Low-Dimensional Spin Systems and Quantum Magnetism

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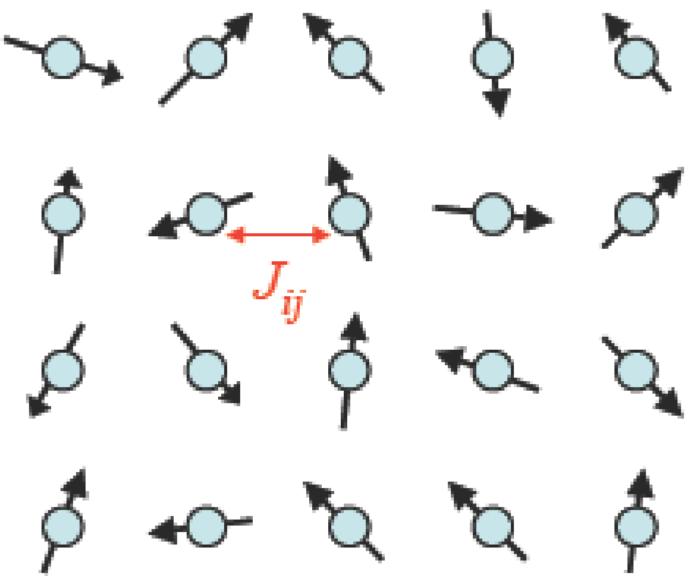
Magnetic Phase Transitions

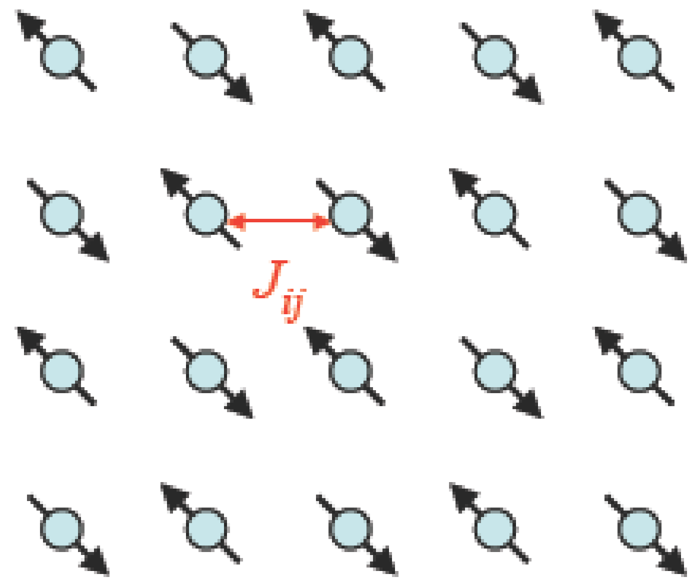
An ordered configuration of magnetic moments with a long correlation length

Disordered State:



Lowering of Temp

Ordered State:



$$\langle S \rangle = 0$$

$k_B T$ vs. Exchange Energy

$$\langle S \rangle \neq 0$$

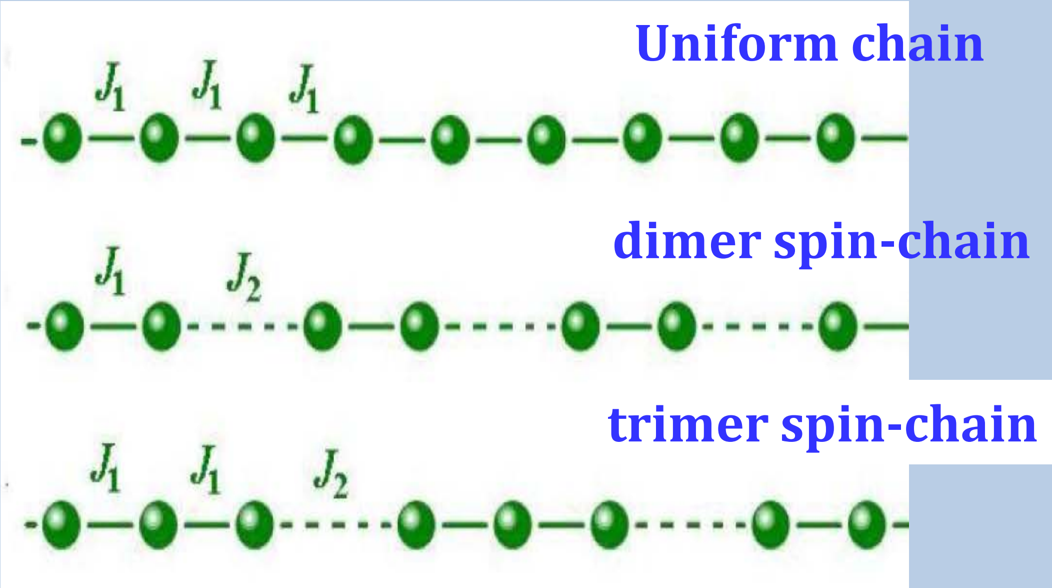
Absence or Presence of a LRO at a Finite *T*

VOLUME 17, NUMBER 22 PHYSICAL REVIEW LETTERS 28 NOVEMBER 1966

N. D. Mermin† and H. Wagner‡
Laboratory of Atomic and Solid State Physics, Cornell University, Ithaca, New York

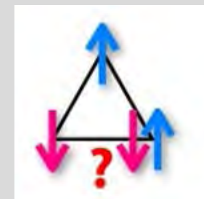
Spin/Space	d =1	d =2	d = 3
Ising	x	Yes	Yes
XY	x	Yes?	Yes
Heisenberg	x	x	Yes

Theorem of Mermin and Wagner

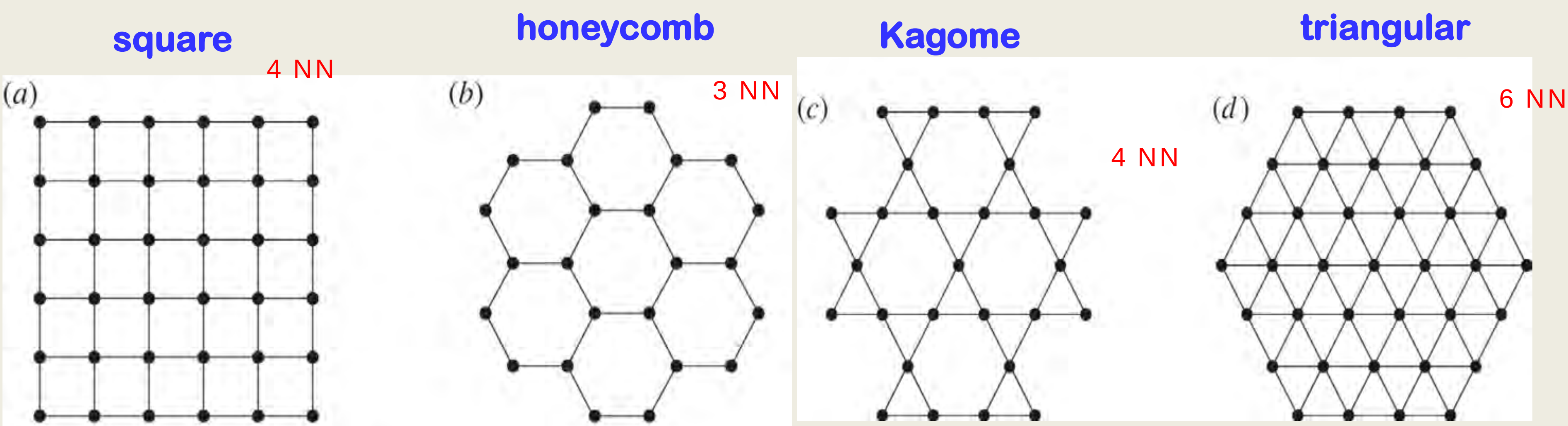


Frustration with NN interactions

Ising

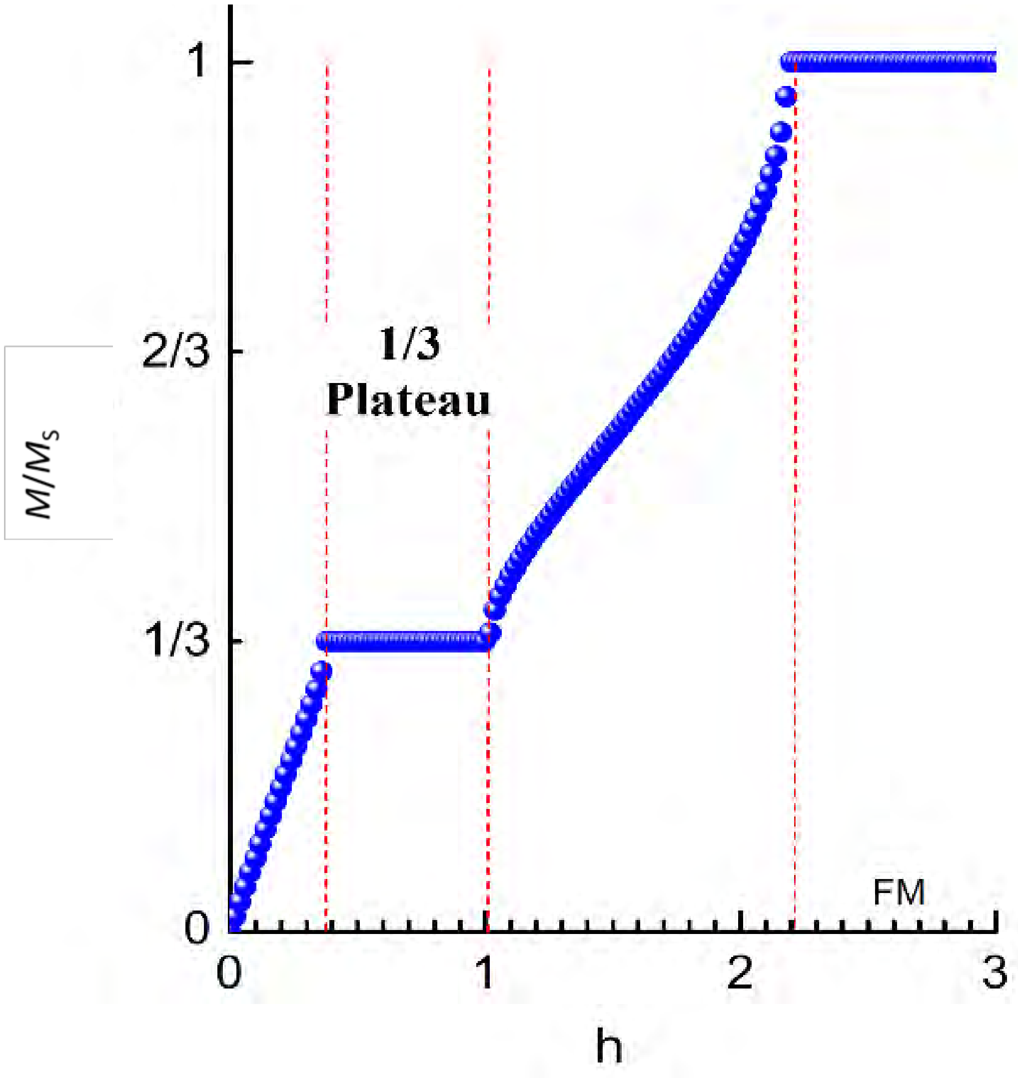


Heisenberg/XY



Magnetic properties dictated by the nature of exchange interactions

Quantum Fluctuations
Quantum Phase Transitions
Quantum Magnetization Plateau



Review Article:

APPLIED PHYSICS REVIEWS **4**, 031303 (2017)

APPLIED PHYSICS REVIEWS

Neutron scattering of advanced magnetic materials

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(Received 23 February 2017; accepted 9 June 2017; published online 16 August 2017)

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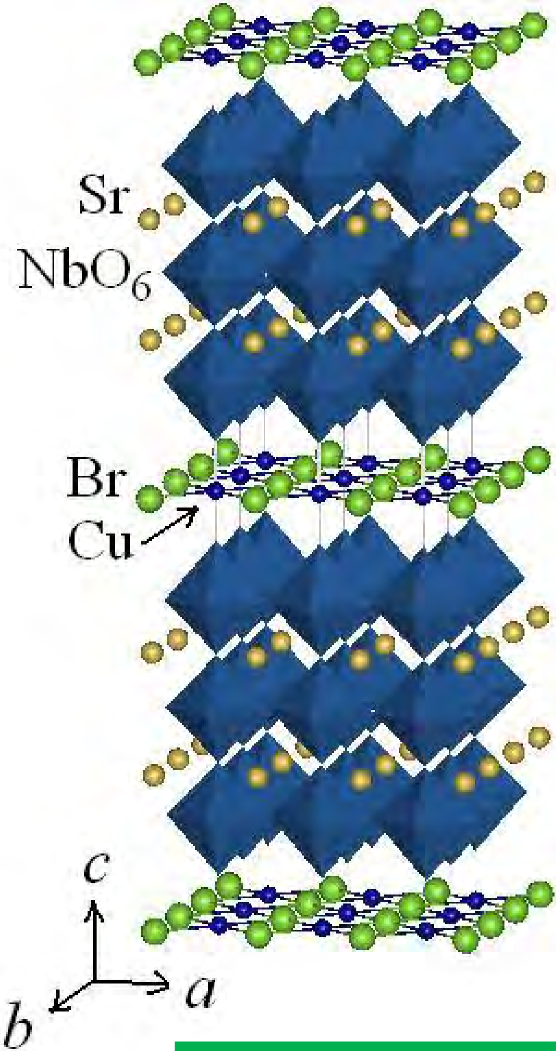
Square-lattice spin system $(CuBr)Sr_2Nb_3O_{10}$

Layered Crystal Structure



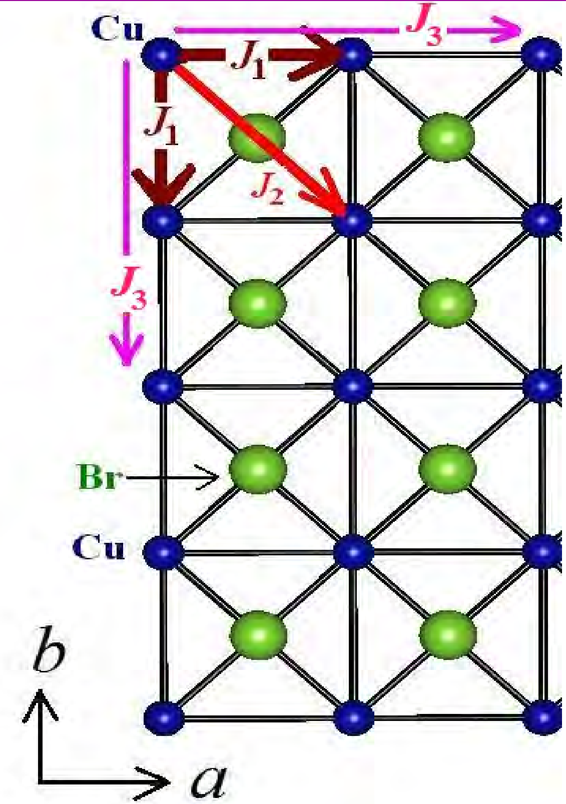
$(CuBr)Sr_2Nb_3$

Tetragonal

$P4/mmm$

$a = 3.888(1)$ Å
$c = 15.947(1)$ Å

Square-lattice Spin ½ System



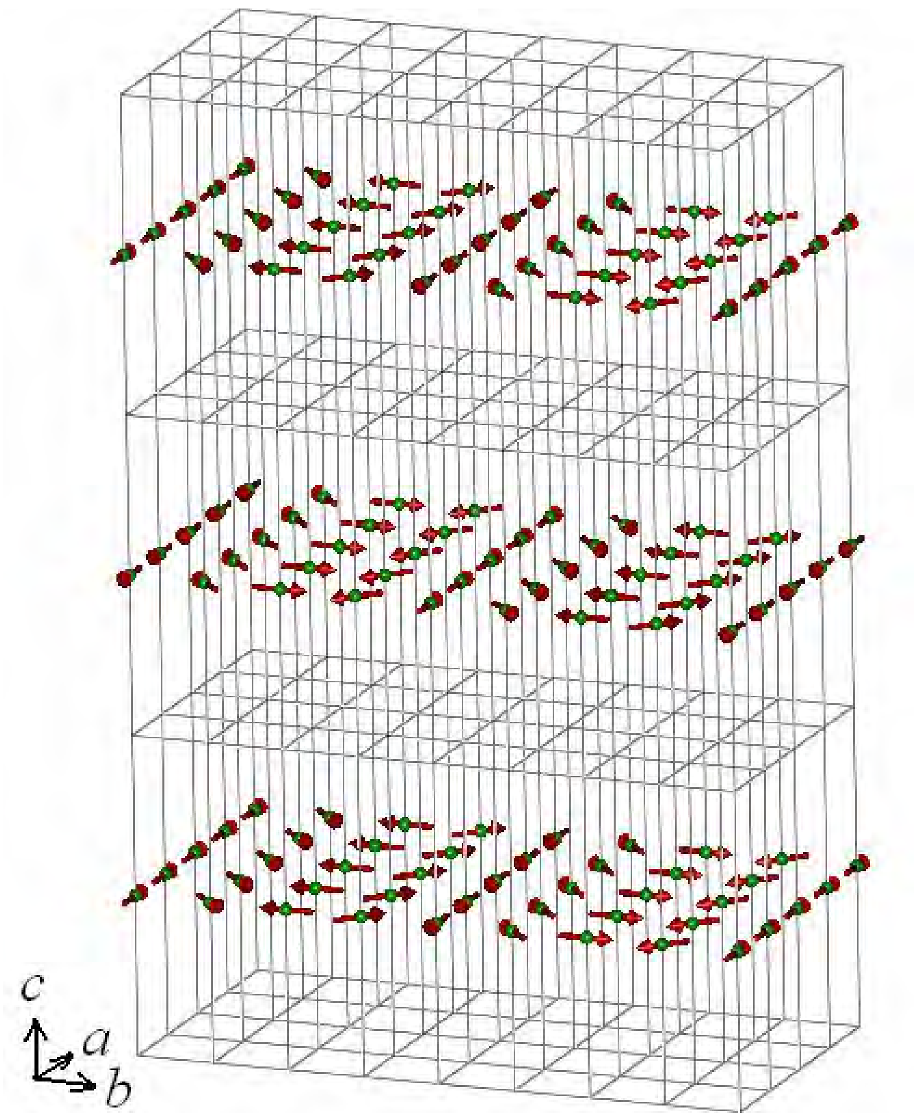
S. M. Yusuf, A. K. Bera, et al.
Phys. Rev. B 84, 064407 (2011)

C Ritter, S M Yusuf, et al.
Phys. Rev. B 88, 104401 (2013)

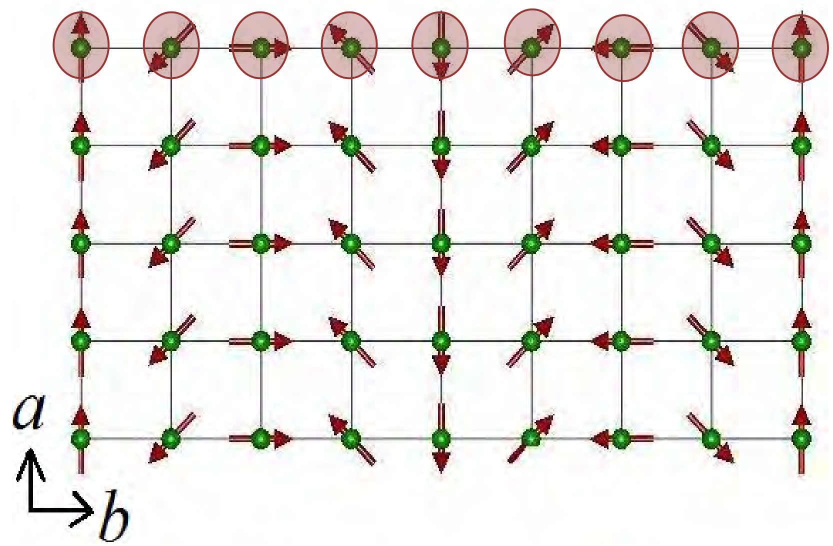
Square-lattice spin system $(CuBr)Sr_2Nb_3O_{10}$

Commensurate in-plane Spiral Order

$k = (0\ 3/8\ 1/2)$ $4a \times 8b$



$4a \times 8b \times 3c$

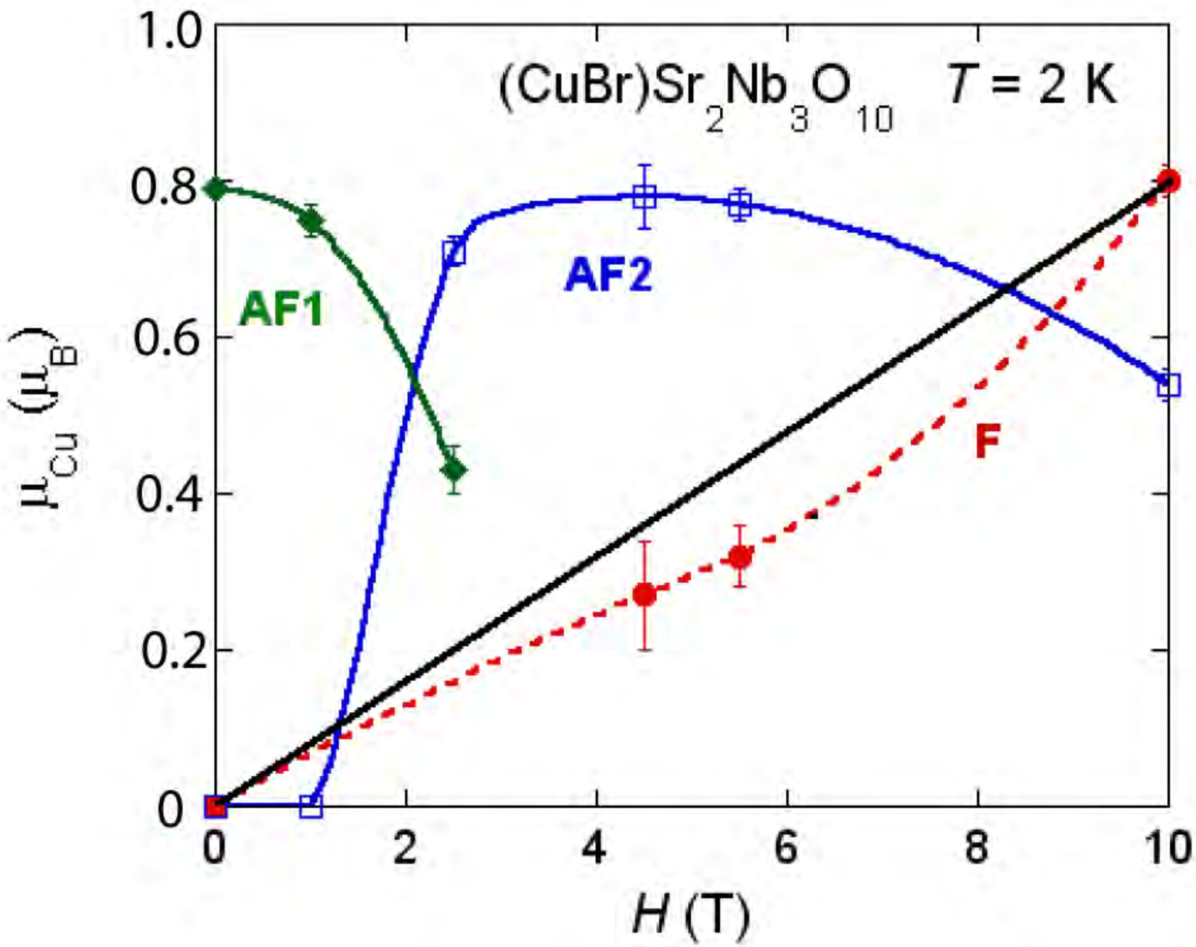


Cu^{2+}*: 0.79(7) μ_B *at 2 K

Quantum fluctuations.

2D *S = ½ AFM square lattice: ~0.6 μ_B*

S. M. Yusuf, et al.
Phys. Rev. B 84, 064407 (2011)



Helical antiferro AF1, with ***κ = [0 3/8 1/2]***

Second AFM, AF2, **with** ***κ = [0 1/3 ~ 0.46]***

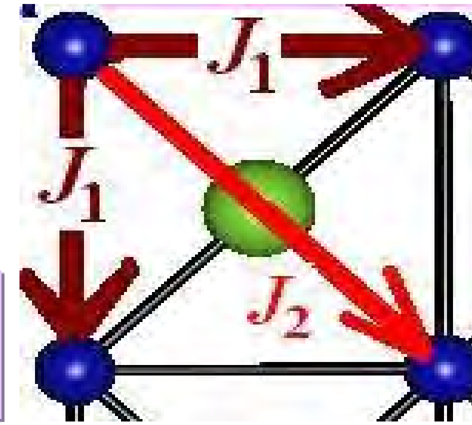
Simple ferro **phase with** ***κ = [0 0 0]***

S. M. Yusuf, A. K. Bera, et al. Phys. Rev. B 84, 064407 (2011)

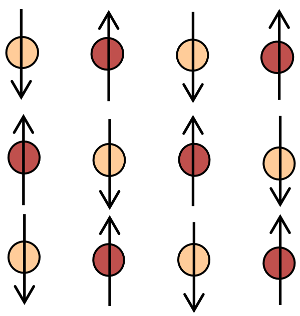
C Ritter, S M Yusuf, et al. Phys. Rev. B 88, 104401 (2013)

S = 1/2 **Square-lattice**

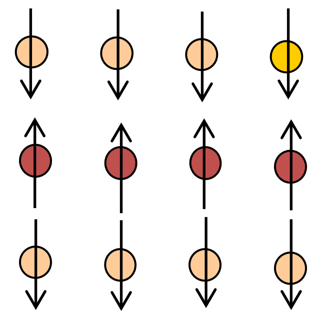
At *T* = 0 K

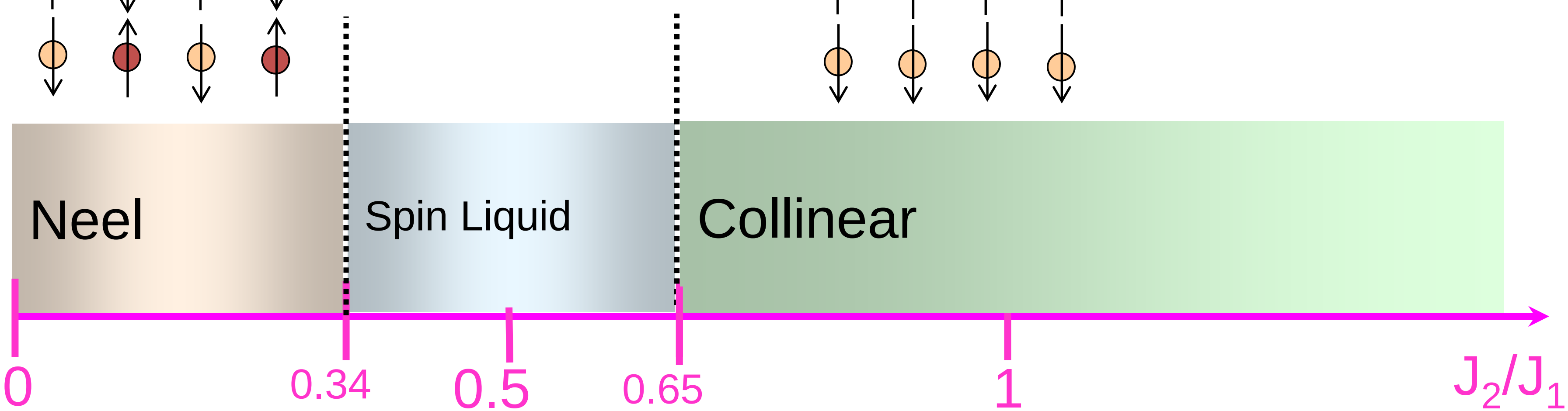


All four nearest neighbour spins are antiparallel



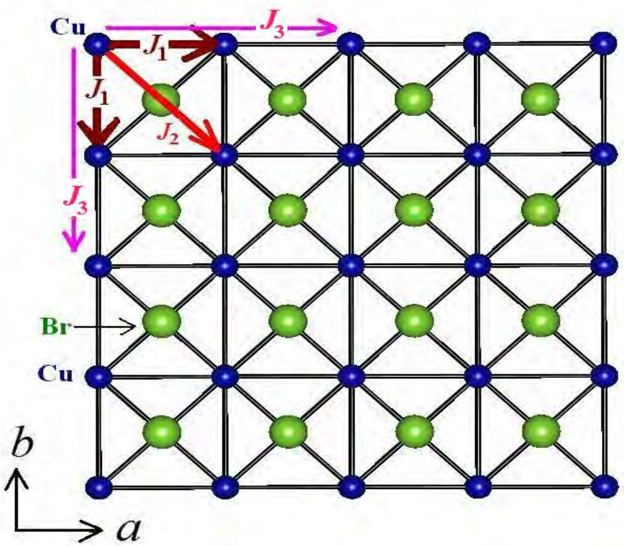
Antiparallel coupling of FM spin chains





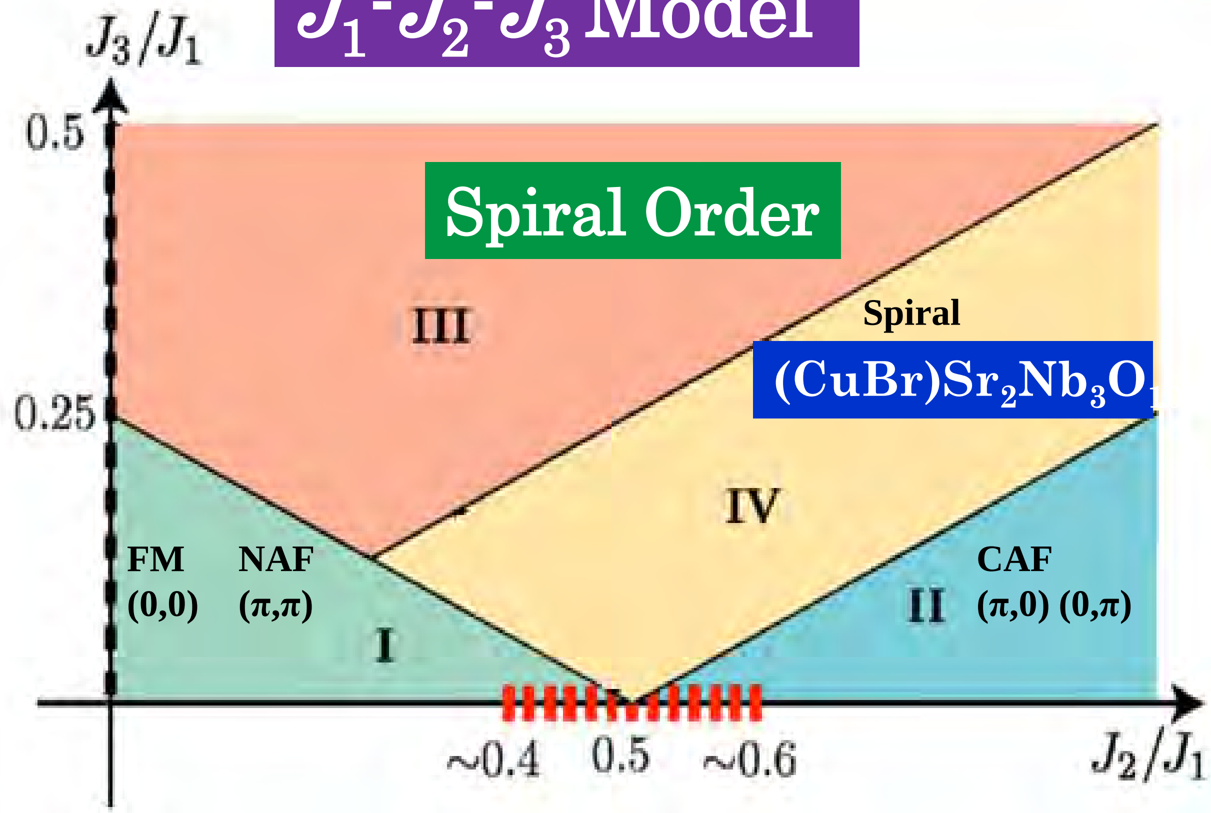
Schmalfuß et al., Phys. Rev. Lett. 97, 157201 (2006)

Square-lattice System



(CuBr)$Sr_2Nb_3O_{10}$

J_1-J_2-J_3 Model



S. M. Yusuf, et al,
Phys. Rev. B84,064407(2011)

C Ritter, S M Yusuf, et al.
Phys. Rev. B 88, 104401 (2013)

Cu^{2+}: 0.79(7) μ_B at 2 K

Quantum fluctuations
2D *S* = ½ *AFM square lattice: ~0.6 μ_B*

Our Research on Haldane chain compound

PHYSICAL REVIEW B **86**, 024408 (2012)

Quantum phase transition from a spin-liquid state to a spin-glass state in the quasi-one-dimensional spin-1 system $Sr_{1-x}Ca_xNi_2V_2O_8$

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(Received 21 September 2011; revised manuscript received 16 June 2012; published 9 July 2012)

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[28]M. D. Mukadam, S. M. Yusuf, P. Sharma, and S. K. Kulshreshtha, J. Magn. Magn. Mater. **269** 317 (2004).
[29]D. Petit, L. Fruchter, and I. A. Campbell, Phys. Rev. Lett. **83**, 5130 (1999).
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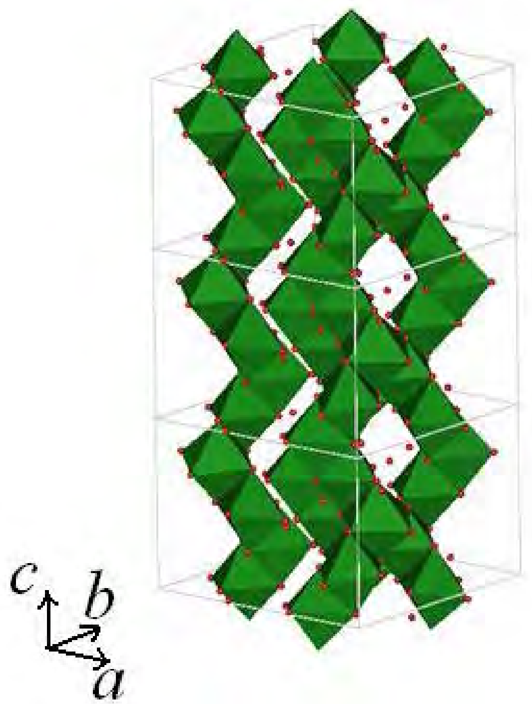
Quantum Spin-chain Systems: $Sr_{1-x}Ca_xNi_2V_2O_8$

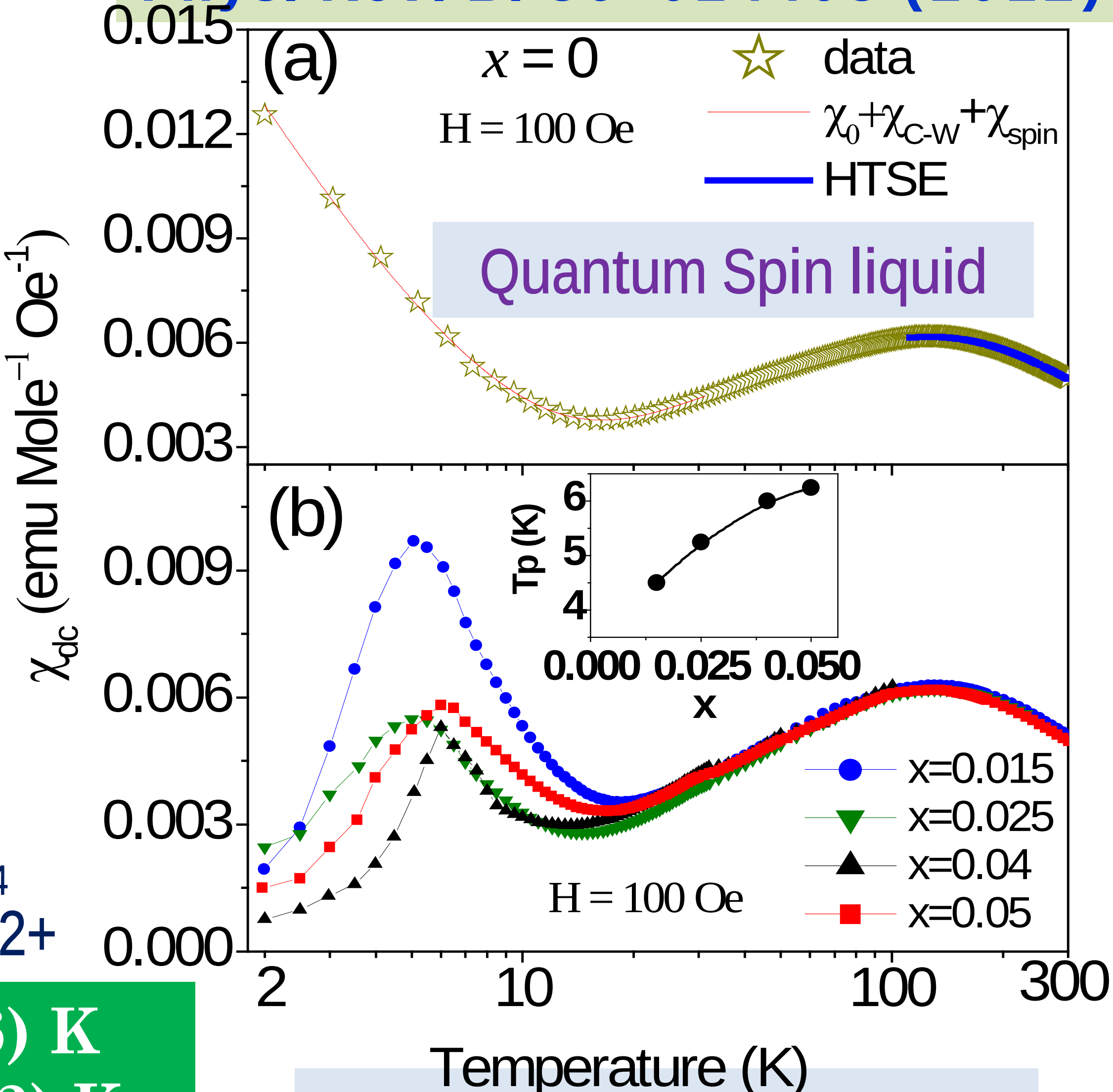
A. K. Bera and S. M. Yusuf
Phys. Rev. B. 86 024408 (2012)



Screw chains of edge-shared NiO_6 (Ni^{2+}; $3d^8$, $S = 1$) octahedra along c-axis.

Separated by nonmagnetic VO_4 (V5+; 3d0, S=0) tetrahedra & Sr2+

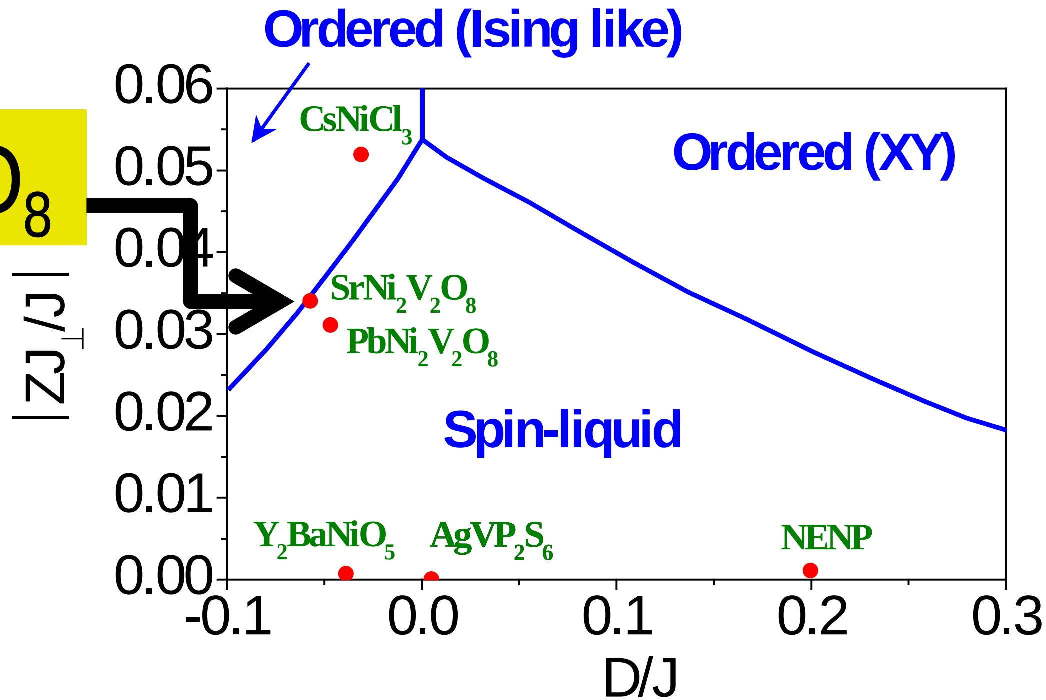
$$\Delta_{gap} = 26.6(6)\ \mathrm{K}$$
$$J/k_B = 106.4(2)\ \mathrm{K}$$



Quantum Phase Transition

Sakai-Takahashi Phase Diagram for weakly coupled 1D spin-chain with S = 1

$SrNi_2V_2O_8$



$J_\perp$ = inter-chain interaction

J = intra-chain interaction

D = single ion anisotropy

Possibility of Quantum Phase Transition

- Enhancement of $J_\perp$
- and/or Reduction in D

$SrNi_2V_2O_8$, $|D/J| = |(-0.56\ meV)/(106.4\ K = 9.17\ meV)| = 0.06$

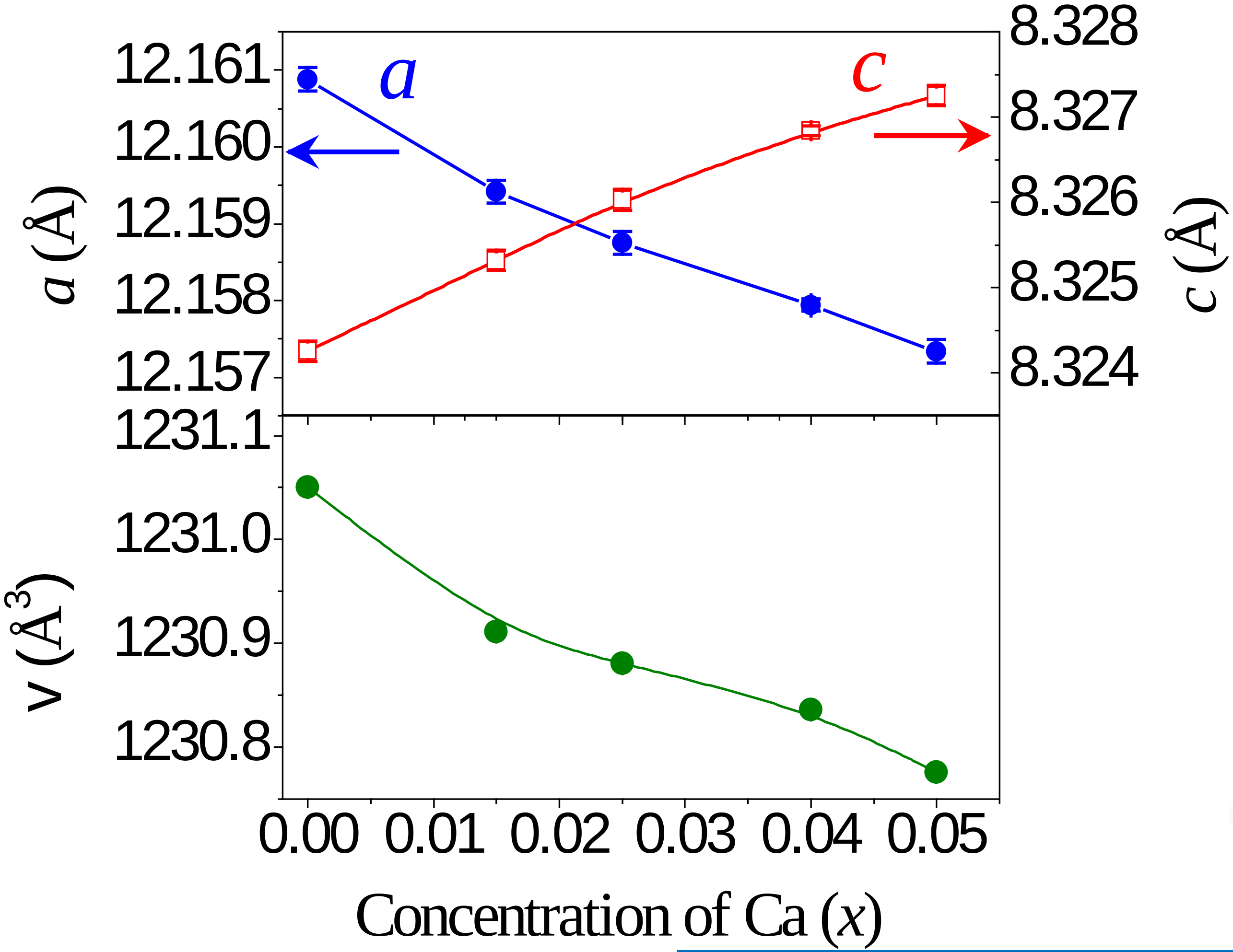
T. Sakai and M. Takahashi, Phys. Rev. B **42**, 4537 (1990).

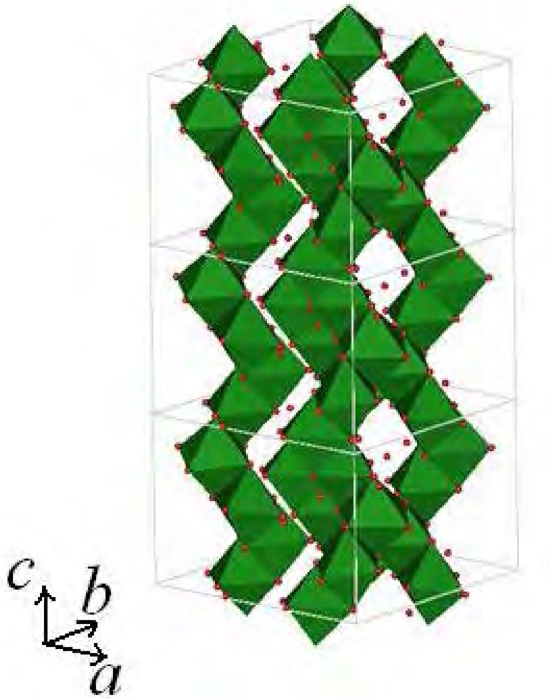
Concentration dependent Lattice Parameter

$Sr_{1-x}Ca_xNi_2V_2O_8$

Sr^{2+} : 1.26 Å

Ca^{2+} : 1.12 Å

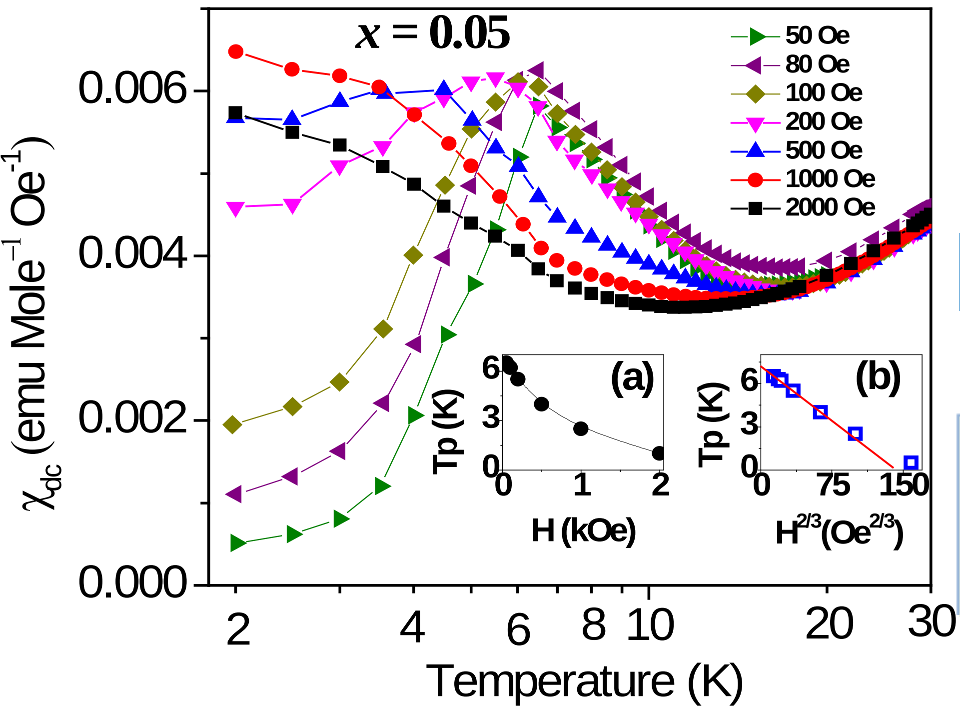




Decrease in the distances between screw chains

Spin-chain System $Sr_{1-x}Ca_xNi_2V_2O_8$

$Sr_{0.95}Ca_{0.05}Ni_2V_2O_8$



dc susceptibility

De Almeida –Thouless (AT)-type Phase boundary

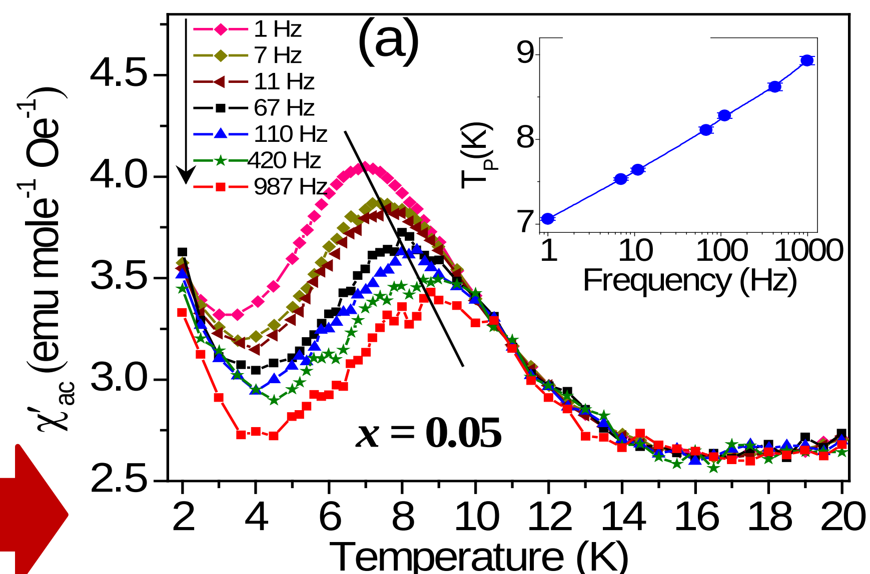
$Tg(0)$ = 7.6±0.1 K, **β = 1.47±0.03**

β = 3/2, predicted by the mean field theory for Ising spin-glass systems

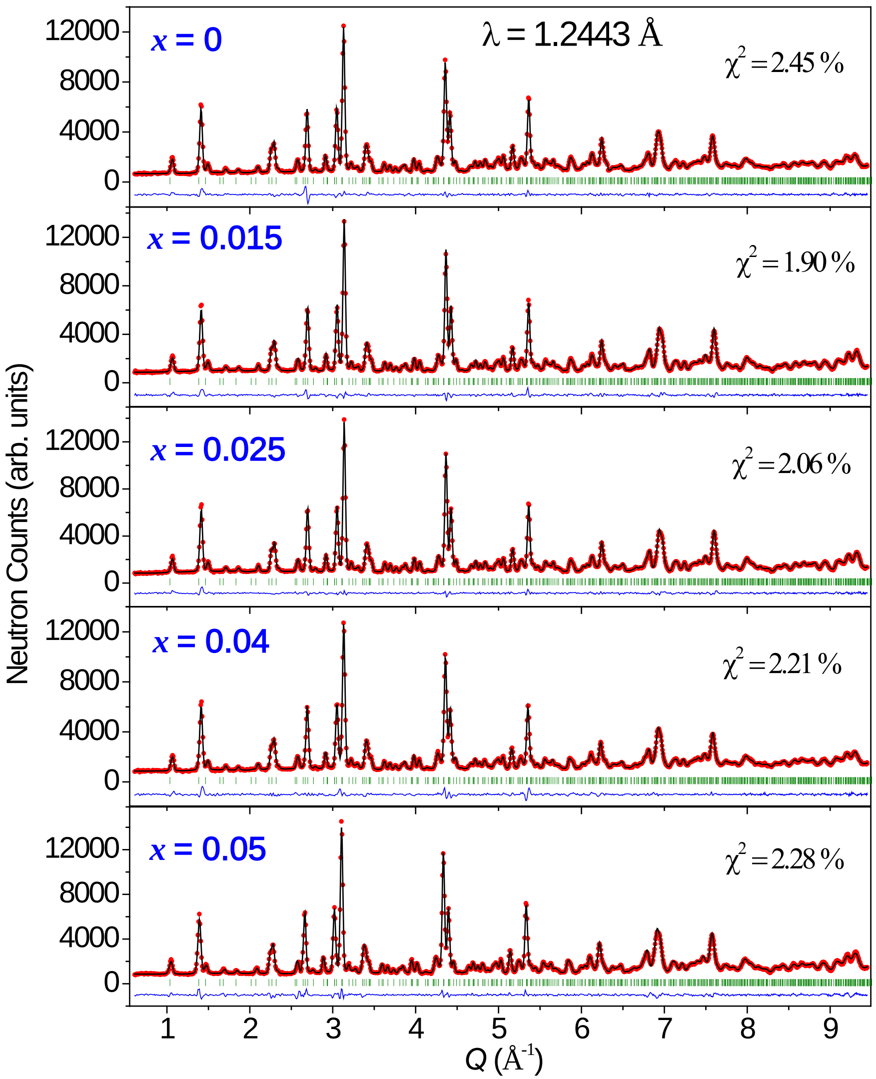
$$H(T_g) \propto \left[1 - \frac{T_g(H)}{T_g(0)}\right]^{\beta}$$

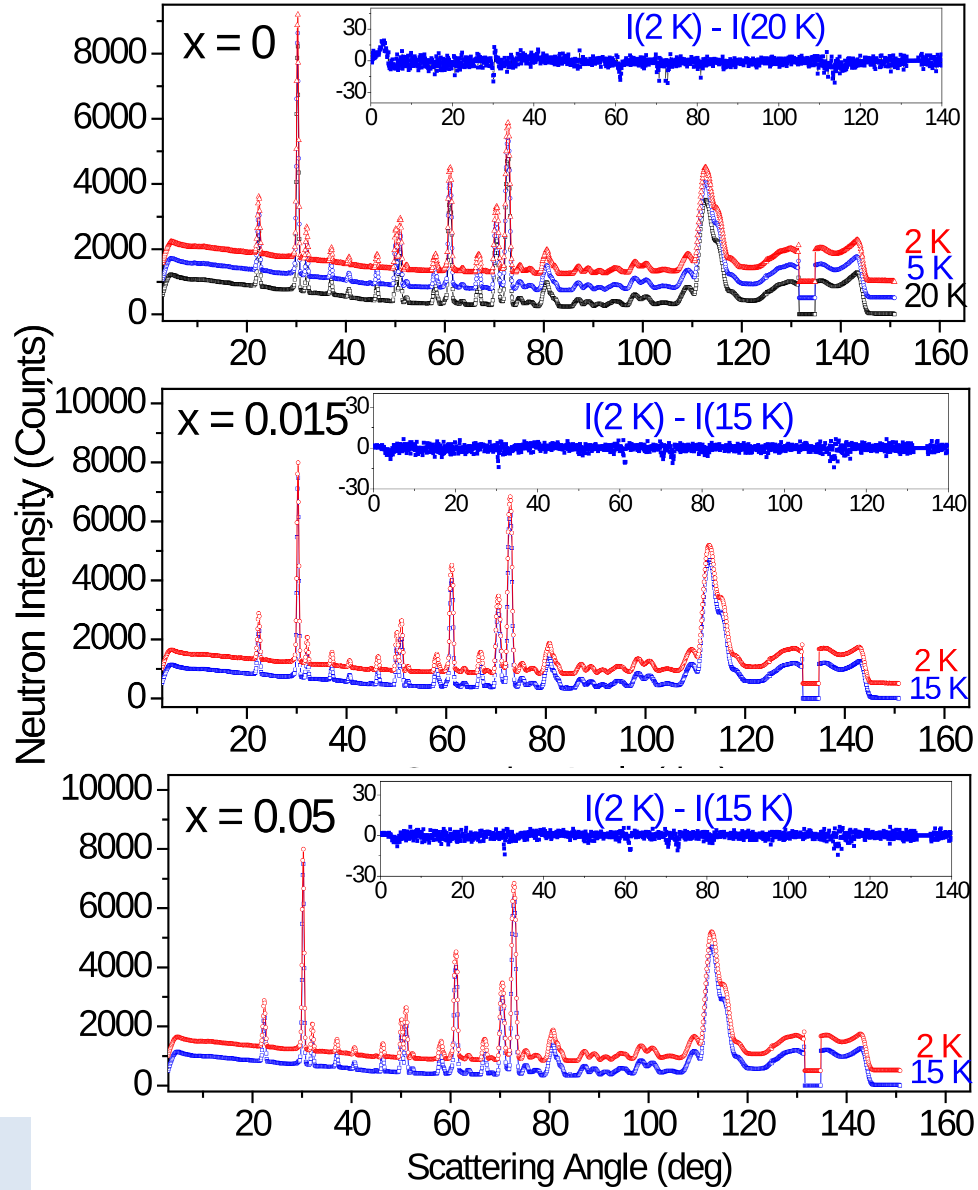
A. K. Bera and S. M. Yusuf
Phys. Rev. B. 86 024408 (2012)

ac susceptibility



Neutron diffraction of $Sr_{1-x}Ca_xNi_2V_2O_8$



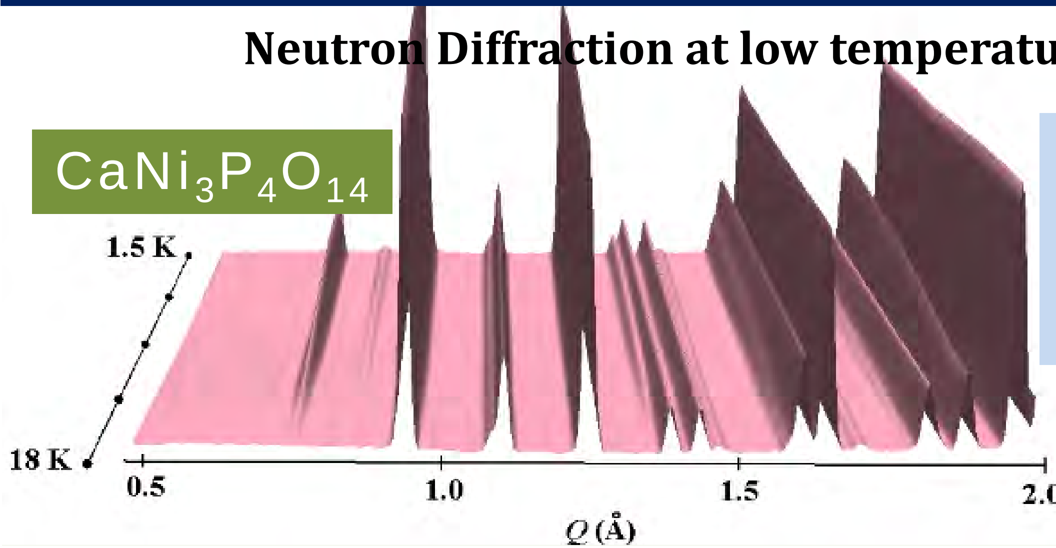


A. K. Bera and S. M. Yusuf
Phys. Rev. B. 86 024408 (2012)

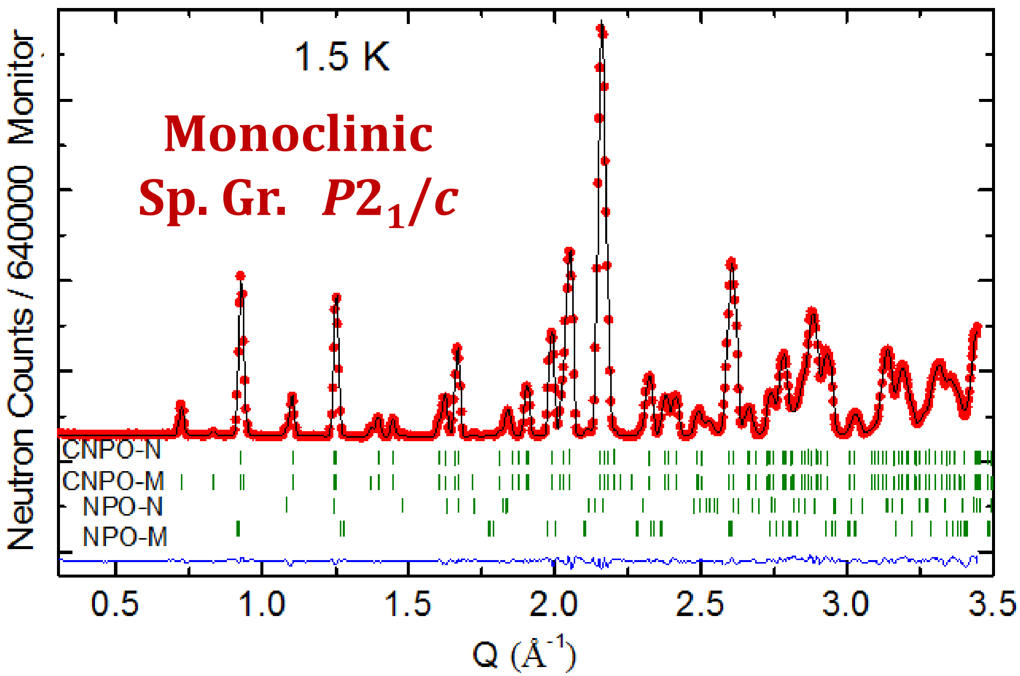
Quantum Phase Transition

Quasi-1D $S = 1$ trimmer chain $CaNi_3P_4O_{14}$

Neutron Diffraction at low temperatures



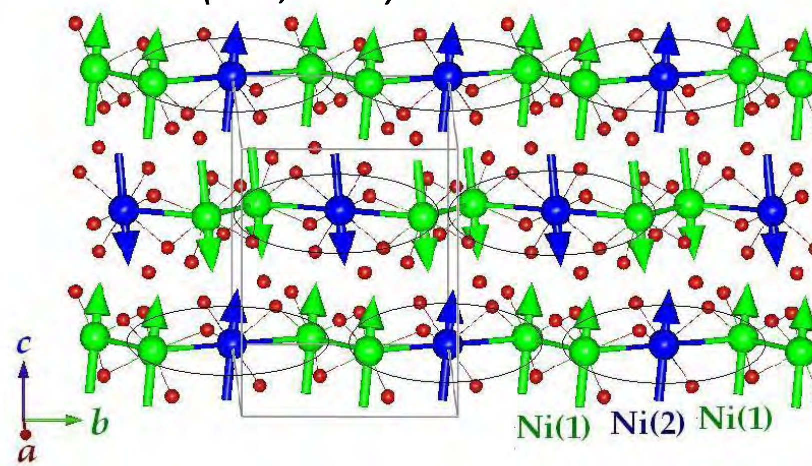
NiO_6 octahedra, forming zigzag chains, *connected by* two corner shared PO_4 tetrahedra



Magnetic Ground State

Ni(1) site:	**Ni(2) site:**
$m_a = -0.13 \pm 0.06 \mu_B$	$m_a = 0.16 \pm 0.10\ \mu_B$
$m_b = 0.18 \pm 0.10 \mu_B$	$m_b = 0.18 \pm 0.10\ \mu_B$
$m_c = 1.92 \pm 0.04 \mu_B$	$m_c = 2.01 \pm 0.06\ \mu_B$

Ni^{2+} ($3d^8$, $S = 1$)



AFM long-range ground state

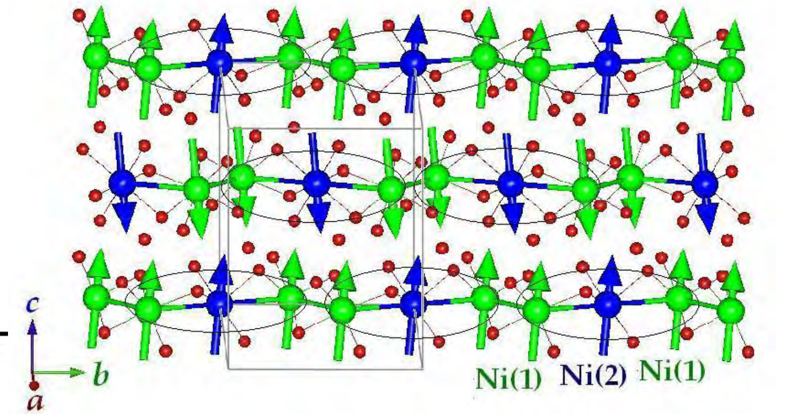
a = 7.3091(8) A°, *b* = 7.5574(9) A°
c = 9.3545(11) A°, *β* = 111.989(7)°

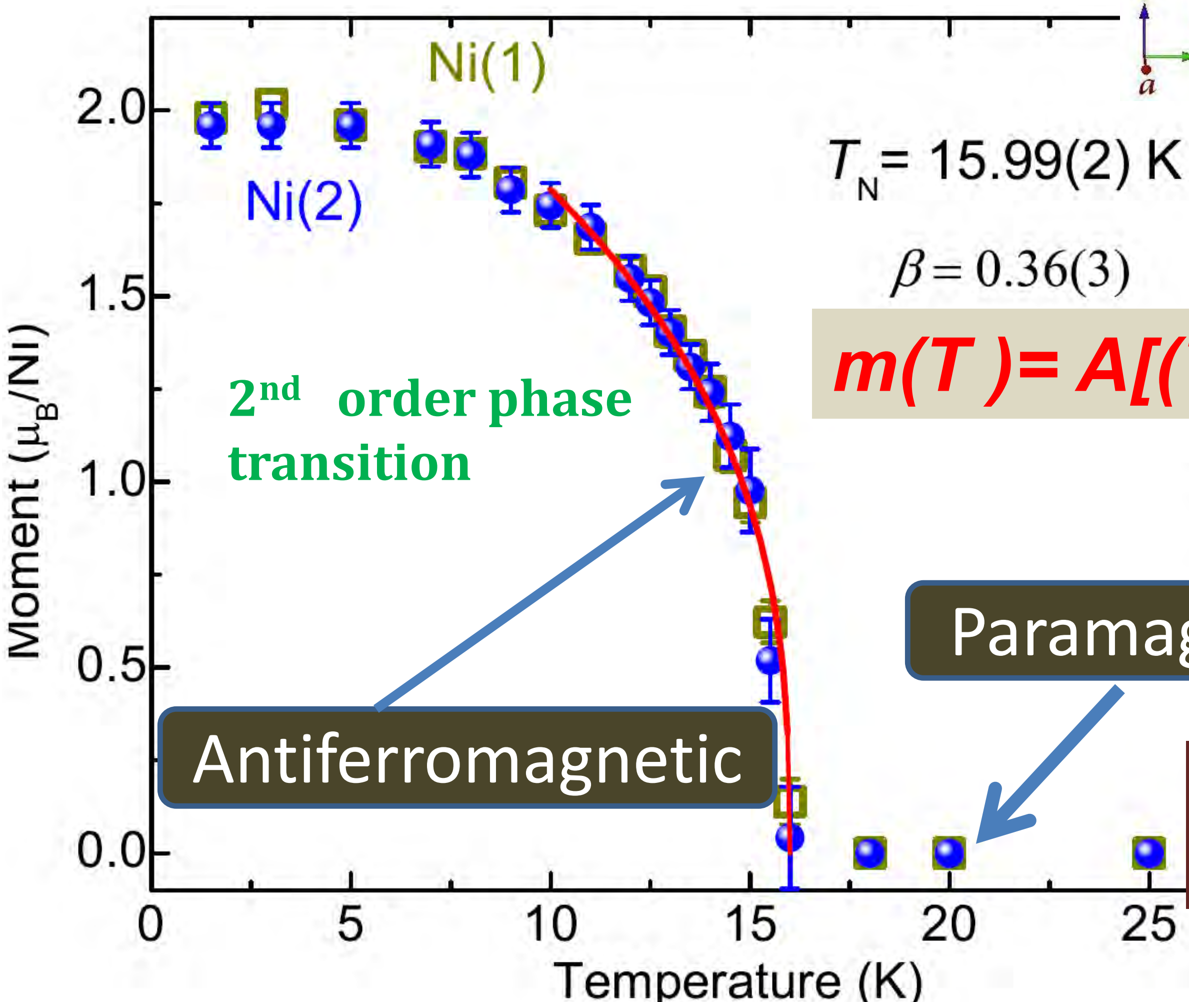
A. K. Bera, S. M. Yusuf *et. al.*, Phys. Rev. B 93, 184409 (2016)

$CaNi_3P_4O_{14}$

Neutron diffraction

Ni^{2+} ($3d^8$, $S = 1$)





$$m(T) = A[(T_c - T)/T_c]^{\beta}$$

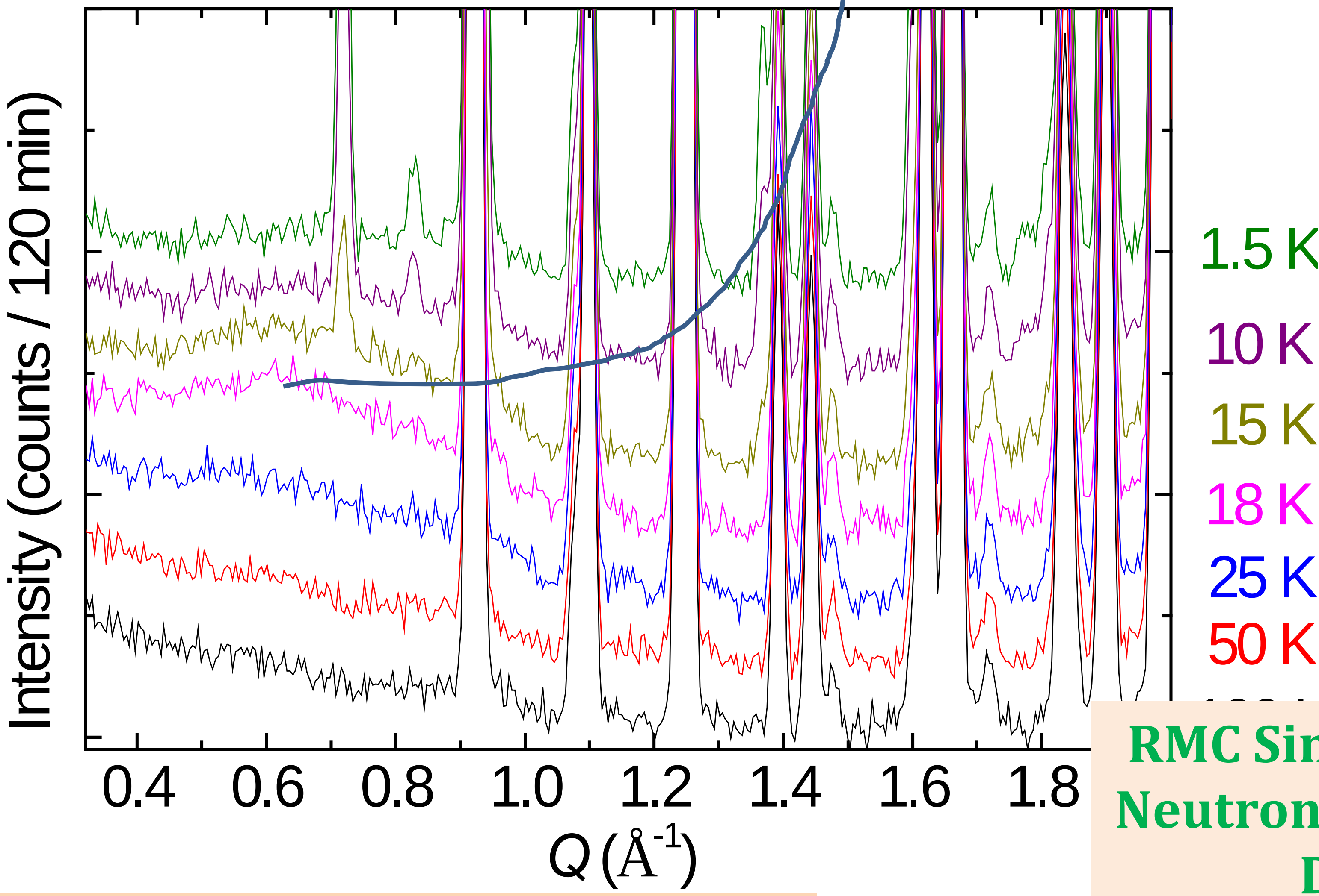
A. K. Bera, S. M. Yusuf *et. al.*, Phys. Rev. B 93, 184409 (2016)

Antiferromagnetic Neel Temperature, T_N = 15.99 K

Quasi-1D $S = 1$ trimmer chain $CaNi_3P_4O_{14}$

Neel Temp = 15.99 K

Short-range magnetic ordering

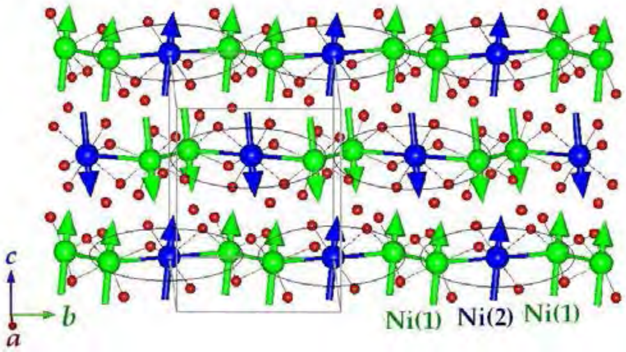


RMC Simulation of Neutron diffraction Data

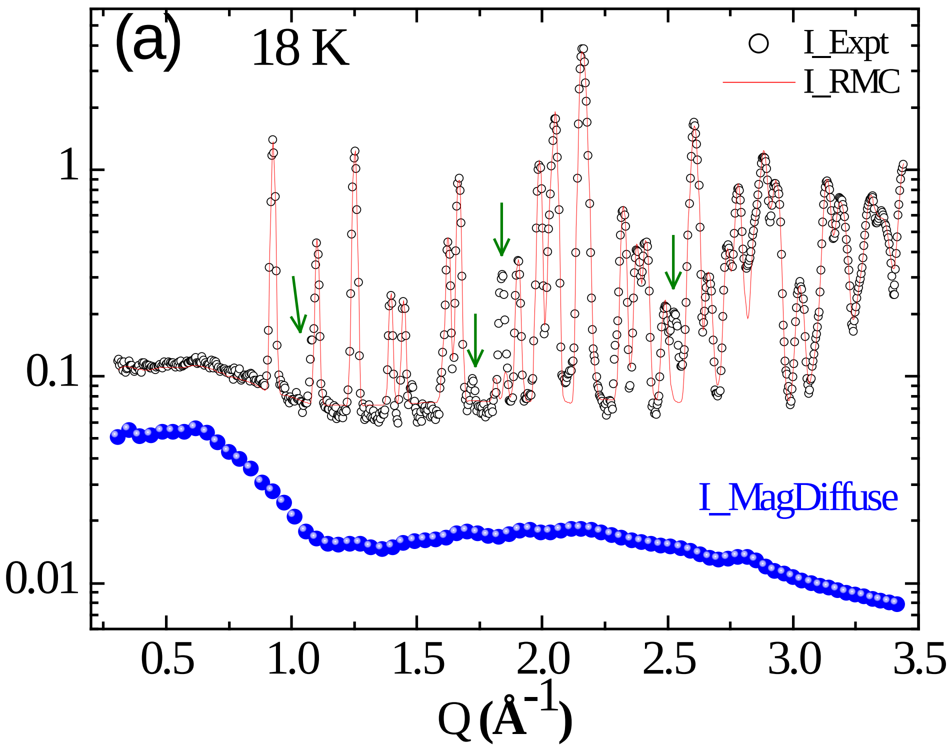
A. K. Bera , S. M. Yusuf, *et al.*
Phys. Rev. B 95, 094424 (2017)

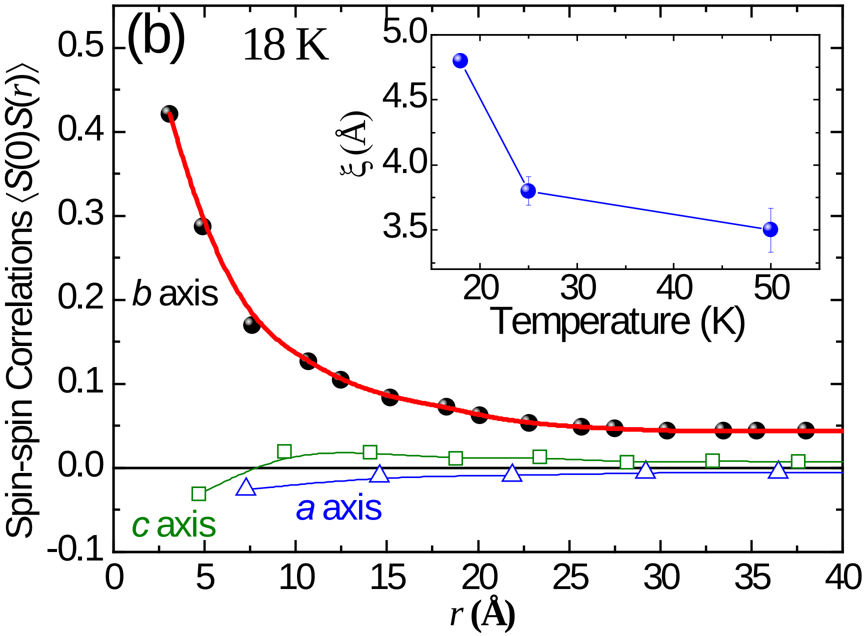
Super cell 8×8×8 containing 3072 spins

Reverse Monte Carlo (RMC) analysis



Super cell 8×8×8 containing 3072 spins





1D short –range FM correlations along b-axis

Realization of a 3D magnetic system with *S = 1 trimer chains*

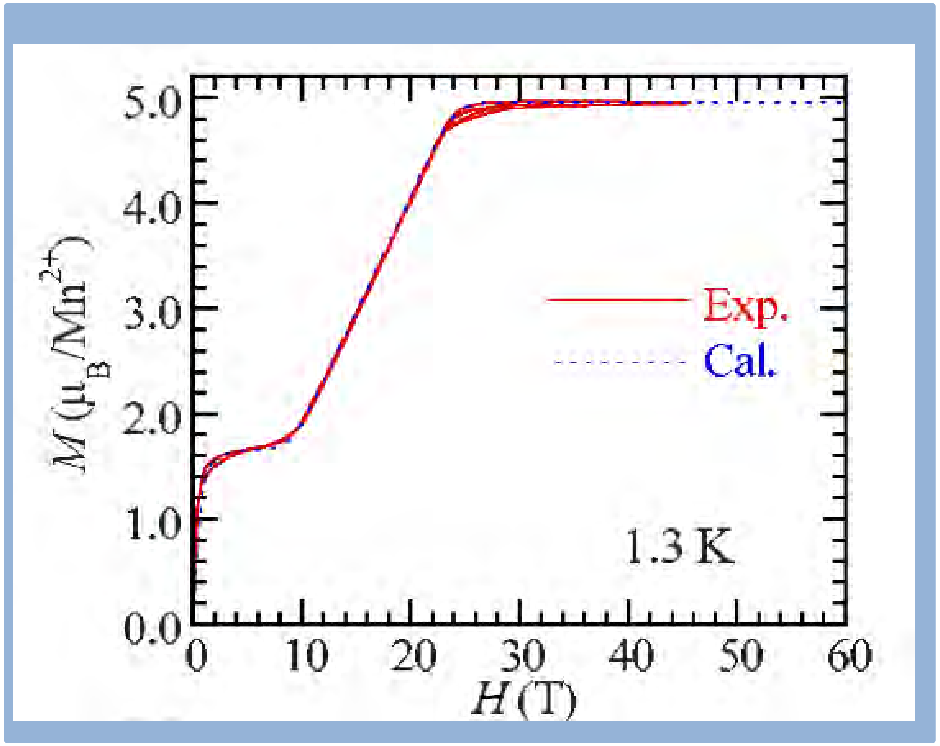
A. K. Bera , S. M. Yusuf, *et al.* Phys. Rev. B 95, 094424 (2017)

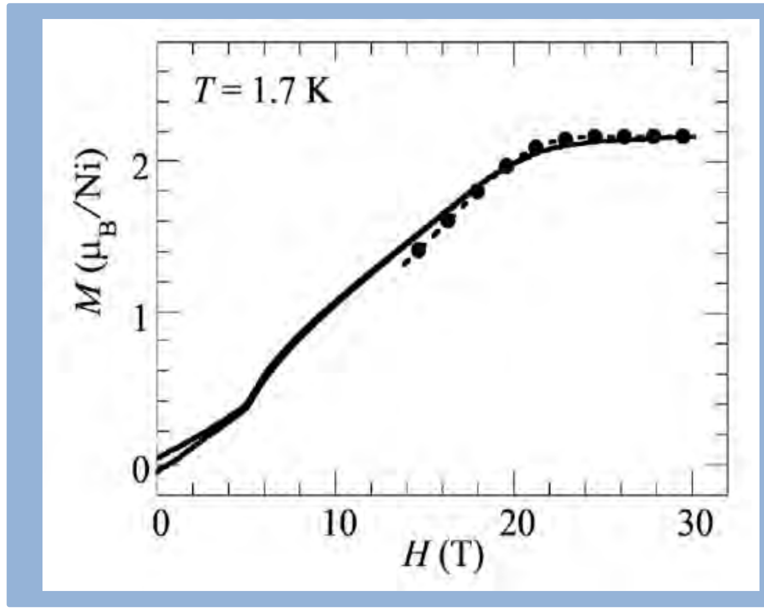
Trimer chain compounds $AM_3P_4O_{14}$

(*A*= Ca, Ba, Sr, and *M* = Co, Mn, Ni)

Plateau state Mn (S=5/2)

No Plateau state Ni (S=1)

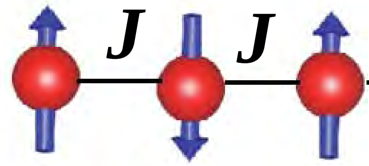




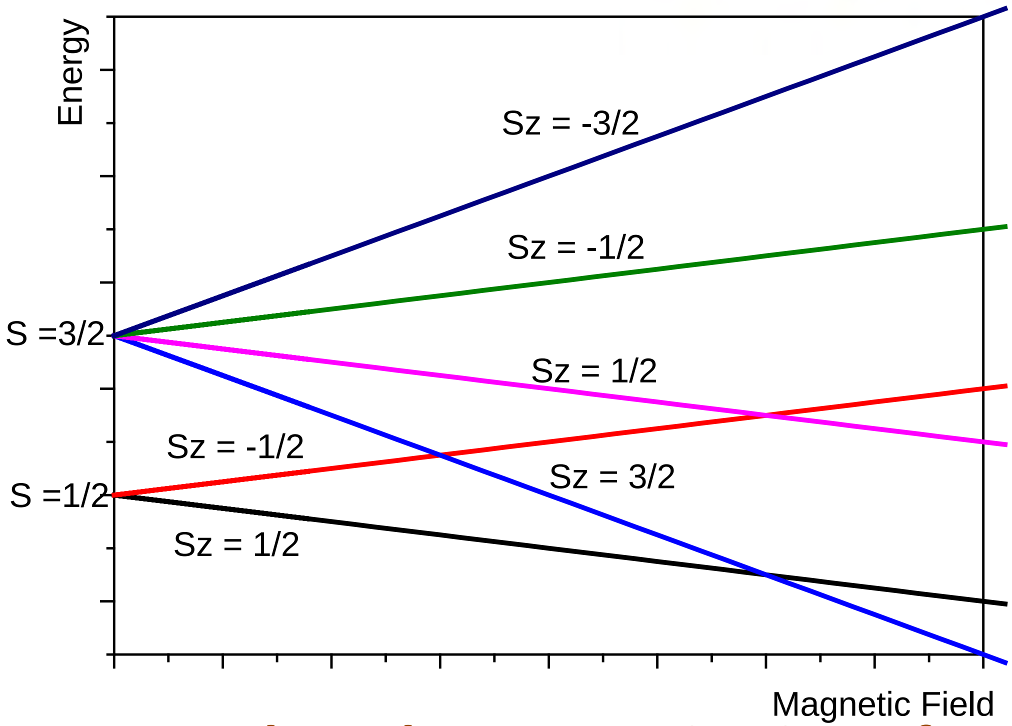
The 1/3- magnetization Plateau

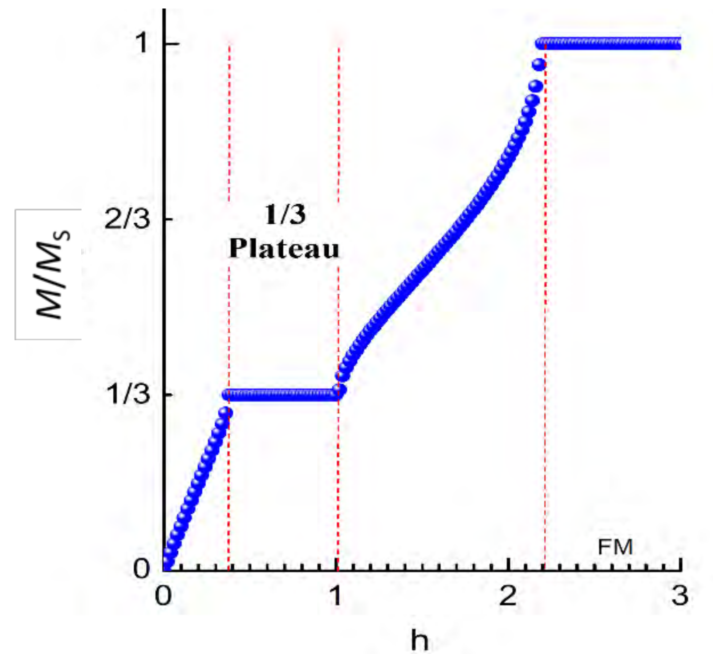
A. K. Bera, S. M. Yusuf *et al.* Phys. Rev. B 97, 224413 (2018)

Spin = ½ Trimer



Magnetization plateau





Appears when the magnetization of the ground state Sz = ½ saturates.

Excited state :

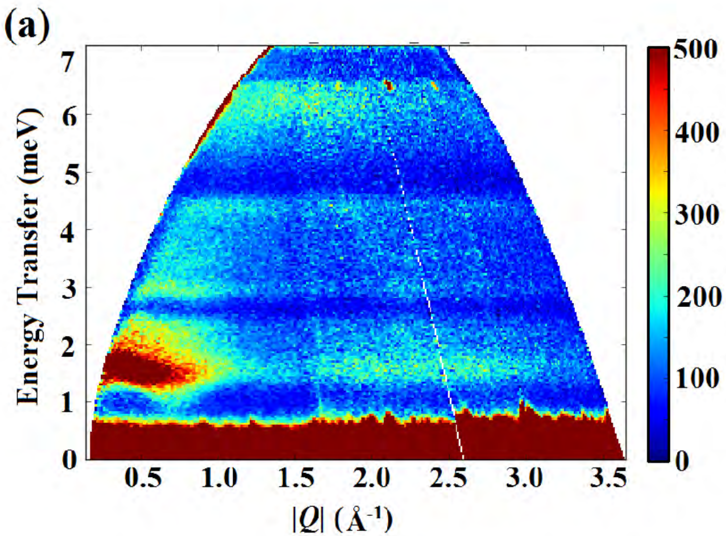
$S = 3/2,\ S^z = \pm 3/2, \pm 1/2$

Ground state :

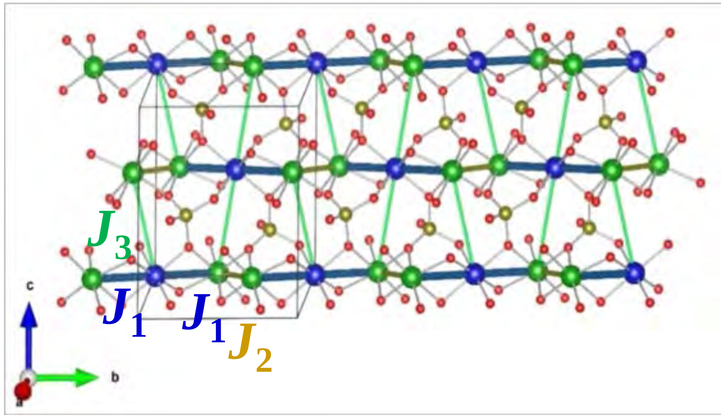
$S = 1/2,\ S^z = \pm 1/2$

Width of the Plateau state: from the saturation of the Sz=1/2 state to the crossover of Sz=1/2 to Sz=3/2 state.

1D trimer spin-chain Compound $CaNi_3P_4O_{14}$



Inelastic neutron scattering



Exchange Interactions

Exchange interaction (meV)	Neutron scattering
J_1	-1.30±0.05 (ferro)
J_2	-1.05±0.05 (ferro)
J_3	0.9±0.1 (anti-ferro)
D	-0.25±0.02

❑ Strong interchain interactions

$$H = \boxed{J_1 \sum_i (\vec{S}_i . \vec{S}_{i+1}) + J_2 \sum_i (\vec{S}_i . \vec{S}_{i+1})}$$ **Intra chain**

$$\boxed{+J_3 \sum_{ij} (\vec{S}_i . \vec{S}_j)}$$ **Inter chain**

$$\boxed{+\sum_i D(S_i^z)^2}$$ **anisotropy**

A. K. Bera, S. M. Yusuf *et al*. Phys. Rev. B 97, 224413 (2018)

Main Contributors

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Thank you