Spin fluctuation induced Weyl semimetal state in the paramagnetic phase of EuCd$_2$As$_2$

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Weyl fermions as emergent quasiparticles can arise in Weyl semimetals (WSMs) in which the energy bands are nondegenerate, resulting from inversion or time-reversal symmetry breaking. Nevertheless, experimental evidence for magnetically induced WSMs is scarce. Here, using photoemission spectroscopy, we observe that the degeneracy of Bloch bands is already lifted in the paramagnetic phase of EuCd$_2$As$_2$. We attribute this effect to the itinerant electrons experiencing quasi-static and quasi-long-range ferromagnetic fluctuations. Moreover, the spin-nondegenerate band structure harbors a pair of ideal Weyl nodes near the Fermi level. Hence, we show that long-range magnetic order and the spontaneous breaking of time-reversal symmetry are not essential requirements for WSM states in centrosymmetric systems and that WSM states can emerge in a wider range of condensed matter systems than previously thought.

INTRODUCTION

In crystals, Kramers’ theorem, together with the combination of inversion ($P$) and time reversal ($T$) symmetries, protects the double degeneracy of fermionic energy bands. Dirac nodes can emerge at the gapless crossing of two doubly degenerate bands, near which the fermionic excitations are described by the massless 4-by-4 Dirac equation (1–4). The twofold band degeneracy can be lifted when $P$ or $T$ symmetry is broken. The crossings of nondegenerate bands then lead to Weyl nodes that always occur in pairs. The electronic states with momenta close to a Weyl node are effectively governed by the 2-by-2 matrix (5). While $P$ symmetry breaking is explicitly present in noncentrosymmetric systems, $T$ symmetry can be broken either explicitly by external magnetic fields or spontaneously through correlation effects. First-principles calculations have predicted a number of Weyl semimetals (WSMs) in noncentrosymmetric or magnetically ordered systems (5–10). From angle-resolved photoemission spectroscopy (ARPES) experiments, the Weyl nodes have been identified in several noncentrosymmetric systems, such as the TaAs family, (Mo,W)Te$_2$, LaAlGe, and TaIrTe$_4$ (11–18). By contrast, there is no well-defined spectroscopic evidence for Weyl nodes in magnetically ordered systems. Moreover, magnetotransport measurements have provided evidence for the chiral anomaly expected from Weyl fermions in TaAs, Na$_3$Bi, GdPtBi, Mn$_5$Sn, and Co$_3$Sn$_2$S$_2$ (19–23). The Weyl nodes in Na$_3$Bi and GdPtBi are created by external magnetic fields.

Here, using ARPES, we show that Weyl fermions emerge already in the paramagnetic (PM) phase of EuCd$_2$As$_2$. Together with measurements of transport, magnetic susceptibility, electron spin resonance (ESR), and muon spin relaxation ($\mu$SR) and with first-principles calculations, we attribute the existence of these Weyl fermions to the effective breaking of $T$ symmetry by ferromagnetic (FM) fluctuations on time and length scales that are long compared to the electronic ones, although the spontaneous $T$ symmetry is preserved in the PM phase when considering dynamical statistics.

RESULTS

EuCd$_2$As$_2$ has a layered crystal structure with space group P-3 m1 (no. 164). The Cd$_2$As$_2$ bilayers are separated by the triangular Eu layers (Fig. 1A). EuCd$_2$As$_2$ is an itinerant magnet with conduction electrons from the Cd and As orbitals. Magnetism originates from large local magnetic moments on the Eu ions. Previous studies revealed that the local Eu 4f moments form a long-range antiferromagnetic (AFM) order with an $A$-type structure, i.e., FM $a\bar{b}$ planes stacking antiferromagnetically along the $c$ axis. This order sets in at the Néel temperature $T_N$ of $\sim$9.5 K (24–26), at which both the resistivity $\rho(T)$ (Fig. 1A) and the magnetic susceptibility $\chi(T)$ (Fig. 1C) show a peak.

Above $T_N$, the longitudinal field (LF) $\mu$SR spectra show no obvious changes and no oscillations when different magnetic fields are applied in the PM phase of EuCd$_2$As$_2$ (Fig. 1G). In agreement with previous Mössbauer spectroscopy (24), the LF $\mu$SR results rule out any static magnetic order above $T_N$. Nevertheless, ESR measurements reveal that the resonance field ($H_{res}$) starts to decrease around 100 K (Fig. 1E),
indicating that (i) an effective internal magnetic field develops as the magnetic fluctuations slow down (27) and (ii) there is a relatively large scale for the magnetic interactions, most likely associated with strong magnetic fluctuations slow down (~100 K). This is also an indication for the onset of quasi-static correlated fluctuating local magnetic fields (Fig. 1D), in agreement with previous measurements (24, 25). The positivity of $T_{\text{CW}}$ suggests that magnetic fluctuations above $T_N$ are FM in nature, whereas its smallness as compared to the fluctuation temperature hints at the presence of competing interactions of either sign. Figure 1D shows that there is a crossing between the out-of-plane and the in-plane susceptibilities, with the out-of-plane one being substantially larger at higher temperatures. Together, this suggests predominantly FM fluctuations with out-of-plane magnetization deep in the PM phase.

Further evidence for the existence of a high characteristic temperature scale $T_F$ where fluctuations set in is found in transport. Figure 1F shows that an anomalous Hall effect (AHE) already develops in the PM phase around 100 to 150 K. At temperatures above 150 K, the Hall resistivity exhibits a simple linear dependence on the magnetic field. In contrast, it deviates from the linear behavior when the temperature is below ~100 K. This is also an indication for the onset of quasi-static and quasi-long-range FM correlations at a fairly high $T_F$ because an AHE is typically related to either FM correlations or a nontrivial Berry curvature, associated with Weyl points. However, in the present context, the latter requires an effective time-reversal symmetry breaking in the form of slow, large-scale FM fluctuations (28–30).

$\mu$SR is one of the most sensitive experimental methods to detect correlated fluctuating local magnetic fields (31–34) as one would expect from FM fluctuations in the present case. The ensuing exponential muon relaxation is indeed observed in zero field (ZF) and LF at different temperatures (Fig. 1, G and H). When lowering the temperature, the dynamical muon relaxation rate $\lambda_2\phi$, which is related to the fluctuating magnetic field, increases, starting at ~100 K. It then goes through a shoulder between 50 and 100 K and increases more steeply thereafter around $T_N$ (Fig. 1I).

**Fig. 1. Slow FM fluctuations in the PM phase of EuCd$_2$As$_2$.** (A) Temperature dependence of the resistivity. The inset shows the crystal structure of EuCd$_2$As$_2$ in one unit cell. (B) 3D Brillouin zone (BZ) with high-symmetry points and coordinate axes. The normal directions of cleaved (001) and (101) surfaces are also indicated. (C) Temperature dependence of the magnetic susceptibility with $H$ parallel and perpendicular to the $c$ axis, respectively. (D) Temperature dependence of the inverse susceptibility. (E) ESR spectra at various temperatures in the PM phase. The inset plots temperature dependence of the resonance field $H_{\text{res}}$, a.u., arbitrary units. (F) Magnetic field dependence of the Hall resistivity at various temperatures under in-plane magnetic fields. (G) $\mu$SR spectra at 20 K in zero field (ZF) and longitudinal field (LF) of 7000 Oe, respectively. (H) $\mu$SR spectra at three representative temperatures. (I) Temperature dependence of the dynamic muon relaxation rate $\lambda_2\phi$. Ma et al., Sci. Adv. 2019;5:eaaw4718 12 July 2019
Because of the layered crystal structure, the in-plane magnetic interactions are expected to be much stronger than the interlayer magnetic interactions. This expectation is confirmed qualitatively by the following first-principles calculations. When the measured lattice constants are imposed in the calculation, the ratio between the FM in-plane and AFM interplane nearest-neighbor magnetic exchange couplings is estimated to be of order three in magnitude. We also find a substantial frustration between nearest- and next nearest-neighbor magnetic exchange couplings. However, because the magnitude of these exchange couplings and even the sign of the interplane coupling change when the crystalline structure is allowed to relax during the calculation, a reliable quantitative prediction of their values is very difficult. The correction is exactly what is observed in Fig. 1D where the in-plane susceptibility starts dominating over the out-of-plane susceptibility below 17 K. This is consistent with recent resonant elastic x-ray scattering measurements, which have confirmed that the magnetic moments lie in the a-b plane below $T_N$ (26).

If above $T_N$ a typical FM fluctuation is correlated over a characteristic linear size $\xi$ and over the characteristic time $\tau$ such that their inverses exceed the momentum and energy resolution needed to discern the lifting of the Bloch band degeneracy that is expected within the Born-Oppenheimer approximation because of the quasi-static FM, then it will have a measurable effect on the itinerant electrons. In ARPES experiments, we observed the splitting of energy bands in the PM phase of EuCd$_2$As$_2$. In Fig. 2, we present the ARPES results acquired on cleaved (001) and (101) surfaces of EuCd$_2$As$_2$ crystals. Figure 2 (A and B) shows a point-like Fermi surface (FS) in the Eu planes by strong FM in-plane interactions, dipolar interactions will then further stabilize FM correlations out of the plane. True long-range FM order will, however, be prevented if, upon further cooling, the preferred magnetization changes from an out-of-plane to an in-plane orientation, in which case both dipolar and AFM interlayer exchange interaction prefer an A-type AFM magnetic structure. Such a change of in-plane magnetization direction is exactly what is observed in Fig. 1D where the in-plane susceptibility starts dominating over the out-of-plane susceptibility below 17 K. This is consistent with recent resonant elastic x-ray scattering measurements, which have confirmed that the magnetic moments lie in the a-b plane below $T_N$ (26).

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the FS in the $k_x$-$k_y$ plane and band dispersions along the $\Gamma$-A line, which is normal to the (001) cleavage surface. The periodic appearance of the FS and the dispersive feature of the energy bands along $\Gamma$-A show that they are three-dimensional (3D) bulk states. Figure 2E shows the band dispersions measured at $11$ K along cut0 in Fig. 2A: There are flat bands located at $\sim 1$ to $1.6$ $eV$ below $E_F$ and several hole-like bands above or below the flat bands. While the flat bands arise from the Eu 4$f$ orbitals, the hole-like bands mainly originate from the As 4$p$ orbitals. As the unit cell of EuCd$_2$As$_2$ contains two As atoms, in total, there are six As 4$p$ bands when both $T$ and $P$ symmetries are preserved. The interlayer coupling within the Cd$_2$As$_2$ bilayer results in three antibonding bands around $E_F$ and three bonding bands below the flat bands. Carefully examining the band dispersions, it can be seen that a band splitting occurs near $E_F$, as indicated by the arrows in Fig. 2 (F and G). To exclude the possibility that the band splitting results from surface effects or the broadening effect of the 3D bulk bands in the photoemission process, we have carried out soft x-ray ARPES measurements to increase the bulk sensitivity in the PM phase (Fig. 2, H and I). The band splitting is still observed in the $k_x$-$k_y$ plane (Fig. 2I), providing evidence that it is an intrinsic effect of bulk states (35). We have also carried out ARPES measurements on the (101) surface. The APRES spectra in Fig. 2 (K and L) were recorded with a photon energy of $88$ $eV$. The corresponding momentum cut almost overlaps with the $\Gamma$-A line near the $\Gamma$ point (Fig. 2J). Note that the band splitting is observed both in the raw ARPES spectra and in the curvature intensity plot, as indicated by the arrows in Fig. 2 (K and L).

Usually, band splitting occurs when either $T$ or $P$ symmetry is broken. Because both $T$ and $P$ symmetries are preserved in the PM phase of EuCd$_2$As$_2$ when considering dynamical statistics over a large enough time scale, we attribute the observed band splitting to slow FM fluctuations with significant spatial correlations, both in plane and out of plane. If the FM fluctuations are much slower than the relevant dynamical time for the itinerant electrons, then a Born-Oppenheimer approximation by which magnetic fluctuations are treated as time-independent background fields for itinerant electrons is justified. A lower bound on the fluctuation time $\tau$ for the Born-Oppenheimer approximation to be justified is given by $\hbar/\Delta E_{\text{spin}}$, with the magnetically induced band splitting $\Delta E_{\text{spin}}$ of $\sim 0.1$ $eV$. This bound is well satisfied because the slow magnetic fluctuations could indeed be detected by $\mu$SR (with time resolution larger than picoseconds), which implies that $\tau \gg \hbar/\Delta E_{\text{spin}}$. The effects of these slow fluctuations can thus be resolved in the spectral functions.

To provide further evidence that the band splitting is induced by spin fluctuations, we have performed ARPES experiments on related compounds in the same family and with the same crystal structure, one magnetic (EuCd$_2$Sb$_2$) and one nonmagnetic (BaCd$_2$As$_2$). EuCd$_2$Sb$_2$ has magnetic properties (such as an AFM phase transition at low temperature and spin fluctuations in the PM phase) very similar to EuCd$_2$As$_2$, except for a slightly lower Néel temperature of $\sim 7.5$ $K$ (24). The band splitting is very clear in EuCd$_2$Sb$_2$, as recorded with both an ultraviolet source and soft x-ray ARPES as shown in Fig. S1. It persists with increasing temperature up to $100$ $K$, above which the splitting cannot be well resolved (Fig. S2). In contrast, we did not observe any band splitting in BaCd$_2$As$_2$ (Fig. S3). We also confirm that the band structure above $T_N$ is very different from that in the low-temperature AFM phase, where a band folding occurs. We provide the associated experimental and numerical data in Fig. S4.

To study the band splitting in the PM phase of EuCd$_2$As$_2$, we have incorporated static FM patterns in our band structure calculations, assuming that fluctuations are much slower than the relevant dynamical time for the itinerant electrons. We carried out density functional theory (DFT) + $U$ calculations with infinitesimal long-range FM order (assuming a large correlation length $\xi$, with the magnetic moments oriented in various directions. Here, $U$ represents the Hubbard interaction among the Eu 4$f$ orbitals. For simplicity, we start the discussion with the magnetic moments oriented along the $c$ axis. When $U = 0$, a number of flat bands associated with the Eu 4$f$ orbitals appear near $E_F$ in fig. S5A. Upon increasing $U$, the flat bands move downward as shown in fig. S5 (B to I). For $U = 5$ $eV$, the flat bands appear at $\sim 1$ to $1.6$ $eV$ below $E_F$ in Fig. 3A, in agreement with our ARPES results in Fig. 2E. In addition, the calculated band structures at $U = 5$ $eV$ include several hole-like bands above and below the flat bands, which are consistent with the observation in Fig. 2. For comparison, the calculated band structure of EuCd$_2$As$_2$ in the absence of magnetic order is shown in Fig. S6. In this case, the six As 4$p$ bands collapse into three doubly degenerate hole-like bands protected by parity-time symmetry.

From our band structure calculations, one can see that the Cd 5$s$ and As 4$p$ states partially hybridize near $E_F$ for all values of $U$. However, when $U < 5$ $eV$, because of hybridization with the Eu 4$f$ bands, the region near the Fermi level becomes rather tangled, as is seen in fig. S5. For $U \geq 5$ $eV$ instead, an ideal band inversion develops near the Fermi level around the $\Gamma$ point. This results in an ideal band crossing of the Nth and $(N + 1)$th bands at $k_z = \pm k'_z$ on the $\Gamma$-A line in the presence of $C_{2z}$ symmetry, as shown in Fig. 3B. In any other $k_x$-$k_y$ planes with $k_x \neq \pm k'_y$, the electronic structures are gapped at $E_F$, which makes it possible to define a Chern number $C$ for these planes. We found $C = 1$ for the planes with $|k_z| < k'_z$ and $C = 0$ for the planes with $|k_z| > k'_z$. Therefore, the band crossing points along the $\Gamma$-A line are topologically protected Weyl nodes. Band crossings resulting in Weyl points can also occur for the $(N - 1)$th and Nth bands and/or the $(N + 1)$th and $(N + 2)$th bands. However, those Weyl nodes are typically farther away from $E_F$ and thus are less relevant for transport. Moreover, they are rather fragile because of the small band inversion and can disappear through pairwise annihilation upon small changes of lattice parameters. Therefore, we focus on the lowest energy pair of Weyl nodes.

When considering FM fluctuations, for the theoretical modeling, we make the following simplifying assumptions: (i) At any given time in the PM phase, the system can be divided into FM correlation domains. (ii) Within each of these domains, the magnetic moments point in the same direction, whereby the orientation in different domains is random and uniformly distributed. (iii) We assume the correlation length to be sufficiently large so that it does not introduce a significant uncertainty in $k$ space. Then, the FM fluctuations in the PM phase are captured by averaging the spectra of infinite large FM domains over the magnetic orientations. The resulting band structure along high-symmetry lines is shown in Fig. 3D. The average over directions preserves the band inversion around the $\Gamma$ point and merely broadens the band structure by an amount $W_s$ (around $0.033 \pm 0.024$ $\AA^{-1}$ along $M-\Gamma$ and around $0.024 \pm 0.012$ $\AA^{-1}$ along $\Gamma-A$). $W_s$ is significantly smaller than the band splitting $W_s$ (0.12$\pm 0.02$ $\AA^{-1}$ along $M-\Gamma$ and 0.086 $\pm 0.030$ $\AA^{-1}$ along $\Gamma-A$), which can thus still be distinguished, as shown in Fig. 3E. The spin splitting $W_s$ observed in ARPES measurements is around $0.066$ $\AA^{-1}$ along $k_z = 0$ plane and $0.033$ $\AA^{-1}$ along $\Gamma-A$ and thus is of the same order of magnitude. The agreement with predicted values is reasonable, given that the above calculation neglects several sources of fluctuations and thus provides at best an upper bound for $W_s$. The effects of finite correlation lengths of the slow magnetic fluctuations on the visibility of the spin splitting are discussed in the “Spin splitting and band broadening by
and C) with cone-like band dispersions below exhibits two separate FS patches along the magnetic polarization direction in a correlation volume is moderate (see Supplementary Text and figs. S7 and S8. For polarization along the magnetic polarization direction in a correlation volume is moderate (see Supplementary Text and figs. S7 and S8.

The variation of the location of the Weyl nodes upon changing the magnetic polarization direction in a correlation volume is moderate (see also table S1). For polarization along the c axis, the C_{3v} symmetry forces the Weyl nodes to lie on the high-symmetry Γ-A line. For different polarizations, they only deviate slightly from the Γ-A line. As illustrated in Fig. 3F, the pairs of parity-related Weyl nodes are confined in two small nonoverlapping regions around the Γ-A line and the size of each region is less than 0.02 Å⁻¹, so the Weyl nodes in the PM phase of EuCd₂As₂ can be well detected despite fluctuations of the magnetic polarization direction.

According to the calculations, the separation of the Weyl nodes along the κ₁ direction is about 0.1 Å⁻¹, which is difficult to resolve in the ARPES spectra acquired from the measurements on the (001) surface because of the intrinsic low momentum resolution in the direction perpendicular to the surface. We thus carried out ARPES measurements on cleaved (101) surfaces, whose normal direction is along Γ-L (Fig. 1B). Figure 4A displays the FS intensity map measured from the cleaved (101) surface by varying the photon energy (hv). The momentum cut corresponding to hv = 88 eV almost coincides with the Γ-Α Γ line (Fig. 4A). The 3D ARPES intensity plot acquired at hv ≈ 88 eV exhibits two separate FS patches along the Γ-A direction (Fig. 4, B and C) with cone-like band dispersions below Eₚ, in agreement with the calculations. To get an ARPES spectrum exactly on the Γ-A line, we collected a large set of ARPES data with photon energies in the vicinity of 88 eV. Figure 4D shows the band dispersions along Γ-A extracted from the photon energy–dependent data, which has much better momentum resolution than that measured on the (001) surface along the same direction (Fig. 2D). The band splitting of the hole-like band can be identified both in the raw data and in the curvature intensity plot (Fig. 4, D and E). In addition, we observed a shallow electron-like band [conduction band (CB)] near Eₚ (Fig. 4, F and H). As indicated in Fig. 4 (F, H, and I), the electron- and hole-like bands, marked as CB and valence band (VB), respectively, cross Eₚ. As the electron band is also spin nondegenerate, the crossings of the Nth and (N + 1)th bands lead to a pair of Weyl nodes around Γ-A, with κ₁ of ~±0.07 Å⁻¹. To further confirm the crossings of CB and VB, we carried out scanning tunneling microscopy/spectroscopy (STM/STS) measurements on the (001) surface (Fig. 4, J and K). The typical dI/dV spectrum in Fig. 4K exhibits a “V” shape with a finite minimal intensity at Eₚ and shows peaks both above and below Eₚ, which agrees well with the inverted VB top (VBT) and CB bottom (CBB), as marked in Fig. 4I. This is in agreement with the expected density of states of a Weyl cone band structure.

In addition to the bulk Weyl nodes, a further important feature of WSMs is surface Fermi arcs. On the (101) cleaved surface, the two Weyl nodes are projected to different points in the surface Brillouin zone (BZ), which should be connected by a surface Fermi arc. We indeed observe a signature of surface states in the photon energy–dependent spectra and in the FS map. However, the Fermi arcs are rather sensitive to fluctuations of the polarization direction, which entails an intrinsic smearing of these surface states between the two Weyl points.

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DISCUSSION AND CONCLUSION

We have shown that the Bloch bands of EuCd$_2$As$_2$ display topological attributes in the form of Weyl nodes that originate from the interplay between itinerant electrons and localized moments in the PM phase below the crossover temperature of ~100 K. Far above 100 K, the Weyl nodes collapse into Dirac nodes as the typical lifetime or the spatial extent of the FM fluctuations becomes too short for the Kramers’ degeneracy to be effectively broken. None of the probes used in this paper have direct access to the magnetic coupling of order 100 K that is responsible for the long-lived FM fluctuations. The observation of Weyl nodes in EuCd$_2$As$_2$ is thus to be interpreted as the imprint on the Bloch bands of rather large competing magnetic interactions of the order of 100 K.

Note that the time scale for collecting ARPES spectra is much longer than that of the spin fluctuations. Therefore, ARPES data can be viewed as a statistical time average of dynamical results. The spin fluctuations...
do have an effect on the electronic structure, as they induce fluctuations on the Weyl nodes and the sign of the topological charge in the two Weyl node groups. These kinds of fluctuations, in Weyl node and charge sign, are sensitive to the magnetization, which can be tuned by an external magnetic field. The fact that Weyl nodes and their topological charge adjust to the orientation of the magnetization, which is itself tunable, could be promising for future spintronic applications.

A recent theoretical study has pointed out that a Dirac semimetal state or magnetic topological insulator state could coexist under certain conditions with long-range AFM order (36). If this is also true for EuCd₂As₂ below Tₙ, then the application of moderate magnetic fields could induce a metamagnetic transition to an FM state that would very substantially split the Kramers’ degeneracy even for a moderate field. We thus expect the phase diagram of EuCd₂As₂ as a function of temperature and magnetic field to be very rich.

**MATERIALS AND METHODS**

Single crystals of EuCd₂As₂ were synthesized using Sn as flux. Starting materials of Eu (ingot, 99.9%), Cd (grain 99.999%), As (ingot, 99.999%), and excess Sn (grain, 99.9699%; all from Alfa Aesar) were mixed and loaded in an alumina crucible at a molar ratio of 1:2:2:10. The operations were performed in a glove box filled with pure argon. Then, the crucible was sealed in a quartz tube under high vacuum. The tube was heated to 900°C and maintained for 20 hours before slowly cooling it to 500°C at a rate of 2°C/hour. Then, the samples were separated from the Sn in a centrifuge.

ARPES measurements were performed at the SIS-HRPE (Surface And Interface Spectroscopy—High-Resolution Photoemission Spectroscopy) beamline with a Scienta 4000 analyzer and at the ADRESS (Advanced RESonant Spectroscopies) beamline with a SPECS analyzer of the Swiss Light Source [Paul Scherrer Institute (PSI)], at the ARPS end station of the Dreamline beamline at the Shanghai Synchrotron Radiation Facility and at the beamline UE112 PGM-2b-1 at BESSY (Berlin Electron Storage Ring Society for Synchrotron Radiation) Synchrotron. The energy and angular resolutions were set to ~5 to 30 meV and 0.2°, respectively. The samples for ARPES measurements were cleaved in situ and measured in a temperature range between 2 and 160 K in a vacuum better than 5 × 10⁻¹⁰ torr. The mSR measurements were carried out using the general purpose spectrometers located at the nM3 beamline of the Swiss Muon Source of the PSI. STM measurements were carried out with a home-built Joule-Thomson STM (37). The EuCd₂As₂ single crystals were cleaved in situ at T = 77 K. Measurements were performed at T = 2.8 to 14 K.

The DFT calculations were carried out by using the projector-augmented wave method implemented in the Vienna ab initio simulation package (VASP) (38, 39). The cutoff energy for the plane-wave expansion was 500 eV. The exchange-correlation functional was treated using the generalized gradient approximation (GGA) parameterized by Perdew et al. (40). Spin–orbit coupling (SOC) was taken into account self-consistently in the calculations. The k-point grids (10 by 10 by 5) were used in the self-consistent simulations. The GGA + U method (41) was used to treat correlation effects in EuCd₂As₂. The s orbitals of Cd and the p orbitals of As were used to construct the maximally localized Wannier functions (42), which were then used to calculate the Chern numbers.

To analyze the effects of the magnetic disorder with different FM clustering properties on the energy band structure of EuCd₂As₂, we carried out DFT + U calculations (U = 5 eV), including SOC, by using a supercell (4 by 4 by 1; 80 atoms). The magnetic moments of the 16 Eu atoms were constrained along arbitrary directions, exploring different arrangements. The band structure was unfolded onto the primitive cell BZ by adopting the unfolding method, as implemented in VASP (43, 44).

**SUPPLEMENTARY MATERIALS**

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/5/7/eaaw4718/DC1

Spin splitting and band broadening by static disorder with finite correlation length

Fig. S1. Band splitting in EuCd₂Sb₂.

Fig. S2. Temperature effects on the band splitting in EuCd₂Sb₂.

Fig. S3. Electronic structure of BaCd₂As₂.

Fig. S4. Comparison of band structures below and above Néel temperature.

Fig. S5. Calculated band structures of EuCd₂As₂ with magnetic moments oriented along the c axis, as a function of onsite Coulomb interaction U.

Fig. S6. Calculated band structure of EuCd₂As₂ along high-symmetry lines, deeply within the BZ by adopting the unfolding method, as implemented in VASP (43, 44).

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