НАЦИОНАЛЬНЫЙ ИССЛЕДОВАТЕЛЬСКИЙ ЦЕНТР «КУРЧАТОВСКИЙ ИНСТИТУТ»

ПЕТЕРБУРГСКИЙ ИНСТИТУТ ЯДЕРНОЙ ФИЗИКИ им. Б.П. Константинова

From spiral to ferromagnetic structure in B20 compounds: role of cubic anisotropy

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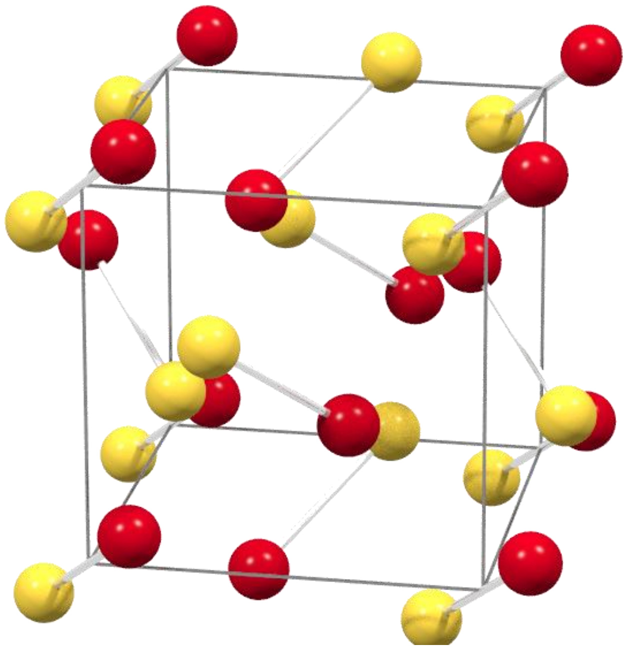
B20 structure



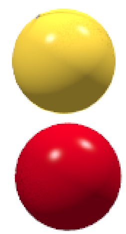
Examples

MnSi, FeSi, CoSi

$Mn_{1-y}Fe_ySi$, $Mn_{1-y}Co_ySi$, $Fe_{1-x}Co_xSi$

MnGe, FeGe, CoGe

$Mn_{1-y}Fe_yGe$, $Fe_{1-y}Co_yGe$, $Mn_{1-y}Co_yGe$

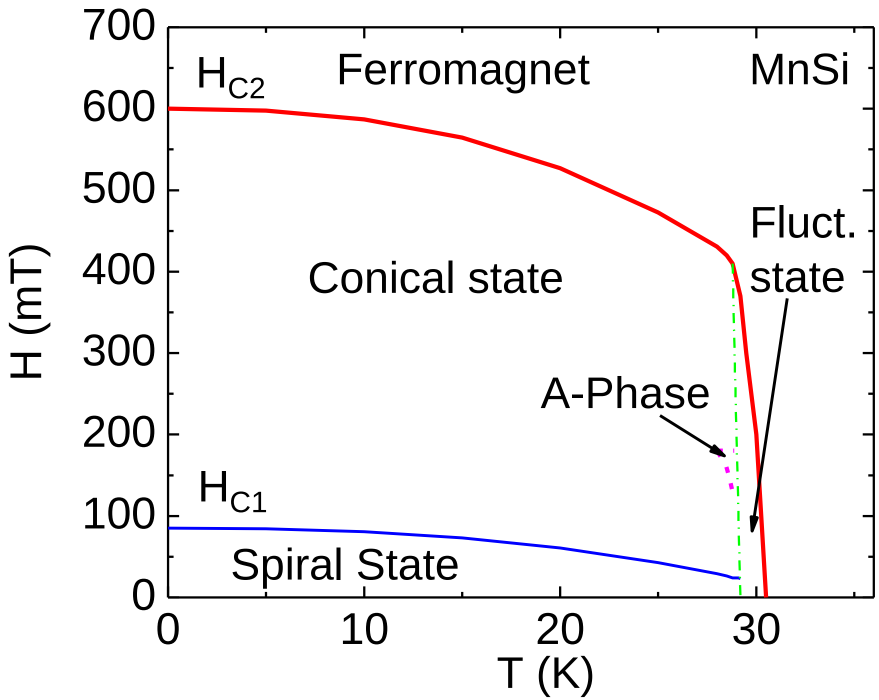


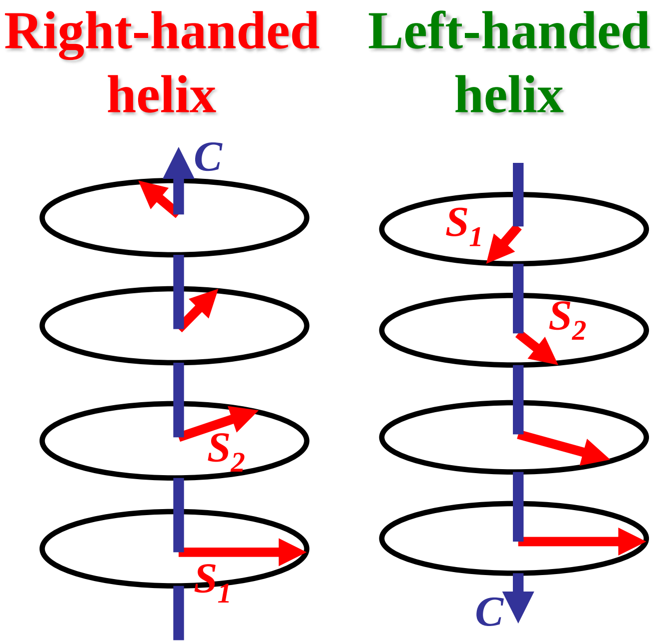
- B20-type cubic
- Space group $P2_13$, $a \approx 4.6 - 4.8$ Å
- 4 Me and 4 Si atoms are inside a unit cell

positions (u,u,u), (1/2+u,1/2-u,u), (1/2-u,-u,1/2+u), (-u,1/2+u,1/2+u) with $u_{Mn} = 0.138$ and $u_{Si} = 0.845$

B-T phase diagram in B20 compounds

[1] Y. Ishikawa, G. Shirane, J.A. Tarvin, M. Kohgi, Phys.Rev.B 16 (1977) 4956.

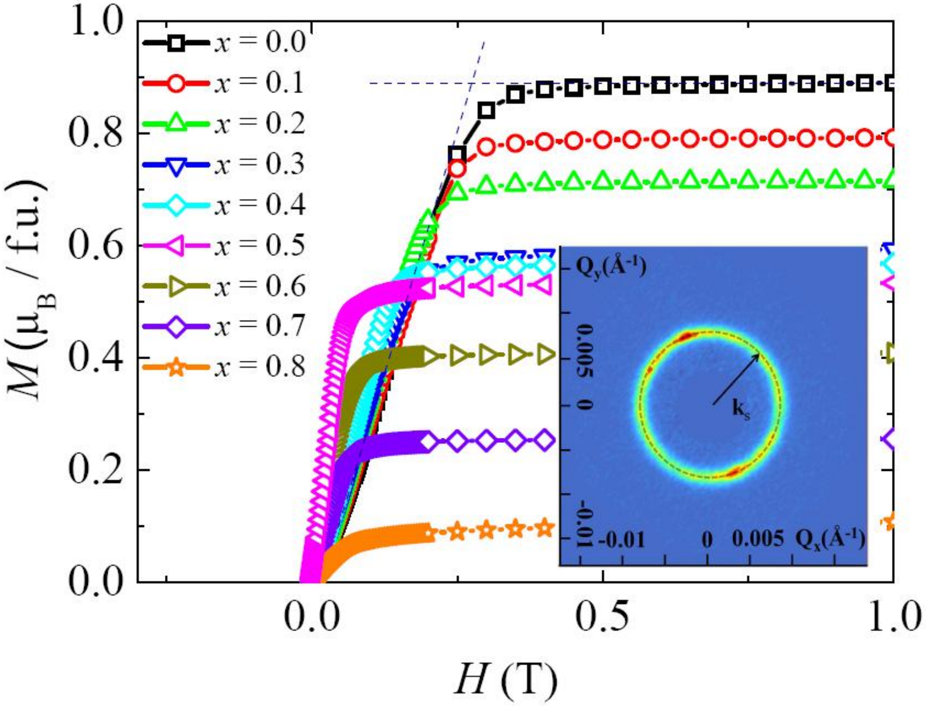


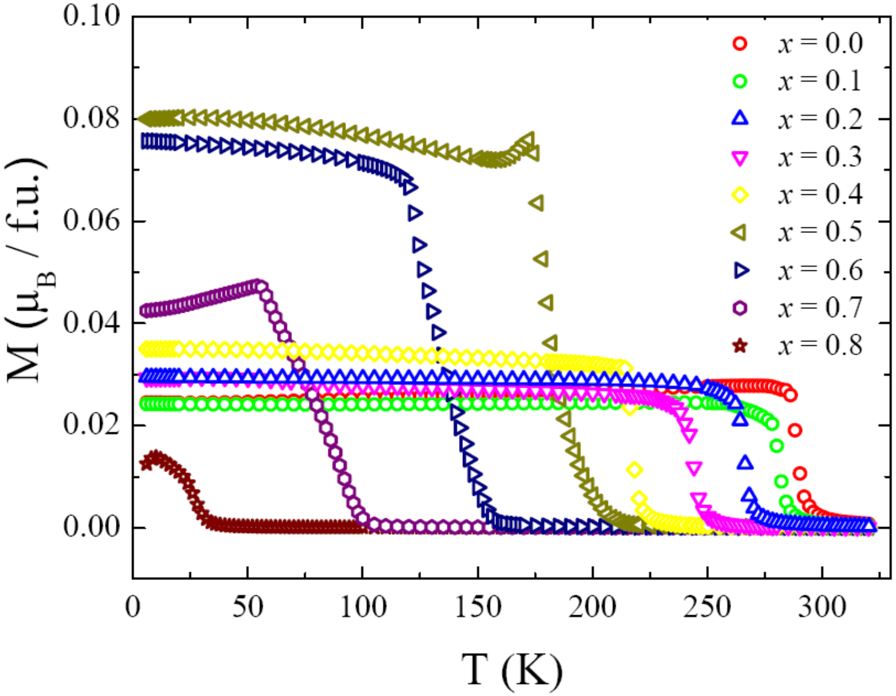


Characteristic parameters:

T_C, S, k, H_{C1}, H_{C2}

Magnetic ordering in $Fe_{1-x}Co_xGe$



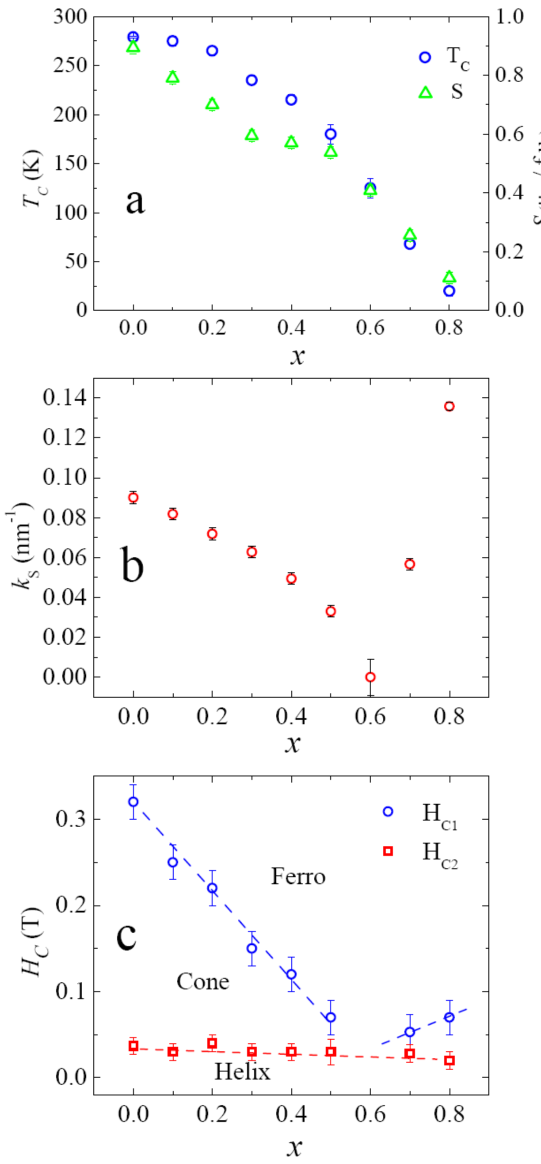


Samples: $Fe_{1-y}Co_yGe$ (0,0.1… -.. 1.0)
(A.V. Tsvyashchenko,
Institute for High Pressure

Physics, Troitsk, Russia)

Susceptibility measurements

Critical temperature T_C, spiral wavevector k and critical fields in $Fe_{1-x}Co_xGe$



Characteristic parameters: T_C, S, k, H_{C1}, H_{C2}

1) $A k^2 = g \mu_B H_{C2}$ критическое поле перехода в ферромагнитную фазу

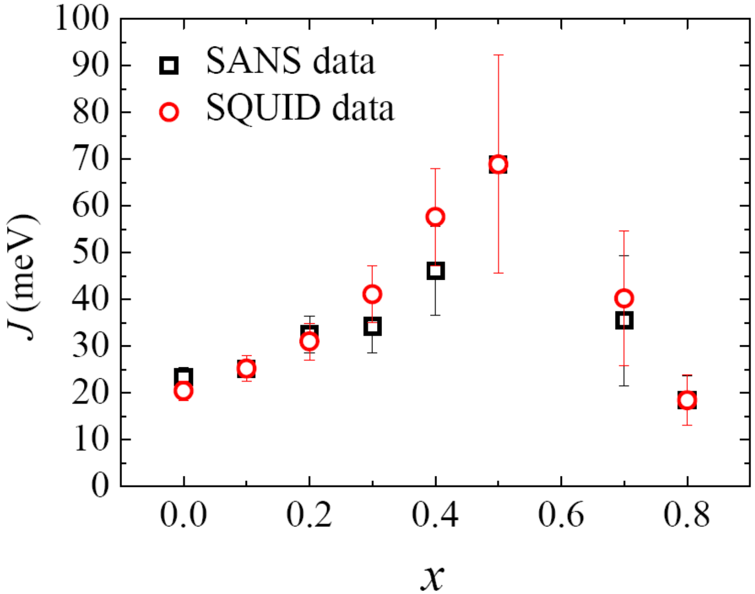
2) k = D / J волновой вектор спирали

3) J = A / S

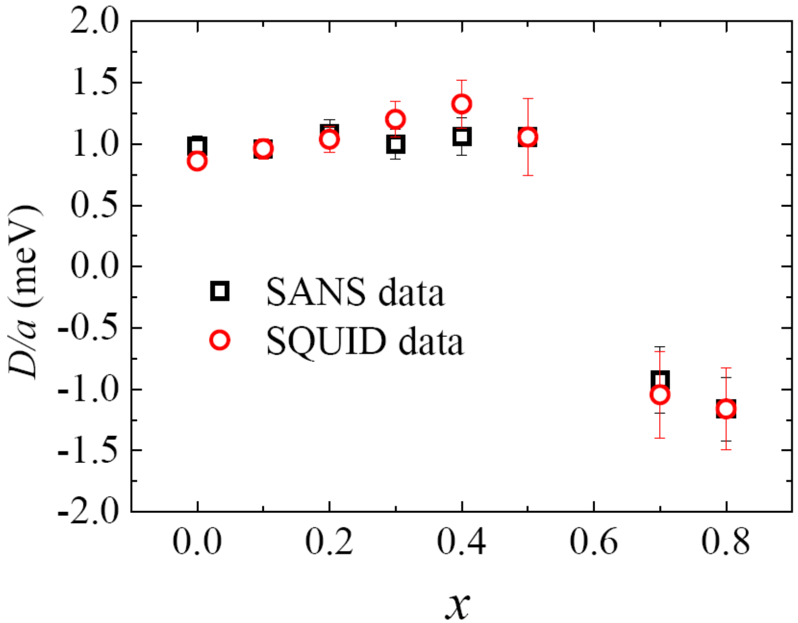
The wavevector k = 0, T_C = 140 K

The system transforms to ferromagnet

Driving interactions of the magnetic system



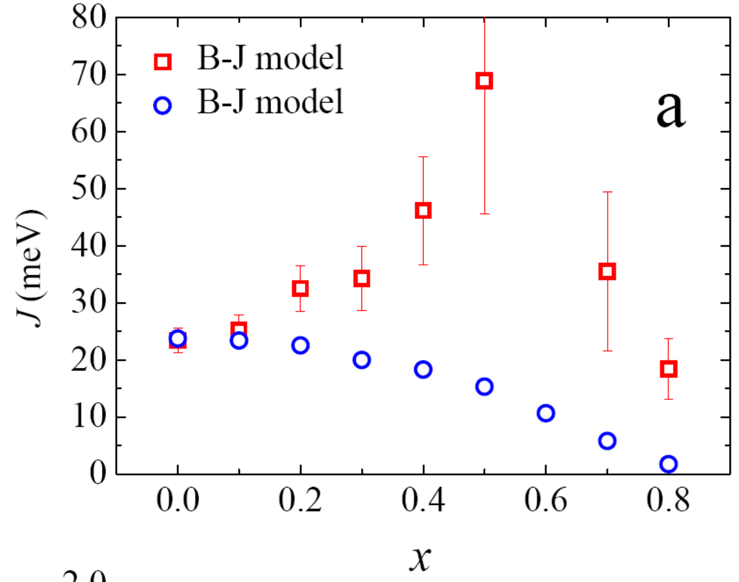
$J = A/S = g\ \mu_B\ H_{C2}\ /\ S\ k^2$



$D/a = J\ k/a$

The “chiral catastrophe” of B-J model

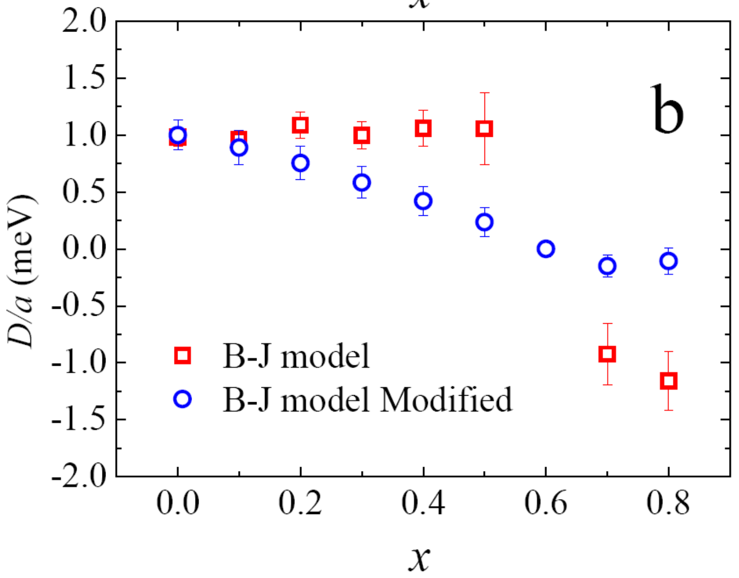
Different approach to treat data

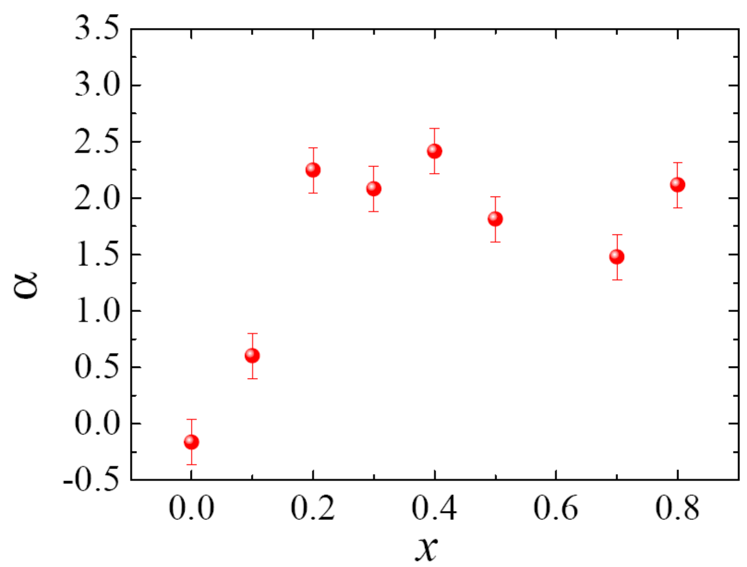


1) $J = k_B T_C$ and $A = S J$

2) $k = D / J$

3) $g \mu_B H_{C2} = A k^2 + \alpha g \mu_B H_{C1}$





Conclusion

- Thus, we show experimentally that the value of H_{C2} has the minimal value of $2H_{C1}$ and that the cubic anisotropy plays an important role in the compounds, where the wave vector k becomes relatively low.
- The theoretical consideration below approves the experimental findings.

Non-CentroSymmetric Magnets (NCSM)

In NCSM Dzyaloshinskii-Moriya interaction (DMI) is allowed between any spin pairs.

It is linear in the spin-orbit interaction and it is the strongest anisotropic interaction.

As was recently shown in [1,2] one can change average value of DMI by mixing magnetic ions.

[1] S. V. Grigoriev, et al, Phys. Rev. Lett. 110 (2013) 207201.
[2] K. Shibata, et al, Nature Nanotechnology 8, 723-728 (2013).

Bak-Jensen Model in B20 compounds

- Cubic symmetry;
- Interactions: Exchange; DMI, Zeeman.
- Assumption: Helical structure.

$$\mathbf{S}_{\mathbf{R}} = S[\hat{c}\, sin\alpha + (\mathbf{A}e^{i\mathbf{k}\cdot\mathbf{R}} + A^{*}e^{-i\mathbf{k}}) \cos\alpha]$$

where $\mathbf{k}$ is the helix wave-vector.

$\mathbf{A} = (\hat{a} - i\hat{b})/2$,

$[\hat{a} \times \hat{b}] = \hat{c}$ determines the spin rotataion plane.

α is the cone angle:

if $\alpha = 0$ we have a plane helix and

if $\alpha = \pi/2$ we have ferromagnet.

Result of B-J model

The helix has lower energy than the ferromagnet.

$$E_{BJ} = [SAk^2 - S^2 D(\mathbf{k} \cdot \hat{c})] \cos^2 \alpha + H \sin \alpha$$

where A and D are the spin-wave stiffness and DMI constant.

E_{BJ} is minimal if

$$\mathbf{k} = (SD/A)\hat{c}; \ \sin \alpha = -H/H_c,$$

here $H = H_{||}$ is the field component along $\hat{c}$ and $H_c = Ak^2$ is the critical field for ferromagnetic transition.

Cubic Anisotropy

- In each lattice point

$$E_{CA} = K(S_x^4 + S_y^4 + S_z^4) = G \begin{cases} 1; \mathbf{S} \parallel (1,0,0), \\ 1/3; \mathbf{S} \parallel (1,1,1). \end{cases}$$

$$G = KS^4; \;\; K > 0, \mathbf{S}||(1,1,1); \;\; K < 0, \mathbf{S}||(0,0,1)$$

DMI Helix in Cubic Crystals

Interactions - Exchange DM and Zeemann - are isotropic. So the helix energy

$$E = -(SAk^2/2)\cos^2\alpha + G[C\sin^4\alpha + (3/8)B\ cos^4\alpha + 3I\sin^2\alpha\cos^2\alpha] + SH_{||}\sin\alpha,$$

The cubic invariants *C*, *B*, *I* are given by

$$C = \sum \hat{c}_j^4; B = \sum(\hat{a}_j^2 + \hat{b}_j^2)^2; I = \sum \hat{c}_j^2(\hat{a}_j^2 + \underline{\mathrm{b}}_j^2)$$

Extremal values:

$C = 1,\ B = 2;\ \ I = 0;\ \hat{c} = (0, 0, 1);$

$C = 1/3, ;\ B = 4/3;\ I = 2/3;\ \hat{c} = (1, 1, 1)/\sqrt{3}$

Equilibrium Conditions

G>0. Results for G<0 are very similar.

The first condition: Extreme values of invariants C,B and I. The field is along (1,1,1). The energy

$$E = (-Ak^2 + G)/2 + (Ak^2/2 + G)\sin^2\alpha - (7/6)\sin^4\alpha + H\sin\alpha,$$

and its minimum condition:

$$[Ak^2 + 2G - (14G/3)\sin^2\alpha]\sin\alpha = -H,$$

Final Results I.

- Zero field H=0, $\bar{A}k^2 > G/3$
- Planar helix-->Ferromagnet.

- Strong DMI: $Ak^2 > 12G;\ g = (Ak^2/G + 2)/14 >$
- Ferromagnetic transition

$$\sin\alpha_c = -1;\ Ak^2 > H_c = AK^2 - 8G/3 > 7Ak^2/9$$

FINAL RESULTS ii.

- Weak DMI: 1> g > q > 1/6;
- (1/6 >g -> ferromagnet.)
- The conical helix is stable if

$$\sin\alpha > -\sqrt{g} > -1$$

- The first order transition to ferromagnet determined by two conditions:
- Energy minimum
- Equality

Conical energy=ferromagnetic=G/3-H.

Final Equations

- Line of transitions

$$28G\sqrt{g/3} > H' > 0; \; -1 < \sin\alpha < 0$$

determined by

$$(g - \frac{\sin^2\alpha}{3}\sin\alpha = H/14G$$

$$\sin^2\alpha = g - \sqrt{(g+1)^2 - 4/3 - \frac{2H}{7G}}$$

Conclusion

- B20 magnets have very complex field behavior. The same holds for other NCSM due to DMI.
- At present we have very poor understanding corresponding phenomena.
- Their study is one of the urgent tasks in magnetism.

THANK YOU