Spin chirality in MnSi probed by polarised neutrons

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Triple-axis and SANS

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- S.V. Maleyev (Petersburg Nuclear Physics Institute)
- ...

Outline

- Introduction

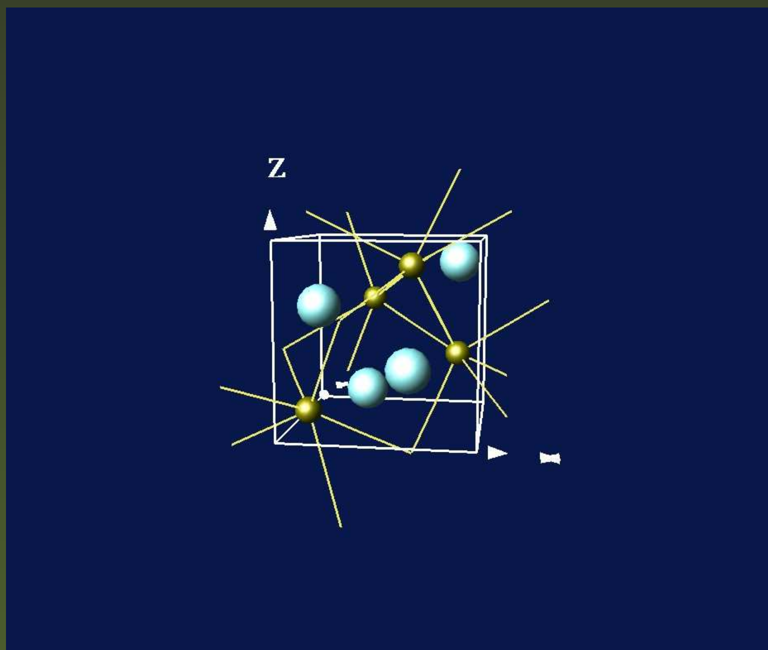
- Elastic neutron cross-section
- Magnetic ground-state of MnSi

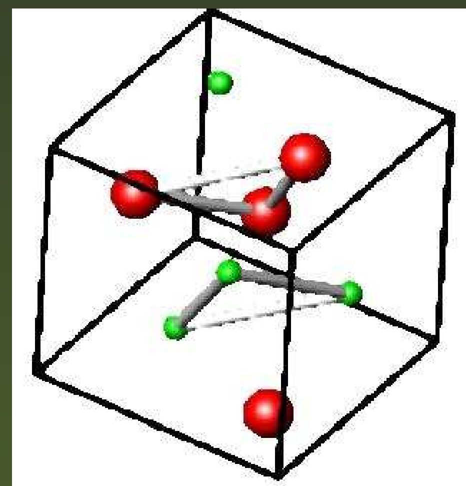
- Inelastic neutron cross-section
- Spin-fluctuations in weak ferromagnetic metals
- Chirality of spin fluctuations in MnSi

- Polarised SANS experiment
- Spin fluctuations with cubic and DM anisotropies
- Polarised SANS experiment under pressure above P_c

Crystal Structure

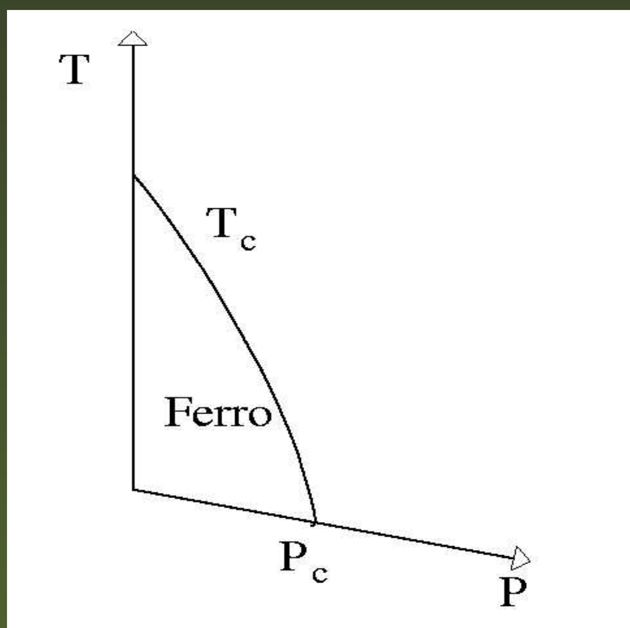
- cubic ($P2_13$)
- non-centrosymmetric

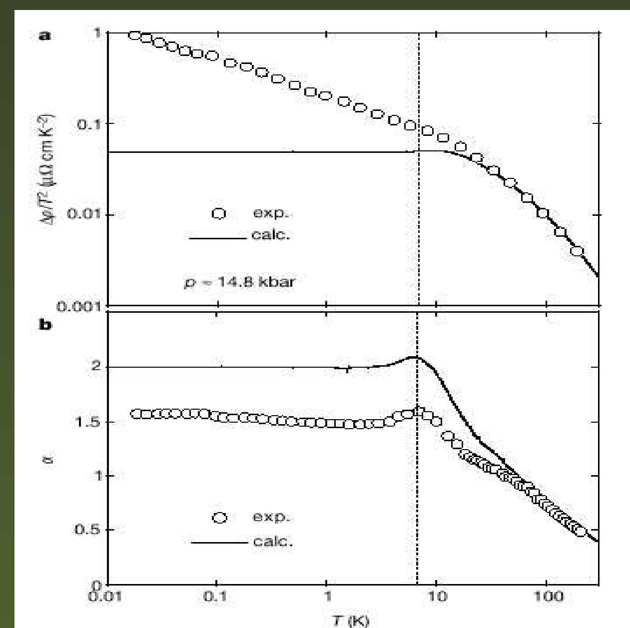




Phase diagram

- Q.C.P. at critical pressure $P_c \sim 15$ kbar
- Resistivity shows non-Fermi liquid behavior ($\sigma \neq T^2$) with Pressure





(C. Pfleiderer *et al.*, Nature **414**, 427)

Elastic neutron cross-section

$$\sigma = NN^* + \vec{D}_\perp \cdot \vec{D}_\perp^* + \vec{P}_i \cdot (\vec{D}_\perp N^* + \vec{D}_\perp^* N) + i\vec{P}_i \cdot (\vec{D}_\perp^* \times \vec{D}_\perp)$$

- σ: total cross section

(M. Blume, Phys. Rev. **130**, 1670)

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- $N = N(\vec{Q}) = \sum_i b_i \exp\left(i\vec{Q} \cdot \vec{r}_i\right)$: atomic structure factor

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- $\vec{D}_\perp$: magnetic interaction vector $(\vec{D}_\perp = \vec{D}_\perp(\vec{Q}) = \hat{\vec{Q}} \times (\vec{\rho}(\vec{Q}) \times \hat{\vec{Q}}))$

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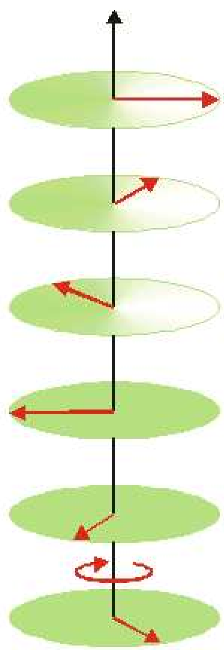
- $\vec{P}_i$: polarisation vector of the neutron beam

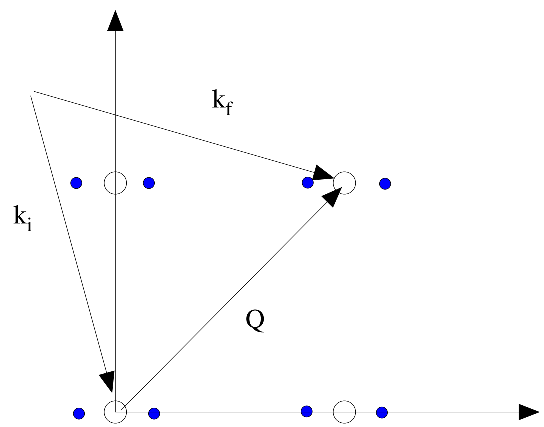
(M. Blume, Phys. Rev. **130**, 1670)

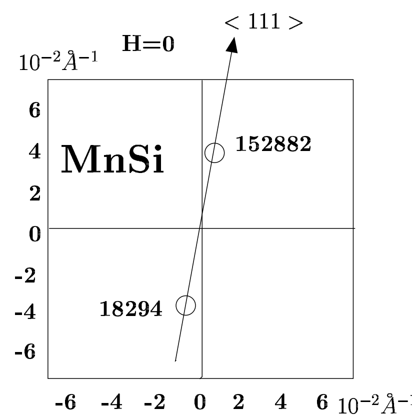
Diffraction by a magnetic spiral

`First case:` non-polarised beam ($\vec{P}_i = 0$)

$$\sigma_{mag.} = \vec{D}_\perp \cdot \vec{D}^*_\perp = \sum_{\vec{\tau}} \{ \delta(\vec{Q} - \vec{\tau} - \vec{q}) + \delta(\vec{Q} - \vec{\tau} + \vec{q}) \}$$







Helix along <111>
Period ∼50 cells

(Ishikawa *et al.*, Solid State Comm. **19**, 525)

Diffraction by a magnetic spiral

`Second case:` polarised beam ($|\vec{P}_i| = 1$)

- $\sigma_{mag.} = \vec{D}_\perp \cdot \vec{D}^*_\perp + i\vec{P}_i \cdot (\vec{D}_\perp \times \vec{D}^*_\perp)$

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- $\sigma_{mag.} = \vec{D}_\perp \cdot \vec{D}^*_\perp + i\vec{P}_i \cdot (\vec{D}_\perp \times \vec{D}^*_\perp)$

- $\rightarrow \sum_{\vec{\tau}} F_+(\vec{P}_i)\delta(\vec{Q} + \vec{q} - \vec{\tau}) + F_-(\vec{P}_i)\delta(\vec{Q} - \vec{q} - \vec{\tau})$

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- with $F_\pm = 1 + (\hat{Q}\cdot\hat{q})^2 + 2(\vec{P}_i\cdot\hat{Q})(\hat{Q}\cdot\hat{q})$

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- if $\vec{Q}//\vec{q}$ **and** $\pm\vec{P}_i//\vec{q}$, then $F_+ = \{0, 1\}$ or $F_- = \{0, 1\}$

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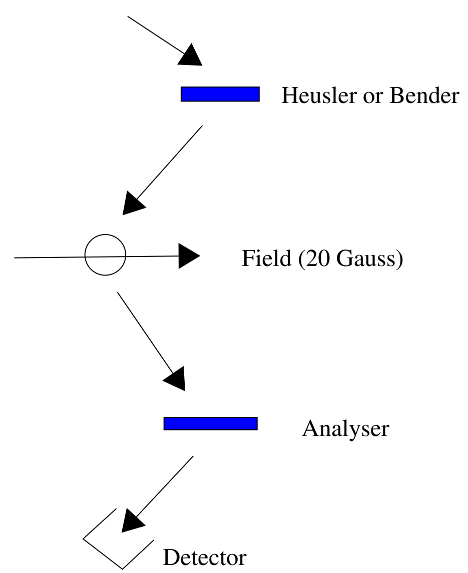
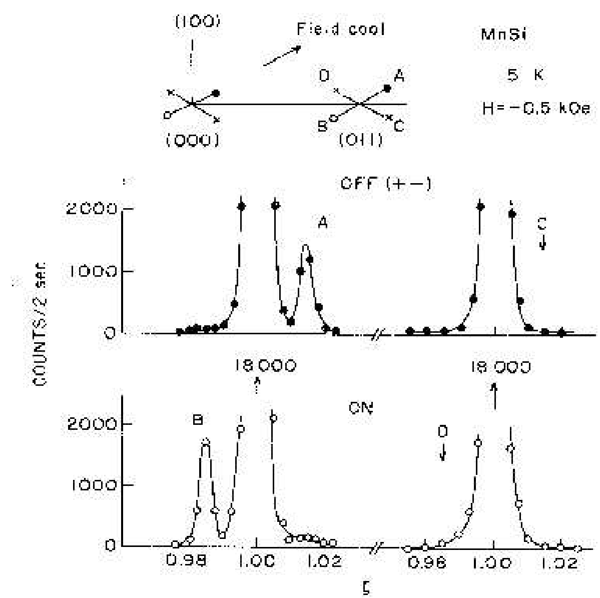
- if $\vec{Q}//\vec{q}$ **and** $\pm\vec{P}_i//\vec{q}$, then $F_+ = \{0,1\}$ or $F_- = \{0,1\}$

- $\rightarrow$ direction of $\vec{q}$ can be determined

Right- vs. left-handed spiral in MnSi

(G. Shirane *et al.*, PRB **28**, 6251 (1983).)





- single-handed spiral
- left-handed chirality

Magnetic INS

Cross-section:

- $S^{\alpha,\beta}(\vec{Q},\omega) = [1-\exp(-\hbar\omega/k_B T)]^{-1}\Im\chi^{\alpha,\beta}(\vec{Q},\omega)$
- $A^{\alpha,\beta} = 1/2(S^{\alpha,\beta} + S^{\beta,\alpha})$
- $B^{\alpha,\beta} = 1/2(S^{\alpha,\beta} - S^{\beta,\alpha})$
- $I(\vec{Q},\omega) \sim \sum_{\alpha,\beta}(\delta_{\alpha,\beta} - \hat{Q}_\alpha\hat{Q}_\beta)A^{\alpha,\beta}(\vec{Q},\omega) + \sum_{\alpha,\beta}(\hat{\vec{Q}}\cdot\vec{P}_i)\sum_\gamma \varepsilon_{\alpha,\beta,\gamma}\hat{Q}^\gamma B^{\alpha,\beta}(\vec{Q},\omega)$

- from unpolarised INS $\rightarrow$ symmetric part of $\Im\chi(\vec{Q},\omega)$
- from polarised INS $\rightarrow$ antisymmetric part of $\Im\chi(\vec{Q},\omega)$

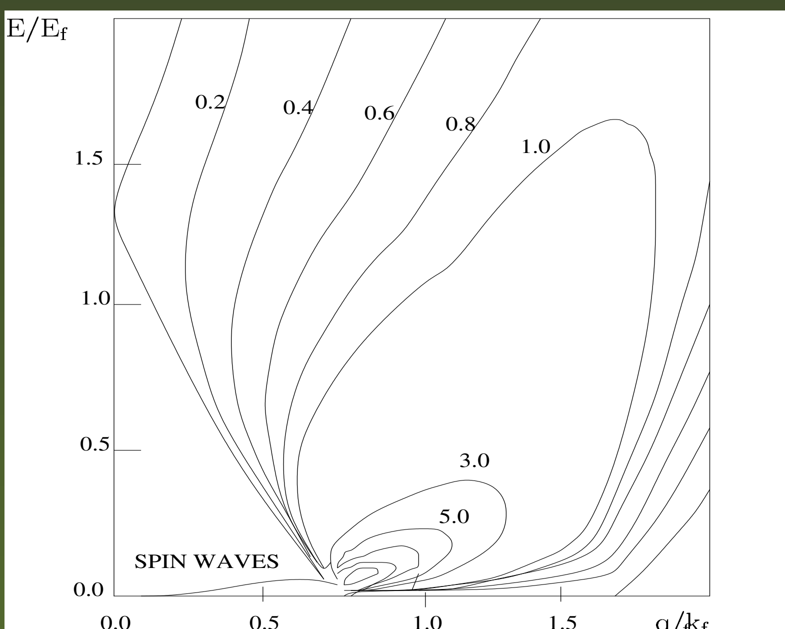
Spin and Stoner excitations in MnSi

1.-Dynamical susceptibility in magnetic metals:

$\chi(\vec{Q},\omega) = \chi_0(\vec{Q},\omega)/(1 - J(\vec{Q})\chi_0(\vec{Q},\omega) + \lambda(\vec{Q},\omega))$ where

- $\chi_0(\vec{Q},\omega)$: non-interacting susceptibility
- $J(\vec{Q})$: exchange interaction
- $\lambda(\vec{Q},\omega)$: damping

Below T_c:

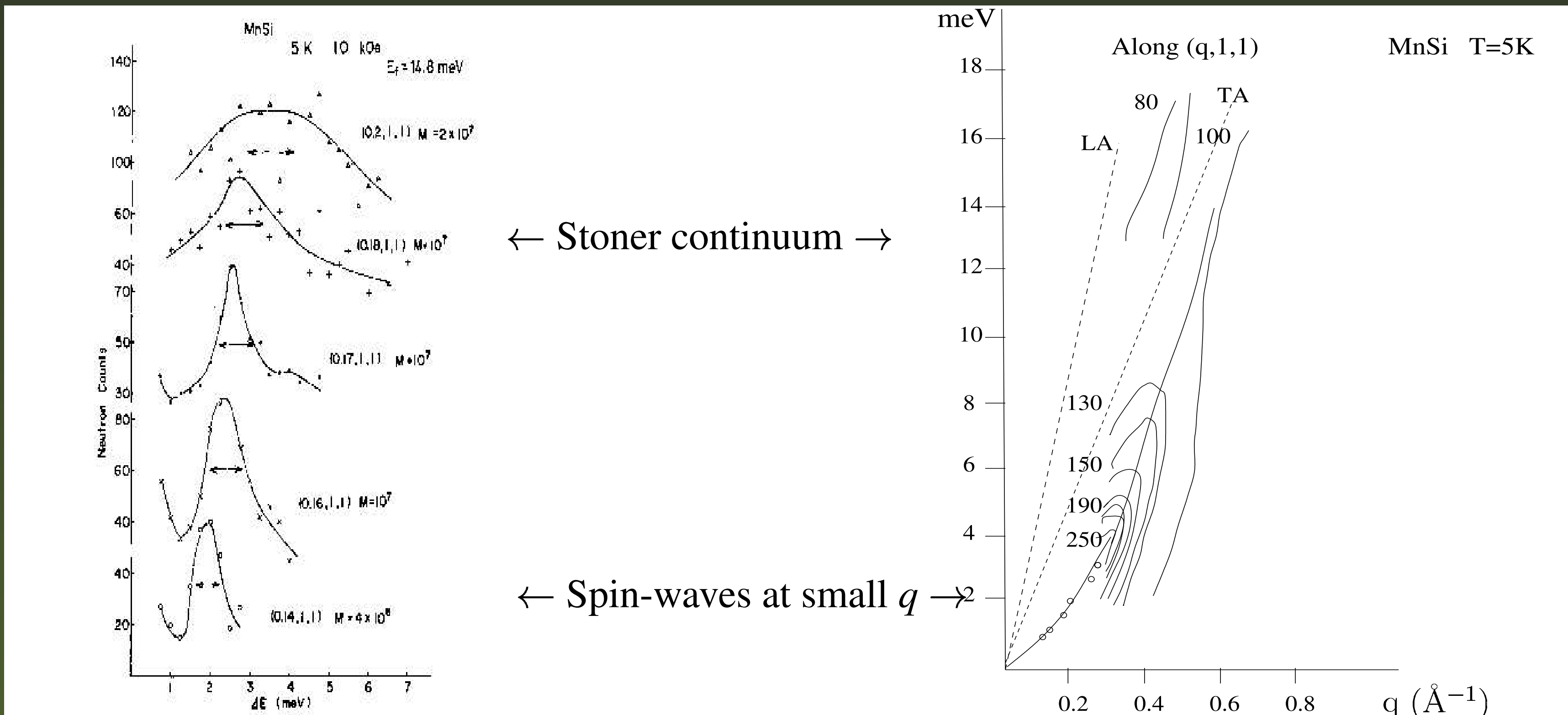


- Spin-waves at small q
- Stoner continuum

(J. R. Sokoloff, Phys. Rev. **185**, 770)

Spin and Stoner excitations in MnSi

2.-INS in the ordered phase (non-polarised)



(Ishikawa *et al.*, Phys. Rev. B **16**, 4956)

Spin fluctuations in metals ($T>T_c$)

Dynamical susceptibility ($q/\kappa << 1$)

$$\chi(\vec{q},\omega) = \chi(\vec{q})/(1 - i\omega/\gamma_q); \quad \chi(\vec{q}) = \chi(0)/(1 + q^2/\kappa^2)$$

- Insulator:

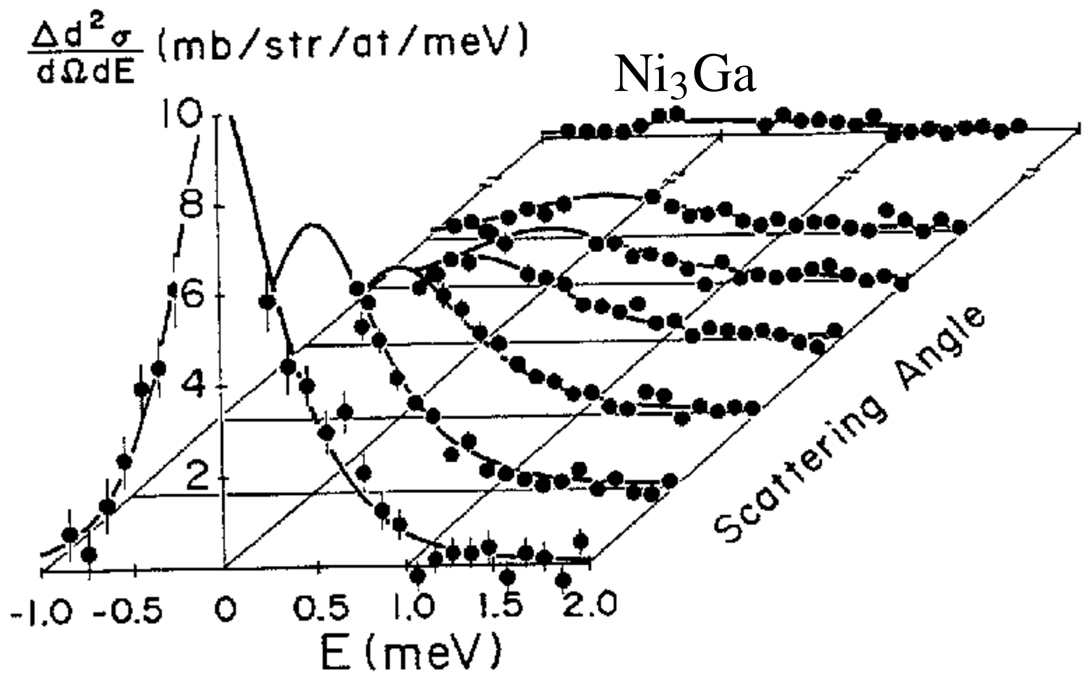
  F: $\gamma_q = \gamma_0 q^{2.5}$

  AF: $\gamma_q = q^{1.5}$

- Metals:

  F: $\gamma_q = \gamma_0 q^3$

  AF: $\gamma_q = q^{2.5}$



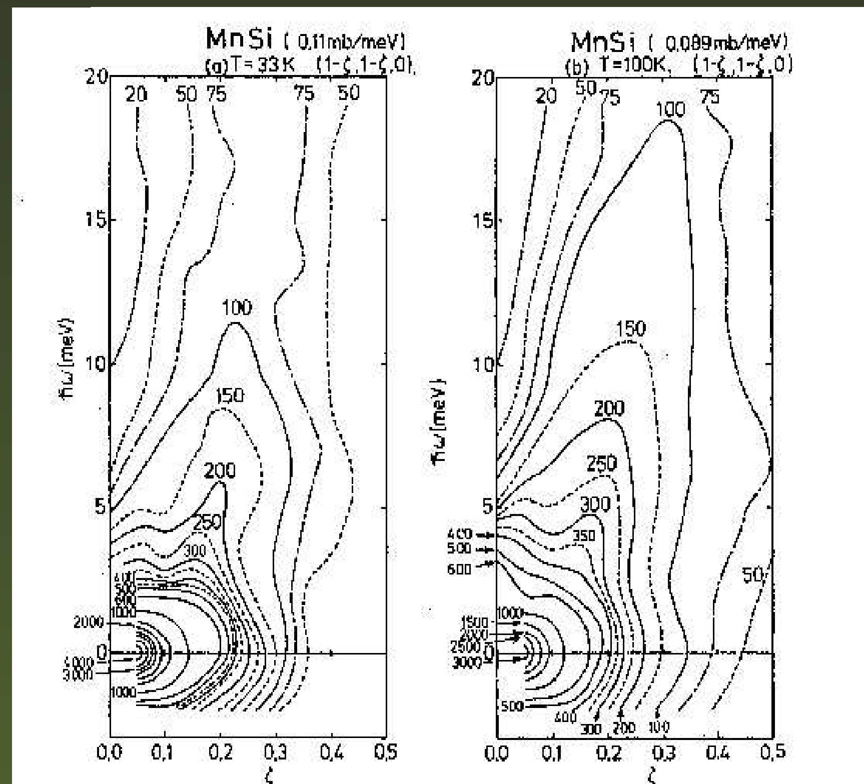
(Bernhoeft *et al.*, Phys. Rev. Lett. **62**, 657)

Spin fluctuations in MnSi

1.- Persistence of Stoner continuum above T$_c$

$\rightarrow$ Stoner continuum up to 300K

$\rightarrow$ Spin-waves replaced by isotropic fluctuations

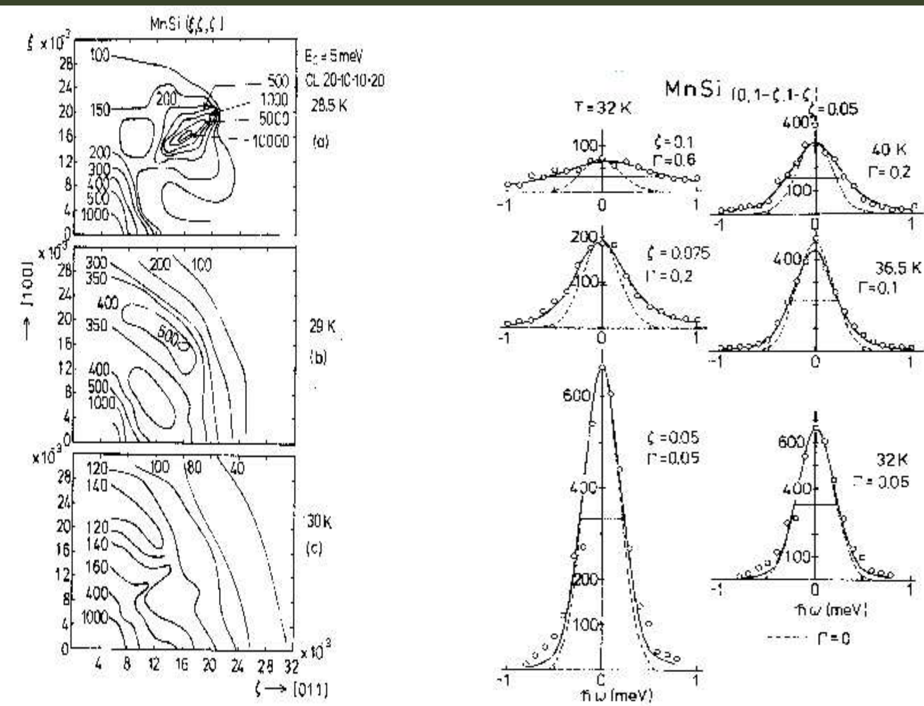


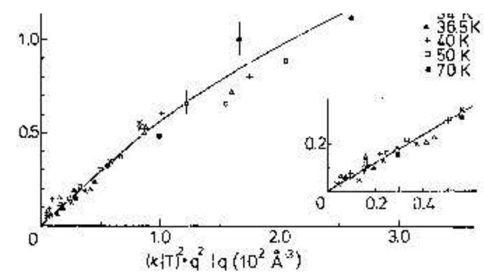
(Ishikawa *et al.*, Phys. Rev. B. **25**, 254)

Spin fluctuations in MnSi

2.- Low-energy fluctuations (non-polarised):

- from spiral to ferromagnetic correlations





$\gamma(q) = Aq(q^2 + \kappa^2)$

$\rightarrow$ typical for weak ferromagnets

(SCR Theory of Moriya)

(Ishikawa *et al.*, Phys. Rev. B. **25**, 254)

Polarized INS in MnSi above T_c

Goal:
is there a non-vanishing antisymmetric part in $\Im\chi(\vec{Q},\omega)$

$\sum_{\alpha,\beta}(\delta_{\alpha,\beta} - \hat{Q}_\alpha\hat{Q}_\beta)A^{\alpha,\beta}(\vec{Q},\omega)$

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$$\sum_{\alpha,\beta}(\delta_{\alpha,\beta}-\hat{Q}_\alpha\hat{Q}_\beta)A^{\alpha,\beta}(\vec{Q},\omega)+\sum_{\alpha,\beta}(\hat{\vec{Q}}\cdot\vec{P}_0)\sum_\gamma\varepsilon_{\alpha,\beta,\gamma}\hat{Q}^\gamma B^{\alpha\beta}(\vec{Q},\omega)$$

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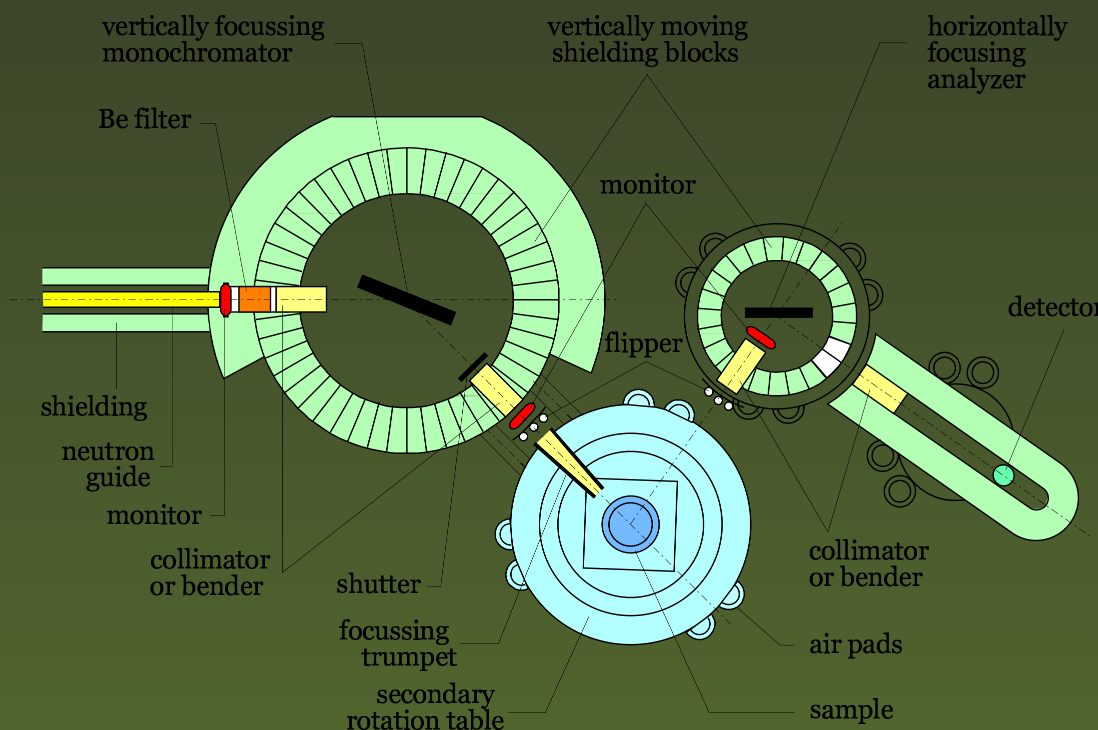
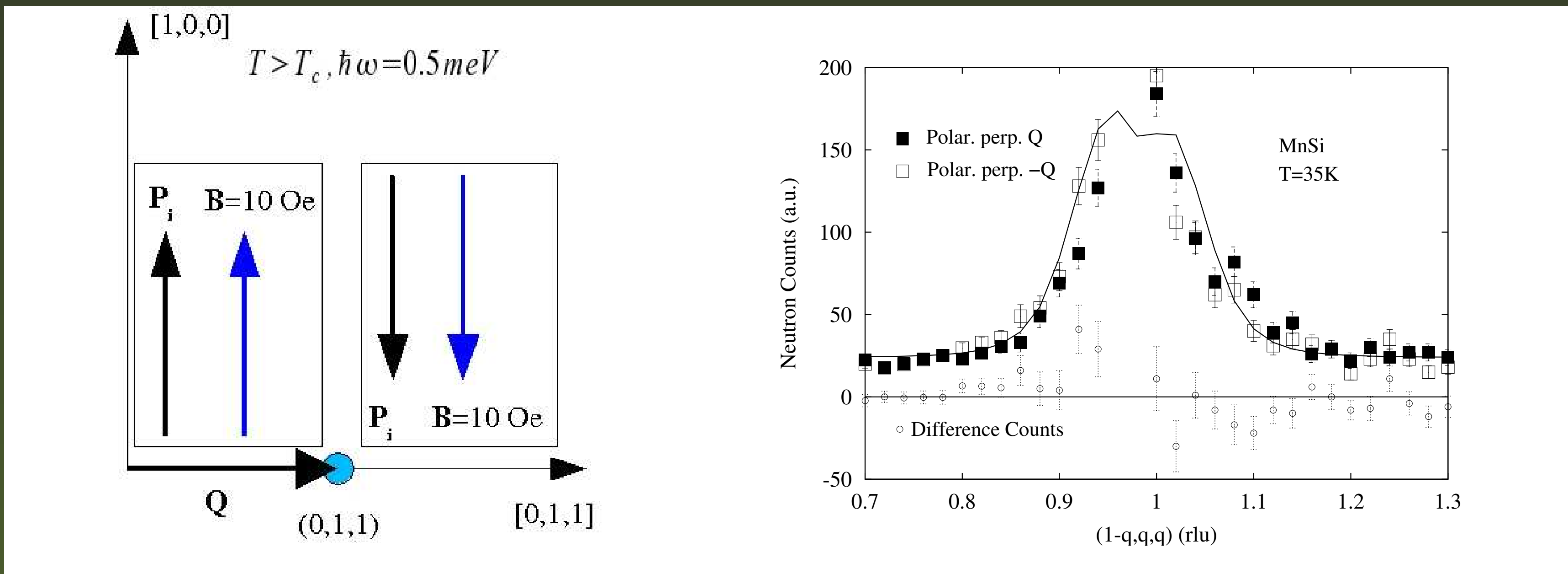


Symmetric part of $\Im\chi(\vec{Q},\omega)$

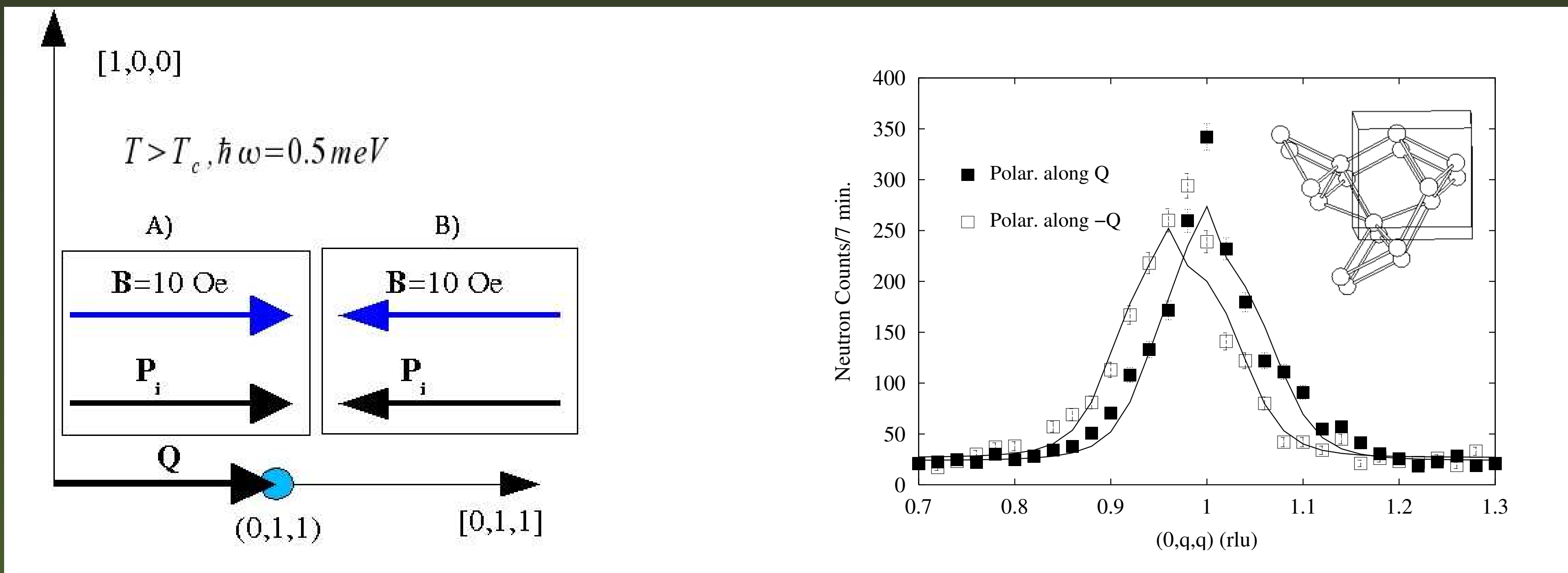
$$\pm\vec{P}_i \perp \vec{Q}$$



- No polarisation dependence
- Appears at commensurate position

Incommensurate spin fluctuations

$\pm\vec{P}_i$ along $\vec{Q}$



- Polarisation dependence
- Incommensurate paramagnetic fluctuations

Chiral parameter

From Polarised INS:

$$B^{\alpha,\beta} \neq 0 \Rightarrow S^{\alpha,\beta} - S^{\beta,\alpha} \neq 0$$

$$\Rightarrow \Im\chi(\vec{Q},\omega) = \Im \begin{pmatrix} \chi^{xx} & \chi^{xy} \\ \chi^{yx} & \chi^{yy} \end{pmatrix} \Rightarrow \Im\chi^{xy} \neq \Im\chi^{yx}$$

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$$(\hat{\vec{Q}} \cdot \hat{\vec{P}}_i)(\hat{\vec{Q}} \cdot \textstyle\int_{-\infty}^{\infty} d\omega \vec{B}(\vec{Q},\omega)) =$$
$$(\hat{\vec{Q}} \cdot \hat{\vec{P}}_i)(1/N)\textstyle\sum_{a,b} \sin(\vec{Q} \cdot (\vec{R}_a - \vec{R}_b))\hat{\vec{Q}} \cdot \underbrace{\left\langle \vec{S}_a \times \vec{S}_b \right\rangle}_{\uparrow\ \text{Chiral parameter}}$$

(S. W. Lovesey *et al.*, J. Phys.: Condensed Matter **10**, 6761)

Dzyaloshinski-Moriya interaction

- Heisenberg operator: $-2\sum_{i,j} J_{i,j}\vec{S}_i \cdot \vec{S}_j$

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- DM-interaction in non-centrosymmetric crystals: $\vec{D} \cdot \sum_{i,j}[\vec{S}_i \times \vec{S}_j]$

Dzyaloshinski-Moriya interaction

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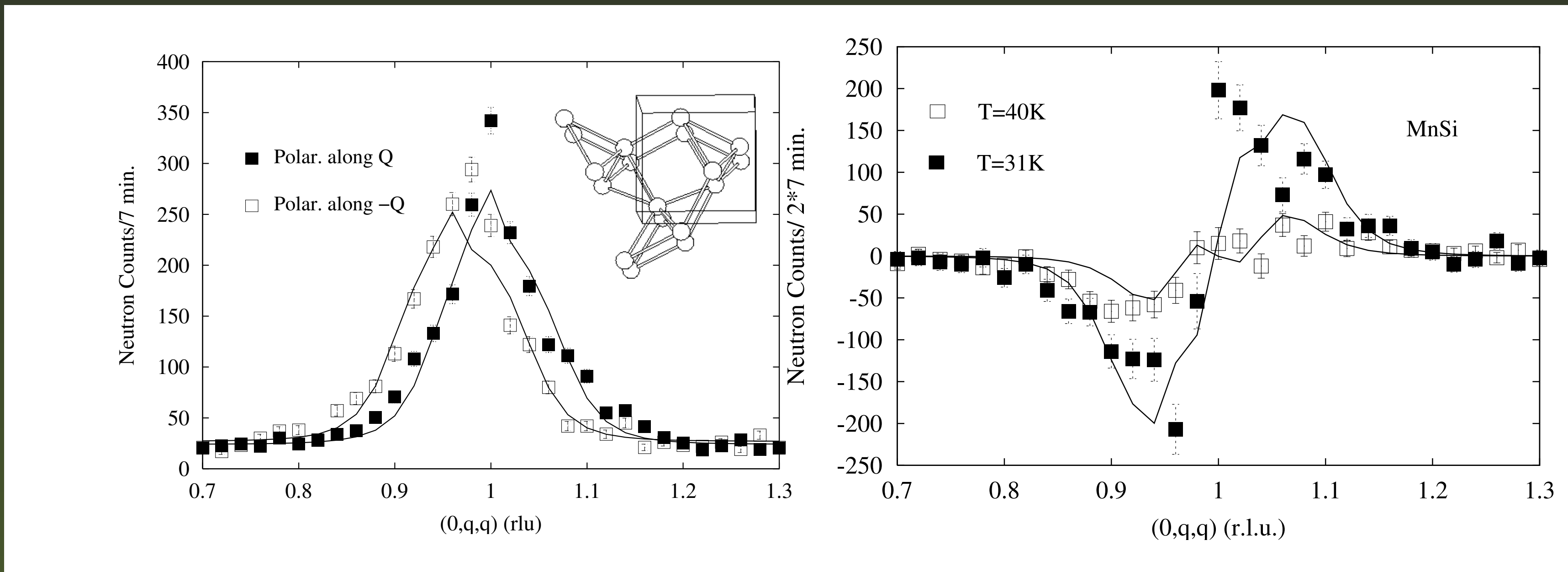
$$\begin{aligned}\frac{d^2\sigma}{d\Omega d\omega} \quad \sim \quad & (1+\hat{\vec{Q}}_z^2)\Im(\chi^T(\vec{q}+\vec{\delta},\omega)+\chi^T(\vec{q}-\vec{\delta},\omega)) \\ & +(\hat{\vec{D}}\cdot\hat{\vec{Q}})(\hat{\vec{Q}}\cdot\hat{\vec{P}}_i)\Im(\chi^T(\vec{q}+\vec{\delta},\omega)-\chi^T(\vec{q}-\vec{\delta},\omega))\end{aligned}$$

- Incommensurate fluctuations $\delta \sim atan(D/J)$
- Polarisation dependent part $\sim (\vec{Q}\cdot\vec{P}_i)$

(D. N. Aristov *et al.*, Phys. Rev. B **62**, R751 (2000).)

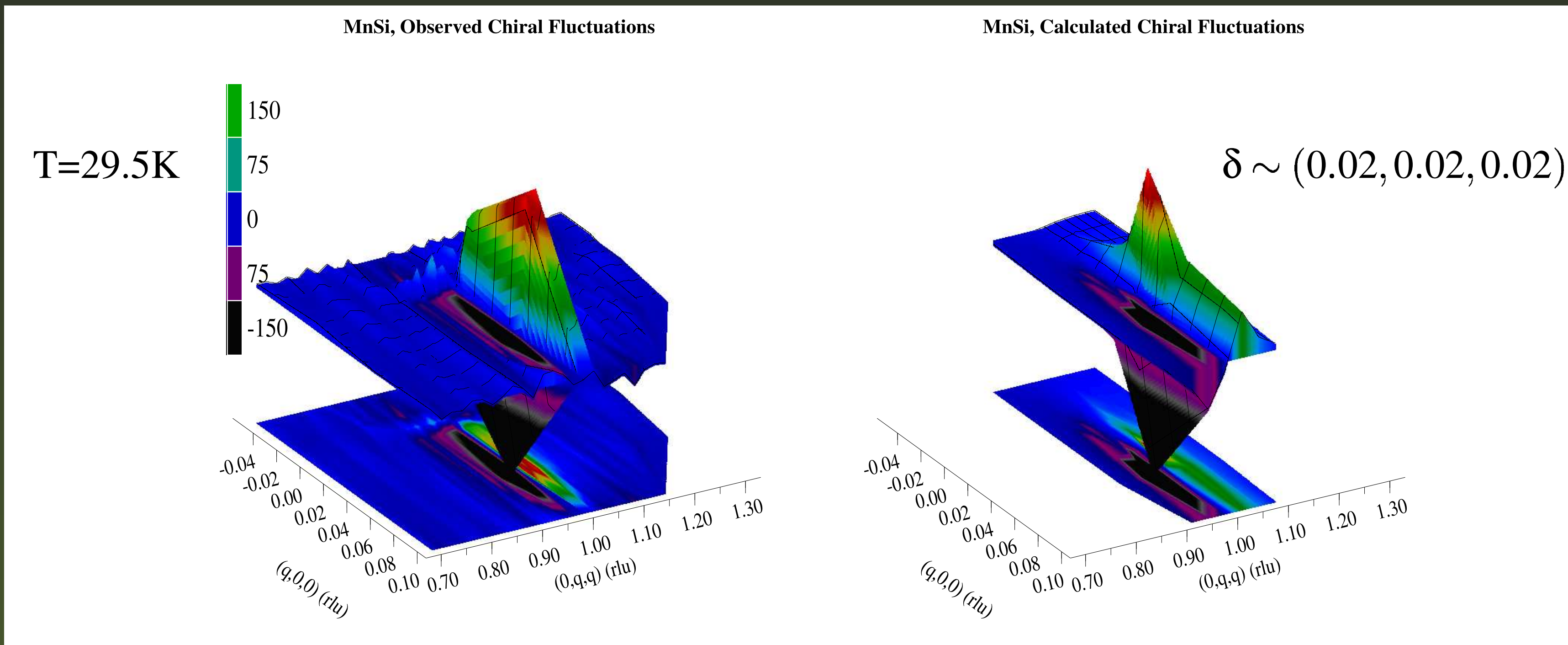
Antisymmetric part of $\Im\chi(\vec{Q},\omega)$

$$I(\vec{P}_i//\vec{Q}) - I(-\vec{P}_i//\vec{Q})$$



- $\Im\chi(\vec{q}(\delta),\omega) \sim \frac{1}{\kappa^2+q^2}\frac{\Gamma\omega}{\Gamma^2+\omega^2}$ with $\Gamma = uq(q^2+\kappa^2)$
- $u = 25meV/\text{Å}^3;\ \kappa = 0.12*(T-T_c)^{0.5}$

Antisymmetric part of $\Im\chi(\vec{Q},\omega)$



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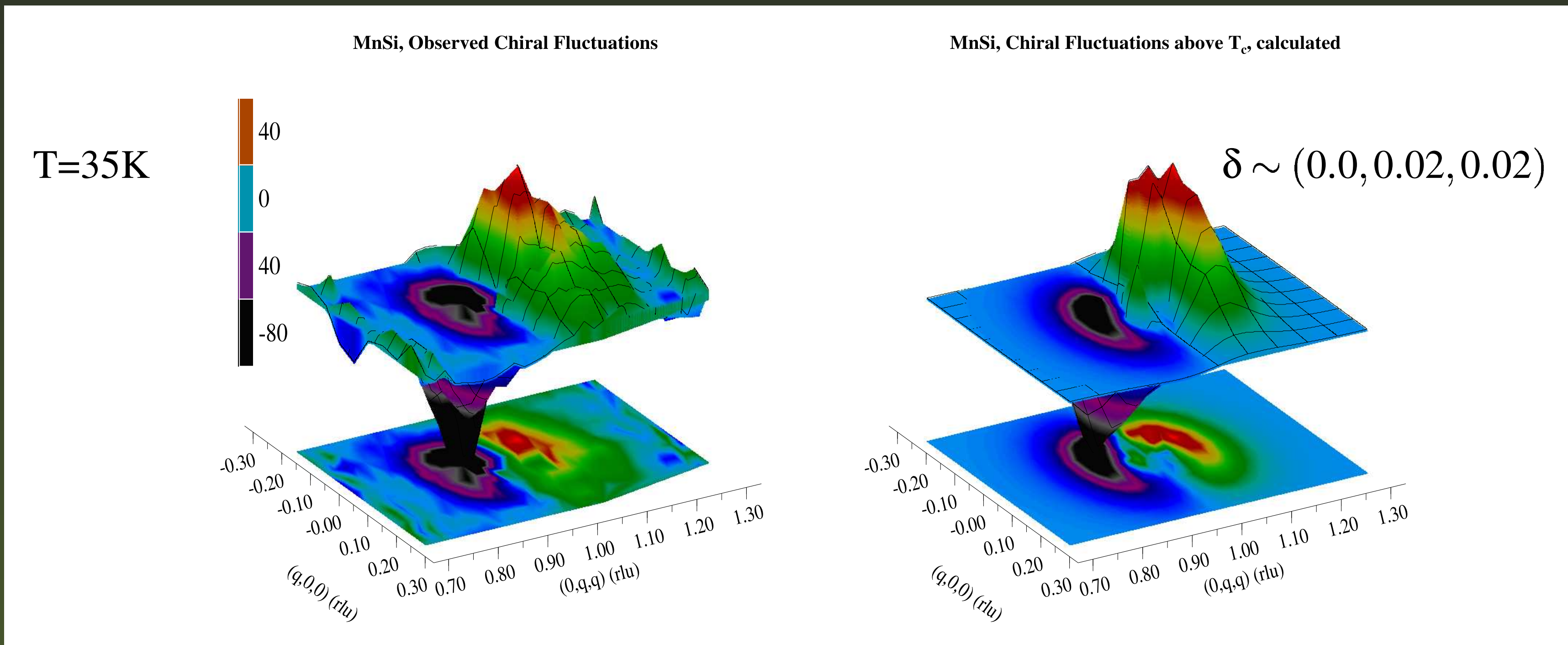

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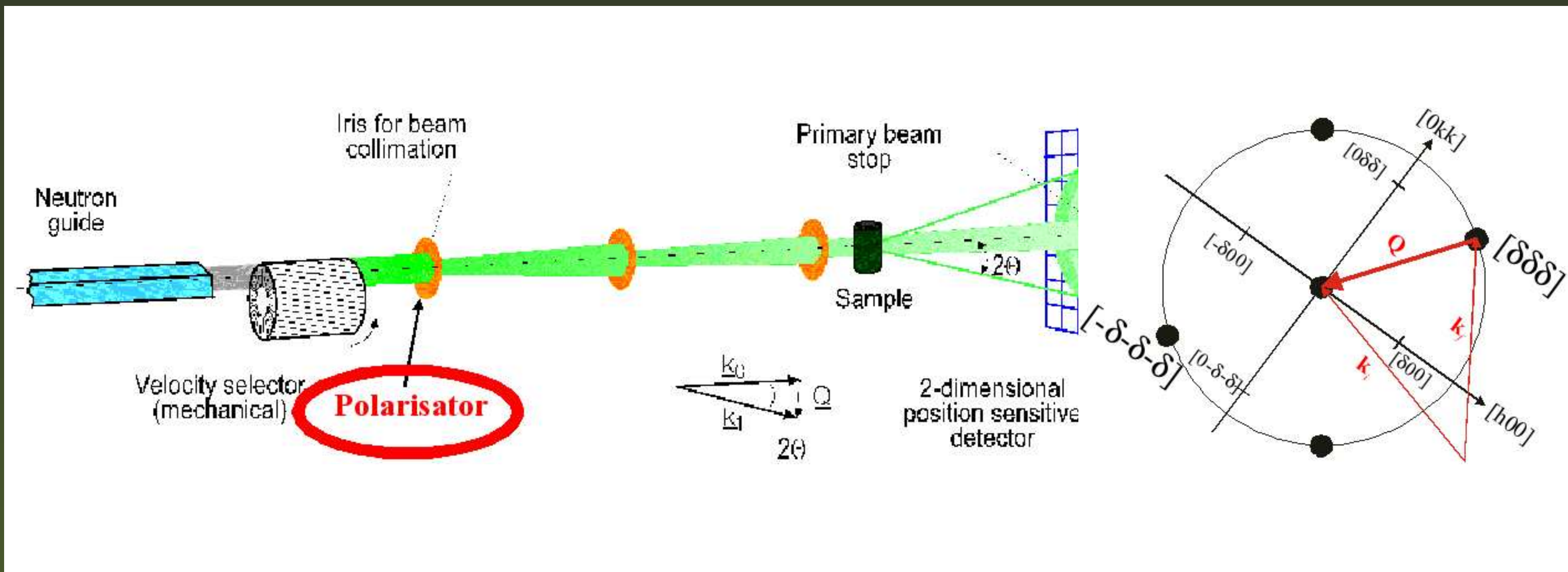
Critical regime ($T \geq T_C$)

Small-angle scattering experiment



(A.I. Okorokov *et al.*, Exp. Report GKSS (2002)); R. Georgii et al., Physica B, **350**, 247 (2004)

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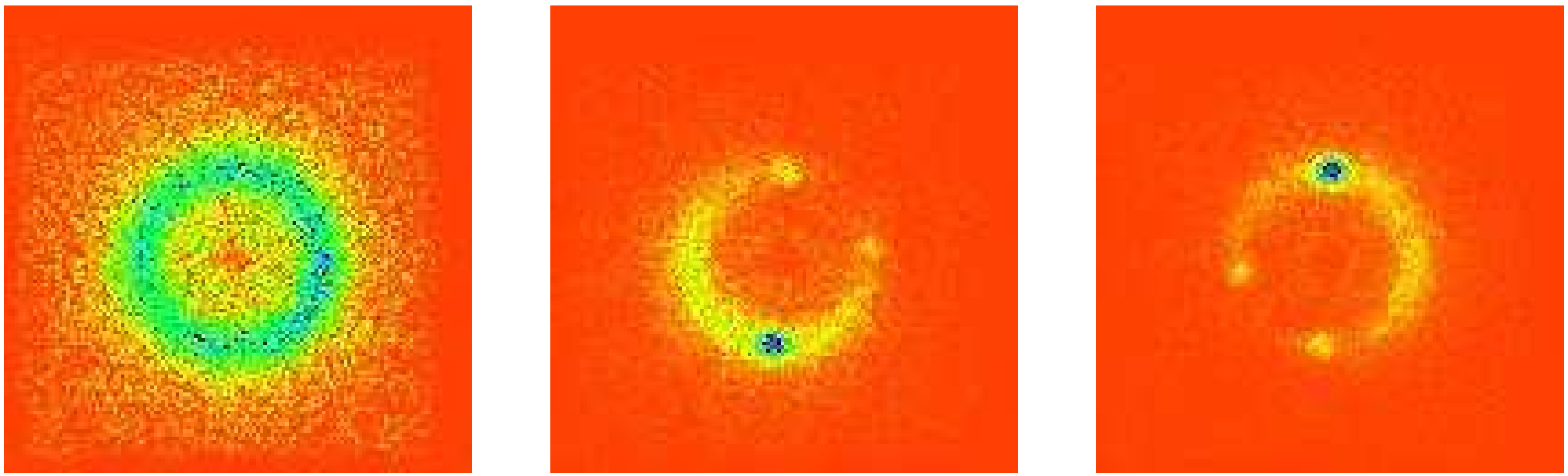

unpolarised $\qquad$ I_S+I_A $\qquad$ I_S-I_A

(A.I. Okorokov *et al.*, Exp. Report GKSS (2002)); R. Georgii et al., Physica B, **350**, 247 (2004)

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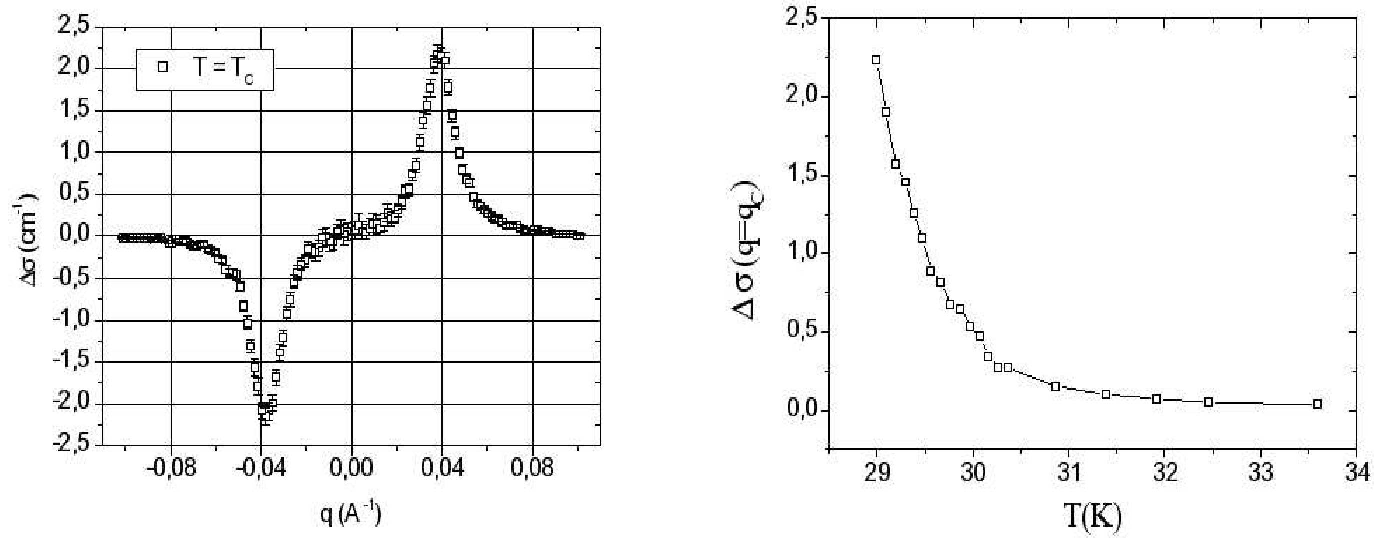


critical/paramagnetic scattering is single-handed

(A.I. Okorokov *et al.*, Exp. Report GKSS (2002)); R. Georgii et al., Physica B, **350**, 247 (2004)

Cubic systems with DM interaction

- exchange interaction
- DM interaction has a tensor form: $D\varepsilon_{\alpha\beta\gamma}$
- cubic anisotropy $F/2(q_x^2|S_q^x|^2 + q_y^2|S_q^y|^2 + q_z^2|S_q^z|^2)$

This leads to a cross-section:

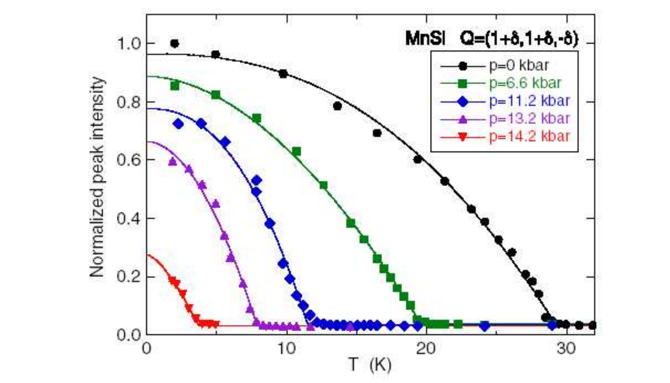
$$\frac{d\sigma}{d\Omega} \propto \frac{k^2+q^2+\kappa^2-2k\mathbf{q}P}{(q-k)^2+\kappa^2+[|F|k^2/2B](\sum \hat{q}_i^4-1/3)},$$

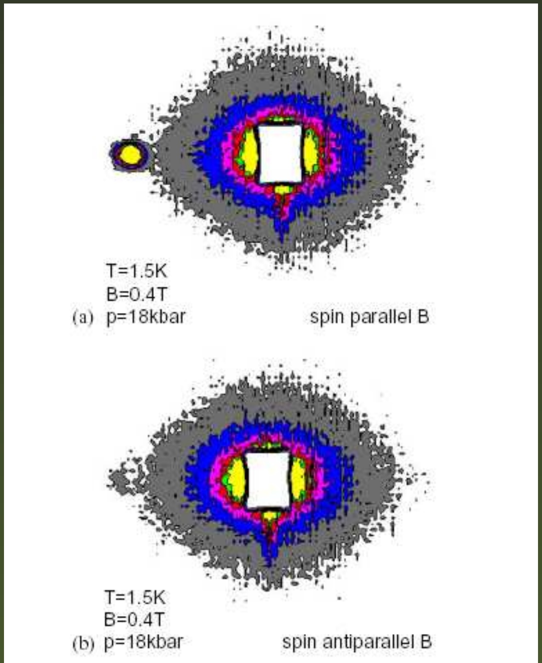
$k = D/B$ (length of helix), B=exchange interaction

i) because of DM interaction, cross section depends on **P**
ii) cross section $\propto qpcos(\phi)$

(S.V. Maleyev, to be published)

Pressure dependence





B. Fak et al., J. Phys.: Cond. Matter **17**, 1635 (2005)

C. Pfleiderer et al., Physica B **359**, 1159 (2005)

Conclusion

- magnetic ground-state is a left-handed spiral
- single handeness of the paramagnetic fluctuations
- pol. triple-axis and SANS measurements on 2 different crystals yield consistent results
- importance of cubic anisotropy and DM-interaction in MnSi