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Measurements of the spin wave stiffness in helimagnets by small-angle polarized neutron scattering

Sergey Grigoriev

Petersburg Nuclear Physics Institute,
RNC “Kurchatov institute”,
Gatchina, St-Petersburg 188300, Russia

SPECTRINA-2016, 22-24 June 2016, Gatchina, Russia

Outline

Motivation

Small-angle polarized neutron scattering as a method to study spin waves in helimagnets

Example of MnSi

Example of FeGe

Conclusion

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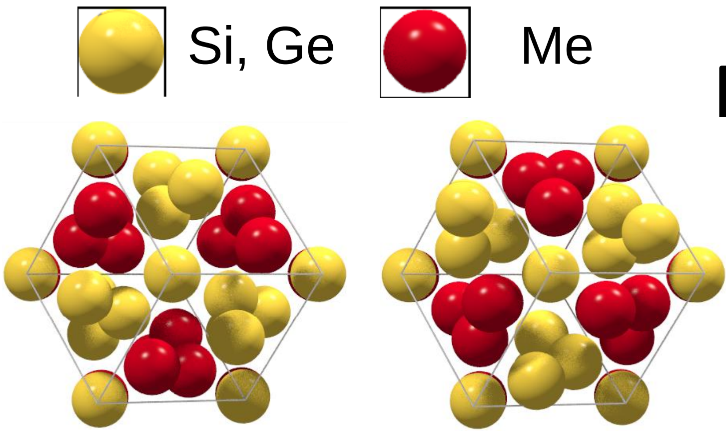
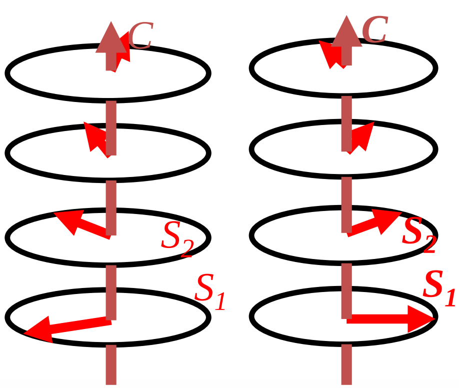
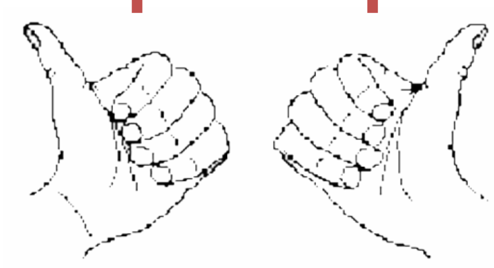


Left-handed helix   Right-handed helix





Driving forces in magnetic system of B20 compounds

[1] O. Nakanishi, A. Yanase, A. Hasegawa, M. Kataoka, Solid State Commun. 35 (1980) 995.
[2] P.Bak, M.H.Jensen, J.Phys. **C13** (1980) L881.

Free energy density

1) isotropic ferromagnetic exchange

$$W(q) = (B/2)\ (q^2 + \kappa_0^2)\delta_{\alpha\beta}\ \mathbf{S}_q^{\alpha}\ \mathbf{S}_{-q}^{\beta} +$$

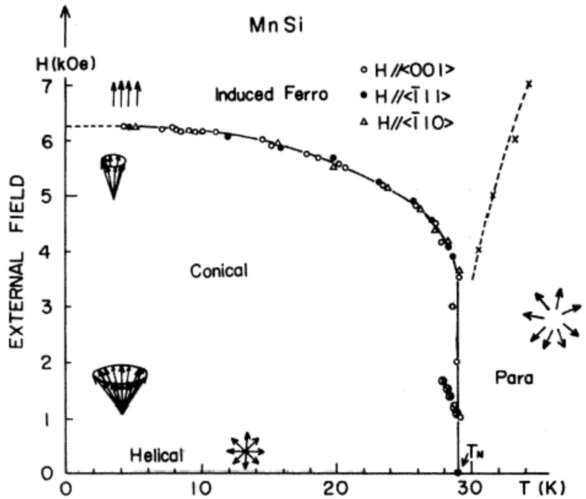
2) isotropic antisymmetric spin exchange Dzyaloshinskii-Moria (DM) due to lack of a symmetry center:

$$+\ i\ D\ \varepsilon_{\alpha\beta\gamma}\ q_\gamma\ \mathbf{S}_q^{\alpha}\ \mathbf{S}_{-q}^{\beta} +$$

3) weak anisotropic exchange (AE) interaction fixes direction of spiral along $\langle 1,1,1 \rangle$:

$$+\ (F/2)(q_x^2\ |\mathbf{S}_q^x|^2 + q_y^2\ |\mathbf{S}_q^y|^2 + q_z^2\ |\mathbf{S}_q^z|^2\ )$$

(H-T) phase diagrams



$$W(q) = E_{EX} + E_{DM} + E_{AE} =$$
$$= (A/2)\ (q^2 + \kappa_0^{\ 2})\ \mathbf{S}_q^{\ 2} +$$
$$+ D\ (\mathbf{q}\ [\mathbf{S}_q \times \mathbf{S}_{-q}]) + E_{AE}$$

1) $k = S\,D/A$ the helix wave vector
2) $A k^2 = g\,\mu_B\,H_{C2}$ the critical field of transition to the fully polarized state

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

for MnSi

1) $A = g\,\mu_B\,H_{C2}/k = 50$ meV A^2

2) $S\,Da = A\,ka = 8$ meV A^2

Triple-axis neutron spectroscopy for MnSi

[1] Y. Ishikawa, G. Shirane, J. A. Tarvin, and M. Kohgi, Phys. Rev. B 16, 4956 (1977)
[2] J. A. Tarvin, G. Shirane, Y. Endoh, and Y. Ishikawa, Phys. Rev. B 18, 4815 (1978)
[3] F. Semadeni, P. Boni, Y. Endoh, B. Roessli, G. Shirane, Physica B 267-268, 248-251 (1999)

The dispersion of SW in fully polarized state like in ferromagnets

$\varepsilon_q = Dq^2 + g\mu H$ with
$D = 52 \pm 2$ meV A^2 at T = 5 K

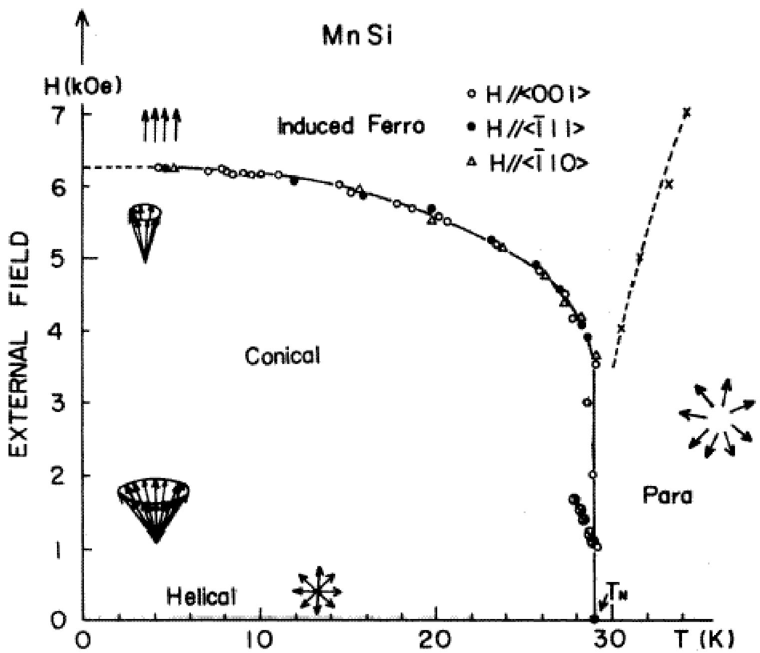
Question reads: what about other compounds ?

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

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

Answer reads: not with this method, which requires (i) large single crystals and
(ii) long time for measurements.

Spin-waves in helimagnets with DM interaction



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

Mitsuo Kataoka, J.Phys.Soc.Jap. 56 (1987) 3635

- Dynamics in the - “field-induced ferromagnetic” – fully polarized state $H > H_{C2}$

Ferromagnet	Helimagnet ($H > H_{C2}$)
$\varepsilon_q = Dq^2 + g\mu H$	$\varepsilon_q = D(\mathbf{q} - \mathbf{k})^2 + g\mu (H - H_{C2})$

Kinematics of the neutron scattering on spin waves in helimagnets

Energy conservation law (1)

$$\hbar\omega = E' - E = \left(\hbar^2/2m\right)\left(k'^2 - k^2\right) = \varepsilon_q$$

$$\varepsilon_q = D(\mathbf{q} - \mathbf{k}_s)^2 + g\mu(H - H_{C2})$$

Impulse conservation law (2)

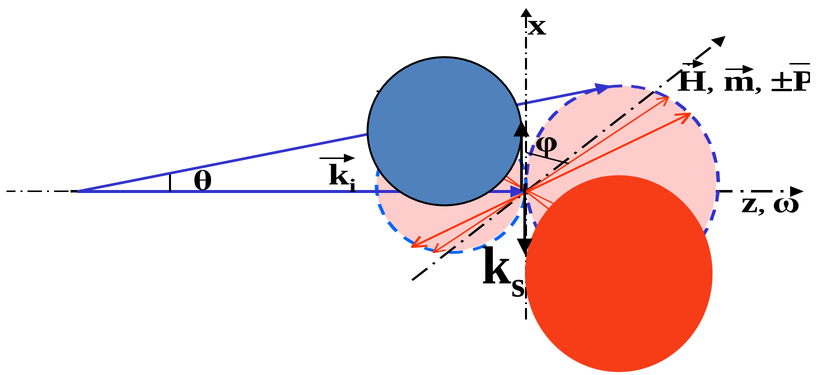
$$q^2 = k'^2 + k^2 - 2k'k\cos\theta$$

One receives the following solution:

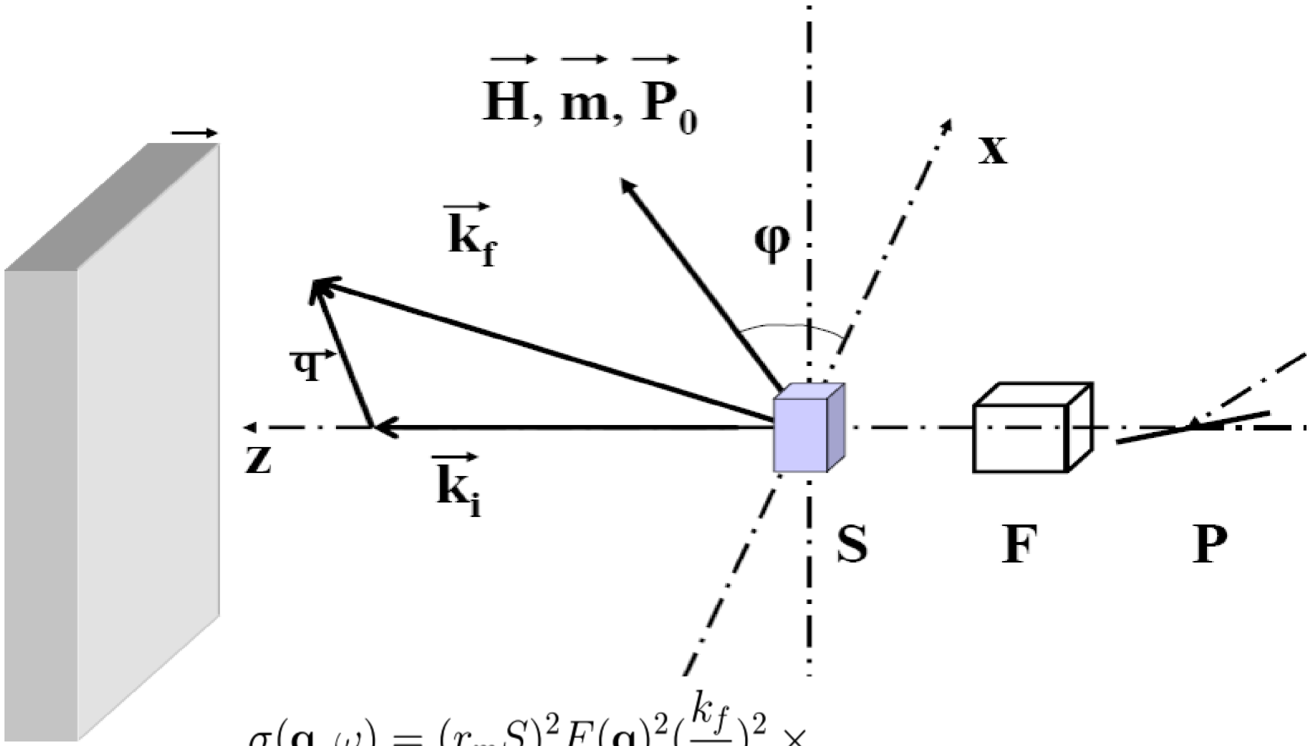
$$\frac{\omega_{1,2}}{2E} = \theta_0 + \frac{k_s}{k_i}\sin\phi \mp \sqrt{C - \left(\theta^2 - \theta\cdot 2\frac{k_s}{k_i}\cos\phi\right)}$$

$$C = \theta_0^2 - \theta_0\cdot\frac{H}{E} + \theta_0\cdot 2\frac{k_s}{k_i}\sin\phi + \left(\frac{k_s}{k_i}\right)^2\sin^2\phi$$

$$\theta_0 = \alpha^{-1} = \hbar^2/2Dm$$

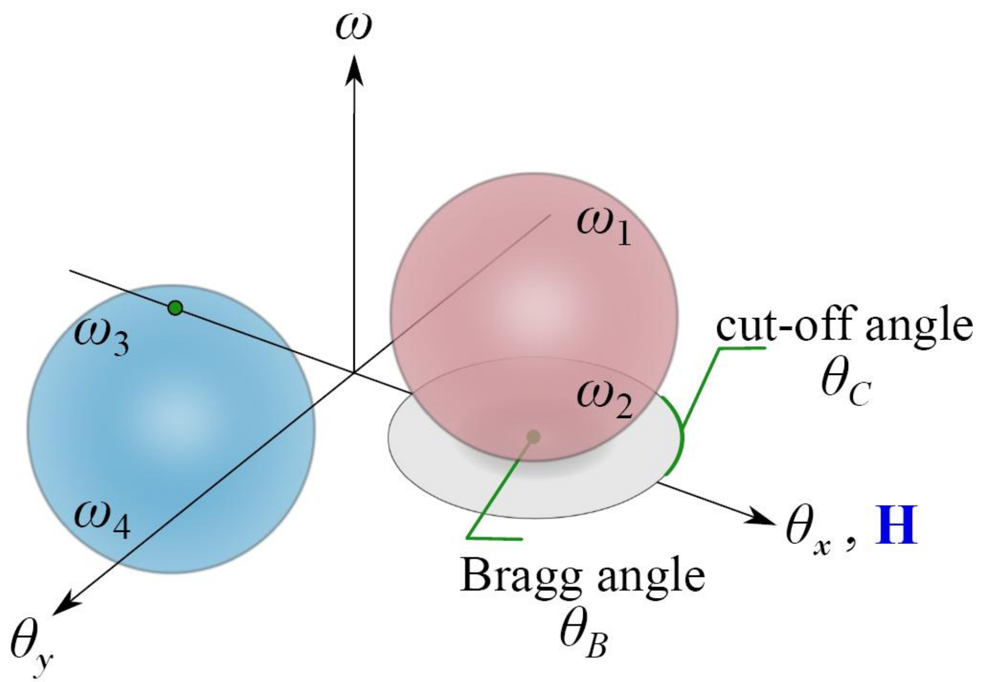


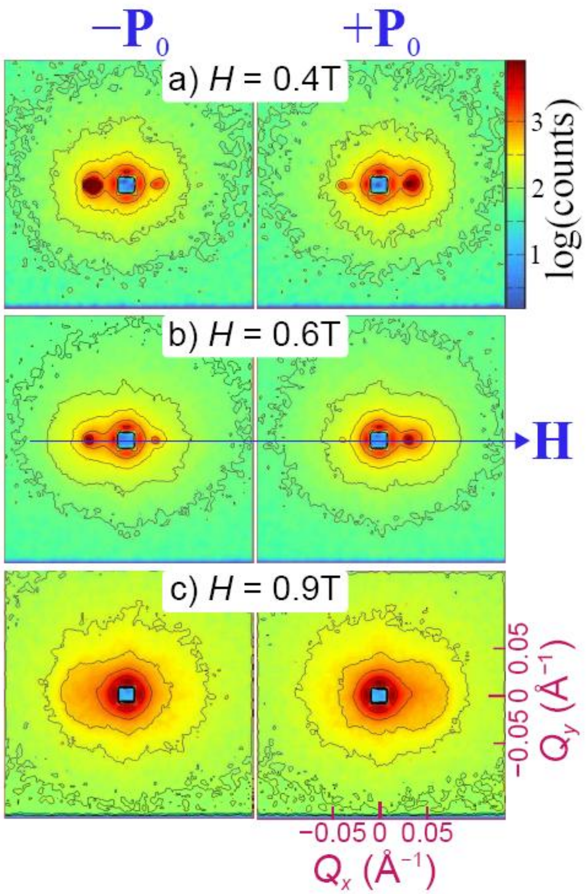
Experimental setup



$$\sigma(\mathbf{q},\omega) = (r_m S)^2 F(\mathbf{q})^2 (\frac{k_f}{k_i})^2 \times$$
$$\times\{[1 + (\mathbf{em})^2 + 2(\mathbf{em})(\mathbf{eP}_0)] n_q \delta(\omega - \epsilon_q) +$$
$$+[1 + (\mathbf{em})^2 - 2(\mathbf{em})(\mathbf{eP}_0)](n_q + 1)\delta(\omega + \epsilon_q)\},$$

Small Angle Polarized Neutron scattering on magnons in MnSi

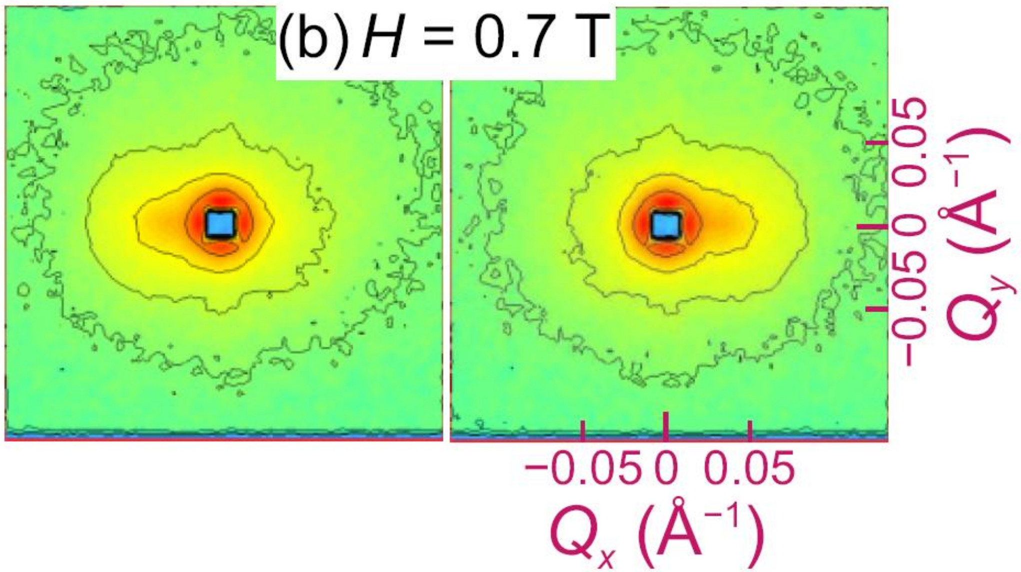


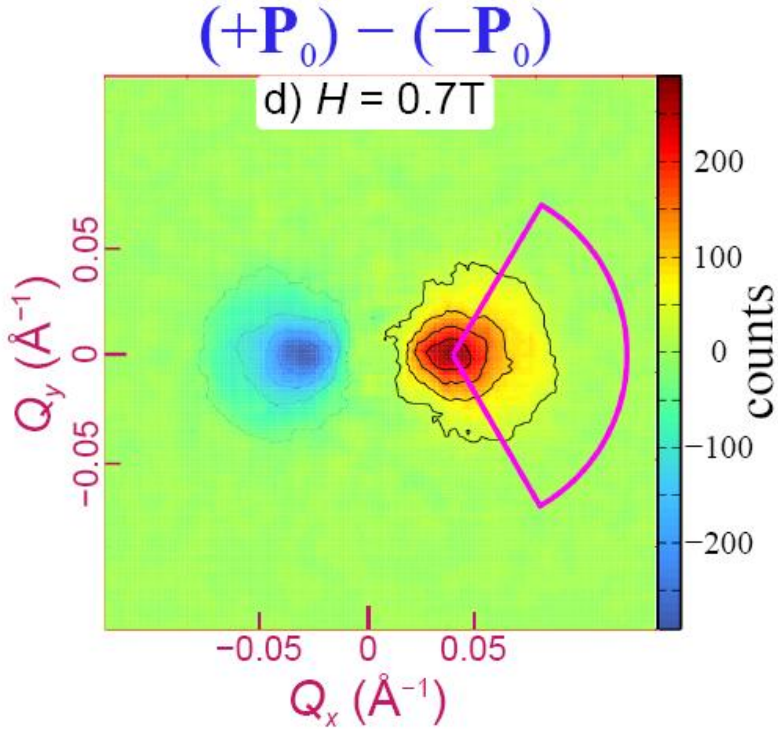


$$\Delta\sigma(\mathbf{q},\omega) = \sigma(\mathbf{q},\omega,+P_0) - \sigma(\mathbf{q},\omega,-P_0) =$$

$$= 4(r_m S)^2 F(\mathbf{q})^2 (\frac{k_f}{k_i})^2 (\mathbf{em})^2 n_q [\delta(\omega - \epsilon_q) - \delta(\omega + \epsilon_q)].$$

Small Angle Polarized Neutron scattering on magnons in MnSi





$$\Delta\sigma(\mathbf{q},\omega) = \sigma(\mathbf{q},\omega,+P_0) - \sigma(\mathbf{q},\omega,-P_0) =$$

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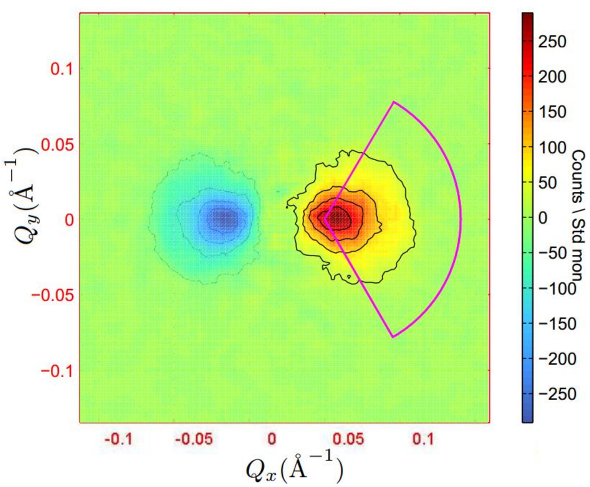
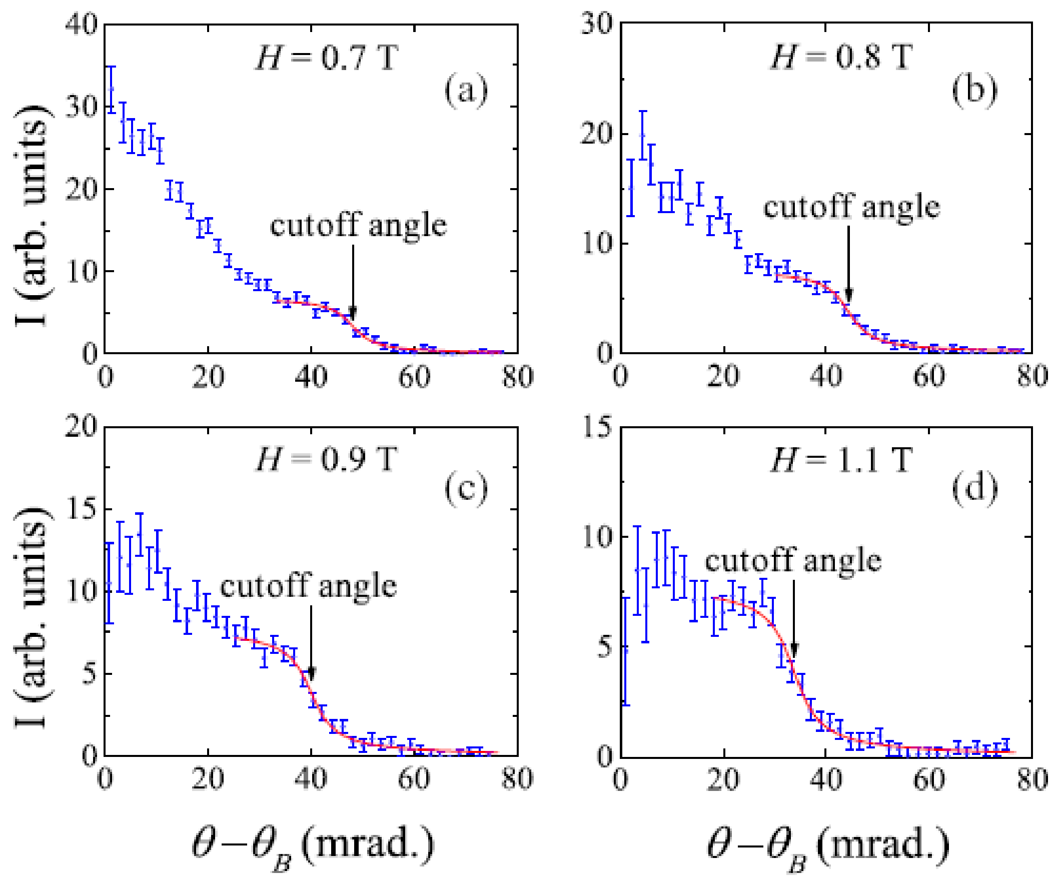
Field-evolution of anti-symmetric part of neutron scattering in MnSi

MnSi, T = 15 K

$H = 0.7$ T



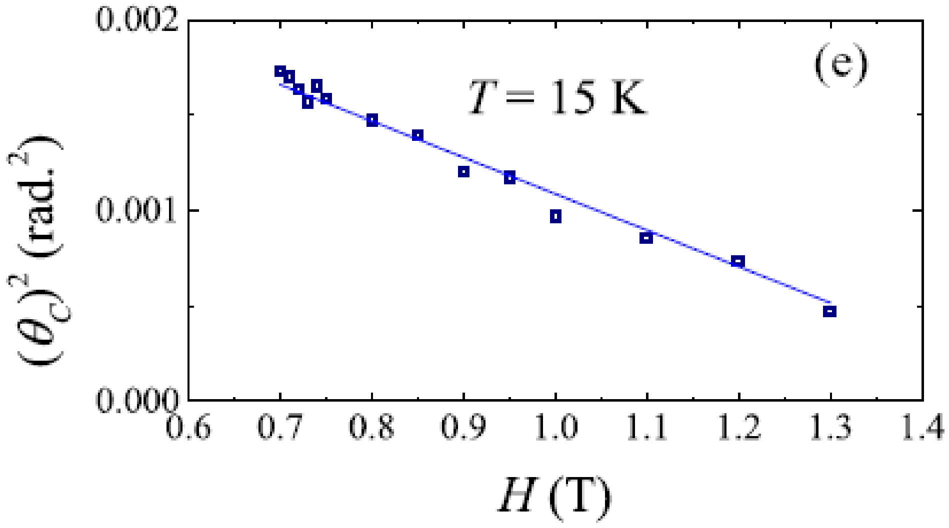


Field dependence of cut-off angle

MnSi

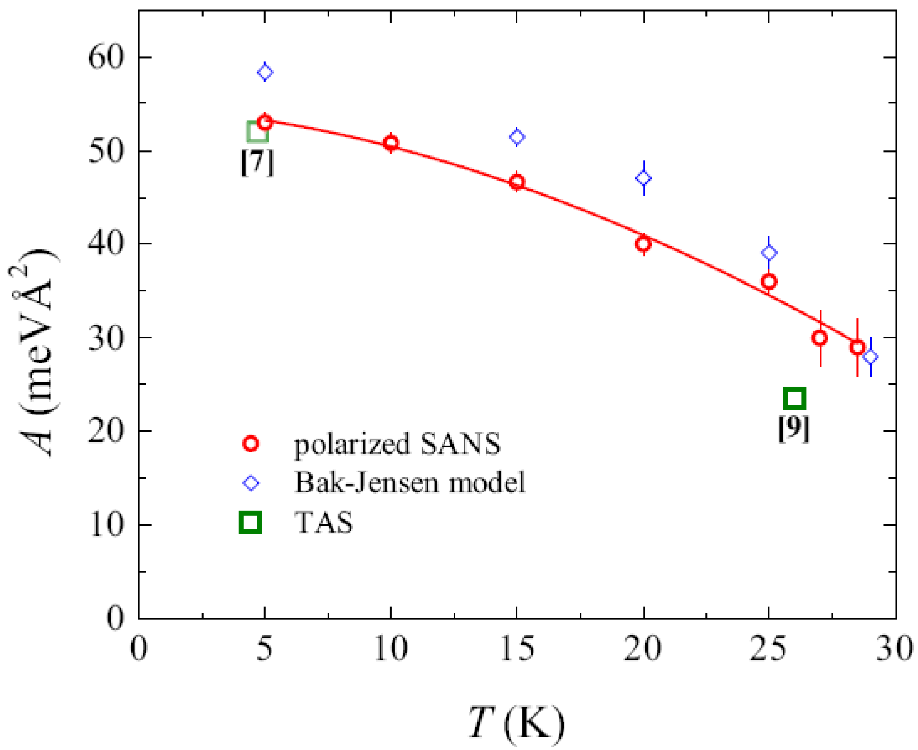
$$\theta_C^2(H) = \theta_0^2 - \frac{g\mu H\theta_0}{E}$$

$$\theta_0 = \alpha^{-1} = \hbar^2 / 2Dm$$



D = 48 meV A^2
T = 15 K (H> H_{C2})

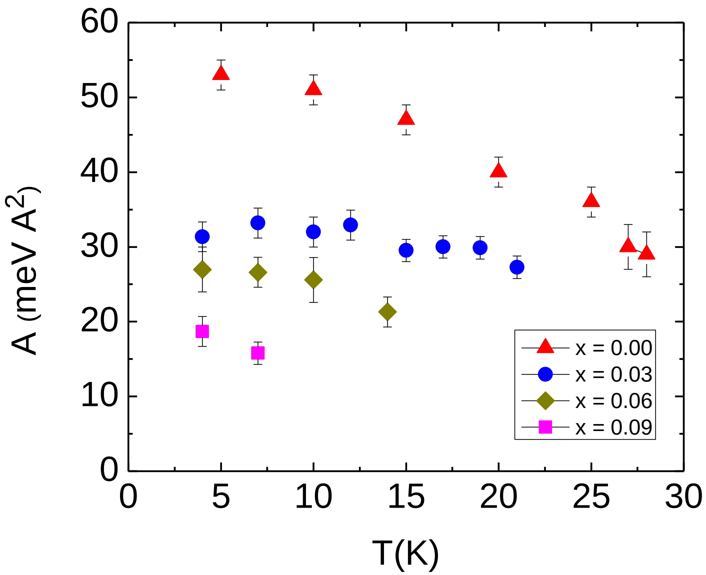
Temperature dependence of spin wave stiffness in MnSi

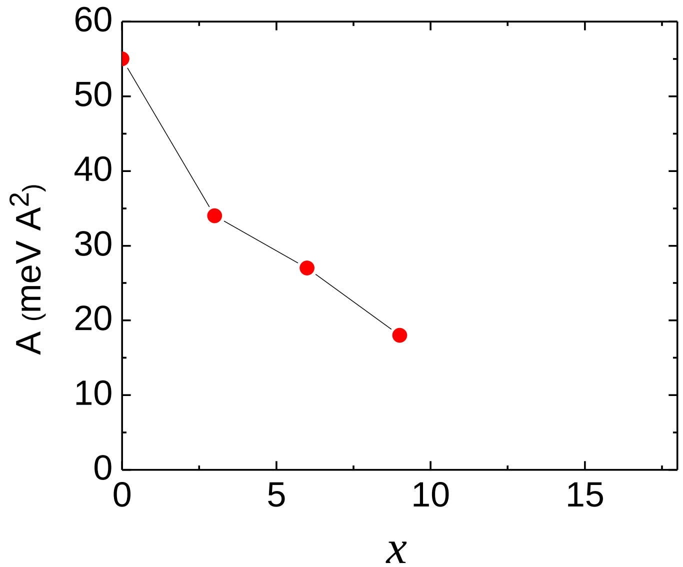


$$A = g\,\mu_B H_{C2}/\,k$$

S. V. Grigoriev, A. S. Sukhanov, E. V. Altynbaev, S.-A. Siegfried, A. Heinemann, P. Kizhe, and S. V. Maleyev, Phys. Rev. B 92, 220415(R) (2015)

Spin wave stiffness in $Mn_{1-x}Fe_xSi$

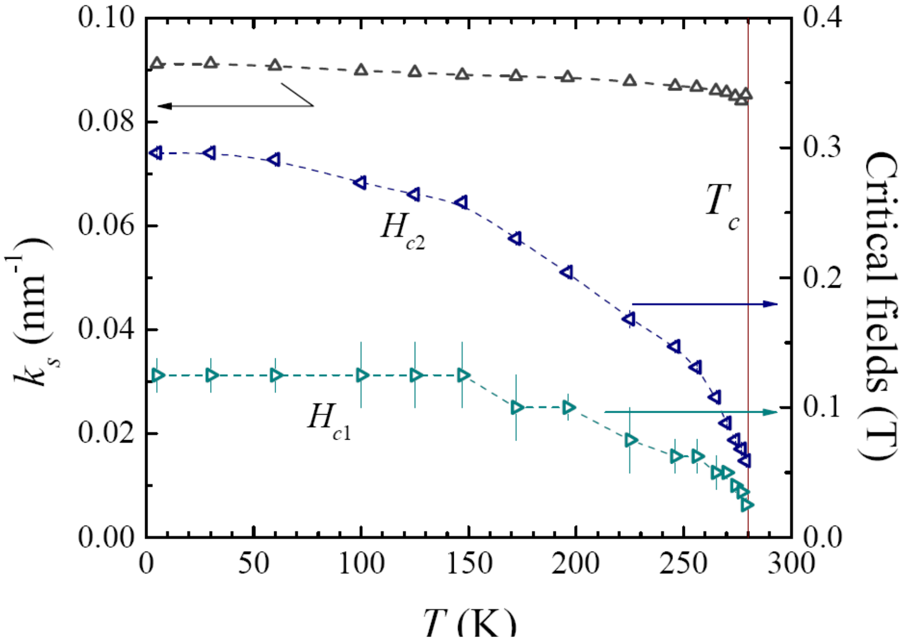


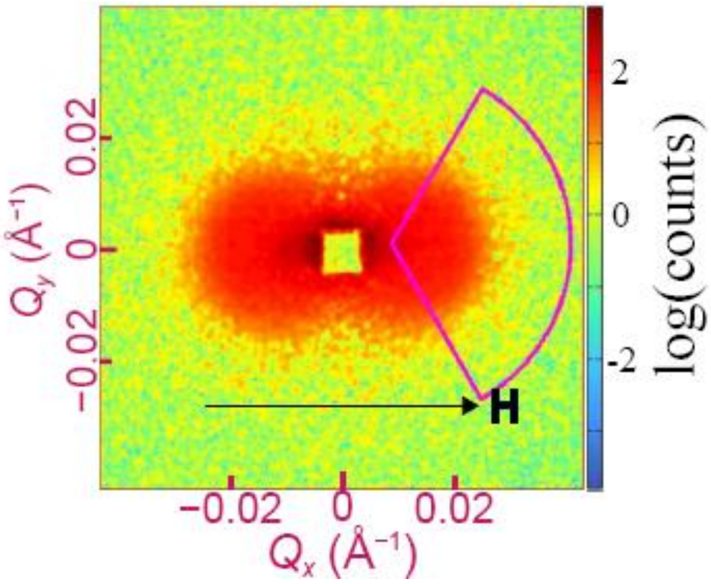


E. V. Altynbaev, S.-A. Siegfried, D. Menzel, G. Chaboussant, and S. V. Grigoriev, unpublished data.

Temperature dependence of spin wave stiffness in FeGe

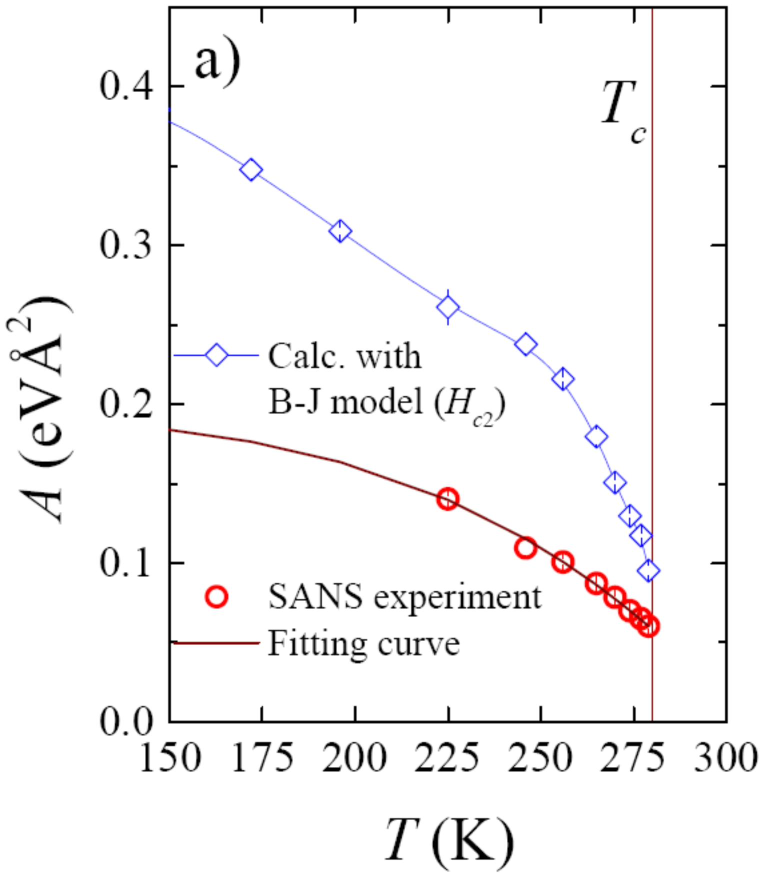
$$A = g\,\mu_B\,H_{C2}/\,k$$





S.-A. Siegfried, A. S. Sukhanov, E. V. Altynbaev, D. Honnecker, A. Heinemann, and S. V. Grigoriev, unpublished data.

Temperature dependence of spin wave stiffness in FeGe



$g\,\mu_B\,H_{c2} = A\,k^2$

$$H_{c2} = Ak_s^2 + 10/3KS_\xi^3$$

S. V. Grigoriev, A. S. Sukhanov, and S. V. Maleyev, Phys. Rev. B **91** (2015) 224429

Perspectives of the SANS method to study spin wave stiffness of helimagnets

Question reads: what about other compounds ?

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

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

Answer reads: can be measured by SANS method.
Method can work with
(i) the powder samples and
(ii) with acceptable statistics in reasonable time to make the wide range temperature scans.

Summary

We have experimentally proven the validity of the spin-wave dispersion relation for helimagnets with the DM interaction in the full-polarized state

$$\varepsilon_q = D(\mathbf{q} - \mathbf{k}_s)^2 + g\mu (H - H_{C2})$$

Small-angle polarized neutron scattering is shown to be a method to study spin waves in helimagnets.

Acknowledgements

A.S. Sukhanov, E.V.Altynbayev, S.V. Maleyev,
Petersburg Nuclear Physics Institute, NRC KI
Gatchina, St-Petersburg 188300, Russia

S.-A. Siegfried, A. Heinemann
Helmholz Zentrum Geesthacht,
21502 Geesthacht, Germany
Dirk Honnecker
Institue Laue-Langevin, 38042 Grenoble Cedex 9, France

The work is supported by the
Russian Foundation of Basic Research (Grant No 14-22-01073)

Many thanks for your attention!

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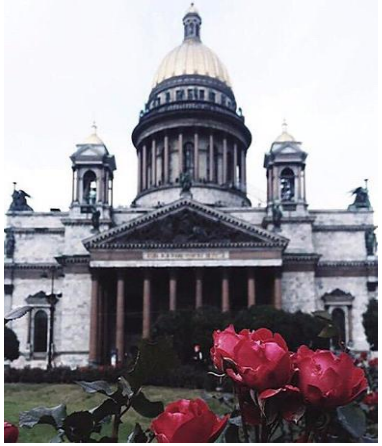

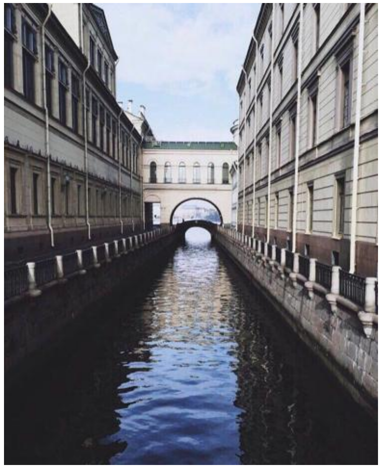

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