SPIN-WAVE INTERACTION IN B20 MAGNETS

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PNPI

MODEL

$$H = -1/2 \sum J_{\mathbf{q}}(\mathbf{S}_{\mathbf{q}} \cdot \mathbf{S}_{-\mathbf{q}}) + \sum \mathbf{D}_{\mathbf{q}} \cdot [\mathbf{S}_{\mathbf{q}} \times \mathbf{S}_{-\mathbf{q}}] + \sqrt{N}(\mathbf{H} \cdot \mathbf{S}_0),$$

$$\mathbf{D}_{\mathbf{q}} = iD\mathbf{q}.$$

$$\mathbf{H} = 0 : [\mathbf{S}_0, H] = 0$$

Gapless spin-waves

Kaplan Helix: Six free parameters.

Classical energy minimum.

B-J RESULTS

- FM exchange+DMI->planar helix. Classical results:

Helix wave vector $\mathbf{k} = (SD/A)\hat{c}$.

A and D are the spin-wave stiffness

and DM constant.

$\hat{c} \perp$ to the spin rotation plane.

D
e
r
r
r
r

$$\text{Cone angle } \sin\alpha = -H/H_c.$$

$$\mathbf{H}||\hat{c},\ H_c = Ak^2$$

SPIN-WAVE S

- Helical stae

$$\epsilon_{\mathbf{q}}^2 = A^2[q^4 + q^2 k^2 \cos^2 \alpha]$$

- Ferromagnetic state

$$\epsilon_{\mathbf{q}} = A(\mathbf{q} - \mathbf{k})^2 + H - H_c$$

UMKLAPPS

- DMI: Spin-wave with momenta $\mathbf{q}$ and $\mathbf{q} \pm \mathbf{k}$ are mixed

$$H_2^U = \sum (d_{\mathbf{q}} a^+_{\mathbf{q}+\mathbf{k}} a_{\mathbf{q}} + d^*_{\mathbf{q}} a^+_{\mathbf{q}-\mathbf{k}} a_{\mathbf{q}});$$

$$d_{\mathbf{q}} =$$

$$-Ak(q_a - iq_b)\cos\alpha$$

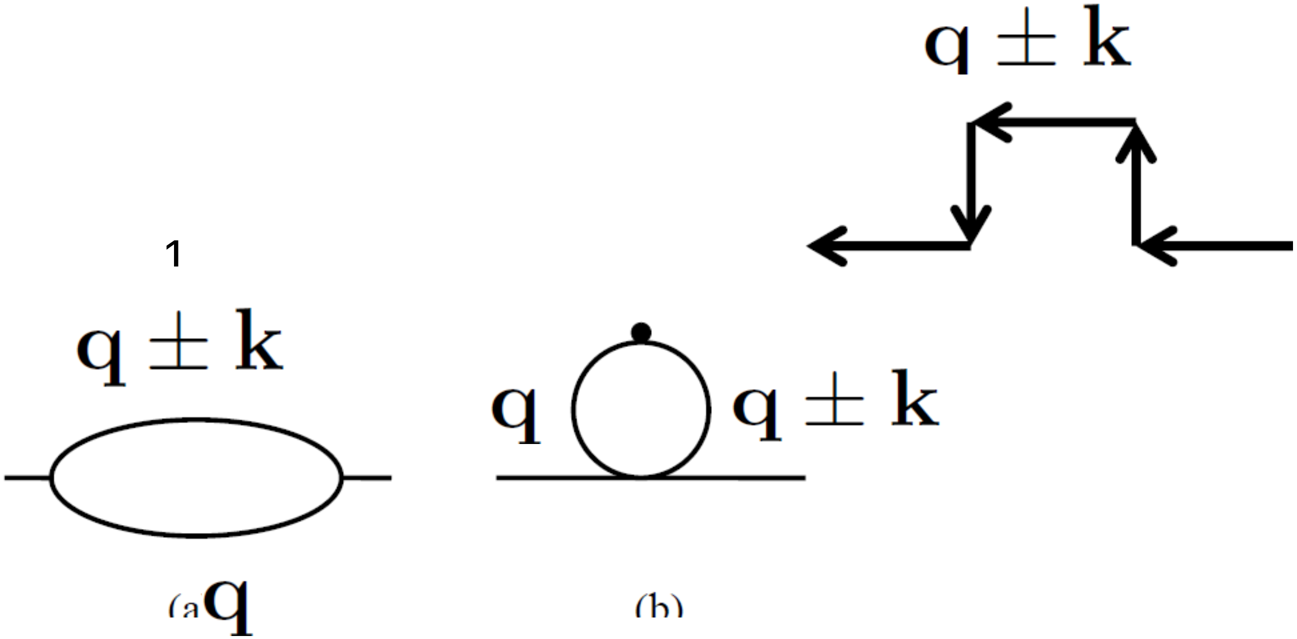
$$\hat{a}, \hat{b} \perp \hat{c} \sim \mathbf{k} : \; |d|^2 \sim \mathbf{q}_\perp^2.$$

- $$q < k, H = 0 \; \epsilon_{\mathbf{q}} \sim q \to q_{||}$$

$T > 0$-infra-red divergence.

DIAGRAMS

- Diagrams for the spin-wave U interactions



Vertexes: d and d^*.

BELAYEV TECHNIQUE

$$G = \frac{E + \bar{\Sigma} + \omega}{Z};\ \ F = -\frac{B + \Pi}{Z};$$

$$Z = \omega^2 - \epsilon^2 - \omega(\Sigma - \bar{\Sigma}) -$$

$$(\Sigma + \bar{\Sigma}) + 2B\Pi - (\Sigma\bar{\Sigma} - \Pi^2)$$

$$\bar{\Sigma} = \Sigma(-\omega) \qquad \epsilon^2 = E^2 - B^2$$

$$E = Aq^2 + B;\ \ B = (Ak^2/2)\cos^2\alpha$$

U2 APPROXIMATION

$$\Sigma_{\mathbf{q}} = |d|^2 \sum_j \frac{E_j + \omega}{\omega^2 - \epsilon_j^2}; \; \Pi_{\mathbf{q}} = |d|^2 \sum_j \frac{B}{\omega^2 - \epsilon_j^1;}$$

$$|d|^2 = (Akp_\perp)^2; \; j = \mathbf{q} \pm \mathbf{k}.$$

$$E = Aq^2 + B; \; B = (Ak^2/2)\cos^2\alpha$$

RESULTS

- Spim-wave energy (H=0).

$$\epsilon_{\mathbf{q}}^2 = A^2\{k^2[q_{||}^2 + (gq_{\perp}^2)/2S] + (q_{||}q_{\perp})^2/2 + q_{||}^4 + 3q_{\perp}^4/2\}$$

$$q < k,\ H = 0$$

$$\text{Factor } g = (ka)^2(Q_M a)/8\pi^2 \ll 1$$

Q_M is the spin-wave band width.

ENERGY 1

$$E = S^2[Ak^2/2S - D(\mathbf{k}\cdot\hat{c})]cos^2\alpha + HS\sin\alpha + E_{SW};$$

$$E_{SW} = \sum[E_{\mathbf{p}} < a^+_{\mathbf{p}} a_{\mathbf{p}} > +B < a_{\mathbf{p}} a_{-\mathbf{p}} > +$$

$$d < a^+_{\mathbf{p}+\mathbf{k}} a_{\mathbf{p}} > +d^* < a^+_{\mathbf{p}} a_{-\mathbf{p}} >],$$

The last two terms connect

$\mathbf{q}$ and $\mathbf{q} \pm \mathbf{k}$ modes.

$$d < ... > +d^* < ... >= \Sigma\bar{G} - \Pi F$$

ENERGY 2

$$E_{SW} = -T \sum_{\omega,\mathbf{p}} \frac{\epsilon_0^2 + W - (E + 2\Sigma - \bar{\Sigma})i\omega}{(i\omega)^2 - \epsilon_0^2 - W};$$

$$W = E(\Sigma + \bar{\Sigma}) - 2B\Pi + (\Sigma\bar{\Sigma} - \Pi^2) +$$

$$i\omega(\Sigma - \bar{\Sigma}); \epsilon_0^2 = E^2 - B^2,$$

ENERGY 3

$$E = S^2[Ak^2/2S - D(\mathbf{k}\cdot\hat{c})]cos^2\alpha + HS\sin\alpha +$$

$$E_{SW} = \sum\left\{\epsilon_{\mathbf{p}}N_{\mathbf{p}} - 3\sum_{j=\pm}\frac{|d_{\mathbf{p}|^2[\epsilon_{\mathbf{p}}(2\mathbf{N}_{\mathbf{p}}+1)-\epsilon_{\mathbf{j}}(2\mathbf{N}_{\mathbf{j}}+1)]}}{2(\epsilon_{\mathbf{p}}^2 - \epsilon_j^2)}\right\};$$

$$\mathbf{p}_j = \mathbf{p} + j\mathbf{k};\ |d_{\mathbf{p}}|^2 = (Akp_\perp)^2\cos^2\alpha.$$

$\epsilon_{\mathbf{p}}$ is U renormalized.

RENORMAOIZATION

$$k = k_{BJ}(1+R);\ H_c = H_{BJ}(1+R);$$

$$R = \frac{3}{S}\sum \frac{p_\perp^2}{p^2}(2N_{\mathbf{p}}+1) = \frac{(Q_M a)^3}{3\pi^2 S} + \frac{0.12}{S}\left(\frac{T}{T_0}\right)^{3/2},$$

$$T_0 = A/a^2$$

$$MnSi\ Q_M a \sim 1, T_0 = 30K \simeq T_c, S = 1.6$$

Experiment:

$k(T)$ increases, $H_c(T)$ decreases

FERROMAGNETIC STATE

- Ferromagnetic without zero-point fluctuations: At $T = 0$ $(k, H_c) = (k, H_c)_{BJ}$

$$\epsilon_{\mathbf{q}} = A(\mathbf{q} - \mathbf{k})^2 + H - H_c.$$

$$k_F = k_{BJ}[1 - 0.06(T/T_0)^{3/2}/S]$$ decreass.

$$H_F = H_{BJ}[1 - 0.15(T_0)^{3/2}/S]$$ decreases.

$H_F < H_c^H$ the first order transition.

SPECIFIC HEAT 1

$$1.\ T < Ak^2 \text{ At } H = 0$$

$$\epsilon_{\mathbf{p}} = A\sqrt{(kp_{||})^2 + p_{||}^4 - p_{\perp}^2 p_{||}^2/2 + 3p_{\perp}^4/2};$$

$$C_V = 0.12(T/Ak^2)^2(ka)^3 \simeq C_F\sqrt{\frac{T}{Ak^2}}.$$

$C_F = 0.11\sqrt{T/T_0}$ is FM CH.

$C_V(H = 0) < C_V(H = Ak^2) = C_F$.

Holds if $T > \Delta$- the spin-wave gap-

the result of anisotropy.

$MnSi : Ak^2 \simeq 0.6T \simeq 1.2K\ \Delta < 01T???; T_0 = 30K.$

SPES IFIC HEAT 2

$$T > AK^2; \; H = 0.$$

$$E_{SW} = \sum A[p^2 - \frac{3(kp_\perp^2}{p^2}]N_{\mathbf{p}}$$

$$C_V = C_F(1 - 1.6Ak^2/T]).$$

In general

$C_V(H = 0) = C_F \Phi[Ak^2/$

What is at $T \sim Ak^2$?

OTHER U SYSTEMS

- Lonolayers;
- Fe on W , Mn on W (Cycloid)
- Multiferroixes.
- Frustrated helices
- : dipolar ineraction,
- Diferent directions of the helix and anisotropt xeces.

THANK YOU