First observation of the inverse Dzyaloshinsky-Moriya effect in metals; magnetization and neutron scattering study on the metallic helimagnet MnP

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In this study, we report a possible inverse effect of the Dzyaloshinsky-Moriya (DM) interaction in the classical metallic helimagnet MnP. Our neutron-scattering and magnetization measurements showed that the previously reported magnetic structures of MnP need to be modified as follows; a canted antiferromagnetic structure with weak ferromagnetic magnetization along the b-axis is realized in the temperature range of 47 K < T < 282 K, whereas at the low temperatures T < 47 K an alternatively tilted helimagnetic structure is obtained. Surprisingly, a distinct enhancement of the weak ferromagnetic magnetization was observed in the canted antiferromagnetic phase after cooling the sample down to the tilted helimagnetic phase once, compared to that for the initial cooling. We suggest that this peculiar temperature hysteresis is due to the inverse effect of the DM interaction; the DM interaction induces the lattice distortion in the tilted helimagnetic phase by its inverse effect, and this distortion remains even when the sample is warmed up to the canted antiferromagnetic phase, resulting in the larger b-component.

1. Introduction

Novel phenomena associated with the spin chirality has attracted many solid-state-physics researchers. The spin chirality is a geometric quantity with two distinct types being well known; a vector chirality $\chi_{ij}$ is defined with two spins as $\chi_{ij} = S_i \times S_j$, whereas a scalar chirality $\chi_{ijk}$ as $\chi_{ijk} = S_i \cdot (S_j \times S_k)$. In early days, they were introduced to describe exotic order parameters in frustrated spin systems, such as a triangular antiferromagnet.¹,² In recent years, the spin chirality brought about several novel phenomena through its coupling to other degrees of freedom.³⁻¹⁵ Multiferroic phenomena in helimagnets is an outstanding example, originating from a coupling between the spin chirality and the electric polarization.³⁻¹⁰

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Fig. 1. (a) Schematically illustrated crystal structure of MnP. The space group is Pbnm. The thick lines represent the bonds of the nn Mn-sites. (b) Projective figure of the crystal structure of MnP from the c-direction. Possible DM-vector at the center of the nn Mn-sites, directing alternately, are represented by the cross- and dot-marks.

For the coupling between the spin chirality and the lattice, the Dzyaloshinsky-Moriya (DM) interaction is essential. The DM interaction is an antisymmetric interaction with the form of $D_{ij} \cdot (S_i \times S_j)$. As the DM interaction can be rewritten by using the vector chirality $\chi_{ij}$ as $D_{ij} \cdot \chi_{ij}$, it may induce $\chi_{ij}$ and stabilize chiral ordered states such as a helimagnetic state and a canted antiferromagnetic state. The DM vector $D_{ij}$ becomes finite only when the inversion symmetry at the center of the magnetic sites of $i$ and $j$ is absent. It, therefore, naturally couples the vector chirality with the lattice.

In some studies of multiferroic materials, an inverse effect of the DM interaction was observed, where the spin chirality distorts the lattice to break the inversion symmetry and consequently induces the ferroelectric polarization. A simultaneous ferroelectric polarization flop driven by magnetic field via a rotation of the vector chirality in MnWO$_4$ is a typical example of the inverse effect of the DM interaction.\textsuperscript{3–9} Such an inverse effect of the DM interaction has never been observed in metallic magnets.

Manganese phosphide MnP has been investigated by a lot of researchers from 1960’s because it exhibits interesting magnetic properties such as the in-field multistep phase transition,\textsuperscript{16–21} the Lifshits critical behavior\textsuperscript{22–27} and the magnetocaloric effect.\textsuperscript{28} The crystal structure is orthorhombic with the space group $Pbnm$. The easy axis of the magnetization is the c-axis, whereas the b- and a-axes are the intermediate- and hard-magnetization directions, respectively. In zero external field, totally three phase transitions have been reported to date. Reported phase transitions and corresponding magnetic structures may be summarized as fol-
First, the para-ferromagnetic phase transition takes place at $T_C = 292$ K, below which the Mn-spins are aligned parallel to the c-axis. Immediately below $T_C$, Becerra recently reported an additional transition at $T^* = 282$ K, suggesting that spins are slightly reoriented toward the b-axis below $T^*$. At the lower temperature $T_N = 47$ K, a further transition into a double spiral-type helical structure was reported. In this helimagnetic state, the spins rotate in the bc-plane (helical plane) with the propagation vector is $Q = (\delta, 0, 0)$ normal to the helical plane. The ordered moment is about $1.3 \mu_B$/Mn-atom. In summary, MnP has four phases in zero field: the low-temperature helimagnetic phase in $T < T_N$, the first intermediate-temperature phase in $T_N < T < T^*$, the second intermediate-temperature phase in $T^* < T < T_C$, and the high-temperature paramagnetic phase in $T > T_C$.

As MnP lacks the inversion symmetry at the center of the nearest-neighbor (nn) Mn-bonds, the DM interaction may remain finite between them. Nevertheless, effect of the DM interaction has never been explored to date. In this work, we revisit the magnetic structures of MnP by performing detailed magnetization and neutron-scattering measurements, aiming at finding intriguing phenomena caused by the DM interaction in metallic helimagnets. As a result, we found the previously reported magnetic structures have to be modified as follows. In the first intermediate phase ($T_N < T < T^*$) a canted antiferromagnetic order of the a-component of spins was observed with a further weak ferromagnetic moment induced along the b-axis. In the low-temperature helimagnetic phase ($T < T_N$), the helical plane is tilted to the a-direction from the bc-plane alternately. We discuss that both the structures are consequence of the finite DM interaction. Moreover, we discovered peculiar temperature hysteresis for the weak ferromagnetic moment in the canted antiferromagnetic phase, accompanied by an irreversible lattice distortion. We successfully explain this temperature hysteresis as an inverse effect of the DM interaction, which is the first confirmation of the inverse effect in metallic systems.

2. Experimental

Single crystalline samples of MnP were grown by the temperature gradient furnace technique. The magnetization was measured by using a SQUID magnetometer MPMS (Quantum Design) at Research Center for Low Temperature and Materials Sciences, Kyoto University. The sizes of the crystals used for the magnetization measurements are $2.5 \times 0.9 \times 0.7$ mm$^3$, $0.7 \times 2.5 \times 1.0$ mm$^3$ and $0.7 \times 0.6 \times 2.5$ mm$^3$ along the a-, b- and c-axes, respectively. The single crystal neutron scattering experiments in the $hk0$ scattering plane were performed using the triple-axis spectrometers ISSP-PONTA and ISSP-HER installed at JRR-3 in Japan Atomic Energy Agency (JAEA). The neutron powder diffraction experiments were performed using...
the multidetector diffractometer IMR-HERMES installed at JRR-3.\textsuperscript{30)} We use the sample with the size of $6.1 \times 3.6 \times 9.6$ mm$^3$ for the single crystal experiments. The powder sample with the weight of 3.6 g, obtained by grinding a single crystalline sample, was used for the powder diffraction experiments.

3. Experimental results

3.1 Magnetization measurements

Temperature ($T$) dependences of the magnetization along the $b$-axis are shown in Fig. 2(a). The measurements were performed in different four $T$-processes after applying a field of 3 Oe at the paramagnetic temperature 350 K: (A) the cool-down process from 350 K; (B) the warm-up process after cooling the sample down to 55 K ($> T_N$); (C) and (D) the warm-up processes after cooling the sample down to 5 K and 35 K ($< T_N$), respectively. Sharp increase of the magnetization at $T^*$ was observed in all processes, however, the size of the magnetization in the first intermediate phase ($T_N < T < T^*$) remarkably depends on the $T$-process. The magnetizations in the processes (A) and (B) are almost same as well as those in the processes (C) and (D) are. Surprisingly, the magnitudes of the magnetization in the latter processes, in which the sample has been once cooled below $T_N$, are about three times larger than those in the former processes, in which the sample has not been cooled below $T_N$. These results clearly indicate a quite peculiar temperature hysteresis, namely, the magnetization along the $b$-axis in the first intermediate-temperature phase is strongly enhanced when the sample has undergone the low-temperature helimagnetic state once. On the other hand, the magnetizations in all processes collapse in the low-temperature helimagnetic phase ($T < T_N$), the second intermediate-temperature phase ($T^* < T < T_C$), and the high-temperature paramagnetic phase ($T > T_C$).

Figure 2(b) shows field ($H$) dependences of the magnetization along the $b$-axis at $T = 100$ K. For the measurements, the sample was set to 100 K via the three different processes as follows: (A’) the sample was cooled from 350 K directly under zero field; (A”) the sample was cooled from 350 K directly at 10 kOe; (C’) the sample was warmed from 5 K after cooled down to 5 K once under zero field. The sample has undergone the helimagnetic state once in the process (C’), corresponding the $T$-process (C). In the same sense, the processes (A’) and (A”) corresponds to the process (A). The measurements were performed with changing the field in the sequence of 0 Oe $\rightarrow$ 30 Oe $\rightarrow$ $-30$ Oe $\rightarrow$ 30 Oe. Ferromagnetic hysteresis loops were observed in all the processes. It indicates that the first intermediate-temperature phase is a ferromagnetic phase with a very small spontaneous magnetization along the $b$-axis. In
this phase the spontaneous magnetization $M_s^\parallel b$ and the coercive field $H_c^\parallel b$ in the process (C') are larger than those in the process (A') and (A''). In particular, $M_s^\parallel b$ is enhanced five times. $M_s^\parallel b$ in the processes (A') and (C') are about $2 \times 10^{-4} \mu_B$/Mn-atom and $1 \times 10^{-3} \mu_B$/Mn-atom, respectively. This process-dependent behavior of $M_s^\parallel b$ corresponds to that observed in the $T$-dependence of the magnetization shown in Fig. 2(a); the spontaneous magnetization and the coercive field are enhanced when the sample has undergone the low-temperature helimagnetic phase. It should be noted that the magnetizations in the processes (A') and (A'') excellently collapse on one curve. It clearly indicates that the magnetic field of 10 kOe, being much higher than the coercive field of about 5 Oe, can not affect the magnetization curve in the low field. Only the $T$-process affects the magnetization curve.

These magnetization measurement results indicate a presence of two different magnetic states in the first intermediate-temperature phase for $T_N < T < T^*$: one is the large magnetization (LM) state and the other is the small magnetization (SM) state. The LM state is realized only by cooling the sample once to the low-temperature helimagnetic phase. The SM state is restabilized after the sample is warmed up to the paramagnetic temperature $T > T_C$. Interestingly, the LM state is not realized by applying strong magnetic field. Hence, the LM state does not originate from alignments of the ferromagnetic domains or the ferromagnetic clusters.

In order to determine which is the thermodynamically equilibrium state, we measured time evolution of the magnetizations in the LM and the SM states. Fig. 3(a) shows the time evolution of the magnetizations at $H = 30$ Oe after approaching the measurement temperature, $T = 100$ K, in the processes (A') and (C'). The process (A') and (C') correspond to the SM and LM states, respectively. Both magnetizations exhibit no time dependence up to 6 hours. We also performed the same measurement at higher temperature $T = 250$ K, where a thermal relaxation of the magnetization should be much faster, however, no time dependences were found up to 16 hours as shown in Fig. 3(b). From these results, it is seen that the energy barrier between the two states is so high that the relaxation cannot occur in a reasonable time scale. Therefore, it is difficult to conclude which is the thermodynamically equilibrium state.

Figures 4(a) and (b) show $T$-dependence of the magnetizations along the c- and a-axes, respectively. The data were obtained in the processes (B) and (C) mentioned earlier. Process-dependent behavior was also observed below $T_C$ along the c- and a-axes. These magnetizations are suppressed once the sample is cooled down to the helimagnetic phase, in striking contrast to that along the b-axis. It should be emphasized that the process-dependence was observed even for the a-axis magnetization. This strongly suggests an existence of the a-component of
Fig. 2. (a) Temperature ($T$) dependences of the magnetization along the b-axis of MnP in the various $T$-processes (A)-(D). The details of the $T$-processes are described in the text. (b) Field ($H$) dependences of the magnetization along the b-axis measured at $T = 100$ K after approaching the measurement temperature in various processes (A’), (A”) and (C’). The details of the processes are described in the text.

Fig. 3. Time dependences of the magnetizations along the b-axis in the small magnetization (SM) and large magnetization (LM) states, measured in a field of $H = 30$ Oe after approaching the measurement temperature in the processes (A’), and (C’), respectively. The measurement temperatures are (a) $T = 100$ K and (b) $T = 250$ K.

the ordered moment below $T_C$, which has not been detected in any earlier studies. A sharp cusp-like anomaly at $T_C$ seen in Fig. 4(a) suggesting that an antiferromagnetic ordering of the a-component is established at this temperature.

3.2 Neutron scattering experiments

In order to see the origin of the peculiar temperature hysteresis observed in the magnetization measurements, we measured $T$-dependence of nuclear Bragg reflections using the single crystalline and powder samples. Two $T$-processes were used in this measurement; the
Fig. 4. $T$-dependences of the magnetizations along (a) the c-axis and (b) a-axis, respectively. In both figures, the data measured in two processes (B) and (C), described in the text, are shown.

Fig. 5. $T$-dependences of the normalized integrated intensities of the (1,1,0)-reflection obtained by using (a) the single crystal sample and (b) powder sample, respectively. In both figures, the data obtained in the cool-down and warm-up processes, described in the text, are shown. The error bars are less than point size in (a).

The warm-up process from 9 K and cool-down process from 350 K, corresponding to the $T$-process (A) and (C), respectively. Fig. 5(a) shows the $T$-dependence of the integrated intensity of the (1,1,0) reflection from the single crystalline sample. In the figure, each intensity is normalized by the value at $T = 350$ K in the cool-down process. Thick arrows in the figure represent the changing sequence of the measurement temperature. The intensity in the first intermediate-temperature phase ($T_N < T < T^*$) measured in the warm-up process is apparently larger than that in the cool-down process. For the (1,1,0)-reflection, there is a magnetic scattering contribution in the first and second intermediate-temperature phases ($T_N < T < T_C$) due to the ferromagnetic ordering, which is the reason why the intensities in these phases are larger than those in the helimagnetic and paramagnetic phases ($T < T_N$ and $T > T_C$). One might
think that the hysteresis of the (1, 1, 0) reflection intensity originates from the hysteresis of the ferromagnetic magnetization, which was indeed detected in the magnetization study. However, the difference of the magnetizations for the cool-down and warm-up processes is a few $10^{-3}$ $\mu_B$, being too small to account for the 5% change of the (1,1,0) reflection intensity detected in the neutron scattering measurements. $T$-dependence of the (1,1,0) reflection intensity from the powder sample is shown in Fig. 5(b). No difference between the intensities in the two $T$-processes is found in the powder experiment. The discrepancy between the single-crystal and powder experiments strongly suggests that the $T$-process dependence for the Bragg intensity in the single crystal experiment is due to the secondary extinction effect. Assuming this extinction origin, the larger (1,1,0) intensity of the warm-up process indicates the lattice is more distorted compared to the one for the initial cooling. Since the lattice distortion is only found for the sample that has experienced the low-temperature helimagnetic phase, it is natural to think that the distortion is introduced in the low-temperature phase. Further discussion will be given later.

We also performed single-crystal neutron scattering experiments in the low-temperature helimagnetic phase, and found a new magnetic Bragg reflection at $(\delta,1,0)$-position, as shown in Fig. 6(a). The magnetic propagation vector of the helimagnetic state of MnP reported previously is $(\delta,0,0)$ and the nuclear (0,1,0)-reflection is forbidden, thus, the magnetic $(\delta,1,0)$-reflection is fundamentally forbidden. In reality, the previously reported magnetic structure is a double spiral one with different phases for the Mn-sites in the chemical unit cell. This allows a very weak $(\delta,1,0)$-reflection. Nonetheless, the observed intensity of the $(\delta,1,0)$-reflection is 70 times larger than the intensity of the $(\delta,1,0)$-reflection using the double spiral structure model. This large discrepancy clearly requires reconsideration of the magnetic structure in the helimagnetic state. We also checked the reflection intensity at $(1+\delta,0,0) = (\delta,1,0) + (1,1,0)$, however, could not detect any magnetic signal, as shown in Fig. 6(b). Assuming the single modulation vector $(\delta,1,0)$ for the additional modulation, we may conclude that this modulation has only the $a$-axis component. This additional modulation is illustrated schematically in Fig. 6(c). By superimposing this modulation to the fundamental proper helimagnetic structure with $Q = (\delta,0,0)$, the magnetic structure shown in Fig. 6 (d) is obtained. In this structure, the helical planes are tilted to the $a$-direction from the $bc$-plane with the angle of $\theta$ and $-\theta$, alternately along the $b$-axis. The size of the $a$-component $m^a$ and the tilt-angle $\theta$ are estimated about 0.046 $\mu_B$/Mn-atom and 2.0 degree from the integrated intensity of the $(\delta,1,0)$-reflection, respectively.
Fig. 6. (a) Neutron scattering profiles of the newly observed magnetic reflection at $(\delta,1,0)$. The data at $T = 9.4$ K ($< T_N$) and at $T = 100$ K ($> T_N$) are shown. (b) Neutron scattering profile at $(1+\delta,0,0)$ at $T = 9.7$ K. (c) Schematic illustration of the $(\delta,1,0)$-modulation of the a-component of the Mn-spins. For visibility, the drawn a-components are enlarged from the scale of those shown in (d). (d) Schematic illustration of the tilted helimagnetic structure, obtained by superposing the $(\delta,1,0)$-modulation shown in (c) on the simple proper helimagnetic structure. The cross- and dot-marks represent the DM vectors at the centers of the nn Mn-sites directing to the c- and anti-c-directions alternately, respectively. (e) Schematic view of the possible explanation of the alternate tilt of the helical plane from the bc-plane to the a-direction by the DM interaction. One nn Mn-chain is picked out in this figure. The DM vectors at the center of the Mn-pairs are represented in the same manner as in (d). (f) Schematic view of the possible explanation of the weak ferromagnetic b-component induced by the DM interaction in the first intermediate-temperature phase.
4. Discussion

4.1 Origin of the tilted helimagnetic structure and the weak ferromagnetism

First, we discuss the origin of the newly proposed magnetic structure below $T_N$, the alternately tilted helimagnetic structure described in Sec. 3.2, from the viewpoint of the crystal symmetry of MnP. As described in Sec. 1, the inversion symmetry is absent at the center of the nn Mn-bonds, and thus finite DM interaction is allowed for them. The DM vector $D$ should be perpendicular to the ab-plane because the c-plane, including the nn Mn-sites, is a mirror plane (see Fig. 1(a)). As shown in Fig. 1(b), Mn-atoms form a zigzag chain along the b-direction by connecting the nn Mn-sites (nn Mn-chain). The DM vectors directing parallel and anti-parallel to the c-axis are aligned alternately along this chain because the crystal structure is invariant under the glide operation along $b$.

With a consideration of such alternate DM interactions between the nn Mn-pairs, the alternate tilt of the helical plane can be naturally elucidated. The DM interaction with $D \parallel c$ only act on the projected Mn-spins to the ab-plane. In the fundamental helimagnetic structure proposed earlier, the projected Mn-spins are parallel to the b-axis and their directions in a nn Mn-chain are same (see open arrows in Fig. 6(e)). The DM interaction with the alternate nn DM vector $D_i = (0, 0, (-1)^i D_c)$ tilt the Mn-spins in the nn Mn-chain toward the a-direction with the alternate angles $\theta$ and $-\theta$ (see filled arrows in Fig. 6(e)). The magnitude of the tilt angle $\theta$ is determined by the ratio of the strength of the c-component of the DM interaction $D_c$ and the symmetric exchange interactions $J$. Consequently, the alternately tilted helimagnetic structure, as shown in Fig. 6(d), is realized. From the experimentally obtained tilt angle of $\theta = 2.0$ degrees, the ratio of the strength of the DM interaction and the symmetric exchange interaction $D_c/J$ is estimated at about 0.03.

Next, we discuss the weak ferromagnetic behavior in the first intermediate temperature phase. The fact that the DM interaction affects the magnetic structure of the low temperature phase strongly suggests that the magnetic properties of other phases can be also affected by the DM interaction. Here the antiferromagnetic behavior of the magnetization along the a-axis below $T_C$ should be recalled, making us assume the antiferromagnetically aligned a-components of Mn-spins below $T_C$. The alternate DM interactions in MnP described above tilt such Mn-spins to the b-direction, and consequently, small ferromagnetic magnetization along the b-axis is induced, as shown in Fig. 6(f). Hence, we propose that the weak ferromagnetism is a manifestation of the canted antiferromagnetic state in the first intermediate-temperature phase. The canted angle should be also due to $D_c/J$, which is probably the same order to that in the low-temperature phase. Assuming the canted angle is almost identical to the tilt
angle of 2.0 degrees in the low-temperature phase, the \( a \)-component of the ordered moment in the first intermediate-temperature phase is estimated at about 0.03 \( \mu_B/Mn \)-atom from the ferromagnetic magnetization along the \( b \)-axis. The smallness may be the reason why the antiferromagnetically aligned \( a \)-component of Mn-spins have been undetected below \( T_C \) to date.

4.2 Origin of the peculiar temperature hysteresis

Most striking feature of MnP found in this study is the peculiar temperature hysteresis: (i) the enhancement of the spontaneous magnetization along the \( b \)-axis and (ii) the lattice distortion are observed in the intermediate-temperature phase only after cooling the sample down to the low-temperature helimagnetic phase once. Here, we discuss this temperature hysteresis. As mentioned in sec. 4.1, the weak ferromagnetism in the first intermediate-temperature phase (\( T_N < T < T^* \)), is due to the canted antiferromagnetic state induced by the alternate DM interactions. In other words, this is a antiferro-chiral order where alternately aligned vector chiralities are stabilized. The weak spontaneous magnetization along the \( b \)-axis is proportional to the \( c \)-component of the staggered vector-chirality \( \chi^c_s \) from the viewpoint of this vector-chiral model, and \( \chi^c_s \) is canonical conjugate to the \( c \)-component of the alternate DM vector \( D^c_s \) as \( E_{DM} = D^c_s \chi^c_s \), where \( E_{DM} \) is a energy of the DM interaction. Thus the experimental fact (i) infers that the DM vector becomes enhanced after cooling the sample down to the low-temperature helimagnetic phase. On the other hand, the experimental fact (ii) suggests that this enhancement is associated with the lattice distortion. Understanding the microscopic atomic displacements for this structural distortion is of significant importance, but is beyond the scope of the present study.

Why does such a lattice distortion occur in the helimagnetic phase? Next, we turn our attention to the magnetic structure in the low-temperature helimagnetic phase. As discussed in sec. 4.1, the magnetic structure is helimagnetic with the helical planes being alternately tilted out from the \( bc \)-plane. The alternate tilt can be also regarded as a staggered order of the vector chirality along the \( c \)-axis. The staggered chirality \( \chi^c_s \) is written as \( \chi^c_s = S^2_{ab} \sin \theta \) where the tilt-angle \( \theta = 2.0 \) degree in both phases and \( S_{ab} \)'s in the helimagnetic and canted antiferromagnetic phases are about 1 \( \mu_B \) and 0.03 \( \mu_B \), respectively. Therefore, we may estimate that \( \chi^c_s \) in the helimagnetic phase is about \( 10^{-3} \) times larger than that in the canted antiferromagnetic phase. Owing to the huge magnitude of the induced chirality in the helimagnetic phase, the gain of the DM interaction energy exceeds the loss of the elastic energy, resulting in the lattice distortion. This mechanism is the inverse effect of the DM interaction, and has been observed
in a number of multiferroic materials.\textsuperscript{3–9)}

Now we describe a possible scenario for the peculiar hysteresis in MnP. When the sample is cooled down from the high-temperature paramagnetic phase, for instance $T = 350$ K, in the initial cool-down process, the phase transition occurs firstly at $T_C = 292$ K, where the ordered moment with the ferromagnetic c-component and the small antiferromagnetic a-component emerges. Successively, the Mn-spins are canted in the ab-plane by the DM interaction and the canted antiferromagnetic state with the very small ferromagnetic component $\sim 2 \times 10^{-4} \mu_B$ along the b-axis, the antiferro-chiral state in other words, is stabilized at $T^* = 282$ K. This is the SM state defined in sec. 3.1. As further decreasing temperature, the tilted helimagnetic state is realized below $T_N = 47$ K, where the the helical planes are slightly tilted alternately out from the $bc$-plane toward the a-direction. In this low-temperature helimagnetic phase, the emergent large staggered chirality along the c-axis $\chi_c$ distorts the lattice slightly, probably by changing the atomic positions of P, to enhance the DM interaction as its inverse effect. This lattice distortion may not be eliminated easily and remains even in the higher temperature phases. In the subsequent warm-up process, the sample goes to the canted antiferromagnetic state again at the little higher temperature than $T_N = 47$ K with a conventional temperature-hysteresis accompanying the first-order phase transition. There, the enhanced DM vectors are maintained, and hence, the relatively large ferromagnetic magnetization along the b-axis $\sim 1 \times 10^{-3} \mu_B$ may be realized. This is the origin of the LM state found in sec. 3.1. Correspondingly, magnetizations along other directions are reduced. The lattice distortion is maintained even above $T^*$ and is eliminated above $T_C$, in the paramagnetic phase, at last.

The above scenario can consistently explain the peculiar features of the temperature hysteresis in MnP. In the first intermediate-temperature phase, the SM state in the initial cool-down process cannot be changed to the LM state by magnetic field, even when applying field up to 10 kOe. It is naturally understood by taking account of the lattice-distortion origin of the LM state. Only the inverse effect of the DM interaction with the large staggered chirality can induce the LM state.

5. Conclusion

In conclusion, we have investigated the magnetic properties of MnP by means of the magnetization and neutron-scattering measurements. The previously reported magnetic structures of MnP have been updated both for the low-temperature and first-intermediate temperature phases; the updated structures are the alternately tilted helimagnetic and the canted antiferromagnetic structures, respectively. Surprisingly, we found the peculiar temperature
hysteresis for b-axis magnetization, as well as enhanced lattice distortion in the intermediate-temperature canted antiferromagnetic phase. The strong coupling between the lattice distortion and magnetization hysteresis, together with the huge vector chirality in the low-temperature helimagnetic phase, indicates that the distortion is induced by the inverse effect of the DM interaction. As far as we know, this is the first observation of the inverse effect of the DM interaction in metallic systems.

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References

1) J. Villain: Journal de Physique 38 (1977) 385.
2) S. Miyashita and H. Shiba: J. Phys. Soc. Jpn. 53 (1984) 1145.
3) T. Kimura, T. Goto, H. Shintani, K. Ishizaka, T. Arima, and Y. Tokura: Nature 426 (2003) 55.
4) Y. Yamasaki, S. Miyasaka, Y. Kaneko, J. He, T. Arima, and Y. Tokura: Phys. Rev. Lett. 96 (2006) 207204.
5) H. Katsura, N. Nagaosa, and A. Balatsky: Phys. Rev. Lett. 95 (2005) 57205.
6) K. Taniguchi, N. Abe, T. Takenobu, Y. Iwasa, and T. Arima: Phys. Rev. Lett. 97 (2006) 97203.
7) Y. Yamasaki, H. Sagayama, T. Goto, M. Matsuura, K. Hirota, T. Arima, and Y. Tokura: Physical Review Letters 98 (2007) 147204.
8) K. Taniguchi, N. Abe, H. Sagayama, S. Ohtani, T. Takenobu, Y. Iwasa, and T. Arima: Phys. Rev. B 77 (2008) 64408.
9) Y. Tokura and S. Seki: Adv. Mater. 22 (2010) 1554.
10) T. Kimura, J. Lashley, and A. Ramirez: Phys. Rev. B 73 (2006) 220401.
11) J. Ye, Y. Kim, A. Millis, B. Shraiman, P. Majumdar, and Z. Tesanovic: Phys. Rev. Lett. 83 (1999) 3737.
12) Y. Taguchi, Y. Oohara, H. Yoshizawa, N. Nagaosa, and Y. Tokura: Science 291 (2001) 2573.
13) G. Tatara and H. Kawamura: J. Phys. Soc. Jpn. 71 (2002) 2613.
14) T. Taniguchi, K. Yamanaka, H. Sumioka, T. Yamazaki, Y. Tabata, and S. Kawarazaki: Phys. Rev. Lett. 93 (2004) 246605.
15) Y. Machida, S. Nakatsuji, S. Onoda, T. Tayama, and T. Sakakibara: Nature 463 (2009) 210.
16) E. Huber, E and H. Ridgley, D: Phys. Rev. 135 (1964) 1033.
17) J. Forsyth, S. Pickart, and P. Brown: Proc. Phys. Soc. 88 (1966) 333.
18) G. Felcher: J. Appl. Phys. 37 (1966) 1056.
19) T. Komatsubara, A. Ishizaki, S. Kusaka, and E. Hirahara: Solid State Commun. 14 (1974) 741.
20) H. Obara, Y. Endoh, Y. Ishikawa, and T. Komatsubara: J. Phys. Soc. Jpn. 49 (1980) 928.
21) M. Moon, R: J. Appl. Phys. 53 (1982) 1956.
22) C. C. Becerra, Y. Shapira, N. F. Oliveira Jr, and T. Chang: Phys. Rev. Lett. 44 (1980) 1692.
23) Y. Shapira, C. C. Becerra, N. Oliveira Jr, and T. Chang: Phys. Rev. B 24 (1981) 2780.
24) H. Yoshizawa, S. Shapiro, and T. Komatsubara: J. Phys. Soc. Jpn. 54 (1985) 3084.
25) V. Bindilatti, C. C. Becerra, and N. F. Oliveira Jr: Phys. Rev. B 40 (1989) 9412.
26) C. C. Becerra, V. Bindilatti, and N. F. Oliveira Jr: Phys. Rev. B 62 (2000) 8965.
27) A. Zieba, M. Slota, and M. Kucharczyk: Phys. Rev. B 61 (2000) 3435.
28) M. Reis, R. Rubinger, N. Sobolev, M. Valente, K. Yamada, K. Sato, Y. Todate, A. Bouravleuv, P. von Ranke, and S. Gama: Phys. Rev. B 77 (2008) 104439.
29) C. C. Becerra, Journal of Physics: Condensed Matter 12 (2000) 5889.
30) K. Ohoyama, T. Kanouchi, K. Nemoto, M. Ohashi, T. Kajitani, and Y. Yamaguchi: Jpn. J. Appl. Phys. 37 (1998) 3319.