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Magnetic topological materials have attracted significant attention due to their potential realization of a variety of novel quantum phenomena. EuIn_2As_2 has recently been theoretically recognized as a long-awaited intrinsic antiferromagnetic bulk axion insulator. However, experimental studies of the transport properties arising from the topological states in this material are scarce. In this paper, we perform detailed magnetoresistance (MR) and Hall measurements to study the magnetotransport properties of this material. We find that the transport is strongly influenced by the spin configuration of the Eu moments from the concomitant change in the field dependence of the MR and that of the magnetization below the Néel temperature. Most importantly, an anomalous Hall effect (AHE) and a large topological Hall effect (THE) are observed. We suggest that the AHE is originated from a nonvanishing net Berry curvature due to the helical spin structure and that the THE is attributed to the formation of a noncoplanar spin texture with a finite scalar spin chirality induced by the external magnetic field in EuIn_2As_2 . Our studies provide a platform to understand the influence of the interplay between the topology of electronic bands and the field-induced magnetic structure on magnetoelectric transport properties. In addition, our observations give a hint to realize axion insulator states and higher-order topological insulator states through manipulating the magnetic state of EuIn_2As_2 .

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I. INTRODUCTION

The success of topological band theory places studies of topological quantum states among the frontier topics in condensed matter physics in the last decades [1–4]. After a good understanding of nonmagnetic topological states, breaking the time-reversal symmetry by introducing magnetism in topological materials provides a more fertile playground to give rise to nontrivial topological phases, such as a quantum anomalous Hall effect and axion insulator states [5–8]. In magnetic topological materials, the interplay between magnetism and nontrivial band topology can generate new exotic quantum states and will give rise to novel transport phenomena. For instance, magnetic Weyl semimetals $\text{Co}_3\text{Sn}_2\text{S}_2$ [9], Mn_3Sn [10], and GdPtBi [11] have been reported to show a large intrinsic anomalous Hall effect (AHE) originated from the net

Berry curvature around the Weyl nodes. On the other hand, a real-space Berry phase arising from a skyrmion phase or a noncollinear spin texture with nonzero scalar spin chirality [$\chi_s = \mathbf{S}_i \cdot (\mathbf{S}_j \times \mathbf{S}_k) \neq 0$, where $\mathbf{S}_i$, $\mathbf{S}_j$, and $\mathbf{S}_k$ are the three nearest spins] can act as a fictitious magnetic field on the conduction electrons, giving rise to the topological Hall effect (THE) [12–15]. For example, an intrinsic THE arising from a noncollinear spin structure under a magnetic field has been established in the bulk antiferromagnetic (AFM) topological insulator MnBi_2Te_4 [16]. However, in contrast to the topology in momentum space, electromagnetic responses caused by the noncollinear spin texture in real space need further study.

The rare-earth Zintl compound EuIn_2As_2 is a new, promising candidate of the AFM topological materials. EuIn_2As_2 crystallizes in the hexagonal $P6_3/mmc$ space group with the alternating stacking of Eu and In_2As_2 layers [17] as shown in Figs. 1(a) and 1(b), realizing a topological transport of conducting electrons in In_2As_2 layers affected by the magnetic moments of Eu^{2+} ions. In fact, a bulk axion insulator phase has been predicted when the Eu moments exhibit the A-type AFM order, in which the ordered Eu moments are ferromagnetically aligned in the ab plane but antiferromagnetically aligned in adjacent layers along the c axis [17]. Furthermore, different topological states are suggested to be realized depending on the direction of the magnetic moments. A topological crystalline insulator phase with gapless surface

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FIG. 1. The crystal structure of EuIn_2As_2 , viewed along the a axis (a) and the c axis (b). (c) The temperature dependence of the magnetic susceptibility [$\chi(T)$, left axis] and that of the inverse magnetic susceptibility [$1/\chi(T)$, right axis] under a magnetic field $B = 0.1$ T applied parallel to the c axis (black) and the ab plane (red). The blue lines show a Curie-Weiss fit for the data. The inset shows the field dependence of the magnetization $M(B)$ at 5 K and at $B \parallel c$ (black) and $B \parallel ab$ (red). (d) The temperature dependence of the resistivity with the current applied along the ab plane at 0 and 5 T ($B \parallel c$). (e) The field dependence of the magnetoresistance (MR) at various temperatures with $B \parallel c$ (left panel) and $B \parallel ab$ (right panel). (f) The field dependence of the MR at different tilted angles from the c axis to the ab plane at 5 K.

states on the (100), (010), and (001) surfaces is expected in EuIn_2As_2 for in-plane-oriented Eu magnetic moments. On the other hand, a higher-order topological insulator phase with chiral hinge states is predicted with out-of-plane magnetic order [17]. These different topological states expected in the different orientations of the Eu moments provide a promising way to control the topological state by the external magnetic field. Angle-resolved photoemission spectroscopy (ARPES) results show an inversion of the bulk band upon entering into the AFM state, suggesting that there is a topological phase transition associated with the magnetic transition [18,19]. Although recent neutron diffraction experiments show that EuIn_2As_2 has a low-symmetry helical AFM order, not an A-type AFM order, it has also been predicted that the direction of a modest applied magnetic field of $B \approx 1\text{--}2$ T can tune between gapless and gapped surface states [20]. Thus the fruitful topological nature and easy magnetic field tunability of this system will be a promising platform to realize a “clean” topological quantum effect and many novel transport phenomena.

In this paper, we perform a systematic study of single-crystal samples of EuIn_2As_2 , focusing on the interplay between the topological transport phenomena and the magnetic state. The nonmonotonic field dependence of the magnetoresistance (MR) reveals that the transport phenomena are strongly influenced by the spin configuration in the EuIn_2As_2 system. Most importantly, we observe an AHE and

a large THE in the AFM state. From the dependence of the AHE on the longitudinal conductivity and the temperature, we find that the AHE is dominated by the intrinsic mechanism. In addition, from the field and the angle dependence of the THE, we suggest that the THE is attributed to a finite χ_s caused by the noncoplanar spin texture formed under the out-of-plane magnetic field.

II. EXPERIMENTAL DETAILS

EuIn_2As_2 single crystals were grown by the self-flux method. Eu, In, and As with a mole ratio 1:12:3 were weighed and ground into an alumina crucible in an Ar-filled glovebox, which was sealed in a quartz ampoule under high vacuum. The sealed quartz ampoule was heated to 1323 K and maintained for 12 h, and then it was cooled down to 873 K over 100 h. At this temperature, the quartz ampoule was quickly taken out from the furnace and decanted with a centrifuge to separate EuIn_2As_2 single crystals. As shown in Fig. S1 of the Supplemental Material [21], the crystal was grown as a hexagonal piece, with dimensions of $2 \times 2 \times 0.1 \text{ mm}^3$. The x-ray diffraction shows sharp peaks on the pattern of the (00/) plane, indicating the high-quality single crystallinity of the samples.

Magnetization and electrical transport measurements were carried out by using a Quantum Design Magnetic Property Measurement System (MPMS-XL5), a Physical Properties

FIG. 2. Anomalous Hall effect (AHE) and topological Hall effect (THE). (a) The magnetic field dependence of the Hall resistivity ρ_{yx} at 5 K. The red dash-dotted line is a fitting curve to estimate the Hall coefficient R_0 , which is used to extract the anomalous Hall part $\Delta\rho_{yx} = \rho_{yx} - R_0 B$ (blue line). The inset shows an enlarged view of ρ_{yx} for 1–2 T. (b) The magnetic field dependence of $\Delta\rho_{yx}$ at different temperatures, obtained after subtracting the normal Hall resistivity. Each solid line shows a fit of the anomalous Hall resistivity ρ_{yx}^A by $\rho_{yx}^A = R_A \mu_0 M$. (c) The magnetic field dependence of the topological Hall resistivity ρ_{yx}^T at various temperatures; the arrows indicate the position of the peak of ρ_{yx}^T (ρ_{yx}^{Tmax}). (d) The temperature dependence of ρ_{yx}^A (black and gray squares for different samples, respectively, left axis), ρ_{yx}^{Tmax} (orange circles, left axis), the anomalous Hall conductivity σ_{yx}^A (red spheres, first right axis), and the magnetization at 2 T above B_{sat} (blue dashed line, second right axis).

Measurement System (PPMS-9 T) for $5 \text{ K} < T < 400 \text{ K}$ and $B < 9 \text{ T}$, and a dilution refrigerator (DR) for $0.1 \text{ K} < T < 30 \text{ K}$ and $B < 14 \text{ T}$. Standard four-probe and five-probe methods were used for the longitudinal resistivity and the Hall measurements with a current in the ab plane, respectively. All the Hall resistivities were obtained by $\rho_{yx}(B) = [\rho_{yx}(+B) - \rho_{yx}(-B)]/2$ to remove the influence of misalignment of the contacts. The reproducibility of our results was confirmed by the measurements done for other samples from different batches as shown in Figs. S2 and S3 of the Supplemental Material [21].

III. RESULTS AND DISCUSSION

Figure 1(c) shows the temperature dependence of the magnetic susceptibility χ under a magnetic field B of 0.1 T applied along the c axis (χ_c) and the ab plane (χ_{ab}). As shown in Fig. 1(c), χ_{ab} is larger than χ_c in the whole temperature range we measured, showing that the easy axis is in the

ab plane. The AFM transition at Néel temperature $T_N = 17 \text{ K}$ is clearly seen by the peak in $\chi(T)$ for both $B \parallel c$ and $B \parallel ab$. The temperature dependence of χ^{-1} above T_N follows the Curie-Weiss law with a positive Weiss temperature of 16.9 and 18.5 K for χ_c and χ_{ab} , respectively, showing a dominant ferromagnetic (FM) interaction in EuIn₂As₂. This dominant FM interaction is suggested to be caused by the magnetic polarons in this material [22,23], which reflects the strong exchange interaction between the spins of conduction electrons and the localized Eu moments in EuIn₂As₂. The effective magnetic moment obtained by the Curie-Weiss fit ($8.0\mu_B$ and $8.7\mu_B$ for χ_c and χ_{ab} , respectively) agrees well with that expected for the high spin state of Eu^{2+} ($7.94\mu_B$). The field dependence of the magnetization M at 5 K [inset of Fig. 1(c)] shows a saturation at $B_{sat} \sim 1.7 \text{ T}$ for $B \parallel c$, which becomes smaller ($\sim 0.5 \text{ T}$) for $B \parallel ab$ at 5 K.

Figure 1(d) shows the temperature dependence of the longitudinal resistivity ρ_{xx} at 0 and 5 T applied along the c axis. As shown in Fig. 1(d), ρ_{xx} at 0 T starts to increase below

FIG. 3. (a) Anomalous Hall conductivity σ_{yx}^A in the low temperature range plotted against σ_{xx} for EuIn_2As_2 and other materials in a log-log graph. The “bad metal regime,” “intrinsic regime,” and “extrinsic regime” of σ_{xx} are denoted with different background colors. The reported data for other materials are obtained from Refs. [9–11,31–37]. (b)–(d) The spin configurations of Eu with out-of-plane magnetic field. The in-plane helical structure at 0 T (b) is modified to a noncoplanar structure for $0 < B < B_{\text{sat}}$ (c) and a polarized one for $B_{\text{sat}} < B$ (d).

~ 60 K as the temperature is lowered, which is followed by a sharp peak at T_N . This peak in ρ_{xx} shows a strong scattering effect on conduction electrons by magnetic fluctuations at 0 T, as it completely disappears at 5 T ($> B_{\text{sat}}$). The high onset temperature of the magnetic scattering, which is far above T_N , shows the presence of a strong magnetic fluctuation above T_N enhanced by the two-dimensional nature of the material. Figure 1(e) shows the field dependence of the longitudinal resistivity ρ_{xx} at different temperatures under the magnetic field applied along the c axis and the ab plane. In the paramagnetic state ($T > T_N$), a negative MR is observed up to the highest field, which reaches a maximum of 60% at T_N . Below T_N , a positive MR appears below B_{sat} , which is followed by a negative MR above B_{sat} . This crossover from the positive MR to the negative one becomes lower as the magnetic field is tilted to the ab plane in accordance with the decrease in B_{sat} as shown in Fig. 1(f), indicating that the positive-to-negative crossover behavior in MR is caused by the magnetic scattering effects enhanced by suppressing the AFM order. Therefore it confirms that the transport phenomena are strongly influenced by the spin configuration. Effects of magnetic polarons formed by the FM interaction and a crossover from weak antilocalization to weak localization above B_{sat} have been put forward for the increase in ρ_{xx} near T_N and the field dependence of MR below T_N [22,23].

Next, we estimate the AHE in the EuIn_2As_2 system. Figure 2(a) shows the field dependence of the Hall resistivity ρ_{yx} at 5 K (the data for different samples at different temperatures are shown in Fig. S3 of the Supplemental Material [21]). As shown in Fig. 2(a), ρ_{yx} shows a nonlinear field dependence near 1.5 T [see the inset of Fig. 2(a)], showing an anomalous contribution in ρ_{yx} . To determine the field dependence of the anomalous part, ρ_{yx} is decomposed into the normal part $\rho_{yx}^N = R_0 B$ and the anomalous part $\Delta\rho_{yx}$ as

$$\rho_{yx} = \rho_{yx}^N + \Delta\rho_{yx} = R_0 B + \Delta\rho_{yx},$$

where R_0 is the Hall coefficient. First, we estimate R_0 by a linear fitting of the field dependence of ρ_{yx} above B_{sat} (the red dash-dotted line) and subtract ρ_{yx}^N from ρ_{yx} to obtain the field dependence of $\Delta\rho_{yx}$ [the blue line in Fig. 2(a)]. For the AHE in this material, we estimate that the anomalous Hall resistivity ρ_{yx}^A linearly scales with M , which arises from both extrinsic and intrinsic contributions [16]. The temperature dependence of ρ_{yx}^A shows a peak at around T_N and decreases as the temperature is lowered [the black squares in Fig. 2(d)]. This decrease in ρ_{yx}^A at lower temperatures continues down to 0.2 K as shown by the data obtained in a different sample by using DR [the gray squares in Fig. 2(d)].

As shown in Fig. 2(b), whereas the relation of $\Delta\rho_{yx} \propto M$ holds above B_{sat} , $\Delta\rho_{yx}$ considerably deviates from ρ_{yx}^A below B_{sat} . This deviation demonstrates an additional component of $\Delta\rho_{yx}$, which we refer to as the topological part, ρ_{yx}^T . We estimate ρ_{yx}^T by subtracting $R_A \mu_0 M$ from $\Delta\rho_{yx}$, where R_A is the modified anomalous Hall coefficient, and plot the field dependence of ρ_{yx}^T in Fig. 2(c). The magnetic field dependence of ρ_{yx}^T at various temperatures below T_N [Fig. 2(c)] shows the negative peak at $\sim B_{\text{sat}}/2$. The magnitude of the peak of ρ_{yx}^T (ρ_{yx}^{Tmax}) is almost temperature independent around $1 \mu\Omega \text{ cm}$ and quickly disappears above T_N [orange circles in Fig. 2(b)].

We first discuss the origin of ρ_{yx}^A in this compound. As current knowledge, it has been well established that an AHE emerges from two mechanisms: an intrinsic one caused by the Berry curvature effect [24,25] and an extrinsic one caused by either skew or side-jump scattering effects [26,27]. The former is observed in a moderately dirty metal in which the anomalous Hall conductivity $\sigma_{yx}^A = \rho_{yx}^A / (\rho_{yx}^2 + \rho_{xx}^2)$ becomes independent of σ_{xx} , whereas the latter is observed in a clean one in which $\sigma_{yx}^A \propto \sigma_{xx}$ [28]. In addition, σ_{yx}^A of the intrinsic AHE is known to linearly scale to M [24,28].

We find that the AHE in EuIn_2As_2 fulfills these features of the intrinsic AHE. We plot the anomalous Hall conductivity σ_{yx}^A against the longitudinal conductivity σ_{xx} with other FM and AFM systems in Fig. 3(a). First, we find that the σ_{xx} is in the range around $6 \times 10^3 \Omega^{-1} \text{ cm}^{-1}$ and the σ_{yx}^A does not depend on σ_{xx} . Both features indicate that EuIn_2As_2 is located in the “intrinsic regime,” where the intrinsic mechanism is suggested to be dominant. In addition, as shown in Fig. 2(d), we find that the temperature dependence of σ_{yx}^A almost follows that of M (i.e., $\rho_{yx}^A \propto \rho_{xx}^2 M$), supporting the dominant intrinsic AHE in ρ_{yx}^A . In fact, in time-reversal-symmetry-broken systems, a band crossing near the Fermi energy E_F with a

FIG. 4. (a) The field dependence of the Hall resistivity ρ_{yx} of EuIn₂As₂ at various tilted angles at 5 K. (b) The field dependence of the magnetization M at the same angles of (a). (c) The magnetic field dependence of the anomalous Hall resistivity $\Delta\rho_{yx}$ under various field orientations. Each solid line shows a fitting of ρ_{yx}^A using the relation $\rho_{yx}^A = R_A \mu_0 M$. (d) The magnetic field dependence of the topological Hall resistivity ρ_{yx}^T at various field tilted angles. The arrows in (b)–(d) indicate the saturation field at different tilted angles.

strong spin-orbit coupling (SOC) can lift the spin degeneracy. The energy gap induced by the SOC produces a large Berry curvature, contributing to the intrinsic AHE. It has been verified that noncollinear antiferromagnets with zero net magnetization can produce a large AHE when their electronic structure exhibits a nonvanishing Berry curvature that acts like a large fictitious magnetic field [10,29,30]. According to a recent neutron diffraction experiment, EuIn₂As₂ has a helical magnetic structure [20], in which the magnetic moment ferromagnetically aligning in the ab plane rotates antiferromagnetically along the c axis with a magnetic space group of $P6_12'2'/C2'2'21$ [Fig. 3(b)]. These symmetries break both the space and time-reversal symmetries, giving rise to local nonzero Berry curvature. In fact, the unitary operators (space symmetry, such as G_1) and the antiunitary operators (such as $T \cdot 2_x$) can own a finite Berry curvature in the reciprocal space, ensuring that AHE can emerge in the helical AFM of EuIn₂As₂.

Having established the origin of the AHE, we now discuss the origin of ρ_{yx}^T . As shown in Fig. 2(d), ρ_{yx}^{Tmax} emerges below T_N and stays a constant at lower temperatures. This temperature dependence is in sharp contrast to ρ_{yx}^A , which decreases below 20 K, suggesting a different origin of ρ_{yx}^T . The field dependence of ρ_{yx}^T [Fig. 2(c)] shows that ρ_{yx}^T is caused by a deformation of the magnetic structure from either the zero-field

state or the fully polarized state. Since no magnetic transition is observed for $B < B_{\text{sat}}$, the helical magnetic structure at $B = 0$ [Fig. 3(b)] is continuously deformed to a noncoplanar structure [Fig. 3(c)] under a magnetic field applied along the c axis, which is followed by the polarized one above B_{sat} [Fig. 3(d)]. Although it remains as a future work to confirm the actual magnetic structure under the magnetic field, this noncoplanar magnetic structure gives rise to a finite χ_s which eventually vanishes in the fully polarized state above B_{sat} . Therefore the field dependence of ρ_{yx}^T is well explained by that of χ_s that develops in the helical magnetic structure under $B \parallel c$ [31,38,39]. A similar THE is observed in the kagome AFM YMn₆Sn₆ with the helical magnetic ground state, where the formation of double-fan spin structure under magnetic field contributes to the THE [40]. We note that a possibility of a field-induced band structure changing, as observed in EuO [41], can be safely excluded as the origin of THE in this material. The band structure calculation of EuIn₂As₂ predicts that the energy shift of the unoccupied band closes the inverted band gap near the Γ point when the magnetic order is changed from helical to FM, suggesting the possibility of band structure control by applying a magnetic field [20]. However, in contrast to these band calculations predicting a semiconducting state for EuIn₂As₂, this compound is a naturally hole-doped metal as shown by our Hall measurements.

In fact, the previous ARPES measurements [18] show that the actual Fermi energy is far below the energy gap (approximately -0.3 eV), indicating that the slight energy shift of the unoccupied band does not affect the electric transport of this material.

To confirm this topological transport caused by χ_s of the noncoplanar magnetic structure in EuIn_2As_2 , we investigate the angle dependence of ρ_{yx}^T by tilting the magnetic field from the c axis to the ab plane. Figure 4(a) shows the field dependence of ρ_{yx} at different angles at 5 K. Simultaneously, we also take the magnetization data at the same tilted angle of the magnetic field, displayed in Fig. 4(b). First, we extract the field dependence of $\Delta\rho_{yx}$ [Fig. 4(c)] by subtracting the normal part. As shown in Fig. 4(c), $\Delta\rho_{yx}$ is gradually suppressed by tilting the magnetic field to the ab plane. Then we focus on the THE below the saturation field at different tilted angles, and we obtain ρ_{yx}^T in the tilted magnetic field by subtracting the M -linear component from $\Delta\rho_{yx}$. As shown in Fig. 4(d), ρ_{yx}^T decreases as the magnetic field is tilted to the ab plane. This angle dependence indicates that χ_s caused by the c -axis component of the applied field is directly linked to the THE.

Similar AHEs are also observed in the related Eu-based compounds EuCd_2Sb_2 [42] and EuCd_2As_2 [43]. In these compounds, the Weyl points near the Fermi energy or a dynamical Weyl semimetal state are suggested to contribute the AHEs. It should be noted that, although a similar THE might be observed in these compounds below the saturation field, the origin of the THE is not discussed in these previous works [42,43]. Given the different collinear AFM state suggested in EuCd_2Sb_2 and EuCd_2As_2 and the different crystal structure of these compounds, the origin of the THE in EuCd_2Sb_2 and EuCd_2As_2 may be different from that in EuIn_2As_2 .

IV. SUMMARY

In conclusion, our detailed transport measurements on bulk EuIn_2As_2 single crystals reveal that the transport properties in this compound are strongly influenced by the spin texture formed below T_N . Most importantly, we find that an AHE and a THE emerge in the AFM state. We suggest that the AHE is originated from a nonvanishing net Berry curvature in the momentum space due to the helical spin structure and that the THE is attributed to the scalar spin chirality of the noncoplanar spin structure caused by the external field. These observations and analysis in EuIn_2As_2 provide fertile ground to understand the influence of the interplay between the topology of electronic bands and field-induced novel magnetic structure on the unconventional magnetoelectric response. Our findings may encourage advanced experiments to understand the nature of this material and other magnetic topological materials.

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- [1] M. Z. Hasan and C. L. Kane, Colloquium: Topological insulators, *Rev. Mod. Phys.* **82**, 3045 (2010).
 - [2] F. D. M. Haldane, Nobel Lecture: Topological quantum matter, *Rev. Mod. Phys.* **89**, 040502 (2017).
 - [3] B. Yan and C. Felser, Topological materials: Weyl semimetals, *Annu. Rev. Condens. Matter Phys.* **8**, 337 (2017).
 - [4] N. Armitage, E. Mele, and A. Vishwanath, Weyl and Dirac semimetals in three-dimensional solids, *Rev. Mod. Phys.* **90**, 015001 (2018).
 - [5] A. M. Essin, J. E. Moore, and D. Vanderbilt, Magnetoelectric Polarizability and Axion Electrodynamics in Crystalline Insulators, *Phys. Rev. Lett.* **102**, 146805 (2009).
 - [6] R. Yu, W. Zhang, H.-J. Zhang, S.-C. Zhang, X. Dai, and Z. Fang, Quantized anomalous Hall effect in magnetic topological insulators, *Science* **329**, 61 (2010).
 - [7] Y. Tokura, K. Yasuda, and A. Tsukazaki, Magnetic topological insulators, *Nat. Rev. Phys.* **1**, 126 (2019).
 - [8] D. Xiao, J. Jiang, J.-H. Shin, W. Wang, F. Wang, Y.-F. Zhao, C. Liu, W. Wu, M. H. W. Chan, N. Samarth, and C.-Z. Chang, Realization of the Axion Insulator State in Quantum Anomalous Hall Sandwich Heterostructures, *Phys. Rev. Lett.* **120**, 056801 (2018).
 - [9] E. Liu, Y. Sun, N. Kumar, L. Muechler, A. Sun, L. Jiao, S.-Y. Yang, D. Liu, A. Liang, Q. Xu, J. Kroder, V. Süß, H. Borrmann, C. Shekhar, Z. Wang, C. Xi, W. Wang, W. Schnelle, S. Wirth, Y. Chen *et al.*, Giant anomalous Hall effect in a ferromagnetic kagome-lattice semimetal, *Nat. Phys.* **14**, 1125 (2018).
 - [10] S. Nakatsuji, N. Kiyohara, and T. Higo, Large anomalous Hall effect in a non-collinear antiferromagnet at room temperature, *Nature (London)* **527**, 212 (2015).
 - [11] T. Suzuki, R. Chisnell, A. Devarakonda, Y. T. Liu, W. Feng, D. Xiao, J. W. Lynn, and J. G. Checkelsky, Large anomalous Hall effect in a half-Heusler antiferromagnet, *Nat. Phys.* **12**, 1119 (2016).
 - [12] K. Ueda, S. Iguchi, T. Suzuki, S. Ishiwata, Y. Taguchi, and Y. Tokura, Topological Hall Effect in Pyrochlore Lattice with Varying Density of Spin Chirality, *Phys. Rev. Lett.* **108**, 156601 (2012).
 - [13] B. G. Ueland, C. F. Miclea, Y. Kato, O. Ayala-Valenzuela, R. D. McDonald, R. Okazaki, P. H. Tobash, M. A. Torrez, F. Ronning, R. Movshovich, Z. Fisk, E. D. Bauer, I. Martin, and J. D. Thompson, Controllable chirality-induced geometrical Hall effect in a frustrated highly correlated metal, *Nat. Commun.* **3**, 1067 (2012).

- [14] N. Nagaosa and Y. Tokura, Topological properties and dynamics of magnetic skyrmions, *Nat. Nanotechnol.* **8**, 899 (2013).
- [15] K. S. Denisov, I. V. Rozhansky, N. S. Averkiev, and E. Lähderanta, General theory of the topological Hall effect in systems with chiral spin textures, *Phys. Rev. B* **98**, 195439 (2018).
- [16] S. H. Lee, Y. Zhu, Y. Wang, L. Miao, T. Pillsbury, H. Yi, S. Kempinger, J. Hu, C. A. Heikes, P. Quarterman, W. Ratcliff, J. A. Borchers, H. Zhang, X. Ke, D. Graf, N. Alem, C.-Z. Chang, N. Samarth, and Z. Mao, Spin scattering and noncollinear spin structure-induced intrinsic anomalous Hall effect in antiferromagnetic topological insulator MnBi_2Te_4 , *Phys. Rev. Research* **1**, 012011(R) (2019).
- [17] Y. Xu, Z. Song, Z. Wang, H. Weng, and X. Dai, Higher-Order Topology of the Axion Insulator EuIn_2As_2 , *Phys. Rev. Lett.* **122**, 256402 (2019).
- [18] S. Regmi, M. M. Hosen, B. Ghosh, B. Singh, G. Dhakal, C. Sims, B. Wang, F. Kabir, K. Dimitri, Y. Liu, A. Agarwal, H. Lin, D. Kaczorowski, A. Bansil, and M. Neupane, Temperature-dependent electronic structure in a higher-order topological insulator candidate EuIn_2As_2 , *Phys. Rev. B* **102**, 165153 (2020).
- [19] T. Sato, Z. Wang, D. Takane, S. Souma, C. Cui, Y. Li, K. Nakayama, T. Kawakami, Y. Kubota, C. Cacho, T. K. Kim, A. Arab, V. N. Strocov, Y. Yao, and T. Takahashi, Signature of band inversion in the antiferromagnetic phase of axion insulator candidate EuIn_2As_2 , *Phys. Rev. Research* **2**, 033342 (2020).
- [20] S. X. Ribberolles, T. V. Trevisan, B. Kuthanazhi, T. Heitmann, F. Ye, D. C. Johnston, S. L. Bud'ko, D. Ryan, P. C. Canfield, A. Kreyssig, A. Vishwanath, R. J. McQueeney, L.-L. Wang, P. P. Orth, and B. G. Ueland, Magnetic crystalline-symmetry-protected axion electrodynamics and field-tunable unpinned Dirac cones in EuIn_2As_2 , *Nat. Commun.* **12**, 999 (2021).
- [21] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/PhysRevResearch.4.013163> for x-ray dispersion characterization and extended Hall data at different temperatures and for different samples.
- [22] W. Shon, J.-S. Rhyee, Y. Jin, and S.-J. Kim, Magnetic polaron and unconventional magnetotransport properties of the single-crystalline compound EuBiTe_3 , *Phys. Rev. B* **100**, 024433 (2019).
- [23] Y. Zhang, K. Deng, X. Zhang, M. Wang, Y. Wang, C. Liu, J.-W. Mei, S. Kumar, E. F. Schwier, K. Shimada, C. Chen, and B. Shen, In-plane antiferromagnetic moments and magnetic polaron in the axion topological insulator candidate EuIn_2As_2 , *Phys. Rev. B* **101**, 205126 (2020).
- [24] R. Karplus and J. M. Luttinger, Hall Effect in Ferromagnetics, *Phys. Rev.* **95**, 1154 (1954).
- [25] T. Jungwirth, Q. Niu, and A. H. MacDonald, Anomalous Hall Effect in Ferromagnetic Semiconductors, *Phys. Rev. Lett.* **88**, 207208 (2002).
- [26] J. Smit, The spontaneous Hall effect in ferromagnetics II, *Physica (Amsterdam)* **24**, 39 (1958).
- [27] L. Berger, Side-jump mechanism for the Hall effect of ferromagnets, *Phys. Rev. B* **2**, 4559 (1970).
- [28] N. Nagaosa, J. Sinova, S. Onoda, A. H. MacDonald, and N. P. Ong, Anomalous Hall effect, *Rev. Mod. Phys.* **82**, 1539 (2010).
- [29] J. Kübler and C. Felser, Non-collinear antiferromagnets and the anomalous Hall effect, *Europhys. Lett.* **108**, 67001 (2014).
- [30] H. Chen, Q. Niu, and A. H. MacDonald, Anomalous Hall Effect Arising from Noncollinear Antiferromagnetism, *Phys. Rev. Lett.* **112**, 017205 (2014).
- [31] N. Kanazawa, Y. Onose, T. Arima, D. Okuyama, K. Ohoyama, S. Wakimoto, K. Kakurai, S. Ishiwata, and Y. Tokura, Large Topological Hall Effect in a Short-Period Helimagnet MnGe , *Phys. Rev. Lett.* **106**, 156603 (2011).
- [32] S.-Y. Yang, Y. Wang, B. R. Ortiz, D. Liu, J. Gayles, E. Derunova, R. Gonzalez-Hernandez, L. Šmejkal, Y. Chen, S. S. P. Parkin, S. D. Wilson, X. S. Toberer, T. McQueen, and M. N. Ali, Giant, unconventional anomalous Hall effect in the metallic frustrated magnet candidate, KV_3Sb_5 , *Sci. Adv.* **6**, eabb6003 (2020).
- [33] T. Miyasato, N. Abe, T. Fujii, A. Asamitsu, S. Onoda, Y. Onose, N. Nagaosa, and Y. Tokura, Crossover Behavior of the Anomalous Hall Effect and Anomalous Nernst Effect in Itinerant Ferromagnets, *Phys. Rev. Lett.* **99**, 086602 (2007).
- [34] S. Onoda, N. Sugimoto, and N. Nagaosa, Quantum transport theory of anomalous electric, thermoelectric, and thermal Hall effects in ferromagnets, *Phys. Rev. B* **77**, 165103 (2008).
- [35] Y. Shiomi, Y. Onose, and Y. Tokura, Extrinsic anomalous Hall effect in charge and heat transport in pure iron, $\text{Fe}_{0.997}\text{Si}_{0.003}$, and $\text{Fe}_{0.97}\text{Co}_{0.03}$, *Phys. Rev. B* **79**, 100404(R) (2009).
- [36] N. Manyala, Y. Sidis, J. F. DiTusa, G. Aeppli, D. P. Young, and Z. Fisk, Large anomalous Hall effect in a silicon-based magnetic semiconductor, *Nat. Mater.* **3**, 255 (2004).
- [37] K. S. Takahashi, H. Ishizuka, T. Murata, Q. Y. Wang, Y. Tokura, N. Nagaosa, and M. Kawasaki, Anomalous Hall effect derived from multiple Weyl nodes in high-mobility EuTiO_3 films, *Sci. Adv.* **4**, eaar7880 (2018).
- [38] P. Bruno, V. K. Dugaev, and M. Taillefumier, Topological Hall Effect and Berry Phase in Magnetic Nanostructures, *Phys. Rev. Lett.* **93**, 096806 (2004).
- [39] J. Ye, Y. B. Kim, A. J. Millis, B. I. Shraiman, P. Majumdar, and Z. Tešanović, Berry Phase Theory of the Anomalous Hall Effect: Application to Colossal Magnetoresistance Manganites, *Phys. Rev. Lett.* **83**, 3737 (1999).
- [40] Q. Wang, K. J. Neubauer, C. Duan, Q. Yin, S. Fujitsu, H. Hosono, F. Ye, R. Zhang, S. Chi, K. Krycka, H. Lei, and P. Dai, Field-induced topological Hall effect and double-fan spin structure with a c -axis component in the metallic kagome antiferromagnetic compound YMn_6Sn_6 , *Phys. Rev. B* **103**, 014416 (2021).
- [41] P. G. Steeneken, L. H. Tjeng, I. Elfimov, G. A. Sawatzky, G. Ghiringhelli, N. B. Brookes, and D.-J. Huang, Exchange Splitting and Charge Carrier Spin Polarization in EuO , *Phys. Rev. Lett.* **88**, 047201 (2002).
- [42] H. Su, B. Gong, W. Shi, H. Yang, H. Wang, W. Xia, Z. Yu, P.-J. Guo, J. Wang, L. Ding, L. Xu, X. Li, X. Wang, Z. Zou, N. Yu, Z. Zhu, Y. Chen, Z. Liu, K. Liu, G. Li *et al.*, Magnetic exchange induced Weyl state in a semimetal EuCd_2Sb_2 , *APL Mater.* **8**, 011109 (2020).
- [43] J. Z. Ma, S. M. Nie, C. J. Yi, J. Jandke, T. Shang, M. Y. Yao, M. Naamneh, L. Q. Yan, Y. Sun, A. Chikina, V. N. Strocov, M. Medarde, M. Song, Y.-M. Xiong, G. Xu, W. Wulfhkel, J. Mesot, M. Reticcioli, C. Franchini, C. Mudry *et al.*, Spin fluctuation induced Weyl semimetal state in the paramagnetic phase of EuCd_2As_2 , *Sci. Adv.* **5**, eaaw4718 (2019).