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Critical small-angle scattering of polarised neutrons in MnSi

R. Georgii[a,*], P. Böni[a], D. Lamago[a], S. Stüber[a], S.V. Grigoriev[b], S.V. Maleyev[b], A.I. Okorokov[b], H. Eckerlebe[c], P.K. Pranzas[c], B. Roessli[d], W.E. Fischer[d]

[a] ZWE FRM-II/E21, Technische Universität München, 85747 Garching, Germany
[b] Petersburg Nuclear Physics Institute, Gatchina, St. Petersburg 188300, Russia
[c] GKSS Forschungszentrum, 21502 Geesthacht, Germany
[d] Laboratory for Neutron Scattering, ETH Zurich & Paul Scherrer Institute, CH-5232 Villigen PSI, Switzerland

Abstract

The chiral fluctuations in the weak itinerant magnet MnSi were studied by means of small-angle neutron scattering with polarized neutrons. Due to the lack of a centre of symmetry, the magnetic moments are arranged along a left-handed spiral due to the Dzyaloshinskii–Moriya (DM) interaction. The experiments show that the incommensurate magnetic peaks evolve with increasing temperature into diffuse scattering that is mainly concentrated in a ring with the radius $q_c = 0.039$ Å^{-1} centred at the position of the direct beam $q = 0$. The scattering is fully polarised for $Q \parallel P_0$ and depolarised for $Q \perp P_0$ proving that the scattering is chiral and that the spiral has a unique handiness. From the data, we have determined the critical exponents of the magnetisation, the susceptibility and the correlation lengths of the chiral fluctuations. The results are discussed in the framework of the renormalisation theory.

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Keywords: Polarised SANS; Spin chirality; Critical exponents; DM interaction

1. Introduction

The weak itinerant ferromagnet MnSi with the space group $P2_13$ and the lattice constant $a = 4.558$ Å lacks a centre of symmetry leading to a left-handed ferromagnetic spiral in the ordered phase along the [1 1 1] direction with a propagation vector $\mathbf{k} = (2\pi/a)$ (0.017, 0.017, 0.017) [1,2]. The helicity is due to the antisymmetric Dzyaloshinskii–Moriya (DM) interaction [3].

The presence of an axial DM vector leads to a polarisation dependence of the magnetic neutron scattering cross section σ as shown in the following: For, the very high cubic symmetry of MnSi the DM vector $\mathbf{D} = d \cdot \mathbf{k}$ is parallel to the momentum transfer vector $\mathbf{Q}$ and the DM-interaction is given by the potential [3]

$$V_{\mathrm{DM}} = \mathrm{i}d \sum_{\mathbf{Q}} \mathbf{Q}[\mathbf{S}_{\mathbf{Q}} \times \mathbf{S}_{-Q}]. \quad (1)$$

*Corresponding author. Fax: +49-89-289-14995.
E-mail address: robert.georgii@frm2.tum.de (R. Georgii).

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If $\chi(Q)$ is the magnetic susceptibility without DM interaction we get in the static approximation [4]

$$\sigma(Q) = 2r^2\chi \frac{1+\chi \mathrm{d}Q \cdot (P_0\hat{\boldsymbol{Q}})}{1-(\chi \mathrm{d}Q)^2}, \tag{2}$$

where $\hat{\boldsymbol{Q}} = \mathbf{Q}/Q$ and P_0 the polarisation of the neutron beam. Due to the second term in the numerator of Eq. (2) the scattering intensity depends strongly on the relative orientation of P_0 and $\mathbf{Q}$. If $\mathbf{Q} \parallel P_0$ the scattering is maximal and if $\mathbf{Q} \perp P_0$ it is minimal.

Since the direction of the spiral in MnSi is single-handed there is no need of any polarisation analysis of the scattered neutrons for measuring polarisation-dependent terms in the cross section. Furthermore, no magnetic field at the sample is required except a weak guide field for preserving the neutron polarisation.

Recently, the paramagnetic chiral fluctuations in MnSi were mapped out in the (1 1 1) plane above $T_c = 28.7$ K using inelastic polarised neutron scattering [5]. This experiment showed that chiral fluctuations persist at least up to $T = 40$ K. In order to characterise these fluctuations, we determined the critical exponents near T_c by measuring the small-angle neutron scattering in MnSi.

In the following, we concentrate on the effects of the critical scattering, while we refer to the paper of Okorokov et al. in this proceedings for a detailed discussion of the behaviour of the system in the ordered helical magnetic phase.

2. Measurements

We performed a small-angle diffraction study with polarised neutrons using SANS-2 at the FRG-1 research reactor at GKSS in Geesthacht. The sample was a disc with a thickness of 2 mm and a diameter of 20 mm. It was cut from a large single crystal that was grown at Ames Laboratory. A beam of neutrons with an initial polarisation $P_0 = 0.97$, a neutron wavelength $\lambda = 5.8$ Å ($\Delta\lambda/\lambda = 10\%$) and a divergence $\alpha = 2.5$ mrad was used. The scattered neutrons were detected by a position sensitive detector with 128×128 pixels (4.4 mm each) placed at a distance of 3 m from the sample.

The scattering intensity was measured in the temperature range near $T_c = 28.7$ K with a step of 0.1 K. The MnSi single crystal was oriented such that the two axes [1 1 1] and [1 1 − 1] were perpendicular to the beam. The polarisation P_0 was chosen such that, in the ordered phase, the direction of the spiral $\mathbf{k}$ would be perpendicular to one of the [1 1 1] axis.

Below T_c, two intense peaks are observed, which indicate that there is indeed a spiral structure. Approaching T_c, the intensity of these intense peaks decreases and slowly smear out until they form a ring around the position of the direct beam at $T = T_c$. The formation of the ring indicates that the anisotropy that determines the direction of the spiral decreases. The ring is clearly visible up to 1–2 K above the critical temperature and then starts to dissolve.

3. Results and interpretation

For the determination of the critical exponents we started to interpret the data by extracting difference spectra of the two beam polarisations. Therefore, the effect of background scattering is eliminated and only the full anti-symmetric part of the magnetic cross section is considered (see Fig. 1). These spectra are integrated along a ring of constant q for both polarisations independently

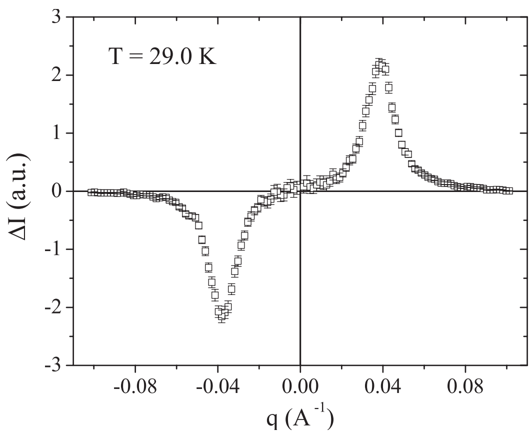

Fig. 1. The difference of the small-angle scattering intensity for the two polarisation directions of MnSi above T_c is fully antisymmetric.

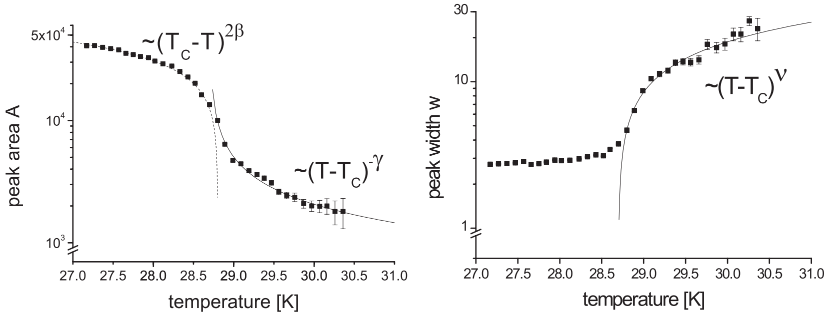

Fig. 2. The intensity and width of the Lorentzian fits versus the temperature. From the intensity plot below T_c the critical exponent γ for the magnetisation M and above T_c the critical exponent β for the paramagnetic susceptibility χ is obtained. From the width one gets the critical exponent v for κ, the inverse of the correlation length.

(i.e. the integration is performed along a half-circle of 180°) and the intensity is plotted against q. The resulting structure is fitted with a Lorentzian peak. The two parameters of this fit, the width and the intensity, are plotted against the temperature as shown in Fig. 2.

From these two plots the following critical exponents can now be extracted (see Fig. 2) using $T_c = (28.7 \pm 0.05)$ K for all fits:

(1) As the imaginary part of the paramagnetic susceptibility is proportional to the neutron magnetic scattering function, we can derive the critical parameter γ for $T \geqslant T_c$ directly from the intensity plot. For MnSi we obtain a value $\gamma = 0.61 \pm 0.01$.

(2) As the intensity of scattering in the ordered phase is proportional to the square of the magnetisation, we get the critical parameter 2β for $T \leqslant T_c$ from the intensity plot. For MnSi we obtain $\beta = 0.218 \pm 0.016$.

(3) The width of the peak is proportional to the inverse of the correlation length, therefore we obtain v from the width of the peak. We find $v = 0.541 \pm 0.011$.

These results are so far only preliminary as we intend to remeasure MnSi for obtaining better statistics and also need to include the effects of the finite instrument resolution. But a few conclusions can already be drawn: while the values for β and v are similar to the values of other magnetic systems [6] the value for γ clearly is smaller. Another interesting observation is that for $d = 2$ we get for $\gamma + 2\beta - d \cdot v = -0.036 \pm 0.017$, indicating a two-dimensional magnetic system.

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