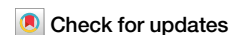


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Néel vector-dependent anomalous transport in altermagnetic metal CrSb

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Altermagnets are predicted to exhibit anomalous transport phenomena, such as the anomalous Hall and Nernst effects, as observed in ferromagnets but with a vanishing net magnetic moment, akin to antiferromagnets. Despite their potential, progress has been limited due to the scarcity of metallic altermagnets. Motivated by the recent discovery of the altermagnetic metal CrSb, we conducted a systematic study of its electrical and thermoelectric transport properties, using first-principles calculations. CrSb exhibits low magnetocrystalline anisotropy energy, enabling the manipulation of the Néel vector in CrSb films through a suitable ferromagnetic substrate. The anomalous Hall and Nernst conductivities reach their maximum when the Néel vector is aligned along $\frac{1}{2}\mathbf{a} + \mathbf{b}$. The origins of both conductivities were analyzed in terms of Berry curvature distribution. Our results demonstrate that CrSb provides a good platform for investigating the Néel vector-dependent anomalous transport in altermagnetic metals.

Magnetism has long been a central topic in condensed-matter physics. Within the domain of collinear magnetism, attention has traditionally been directed toward two primary types: ferromagnetism, where spins in a lattice align in a uniform direction, and antiferromagnetism, characterized by two spin sublattices with opposite orientations. Recently, a novel class of magnetism, termed altermagnetism, has been proposed^{1–7}. This emerging class distinguishes itself from the two conventional types. In altermagnets, the net magnetization is vanishing, similar to antiferromagnets. However, it is the rotational symmetry (proper or improper, symmorphic or non-symmorphic) not the inversion or translation symmetry operation that relates the two antiparallel sublattices, leading to a spin-splitting band structure, reminiscent of ferromagnets. As a key characteristic of altermagnets, the spin-splitting electronic structure has been widely investigated through theoretical calculations^{8,9,31}, but experimental evidence remains scarce. The first experimentally confirmed altermagnet, identified through angle-resolved photoemission spectroscopy (ARPES) measurements, is MnTe^{32–34}.

Owing to the odd parity of Berry curvature (BC) with respect to time-reversal operation, nonmagnetic systems with time-reversal symmetry exhibit no anomalous Hall effect (AHE), whereas the situation is different for ferromagnets^{35,36}. In certain magnetic materials, while time-reversal symmetry is broken, the combination of time-reversal symmetry with specific space group operation ensures that the net BC over the entire Brillouin zone sums to zero^{37,38}. This generally applies to antiferromagnets

with two magnetic sublattices connected by PT or $T|t$ symmetry, where P is inversion, T is time reversal, and t is a lattice translation. However, a nonzero net BC and a finite intrinsic AHE are permitted in altermagnets with spin splitting. The AHE in altermagnets has been both theoretically studied and experimentally observed in RuO₂³⁹, Mn₅Si₃⁴⁰, and MnTe³³. However, specific constraints within these materials limit further exploration of AHE. To be specific, the magnetic ground state of RuO₂ remains under debate^{41–47}. MnTe is a semiconductor with a band gap of about 1.3 eV, exhibiting suboptimal conductivity compared to metals^{48,49}. As for Mn₅Si₃, its magnetic states are sensitive to temperature and noncollinear magnetic structures are involved, which limits the measurements and applications in anomalous transport of collinear altermagnetic phase^{50–53}. Therefore, altermagnetic metals with high Néel temperatures are widely sought after.

Recently, CrSb was identified as a new altermagnetic metal through experimental studies, unveiling a range of novel physical phenomena. The existence of different carriers with high mobility yielding a nonlinear magnetic field dependence of the Hall effect was revealed⁵⁴. Additionally, ARPES measurements and first-principles calculations identified surface Fermi arcs near the Fermi level, which originate from bulk band topology⁵⁵. Most notably, the key characteristic of altermagnets, spin splitting up to 1.0 eV along non-high-symmetry paths near the Fermi level, was observed by ARPES measurements from different groups^{55–59}. These properties establish CrSb as a prominent material among altermagnets. In comparison to MnTe, CrSb exhibits metallic characteristics that offer superior

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conductivity, thereby benefiting transport property measurements. Furthermore, in contrast to Mn_5Si_3 , the altermagnetic ground state of CrSb exhibits little sensitivity to temperature, with a relatively high Néel temperature exceeding 700 K^{60} , thereby offering a broad temperature range for investigating properties related to the altermagnetic state.

Considering the significance of altermagnetic metals in the study of anomalous transport and the remarkable characteristics of CrSb, including its high T_N and large spin splitting, exploring anomalous transport in CrSb is of great importance. In this study, we conducted a comprehensive investigation of the anomalous transport properties in CrSb. First, the magneto-crystalline anisotropy energy (MAE) of CrSb was evaluated based on total energy calculations. Next, we examined the dependence of the anomalous Hall conductivity (AHC) and anomalous Nernst conductivity (ANC) in CrSb on the orientation of the Néel vector. Finally, the origins of AHC and ANC were explored by analyzing the BC distribution across the entire Brillouin zone.

Methods

We performed density functional theory (DFT) calculations using the Vienna ab initio simulation package (VASP)⁶¹. The experimental lattice constants $a = b = 4.103\text{ Å}$ and $c = 5.463\text{ Å}$ were used, which theoretically reproduced the ARPES results very well^{55,59}. The exchange-correlation functional was treated using the Perdew-Burke-Ernzerhof (PBE) generalized-gradient approximation⁶². An energy cutoff of 400 eV was employed, with an energy criterion of 10^{-7} eV , and a k mesh of $11 \times 11 \times 9$ points was used. From the DFT band structure, Wannier functions were generated using WANNIER90⁶³, with initial projections onto the $3d$ orbitals of Cr and the $5p$ orbitals of Sb. To evaluate the BC, the tight-binding Hamiltonian H was constructed from the Wannier functions and applied with the Kubo formula

$$\Omega_{ij}^n = \text{Im} \sum_{m \neq n} \frac{\langle n | \frac{\partial H}{\partial k_i} | m \rangle \langle m | \frac{\partial H}{\partial k_j} | n \rangle - (i \leftrightarrow j)}{(E_n - E_m)^2}, \quad (1)$$

where Ω_{ij}^n denotes the ij component of the BC of the n th band, $|n\rangle$ and $|m\rangle$ represents the eigenstates of H , respectively. Based on this equation, we can obtain the ij component of the AHC σ_{ij} by integrating the BC over the entire Brillouin zone

$$\sigma_{ij} = \frac{e^2}{h} \sum_n^{\text{occ}} \int \frac{d^3k}{(2\pi)^3} \Omega_{ij}^n, \quad (2)$$

where occ denotes the bands occupied by electrons. The ANC α_{ij} can be obtained by

$$\alpha_{ij} = \frac{1}{T} \frac{e}{h} \sum_n \int \frac{d^3k}{(2\pi)^3} \Omega_{ij}^n \left[(E_n - E_F) f_n + k_B T \ln \left(1 + \exp \frac{E_n - E_F}{-k_B T} \right) \right], \quad (3)$$

where T denotes the temperature, k_B is the Boltzmann constant, E_F is the Fermi level, and f_n is the Fermi distribution. A k mesh of $192 \times 192 \times 192$ points was used for both AHC and ANC calculations to obtain convergent values.

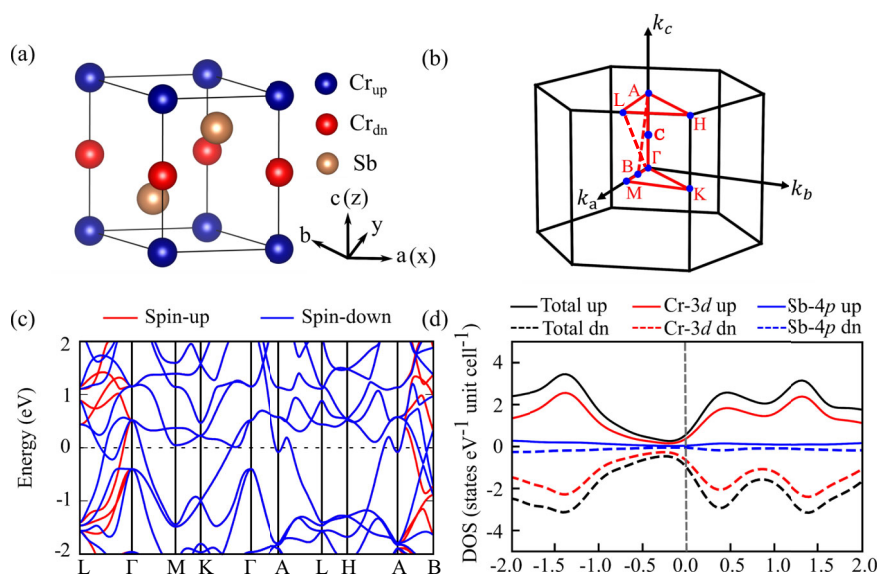
RESULTS

Spin-splitting band structure of CrSb

Figure 1(a) presents the three-dimensional crystal structure of CrSb, which has a typical hexagonal NiAs-type configuration. Within one unit cell, there are two Cr atoms and two Sb atoms. The space group of CrSb is $P6_3/mmc$, where each Cr atom is surrounded by six Sb atoms. Along the c direction, the layers of Cr and Sb atoms alternate in stacking. The Cr atoms within the same layer have the same spin orientation along the c direction, while Cr atoms in different layers exhibit opposite spin orientations. Considering only the two opposite magnetic sublattices, CrSb displays typical A-type antiferromagnetism. However, when taking the local environment formed by the Sb atoms into account, CrSb behaves as an altermagnet due to the M_z mirror operation, or the combination of the rotation operation C_{6z} and translation operations relating two sublattices, rather than inversion or translation operation typical in antiferromagnets. In the spin-group formalism, CrSb is a g-wave altermagnet with four nodal planes protected by $[C_2||C_{6z}t]$ and $[C_2||M_z]$, and belongs to $2^6/m^2m^1m$ spin Laue group².

The fundamental hallmark of altermagnetism lies in the spin-splitting band structure. Figure 1(c) presents the band structure along the high-symmetry lines, as well as along a non-high-symmetry path, labeled $A - B$, as shown in Fig. 1(b). The bands along $\Gamma - M - K - \Gamma$ on the $k_z = 0$ plane and $A - L - H - A$ on the $k_z = \pi$ plane are spin-degenerate. In contrast, this is not the case along the $L - \Gamma$ and $A - B$ path, where point B locates at midpoint of $\Gamma - M$, indicating the spin-splitting characteristic in CrSb. The calculated band structure agrees with the results reported in ref. 2, which was the first to identify the altermagnetic band structure of CrSb. Figure 1(d) shows the density of states (DOS), where the total and orbital-resolved DOS for opposite spins are identical in magnitude. This equality arises because the symmetry operations connecting the two sublattices also relate the energy bands with opposite spins in reciprocal space.

Fig. 1 | Crystal structure and electronic structure of CrSb. **a** Crystal structure of CrSb with space group $P6_3/mmc$ (No. 194). The blue and red spheres represent Cr atoms with opposite magnetic moment, and the brown spheres represent Sb atoms. **b** Brillouin zone of the CrSb structure. **c** Band structure of CrSb, with red and blue lines denoting spin-up and spin-down bands, respectively. **d** The total electronic density of states and partial orbit-resolved electronic density of states with spin up and spin down character in the altermagnetic state.



Magnetocrystalline anisotropy energy in CrSb

Despite the spin-splitting characteristics in CrSb, the AHE is symmetry-forbidden when the Néel vector aligned along c . Interestingly, the calculated MAE is found to be rather weak, indicating that the Néel vector can be easily tuned by an external field. Figure 2 illustrates the dependence of total energy on the Néel vector, with the total energy of the nonmagnetic state normalized to zero. The inset depicts the

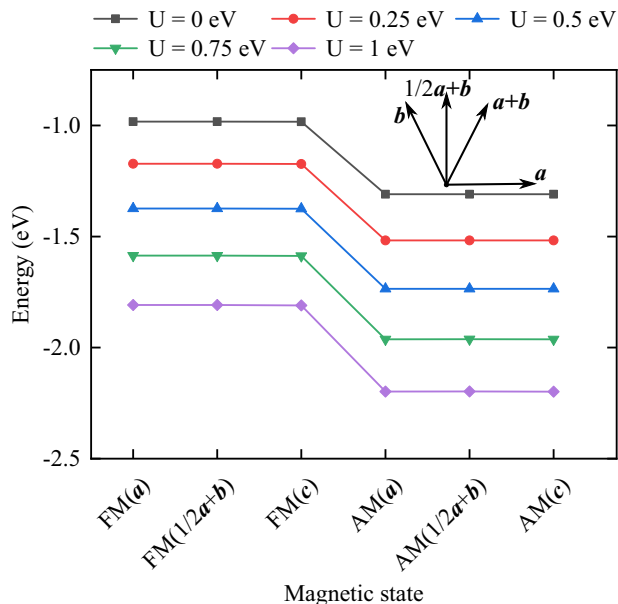


Fig. 2 | Dependence of total energy on the orientation of the magnetic moment in the ferromagnetic state and the Néel vector in the antiferromagnetic state. The total energy of the nonmagnetic state is aligned to zero. Different lines represent results obtained with varying Coulomb repulsion energies, ranging from 0 to 1 eV. The inset depicts the vector orientations, with c indicating the out-of-plane direction.

Table 1 | Total energy of CrSb in units of meV, calculated for different Néel vectors and on-site Coulomb repulsion energies U

	$U = 0$ eV	$U = 0.25$ eV	$U = 0.5$ eV	$U = 0.75$ eV	$U = 1$ eV
a	0.008	0.185	0.064	-0.033	0.335
$\frac{1}{2}a + b$	0.164	0.153	0.230	0.119	0.567
c	0	0	0	0	0

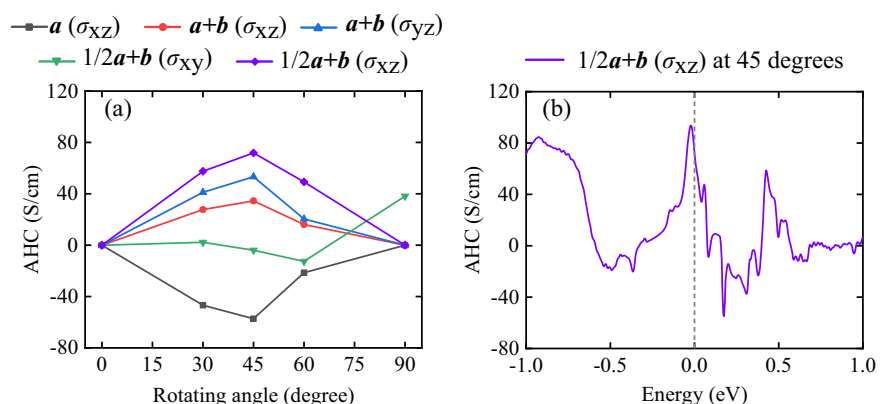
The total energy with the Néel vector aligned along c is aligned to zero.

vector orientations, where c indicates the out-of-plane direction. All ferromagnetic and antiferromagnetic states have negative energies, and the antiferromagnetic states are significantly lower than the ferromagnetic ones. This result is robust, remaining consistent even when the Hubbard U is applied to the Cr 3d orbitals, and it aligns well with experimental findings that confirm the antiferromagnetic state as the magnetic ground state⁶⁰. Moreover, the difference of total energies among different ferromagnetic or antiferromagnetic states with different magnetic moments and Néel vector orientations is too small to be discernible in Fig. 2. Table 1 lists the total energies of antiferromagnetic states calculated with different Néel vectors. The difference of total energies is smaller than 1 meV, approaching the accuracy limit of DFT. Besides, except for the case with $U = 0.75$ eV, the antiferromagnetic state with Néel vector aligned along c turns to be the magnetic ground state, the same as experimental findings⁶⁰. Additionally, calculations with different Néel vector orientations, without using a penalty functional to constrain the magnetic moment, easily converge to the given orientation of the Néel vector, further confirming the weak MAE of CrSb. Within this context, it is meaningful to study the dependence of anomalous transport on the orientation of the Néel vector.

Anomalous Hall and Nernst conductivities

Figure 3 (a) presents the nonzero elements of the AHC tensor as the Néel vector rotates from c to three representative orientations, within the corresponding plane formed by the Néel vector present in the legend and c . Notably, using the Cartesian coordinates defined in Fig. 1 (a), there are two independent nonzero elements of the AHC tensor, namely σ_{xz} and σ_{yz} when the Néel vector rotates from c to $a + b$, and σ_{xy} and σ_{xz} when it rotates from c to $\frac{1}{2}a + b$. This is consistent with symmetry analysis. For example, When the Néel vector is oriented between c and $\frac{1}{2}a + b$, the presence of the combined symmetry of $\{m_z | 00\frac{1}{2}\}$ and the combination of $\{C_{2y} | 00\frac{1}{2}\}$ with the time-reversal operation T implies that $\sigma_{yz} = 0$. Specifically, when considering the C_{2y} symmetry operation, the three components of the Berry curvature $[\Omega_{yz}(k_x, k_y, k_z), \Omega_{zx}(k_x, k_y, k_z), \Omega_{xy}(k_x, k_y, k_z)]$ transform to $[-\Omega_{yz}(-k_x, k_y, -k_z), \Omega_{zx}(-k_x, k_y, -k_z), -\Omega_{xy}(-k_x, k_y, -k_z)]$. When m_z is taken into consideration, $[\Omega_{yz}(-k_x, k_y, k_z), -\Omega_{zx}(-k_x, k_y, k_z), -\Omega_{xy}(-k_x, k_y, k_z)]$ are derived. Finally, when considering the time-reversal operation, $[-\Omega_{yz}(k_x, -k_y, -k_z), \Omega_{zx}(k_x, -k_y, -k_z), \Omega_{xy}(k_x, -k_y, -k_z)]$ are obtained. Consequently, the Hall vector $\mathbf{h}$ lacks an x component and thus takes the form $(0, -\sigma_{xz}, \sigma_{xy})$, which is consistent with previous symmetry analysis results⁶⁴ and double-checked using the *Symmetry* software⁶⁵. As shown in Fig. 3(a), the whole AHC tensor elements transition from zero to a maximum at a rotation angle of 45 degrees and ultimately return to zero as the Néel vector rotates, excluding σ_{xy} . Our calculations indicate that the strongest AHC, $\sigma_{xz} \approx 72$ S/cm, occurs when the Néel vector is rotated 45 degrees from c to $\frac{1}{2}a + b$. Figure 3(b) shows its dependence on energy, revealing a sharp peak of approximately 98 S/cm located to the left of the Fermi level, suggesting that a rapid increase in AHC can be expected with light hole doping.

Fig. 3 | Rotating angle-dependent and energy-dependent AHC. **a** Dependence of AHC on the Néel vector as it rotates from c to the orientations indicated in the legend. The letters in parentheses denote the nonzero elements of the AHC tensor σ corresponding to Néel vector. Note that there are two independent nonzero AHC tensor elements when the Néel vector rotates from c to $a + b$ and $\frac{1}{2}a + b$. **b** Energy dependence of σ_{xz} with the Néel vector aligned at 45 degrees from c , as it rotates from c to $\frac{1}{2}a + b$.



We next examine the dependence of ANC on the orientation of the Néel vector. Table 2 presents the calculated values of the nonzero elements of the ANC tensor as the Néel vector is rotated. Notably, the Néel vector corresponding to the strongest AHC exhibits a maximal ANC value of -0.19 A/m/K. Figure 4(a) presents its dependence on energy. At low temperatures, ANC can be derived from AHC using Mott relation

$$\alpha_{ij} = \frac{\pi^2 k_B^2 T}{3e} \frac{\partial \sigma_{ij}}{\partial E}(E_F). \quad (4)$$

The pink dashed line in Fig. 4(a) represents the ANC at $T = 50$ K derived from the AHC shown in Fig. 3(b) using Eq. (4). The large value of ANC around the Fermi level arises from the sharp variation of AHC at the corresponding energy position. The ANC calculated using the BC formalism (see the blue solid line in Fig. 4(a) using Eq. (3)) agrees well with the results from the Mott relation.

From an application perspective, investigating the dependence of the ANC on temperature is meaningful. Given that CrSb has a high Néel temperature, we calculated the ANC at temperatures around room temperature. Figure 4(b) shows the calculated ANC at the Fermi level as a function of temperature. The absolute value of ANC increases sharply from 50 K to 125 K, then decreases gradually from 125 K to 450 K. The maximum absolute value of ANC is about 0.224 A/m/K, which is lower than that of typical ferromagnets⁶⁶ but comparable to RuO_2 ¹¹. Notably, the ANC remains significant at -0.185 A/m/K at room temperature, and its decrease slows as the temperature rises, indicating potential for thermoelectric applications.

Berry curvature distribution

To gain deeper insight into the significant AHC and ANC with the Néel vector oriented at 45 degrees from $\mathbf{c}$ during its rotation from $\mathbf{c}$ to $\frac{1}{2}\mathbf{a} + \mathbf{b}$, we investigate the origin of them by analyzing the BC distribution within the Brillouin zone. Figure 5(a) shows the band structure along the $M-C-B$ path, excluding SOC, where C is located at the midpoint of $A-\Gamma$ and B at the midpoint of $M-\Gamma$, as shown in Fig. 1(b). The spin-down bands exhibit two

crossing points near the Fermi level, indicated by green circles. As shown in Fig. 5(b), when SOC is included, these crossing points open gaps, positioning the Fermi level within the gap along the $C-B$ path, which contributes to a nonzero BC at the Fermi level. A thorough analysis of the crossing points across the entire Brillouin zone reveals multiple nodal rings formed by both spin-up and spin-down bands. Figure 5(c) shows the locations of these nodal rings, with red and blue lines representing those formed by spin-up and spin-down bands, respectively. The nodal rings can be categorized into two groups for each spin. One group consists of two nodal rings lying in the $M-C-B$ plane, with three equivalent planes in the Brillouin zone, resulting in a total of six nodal rings protected by corresponding mirror planes. The other group comprises a wave-like nodal ring around the $k_z = 0$ plane, protected by a complex conjugation symmetry, as discussed in ref. 55. Nodal rings with different spin characters can be related by the M_z mirror operation. With the inclusion of SOC, these nodal rings become gapped, resulting in significant BC around the former nodal rings. Figure 5(d) displays the BC distribution and the nodal rings, showing intimate connection between them. Thus, we conclude that the significant AHC and ANC in CrSb arise from the SOC-induced gap openings of the numerous nodal rings.

Experimental setups for detecting the anomalous Hall effect

At last, we related our theoretical results to the practical realization of such configurations in experiments. Park et al. reported that the Néel vector of an antiferromagnetic IrMn film can be tuned by an adjacent ferromagnetic film, where exchange coupling between the ferromagnet and antiferromagnet is the driving force⁶⁷. Based on this experimental finding, we designed experimental setups to achieve the aforementioned rotations of the Néel vector from $\mathbf{c}$ to desired orientations and to detect the anomalous Hall signal. For example, Fig. 6(a) presents the experimental setup for the detection of σ_{xz} when the Néel vector rotates from $\mathbf{c}$ to $\mathbf{a}$. The CrSb (0110) film grown along $\frac{1}{2}\mathbf{a} + \mathbf{b}$ is adequate for measuring the anomalous Hall signal originating from nonzero σ_{xz} . The orientation of the Néel vector along $\mathbf{c}$ in the ground state would tilt towards the direction of the ferromagnetic moments in the ferromagnetic substrate. The canting of the Néel vector could be less prominent than the rotation due to the strong antiferromagnetic coupling between opposite magnetic sublattices in CrSb, which gives rise to the rather high Néel temperature (exceeding 700 K). In fact, although Néel vector canting could be induced by damping-like spin-orbit torque and Dzyaloshinskii-Moriya torque, the observed AHE signal has been demonstrated to originate primarily from the altermagnetic order in the mirror-symmetry-broken CrSb films rather than from canting⁶⁸. Note that the magnetic moments of the ferromagnetic substrate in Fig. 6(a) are along $\mathbf{a}$, and thus the ferromagnetic substrate does not contribute to the anomalous Hall signal in this setup, owing to the common expression $J^{\text{AHE}} \sim M \times E$, which is suitable for most ferromagnets. As shown by the gray line in Fig. 3(a), once the Néel vector tilts from $\mathbf{c}$ to $\mathbf{a}$, σ_{xz} becomes nonzero, the AHE signal can be detected. The ease and amplitude of Néel vector rotation driven by the ferromagnetic substrate depend on external stimuli such as temperature, the exchange energy between the ferromagnetic substrate and

Table 2 | ANC α at 300 K, in units of A/m/K, as the Néel vector rotates from $\mathbf{c}$ to the orientations listed in the first column

		0	30	45	60	90
$\mathbf{a}$	α_{xz}	0	0.07	0.10	0.05	0
$\mathbf{a} + \mathbf{b}$	α_{xz}	0	-0.02	-0.02	0.02	0
$\mathbf{a} + \mathbf{b}$	α_{yz}	0	-0.06	-0.07	-0.02	0
$\frac{1}{2}\mathbf{a} + \mathbf{b}$	α_{xy}	0	-0.06	-0.07	-0.08	0.06
$\frac{1}{2}\mathbf{a} + \mathbf{b}$	α_{xz}	0	-0.11	-0.19	-0.18	0

Note that there are two independent nonzero ANC tensor elements when the Néel vector rotates from $\mathbf{c}$ to $\mathbf{a} + \mathbf{b}$ and $\frac{1}{2}\mathbf{a} + \mathbf{b}$. The rotation angles range from 0–90 degrees.

Fig. 4 | Energy-dependent and temperature-dependent ANC. a ANC α_{xz} in CrSb at 50 K, with the Néel vector aligned at 45 degrees from $\mathbf{c}$ during rotation from $\mathbf{c}$ to $\frac{1}{2}\mathbf{a} + \mathbf{b}$. Results are calculated using both the BC formalism in Eq. (3) (blue solid line) and the Mott relation in Eq. (4) (pink dashed line). **b** Temperature dependence of ANC α_{xz} , with red points representing the original calculation results and the blue line indicating the fitting curve.

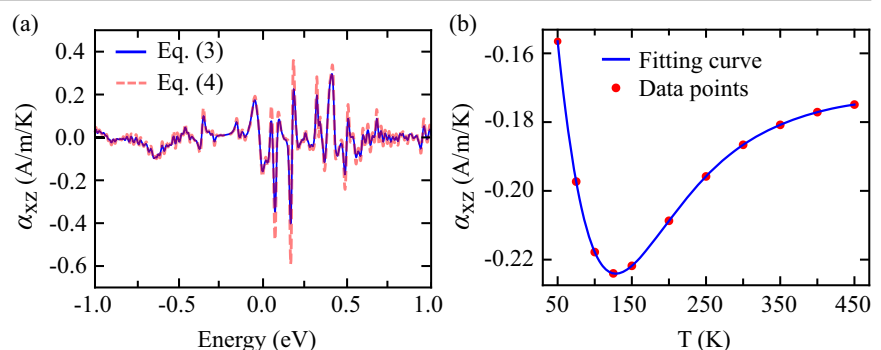


Fig. 5 | Berry curvature distribution in CrSb. Band structures with the Néel vector aligned at 45 degrees from c during its rotation from c to $\frac{1}{2}a + b$, calculated (a) without and (b) with SOC. The green circles in (a) indicate the crossing points formed by the 25th and 26th spin-down bands, red and blue represent spin-up and spin-down bands, respectively. c Nodal rings formed by the 25th and 26th bands, showing both spin-up (red) and spin-down (blue) characters. d Distribution of Berry curvature and nodal rings in the Brillouin zone, with nodal rings represented by black dashed lines.

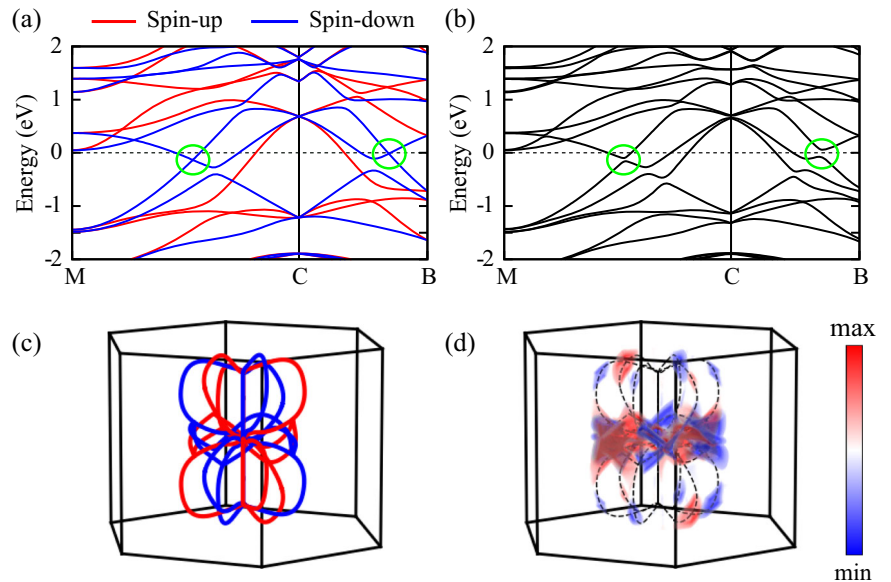
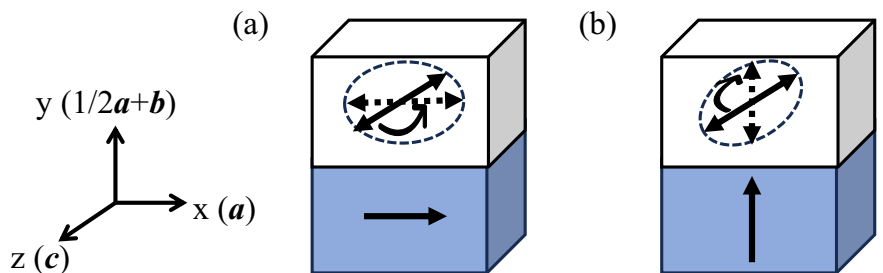


Fig. 6 | Experimental setups where CrSb films are grown on the ferromagnetic substrates for the detection of σ_{xz} as Néel vectors rotate from c to (a) a and (b) $\frac{1}{2}a + b$. The arrows in the substrates and CrSb films indicate the orientations of the ferromagnetic moments and Néel vectors, respectively. The substrate in (a) can be a conventional ferromagnet, which meets the common expression $j^{\text{AHE}} \sim M \times E$, the substrate in (b) can be an insulating ferromagnet, such as CrI_3 and $\text{Cr}_2\text{Ge}_2\text{Te}_6$.



CrSb, and the antiferromagnetic exchange stiffness in CrSb. Figure 6(b) presents the experimental setup for detecting σ_{xz} when the Néel vector rotates from c to $\frac{1}{2}a + b$, as shown by the purple line in Fig. 3(a). To induce the rotation of the Néel vector towards $\frac{1}{2}a + b$, the ferromagnetic substrate should have an easy-axis magnetocrystalline anisotropy along $\frac{1}{2}a + b$. Most importantly, the ferromagnetic substrate should preferably be an insulator, as metallic substrates with magnetic moments along $\frac{1}{2}a + b$ would contribute to an additional AHE signal, thereby hindering the detection of the intrinsic AHE signal from CrSb. Therefore, insulating ferromagnetic materials, such as CrI_3 and $\text{Cr}_2\text{Ge}_2\text{Te}_6$, are preferred for the substrate.

Discussion

In summary, our DFT calculations revealed the magnetism and anomalous transport properties of CrSb. The weak MAE suggests flexibility in adjusting the Néel vector orientation. By examining the dependence of the AHC and ANC on the orientation of the Néel vector, we determined that alignment along $\frac{1}{2}a + b$ results in significant values for both AHC and ANC. These pronounced values are attributed to SOC-induced gap openings at numerous nodal rings. The substantial AHC and ANC, together with other intriguing features such as the high Néel temperature, surface Fermi arcs, and high-mobility carriers, establish CrSb as a compelling platform for investigating novel altermagnetism-related properties.

Data availability

Data are available from the corresponding authors upon reasonable request.

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Author contributions

D.S., X.C. and Y.S. conceived and designed the research project. T.Y. and S.I. performed the calculations. T.Y., I.S., P.L., D.S., X.C. and Y.S. wrote the paper.

Competing interests

The authors declare no competing interests.

Additional information

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