Very recently, a series of experiments suggest that Shandite-type compound CoSnS\(_2\) can be a magnetic Weyl semimetal and shows a giant anomalous Hall conductivity (AHC) \([16, 17]\). CoSnS\(_2\) consists of Co\(_{12}\)Sn\(_{24}\) clusters, which are stacked along the c-axis with a triangular lattice of sulfur atoms. It is known as half-layers sandwiched by sulfur atoms. In this work, we systematically investigate the pressure tuneable large anomalous Hall effect of the ferromagnetic kagome-lattice Weyl semimetal CoSnS\(_2\). We report the pressure evolution of the anomalous Hall effect in magnetic CoSnS\(_2\) by high pressure experiments up to 44.9–50.9 GPa, where we can clearly observe the pressure-induced incoherent transition between the metallic ferromagnet and the insulator, whose magnetization originates from the magnetic cobalt atoms on a kagome lattice and the spontaneous polarization along the a-b plane with the spontaneous magnetization along the c-axis \([18–20]\). The interplay between the out-of-plane and the in-plane electronic responses accounts for the novel electronic responses of the Bloch electronic states. We observe the anomalous Hall transport in CoSnS\(_2\) under high pressure, which could further enrich the physical properties of quantum states, resulting in many novel potential applications of quantum materials in next generation quantum electronics.

In this work, we systematically investigate the pressure tuneable large anomalous Hall effect of the ferromagnetic Weyl semimetal CoSnS\(_2\) through multiple experimental measurements and mechanisms of the AHE. We report the pressure evolution of the anomalous Hall effect in magnetic CoSnS\(_2\) by high pressure experiments up to 44.9–50.9 GPa, where we can clearly observe the pressure-induced incoherent transition between the metallic ferromagnet and the insulator, whose magnetization originates from the magnetic cobalt atoms on a kagome lattice and the spontaneous polarization along the a-b plane with the spontaneous magnetization along the c-axis \([18–20]\). The interplay between the out-of-plane and the in-plane electronic responses accounts for the novel electronic responses of the Bloch electronic states. We observe the anomalous Hall transport in CoSnS\(_2\) under high pressure, which could further enrich the physical properties of quantum states, resulting in many novel potential applications of quantum materials in next generation quantum electronics.
in diamond anvil cells (DAC) with pressures up to 44.9-50.9 GPa combined with first principle calculations. The anomalous Hall resistivity and the ferromagnetism are greatly suppressed as pressure increases and vanish simultaneously around 22 GPa. The AHC shows a non-monotonic change with pressure in the low temperature region, which can be captured by theoretical calculations in terms of competing evolutions of original and emergent Weyl nodes.

Experimental characterizations of our single crystal samples at ambient pressure, including powdered and single crystal X-ray diffraction (XRD), magnetization, longitudinal and Hall resistivity (Fig. S1 in Supplementary Material [31]), are in good accordance with previous reports [16, 17]. In situ high-pressure angular dispersive synchrotron XRD experiments were performed with Co₃Sn₂S₂ fine powder sample at room temperature (λ = 0.6199 Å). The DC magnetization of Co₃Sn₂S₂ under high pressure was investigated by using a commercial SQUID (Quantum Design, MPMS3) equipped with a Be-Cu alloy DAC. The electrical transport measurements were carried out on a home-built system (1.8-300 K; ±9 T) by using a five-probe method in a Be-Cu alloy DAC. First principles calculations were performed by using VASP [32] based on the DFT with Perdew-Burke-Ernzerhof (PBE) parameterization of GGA [33, 34]. The intrinsic AHC was calculated based on the wannier90 code [35, 36]. More details on materials preparation and experimental methods are presented in Supplementary Material [31].

Our high-pressure XRD data shows that the structure of Co₃Sn₂S₂ is stable with pressures up to 50.9 GPa. XRD peaks (Fig. S2) at all pressures can be well indexed by the Shandite-type structure with space-group R̅3m (No. 166) and no secondary phase is detected. The structural parameters a, c and c/a extracted from the standard Rietveld refinement vary smoothly with pressure and show no anomaly. Experimental XRD patterns and more fitting details can be found in Fig. S2.

The temperature and pressure dependences of the magnetization are shown in Fig. 1(a). At 0.1 GPa, the magnetization increases rapidly with decreasing temperature below the Curie temperature \( T_C \) \( \sim \) 174 K, similar to previous results at ambient pressure [16, 17]. Here the Curie temperature \( T_C \) is obtained from the first-order derivative of the \( M-T \) curve. With increasing pressure, both \( T_C \) and the magnitude of magnetization decrease monotonically. Figure 1(b) shows the temperature dependence of the resistivity \( \rho_{xx} \) of Co₃Sn₂S₂ at zero field and selected pressures. At 0.2 GPa, the resistivity exhibits a metallic behavior in the whole temperature range. A sluggish kink appears at \( \sim 167 \) K, as indicated by the arrow, which is obtained from the first derivative of the \( \rho_{xx}-T \) curve. This feature is related to the paramagnetic-ferromagnetic transition in Fig. 1(a). Upon further compression, the metallic behavior main-

![FIG. 1. (a) Temperature dependence of magnetization \( M \) under different pressures to 7.2 GPa with an applied magnetic field of 100 Oe. (b) Temperature dependence of electric resistivity \( \rho_{xx} \) at selected pressures up to 44.9 GPa.](image1)

![FIG. 2. (a-g) Magnetic field dependence of the Hall resistivity \( \rho_H \) at various temperatures and selected pressures. (h) Temperature dependence of the coercive field \( H_C \) at different pressures.](image2)
FIG. 3. (a) Temperature dependence of the anomalous Hall resistivity $\rho_{Axy}$ under different pressures. Inset shows an enlarged view of $\rho_{Axy} - T$ from 7.1 to 17.6 GPa. (b) Temperature dependence of the AHC $\sigma_{Axy}$ under different pressures. (c) plot of AHC $\sigma_{Axy}$ as a function of $\sigma_{xx}$. (d) Anomalous Hall resistivity $\rho_{Axy}$ as a function of $\rho_{xx}^2$. Only data below $T_{max}$ is taken. (e) Temperature versus pressure phase diagram for Co$_3$Sn$_2$S$_2$. PM and FM stand for paramagnetic and ferromagnetic phases, respectively. $P_C$, obtained by linear extrapolations of the low-pressure data, denotes a critical pressure where the ferromagnetism and AHE vanish completely.

...tains to the highest pressure of 44.9 GPa. Meanwhile, the sluggish kink shifts to lower temperatures gradually and becomes almost indistinguishable above 11.6 GPa, in accordance with the gradual suppression of the ferromagnetism as increasing pressure [Fig. 1(a)]. In addition, compression reduces the whole $\rho_{xx}$ greatly and no superconductivity is observed down to 1.8 K and up to 44.9 GPa.

Figures 2(a)-2(g) display hysteresis loops in the Hall measurement under different pressures, which are characteristic of the AHE in Co$_3$Sn$_2$S$_2$. Firstly, starting at 0.2 GPa, the saturation value of the Hall resistivity $\rho_H$ first increases upon warming and then decreases; meanwhile, hysteresis loops can be clearly observed up to around $T_C$. Similar trends are observed with further increasing pressure to 17.6 GPa, except that the highest saturation value decreases. Secondly, at 20.0 GPa, no evident hysteresis loop is observed through the whole temperature range [Fig. 2(g)], indicating a significant suppression of the AHE. Thirdly, the ordinary Hall coefficient at high temperature changes from a positive sign to a negative one when going from 4.9 to 7.1 GPa [Figs. 2(c)-2(e) or Fig. S3], which implies a pressure-induced crossover of charge carrier type from low-pressure hole dominated to high-pressure electron dominated. Finally, the coercive field $H_C$ for all pressures decreases almost linearly with increasing temperature except in the vicinity of $T_C$ [Figs. 2(h)]. Compared with the reported value at ambient pressure ($\sim$0.35 T at 5 K [16]), the $H_C$ at 5 K here is enhanced by two-four times.

In Fig. 3(a), we plot the temperature variation of the anomalous Hall resistivity $\rho_{Axy}$ of Co$_3$Sn$_2$S$_2$ at various pressures to 17.6 GPa. Upon cooling, the anomalous Hall resistivity at 0.2 GPa increases remarkably around $T_C$, and shows a peak value of $\sim$8 $\mu$Ω cm at $T_{max} \sim 120$ K. This peak value is smaller than those reported at ambient pressure [16, 17]. Below $T_{max}$, the AHC decreases monotonically with decreasing temperature. The whole temperature evolution of the anomalous Hall resistivity is in agreement with that at ambient pressure [16]. With further increasing pressure, both the peak value of $-\rho_{Axy}$ and $T_{max}$ decrease gradually, corresponding to the suppression of the ferromagnetism [Fig. 1(a)]. At 17.6 GPa, the peak value of $-\rho_{Axy}$ reduces to $\sim$0.1 $\mu$Ω cm and the $\rho_{Axy} - T$ curve shows a very broadening shape ranging from 5 to 75 K [inset of Fig. 3(a)].

The temperature dependence of the AHC $\sigma_{Axy}$ ($\sigma_{Axy} = -\rho_{Axy}/[(\rho_{Axy})^2 + (\rho_{xx})^2]$) is presented in Fig. 3(b). With decreasing temperature, $\sigma_{Axy}$ at 0.2 GPa first increases below $T_C$ and then decreases gradually after reaching a maximum of $\sim$ 250 $\Omega$ cm$^{-1}$. However, the pressure evolution of $\sigma_{Axy}$ at low temperatures is non-monotonic; it first increases from 0.2 to 4.9 GPa and then starts to decrease abruptly upon further compression. Meanwhile, a pressure-induced crossover of the charge carrier type occurs simultaneously [Figs. 2(c)-2(d) or Fig. S3].
In addition, we plot the $\sigma_{xx}^A$ as a function of the longitudinal conductivity $\sigma_{xx}$ in Fig. 3(c). One can find that $\sigma_{xx}$ ranges from $10^4$ to $10^6$ $\Omega^{-1}$ cm$^{-1}$ with pressures to 17.6 GPa; roughly, $\sigma_{xx}^A$ varies slightly with $\sigma_{xx}$ at low temperatures, suggesting that the present system is in the intermediate regime. Interestingly, the anomalous Hall resistivity $-\rho_{xy}^A$ below $T_{\text{max}}$ and at different pressures can be scaled with the longitudinal resistivity $\rho_{xx}$ as a power law of $-\rho_{xy}^A \propto \rho_{xx}^4$ [Fig. 3(d)].

Based on the pressure evolutions of $T_C$ and $T_{\text{max}}$, we construct a temperature-pressure phase diagram for Co$_3$Sn$_2$S$_2$ as displayed in Fig. 3(e). It is clear that both $T_C$ and $T_{\text{max}}$ decrease linearly upon compression. By linearly extrapolating the trends of $T_C$ vs. $P$ and $T_{\text{max}}$ vs. $P$ to higher pressures, one finds that the two curves eventually intersect at a common pressure $P_C \sim 22$ GPa. Around the critical pressure $P_C$, both the ferromagnetism and the AHE are suppressed simultaneously.

In order to understand the AHE under pressure, we investigated pressure effect on the band structure, the AHC and the Weyl nodes through first-principle calculations. According to Figs. 3(a)-3(b), we find that compression not only enlarges some local band gap (such as L point) but also shifts the Fermi energy away from the resonant enhancement regions (gapped nodal rings) of the AHC. Meanwhile, our calculations also show that the electron pockets around the G point grow up gradually with pressure (as shown in Fig. S4 in Supplementary Material [31]), in excellent line with the experimental observation of a pressure-induced change of the charge carrier type (see Fig. S3). In addition, our calculations further reveal that high pressure can effectively tune the Berry curvature of Bloch bands (the evolution of Berry curvature under pressures is given in Fig. S5 in Supplementary Material [31]) and thereby modify the AHC accordingly. It is clear that the intrinsic AHC strongly depends on the doping electron number per unit cell $N_e$ and on the pressure, as shown in Fig. 4(c). When the $N_e$ lies at around 1.03 ($E_F \sim 0.2$ eV), the intrinsic AHC changes non-monotonically with pressure [inset of Fig. 4(c)], qualitatively consistent and quantitatively comparable ($\sim 200$ $\Omega^{-1}$ cm$^{-1}$) with the pressure evolution of the AHC observed experimentally [Fig. 3(c)].

A long distance $\Delta_d$ between Weyl nodes with opposite chirality in momentum space usually leads to a large intrinsic AHC $\sigma_{xy}^A$, as is described by $\sigma_{xy}^A \propto \Delta_d \cdot e^2/h$ [37]. We thus further track the evolution of the Weyl nodes ($\sim 0.2$ eV). At ambient pressure, the AHC is dominated by the Weyl nodes, marked by red dots $\Delta_d^{\text{red}}$ in Fig. 4(d). Upon initial compression, $\Delta_d^{\text{red}}$ becomes a little longer. However, at around 8.46 GPa another two bands touch with each other, leading to a new pair of Weyl nodes with an opposite vector as labeled by blue dots $\Delta_d^{\text{blue}}$ (Fig. 4(e)). With further increasing pressure, the new pair of Weyl nodes moves towards to the original one, making the effective Weyl nodes distance $\Delta_d^{\text{eff}}$ shortening ($\Delta_d^{\text{eff}}=\Delta_d^{\text{red}}-\Delta_d^{\text{blue}}$), and eventually the two pairs annihilate with each other ($\Delta_d^{\text{eff}}=0$). This could account for the observed non-monotonic change of the AHC [Fig. 2(c)]. The consistency between calculations

![Image](image_url)
and experiments suggests that the intrinsic mechanism due to the Berry curvature dominates the AHE at high pressures.

In summary, we have studied the high pressure effect on the AHE in Co$_3$Sn$_2$S$_2$. While the structure of Co$_3$Sn$_2$S$_2$ is stable with pressures up to 50.9 GPa, both the anomalous Hall resistivity and ferromagnetism of Co$_3$Sn$_2$S$_2$ are gradually suppressed and finally disappears above 22 GPa. The AHC first increases to 4.9 GPa and then begins to decreases abruptly above 7.1 GPa. Meanwhile, a pressure-induced crossover of the charge carrier type from the low-pressure hole-dominated to high-pressure electron-dominated occurs. Our first-principle calculations qualitatively support these experimental observations, suggesting that the intrinsic mechanism should still dominate the AHE of Co$_3$Sn$_2$S$_2$ under high pressure.

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* These authors contributed equally to this work.

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