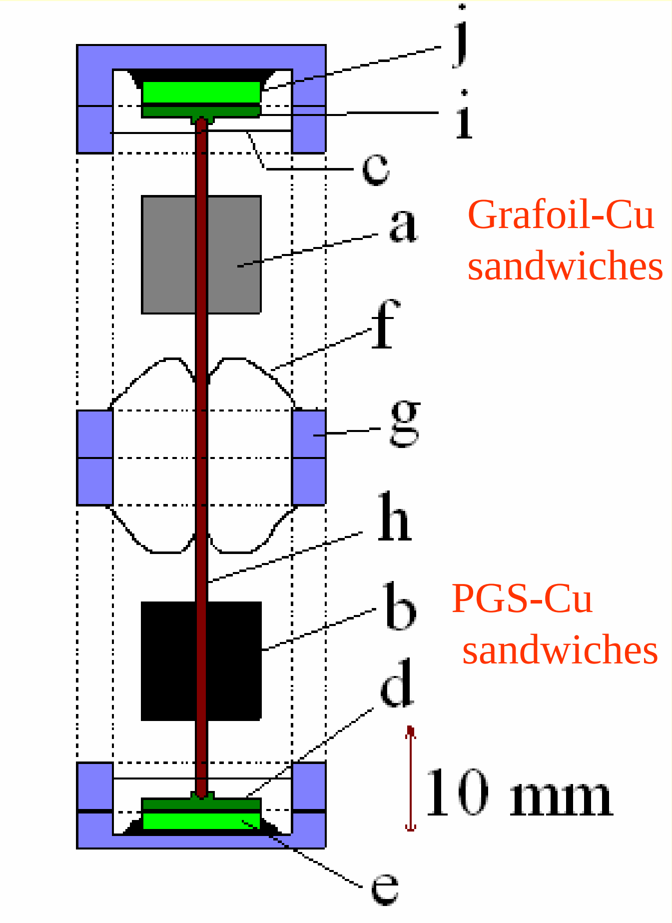
Double gradient Faraday gauge



a: Double gradient coils
b: Ti can
c: Pure silver thermal link

(a) (b) (c)

$(dH/dz)_{max}$=10 T/m



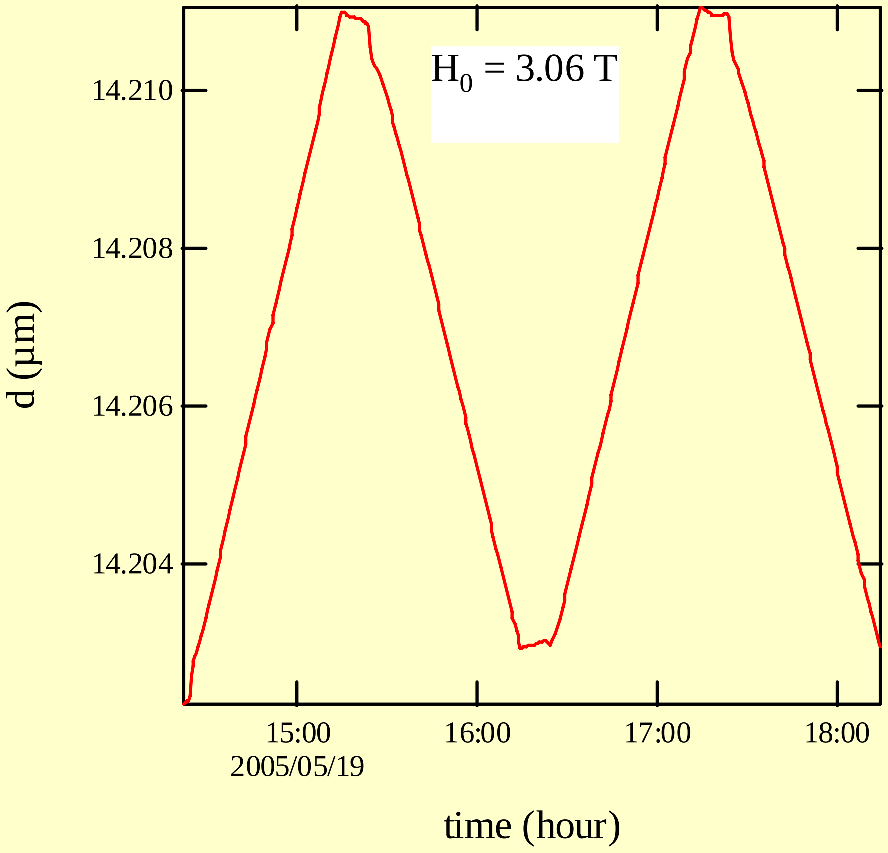
Grafoil-Cu sandwiches

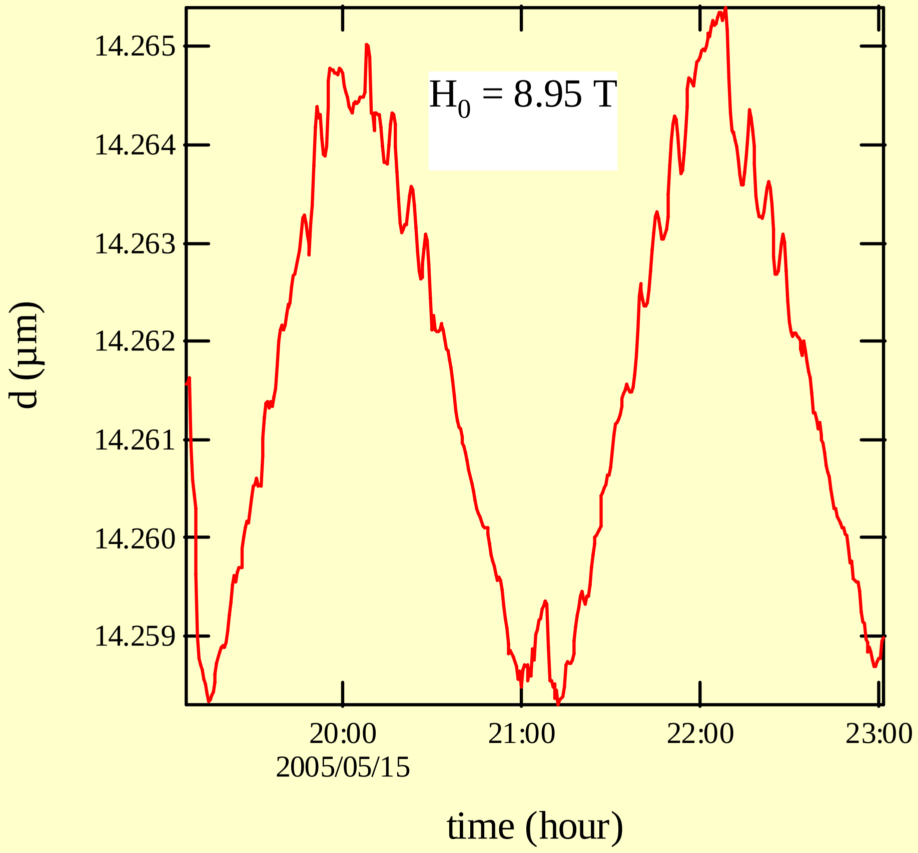
PGS-Cu sandwiches

a: Grafoil-Cu sandwiches,
b: PGS-Cu sandwiches
(no surface area),
c: phosphor bronze wires,
d: movable plate, e: fixed plate,
f: pure copper foiles as thermal link, g: silver cage, h: copper plate

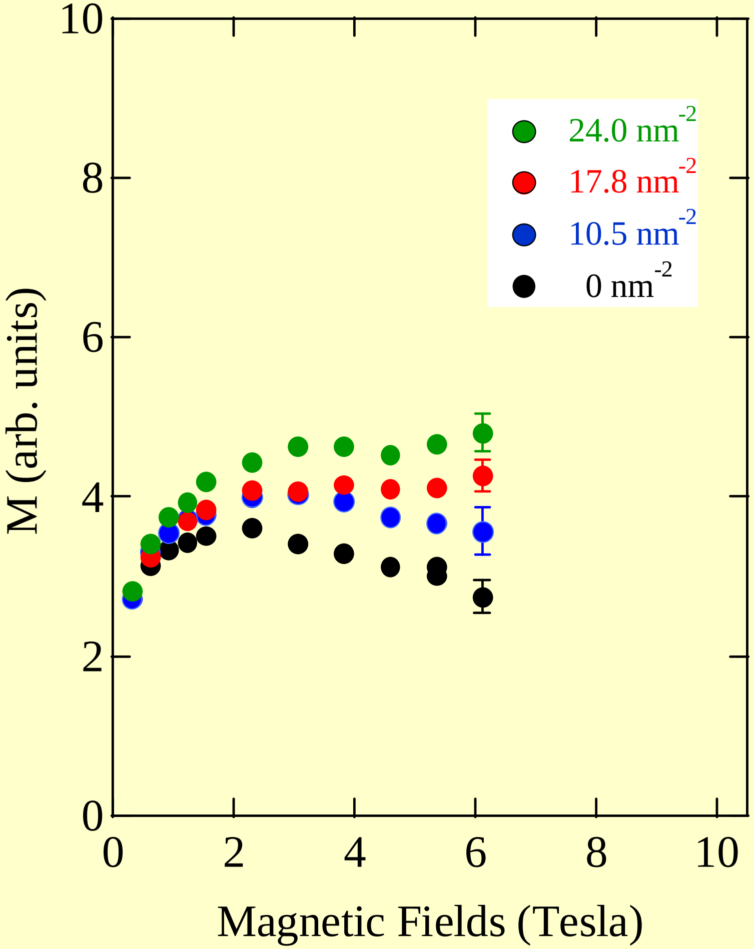
Results

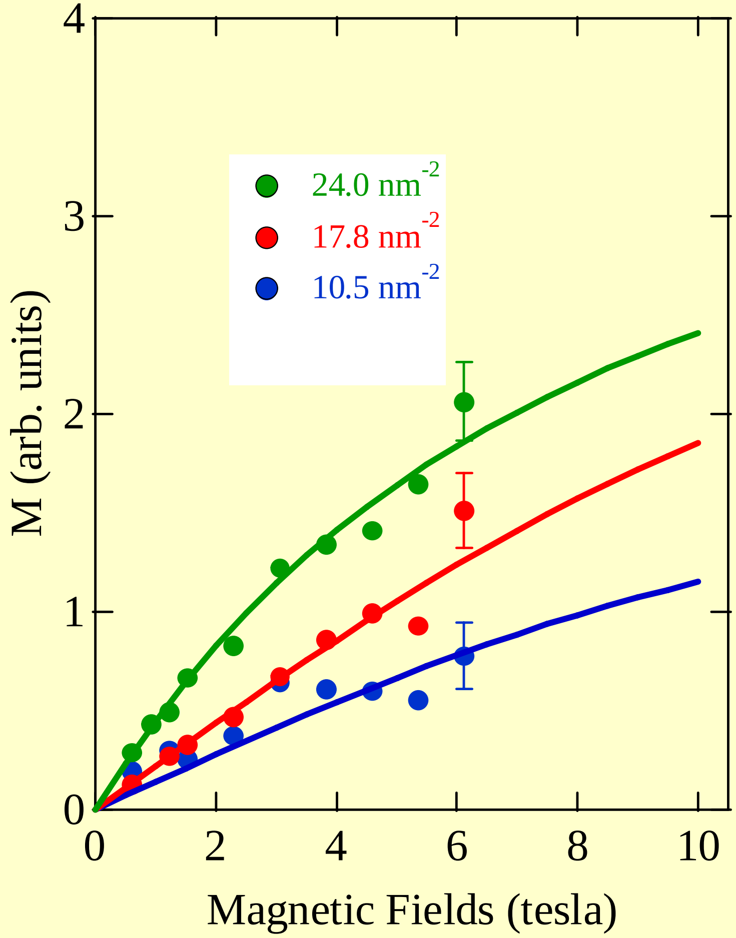
Displacement of electrode during sweeping the field gradient at constant T and B (^{3}He/^{3}He/Gr, 1.1 mK, 24.0 nm^{-2})



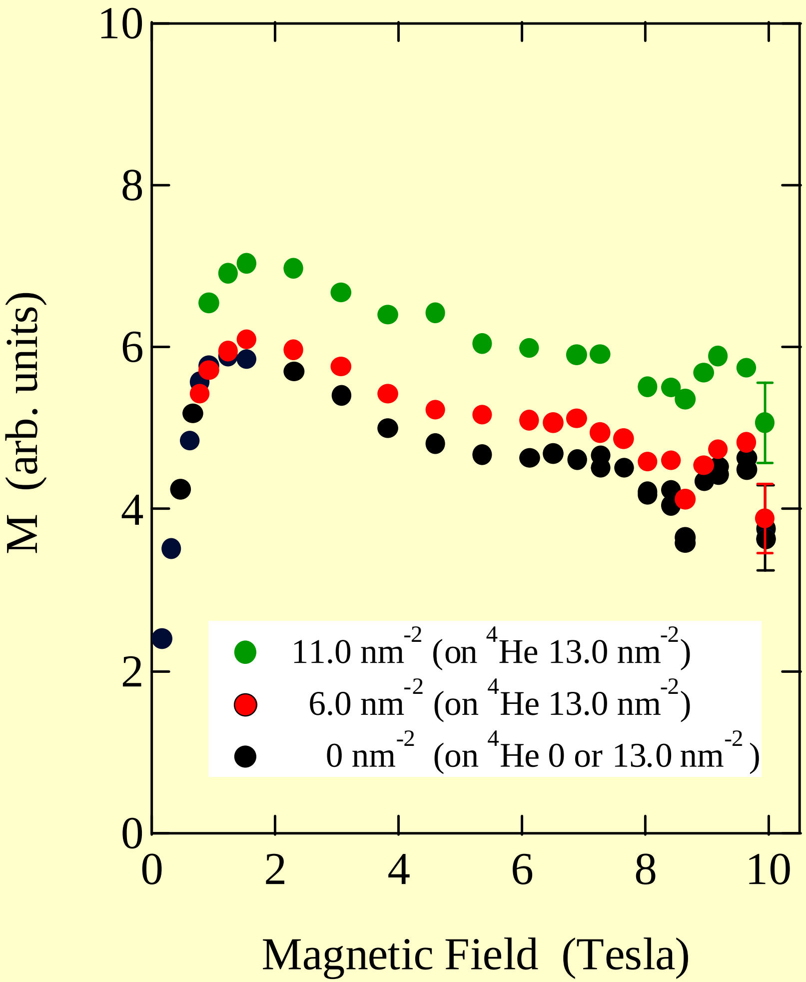


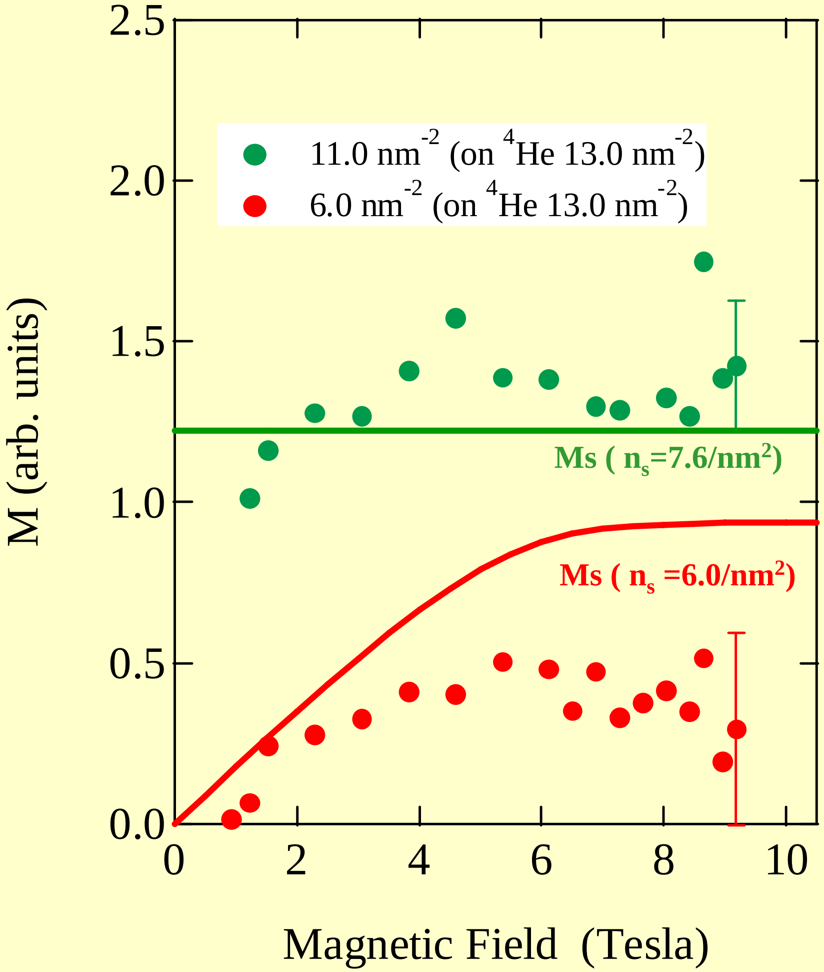
^{3}He/^{3}He/Gr 9.3 mK





^{3}He/^{4}He/Gr 1.1 mK





Fitting parameter

— AFM 5.85 nm^{-2} , J = -1 mK

— FM 7.63 nm^{-2} , J = 2 mK

5. Conclusion

2D AFM solid ^{3}He with MSE on triangular lattice (4/7 phase)

^{3}He/^{3}He/Gr, ^{3}He/^{4}He/Gr, ^{3}He/HD/HD/Gr

Exp. Results

1) no drop in susceptibility down to 10 μK

gapless spin liquid ground state

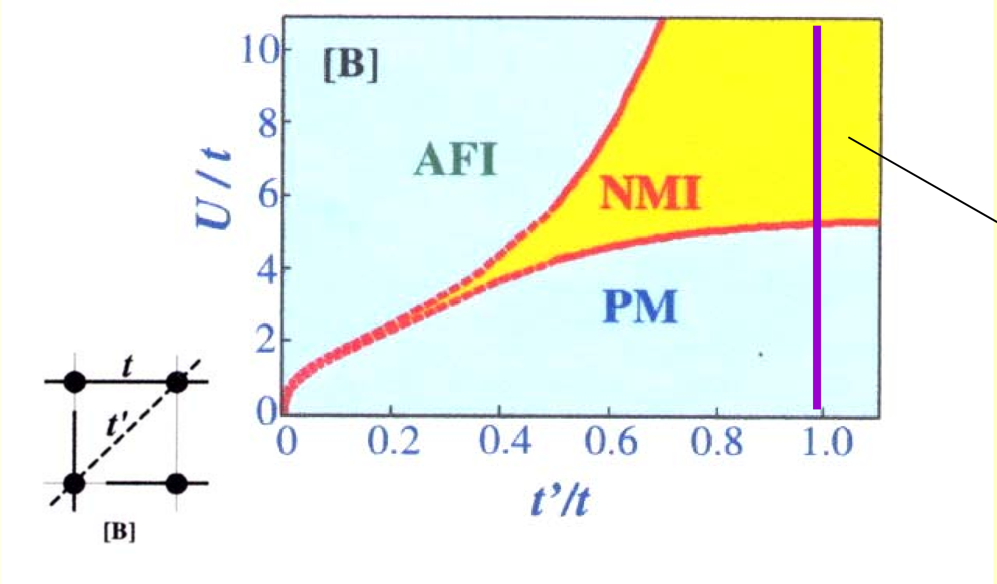
2) no saturation of magnetization even at 9 T and 1 mK

magnetization plateau 1/2 (?)

Theory

1) Exact diagonalization : too small a size ?

2) PIRG (Path integral renormalization group) for Hubbard model (M.Imadaet al.) ?



4/7 phase
（ t = t', t= (U/2J)$^{1/2}$,
U/t ~ 60）

Non magnetic insulator
(No spin gap, constant χ)