

Ground state magnetic structure of Mn_3Sn

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We use spherical neutron polarimetry to determine the ground state magnetic structure of Mn_3Sn . We find that Mn_3Sn adopts an inverse triangular structure with spins parallel to $\langle 100 \rangle$ (type III) rather than spins parallel to $\langle 110 \rangle$ (type IV). Density functional theory calculations reveal no energy difference between these two structures, suggesting that the selection is caused by subtle effects such as sixth-order anisotropy. Partial control of the magnetic domain population through a moderate magnetic field is key to distinguishing between the two models. We find that three of the six domains are approximately equally populated, while the others have negligible population. Upon entering the low temperature incommensurate phase, the domain structure is lost. The domains in this phase are decoupled from the magnetic field and can therefore not be controlled by any known method.

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I. INTRODUCTION

The noncollinear antiferromagnets Mn_3X ($X = \text{Sn, Ge, Ga}$) display a very large anomalous Hall effect (AHE) at room temperature [1–6]. The sign of the AHE can be switched by the application of a small magnetic field, by strain [7,8], and even with electrical fields, which makes these materials interesting candidates for antiferromagnetic spintronic applications [9–11]. The AHE in Mn_3X arises from a large Berry curvature, which originates from Weyl points near the Fermi level [1,12,13]. For such Weyl points to exist, either time reversal or inversion symmetry must be broken [14]. In Mn_3X , time reversal symmetry is broken by the noncollinear magnetic structure.

The Mn atoms form a kagome lattice, as illustrated in Fig. 1. Noncollinear antiferromagnetic order with propagation vector $\mathbf{k} = 0$ sets in below the Néel temperature, which for Mn_3Sn is 420 K. Here, neighboring Mn spins within the kagome layers align at 120° to each other accompanied by a tiny ferromagnetic moment. Depending on the exact composition [15,16], Mn_3Sn undergoes a transition to an incommensurate (IC) phase upon cooling below $T_S \approx 290$ K, with two propagation vectors $\mathbf{k}_L \sim (0, 0, 0.08)$ and $\mathbf{k}_T \sim (0, 0, 0.11)$ [17–22]. The IC phase restores time reversal symmetry [22] and the AHE goes to zero.

Mn_3Sn crystallizes in space group $P6_3/mmc$ and several magnetic structures with moments at 120° and a small ferromagnetic component are compatible with this space group, as discussed in Refs. [18,23–25]. Some of the structures are illustrated in Fig. 2 [26]. Several neutron diffraction experiments have been performed to determine which of these structures is correct in the high temperature phase [19,22–24,27]. Despite this effort, the structure has not yet been uniquely determined; it has been narrowed down to two similar structures [23]. Following Ref. [25], we label these structures type III or IV, as shown in Fig. 2. A recent study in magnetic

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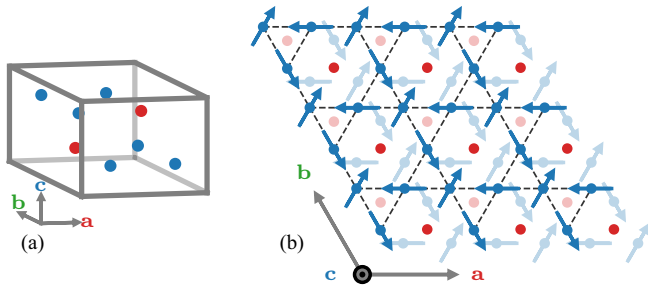


FIG. 1. Crystal structure of Mn₃Sn, with Mn atoms marked in blue and Sn atoms marked in red. Faded atoms are at a lower layer than nonfaded atoms. (a) The unit cell of Mn₃Sn. (b) Several unit cells viewed along the *c* axis, showing how each layer of Mn atoms forms a kagome lattice.

fields found type III to be the most likely ground state [21]. However, no study has determined the ground state in zero field.

Part of the difficulty comes from the fact that both type III and IV allow for six magnetic domains, illustrated in Fig. 3, which complicates the analysis of neutron diffraction data. The domain population can strongly influence the behavior of the material. For example, the switching of the sign of the AHE by a magnetic field is because the magnetic domains (partially) align with the field. Understanding and controlling the domains is therefore vital to determining the magnetic structure of Mn₃Sn, which in turn is an important step towards applications in spintronics [10].

Spherical neutron polarimetry (SNP) on Mn₃Ge has shown that its magnetic structure is type IV [25]. Given the similar structures and transport behavior, it has therefore been assumed that Mn₃Sn and Mn₃Ge have the same magnetic structure, e.g., Refs. [6,20,28].

Here, we use SNP to show that the magnetic structure of Mn₃Sn is not the same as that of Mn₃Ge, but actually type

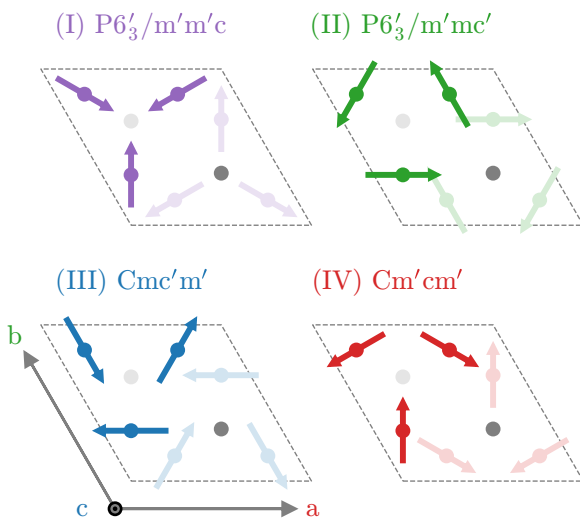


FIG. 2. Four symmetry-allowed magnetic structures of Mn₃Sn. The Mn atoms are shown with colored circles, while Sn atoms are shown with gray. Faded atoms are at a lower layer than nonfaded atoms. We find that type III gives the best agreement with data.

III as also found in the in-field study [21]. Interestingly, our density functional theory (DFT) calculations show no difference between the band structure of types III and IV, indicating that the energy difference between the two types of order must be small and most likely governed by sixth order anisotropy. The population of the six domains in the high temperature phase can be controlled to some extent via an external magnetic field. We furthermore show that the domain distribution in the low-temperature IC phase is decoupled from the magnetic field. Finally, we use unpolarized neutron diffraction to determine the temperature dependence of the incommensurate structure below T_5 .

II. EXPERIMENTAL DETAILS

High-quality Mn₃Sn single crystals were synthesized via a Bi-flux method. Stoichiometric mixtures of Mn powder (99.95% purity), Sn granules (99.999% purity), and Bi granules (99.999% purity) were combined in a molar ratio of 3:1:3. The mixture was sealed in an alumina crucible under a partial argon atmosphere within a quartz ampoule and heated to 1150 °C over 15 h. After holding at this temperature for 10 h to ensure homogeneity, the assembly was slowly cooled to 700 °C at a controlled rate of 50 °C/h and annealed for an additional 10 h. To optimize crystal growth, the temperature was further reduced to 300 °C at a slower rate of 2 °C/h and maintained for 50 h. Finally, the ampoule was removed from the furnace and the Mn₃Sn crystals were isolated from the residual Bi flux via centrifugation. The sample used here was a $3 \times 0.8 \times 0.8$ mm³ single crystal.

Magnetic susceptibility and standard transport measurements confirm the large AHE at 300 K and show a magnetic phase transition at 292 K. Details of these measurements can be found in the Appendixes.

Spherical neutron polarimetry (SNP) measurements were performed on D3 at the Institut Laue-Langevin (ILL) in Grenoble, France [29]. The SNP method involves measuring the diffraction intensity of spin-up and spin-down polarized neutrons for all nine combinations of initial and final neutron polarization along three orthogonal directions, *x*, *y*, and *z*. On D3, the Blume-Maleev coordinate system is used [30], in which *x* is along the scattering vector **Q**, *z* is perpendicular to the scattering plane, and *y* completes a right-handed coordinate system. The final polarization is measured along these three directions, resulting in a 3×3 polarization matrix. The matrix elements are defined as P_{fi} , where *i* and *f* refer to the initial and final polarization directions (*x*, *y*, *z*). The experiment was performed in zero field using Cryopad [31,32]. The incident wavelength was $\lambda = 0.83$ Å. The incident beam was polarized by Bragg reflection from a monochromator of a ferromagnetic Heusler alloy (Cu₂MnAl). Nutators and precession fields were used to control the direction of the incident and final neutron polarization. The scattered polarization was analyzed with a ³He neutron spin filter. The analyzing efficiency of the polarization, which decays over time, was corrected from several measurements of P_{zz} on the (0,0,2) reflection. This reflection is purely nuclear and therefore does not affect the neutron spin.

We first oriented the sample with **b** perpendicular to the scattering plane, to access the *h0l* reflections. The crystal

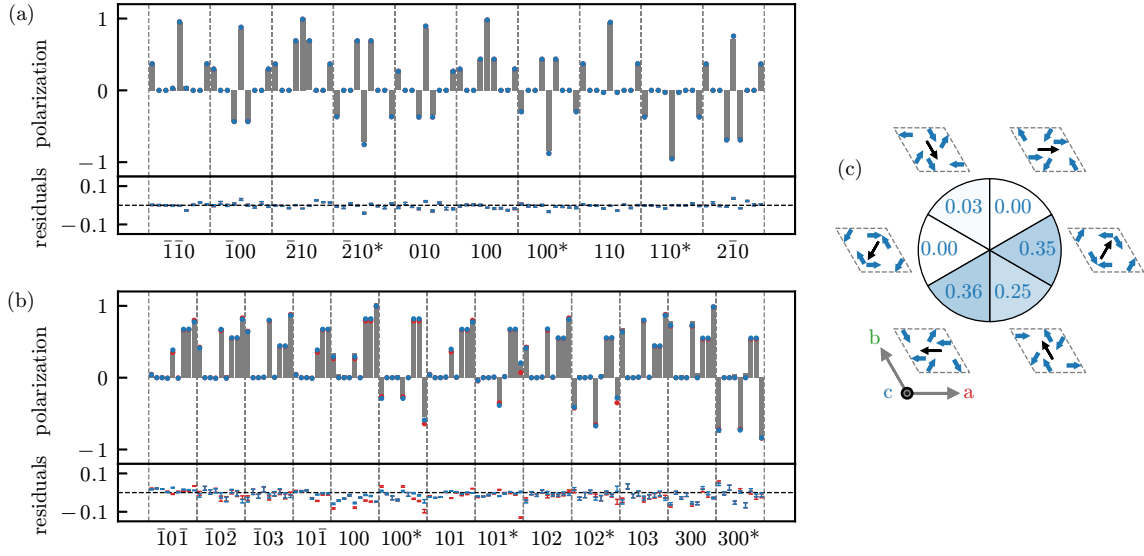


FIG. 3. Comparison between the observed and calculated polarization matrix elements P_{ij} for the Bragg peaks measured in the (a) $(hk0)$ and (b) $(h0l)$ scattering planes. For each reflection, the symbol (fit) and vertical bar (data) represent (from left to right) $P_{xx}, P_{yx}, P_{zx}, P_{xy}, P_{yy}, P_{zy}, P_{xz}, P_{yz}$, and P_{zz} . Reflections marked with an asterisk (*) are measurements that were repeated with the incident polarization reversed. The measured data are plotted as columns with error bars and the red and blue points represent the best fits for type III and IV structures, respectively. The difference between data and fit is shown at the bottom of the figures. (c) The domain distribution from our fit to (b). Each section in the pie chart shows the relative population of the domain, with the corresponding structure given outside the pie chart. The statistical uncertainty on these values is about 0.01. The black arrows show the direction of the small magnetic moment in the domain. The magnetic field was applied along **b**.

was placed in a 1 T magnetic field parallel to **b** to align the domain population of the magnetic structure and then transferred to Cryopad. This step was essential, as it is not possible to distinguish the two possible magnetic structures without aligning the domain population [23]. We measured a series of reflections in this orientation in the commensurate phase at 295 K, then cooled the sample to 160 K to measure in the IC phase. We next reoriented the sample to have **c** perpendicular to the scattering plane to access the $hk0$ reflections and remagnetized the sample at 295 K.

To investigate the influence of a magnetic field on the magnetic domains, we performed an unpolarized neutron diffraction experiment on the D23 instrument at the ILL [33]. The sample was mounted in a 15 T vertical field magnet with $(h, 0, l)$ as the scattering plane.

We first heated the sample to 440 K, about 20 K above the Néel temperature, to reset the magnetic domains. We then measured along $(1, 0, l)$ in zero field in the high temperature commensurate phase and in the low temperature IC phase. We observed the phase transition by the appearance of satellite peaks, consistent with earlier reports [17–22].

We then applied a magnetic field of 1 T along $-b$ (labeled -1 T) and measured along $(1, 0, l)$ for various temperatures upon heating, both in the commensurate and in the IC phase. We next heated the sample to the commensurate phase and applied a field of 10 T along **b**. If the domains were retained upon entering the IC phase, this should be observable as a change in the observed scattering pattern depending on the direction and magnitude of the applied magnetic field.

DFT calculations were performed using the atomic simulation environment (ASE) [34] in conjunction with the GPAW electronic structure code [35–37]. The experimental lattice

constants and atomic positions were taken from Ref. [23] to ensure realistic structural input and, given the noncollinear antiferromagnetic order of Mn_3Sn , the local spin-density approximation (LSDA) [38] implemented within the locally collinear approximation framework [39] was adopted for the exchange-correlation potential. Self-consistent states were obtained using a **k**-point density of at least $15 \text{ \AA}$, a plane-wave cutoff of 800 eV, and the energy per unit cell for each iteration was converged below changes of $1 \text{ \mu eV}$.

III. RESULTS

In Figs. 3(a) and 3(b) we depict the set of measured polarization matrix elements P_{fi} in the two crystal orientations. For each peak, we show, from left to right, the measured $P_{xx}, P_{yx}, P_{zx}, P_{xy}, P_{yy}, P_{zy}, P_{xz}, P_{yz}$, and P_{zz} as vertical bars. Colored points show the model. The top panel contains reflections in the $(h, k, 0)$ plane, while the bottom panel is for the $(h, 0, l)$ plane. A few of the reflections, marked by an asterisk, were measured with reversed incident polarization. The fits were performed using MAG2POL [40], based on the Blume-Maleev equations [41,42]. The incident polarization of the monochromator was $P_i = 0.95$. Each crystal orientation was fitted separately to the four magnetic structures illustrated in Fig. 2. Fitting the two orientations simultaneously was not possible, as the sample was cooled to the IC phase between the different orientations, and the magnetic field was reapplied. As we discuss below, the domains are reset upon entering the IC phase. The only fit parameters were the population of the domains and the magnitude of the magnetic moments.

Table I shows the reduced χ^2 and magnetic moment μ for each of the four models for the two orientations. It is clear that

TABLE I. Results of fits of magnetic structure models for Mn_3Sn to SNP data. The reduced χ^2 and ordered magnetic moment μ are listed for the two crystal orientations. The numbers in parentheses are standard deviations obtained from the fits. Type I and II have two domains each. Type III and IV have six domains each. Bottom row shows our DFT energies of the self-consistent state of the Mn_3Sn crystal (relative to the lowest energy).

Magnetic structure		I	II	III	IV
$(h, k, 0)$	χ_R^2	4945	10368	16.00	16.02
	μ (μ_B)	1.7(2)	1.7(3)	2.447(9)	2.442(5)
$(h, 0, l)$	χ_R^2	18477	1701	37.14	73.03
	μ (μ_B)	1.8(3)	1.78(6)	2.506(5)	2.46(1)
DFT energy (meV)		7.416	8.382	0.000	0.000

only models III and IV give a reasonable fit to the data and, in the $(h, 0, l)$ plane, type III is significantly better than type IV.

Our DFT calculations are in agreement with this result, as shown in the final row of Table I. The calculated energy of models I and II is significantly higher than that of models III and IV. Interestingly, the energy differences between types III and IV are below one μeV and the two structures can be regarded as degenerate within DFT. This is expected since sixth order magnetic anisotropy terms are required to distinguish the two states and such higher order effects typically yield very small energy differences.

To further confirm this, we also calculated the energy of the four models for Mn_3Ge ; see Table II. We again find that types III and IV have the same energy.

For the best fit of type III, we find that three domains are approximately equally populated, while three have a negligible population. The domains and their distribution are illustrated in Fig. 3(c). The exact values with uncertainties are given in Table III in the Appendixes.

We also measured selected peaks in the incommensurate phase at 160 K. Unfortunately, as discussed below, the data was not of sufficient quality to find a model that gave an unambiguous fit of that data.

Our experiment at D23, discussed below, confirms that the magnetic domains cannot be controlled by a magnetic field in the incommensurate phase. Therefore, all possible domains were equally populated and most of the SNP terms canceled out.

To investigate the possibility of controlling the magnetic domains in the incommensurate phase, we measured the peaks from this phase as a function of temperature and magnetic field at D23. We extracted the position and amplitude of the peaks by fitting the peaks to Gaussians.

TABLE II. Bottom row shows our DFT energies of the self-consistent state of the pristine Mn_3Sn and Mn_3Ge crystals (relative to the lowest energy for each crystal).

Magnetic structure	I	II	III	IV
Mn_3Sn	7.416	8.382	0.000	0.000
Mn_3Ge	3.397	3.470	0.000	0.000

TABLE III. Domain populations in Mn_3Sn for various fits. We use model III ($h0l$) in the main text.

Domain	III ($hk0$)	III ($h0l$)	IV ($hk0$)	IV ($h0l$)
1	0.024(12)	0.027(12)	0.364(9)	0.159(11)
2	0.274(7)	0.255(7)	0.000	0.166(6)
3	0.354(7)	0.353(4)	0.180(4)	0.341(1)
4	0.000	0.0014(56)	0.136(3)	0.000
5	0.062(5)	0.364(7)	0.000	0.000
6	0.286(5)	0.000	0.320(7)	0.338(9)

Figure 4 shows a summary of the results of these fits. Figure 4(a) shows the peak position of the four incommensurate peaks at $(1, 0, \pm\mathbf{k}_T)$ and $(1, 0, \pm\mathbf{k}_L)$ as a function of temperature, with colors indicating the applied magnetic field. Figure 4(b) shows the intensity of the peaks. Within statistical error, there is no difference between data taken in the three different field configurations. It is therefore clear that, although the magnetic domains can be controlled in the high temperature commensurate phase with a moderate magnetic field, the domains are not retained upon cooling into the incommensurate phase. The domains in the incommensurate phase can therefore not be controlled using any known methods, which unfortunately hinders the exact determination of the structure.

IV. DISCUSSION

The clear preference for type III in our SNP analysis provides unambiguous evidence that the magnetic ground state of Mn_3Sn differs from that of isostructural Mn_3Ge , which adopts type IV [25]. In that work, it was shown that sixth order

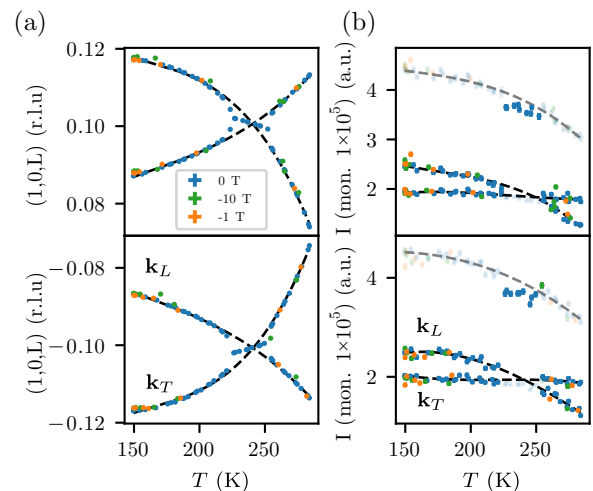


FIG. 4. (a) Position and (b) the intensity of the peaks in the incommensurate phase as a function of temperature. Blue, green, and orange markers indicate data at zero field, 10 T and -1 T, respectively. Neither the peak position nor the integrated intensity is affected by the magnetic field. Lines are guides to the eye. In a region around 230 K, the peaks are too close to be fitted separately and a single peak was fitted instead. In (b), we show half the peak intensity in this region with faded markers. Outside that region, the faded markers indicate the sum of the two peaks.

anisotropy can distinguish between the models and is allowed by symmetry. Our results imply that the magnetic anisotropy has opposite sign in Mn_3Sn , as has indeed been proposed earlier [7,21,43]. In other words, the easy axis direction of Mn_3Ge is along the reciprocal lattice vectors $\mathbf{a}^*$, while for Mn_3Sn it is along the direct lattice vectors $\mathbf{a}$.

Our results are consistent with the work of Ref. [43], which finds a sixth-order anisotropy term of $K_6 = -2210 \text{ erg/cm}^3$, which corresponds to $2.9 \times 10^{-5} \text{ meV/Mn}$. Such small energies cannot be distinguished by our DFT calculations, which indeed yield identical energies for types III and IV.

Our experiments show that magnetic domains can be partially aligned using a moderate field in the high-temperature phase. Interestingly, three domains are selected with almost equal population, rather than one as might be expected. This can be understood as follows. Each of the six domains have a small net magnetic moment, indicated by arrows in Fig. 3(c) [27]. This moment (μ_F) couples to the magnetic flux density ($\mathbf{B}$) via a Zeeman term, $\mathcal{H} = -\mathbf{B} \cdot \mu_F$. The net moment of three of the domains has a component parallel to the magnetic field, while the other three have an antiparallel component. The Zeeman energies of the domains with parallel moments are lower than those with antiparallel moments, and so the former three are preferentially populated. Within this model we would expect the domain with moment along $\mathbf{b}$ to have the largest population, which we do not observe. It is unclear what causes this discrepancy. It may be related to the anisotropy not being uniform [43] or to small systematic errors in the data caused, e.g., by slight depolarization of the beam at domain boundaries or due to the small ferromagnetic moment in the sample [25].

In the previous SNP measurements of Mn_3Ge , type IV was the ground state and only two domains had significant populations of 60% and 36% [25]. There are two notable differences between the two experiments. First, as mentioned above, the easy axis direction of Mn_3Ge is along the reciprocal lattice vectors $\mathbf{a}^*$, while for Mn_3Sn it is along the direct lattice vectors $\mathbf{a}$. The magnetic field was applied along $\mathbf{b}$ in both experiments and thus not along an easy axis for Mn_3Ge . Second, the Mn_3Ge experiment was carried out at 2 K, whereas our experiment on Mn_3Sn had to be carried out at 295 K to be in the correct phase. It is unclear whether the different domain populations are simply caused by temperature or if other effects are at play.

Either way, control of the magnetic domains plays a significant role in potential applications [10]. In thin films, it has furthermore been shown that the sign of the AHE (and therefore to some extent the magnetic domains) can be controlled electrically, which offers significant advantages for applications over control via magnetic field [28,44].

Some research into spintronic applications uses the chirality of spin spirals to store information [45]. It is therefore of great interest to control the magnetic structure of Mn_3Sn in the low temperature phase.

We attempted to determine the exact nature of the IC phase using SNP by measuring several of the IC peaks. However, only the diagonal elements of the polarization matrix were nonzero and we therefore did not have enough independent data points to obtain a unique solution. Although the available data were insufficient to fully resolve the structure, they are

consistent with the model proposed in Ref. [22], reproduced in the Appendixes, Fig. 9. This model would allow for only two domains related by inversion along the c axis. As we have shown here, these domains do not couple to a magnetic field and we have therefore been unable to control them.

When moving along c in the IC phase, the spins rotate by about 15 degrees between each layer (the exact rotation depends on the temperature). The magnetic domains are related by a rotation of 60 degrees and the structure in the IC phase will therefore be similar to different domains in the commensurate phase at various layers (see Fig. 9 in the Appendixes).

We further note that models III and IV are related by a 30° rotation of all the spins. The magnetic structure will therefore also be similar to various domains of type IV in some layers. This is consistent with the fact that types III and IV have very similar energies in the commensurate phase.

In agreement with previous reports [22], we find that the IC phase has two pairs of peaks associated with propagation vectors $\mathbf{k}_T \approx (0, 0, \pm 0.09)$ and $\mathbf{k}_L \approx (0, 0, \pm 0.11)$, respectively. We also find a third peak k_3 at $2k_L + k_T$ (see Fig. 8 in the Appendixes). This can be understood as a superposition of a longitudinal spin-density wave ($\mathbf{k}_L$) and a coplanar helical magnetic order [22].

V. CONCLUSION

In conclusion, we have shown that the magnetic structure of Mn_3Sn in the high temperature phase is type III, i.e., space group $Cmc'm'$ (see Fig. 2). This is in contrast with Mn_3Ge , which has the type IV structure (space group $Cm'cm'$). The ground state is most likely selected by sixth-order anisotropy, which therefore has the opposite sign in Mn_3Sn relative to Mn_3Ge . There are six possible magnetic domains in this phase and a magnetic field applied along $\mathbf{b}$ selects not one but three of them with roughly equal population. Upon cooling below $\sim 290 \text{ K}$, Mn_3Sn enters an incommensurate phase, which is completely decoupled from external magnetic fields. This means that there is currently no known method of controlling the domain distribution in this phase. It would be interesting to pursue routes other than external magnetic fields to manipulate the domains in this phase, such as pulsed currents as demonstrated for MnAu_2 thin films [46] or electric fields as demonstrated for the helical magnetic phase of CuO [47].

ACKNOWLEDGMENTS

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DATA AVAILABILITY

The data that support the findings of this article are openly available [29,33]; embargo periods may apply.

APPENDIX A: MAGNETIC SUSCEPTIBILITY AND TRANSPORT MEASUREMENTS

The magnetic susceptibility of the sample was measured at the École Polytechnique Fédérale de Lausanne (EPFL), Switzerland, using a Superconducting Quantum Interference Device (SQUID) magnetometer from Quantum Design. The sample was cooled to 10 K in zero field; then a field of 0.1 T was applied and magnetic susceptibility measurements were made while warming up to 400 K. We measured with the magnetic field along the a and c axes. The results are shown

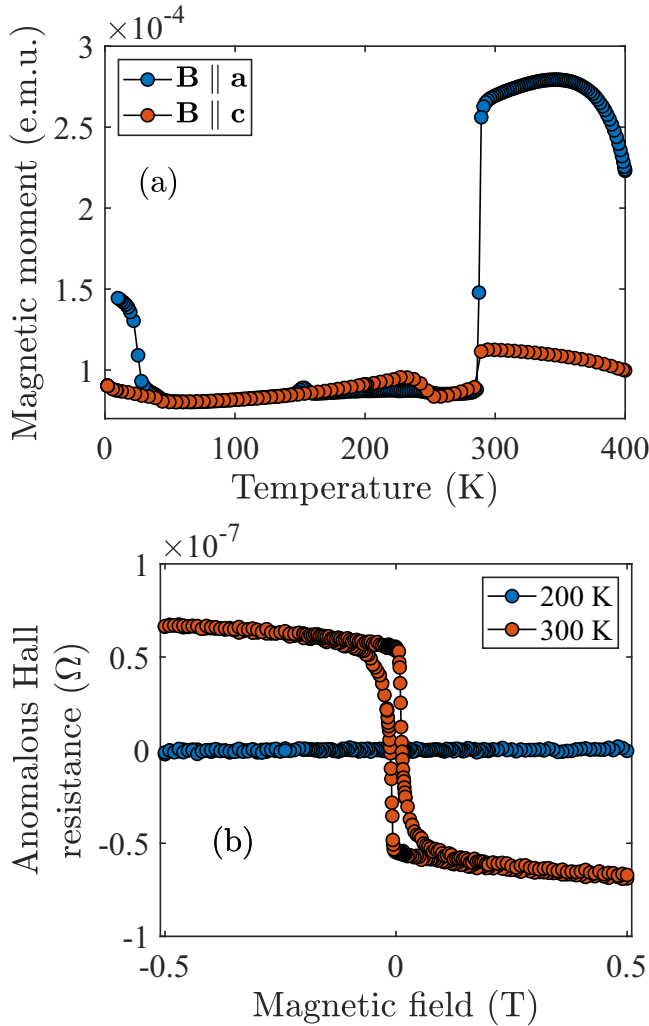


FIG. 5. (a) Magnetic susceptibility of Mn₃Sn with the magnetic field of strength $\mu_0 H = 0.1$ T parallel to the a (blue points) and c (red points) axes. (b) The anomalous Hall resistance of Mn₃Sn at 300 K (red points) and at 200 K (blue points), showing the absence of AHE in the incommensurate phase.

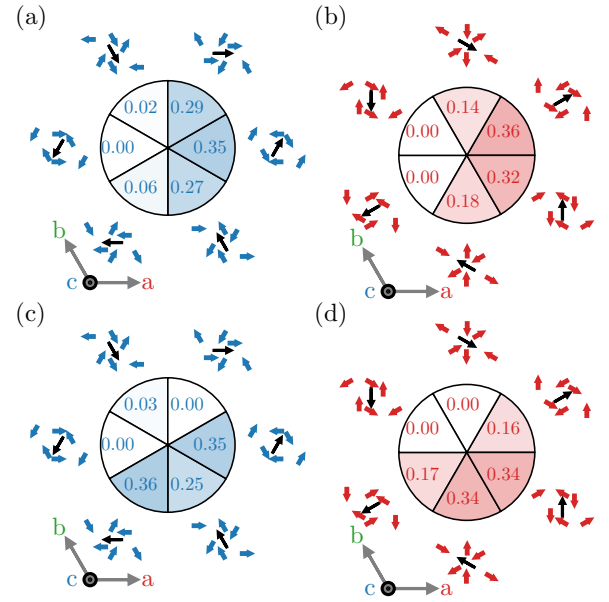


FIG. 6. Domain distribution from our fits to models III and IV. Each subfigure shows the population of each domain in the pie chart and the spin directions of each domain. The black arrows show the direction of the small magnetic moment in the domain. (a) Type III in the $(h, k, 0)$ plane. (b) Type IV in the $(h, k, 0)$ plane. (c) Type III in the $(h, 0, l)$ plane. (d) Type IV in the $(h, 0, l)$ plane.

in Fig. 5. The magnetic phase transition at ~ 290 K is clearly visible.

The Hall resistance was measured using the standard four-probe setup in a Physical Property Measurement System

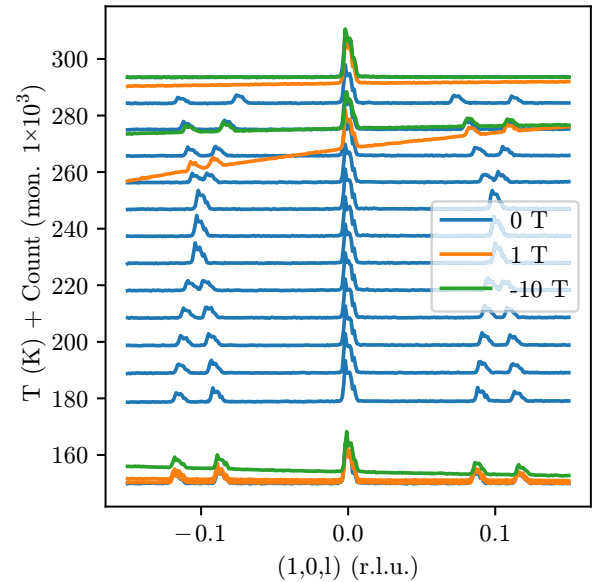


FIG. 7. Selected data from the D23 experiment with magnetic fields of 0 T (blue), 1 T (orange), and -10 T (green). On the y axis is a combination of the count and the temperature. Some measurements were made during heating and cooling. The two incommensurate peaks are visible near $l \sim \pm 0.1$, merging to one near 240 K. There is no evidence of an impact of the magnetic field.

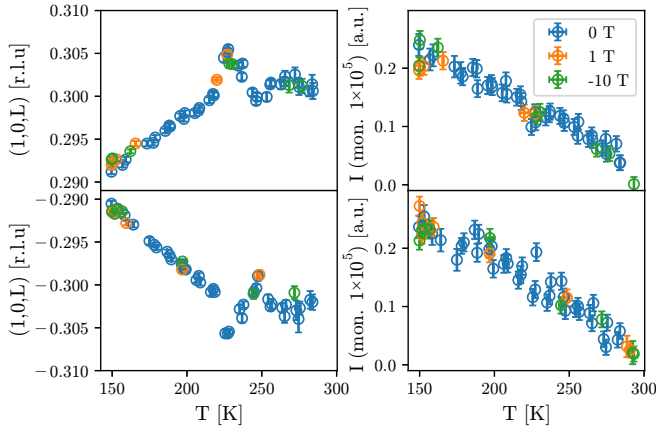


FIG. 8. (Left) Peak position of higher order peaks from D23 experiment with magnetic fields of 0 T (blue), 1 T (orange), and -10 T (green). (Right) Intensity of peaks as a function of temperature. Neither peak position nor intensity is affected by the magnetic field.

(PPMS) from Quantum Design, also at EPFL. Contacts were made on the surface of the sample using DuPont 4929N-100 silver paste from Delta Technologies. The Hall resistance was measured in magnetic fields along a between -1 and 1 T, at various temperatures between 10 and 400 K, using a current of 8 mA. We estimated the background resistance (which includes the normal Hall contribution) by averaging over the magnetic field and subtracting it, leaving only the anomalous Hall resistance.

Due to the hexagonal shape of the sample, converting to resistivity would be prone to large systematic errors and we therefore did not do this conversion. However, the numbers we find are close to previously published values [1]. The results are shown in Fig. 5.

APPENDIX B: DOMAINS FROM SNP FITS

Between reorienting the sample from the $(h, 0, l)$ plane to the $(h, k, 0)$ plane in our SNP experiment at D3, we cooled the sample to measure the incommensurate phase. As shown in the main text, this reset the magnetic domains and we therefore had to apply the magnetic field again to align the domains.

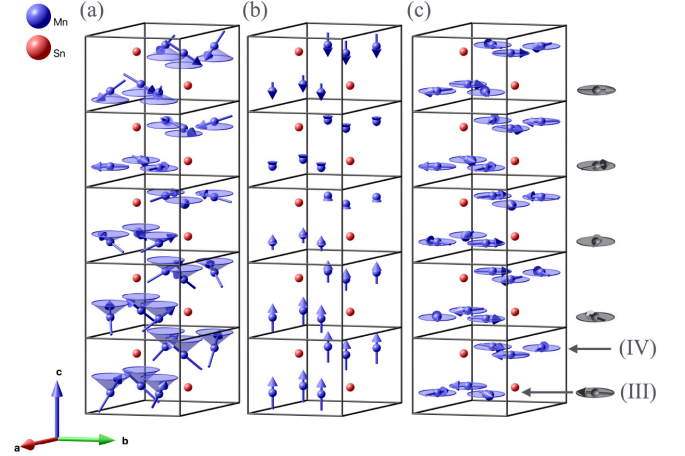


FIG. 9. (a) Full incommensurate magnetic structure as a superposition of a spin density wave (b) and an in plane helical structure (c) adapted from Ref. [22]. Due to the in plane rotation of the spins in the helical, and that structures (III) and (IV) are a 30° rotation of each other, both spin configurations show up in the incommensurate structure, as indicated in (c). Spins in gray are the direction of the expected residual ferromagnetic moment for every second layer given only the in plane component (c).

The fitted domain populations are reported in Table III and for the $(h, k, 0)$ plane is shown in Fig. 6(a). Here, we see the domains align along the (real space) $[110]$ direction, which is equivalent to b . This is compatible with the magnetic field being applied along $[110]$ in this measurement.

Figures 6(b) and 6(d) show the best fit results for type IV in the $(h, 0, k)$ and $(h, 0, l)$ planes, respectively. In type IV we consistently find four domains populated instead of three.

APPENDIX C: RAW DATA FROM D23

In Fig. 7 we show the raw data from the D23 experiment, showing intensity as a function of $(1, 0, l)$ and temperature.

In Fig. 8 we show the peak position and intensity of the higher order peaks.

APPENDIX D: INCOMMENSURATE STRUCTURE

In Fig. 9 we show the full incommensurate magnetic structure.

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