Phase competition in anisotropic frustrated antiferromagnets

DMI 2021 WORKSHOP

PNPI

NRC “Kurchatov Institute”

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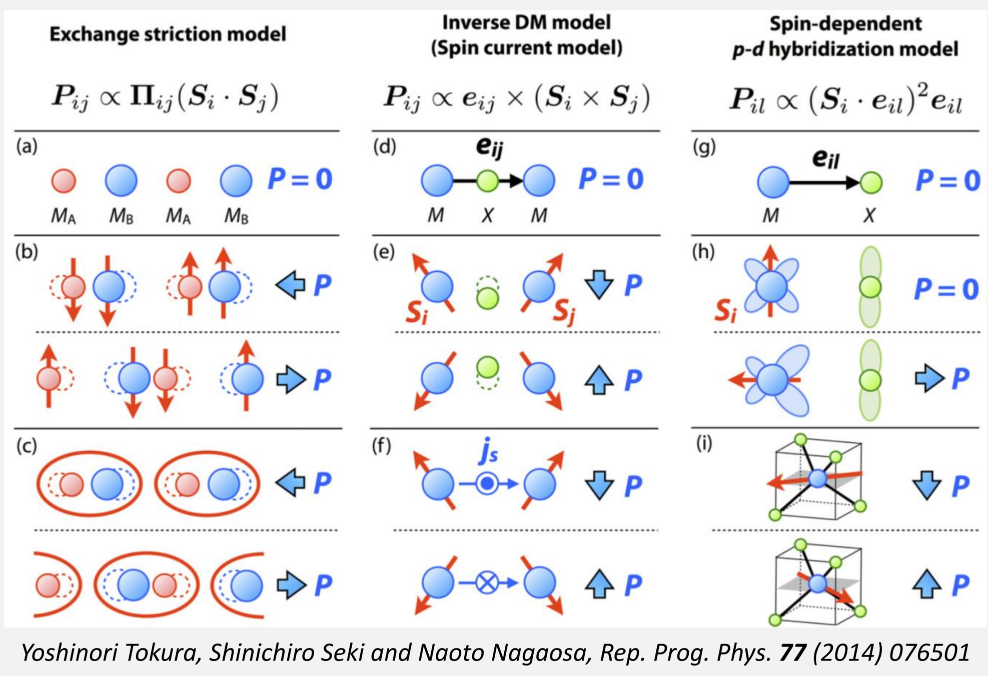
Motivation: multiferroics of spin origin



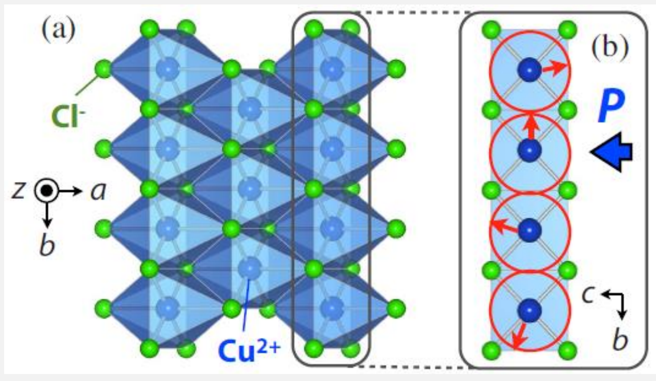
Yoshinori Tokura, Shinichiro Seki and Naoto Nagaosa, Rep. Prog. Phys. ***77*** *(2014) 076501*

Frustration can lead to noncollinear spin structures
Research on corresponding phase transitions is important

Spiral plane flop. Experiment

$CuCl_2$, *Seki et al., Phys. Rev. B* ***82****, 064424 (2010)*

q ∥ b, cycloid in bc plane in the absence of the external field



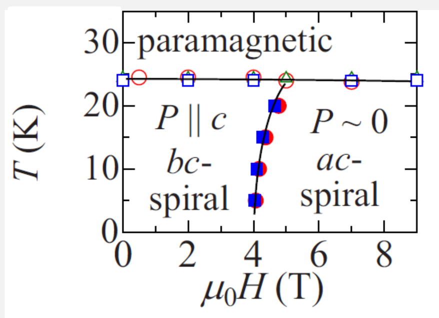
$$\vec{p}_{ij} = A\vec{e}_{ij} \times (\vec{S}_i \times \vec{S}_j)$$

$\vec{e}_{ij} \| b$

H=0, P ∥ c

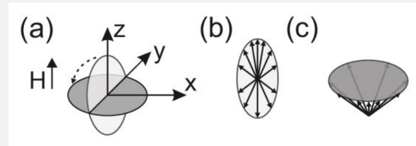
For fields greater than 4 T along **b** – spiral with the plane ac, P=0

Spiral plane is determined by small anisotropic interactions (we notice difference with DMI spirals)



Spiral plane flop in helimagnets

In anisotropic antiferromagnets there is famous spin flop transition for magnetic field along easy axis. Similarly, in frustrated helimagnets spiral plane flop can be observed



$$\mathcal{H} = \mathcal{H}_{ex} + \mathcal{H}_{an} + \mathcal{H}_z,$$
$$\mathcal{H}_{ex} = -\frac{1}{2}\sum_{i,j} J_{ij}\,(\mathbf{S}_i \cdot \mathbf{S}_j),$$
$$\mathcal{H}_{an} = -\sum_i \left[D(S_i^z)^2 + E(S_i^y)^2\right],$$
$$\mathcal{H}_z = -\sum_i (\mathbf{h} \cdot \mathbf{S}_i),$$

Considered model consists of frustrated exchange with two minima at $\mathbf{q} = \pm\mathbf{k}$, biaxial anisotropy (or dipolar forces) and Zeeman term.

If magnetic field is applied in *yz* plane there is first order transition from helicoid with spins rotating in easy plane (**YZ**) to conical spiral state (**XY**), where the spiral plane is perpendicular to the field.

Theoretical description is based on accurate accounting for magnetic field and anisotropy effects on spin structure by virtue of their smallness

Spiral plane flop 2

Anisotropy distorts helicoid and produces higher order odd harmonics, magnetic field provides even harmonics in **YZ** helicoid, and conical tilt of spins in **XZ** one.

For field along easy $\hat{z}$ axis:

$$\frac{1}{N}\mathcal{E}^{yz} = -\frac{S^2 J_{\mathbf{k}}}{2} - \frac{S^2(D+E)}{2} - \frac{S^2(D-E)^2}{2(J_{\mathbf{k}} - J_{3\mathbf{k}})} - \frac{h^2}{2(2J_{\mathbf{k}} - J_{\mathbf{0}} - J_{2\mathbf{k}})}$$
$$\frac{1}{N}\mathcal{E}^{xy} = -\frac{S^2 J_{\mathbf{k}}}{2} - \frac{S^2 E}{2} - \frac{S^2 E^2}{2(J_{\mathbf{k}} - J_{3\mathbf{k}})} - \frac{h^2}{2(J_{\mathbf{k}} - J_{\mathbf{0}})}$$

in this case

$$\boxed{h_{flop} = S\sqrt{D\tilde{J}},} \qquad \tilde{J} = \frac{(J_{\mathbf{k}} - J_{\mathbf{0}})(2J_{\mathbf{k}} - J_{\mathbf{0}} - J_{2\mathbf{k}})}{J_{\mathbf{k}} - J_{2\mathbf{k}}}$$

for other in-plane directions

$$h_{flop} = S\sqrt{\tilde{J}\frac{ED}{E\cos^2 t + D\sin^2 t}}$$

in case of dipolar forces $E = \lambda_1(\mathbf{k}) - \lambda_2(\mathbf{k}),\ D = \lambda_1(\mathbf{k}) - \lambda_3(\mathbf{k})$

O.I. Utesov and A. V. Syromyatnikov, Phys. Rev. B ***98****, 184406 (2018)*

Competition with commensurate structure

It is well-known that anisotropy can destroy helical order in case of competing collinear spin ordering (e.g. antiferromagnetic). So, at small fields one should compare energies of **YZ** and **XY** helicoids with collinear (**AF**) and canted AF (**CAF**) order

$$\frac{1}{N}\mathcal{E}_{\mathrm{AF}} = -\frac{S^2}{2}J_{\mathbf{k}_0} - S^2 D,$$
$$\frac{1}{N}\mathcal{E}_{\mathrm{CAF}} \approx -\frac{S^2}{2}J_{\mathbf{k}_0} - S^2 E - \frac{h^2}{2(J_{\mathbf{k}_0} - J_0)}$$

1. The spin-flop field reads $h_{\mathrm{sf}} = S\sqrt{2(D-E)(J_{\mathbf{k}_0} - J_0)}$
2. AF phase is stable at $h = 0$ if $D - E > J_{\mathbf{k}} - J_{\mathbf{k}_0} \equiv \alpha$
3. Moreover, CAF is preferable in comparison with XY if $E > \alpha$

If this conditions hold, spin-flop transition is split and intermediate **YZ** helicoid phase appears. One has sequence of phase transitions

$$\mathbf{AF \leftrightarrow YZ \leftrightarrow CAF}$$

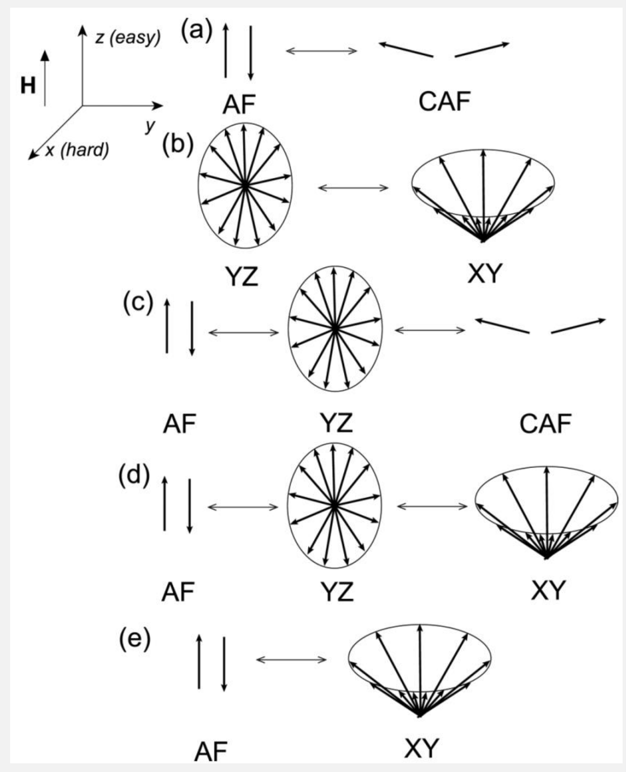
If $E < \alpha$ **XY** phase has lower energy than **CAF** and two other sequences become possible: $\mathbf{AF \leftrightarrow YZ \leftrightarrow XY}$

$$\mathbf{AF \leftrightarrow XY}$$

Small fields: summary

In small fields domain, along with conventional spin-flop transition in antiferromagnets and spiral plane flop in helimagnets, there are three other sequences of phase transitions involving helical structures

Corresponding critical fields and conditions for these scenarios to take place are presented in paper *O.I. Utesov and A. V. Syromyatnikov, Phys. Rev. B* ***100****, 054439 (2019)*



Sequence (e) was observed experimentally in *J. Lass, et al., Phys. Rev. B 101, 054415 (2020).*

Strong fields: transition to fan phase

First, we assume that at moderate fields conical helicoid is the ground state. Due to biaxial anisotropy or dipolar forces the spiral plane is anisotropic, thus the helical component of spin ordering is distorted.

1. Ratio between spin component along easy and hard in-plane axes diverges upon field increase; ellipse reduces to a line
2. Perturbation theory in powers of anisotropy constant breaks down
3. Magnon spectrum softens, developing roton-like minimum at $\mathbf{q} = -2\mathbf{k}$

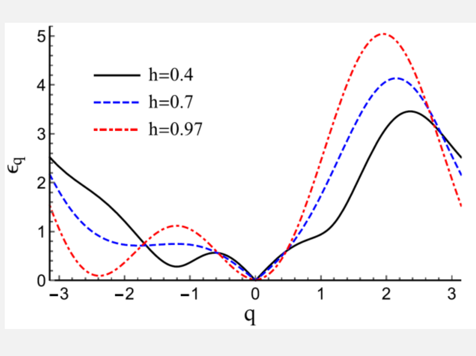
These facts manifest Ising-type quantum phase transitions to pre-saturation fan phase, where broken chiral symmetry in restored

Using spin quantization in approximate local basis for fan phase one can find the Hamiltonian instability at

$$h_{cr} = h_s^{FAN} - SE\frac{3J_{\mathbf{k}} - 2J_{\mathbf{0}} - J_{2\mathbf{k}}}{J_{\mathbf{k}} - J_{2\mathbf{k}}}$$

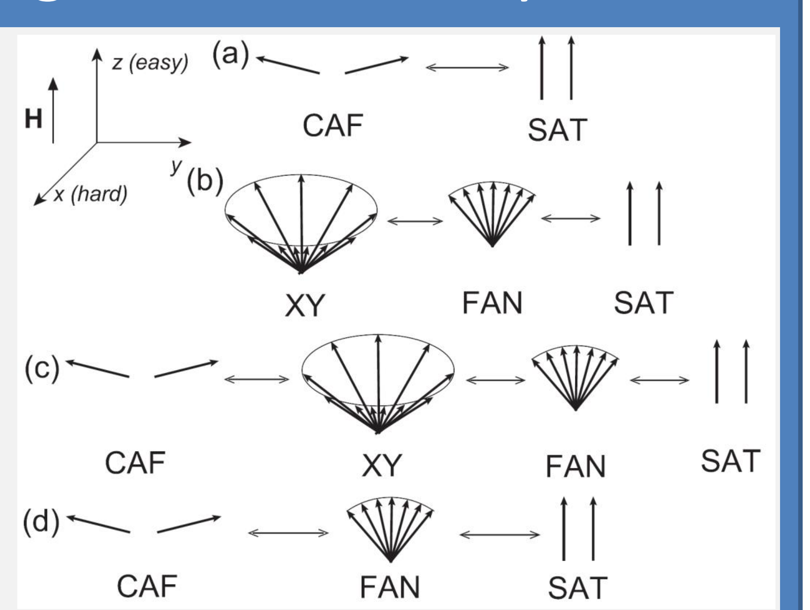
where the saturation field reads

$$h_s^{FAN} = S\left(J_{\mathbf{k}} - J_{\mathbf{0}} + 2E - 2D\right)$$



Strong fields: summary

In conventional AFs the **CAF** phase continuously transforms into collinear saturated phase. In frustrated AFs with biaxial anisotropy or dipolar forces intermediate fan phase appears before the saturation



If we consider competition between commensurate and incommensurate ordering for $E > J_{\mathbf{k}} - J_{\mathbf{k}_0}$ **CAF** phase is the ground state at moderate fields, however it cannot transform continuously into the saturated phase, and one of scenarios (c) or (d) should take place. Details can be found in *O. I. Utesov and A. V. Syromyatnikov, Jour. Mag. Mag. Mater.* ***527****, 167732 (2021).*

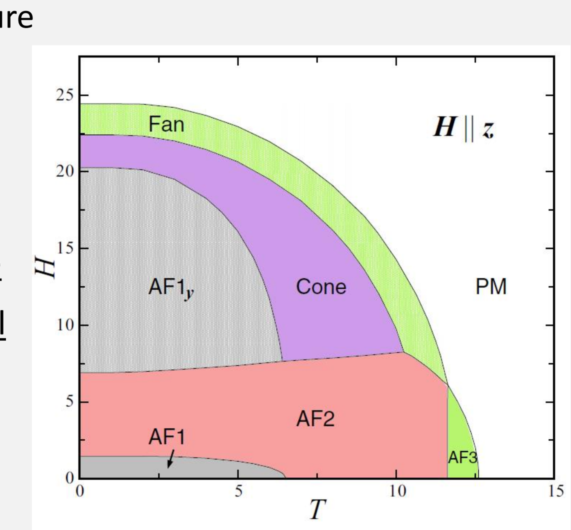
Comparison with numerical approach for $MnWO_4$

Numerical phase diagram for **ANNNH** model (reproduces qualitatively behavior of $MnWO_4$) *M.V. Gvozdikova et al., Phys. Rev. B* ***94****, 020406(R) (2016)*

$\mathbf{k}_0$ - vector of ↑↑↓↓ structure

AF2 ⟺ YZ

$AF1_y$ ⟺ CAF



Our theory is directly applicable

Analytical equations for critical fields yield

$$h_1 \approx 2.7,\ h_2 \approx 7.4,$$
$$h_3 \approx 21,\ h_{cr} \approx 21.9,$$
$$h_s^{FAN} \approx 24.3$$

Our analytical approach successfully describes all five magnetic-field induced phase transitions at small temperatures (all three for the field along middle axis)

Acknowledgments

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