GDR 3183 MICO:
Matériaux et Interactions
en COmpétition

Autrans, 1-4 décembre 2008

New Quantum Magnetic Phases in $SrCu_2(BO_3)_2$: A Route to Supersolid Phases ?

M. Horvatić

high-field NMR in Solids
http://ghmfl.grenoble.cnrs.fr/spip.php?rubrique33

Grenoble High Magnetic Field Laboratory

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NMR investigation of plateaus in the $SrCu_2(BO_3)_2$ system

[K. Kodama *et al.*, Science **298**, 395 (2002) and J. Phys.: Condens. Matter **17**, L61 (2005); S. Miyahara, F. Becca, F. Mila, Phys. Rev. B **68**, 024401 (2003); F. Lévy *et al.*, EPL **81**, 67004 (2008) and unpublished; M. Takigawa *et al.*, PRL **101**, 037202 (2008) and unpublished]

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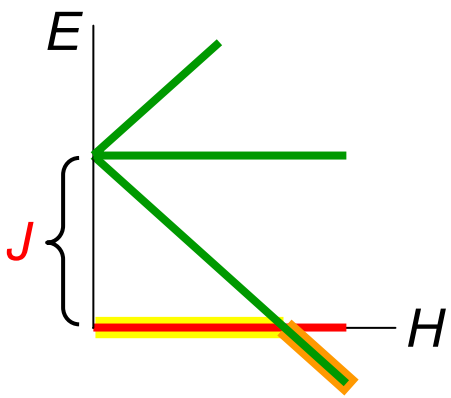
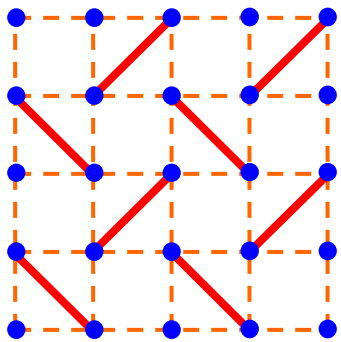
Low-D, quantum, AF spin systems - Definition:

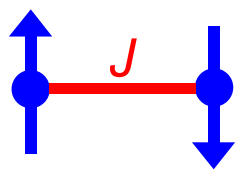
Heisenberg Hamiltonian: $\mathcal{H}_H = \sum_{i,\delta} J_{i,\delta}\, \vec{S}_{i+\delta} \cdot \vec{S}_i$

$(+ \vec{D} \cdot \vec{S}_{i+\delta} \times \vec{S}_i + J_{3D} \vec{S}_i \cdot \vec{S}_j)$

$S = 1/2$ spin-dimer systems:







$SrCu_2(BO_3)_2$:

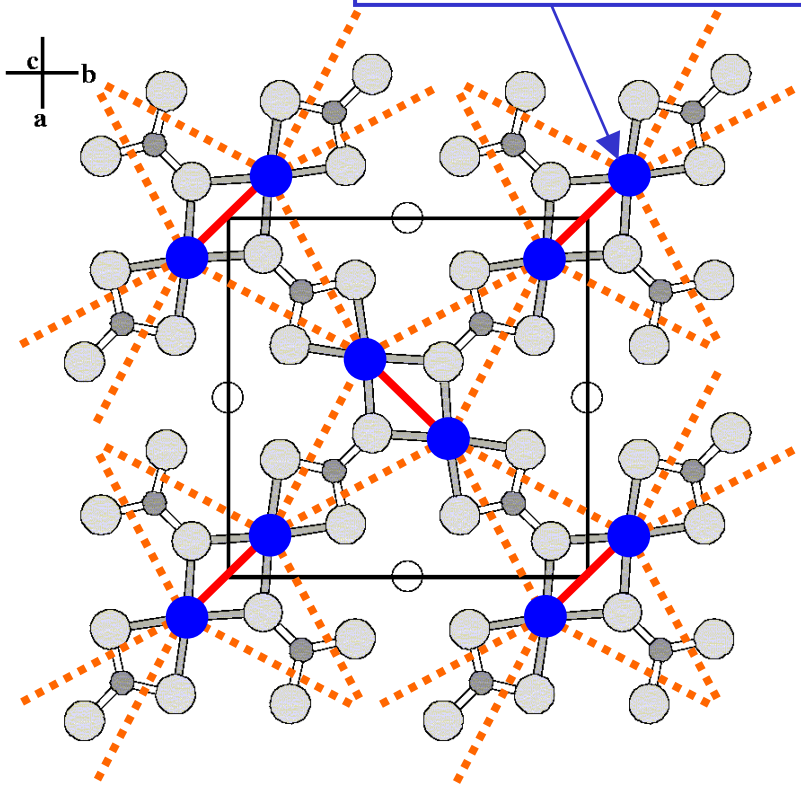
Shastry-Sutherland

(plateaus, supersolid ?)

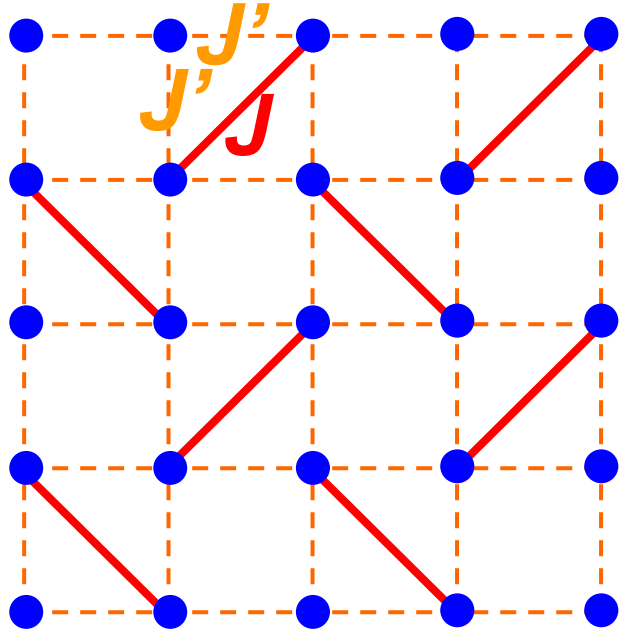
System: $S = ½$, 2D, AF, frustrated, highly symmetric !

$SrCu_2(BO_3)_2$

Cu: S = 1/2 spins



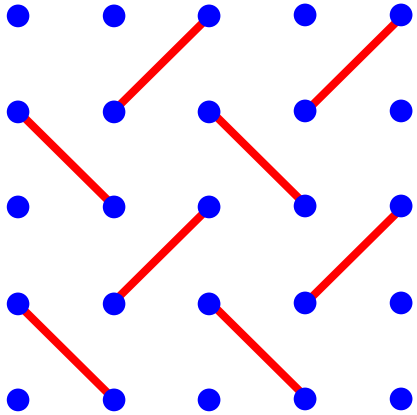
Shastry-Sutherland Hamiltonian



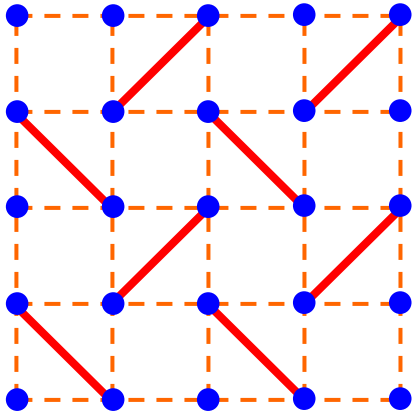
$$\mathcal{H} = \sum_{\substack{\text{"diagonal"} \\ \text{bonds}}} J\,\vec{\mathbf{S}}_i \cdot \vec{\mathbf{S}}_j + \sum_{\substack{\text{"square"} \\ \text{bonds}}} J'\,\vec{\mathbf{S}}_i \cdot \vec{\mathbf{S}}_j - B\sum_i S_i^z$$

[B.S. Shastry, B. Sutherland, Physica (Amsterdam) B**108**, 1069 (1981)]

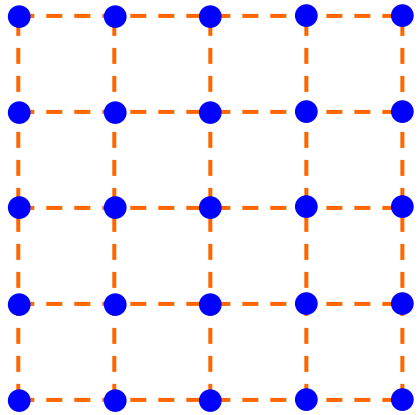
Separated Dimers (J)



Shastry-Southerland



2D square lattice (J')

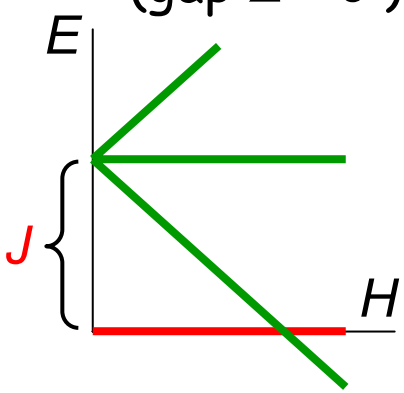


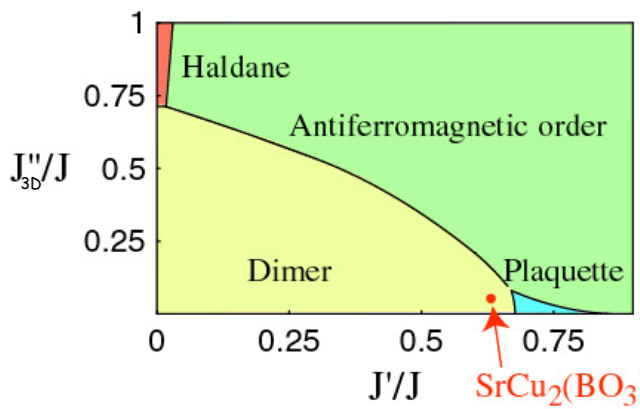
$|\Psi\rangle = \Pi_i |\Psi_{dimer}\rangle_i$

product of singlets is always an eigenstate ! and at $J' < 0.7\ J$ = ground state

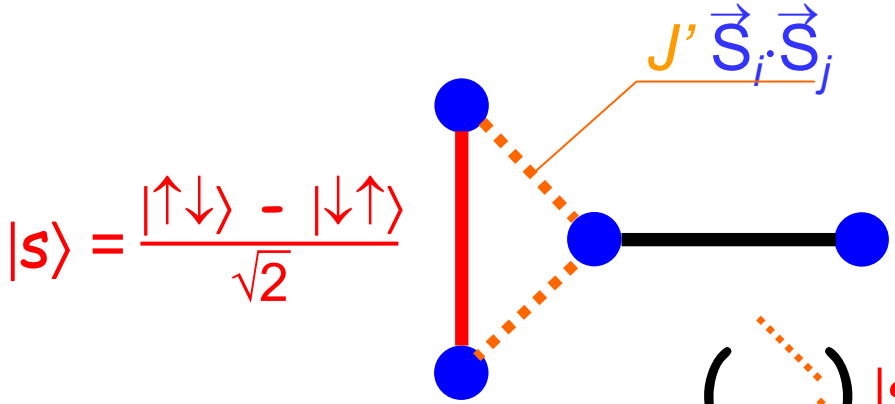
AF ground state

(product of) localized singlets + triplet excitations (gap $\Delta = J$)





A. Koga, JPSJ **69**, 3509 (2000)



$$|\Psi_{GS}\rangle = \Pi_i |s\rangle_i$$

$$(\quad)\ |s\rangle|?\rangle = 0$$

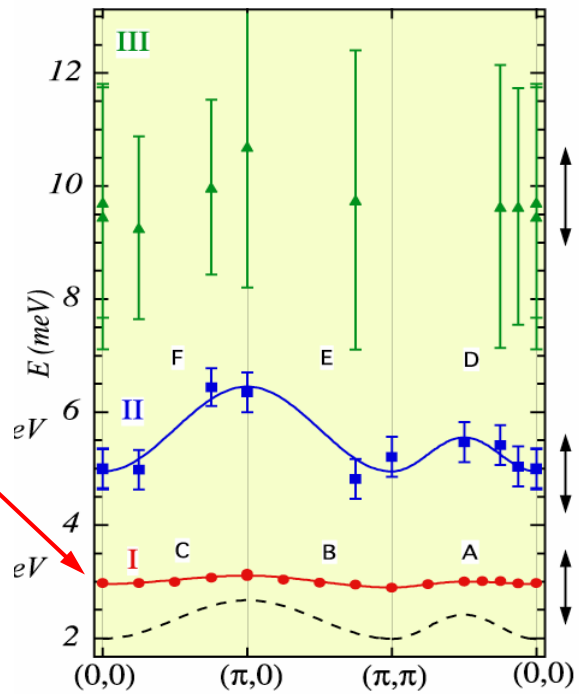
$$(\quad)\ |t_1\rangle|s\rangle = J'/2\,(|t_1\rangle|t_0\rangle - |t_0\rangle|t_1\rangle)$$

correction to localized triplets very small - starting only in 6-th order of perturbation $(J'/J)^6$

(negligible dispersion)

very small kinetic energy ($E_k \approx \hbar^2 k^2 / 2m$)

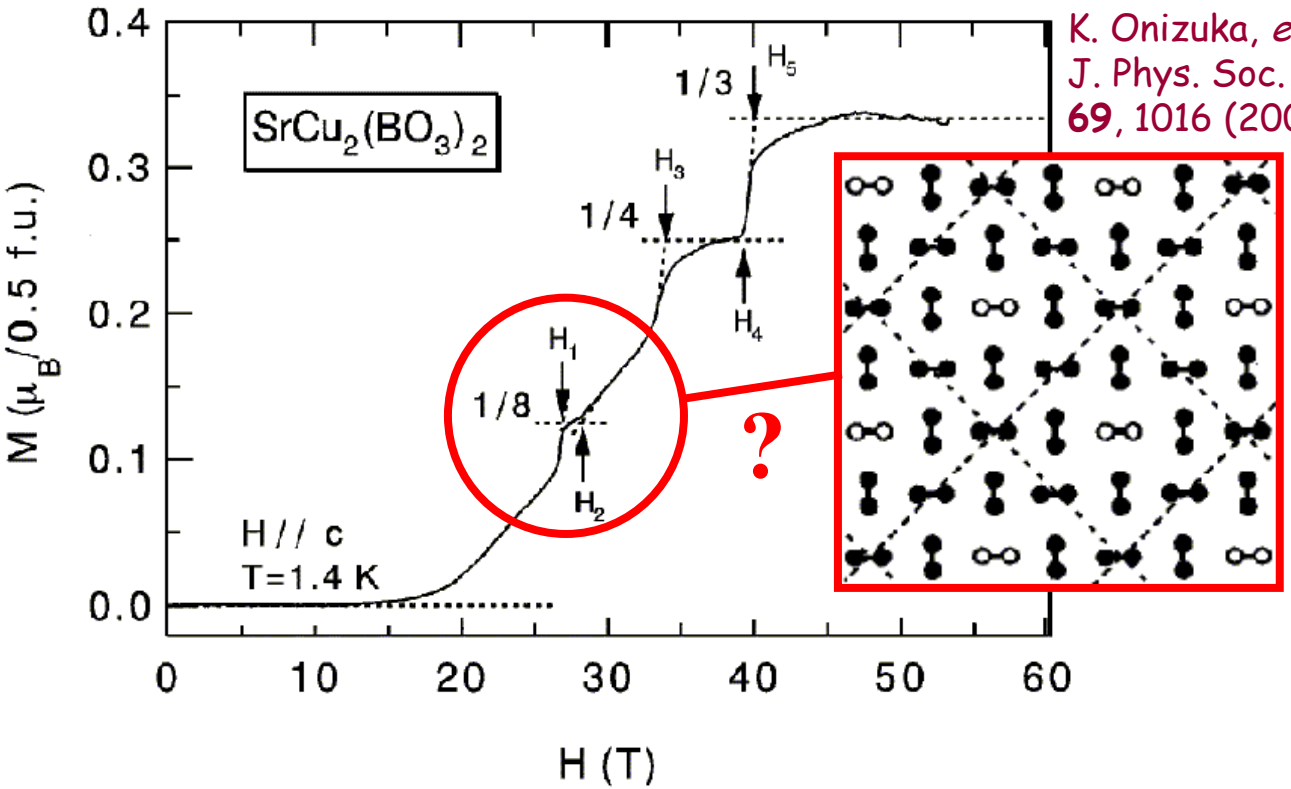
$\Rightarrow$ can easily crystallize !



[Kageyama *et al.*, PRL **84**, 5876 (2000)]

"Magnetic crystal" ?

1/8 plateau ?



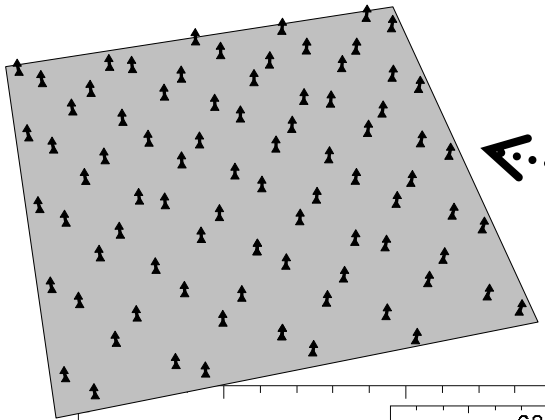
K. Onizuka, *et al.*, J. Phys. Soc. Jpn. **69**, 1016 (2000)

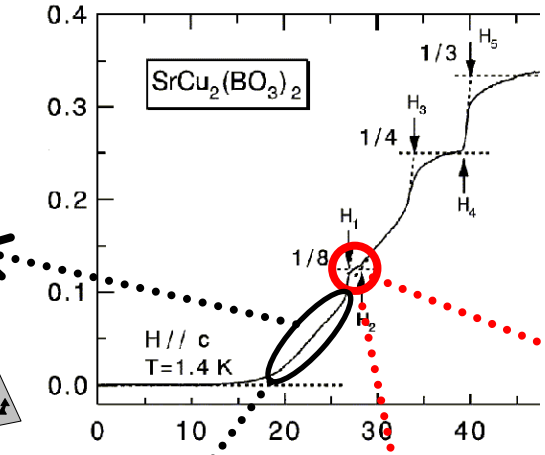
Problem:

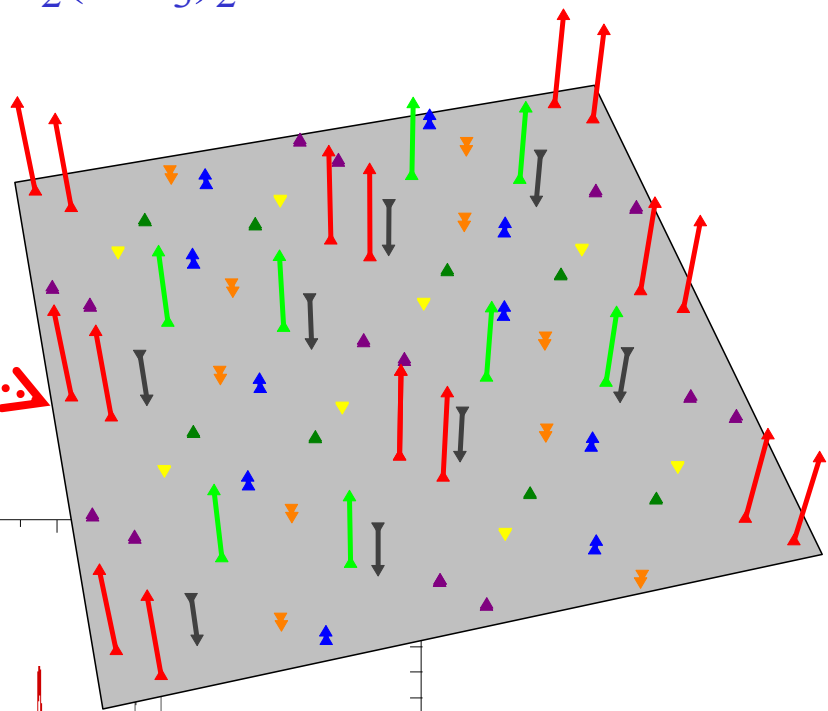
Plateaus of "fractional" magnetisation are supposed to be particularly stable, commensurate, spin-textured states.

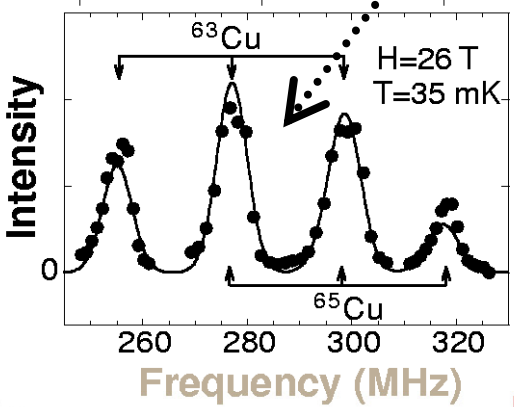
Experimentally, due to high magnetic field involved, their magnetic structure can be accessed only by NMR !

^{63,65}Cu (I=3/2) NMR spectrum of $SrCu_2(BO_3)_2$ at 35 mK





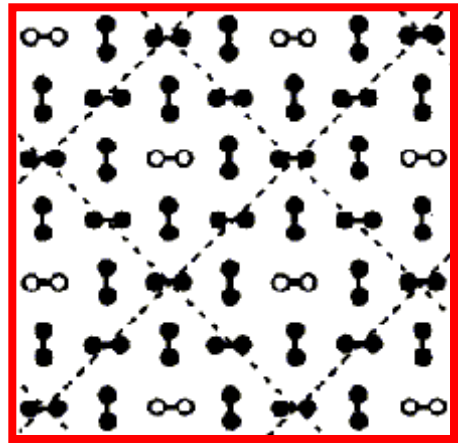


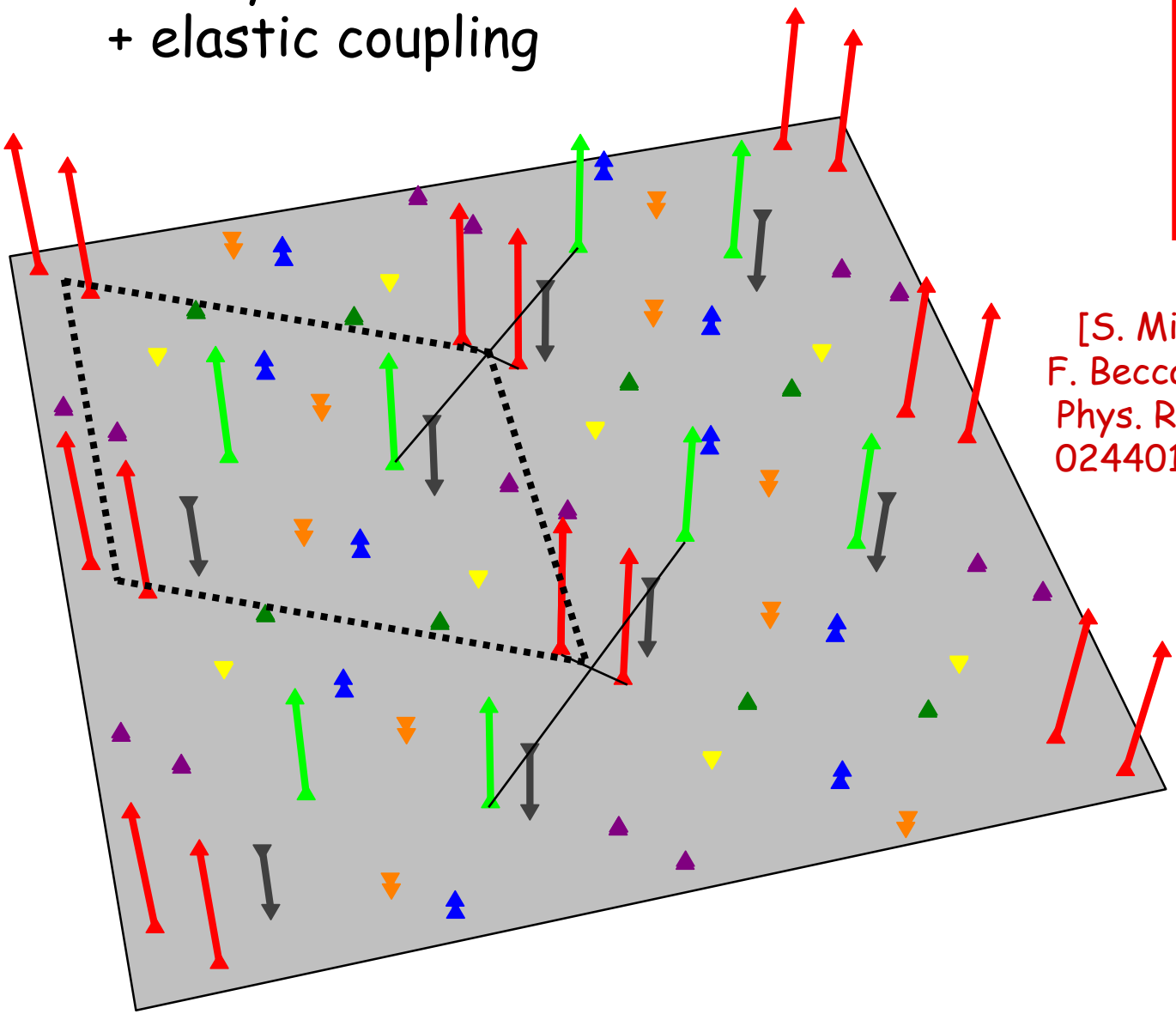


the most expensive NMR spectrum ...

K. Kodama *et al.*, Science **298**, 395 (2002)

numerics on
Shastry-Sutherland
+ elastic coupling





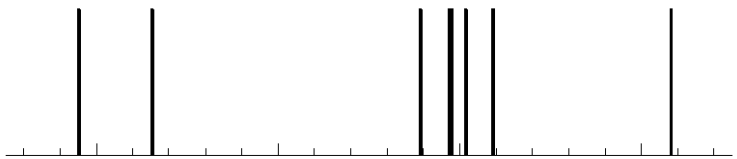
[S. Miyahara, F. Becca, F. Mila, Phys. Rev. B **68**, 024401 (2003)]

$\langle S_z \rangle =$

0.386
–0.215
0.312

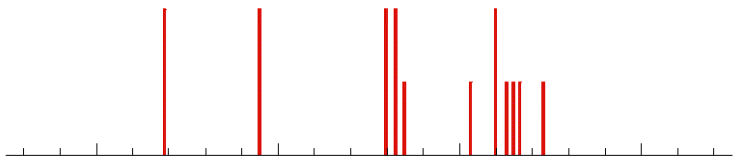
0.010
–0.035
0.040
–0.0063
0.0073

Theory + on-site hyperfine coupling:

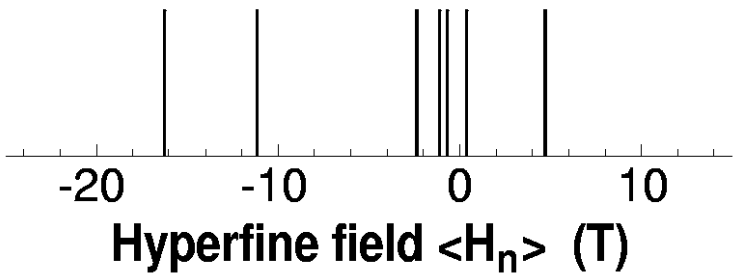


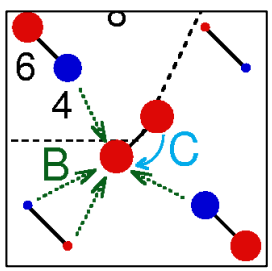
$A = -23.8\ \mathrm{T}/\mu_B$

Experiment:



Theory + on-site and NN coupling:





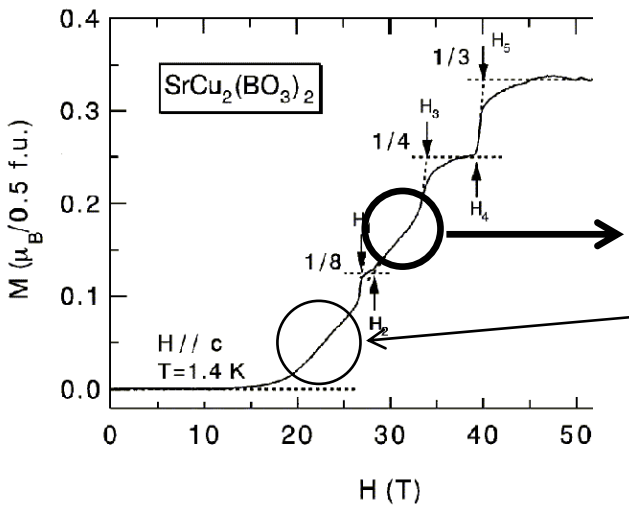
$A + 4B + C = -23.8\ \mathrm{T}/\mu_B$

$\Downarrow$

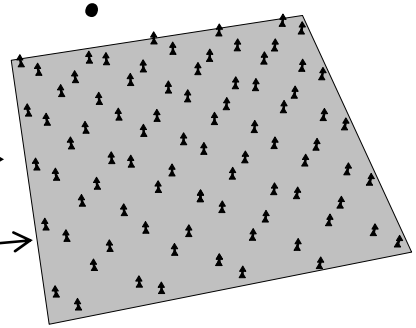
$B = -1.04\ \mathrm{T}/\mu_B$

$C = -2.45\ \mathrm{T}/\mu_B$

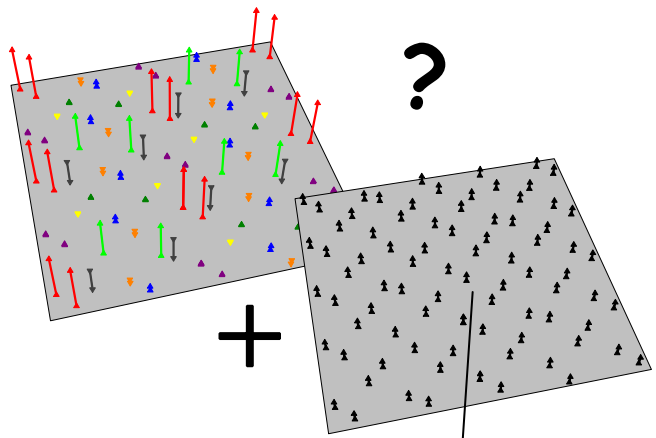
What is expected above the 1/8 plateau, at 28 - 33 T ?



?



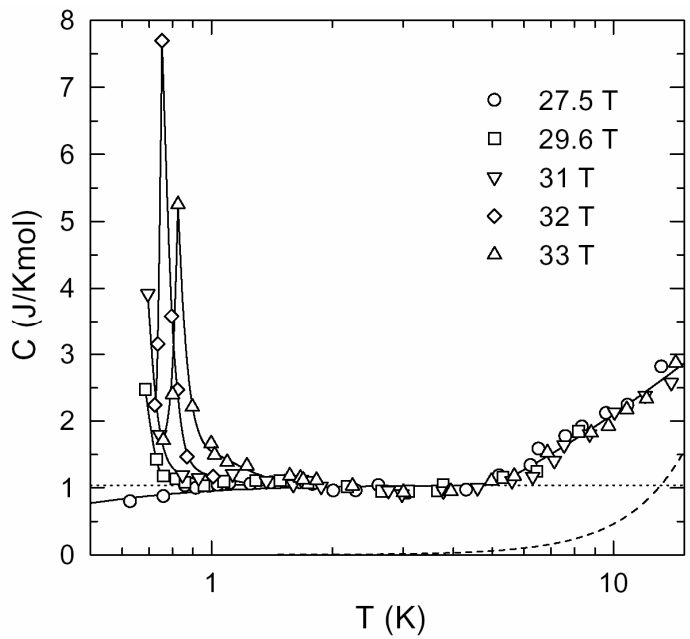
or



?

+

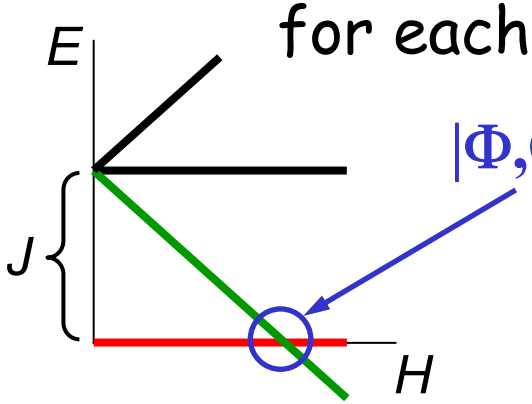
if BEC ⇒ supersolid



At and above plateau, specific heat sees only the same 2D gas of 1/8 of triplets, and not the particles that carry additional magnetization !

[H. Tsujii *et al.*, cond-mat/0301509]

Bose condensation of hard core bosons ?

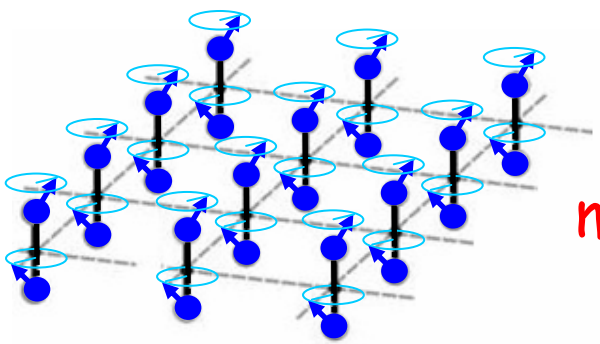


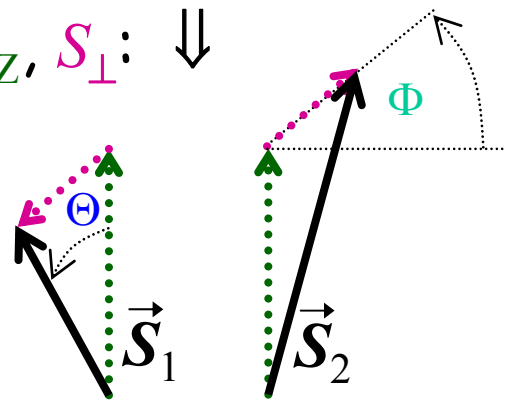
for each dimer:

[Momoi and Totsuka, PRB **62**, 15067 (2000)]

$$|\Phi,\Theta\rangle = e^{-i\Phi/2}\cos\Theta\,|\uparrow\uparrow\rangle + e^{+i\Phi/2}\sin\Theta\,\{|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\}/\sqrt{2}$$

local projections of S_z, $S_\perp$: ⇓

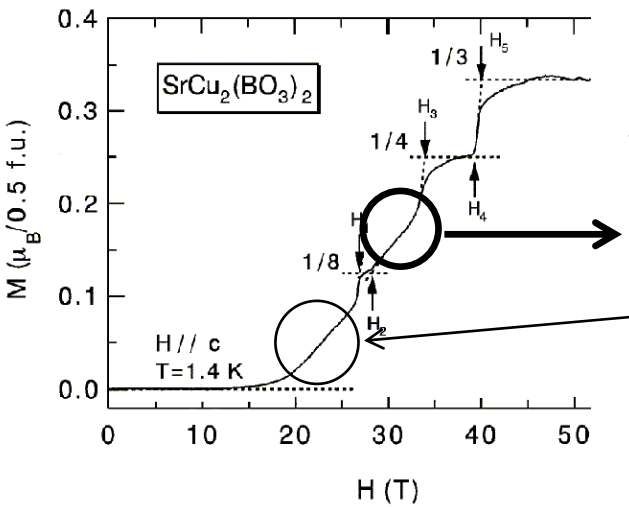




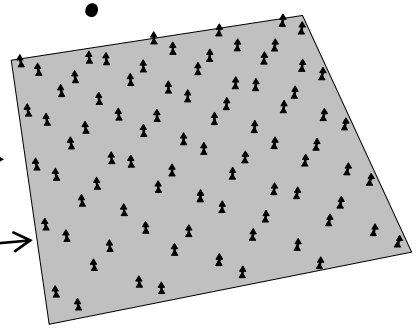
staggered $S_\perp$ moments - may order ! (gapless ODLRO)

NMR should detect a line-splitting (into two lines) corresponding to a Néel type order !

What is expected above the 1/8 plateau, at 28 - 33 T ?

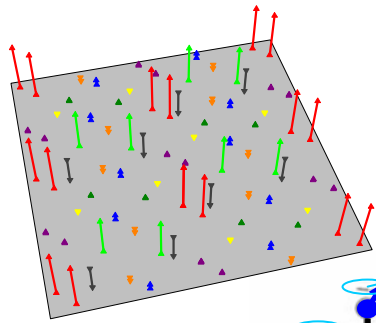


?



or

?



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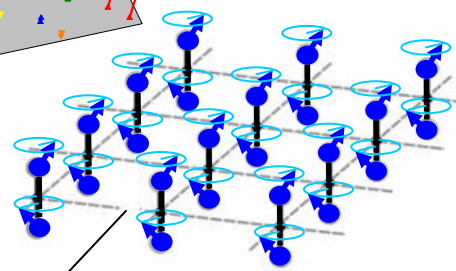
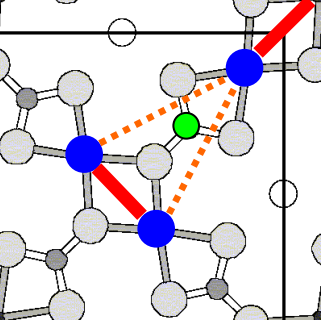


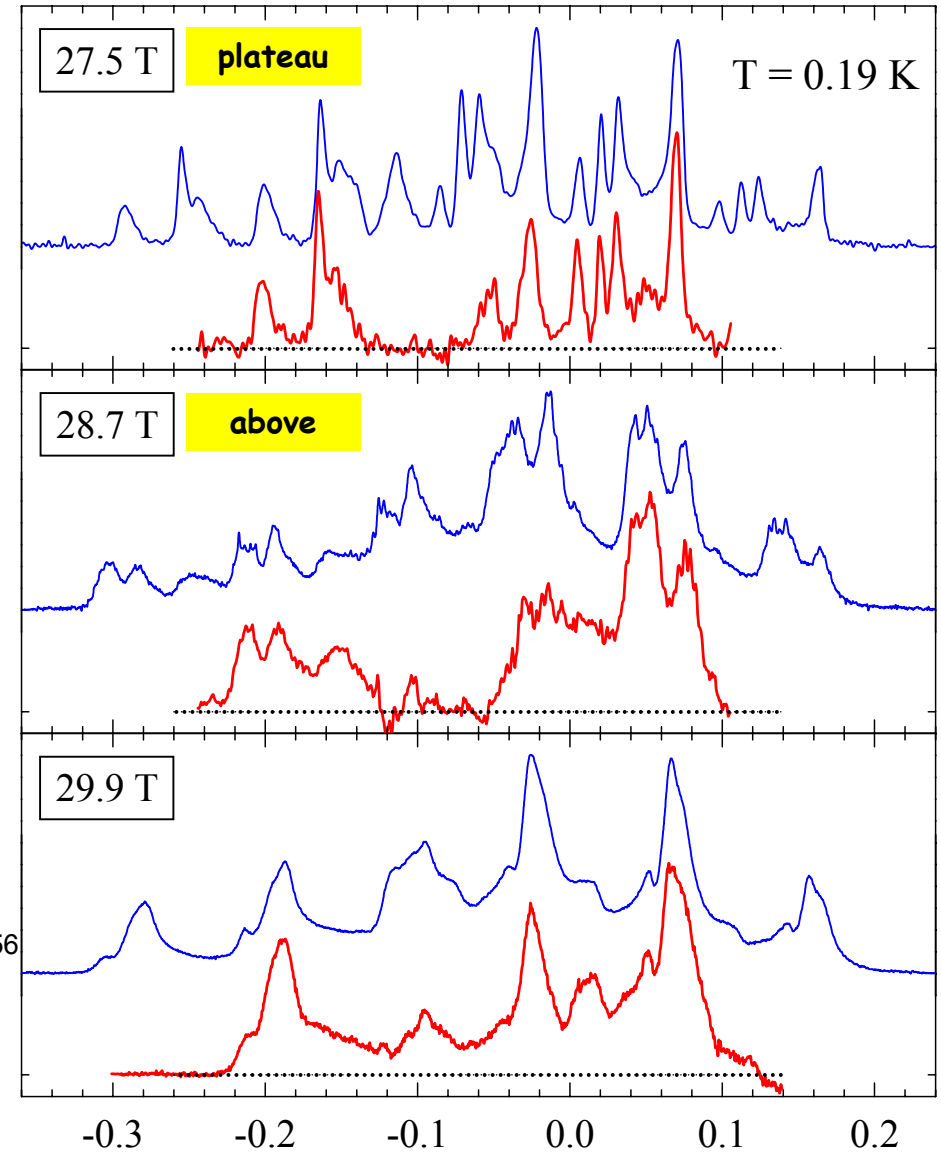
if BEC ⇒ supersolid

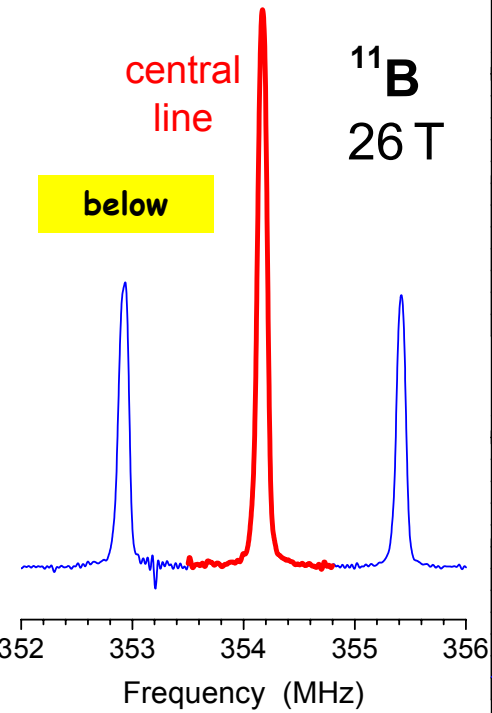
but DM terms $\vec{D}\cdot\vec{S}_{i+\delta}\times\vec{S}_i$
break the U(1) symmetry

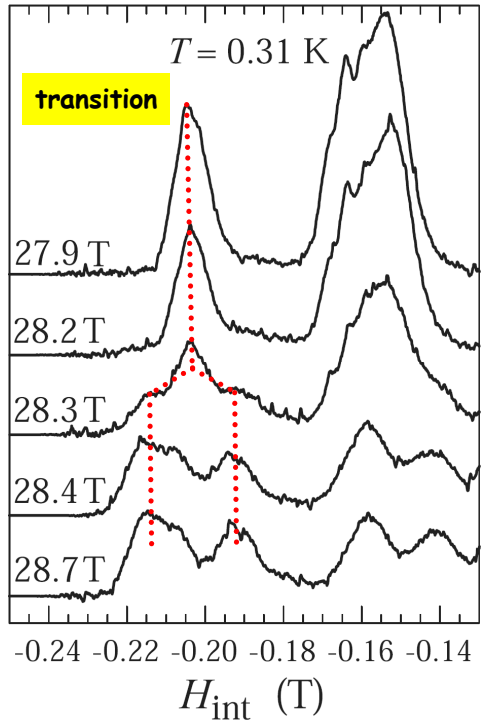


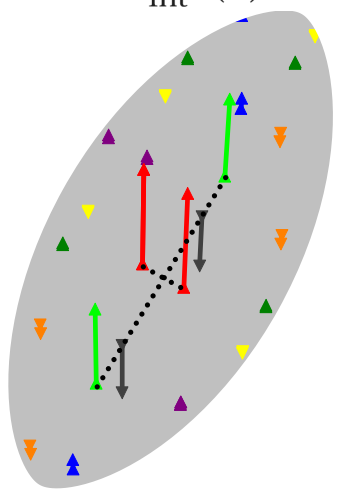
^{11}B NMR above the 1/8 plateau

$H_{c2} = 28.35$ T





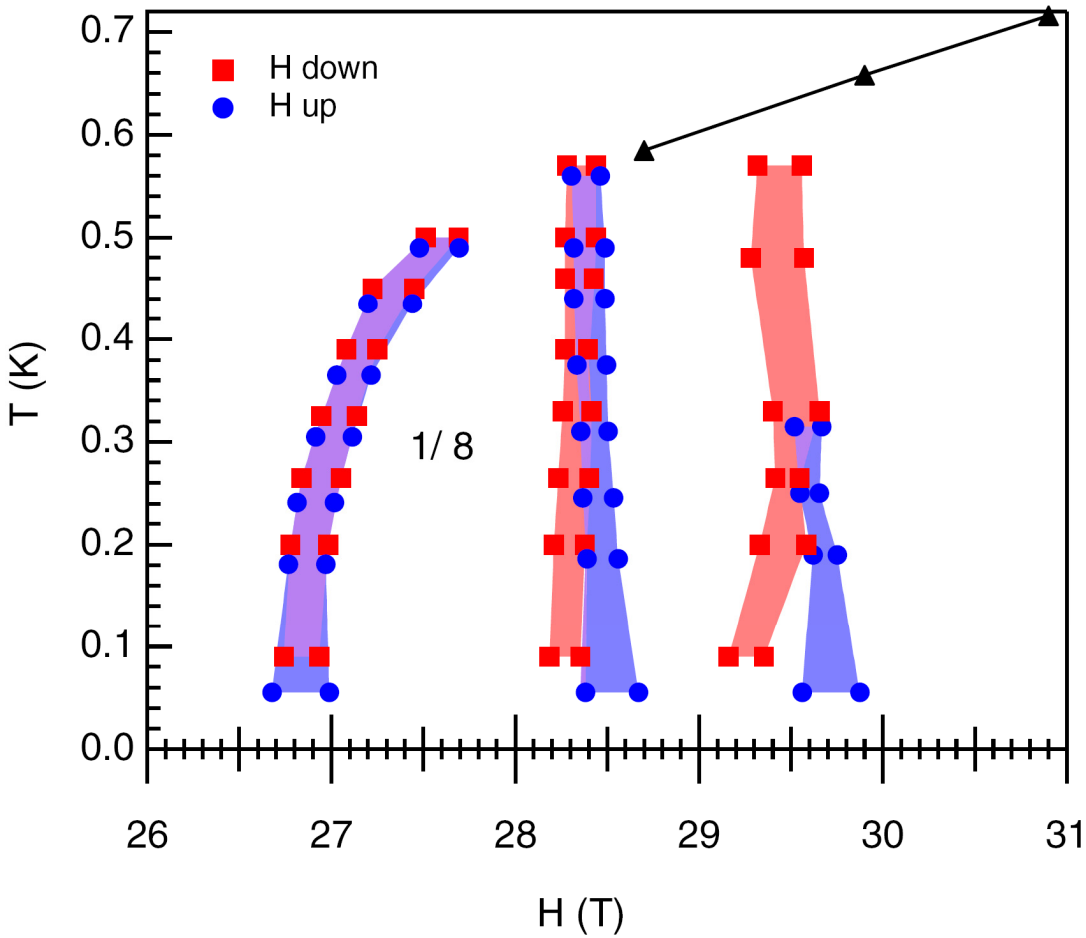


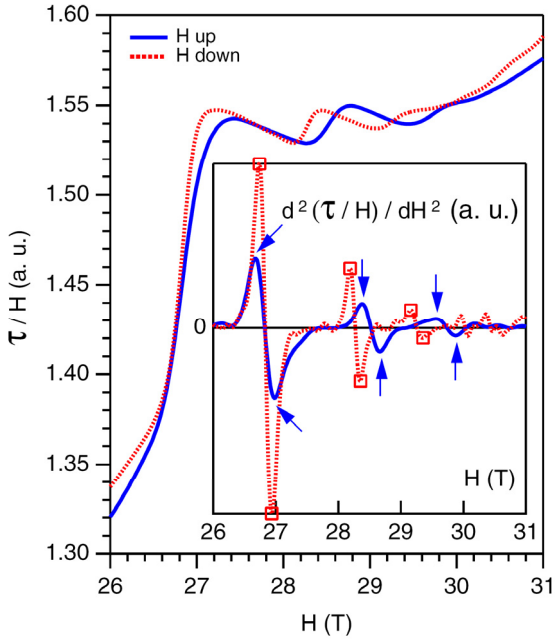


M. Takigawa *et al.*,
PRL **101**, 037202 (2008)

superstructure persists !

Torque:

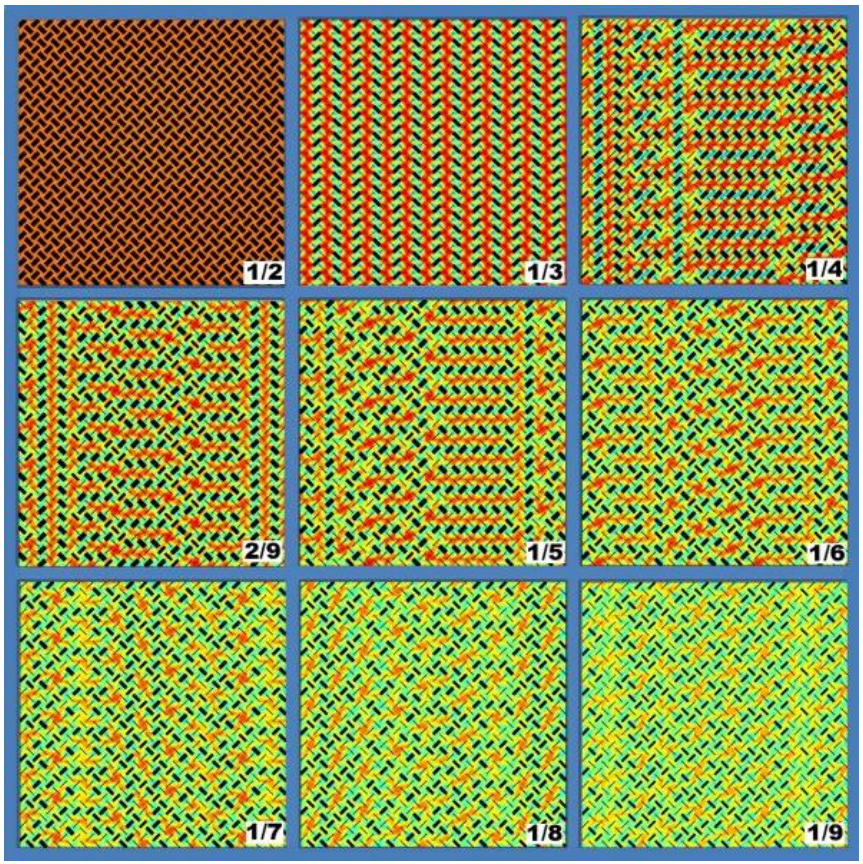




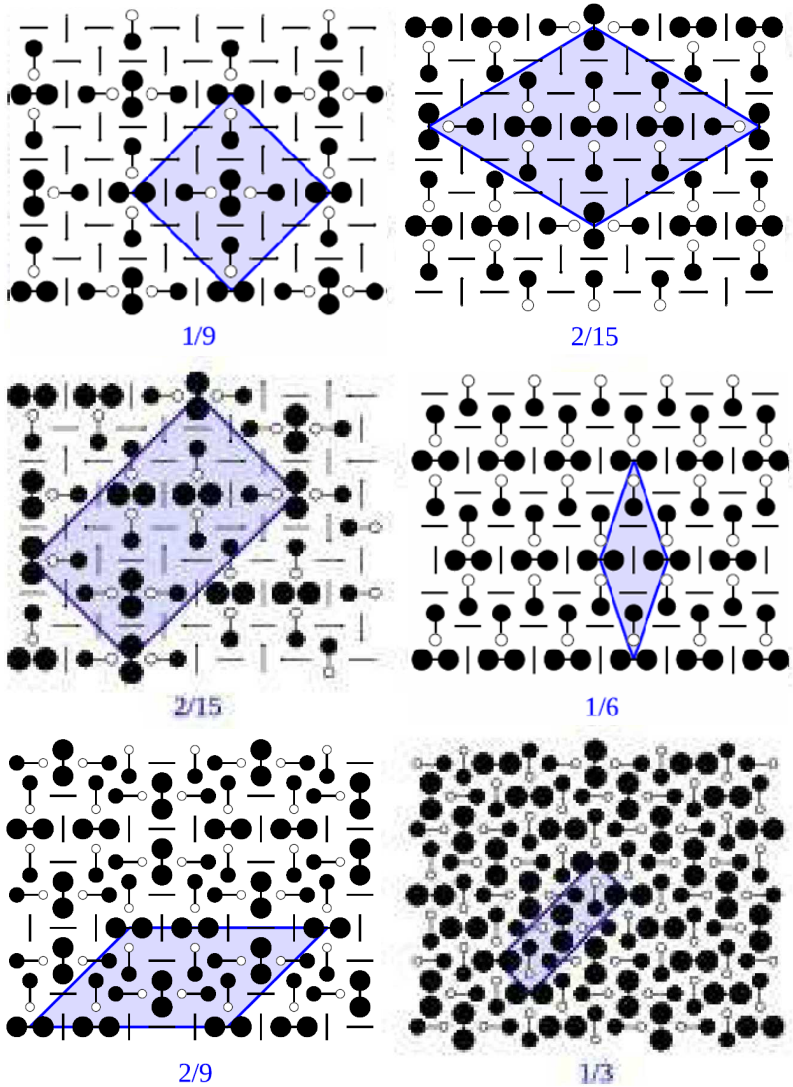
F. Lévy *et al.*, EPL 81, 67004 (2008)

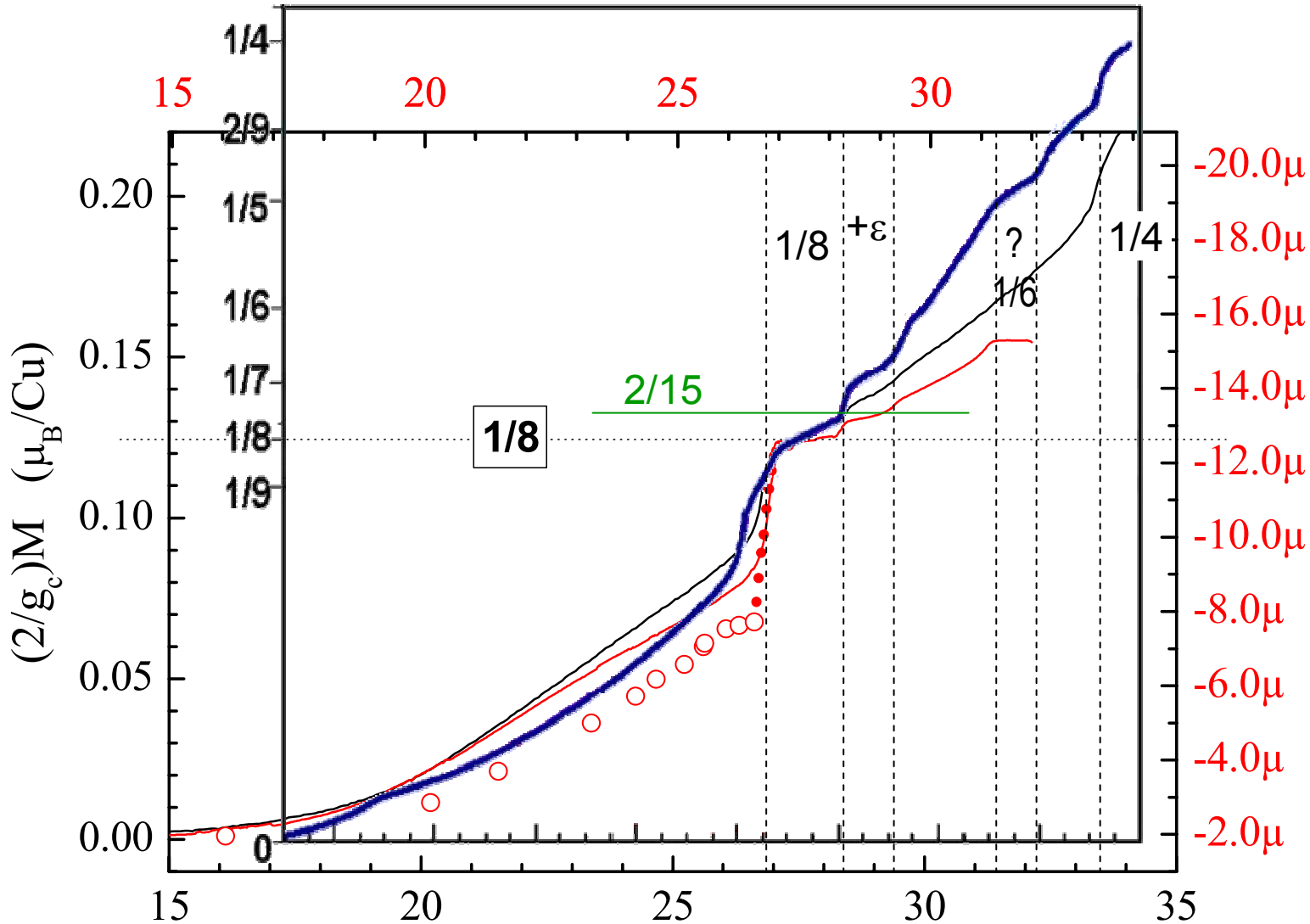
"only" 1/8, 1/4 and 1/3 ?
or more ?

Sebastian S.E. *et al.*,
arXiv:0707.2075



J. Dorier, K. P. Schmidt & F. Mila,
arXiv:0806.3406





○ NMR lineposition

• NMR intensity in the mixed phase

—— pulsed field at 1.5 K (+ adiabatic cooling), K. Onizuka *et al.*, J. Phys. Soc. Jpn. **69**, 1016 (2000).

—— by torque @ GHMFL, F. Lévy *et al.*, EPL **81**, 67004 (2008) and unpublished

—— by torque @ NHMFL, S. Sebastian *et al.*, arXiv:0707.2075

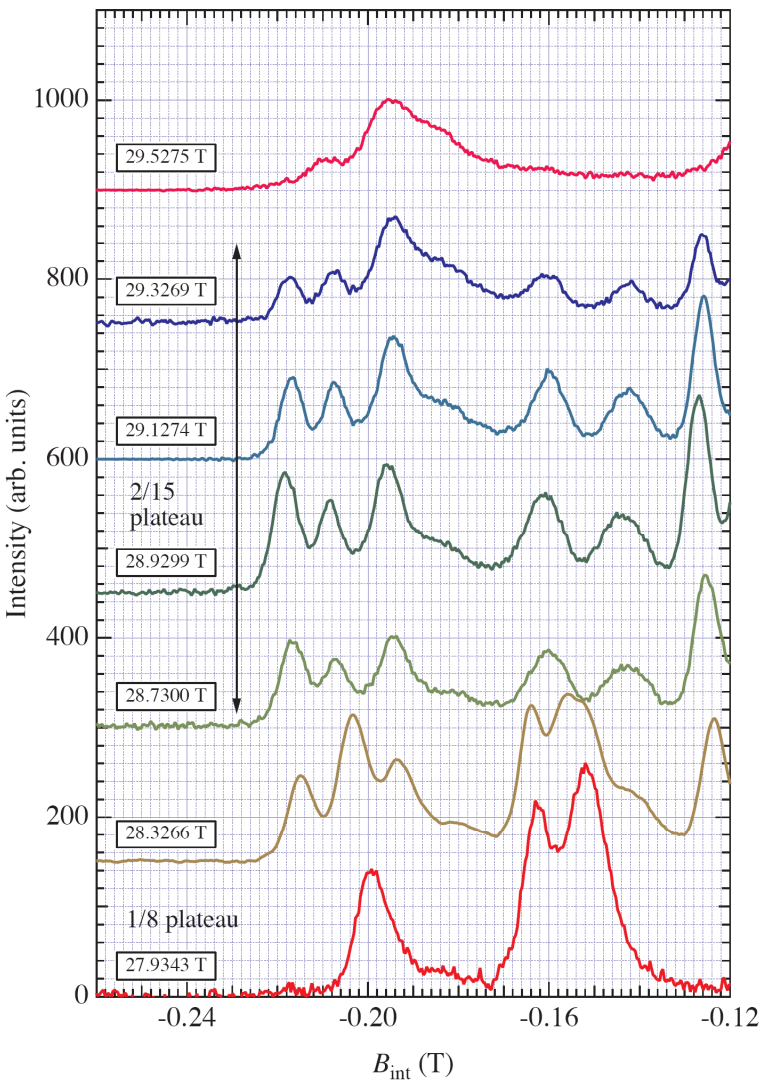
Theory: new fractions by Dorier, Schmidt & Mila, arXiv:0806.3406: **1/9, 2/15, 1/6, 2/9, 1/3**

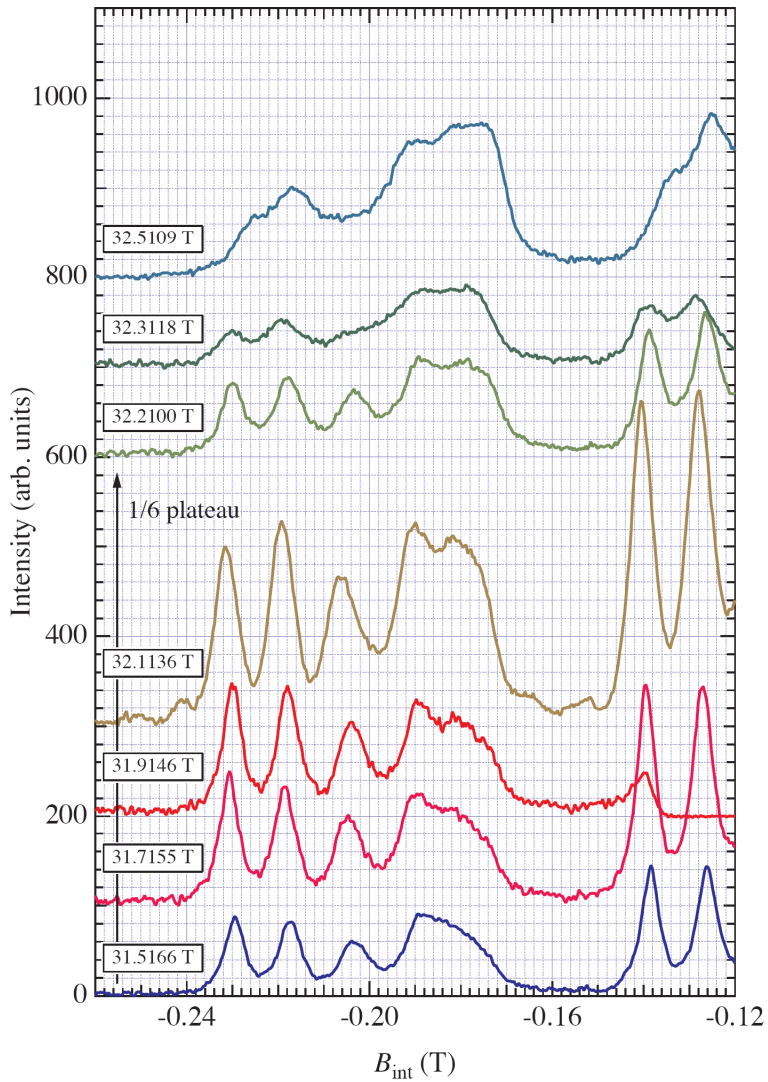
Plateau: field independent spin superstructure / NMR spectra

1/8+ε

1/6 ?

T = 0.43 K





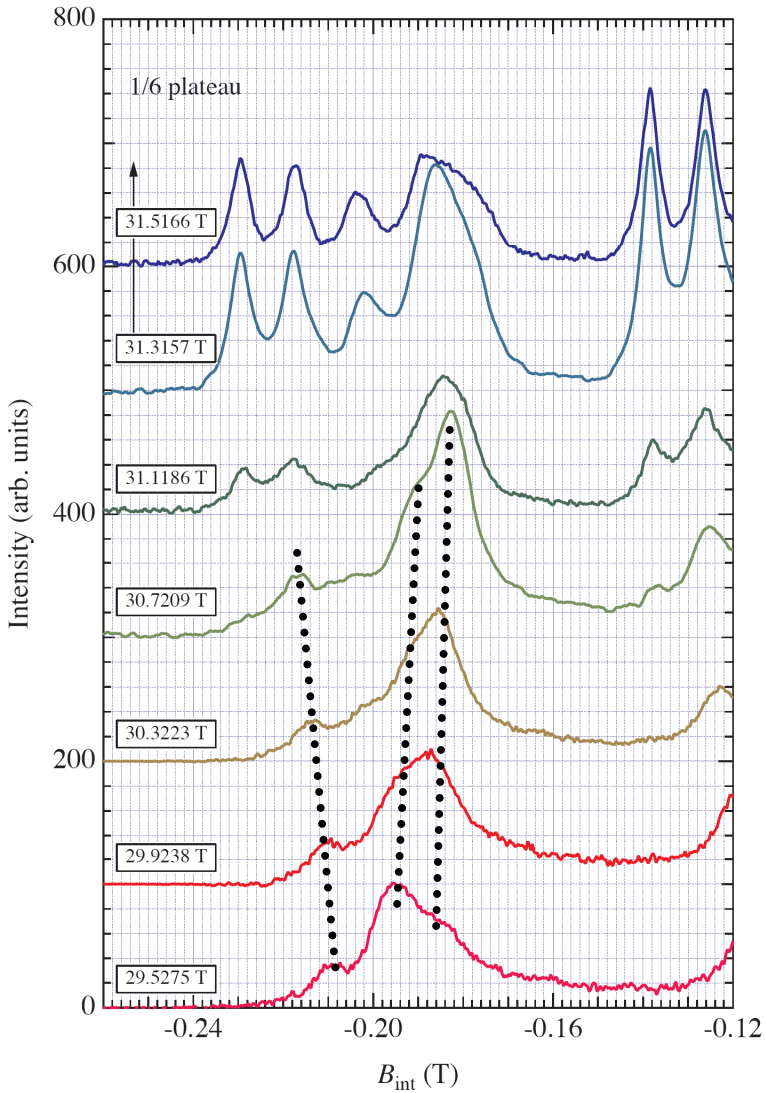
M. Takigawa *et al.*, June 2008, unpublished

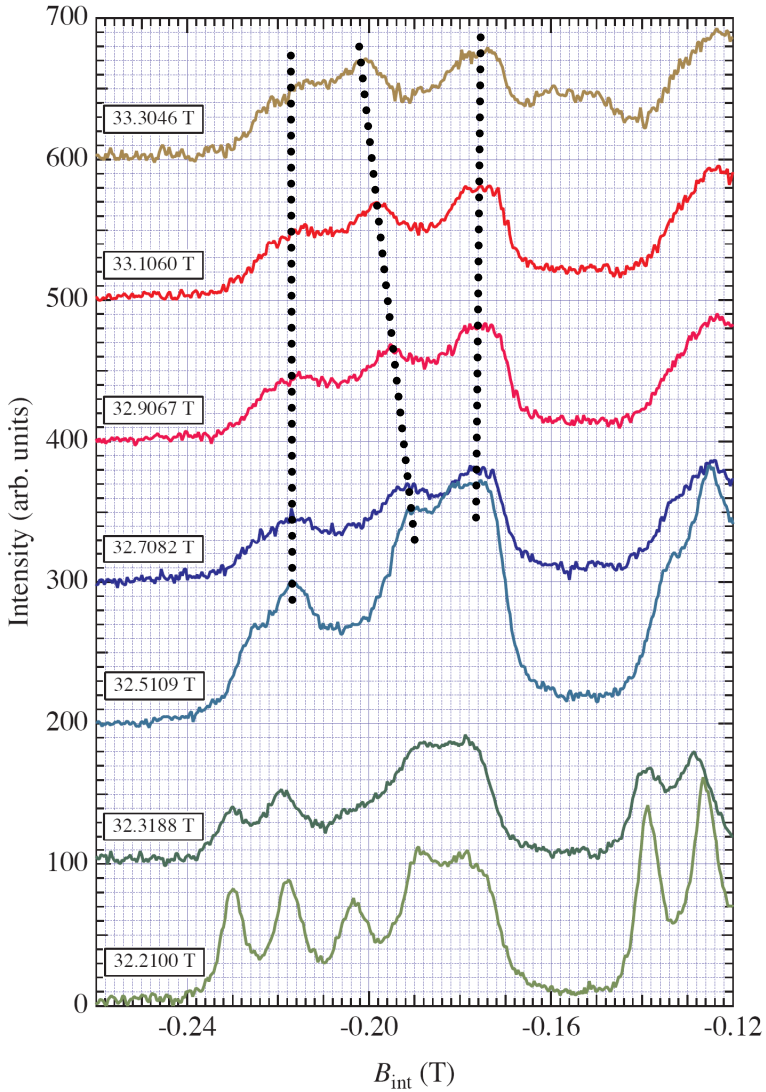
Continuous field dependence in-between the plateaus

1/8+ε ↔ 1/6 ?

T = 0.43 K

1/6 ? ↔ "1/4"





M. Takigawa *et al.*, June 2008, unpublished

phase diagram:

by NMR:

▲ K. Kodama *et al.*, Science **298**, 395 (2002)

● M. Takigawa *et al.*, PRL **101**, 037202 (2008) and

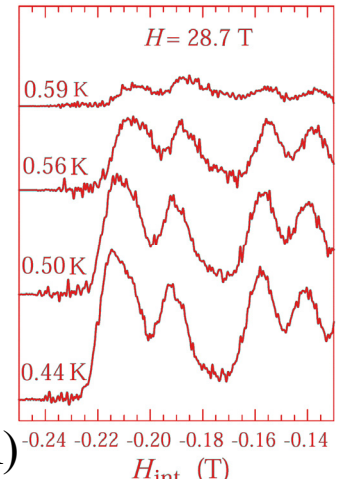
× unpublished (June 2008)

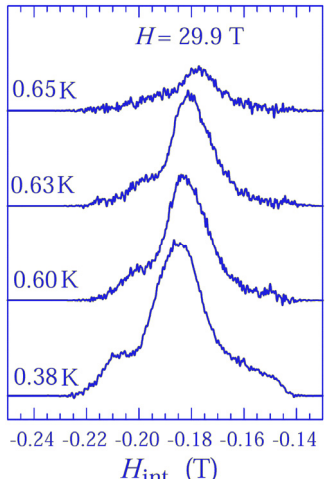
also by: torque

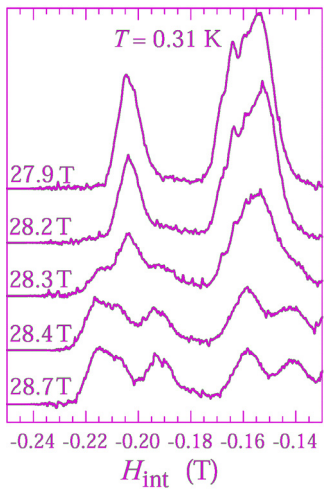
F. Lévy *et al.*, EPL **81**, 67004 (2008) and unpublished

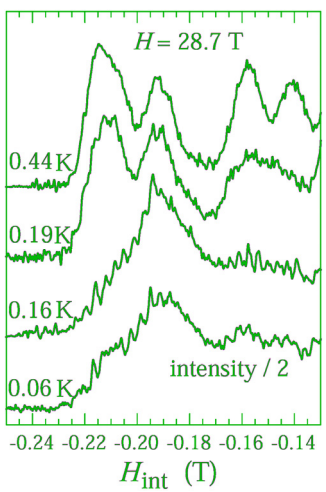
□ specific heat

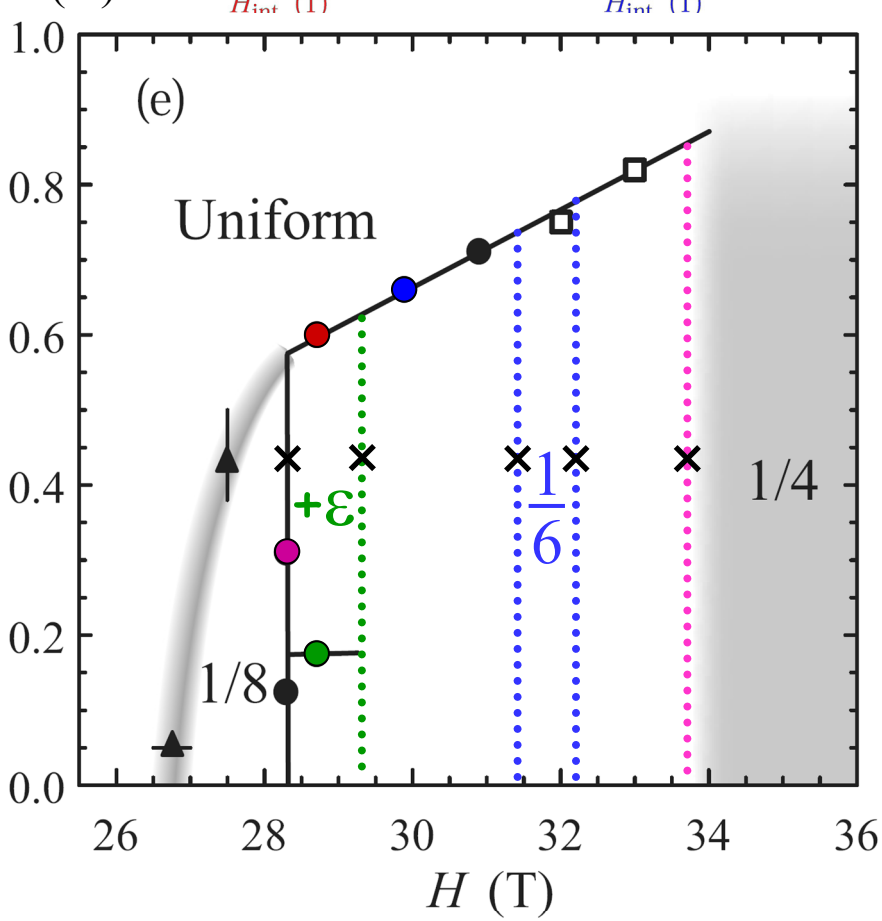
H. Tsujii *et al.*, cond-mat/0301509











linesplitting:

supercell

of extended triplets

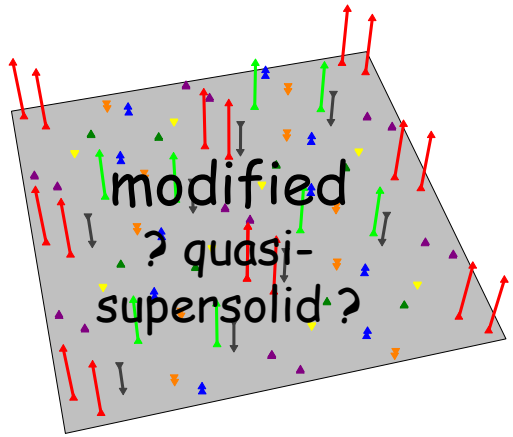
or

"quasi-BEC" staggered moments ?

[rotational symmetry already broken by DM $(\vec{D}\cdot\vec{S}_1\times\vec{S}_2)$ interaction]

$SrCu_2(BO_3)_2$ conclusions:

[M. Takigawa *et al.*, PRL **101**, 037202 (2008) and unpublished]



Spin superstructure persists
in-between "1/8" and "1/4" plateau

New plateau phases discovered:
1/8+ε or 2/15 (?) and 1/6 (?)

NMR line-splitting in these phases:
"supercell" or "quasi-supersolid" (BEC) ?

↓ ↓ ↓ ↓ ↓

NMR: simulate spectra, importance of staggered moments …

Theory: stable structures, supersolid in presence of symmetry breaking DM terms ?