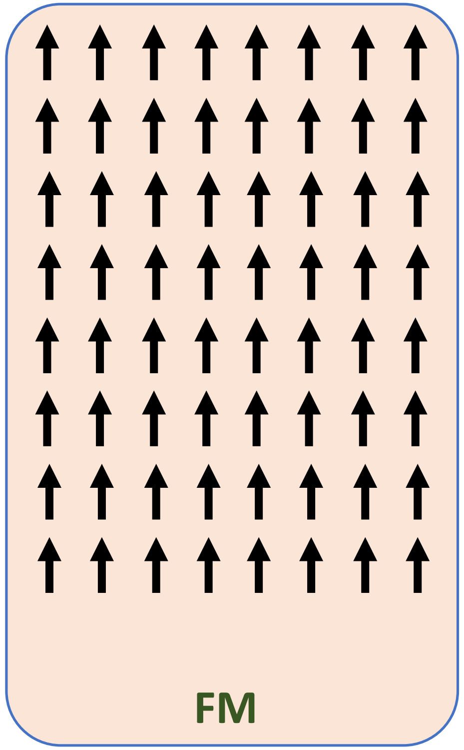
MAGNETISM IN MATERIALS

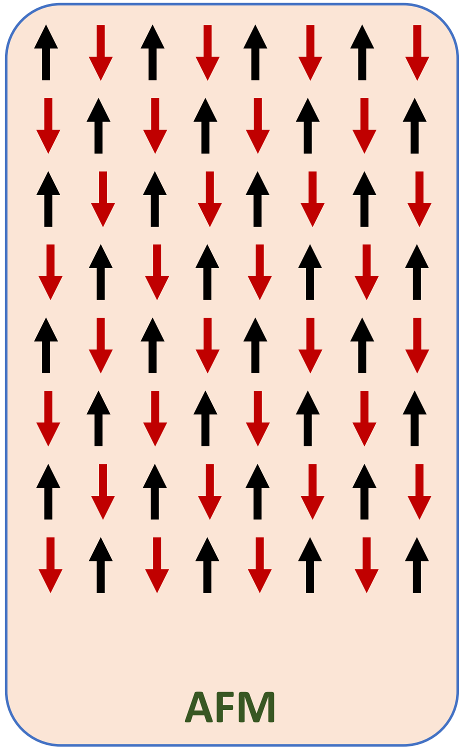
Lecture 6: Magnetic Ordering (cont.)

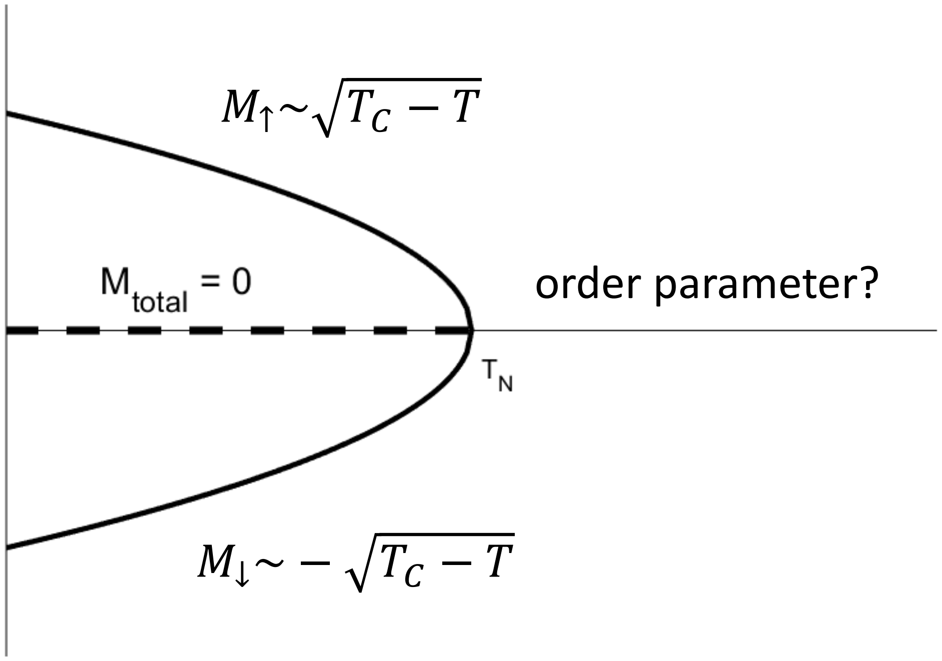
Ivica Zivkovic / Henrik Ronnow

MAGNETIC ORDERING

- antiferromagnetism
- ferrimagnetism
- incommensurate order
- spin-glass







$$\boldsymbol{B}_{\boldsymbol{mf}} = \lambda \boldsymbol{M}$$

$$M = g\mu_B S B_S(x)$$

$$x = \frac{g\mu_B S(B_{out} + \lambda M)}{k_B T}$$

$$\boldsymbol{B}_\uparrow = -\lambda \boldsymbol{M}_\downarrow \qquad \boldsymbol{B}_\downarrow = -\lambda \boldsymbol{M}_\uparrow$$

$$M_\uparrow = g\mu_B S B_S(x)$$

$$x = \frac{g\mu_B S(B_{out} + \lambda M_\downarrow)}{k_B T}$$

- paramagnet → Curie law
- ferromagnet → Curie-Weiss law

$$\frac{C}{T} = \frac{\mu_0 M}{B + \lambda M} \qquad \chi = \frac{C}{T - T_C}$$

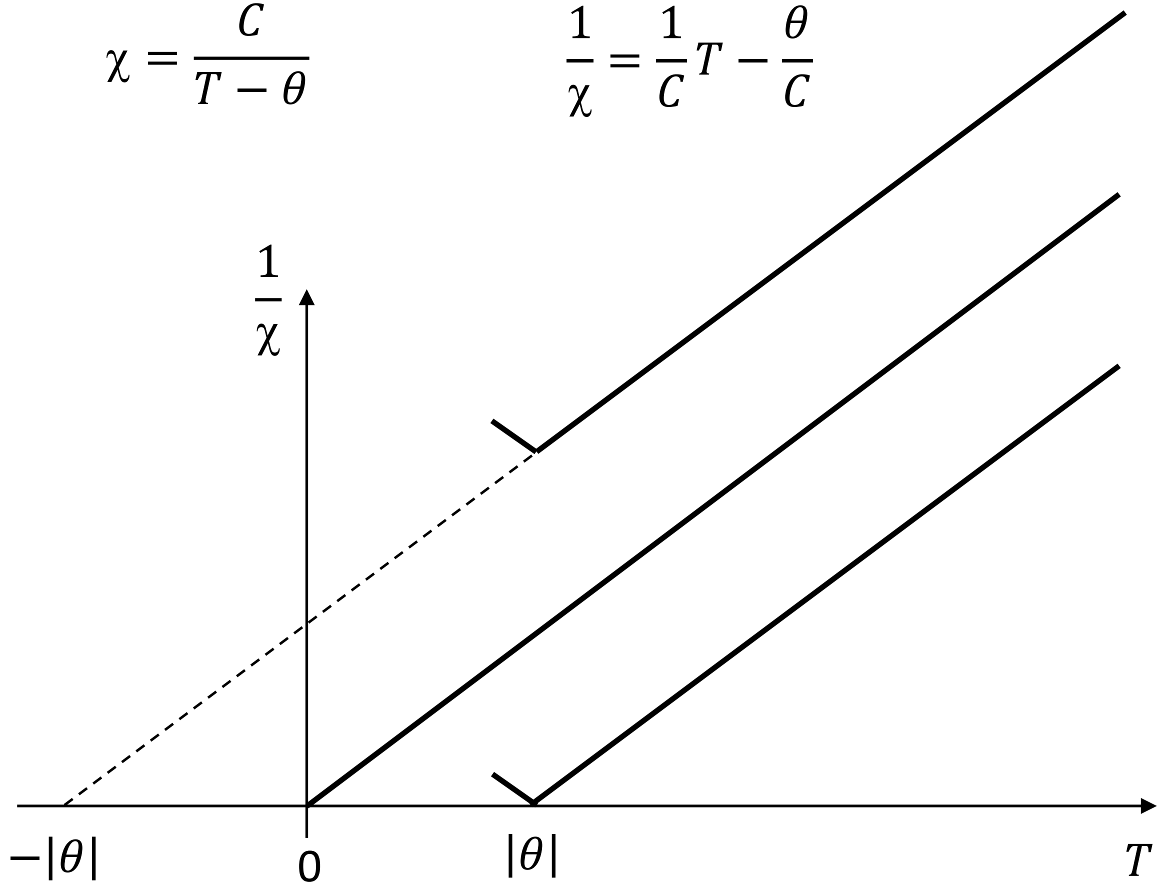
- antiferromagnet → Curie-Weiss law

$$\frac{C}{T} = \frac{\mu_0 M}{B - \lambda M} \qquad \chi = \frac{C}{T + T_N}$$

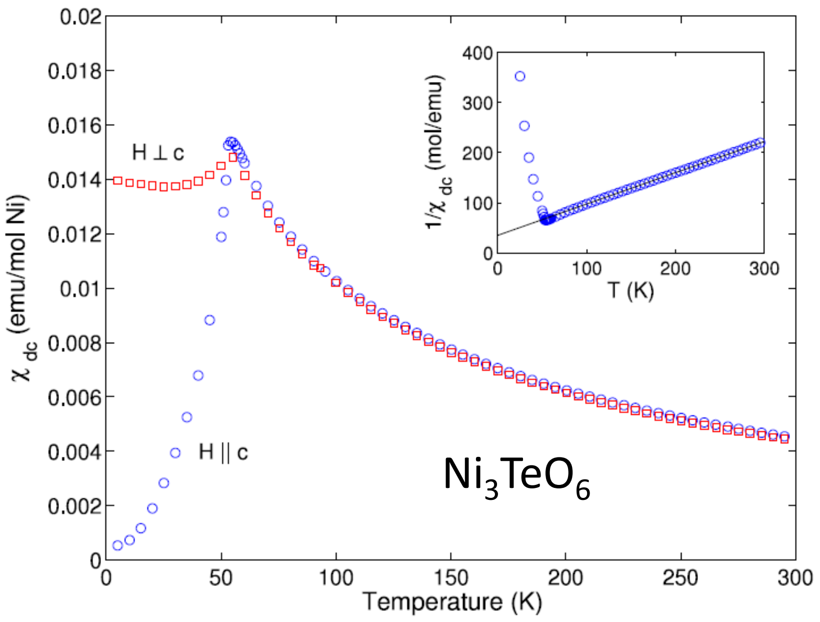
C: Curie constant
T_C: Curie temperature/critical temperature
T_N: Néel temperature
θ: Weiss temperature

- general approach

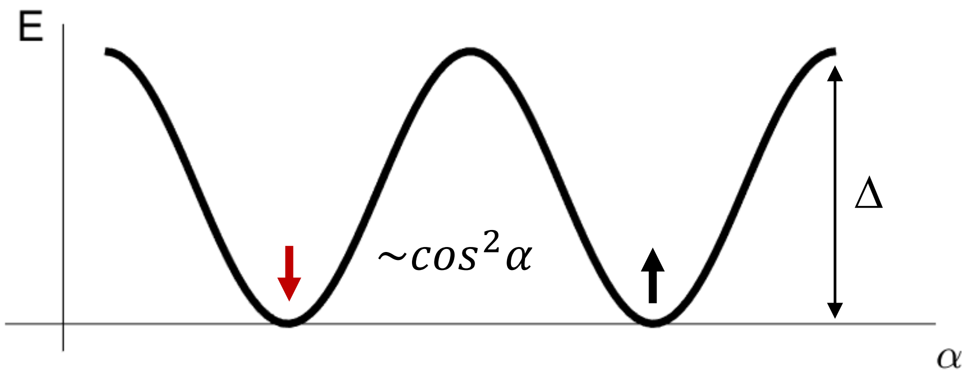
$$\chi = \frac{C}{T - \theta} \qquad \frac{1}{\chi} = \frac{1}{C}T - \frac{\theta}{C}$$



- very anisotropic magnetic response (susceptibility) below T_N



- anisotropy energy
- in the simplest form: $\mathrm{E} = \Delta cos^2\alpha$
- origin in SOC



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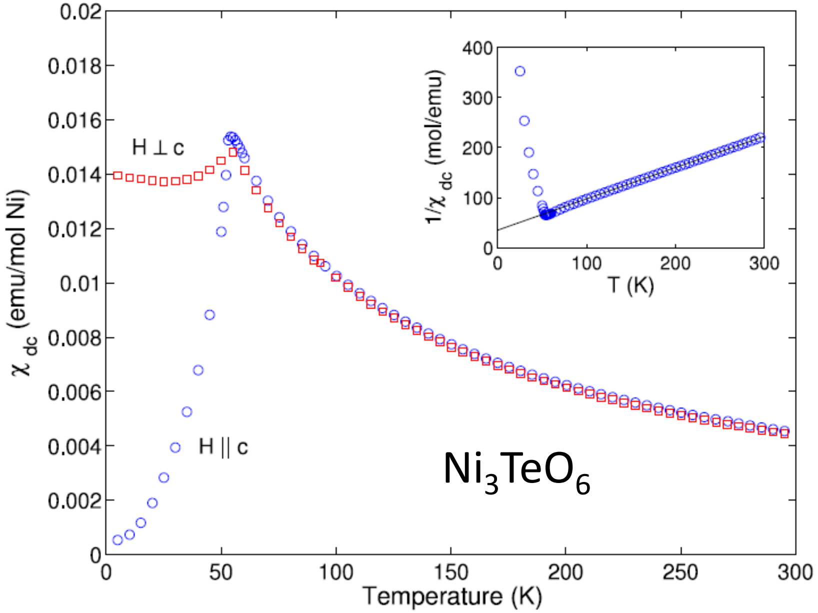

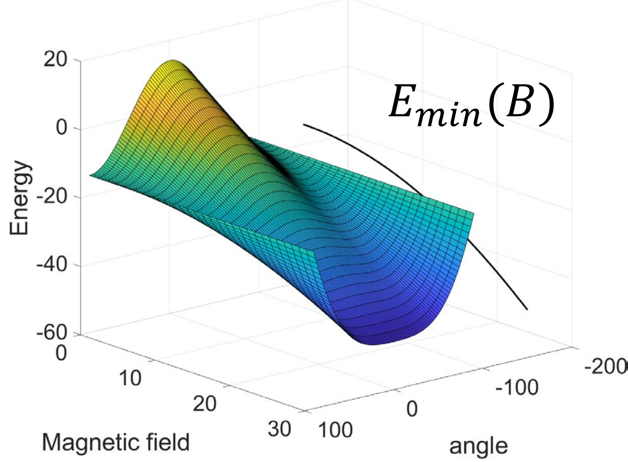

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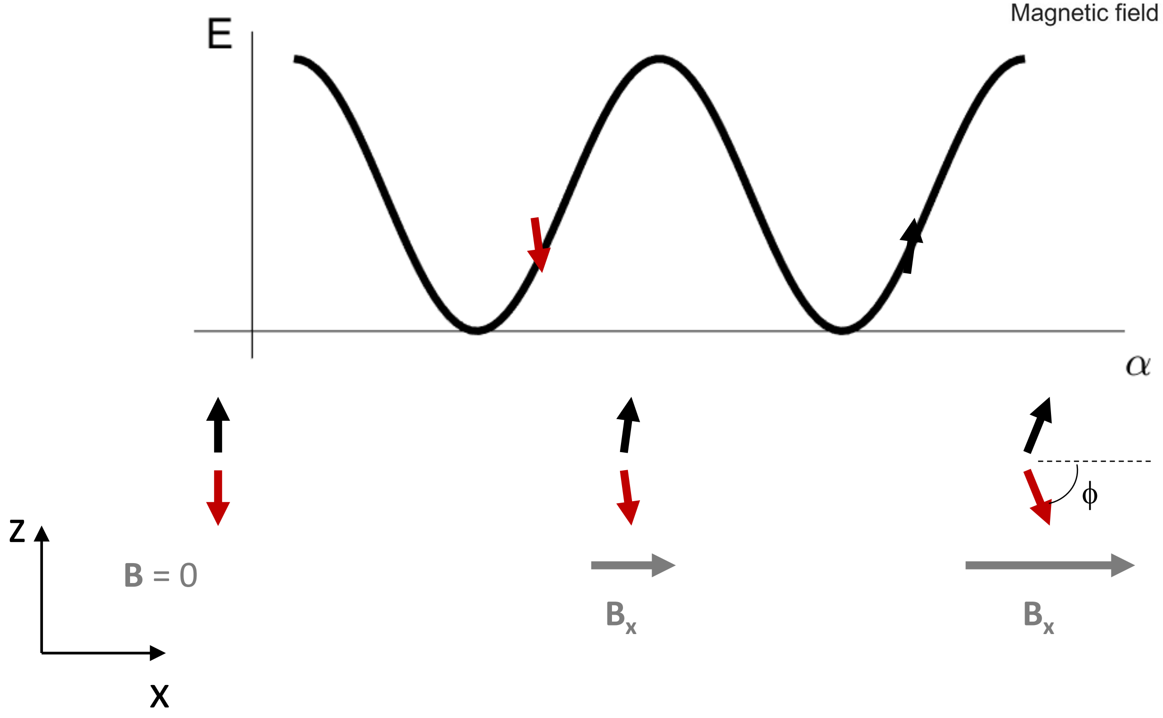
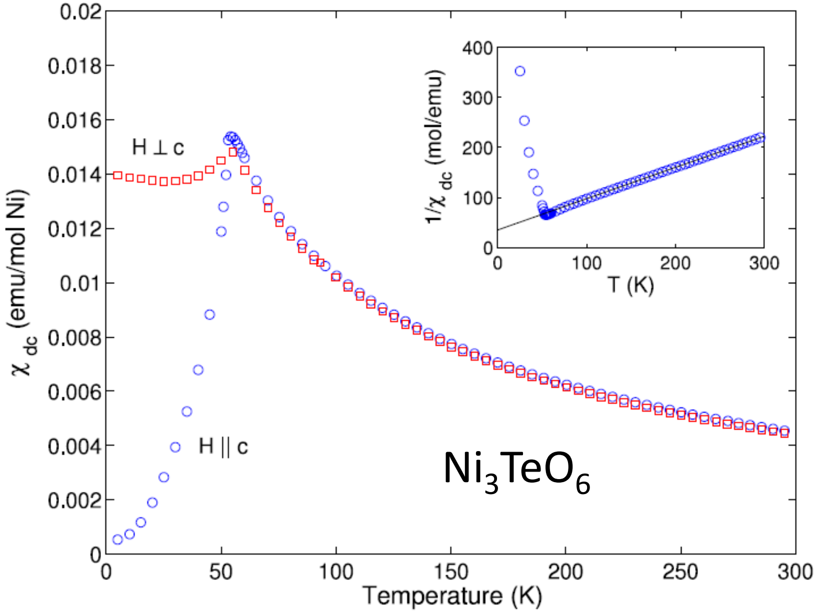
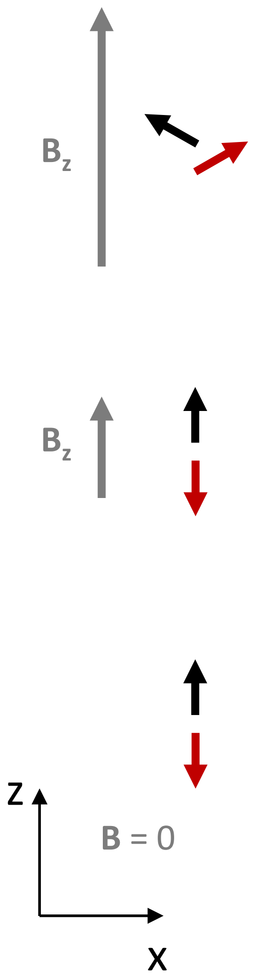
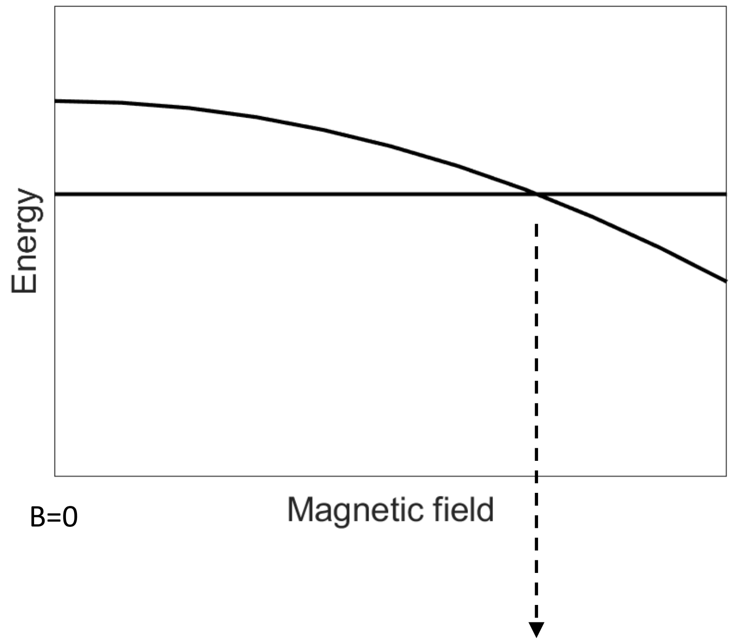


$$\hat{\mathcal{H}} = J\boldsymbol{S_1}\boldsymbol{S_2} + g\mu_B\boldsymbol{B}(\boldsymbol{S_1} + \boldsymbol{S_2}) \rightarrow E = C(J)M^2\cos 2\varphi - 2BM\cos\varphi + 2\Delta cos^2\varphi$$

❖ very anisotropic magnetic response (susceptibility) below T_N







spin-flop: $B \approx \sqrt{C(J)\Delta}$

$$E = C(J)M^2\cos(\theta+\gamma) - BM\cos\theta - BM\cos\gamma + \Delta sin^2\theta + \Delta sin^2\gamma$$

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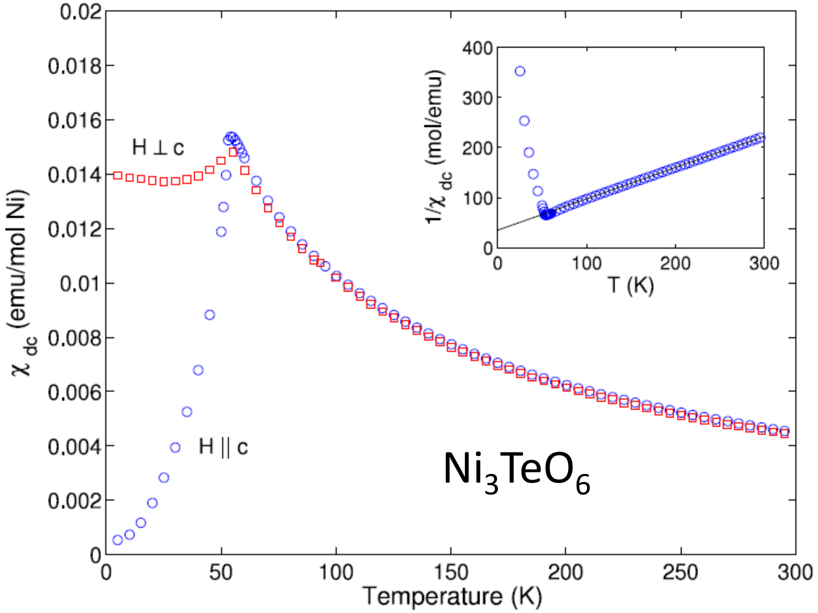
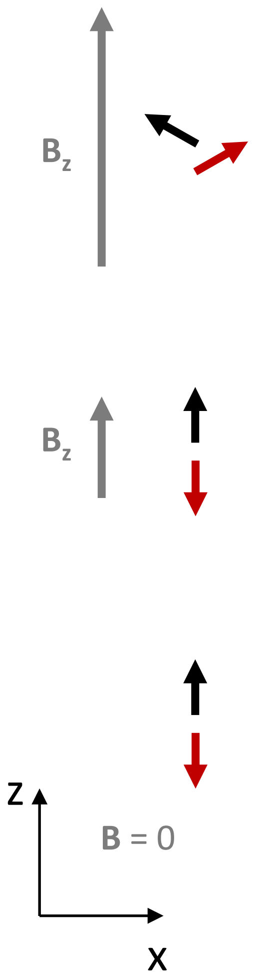
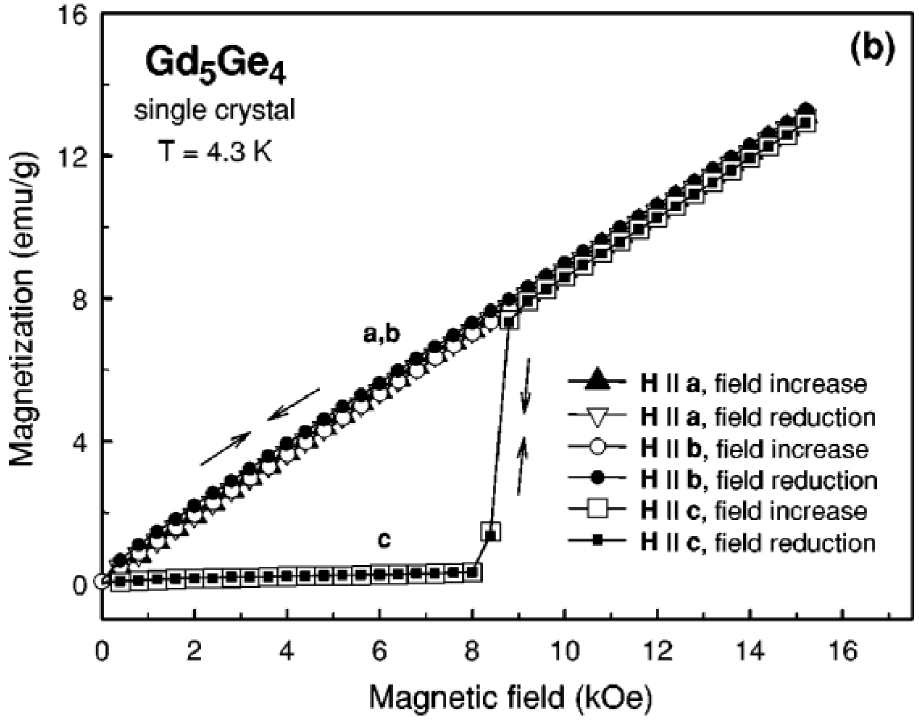




PRB 69, 144428 (2004)



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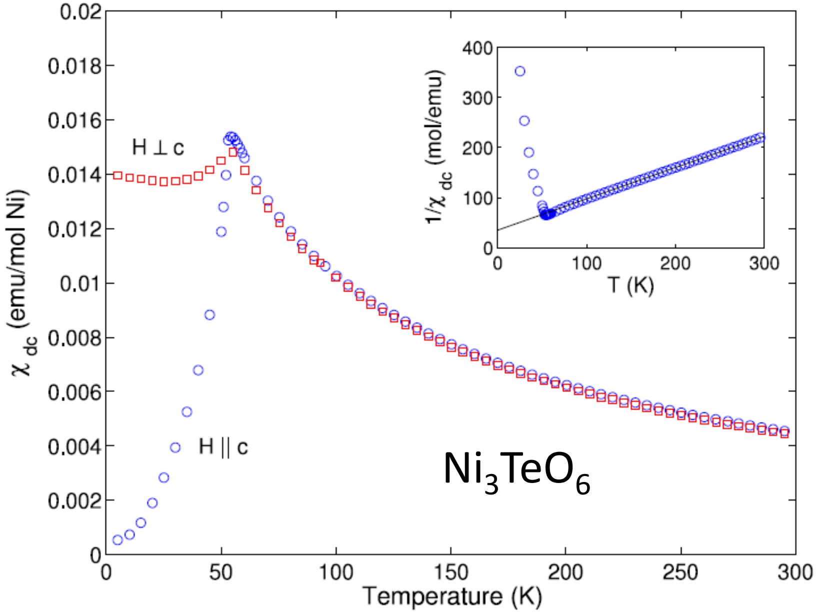

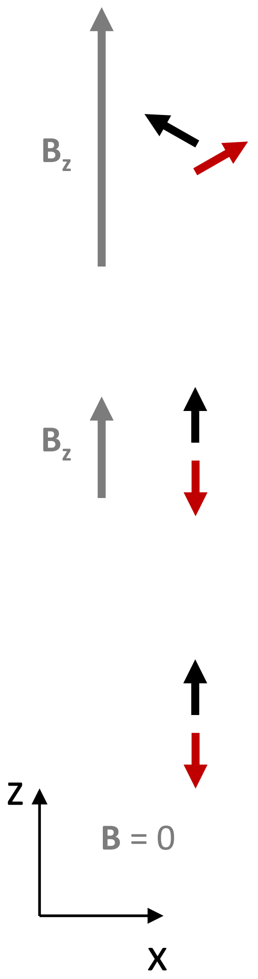

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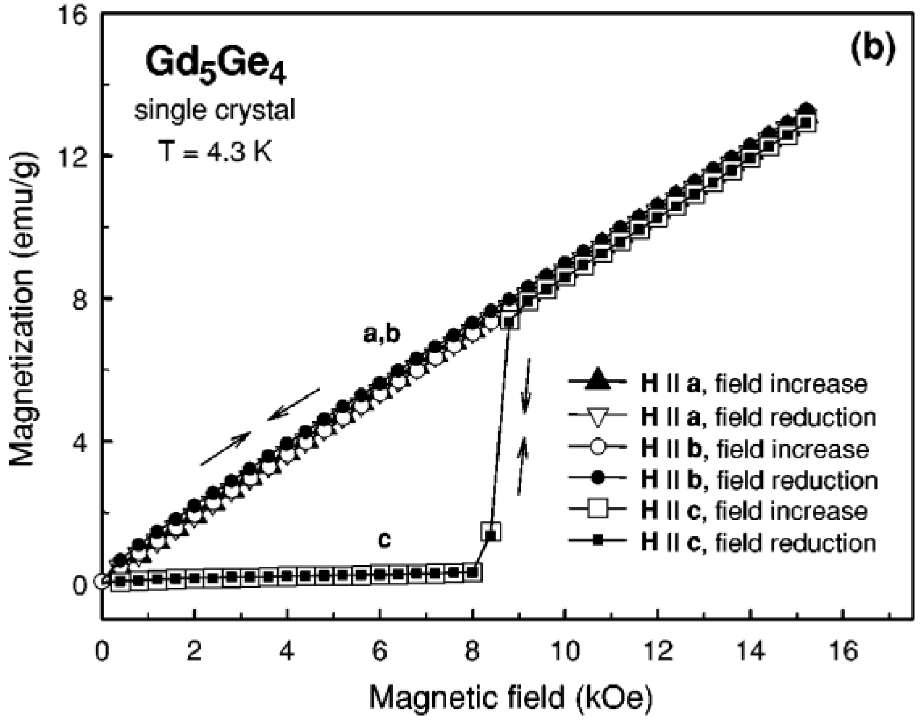

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spin-flip: $B = C(J)$

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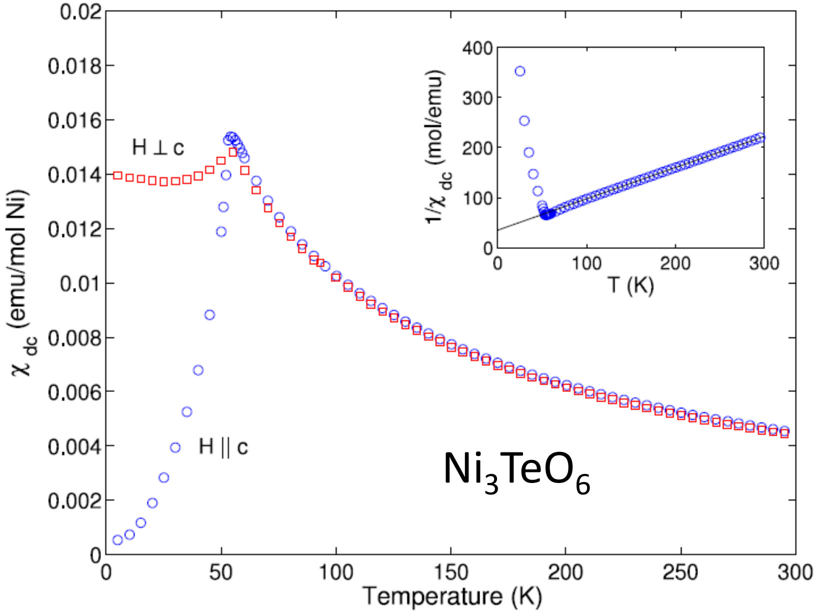

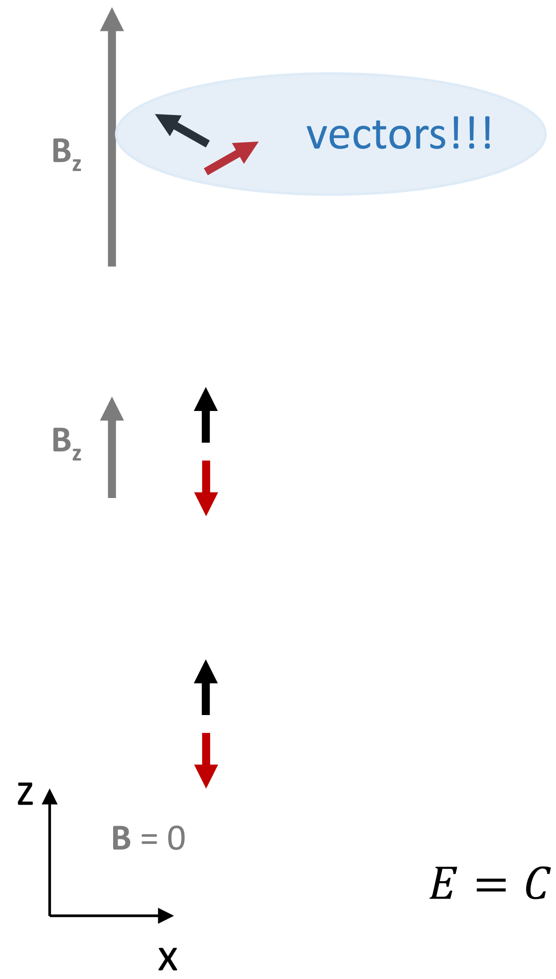

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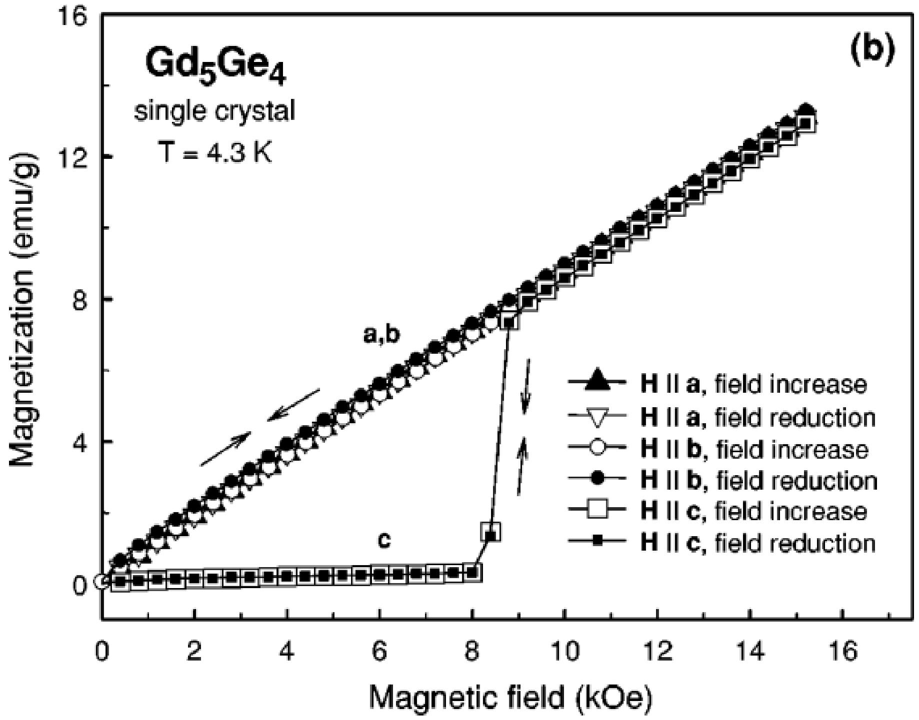

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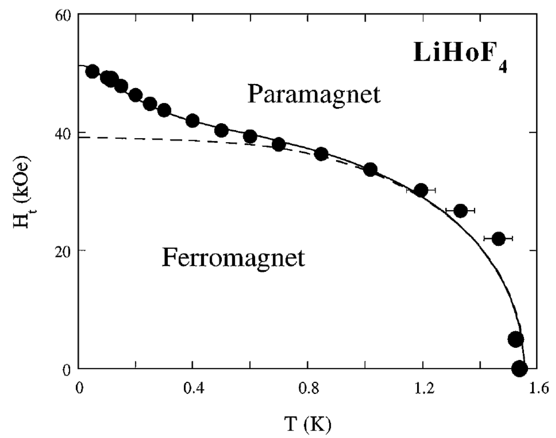
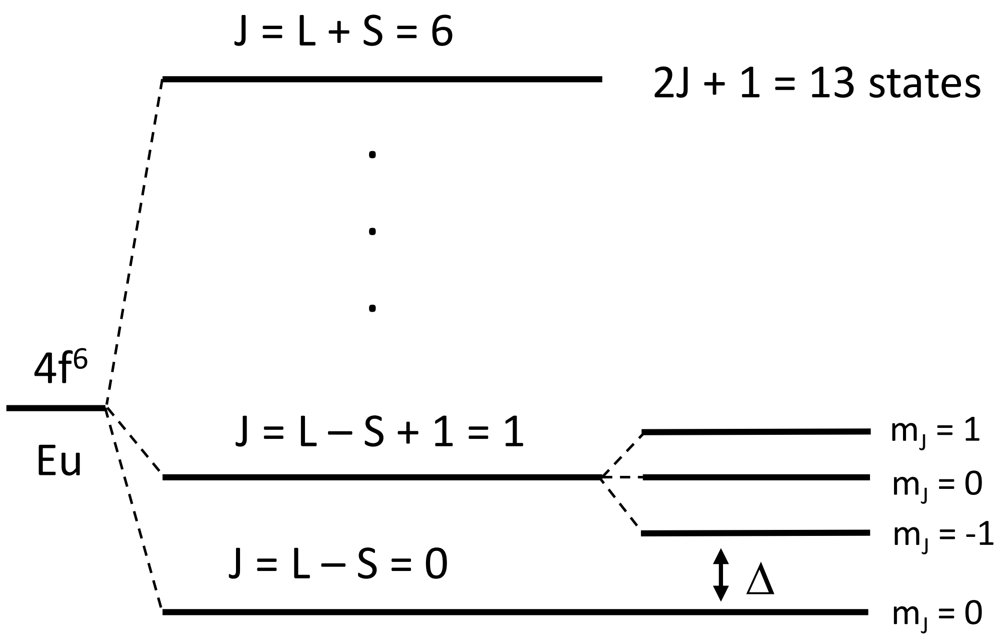
- *RE* = Ho (*c*-axis anisotropy) a ferromagnet with Tc=1.5K
- *RE* = Er (*ab*-plane anisotropy) an antiferromagnet with Tc=0.38K
- transverse field induced QPT

$$H = \sum_{i,j}^{N} J_{ij}\sigma_i^z\sigma_j^z - \Gamma\sum_{i}^{N}\sigma_i^x$$



PRL 77, 940 (1996)



when $k_BT \sim \Delta$ (~500 K), $\mu > 0$

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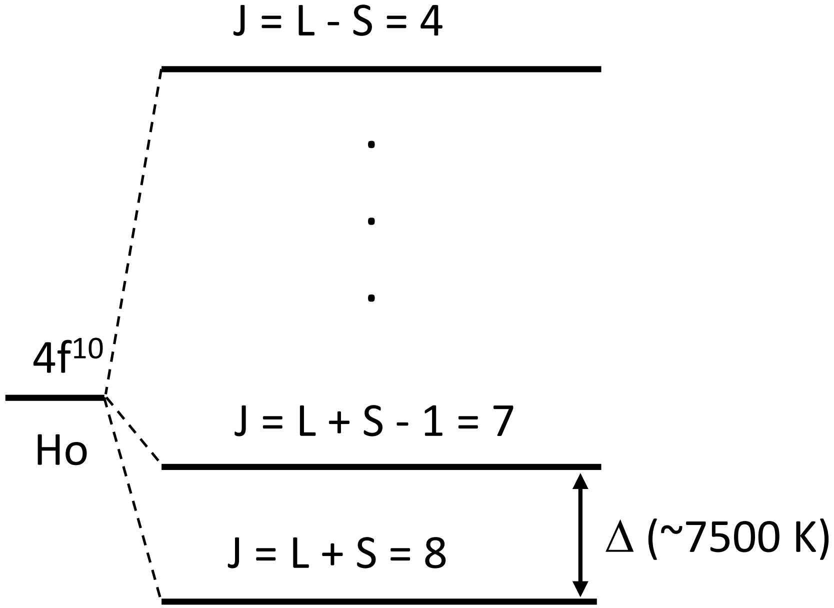

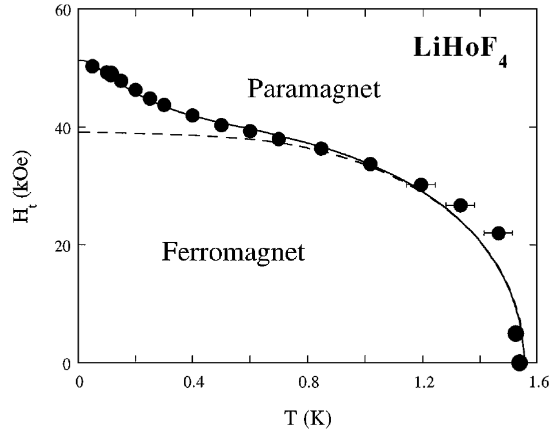

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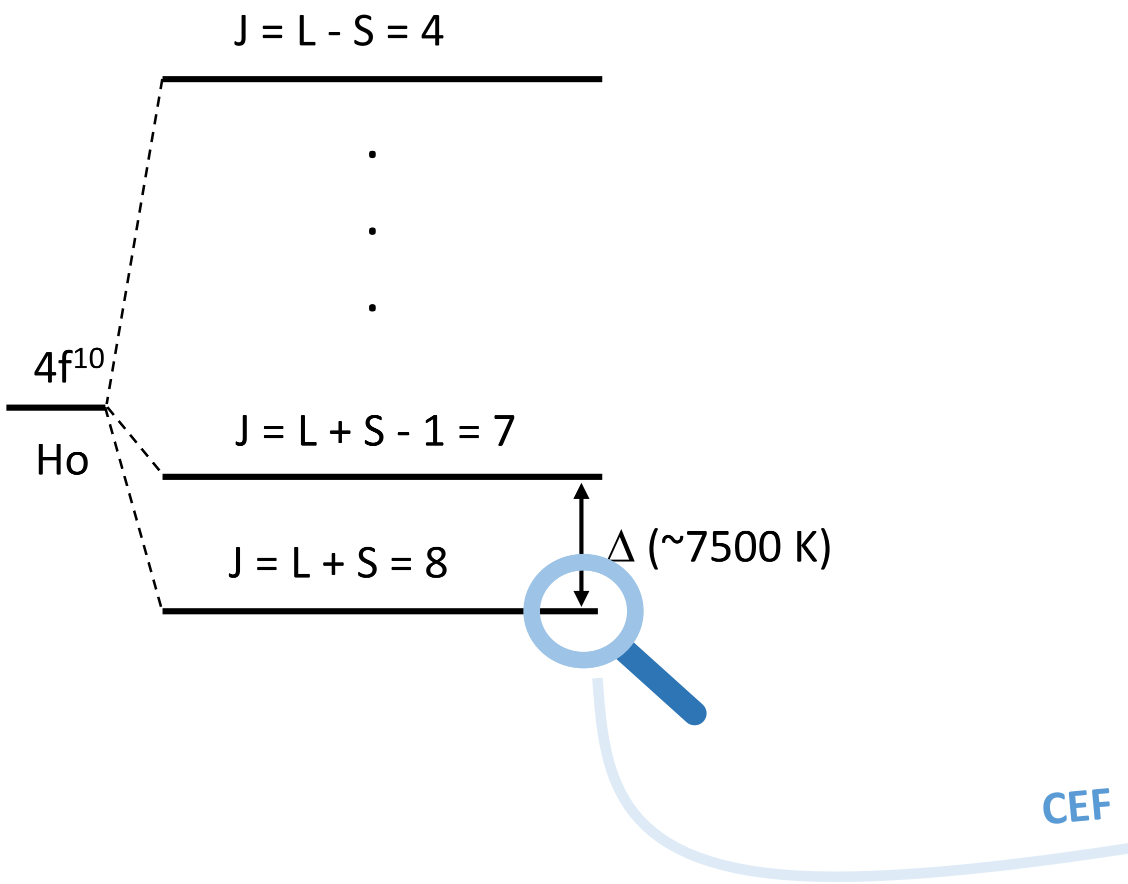

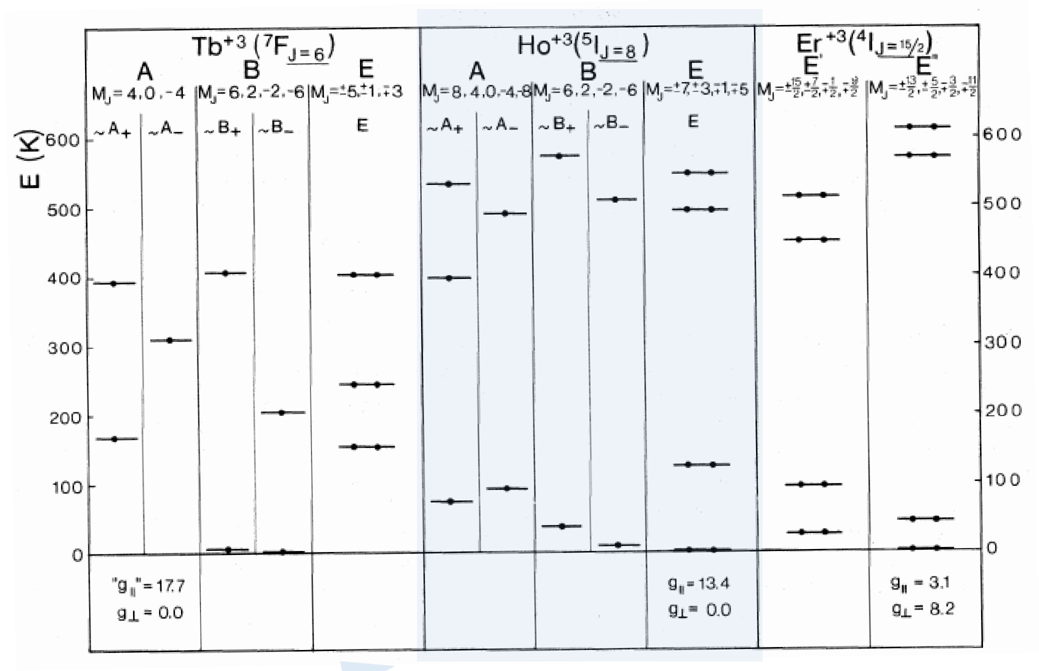

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TABLE VII. Energies and wave functions for the crystal levels of Ho in $LiHoF_4$ transforming according to the A, E, and B representations of the S_4 point group. For the doubly degenerate levels (E representations) $g_\parallel$ are included, $g_\perp = 0$.

A

E (K)	$e^{i1.7°}\|8\rangle$	$e^{-i8.2°}\|4\rangle$	$\|0\rangle$	$e^{i8.2°}\|-4\rangle$	$e^{-i1.7°}\|-8\rangle$	
535	0.397	−0.437	0.551	−0.437	0.397	$\sim A_+$
492	0.530	−0.468	0.000	0.468	−0.530	$\sim A_-$
398	−0.386	0.158	0.807	0.158	−0.386	$\sim A_+$
92	0.468	0.530	0.000	−0.530	−0.468	$\sim A_-$
74	0.440	0.533	0.212	0.533	0.440	$\sim A_+$

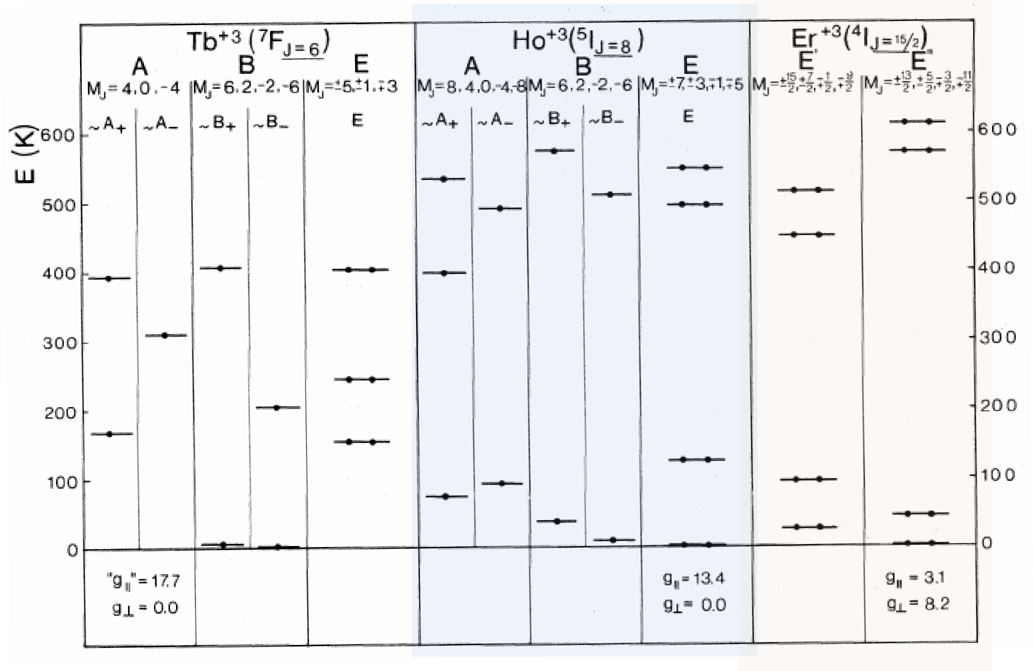
E

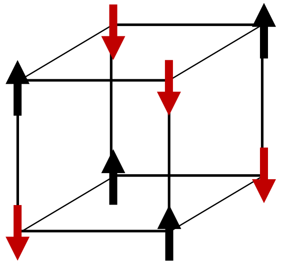
E (K)	$\|\pm 7\rangle$	$e^{\mp i9.2°}\|\pm 3\rangle$	$e^{\mp i88.1°}\|\mp 1\rangle$	$e^{\mp i92.5°}\|\mp 5\rangle$	$\|g_\parallel\|$
546	0.562	−0.717	−0.371	0.183	8.6
497	0.281	−0.305	0.788	−0.456	2.1
124	0.070	0.023	0.488	0.870	10.0
0	0.775	0.627	−0.060	−0.045	13.4

B

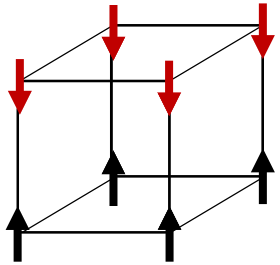
E (K)	$e^{i30.4°}\|6\rangle$	$e^{i22.7°}\|2\rangle$	$e^{-i22.7°}\|-2\rangle$	$e^{-i30.4°}\|-6\rangle$	
575	0.374	−0.600	−0.600	0.374	$\sim B_+$
511	−0.423	0.566	−0.566	0.423	$\sim B_-$
39	0.600	0.374	0.374	0.600	$\sim B_+$
9	−0.566	−0.423	0.423	0.566	$\sim B_-$

Kramers theorem:
levels with half-integer spins
are at least doubly degenerate

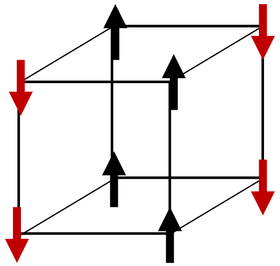




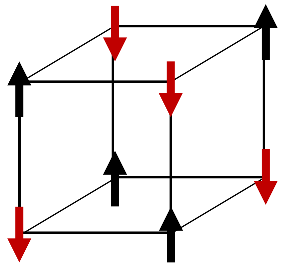
G-type AFM



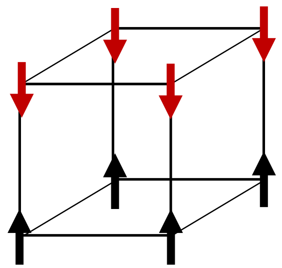
A-type AFM (FM planes)



C-type AFM (FM chains)



G-type AFM



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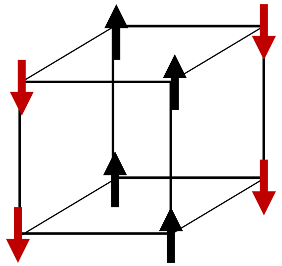
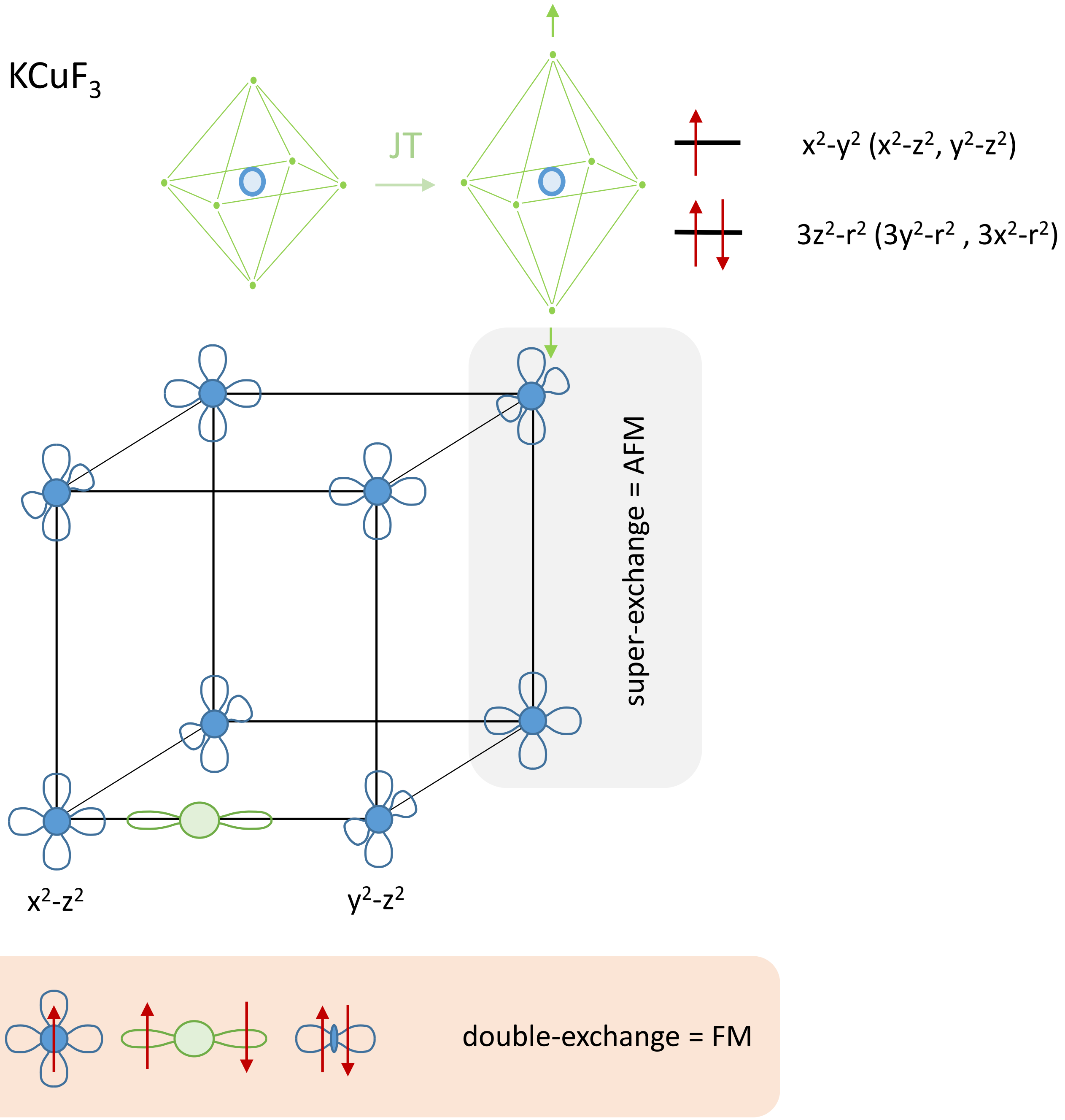
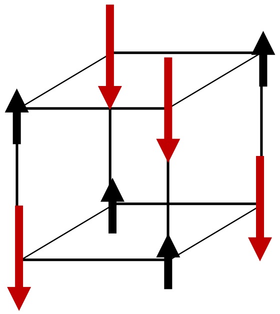
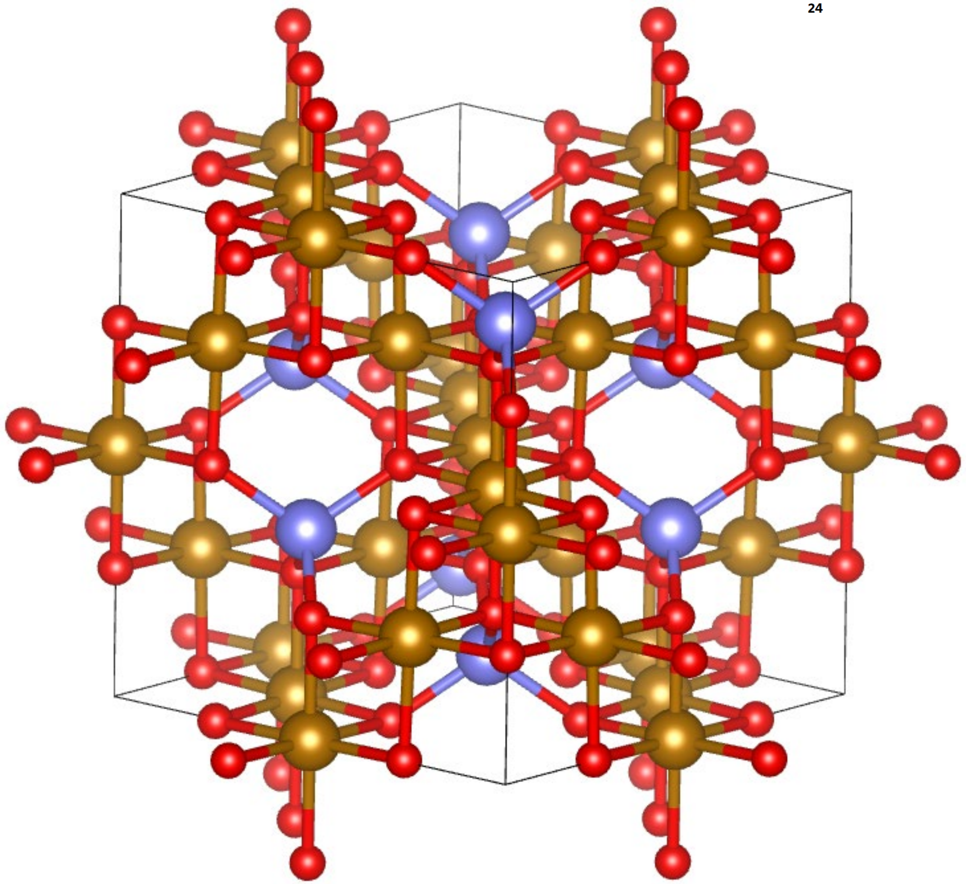


C-type AFM (FM chains)



- FiM = unequal sublattices
- more often multiple sites with a resultant FM moment
- sometimes with a compensation point





REVIEW ARTICLE
https://doi.org/10.1038/s41563-021-01139-4
nature materials
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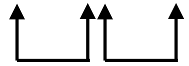
Ferrimagnetic spintronics

Se Kwon Kim[1], Geoffrey S. D. Beach[2], Kyung-Jin Lee[1,3,4], Teruo Ono[5,6], Theo Rasing[7,8] and Hyunsoo Yang[9]

24 NATURE MATERIALS | VOL 21 | JANUARY 2022 | 24–34 | www.nature.com/naturematerials

magnetite

$Fe_3O_4 \rightarrow Fe^{3+}Fe^{3+}Fe^{2+}O_4$



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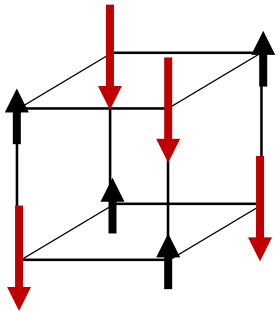
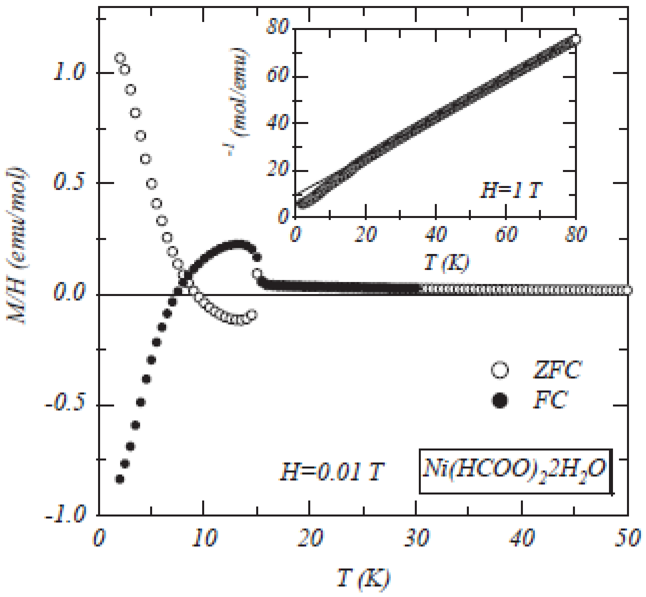
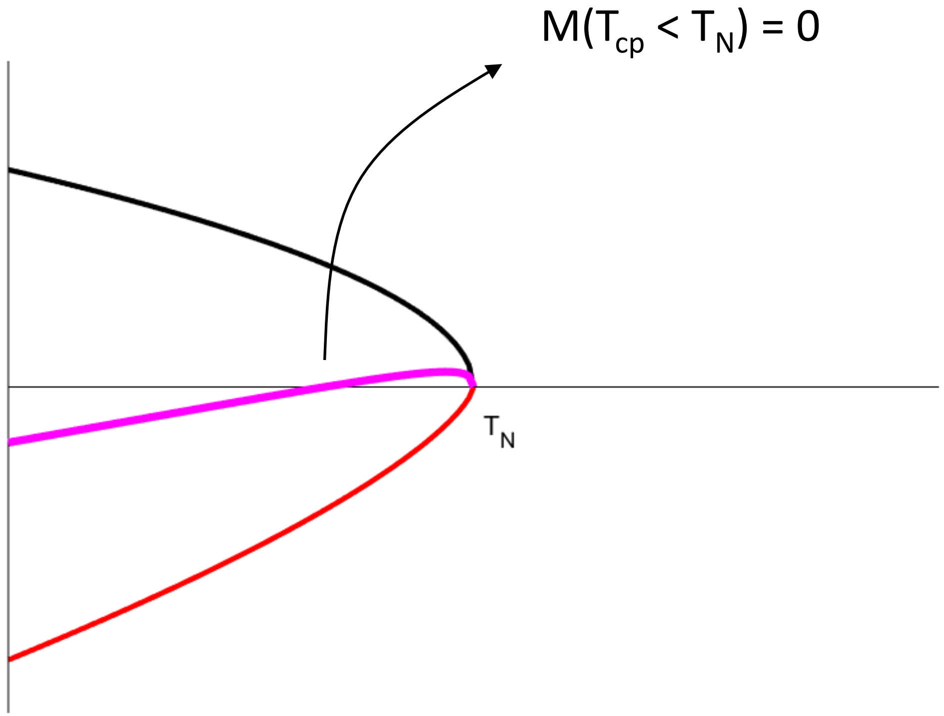
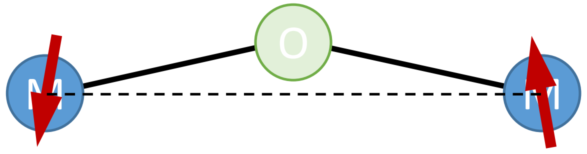


Physica B, 329 (2003)

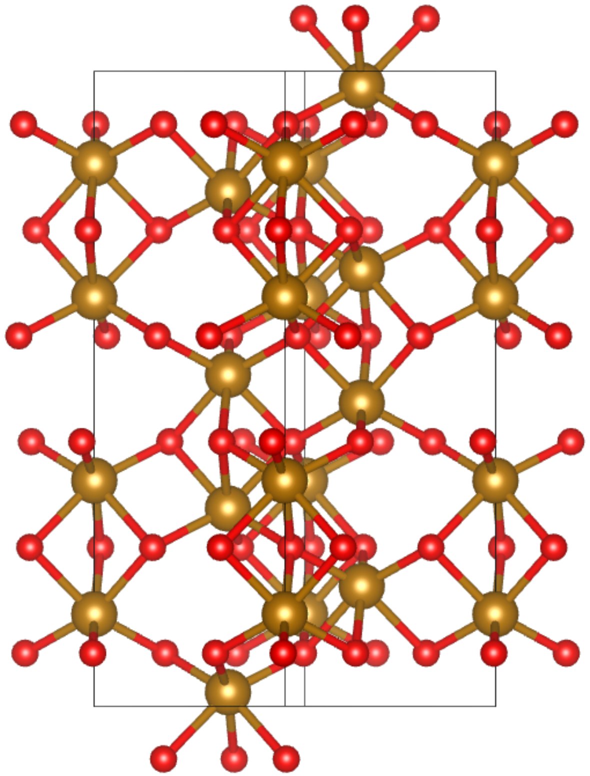




- AFM - canting

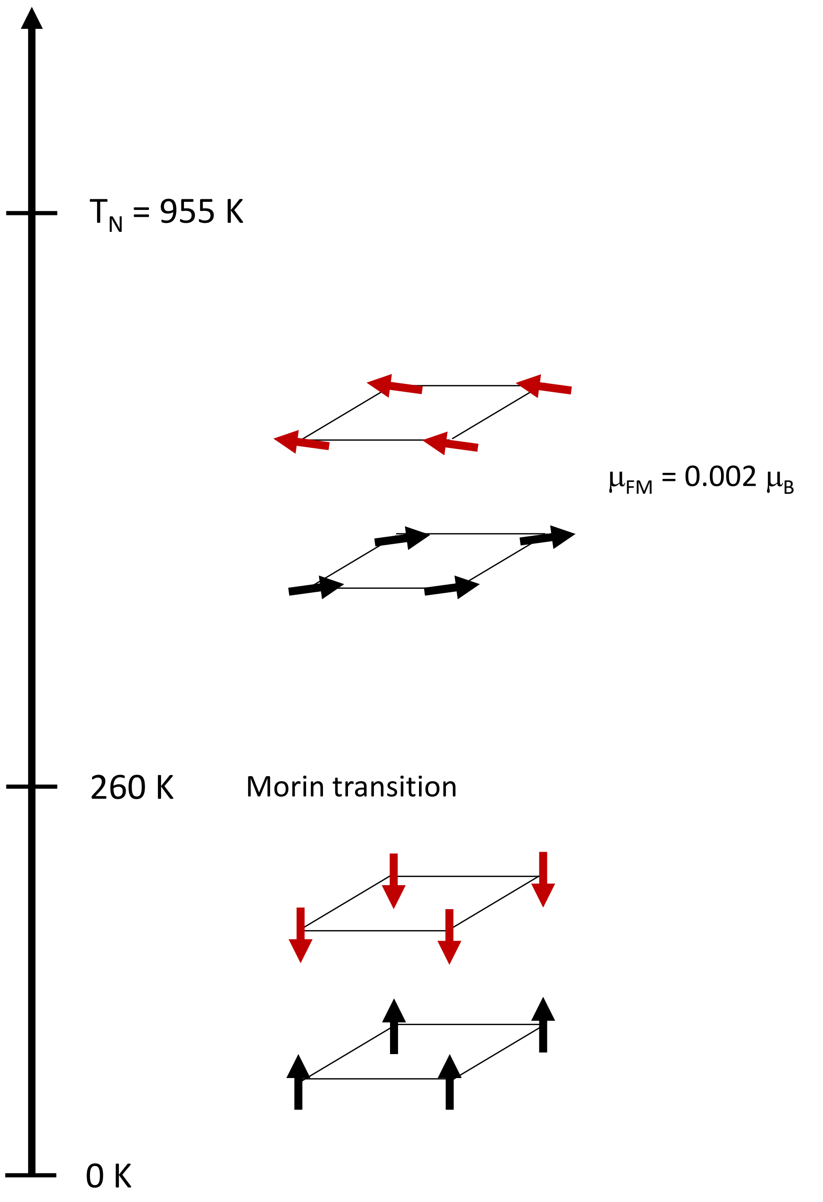


$$\hat{\mathcal{H}} = -J\boldsymbol{S}^a\boldsymbol{S}^b + \boldsymbol{D}(\boldsymbol{S}^a \times \boldsymbol{S}^b)$$

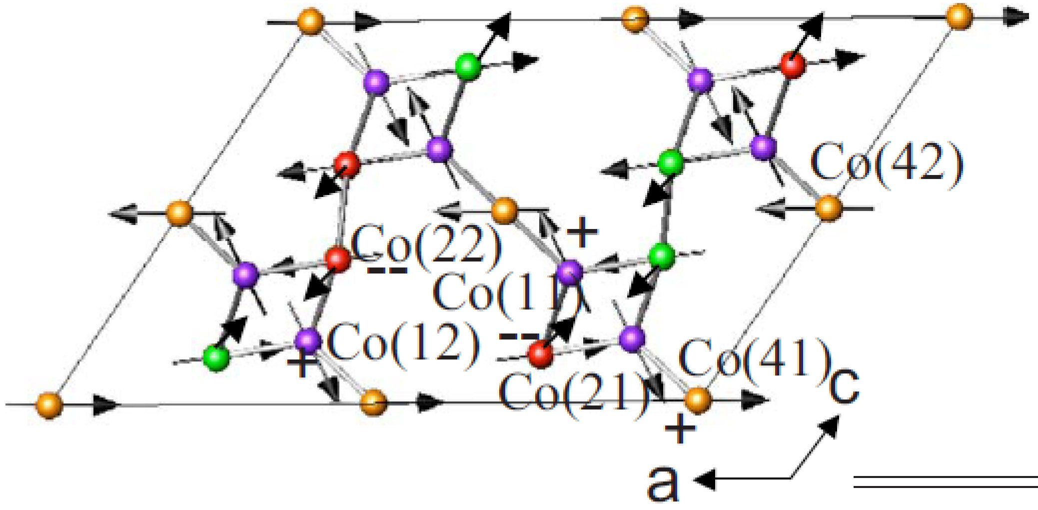


hematite

Fe_2O_3 (rust!)



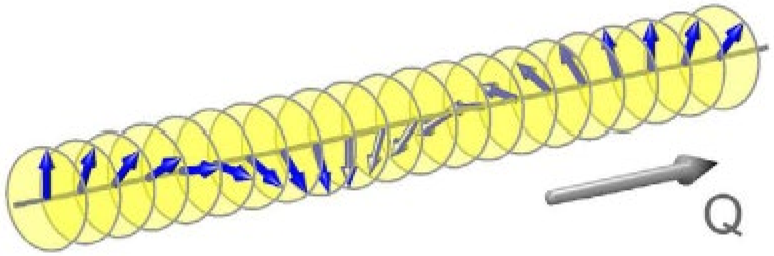
- sometimes it gets very complicated



Co7(TeO3)4Br6

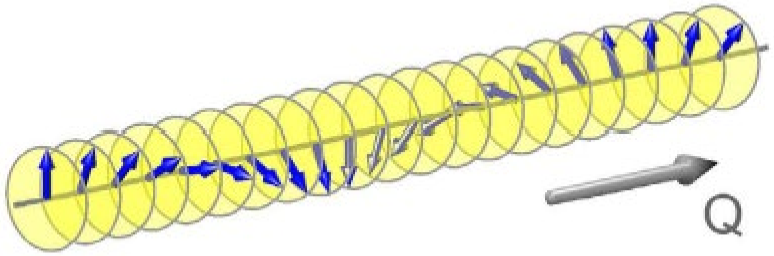
Ions	M_x	M_y	M_z	μ_B/Co	α_{1i}
Co(11)	2.64(9)	1.86(6)	2.77(9)	4.25(7)	0
Co(12)	−2.64(9)	1.86(6)	−2.77(9)	4.25(7)	125(2)
Co(21)	−3.08(7)	−1.1(1)	3.08(7)	4.4(1)	95(2)
Co(22)	3.08(7)	−1.1(1)	−3.08(7)	4.4(1)	97(2)
Co(31)	−0.43(8)	−3.1(1)	2.22(8)	3.8(1)	93(2)
Co(32)	0.43(8)	−3.1(1)	−2.22(8)	3.8(1)	131(2)
Co(41)	−3.51(8)	1.33(9)	2.48(8)	4.5(1)	90(2)
Co(42)	3.51(8)	1.33(9)	−2.48(8)	4.5(1)	75(2)

❖ FM + DMI → <u>helical order</u>

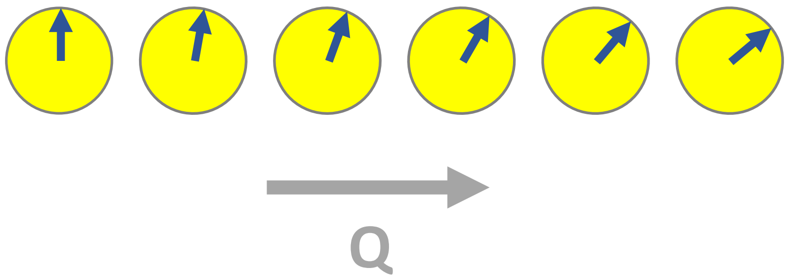


$\lambda = 2\pi/Q >> \text{unit cell}$

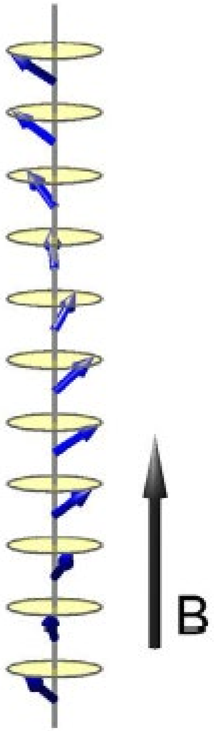
- FM + DMI $\rightarrow$ helical order



spiral order

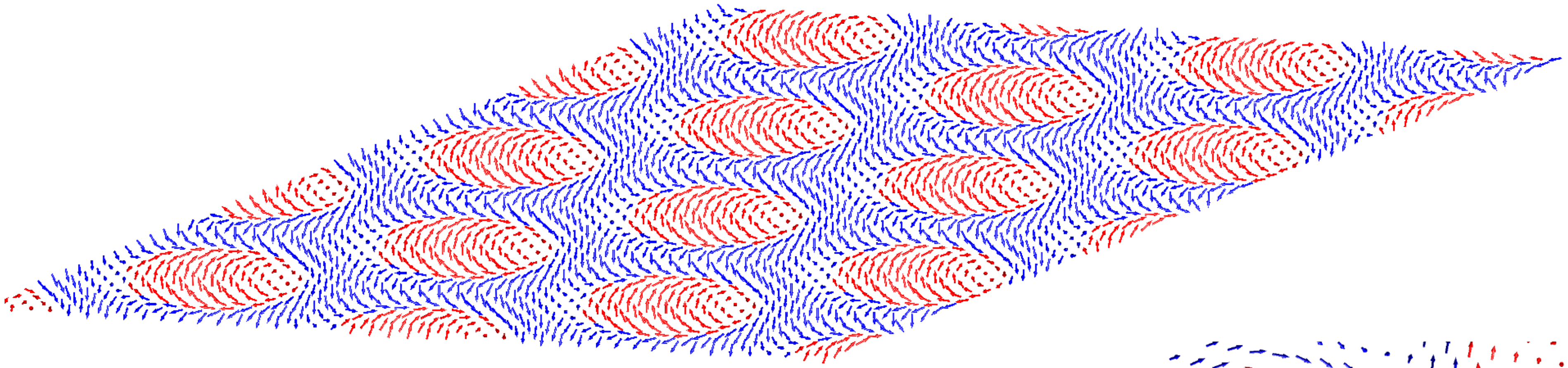


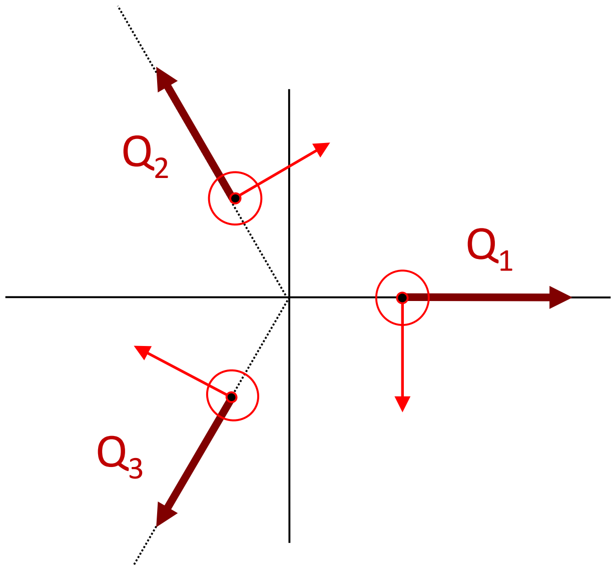
$\lambda = 2\pi/Q \gg$ unit cell

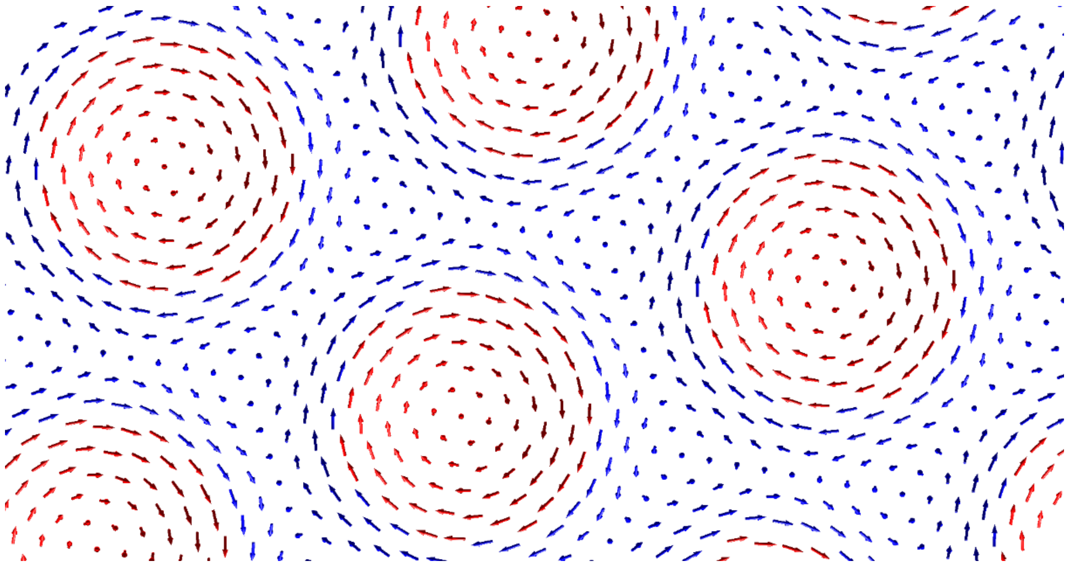


conical order (Q weakly coupled to lattice)

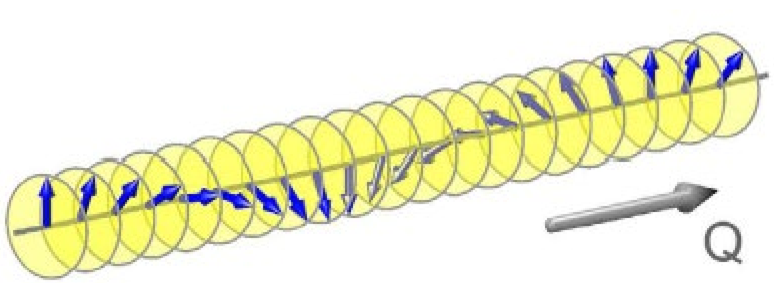
Skyrmion lattice

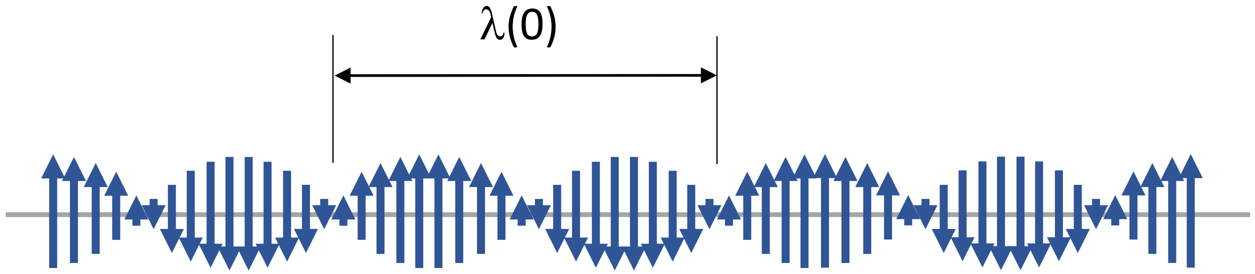




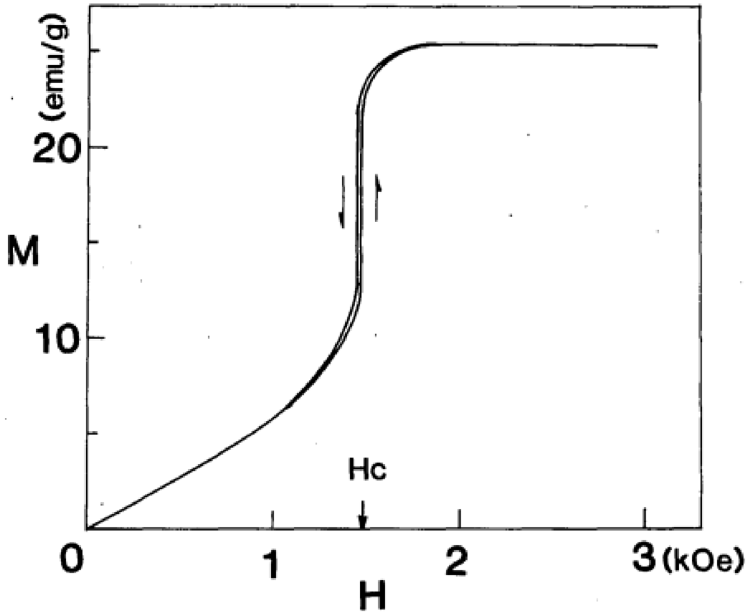


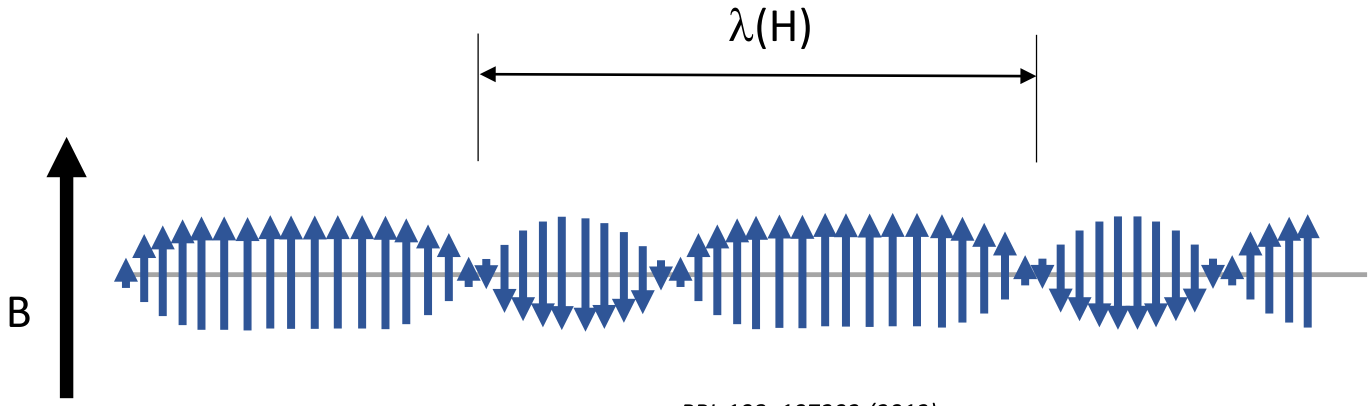
❖ soliton lattice ($Cr_{1/3}NbS_2$)



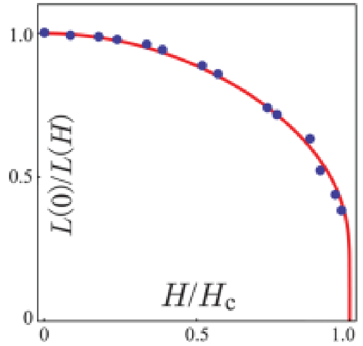


JPJS 52, 1394 (1983)

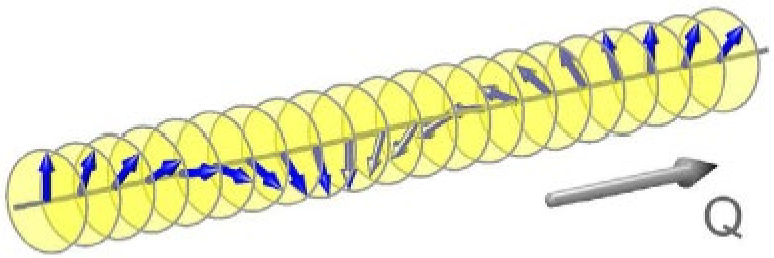


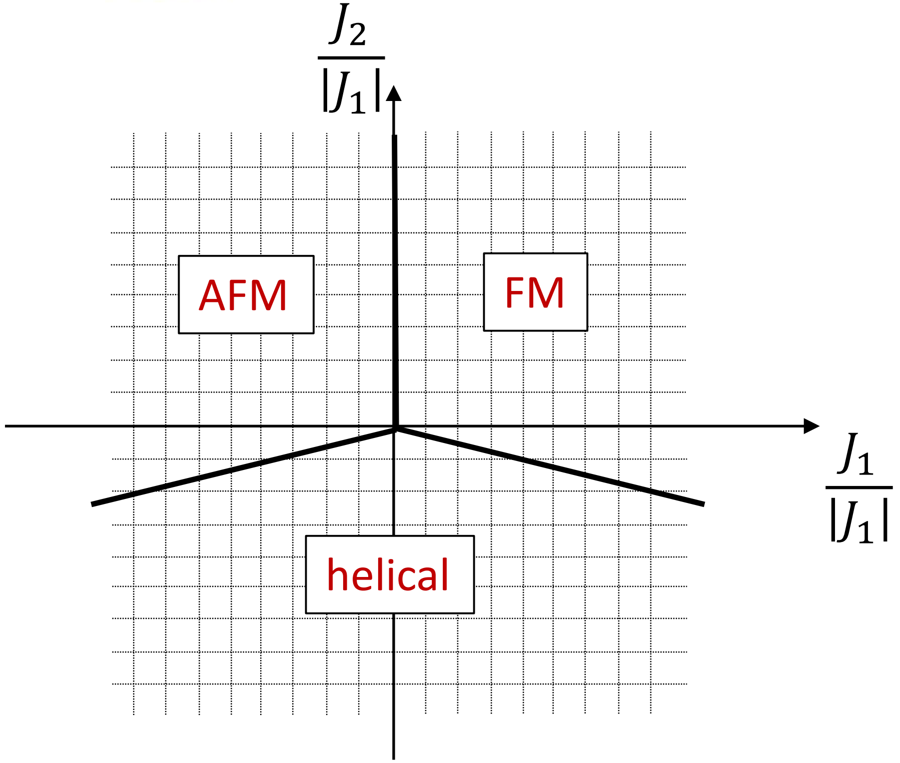


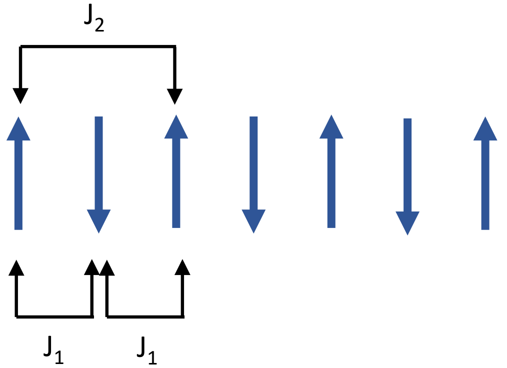
PRL 108, 107202 (2012)



❖ helical order from AFM







$$\mathcal{H} = -J_1 \boldsymbol{S}_i \boldsymbol{S}_{i+1} - J_2 \boldsymbol{S}_i \boldsymbol{S}_{i+2}$$

$$E = -J_1 \cos\theta - J_2 \cos 2\theta$$

$\theta = 0$: FM
$\theta = \pi$: AFM

$$\frac{\partial E}{\partial \theta} = (J_1 + 4J_2 \cos\theta) \sin\theta = 0$$

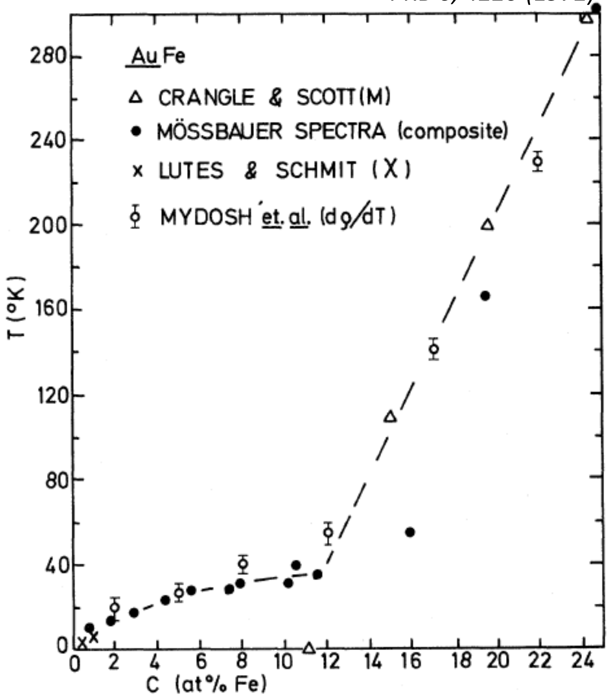
$$\cos\theta = -\frac{J_1}{4J_2}$$

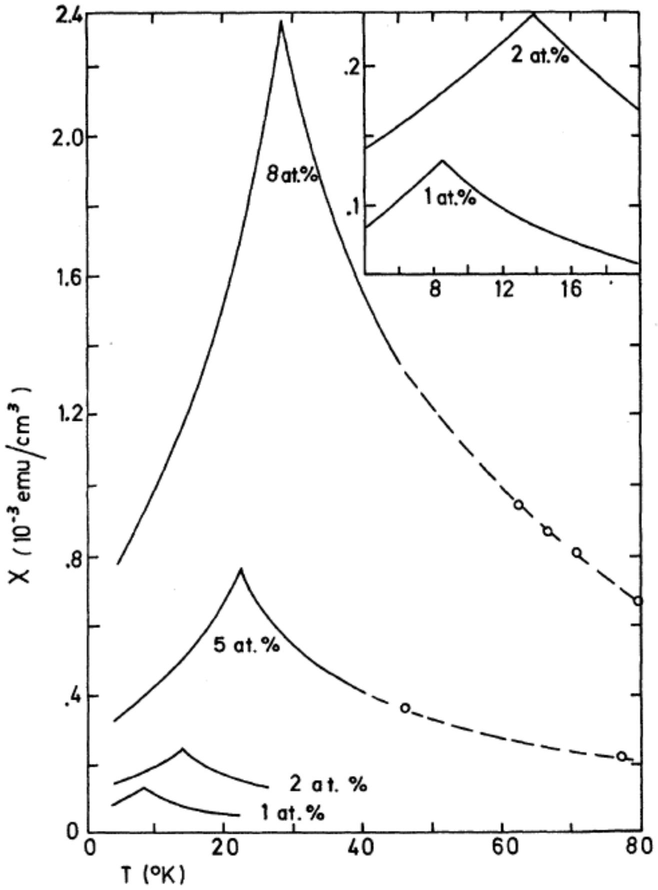
$$\downarrow \quad J_2 < 0$$

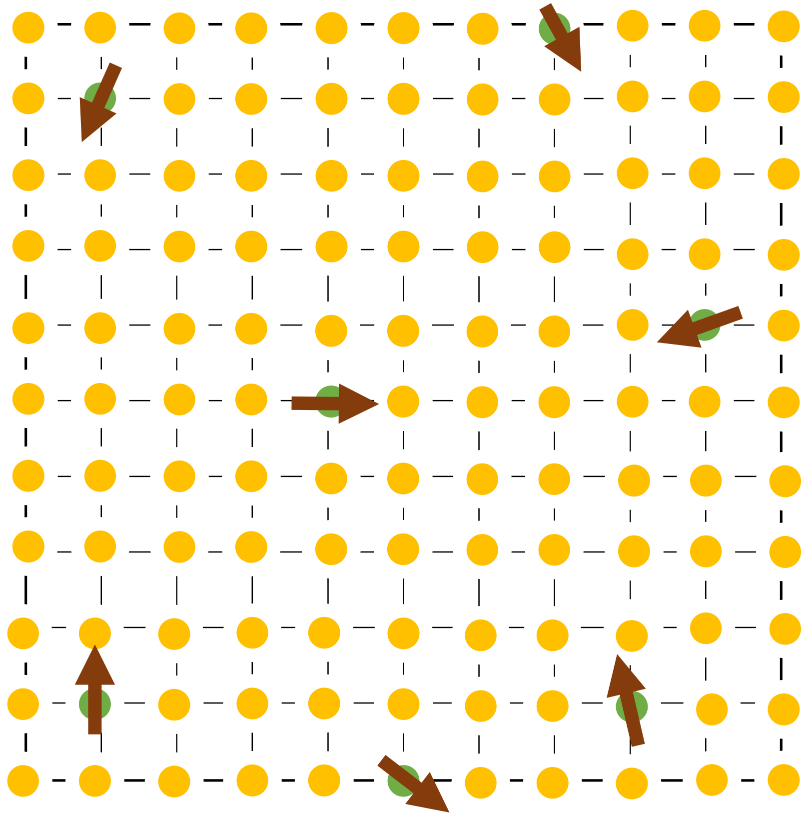
$$\cos\theta = \frac{J_1}{4|J_2|} < 1$$

- often claimed, rarely proven
- started in ‘70s, not-so-good analogy with amorphous glasses
- a follow-up of a Kondo problem (interaction between localized and conduction electrons in a very dilute limit)

PRB 6, 4220 (1972)



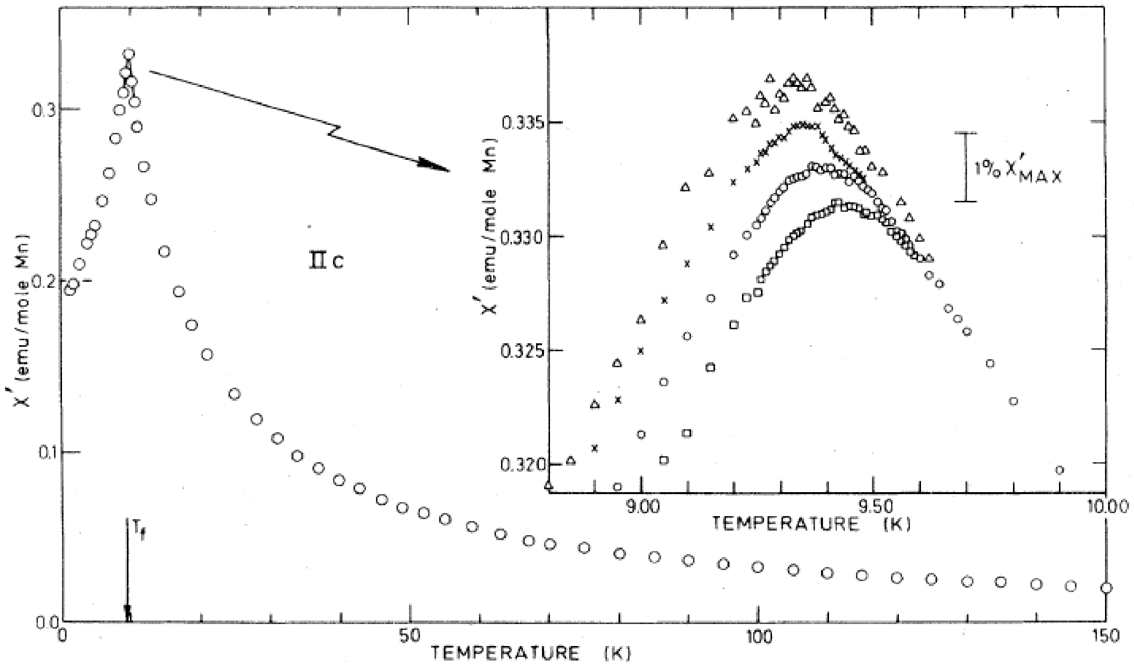




- random-site in CuMn, AuFe; random-bond in (Fe,Mn)TiO3
- randomness, frustration, competing interactions
- canonical and 'other' spin-glasses

1) frequency dependence of T_g
2) FC/ZFC protocol
3) specific heat
4) aging, memory and rejuvenation effects

PRB 23, 1384 (1981)



no divergence of χ but divergence of non-linear χ

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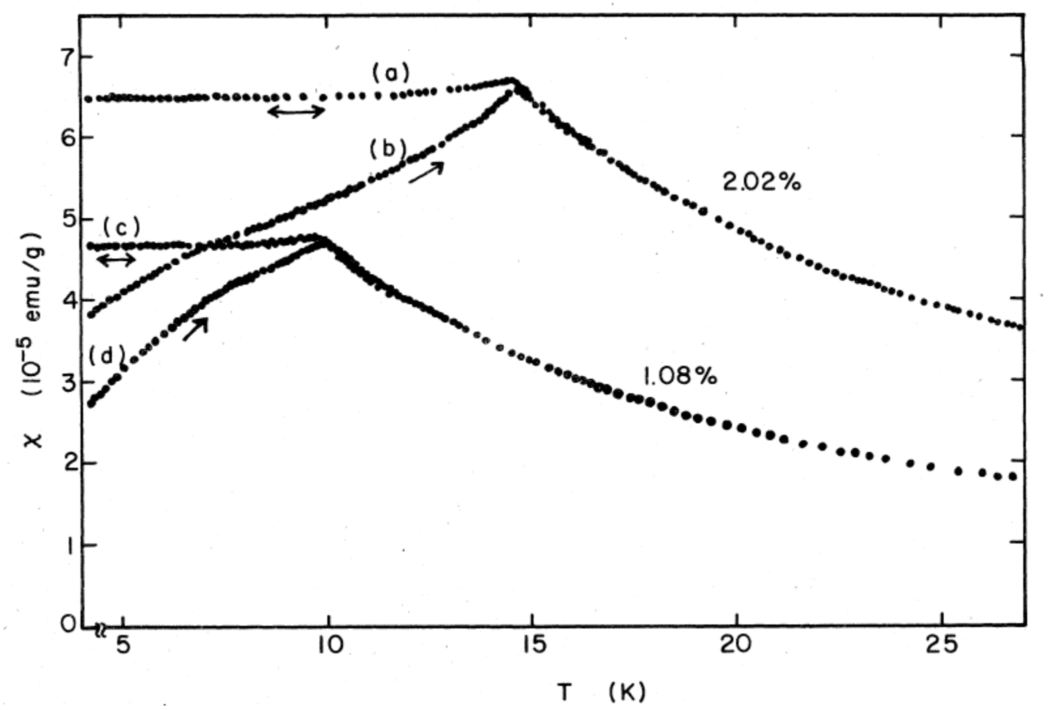
PRB 19, 1633 (1979)



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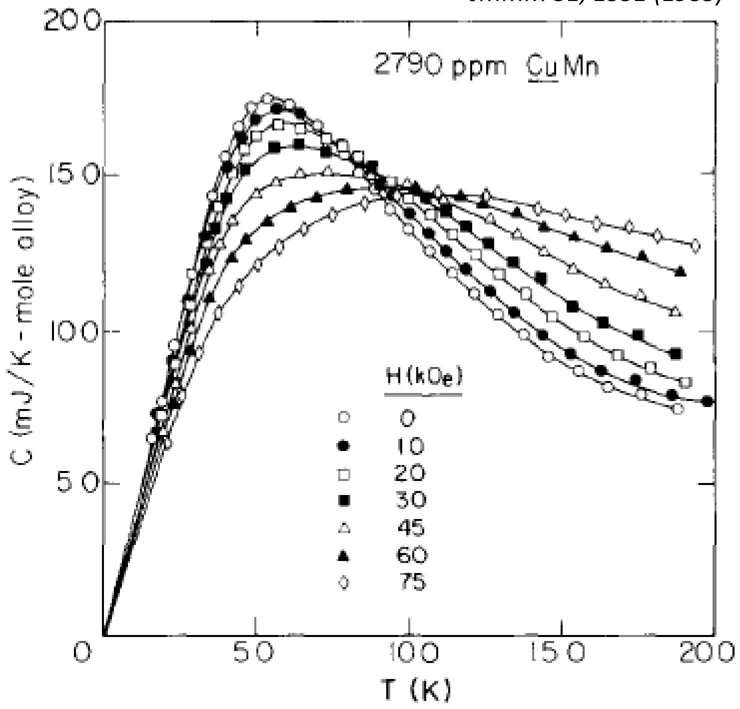
JMMM 31, 1331 (1983)



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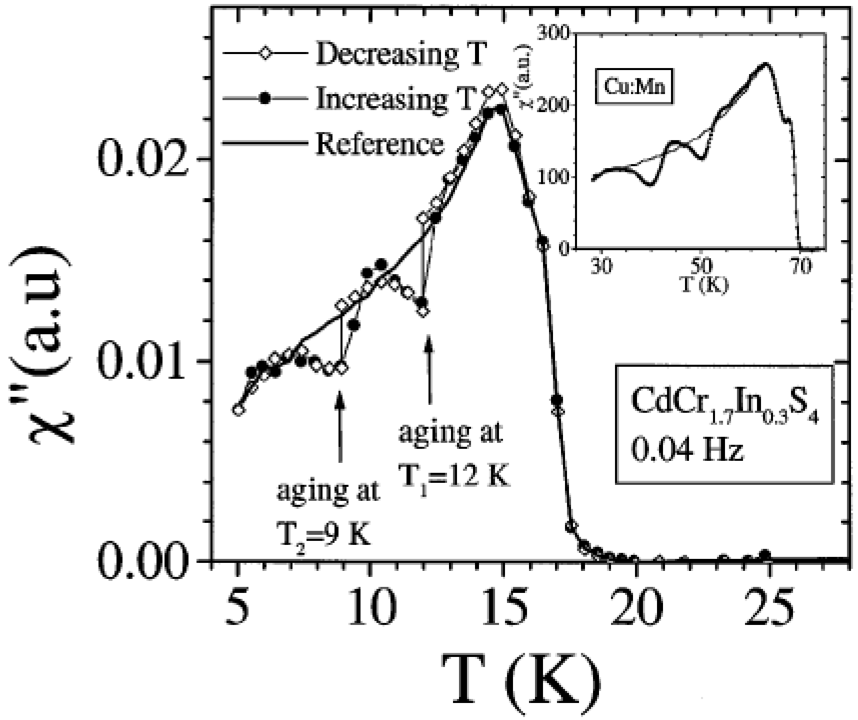
PRL 81, 3243 (1998)



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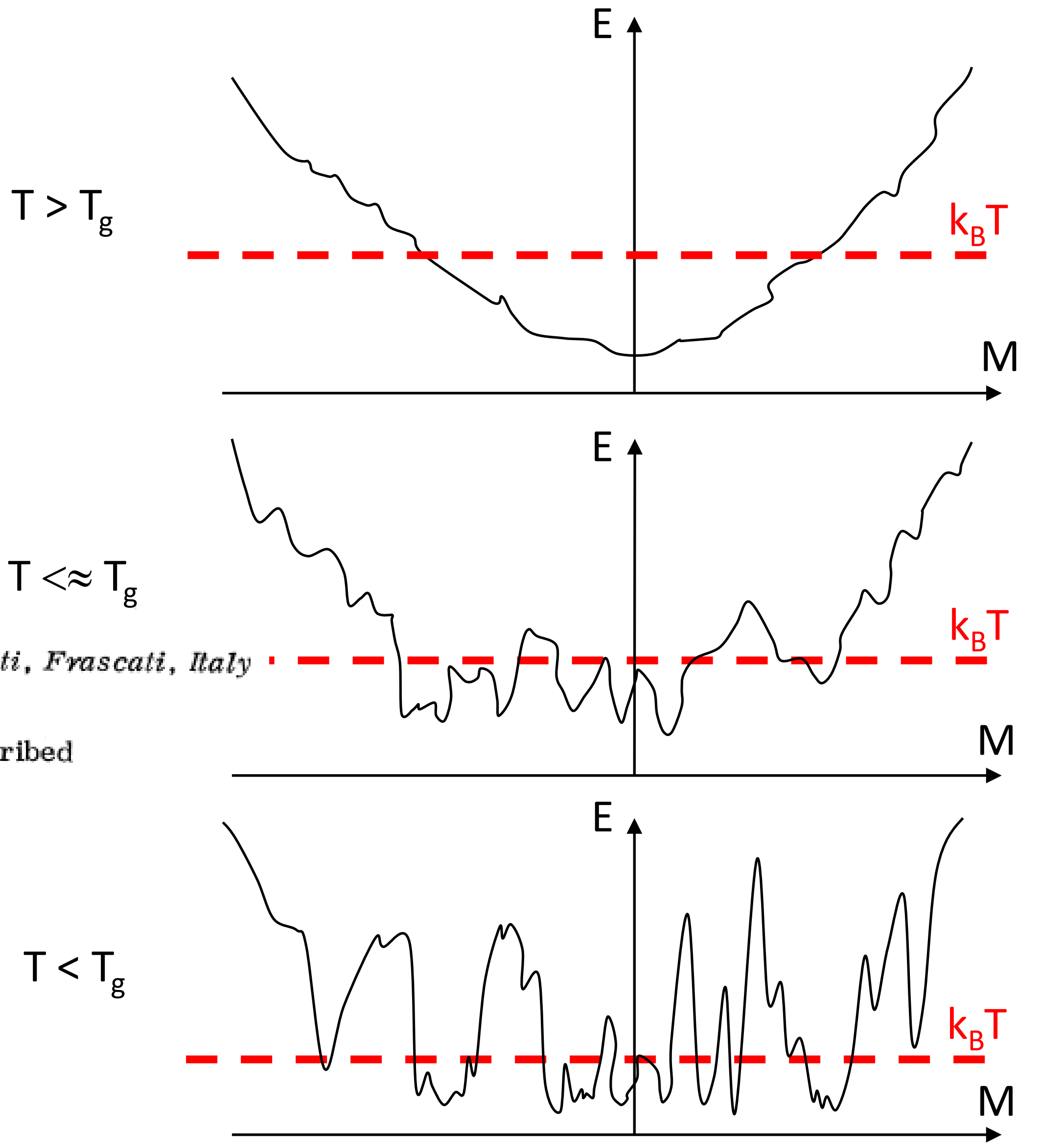

Infinite Number of Order Parameters for Spin-Glasses

G. Parisi
Servizio Documentazione, Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali di Frascati, Frascati, Italy
(Received 22 June 1979)

This Letter shows that in the mean-field approximation spin-glasses must be described by an infinite number of order parameters in the framework of the replica theory.

Order Parameter for Spin-Glasses

Giorgio Parisi
Universitá di Roma II, Tor Vergata, Rome, Italy, and Laboratori Nazionali, Istituto Nazionale di Física Nucleare, Frascati, Italy
(Received 1 February 1983)

An order parameter for spin-glasses is defined in a clear physical way: It is a function on the interval 0–1 and it is related to the probability distribution of the overlap of the magnetization in different states of the system. It is shown to coincide with the order parameter introduced by use of the broken replica-symmetry approach.

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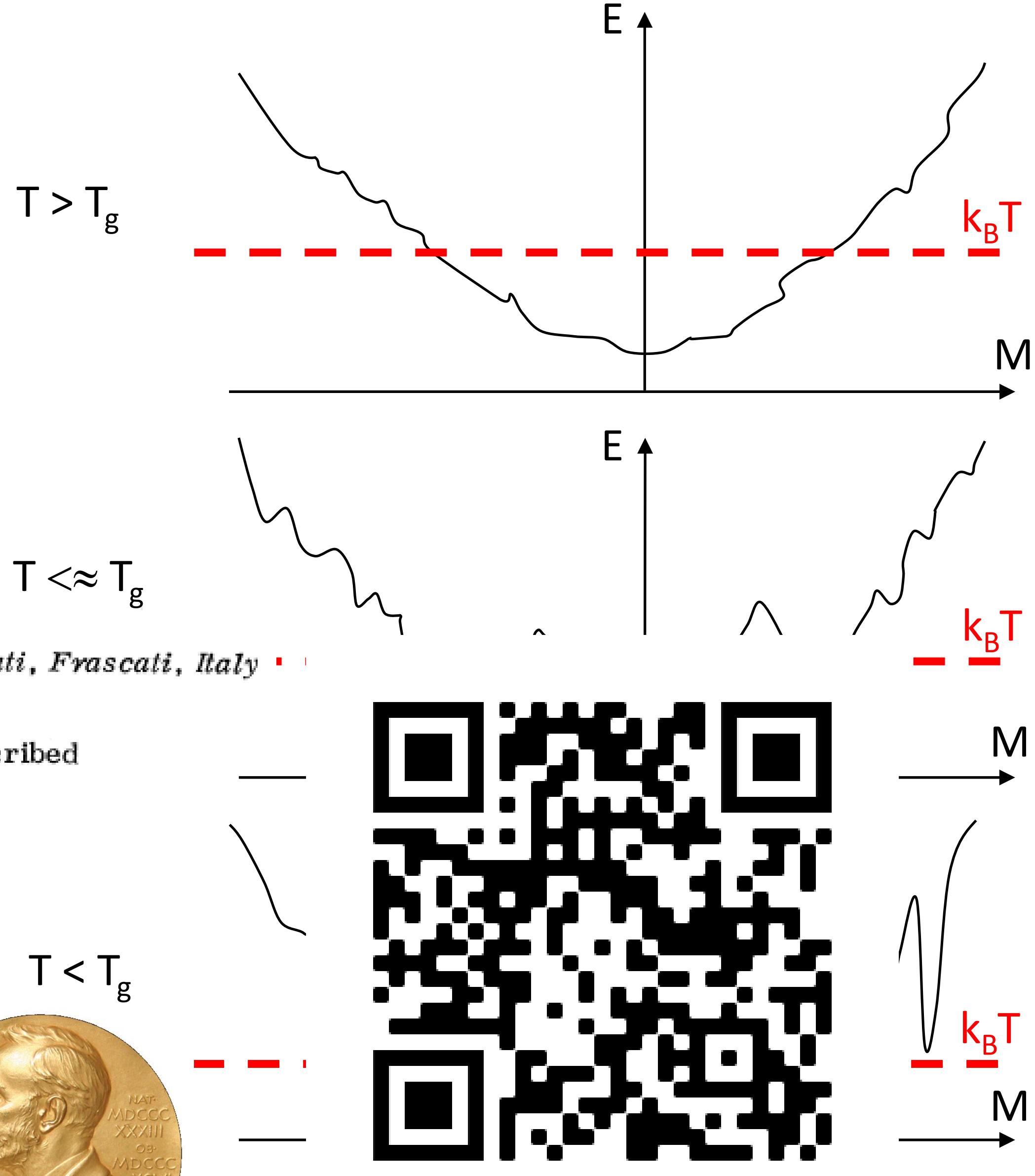

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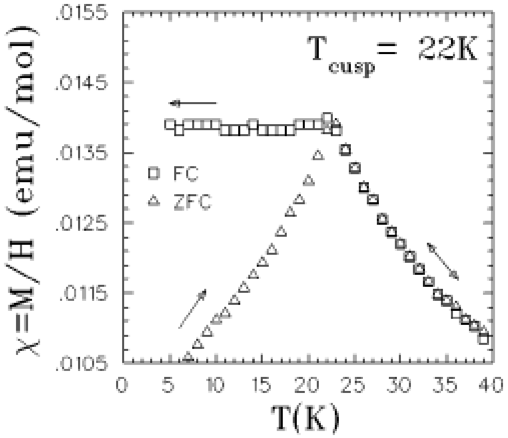
VOLUME 78, NUMBER 5 PHYSICAL REVIEW LETTERS 3 FEBRUARY 1997

Static Critical Behavior of the Spin-Freezing Transition in the Geometrically Frustrated Pyrochlore Antiferromagnet $Y_2Mo_2O_7$

M. J. P. Gingras,[1,*] C. V. Stager,[2] N. P. Raju,[3] B. D. Gaulin,[2] and J. E. Greedan[3]
[1] *TRIUMF, Theory Group, 4004 Wesbrook Mall, Vancouver, British Columbia, V6T-2A3, Canada*
[2] *Department of Physics and Astronomy, McMaster University, Hamilton, Ontario, L8S 4M1, Canada*
[3] *Department of Chemistry, McMaster University, Hamilton, Ontario, L8S 4M1, Canada*
(Received 5 August 1996)

Some frustrated pyrochlore antiferromagnets, such as $Y_2Mo_2O_7$, show a spin-freezing transition and magnetic irreversibilities below a temperature T_f similar to what is observed in *randomly* frustrated spin-glasses. We present results of nonlinear dc magnetization measurements on $Y_2Mo_2O_7$ that provide strong evidence that there is an underlying thermodynamic phase transition at T_f, which is characterized by critical exponents $\gamma \approx 2.8$ and $\beta \approx 0.8$. These values are typical of those found in random spin-glasses, despite the fact that the level of random disorder in $Y_2Mo_2O_7$ is immeasurably small.



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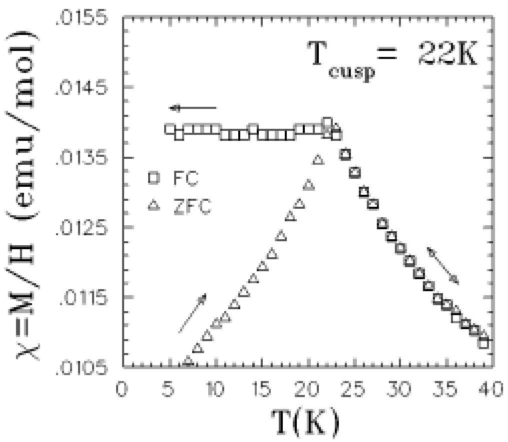

Self-induced spin glass state in elemental and crystalline neodymium

Umut Kamber[1], Anders Bergman[2], Andreas Eich[1], Diana Iuşan[2], Manuel Steinbrecher[1], Nadine Hauptmann[1], Lars Nordström[2], Mikhail I. Katsnelson[1], Daniel Wegner[1]*, Olle Eriksson[2,3], Alexander A. Khajetoorians[1]*

Spin glasses are a highly complex magnetic state of matter intricately linked to spin frustration and structural disorder. They exhibit no long-range order and exude aging phenomena, distinguishing them from quantum spin liquids. We report a previously unknown type of spin glass state, the spin-Q glass, observable in bulk-like crystalline metallic neodymium thick films. Using spin-polarized scanning tunneling microscopy combined with ab initio calculations and atomistic spin-dynamics simulations, we visualized the variations in atomic-scale noncolinear order and its response to magnetic field and temperature. We quantified the aging phenomena relating the glassiness to crystalline symmetry and the energy landscape. This result not only resolves the long-standing debate of the magnetism of neodymium, but also suggests that glassiness may arise in other magnetic solids lacking extrinsic disorder.

Kamber *et al.*, *Science* **368**, eaay6757 (2020)