Giant anomalous Hall effect in a ferromagnetic kagome-lattice semimetal

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Magnetic Weyl semimetals with broken time-reversal symmetry are expected to generate strong intrinsic anomalous Hall effects, due to their large Berry curvature. Here, we report a magnetic Weyl semimetal candidate, Co$_3$Sn$_2$S$_2$, with a quasi-two-dimensional crystal structure consisting of stacked kagome lattices. This lattice provides an excellent platform for hosting exotic topological quantum states. We observe a negative magnetoresistance that is consistent with the chiral anomaly expected from the presence of Weyl fermions close to the Fermi level. The anomalous Hall conductivity is robust against both increased temperature and charge conductivity, which corroborates the intrinsic Berry-curvature mechanism in momentum space. Owing to the low carrier density in this material and the considerably enhanced Berry curvature from its band structure, the anomalous Hall conductivity and the anomalous Hall angle simultaneously reach 1,130 $\Omega^{-1}$ cm$^{-1}$ and 20%, respectively, an order of magnitude larger than typical magnetic systems. Combining the kagome-lattice structure and the long-range out-of-plane ferromagnetic order of Co$_3$Sn$_2$S$_2$, we expect that this material is an excellent candidate for observation of the quantum anomalous Hall state in the two-dimensional limit.

The anomalous Hall effect (AHE) is an important electronic transport phenomenon. It can arise because of two qualitatively different microscopic mechanisms: extrinsic processes due to scattering effects, and an intrinsic mechanism connected to the Berry curvature. The large Berry curvature comes from the entangled Bloch electronic bands with spin–orbit coupling when the spatial-inversion or time-reversal symmetry of the material is broken. The quantum AHE in two-dimensional (2D) systems is determined solely by this intrinsic contribution. It manifests itself as a quantized anomalous Hall conductance due to the presence of a bulk gap in combination with dissipationless edge states.

A magnetic Weyl semimetal with broken time-reversal symmetry can be interpreted as a stacked heterostructure of such quantum anomalous Hall insulator layers, where the coupling between the layers closes the bulk bandgap at isolated Weyl nodes. At these Weyl nodes, the Berry curvature is enhanced whereas the carrier density vanishes. This suggests that an intrinsic large anomalous Hall conductivity and a large anomalous Hall angle can be expected in such systems.

To date, a number of promising candidates for magnetic Weyl semimetals have been proposed, including Y$_2$Ir$_2$O$_7$, HgCr$_2$Se$_4$, and certain Co$_3$-based Heusler compounds. The experimental identifications for this Weyl phase in these systems are also on the way. Indeed, an anomalous Hall angle of approximately 16% was recently observed at low temperatures in the magnetic-field-induced Weyl semimetal GdPtBi. However, a finite external magnetic field is mandatory to make GdPtBi a Weyl semimetal. Therefore, the search for intrinsic magnetic Weyl semimetals with Weyl nodes close to the Fermi level is not only an efficient strategy to obtain materials exhibiting both a high anomalous Hall conductivity and large anomalous Hall angle, but also important for a comprehensive understanding of Weyl topological effects on the AHE in real materials.

The kagome lattice has become one of the most fundamental models for exotic topological states in condensed matter physics. In particular, the kagome lattice with out-of-plane ferromagnetic order is an excellent platform for investigating the quantum anomalous Hall effect. Thus, it provides an effective guiding principle for realizing magnetic Weyl semimetals via stacking. Although a Dirac dispersion with a finite spin–orbit-coupling-induced gap has recently been observed in a kagome-lattice metal, the Weyl phase in a magnetic kagome material still remains elusive. Here, we report a time-reversal-symmetry-breaking Weyl semimetal in the magnetic kagome-lattice compound Co$_3$Sn$_2$S$_2$ with out-of-plane ferromagnetic order, and demonstrate both a large intrinsic anomalous Hall conductivity (1,130 $\Omega^{-1}$ cm$^{-1}$) and a giant anomalous Hall angle (20%).

Co$_3$Sn$_2$S$_2$, a Shandite compound, is known to be a ferromagnet with a Curie temperature ($T_C$) of 177 K and a magnetic moment of 0.29 $\mu_B$/Co. Magnetization measurements have shown that the easy axis of the magnetization lies along the c axis, while photoemission measurements and band structure calculations revealed that, below $T_C$, Co$_3$Sn$_2$S$_2$ exhibits Type-IA half-metallic ferromagnetism in which spin-minority states are gapped. Figure 1 summarizes the structural and electronic properties of Co$_3$Sn$_2$S$_2$. As shown...
The crystal possesses a quasi-2D dependences of the longitudinal electric resistivity (\(\rho\)) under spin–orbit coupling calculations. Different colours indicate different parts of the Fermi surface in the Brillouin zone.

Our magnetization measurements revealed a magnetic anisotropy, this material shows a long-range quasi-2D a–b–c plane configuration with \(T_{C} = 175\) K and a moderate residual resistivity of approximately 50 \(\mu\)Ω cm at 2 K. In a high field of 9 T, a negative magnetoresistance appears around the Curie temperature owing to the spin-dependent scattering.

Furthermore, for the spin-up states, we observe linear band crossings along the \(\Gamma–L\) and \(L–U\) paths, just slightly above and below the Fermi energy, respectively. For finite spin–orbit coupling, these linear crossings open small gaps with band anti-crossings, and make this compound semimetal-like. The relatively small Fermi surfaces (Fig. 1c), showing the coexistence of holes and electrons, further corroborate the semi-metallic character of this compound. This calculated band structure is in good agreement with our angle-resolved photoemission spectroscopy (ARPES) measurements (see Supplementary Information). When these results are considered in conjunction with the ferromagnetism of Co\(_3\)Sn\(_2\)S\(_2\) (refs 27–30), they suggest that a time-reversal-symmetry-breaking Weyl semimetal phase might be hidden in this compound.

In order to confirm this prediction, single crystals of Co\(_3\)Sn\(_2\)S\(_2\) were grown for further experimental investigations (see Methods and Supplementary Information). The high quality of the crystals was confirmed by structure refinement based on single-crystal X-ray diffraction and topographic images of the hexagonal lattice array obtained using scanning tunnelling microscopy (see Supplementary Information). As shown in Fig. 1d, the longitudinal electric resistivity (\(\rho\)) decreases with decreasing temperature, showing a kink at \(T_{C} = 175\) K and a moderate residual resistivity of approximately 50 \(\mu\)Ω cm at 2 K. In a high field of 9 T, a negative magnetoresistance appears after the Curie temperature owing to the spin-dependent scattering in magnetic systems. At low temperatures, the magnetoresistance
increases and becomes positive (Fig. 1d). This behaviour is further demonstrated by the field-dependent resistance (Fig. 1e). Importantly, the positive magnetoresistance shows no signature of saturation even up to 14 T, which is typical of a semimetal\(^{1,3,11}\).

The notable nonlinear field dependence of the Hall resistivity \(\rho_{xy}\) (Fig. 1f) further indicates the coexistence of hole and electron carriers at 2 K, which is in good agreement with our band structure calculations (Fig. 1b, c). By using the semiclassical two-band model\(^2\), we extract the carrier densities of holes \((n_h = 9.3 \times 10^{19} \text{ cm}^{-3})\) and electrons \((n_e = 7.5 \times 10^{19} \text{ cm}^{-3})\) of our Co\(_3\)Sn\(_2\)S\(_2\) samples. These relatively low carrier densities and a near compensation of charge carriers further confirm the semi-metallicity of Co\(_3\)Sn\(_2\)S\(_2\).

In order to further analyse the topological character of Co\(_3\)Sn\(_2\)S\(_2\) suggested by Fig. 1b, we now consider the linear band crossings in more detail. The space group \(R-3m\) of Co\(_3\)Sn\(_2\)S\(_2\) has one mirror plane \((M_{00h})\). Without spin–orbit coupling, the interaction between spin-up and spin-down states is ignored and the mirror plane is a high-symmetry plane of the Hamiltonian. Thus, as they are protected by this mirror symmetry, the linear band crossing identified in Fig. 1b forms a nodal ring in the mirror plane based on the band inversion, as shown in Fig. 2a. Moreover, the linear crossings between the \(L\)–\(\Gamma\) and \(L\)–\(U\) paths are just single points on the ring. When the \(C\)\(_4\)-rotation and inversion symmetries of the material are considered, one finds a total of six nodal rings in the Brillouin zone, as shown schematically in Fig. 2b.

On taking spin–orbit coupling into account, the spin \(s_z\) is no longer a good quantum number and the mirror symmetry of the Hamiltonian is broken, which causes the linear crossings of the nodal lines to split, as presented in Fig. 2c. Interestingly, one pair of linear crossing points remains in the form of Weyl nodes along the former nodal line. These two Weyl nodes act as a monopole sink and source of Berry curvature (see Supplementary Information) and possess opposite topological charges of +1 and −1, respectively. In total, there are three such pairs of Weyl nodes in the first Brillouin zone due to the inversion and \(C\)\(_4\)-rotation symmetries of the crystal, and their distribution is presented in Fig. 2b. It is important to emphasize that the Weyl nodes in Co\(_3\)Sn\(_2\)S\(_2\) are only 60 meV above the charge neutrality point, which is much closer to the Fermi energy than for previously proposed magnetic Weyl semimetals. These Weyl nodes and non-trivial Weyl nodal rings together make this material exhibit a simple topological band structure around the Fermi level. It is thus easy to further observe the surface Fermi arcs\(^5\). As a result, the Weyl-node-dominated physics in Co\(_3\)Sn\(_2\)S\(_2\) should be prominent and easy to detect in experiments.

We now address the AHE response of Co\(_3\)Sn\(_2\)S\(_2\) that can be expected from the particular band structure properties outlined above. In order to obtain a complete topological character, we integrated the Berry curvature \(\Omega^\text{xy}\) along \(k\) in the Brillouin zone. Our results reveal two main types of hot spot for the integrated Berry curvature: one located around the Weyl nodes, and the other located near the edge of the nodal lines (see equation (3), Methods). The colour bars for d and e are in arbitrary units.

Fig. 2 | Theoretical calculations of the Berry curvature and anomalous Hall conductivity. a, Linear band crossings form a nodal ring in the mirror plane. b, Nodal rings and the distribution of the Weyl points in the Brillouin zone. c, Spin–orbit coupling breaks the nodal ring band structure into opened gaps and Weyl nodes. The Weyl nodes are located just 60 meV above the Fermi level, whereas the gapped nodal lines are distributed around the Fermi level. d, Berry curvature distribution projected to the \(k_x\)-\(k_z\) plane. e, Berry curvature distribution in the \(k_x\) plane. The colour bars for d and e are in arbitrary units. f, Energy dependence of the anomalous Hall conductivity in terms of the components of \(\Omega^\text{xy}\) \((k)\).
neutral or slightly p-doped Co$_3$Sn$_2$S$_2$ samples. We also consider the non-collinear magnetic structure of the kagome lattice in Co$_3$Sn$_2$S$_2$. During spin tilting away from the $c$ axis, the calculated $\sigma_c$ always stays above 1,000 $\Omega^{-1}$ cm$^{-1}$. The existence of Weyl nodes and the large anomalous Hall conductivity are robust against the change of the magnetic structure of Co$_3$Sn$_2$S$_2$ (see Supplementary Information).

A Weyl semimetal is expected to exhibit the so-called chiral anomaly in transport, when the conservation of chiral charges is violated in the case of a parallel magnetic and electric field, as shown in Fig. 3a. We measured the impact of the magnetic field orientation on the transverse resistivity at 2 K (Fig. 3b). For $B \perp I$ ($\theta = 90^\circ$), a positive unsaturated magnetoresistance (also see Fig. 1e) is observed. The magnetoresistance decreases rapidly with decreasing angle. A negative magnetoresistance appears when $B // I$ (Fig. 3d), and the coercive field is 0.33 T at 2 K (also see Supplementary Information). As is evident from the figure, a large remanent Hall effect at zero field is observed in this material.

We plot $\rho_{H}^{A}$ as a function of temperature in Fig. 4c. A large peak in $\rho_{H}^{A}$ with a maximum of 44 $\mu$\Omega cm appears at 150 K. When $\sigma^0$ is plotted against $\sigma_A$, as presented in Fig. 4d, we also find that $\sigma^0_A$ is nearly independent of $\sigma$ (that is, $\sigma^0_A \sim (\sigma)^2$ constant) for temperatures below 100 K, as expected for an intrinsic AHE in the framework of the unified model for AHE physics$^{39,40}$ (see Supplementary Information for more details). This independence of $\rho_{H}^{A}$ with respect to both $T$ and $\rho$ indicates that the AHE originates only from the intrinsic scattering-independent mechanism, and is thus dominated by the Berry curvature in momentum space. This scaling behaviour is consistent with our first-principles calculations and provides another important signature for the magnetic Weyl fermions in Co$_3$Sn$_2$S$_2$.

In addition to a large $\sigma^0_A$, and arguably more importantly, the magnetic Weyl semimetal Co$_3$Sn$_2$S$_2$ also features a giant anomalous Hall angle that can be characterized by the ratio of $\sigma^0_A/\sigma$. The temperature dependence of $\sigma^0_A/\sigma$ is shown in Fig. 5a. With increasing temperature, $\sigma^0_A/\sigma$ first increases from 5.6% at 2 K, reaching a maximum...
of approximately 20% around 120 K, before decreasing again as the temperature increases above \( T_C \). The contour plot of \( \sigma_H/\sigma \) with respect to \( B \) and \( T \) is depicted in Fig. 5b, and makes it intuitively clear that a giant Hall angle appears between 75 and 175 K irrespective of the magnetic fields magnitude. This can be straightforwardly understood by considering that \( \sigma_H \) arises from the Berry curvature of the occupied states. The band topology of these states is basically unaffected by the small energy scale of thermal excitations up to room temperature\(^4^1\). In other words, the topologically protected \( \sigma_H \) is relatively robust against temperature. In contrast, the Weyl-node-related charge conductivity (\( \sigma \)) is sensitive to temperature, due to electron–phonon scattering\(^4^2\). These behaviours are also shown in Fig. 5a. Therefore, \( \sigma_H/\sigma \) is expected to increase with increasing temperature in a wide temperature range below \( T_C \). The semimetallicity (low carrier density and low charge conductivity) largely improves the value of \( \sigma_H/\sigma \) in this system.

When compared to previously reported results for other AHE materials (see Fig. 5c), the value of the anomalous Hall angle in \( \text{Co}_3\text{Sn}_2\text{S}_2 \) observed in this work is seen to be the largest by a prominent margin. For most of these materials—formed mainly of ferromagnetic transition metals and alloys—the anomalous Hall conductivities originate from topologically trivial electronic bands. A typical feature of these materials is that both \( \sigma_{H} \) and \( \sigma \) are either large or small, and therefore \( \sigma_{H}/\sigma \) for these materials typically cannot be large. Although the magnetic-field-induced Weyl semimetal \( \text{GdPtBi} \) has a large \( \sigma_{H}/\sigma \) (16%), its \( \sigma_{H} \) is very small and, moreover, it requires an external field to induce the Weyl phase\(^3^5\). In contrast, owing to the non-trivial Berry curvature and the Weyl semi-metallic character, the kagome-lattice \( \text{Co}_3\text{Sn}_2\text{S}_2 \) possesses both a large \( \sigma_{H} \) and giant \( \sigma_{H}/\sigma \), simultaneously and at zero magnetic field, which makes this system unusual among the known AHE materials.

As a consequence, a large anomalous Hall current can be expected in thin films of this material, which may even reach the limit of a quantized AHE with dissipationless quantum Hall edge states\(^2^4\). In more general terms, a clean topological band structure induces both a large anomalous Hall conductivity and giant anomalous Hall angle (as demonstrated here for the Weyl semimetal \( \text{Co}_3\text{Sn}_2\text{S}_2 \)), and so can be seen as a guide for the realization of strong AHE in (half-metallic) magnetic topological Weyl semimetals.

In summary, \( \text{Co}_3\text{Sn}_2\text{S}_2 \) is a Weyl semimetal candidate derived from a ferromagnetic kagome lattice. It is the first material that hosts both a large anomalous Hall conductivity and a giant anomalous Hall angle that originate from the Berry curvature. This compound is an ideal candidate for developing a quantum anomalous Hall state due to its long-range quasi-2D out-of-plane ferromagnetic order and simple electronic structure near the Fermi energy. Moreover, it is straightforward to grow large, high-quality, single crystals, which makes \( \text{Co}_3\text{Sn}_2\text{S}_2 \) and the Shandite family an excellent platform for comprehensive studies on topological electron behaviour. Our work motivates the study of the strong anomalous Hall effect based on magnetic Weyl semimetals, and establishes the ferromagnetic kagome-lattice Weyl semimetals as a key class of materials for fundamental research and applications connecting topological physics\(^4^6\) and spintronics\(^4^9\).

**Methods**

Methods, including statements of data availability and any associated accession codes and references, are available at https://doi.org/10.1038/s41567-018-0234-5.

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Fig. 5 | Transport measurements of the anomalous Hall angle. a, Temperature dependences of the anomalous Hall conductivity ($\sigma_{\text{H}}$), the charge conductivity ($\sigma$) and the anomalous Hall angle ($\alpha_{\text{H}}$) at zero magnetic field. Since the ordinary Hall effect vanishes at zero field, the anomalous Hall contribution prevails (see Supplementary Information). b, Contour plots of the Hall angle in the $B$–$T$ space. c, Comparison of our $\alpha_{\text{H}}$-dependent anomalous Hall angle results and previously reported data for other AHE materials. ‘(f)’ denotes thin-film materials. The dashed line is a guide to the eye. The reported data were taken from references that can be found in the Supplementary Information.

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**Author contributions**

The project was conceived by E.L. and C.F. Single crystals were grown by E.L., who performed the structural, magnetic and transport measurements with assistance from A.S., J.K., S.Y., V.S., H.B., N.K. and W.S. The STM characterizations were performed by L.J. and S.W. The ARPES measurements were conducted by D.L., A.L. and Y.C. The static high-magnetic-field measurements were performed and analysed by Z.W., C.S. and L.J. The theoretical calculations were carried out by Y.S., L.M., Q.X. and E.L. All the authors discussed the results. The paper was written by E.L., Y.S. and S.T.B.G. with feedback from all the authors. The project was supervised by C.F.

**Competing interests**

The authors declare no competing interests.

**Additional information**

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Methods

Single-crystal growth. The single crystals of Co3Sn2S2 were grown by self-flux methods with Sn as flux or with the congruent composition in a graphite crucible sealed in a quartz tube (see Supplementary Information). The stoichiometric samples (Co:Sn:S = 3:2:2) were heated to 1,000 °C over 48 hours and kept there for 24 hours for being slowly cooled to 600 °C over seven days. The samples were kept at 600 °C for 24 hours to obtain homogeneous and ordered crystals. The compositions of crystals were checked by energy-dispersive X-ray spectroscopy. The crystals were characterized by powder X-ray diffraction as single phase with a Shandite-type structure. The lattice parameters at room temperature are a = 5.3689 Å and c = 13.176 Å. The single crystals and orientations were confirmed by a single-crystal X-ray diffraction technique.

Scanning tunnelling microscopy (STM). Topographic images of the crystal surface were characterized by cryogenic STM, taken at conditions of T = 2.5 K, a bias voltage of Vc = 100 mV and a tunnel current of I = 500 pA. The sample was cleaved in situ (p < 2 × 10⁻⁵ Pa) at 20 K. The high quality of the single crystals was confirmed by STM (see Supplementary Information).

Magnetization measurements. Magnetization measurements were carried out on oriented crystals with the magnetic field applied along both the a and c axes using a vibrating sample magnetometer (MPMS 3, Quantum Design). The results on oriented crystals with the magnetic field applied along both the a and c axes. The magnetic anisotropy in Co3Sn2S2 (see Supplementary Information).

Out-of-plane transport measurements. The out-of-plane transport measurements on longitudinal charge and Hall resistivities, with B // z // [0001] and I // x // [1110], were performed on a PPMMS 9 (Quantum Design) using the low-frequency alternating current (ACT) option. The standard four-probe method was used to measure the longitudinal electrical resistivity, whereas for the Hall resistivity measurements, the five-probe method was used with a balance protection meter to eliminate possible magnetoresistance signals. The charge and Hall resistivities were measured in turn at each temperature.

Angle-dependent longitudinal electric resistivity. The angle dependence of longitudinal electric resistivity was measured on a PPMS DynaCool (Quantum Design) using the ‘DC Resistivity’ option. For the angle-dependent measurements, B // θ and I // x // [1110], while θ is the angle with respect to x // [1110]. The currents were always applied along the a axis, for example, I // x // [1110] (a axis = x axis). Different crystals, grown by two self-flux methods and with different RRR (ρ_arr/ρ_ab) values, were used in this study.

Analysis of Hall effect and semi-metallicity. At high temperatures (50 K < T < Tc), the Hall signal shows a linear field-dependent behaviour after saturation. At low temperatures (T < 50 K), a notable non-linear field dependence of the Hall resistivity is observed, indicating the existence of two types of carriers (electrons and holes). The electronic carriers appear at low temperatures. The single-band and two-band models were thus applied to extract the pure anomalous Hall resistivity, carrier densities and mobilities, for high-temperature and low-temperature cases, respectively.

The anomalous Hall conductivity was calculated by

$$\sigma_{iH} = \frac{\rho_i}{\rho} \delta_i$$

Here $\rho_i$ is the anomalous Hall resistivity at zero field and $\rho$ is the longitudinal resistivity at zero field.

The two-band model was applied to extract the densities of both carriers at low temperatures.

$$\sigma(B) = \frac{\eta_i \mu_i}{1 + \mu_i^2 B^2} + \frac{\eta_i \mu_i}{1 + \mu_i^2 B^2}$$

$$\sigma_{iH}(B) = \frac{\eta_i \mu_i \mu_e B}{1 + \mu_e^2 B^2} + \frac{\eta_i \mu_i \mu_h B}{1 + \mu_h^2 B^2}$$

Here $B$ is the applied magnetic field, $\sigma(B)$ is the longitudinal charge conductivity, $\sigma_{iH}(B)$ is the anomalous Hall effect, $n_i$ is the carrier concentration of holes, $\mu_i$ is the carrier mobility of holes, $n_e$ is the carrier concentration of electrons and $\mu_e$ is the carrier mobility of electrons.

Longitudinal magnetoresistance in static high magnetic fields. The field-dependent longitudinal magnetoresistance was measured in static magnetic fields as high as 37 T, by a standard four-probe method in a 3He cryostat with B // c axis, using a hybrid magnet at the High Magnetic Field Laboratory, Chinese Academy of Sciences. The current was 5 mA, modulated at a frequency of 13.7 Hz by means of a Keithley 6221. The voltage was measured by a SR830 Lock-In Amplifier. The Shubnikov–de Haas (ShD) quantum oscillations of magnetoresistivity were observed above 17 T in the present crystal. A cubic polynomial background was subtracted from the resistivity data. For the fast Fourier transform, a Hanning window was applied in the Origin software.

Density functional theory (DFT) calculations. The electronic structure calculations were performed on the basis of DFT using the Vienna ab-initio simulation package (VASP),25. The exchange and correlation energies were considered in the generalized gradient approximation (GGA), following the Perdew–Burke–Ernzerhof parametrization scheme.25. We have projected the Bloch wavefunctions into Wannier functions,10 and constructed the tight-binding model Hamiltonian based on Wannier functions. The anomalous Hall conductivity and Berry curvature were calculated by the Kubo formula approach in the linear response and clean limit:

$$\sigma_{iH}(E) = e^2 h \left( \frac{1}{2\pi} \right)^3 \int d\mathbf{k} \sum_{\nu,\ell} f(n,\mathbf{k}) \Omega_{i\nu}(\mathbf{k})$$

$$\Omega_{i\nu}(\mathbf{k}) = \text{Im} \sum_{\nu,\ell} \frac{\langle \mathbf{u}(n,\mathbf{k}) | \mathbf{F}^\dagger_{\nu,\ell} | \mathbf{u}(n,\mathbf{k}) \rangle \langle \mathbf{u}(n,\mathbf{k}) | \mathbf{F}^\dagger_{\nu,\ell} | \mathbf{u}(n,\mathbf{k}) \rangle - (x \leftrightarrow y)}{(E(n,\mathbf{k}) - E(n,\mathbf{k}))^2}$$

where $f(n,\mathbf{k})$ is the Fermi–Dirac distribution, $E(n,\mathbf{k})$ is the eigenvalue of the nth eigenstate of $\mathbf{u}(n,\mathbf{k})$ at the k point, and $\mathbf{F}^\dagger_{\nu,\ell}$ is the velocity operator.

The numerical integration was performed using a 501 × 501 × 501 k-grid. The Fermi surfaces were calculated by means of a k-grid of 120 × 120 × 120 from the tight-binding model Hamiltonian, and the frequencies of electron oscillations were calculated from the extremal cross-sectional areas of the Fermi surface perpendicular to the applied magnetic field (see Supplementary Information).

Angle-resolved photoemission spectroscopy (ARPES). ARPES measurements on single crystals were performed at beamline B1.5.2 of the Stanford Synchrotron Radiation Lightsource, SLAC National Accelerator Laboratory, and beamline B1.10.0.1 of the Advanced Light Source (ALS). The data were recorded by a Scienta-RA-000 Analyzer at $p = 4 \times 10^{-10}$ Pa at 20 K in both facilities. The total convolved energy and angle resolutions were $E = 10$ to 20 meV and $\theta = 0.2^\circ$, respectively. Good agreements of the Fermi surfaces and energy dispersions from ARPES measurements and DFT calculations are also obtained (see Supplementary Information).

Data availability. The data that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request.

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