An ordinary Hall effect in a conductor arises due to the Lorentz force acting on the charge carriers. In ferromagnets, an additional contribution to the Hall effect, the anomalous Hall effect (AHE), appears proportional to the magnetization. While the AHE is not seen in a collinear antiferromagnet, with zero net magnetization, recently it has been shown that an intrinsic AHE can be non-zero in non-collinear antiferromagnets as well as in topological materials hosting Weyl nodes near the Fermi energy. Here we report a large anomalous Hall effect with Hall conductivity of 27 \( \Omega^{-1} \text{cm}^{-1} \) in a chiral-lattice antiferromagnet, CoNb\(_3\)S\(_6\) consisting of a small intrinsic ferromagnetic component (\(\approx 0.0013 \mu_B\) per Co) along c-axis. This small moment alone cannot explain the observed size of the AHE. We attribute the AHE to either formation of a complex magnetic texture or the combined effect of the small intrinsic moment on the electronic band structure.
The anomalous Hall effect (AHE) is a signature of emergent electromagnetic fields in solids that affect the motion of the electrons, and hence it has been a recent topic of intense study in the context of the topological materials. The Hall effect in general is an intrinsic property of a conductor due to the Lorentz force experienced by the charge carriers. In systems with spontaneously broken time-reversal symmetry, an additional contribution, independent of the Lorentz force, is observed, the AHE. AHE was first observed in ferromagnets where its origin lies in the interplay between spin–orbit coupling (SOC) and magnetization. Reformulation of the SOC-induced intrinsic mechanism of AHE in ferromagnets to the Berry phase curvature in momentum space has been fruitful in predicting and describing the AHE in several other systems, including Weyl (semi)metals, non-collinear antiferromagnets, non-coplanar magnets, and other nontrivial spin textures. Recent observations of the large anomalous Hall effect in metals with possible Weyl and massive Dirac fermions, established by neutron diffraction and optical studies. Resistivity shows metallic behavior over the measured temperature range of 1.8–300 K, with a sudden drop below 27.5 K ($T_N$), presumably due to the reduction of electron scattering with the onset of the spin ordering (Fig. 1c). CoNb$_3$S$_6$ has a very small magnetoresistance of 0.2% at 2 K in the field of 9 T applied along c-axis, as shown in the inset of Fig. 1c.

**Results**

**Crystal structure and physical properties of CoNb$_3$S$_6$.** We verified the room temperature crystal structure of CoNb$_3$S$_6$ in the chiral space group $P6_3$ by means of single crystal X-ray diffraction (see Supplementary Note 1 and Supplementary Fig. 1). A sketch of the crystal structure adopted by CoNb$_3$S$_6$ is shown in Fig. 1a, where the Co atoms occupy the octahedral position between the triangular prismatic layers of the parent compound 2H-NbS$_2$. Figure 1b shows the magnetic susceptibility of CoNb$_3$S$_6$ as a function of temperature measured with a magnetic field of 0.1 T applied along a- and c-axis ($\chi_a$ and $\chi_c$, respectively). Over the entire temperature range, $\chi_c$ exceeds $\chi_a$, consistent with behavior reported in the literature. $\chi_a$ shows a kink at $T_{N_a} = 27.5$ K corresponding to the antiferromagnetic transition and decreases on further cooling down to 1.8 K. The field cooled (FC) and zero field cooled (ZFC) measurements show identical behavior. Along the c-axis, the susceptibility below $T_N$ shows irreversibility between FC and ZFC measurements. The ZFC $\chi_c$ shows a behavior similar to that of $\chi_a$. However, the FC $\chi_c$ increases on cooling below $T_N$, becomes maximum at 25 K and decreases on further cooling. This increase in FC susceptibility along the c-axis near the transition temperature has been reported in previous studies and implies the presence of a small ferromagnetic component along the c-axis. With increasing magnetic field, the magnitude of this jump decreases, and at 3 T, FC susceptibility shows a continuous decrease below $T_N$, as shown in the inset of Fig. 1b, suggesting that the moment along the c-axis is suppressed by a sufficiently large magnetic field. At higher temperatures, the susceptibility shows Curie–Weiss behavior. A Curie–Weiss fit to the data between 200 and 300 K (Supplementary Note 2 and Supplementary Fig. 2) yields the powder averaged effective moment of 3.0 $\mu_B$ per Co. This value is smaller than the spin-only moment expected for Co($^{63}$Co) ($3.87 \mu_B$) established by neutron diffraction and optical studies. Resistivity shows metallic behavior over the measured temperature range of 1.8–300 K, with a sudden drop below 27.5 K ($T_N$), presumably due to the reduction of electron scattering with the onset of the spin ordering (Fig. 1c). CoNb$_3$S$_6$ has a very small magnetoresistance of 0.2% at 2 K in the field of 9 T applied along c-axis, as shown in the inset of Fig. 1c.

**Hall effect.** Hall resistivity ($\rho_{xy}$) vs H measured between 28 and 23 K with current along a-axis and magnetic field along c-axis is depicted in Fig. 3a. The Hall effect at each temperature was measured by cooling the sample in a magnetic field of 9 T and then by changing the magnetic field from 9 to −9 T and subsequently from −9 to 9 T. At 28 K, which is just above $T_N$, the Hall resistivity is linear, as expected for a normal conductor. The sign of the Hall resistivity indicates that holes are the majority charge carriers in CoNb$_3$S$_6$. Within the single band model, the estimated carrier concentration ($n = 1/|eR_0|$) is $2.49 \times 10^{21}$ cm$^{-3}$, where $e$ is the charge of an electron and $R_0$ is the ordinary Hall coefficient. When the temperature is lowered below $T_N$, an additional contribution appears in the Hall resistivity. At 27 K, this anomalous
Hall signal is small. It increases both in magnitude and in field with decreasing temperature, becoming maximum at 23 K. Below 23 K, no switching behavior of the Hall resistivity is observed when measured with the maximum field of 9 T. However, the Hall resistivity increases down to 20 K (Supplementary Note 3 and Supplementary Fig. 3). At 15 K, a very small AHE is observed, and at 2 K there is no anomalous Hall effect. These observations reveal two important points. (1) Hysteresis in the observed, and at 2 K there is no anomalous Hall effect. These and Supplementary Fig. 3). At 15 K, a very small AHE is observed due to the magnetic structure of CoNb3S6. Each Co atom is octahedrally coordinated with S atoms. When measured with the maximum field of 9 T cannot switch the FM component due to simple magnetic effects. Conventionally, the Hall resistivity in a ferromagnet is given by the relation $\rho_{yx} = R_0 B + \rho_{yx}^A$, where $R_0$ is the ordinary Hall coefficient, $B = \mu_0 H$, and $\rho_{yx}^A$ is the anomalous Hall resistivity. In Fig. 3a, we see that the Hall resistivity measured in the paramagnetic state, i.e., at 28 K and in the antiferromagnetic state, except near the switching fields has the same slope. This indicates that $R_0 B$ is constant between 28 and 23 K, and allows us to subtract the ordinary Hall resistivity to obtain the anomalous part. Figure 3b shows $\rho_{yx}^A$ vs $H$, where $\rho_{yx}^A$ is obtained by subtracting the data measured at 28 K from $\rho_{yx}$ measured below $T_N$. As there is a finite ferromagnetic component along the $c$-axis, we first examine the effect of this small ferromagnetic component on the anomalous Hall effect. For a ferromagnet, $\rho_{yx}^A = R_0 \mu_0 M$, where $R_0$ is the anomalous Hall coefficient, $\mu_0$ is the permeability, and $M$ is the magnetization. $R_0$ scales the $M$–$H$ curve to the anomalously large value. At 2 K, a magnetic component, and hence the AHE does not switch sign, but gives the same large value. At 2 K, a magnetic field of 9 T cannot switch the FM component, which is observed between 25 K, which shows the maximum remanent magnetization. The obtained magnetization multiplied by $-1$, ($-\Delta M$) vs $H$ is plotted in Fig. 3c. The anomalous Hall resistivity measured at 25 K is also plotted in the same figure. These plots show that the anomalous Hall effect does scale with magnetization. $R_0$ is negative and has an exceedingly large value compared to $R_0$. $R_0$ estimated from this scaling at 25 K is $-1.41 \times 10^{-4}$ m$^2$ C$^{-1}$, which is four orders of magnitude larger than $R_0 = 2.4 \times 10^{-4}$ m$^2$ C$^{-1}$. In a canonical ferromagnet-like Fe$^{2+}$ or ferromagnets with closely related and even the same crystal structure as CoNb$_3$S$_6$, such as Fe$_{1/3}$TaS$_2$ and Fe$_{1/3}$TaS$_2$, $R_0/R_0 \approx 100$, two orders of magnitude smaller than that in CoNb$_3$S$_6$. This significant boost of the coefficient of AHE in CoNb$_3$S$_6$ is unlikely to be accounted for by the effect of the weak $c$-axis ferromagnetic component alone and therefore must have an additional contribution.

The contribution of the ferromagnetic component to the anomalous Hall resistivity, i.e., $R_0$ can be estimated from the high magnetic field part of the anomalous Hall resistivity vs magnetization plot. As $\rho_{yx}^A = R_0 \mu_0 M$, the slope of $\rho_{yx}^A$ vs $M$ gives $\mu_0 R_0$. In Fig. 3d, we see that $\rho_{yx}^A$ vs $M$ resembles $\rho_{yx}^A$ vs $H$ such that $\rho_{yx}^A$ changes sign at the coercive fields. After the abrupt sign change, $\rho_{yx}^A$ shows a linear variation with $M$. This linear behavior of $\rho_{yx}^A$ vs $M$ at high field arises from the continuous spin tilting by the magnetic field toward the $c$-axis and represents the contribution from the field-induced ferromagnetic component. The slope in this linear regime gives $\mu_0 R_0$ for this compound, which is represented by dashed lines in Fig. 3d. $R_0$ estimated from this slope is $-1.12 \times 10^{-7}$ m$^2$ C$^{-1}$, which is comparable to that of the ferromagnet Fe$_{1/3}$TaS$_2$. The extra component in the anomalous Hall resistivity, which we label as $\rho_{yx}^A$, can be obtained by subtracting this linear part from the anomalous Hall effect: $\rho_{yx}^A = \rho_{yx}^A - R_0 \mu_0 M$ and is shown in Fig. 3e, which shows that contribution from the FM component from spin tilting is negligibly small compared to $\rho_{yx}^A$. In Fig. 3f, we plot the anomalous Hall conductivity $\sigma_{yx}^A = \rho_{yx}^A/\left[(\rho_{yx}^A)^2 + (\rho_{xx})^2\right]^{1/2}$ as a function of magnetic field between 27 and 23 K. The anomalous Hall conductivity at 23 K takes the value $27 \Omega^{-1}$ cm$^{-1}$. A similar behavior, in which a very small ferromagnetic component and its anomalously large scaling with the anomalous Hall resistivity, has been observed in Mn$_3$Sn and Mn$_3$Ge. Here, the anomalous Hall effect has been attributed to the combined effect of non-collinear antiferromagnetic spin texture and electronic band structure. A large anomalous Hall coefficient, reported for Fe$_{24}$Sn$_{16}$ cannot be described by the ferromagnetic component alone and is believed to be due to the massive quasi-2D Dirac cones near the Fermi energy. Likewise, the large AHE observed in frustrated systems such as Pr$_2$Ir$_2$O$_7$ has been attributed to the non-coplanar spin texture.

**Discussion**

We now discuss possible origins of the anomalous Hall effect in CoNb$_3$S$_6$. First, we can rule out impurity-related extrinsic mechanisms of the AHE from the fact that the AHE vanishes at low temperatures, where the laboratory magnetic fields are insufficient to alter spins state, e.g., at 2 K as shown in Fig. 3a and Supplementary Fig. 3a. Second, a collinear antiferromagnetic state cannot give rise to the anomalous Hall effect. Finally, we showed above that an FM component due to simple magnetic field-induced spin tilt alone cannot account for the observed AHE. We thus consider other scenarios for the origin of the AHE in
CoNb$_3$S$_6$: (1) non-collinear, non-coplanar or other complex magnetic textures, or (2) interplay of electronic and magnetic degrees of freedom.

CoNb$_3$S$_6$ has a chiral crystal structure. In a magnet with such a chiral lattice, competition among the exchange interaction, Dzyaloshinskii–Moriya interaction (DMI), magnetocrystalline anisotropy, and Zeeman energy may result in complex magnetic textures$^{28-30}$, including non-collinear or non-coplanar spins that can give rise to large AHE$^{10-13,27,31}$. The neutron diffraction experiment reported by Parkin et al.$^{20}$ revealed no such complex spin structure. However, this is not unexpected given (1) the measurement is carried out in zero field at 4 K, where our data does not show AHE when measured up to the magnetic field of 9 T, and (2) a diffraction experiment such as that carried out by Parkin et al.$^{20}$ revealed no such complex magnetic textures. Thus, the nature of the spin structure in CoNb$_3$S$_6$ near $T_N$ remains an open question.

Figure 4a–c shows the paramagnetic band structure of CoNb$_3$S$_6$ without inclusion of SOC. The metallic character of CoNb$_3$S$_6$ is evident by the presence of the hole pockets along $\Gamma - A$, which is consistent with the measured hole-like character of the charge carriers. There are two linear electron and hole band crossings along $\Gamma - M$ and $K - \Gamma$. Inclusion of SOC (Fig. 4b) opens a small gap at the band crossings along these lines and splits the bands due to the lack of inversion symmetry$^{32,33}$. The band structure along $\Gamma - A$ is enlightening in this regard. In the calculation with SOC (Fig. 4a) both at $\Gamma$ and $A$, two doubly degenerate bands touch at a point $\approx 40$ meV above the Fermi energy ($E_F$). The splitting of these bands due to SOC along $\Gamma - A$ (Fig. 4b) is remarkably large and results in the formation of several linearly crossing bands and avoided crossings. In Fig. 4d, we show the band dispersion along $A - \Gamma - A$ near $E_F$ (see Supplementary Note 4 and Supplementary Fig. 4 for symmetry analysis). Bands cross linearly at all of these points. Two of these points lie within $\approx 15$ meV of $E_F$. It has been established rigorously that in nonmagnetic crystals and in directions parallel to a $\delta_3$ screw axis (along $\Gamma - A$ in CoNb$_3$S$_6$), band degeneracies at the $\Gamma$ points are Weyl nodes$^{34}$. The AHE in CoNb$_3$S$_6$ is observed only when the external magnetic field induces a small moment along $c$-axis, which suggests that the large enhancement in AHE may result due to the combined effect of such a field in the presence of the near $E_F$ Weyl nodes.

In summary, CoNb$_3$S$_6$ is a member of the class of antiferromagnets that show a large anomalous Hall effect. The large AHE is not explained by the reported collinear antiferromagnetic structure, and we suggest the formation of complex, noncollinear magnetic textures or an interplay between the magnetic texture.
and electronic band structure as two possible mechanisms for the large AHE. CoNbS$_2$ is a member of a large family of the 1/3 intercalated TX$_2$ compounds, where T is a 4- or 5-$d$ transition metal element, and X is a chalcogen (S, Se). As the change in the intercalated 3$d$ element changes the nature of both magnetic and electronic structure, our realization of the AHE in CoNbS$_2$ opens a platform to explore and perhaps manipulate the interplay among spin texture, electronic band structure, and the associated emergent phenomena in a large class of poorly explored materials.

**Methods**

Crystal growth and characterization. Single crystals of CoNbS$_2$ were grown by chemical vapor transport using iodine as the transport agent. First, a polycrystalline sample was prepared by heating stoichiometric amounts of cobalt powder (Alfa Aesar 99.98%), niobium powder (Johnson Matthey Electronics 99.8%), and sulfur pieces (Alfa Aesar 99.9995%) in an evacuated silica ampoule at 400°C for 5 days. Subsequently, 2 g of the powder was loaded together with 0.5 g of iodine in a fused silica tube of 14 mm inner diameter. The tube was evacuated and sealed under vacuum. The ampoule of 11 cm length was placed in a horizontal furnace tube in which the temperature of the hot zone was kept at 950°C and that of the cold zone was ≈850°C for 7 days. Several CoNbS$_2$ crystals formed with a distinct, well-faceted flat plate-like morphology. The crystals of CoNbS$_2$ were examined by single crystal X-ray diffraction at beamline 15-ID-D at the APS, Argonne National Laboratory (ANL), where the data were collected with an APEX2 Area Detector using synchrotron radiation (λ = 0.4132 Å) at 293 K. Compositional analysis was done using an energy dispersive X-ray spectroscopy (EDS) at the Electron Microscopy Center, ANL.

Magnetic and transport property measurements. Magnetization measurements were made using a Quantum Design VSM SQUID. Both in FC and ZFC mode, susceptibility data were measured by sweeping temperature up from 1.8 K. In the derivative of M vs $H$, we observed a small peak around $H = 0$ both above and below $T_N$, and both along $a$- and $c$-axis, possibly due to an unknown paramagnetic impurity. For data at all temperatures presented in Fig. 2, a background measured at 30 K was subtracted. A small asymmetry of the peak position in the $dM/dH$ vs $H$ was observed when only one loop of $M$ vs $H$ was measured. We did not see such an asymmetry when a second loop of the $M$ vs $H$ was measured, which is presented in Fig. 2. Transport measurements were performed on a quantum design PPMS following a conventional 4-probe method. Au wires of 25 μm diameter were attached to the sample with Epotek H20E silver epoxy. An electric current of 1 mA was used for the transport measurements. In magnetoresistance measurements, the contact misalignment was corrected by field symmetrizing the measured data. The following method was adopted for the contact misalignment correction in Hall effect measurements. The Hall resistance was measured at $H = 0$ by decreasing the field from the positive magnetic field ($R_{xy}$), where $H$ represents the external magnetic field. Again the Hall resistance was measured at $H = 0$ by increasing the field from negative magnetic field ($R_{xy}$). Absolute value of the $(R_{xy})_L$ and $(R_{xy})_R$ was then subtracted from the measured Hall resistance. The conventional antisymmetrization method was also used for the Hall resistance measured at 28 K (above $T_N$) and at 2 K (where no anomalous Hall effect was observed), which gave same result as obtained from the former method.

**Electronic structure calculations.** The electronic structure calculations were carried out within density functional theory (DFT) using the all-electron, full potential code WIEN2K$^{35}$ based on the augmented plane wave plus local orbital (APW+lo) basis set$^{36}$. The Perdew-Burke-Ernzerhof (PBE) version of the generalized gradient approximation (GGA)$^{37}$ was chosen as the exchange correlation potential. Spin–orbit coupling (SOC) was introduced in a second variational procedure$^{38}$. A dense $k$-mesh of 28 × 28 × 12 was used for the Brillouin zone (BZ) sampling. A $R_{	ext{max}}$ of 7.0 was chosen for all calculations. Muffin tin radii were 2.5 a.u. for Nb, 2.45 a.u. for Co, and 2.01 a.u. for S.

**Data availability.** The authors declare that the main data supporting the findings of this study are available within the article and its Supplementary Information files. Extra data are available from the corresponding author on request.

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![Fig. 2](image1.png)

**Fig. 2**. Transport measurements were performed on a quantum design PPMS at 30 K was subtracted. A small asymmetry of the peak position in the $dM/dH$ vs $H$ was observed when only one loop of $M$ vs $H$ was measured. We did not see such an asymmetry when a second loop of the $M$ vs $H$ was measured, which is presented in Fig. 2. Transport measurements were performed on a quantum design PPMS following a conventional 4-probe method. Au wires of 25 μm diameter were attached to the sample with Epotek H20E silver epoxy. An electric current of 1 mA was used for the transport measurements. In magnetoresistance measurements, the contact misalignment was corrected by field symmetrizing the measured data. The following method was adopted for the contact misalignment correction in Hall effect measurements. The Hall resistance was measured at $H = 0$ by decreasing the field from the positive magnetic field ($R_{xy}$), where $H$ represents the external magnetic field. Again the Hall resistance was measured at $H = 0$ by increasing the field from negative magnetic field ($R_{xy}$). Absolute value of the $(R_{xy})_L$ and $(R_{xy})_R$ was then subtracted from the measured Hall resistance. The conventional antisymmetrization method was also used for the Hall resistance measured at 28 K (above $T_N$) and at 2 K (where no anomalous Hall effect was observed), which gave same result as obtained from the former method.

![Electronic structure calculations](image2.png)

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Author contributions

N.I.G. and J.F.M. conceived the project. N.I.G. grew the crystals, performed the magnetic and magnetotransport measurements. J.S.J. contributed to the transport measurements. A.B. calculated the electronic band structure. Y.S.C. and J.Z. did the single crystal X-ray diffraction experiments. N.I.G. and J.F.M. wrote the manuscript. All authors contributed to the discussion of the results.

Additional information

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