The anomalous Hall effect (AHE) is one of the most fundamental phenomena in physics. In the highly conductive regime, ferromagnetic metals have been the focus of past research. Here, we report a giant extrinsic AHE in KV$_3$Sb$_5$, an exfoliable, highly conductive semimetal with Dirac quasiparticles and a vanadium Kagome net. Even without report of long range magnetic order, the anomalous Hall conductivity reaches 15,507 Ω$^{-1}$ cm$^{-1}$ with an anomalous Hall ratio of $\approx 1.8$%; an order of magnitude larger than Fe. Defying theoretical expectations, KV$_3$Sb$_5$ shows enhanced skew scattering that scales quadratically, not linearly, with the longitudinal conductivity, possibly arising from the combination of highly conductive Dirac quasiparticles with a frustrated magnetic sublattice. This allows the possibility of reaching an anomalous Hall angle of 90° in metals. This observation raises fundamental questions about AHEs and opens new frontiers for AHE and spin Hall effect exploration, particularly in metallic frustrated magnets.
frustrated magnetic sublattices, particularly when combined with relativistic carriers, are uncommon, and investigation of their Hall effects has been sparsely performed. For example, the metallic spin liquids, Pr$_2$Ir$_2$O$_7$ and LiV$_2$O$_4$ are a Luttinger semimetal and heavy-fermion metal, respectively; neither of these has Dirac band crossings or low-mass carriers (29–32).

In this work, we present the observation of a giant extrinsic AHE in KV$_3$Sb$_5$, which is a high-conductivity semimetal with Dirac quasiparticles and geometric frustration due to its vanadium Kagome net. The highly dispersive Dirac bands of KV$_3$Sb$_5$ are observed using angle-resolved photoelectron spectroscopy (ARPES) as shown in Fig. 1B, along with the density functional theory (DFT)–calculated band structure. The DFT and ARPES match well, both in terms of band dispersion and the Fermi surface geometry with the experimentally determined Fermi level appearing to be slightly below the predicted level (≈−10 meV). Although there has been no report of magnetic ordering of KV$_3$Sb$_5$ down to 0.25 K (33), the anomalous Hall conductivity (AHC), at 2 K, reaches as high as≈15,507 ohm$^{-1}$ cm$^{-1}$ with an anomalous Hall ratio (AHR) of≈1.8%; an order of magnitude larger than Fe (34) and one of the largest AHEs ever observed. Unexpectedly, this AHE scales quadratically with $\alpha_{\text{xx}}$, deviating from the linear scaling predicted from current skew scattering theories. This is the first example of a giant AHE without ferromagnetic ordering in a magnetic system and prompts investigations into previously unconsidered material families, particularly metallic geometrically frustrated magnets, spin liquid candidates, and cluster magnets. It also raises new questions on the fundamental theory regarding AHE mechanisms in the high-conductivity regime and poses the possibility of realizing an AHA of 90° in metallic systems. This observation opens a new frontier for the AHE [and spin Hall effect (SHE)] born from the intersection of geometrically frustrated/cluster magnets and topological semimetals/metallics, inviting exploration not only from theoretical and experimental physicists but also materials scientists and solid-state chemists.

**RESULTS**

KV$_3$Sb$_5$ crystallizes in the P6/mmm space group (SG: 191) and as shown in the inset of Fig. 1C, and its stacking is composed of a Kagome...
lattice of vanadium coordinated by antimony in distorted octahedra with potassium intercalated between layers. Previous work by Ortiz et al. (33) found that the compound displays paramagnetic behavior at high temperatures, before undergoing a transition at 80 K to either a dilute trimerized state from orbital ordering effects or a highly frustrated state with localized moments. Considering the vanadium Kagome net, geometrical frustration of the magnetic sublattice is expected. DFT + U calculations carried out by Ortiz et al. (33) comparing disordered AFM and ferrimagnetic ordering also support this expectation. Transport experiments on those same crystals were carried out here on a series of KV3Sb5 nanoflakes of different thicknesses. Figure 1C shows the typical temperature dependence of an effective mass of 0.125 m for a 105-nm-thick device (see the Supplementary Materials for fabrication information); with decreasing temperature, a kink is visible in \( \rho_{\text{xx}} \) around 80 K, corresponding to the known magnetization and heat capacity anomaly (33). At low temperature, the \( \rho_{\text{xx}} \) reaches \( \approx 1.5 \) \( \mu \Omega \) cm, which is comparable to that of high purity bulk Bismuth (35). The magnetoresistance (MR) at various temperatures is shown in Fig. 1D, with Shubnikov de Hass (SDH) oscillations clearly visible above 4 T. Below 3 T, the MR is linear, while at higher field, it adopts a standard quadratic dependence with \( \rho_{\text{xx}} \) for carriers related to the 34.6 T orbit. If the OHE was not properly subtracted, then the angle-dependent behavior would be skewed toward the expected linear response. If the OHE is also subtracted, then the angle-dependent behavior would be skewed toward the expected linear response.

In the low-field region, highlighted by the blue shading in Fig. 2A, an antisymmetric sideways "S" shape is observed, which is a characteristic of either an AHE or a two-band OHE. Below 35 K, \( \rho_{\text{xy}} \) exhibits a second broad hump centered around 7 T, but as the temperature is increased, this hump is gradually lost and a one band linear field dependence is recovered (Fig. 2B, inset). The S-shaped Hall resistivity feature, however, persists throughout this changeover and remains visible at higher temperature where the Hall resistivity appears to be linear. This indicates that the high-field behavior of the Hall effect is related to the two-band OHE and that the low-field S shape is related to an AHE. Within the one-band temperature range, the electron concentrations \( (n_e) \) and mobilities \( (\mu_e) \) are extracted from linear fitting of the OHE and shown in Fig. 2B (the simultaneous fitting of the two-band model with MR and Hall is not possible due to the linear MR behavior in this regime). As the temperature is lowered, \( \mu_e \) monotonically increases, while \( n_e \) shows a minimum at around 65 K, which may be related to the magnetic transition mentioned above. Figure 2C shows the extracted \( \rho_{\text{xy}}^{\text{AHE}} \) taken by subtracting the local linear OHE background. The magnitude of the AHE monotonically decreases with increasing temperature until it is lost at around 50 K. To precisely extract the AHC (\( \sigma_{\text{xy}}^{\text{AHE}} \)) with no approximation, we first obtained the Hall conductivity by inverting the resistivity matrix, \( \sigma_{\text{xy}} = -\rho_{\text{xy}}/(\rho_{\text{xx}}^2 + \rho_{\text{yy}}^2) \). Afterward, the local linear ordinary Hall conductivity background is subtracted, leaving the \( \sigma_{\text{xy}}^{\text{AHE}} \), as shown in Fig. 2C (inset).

To further confirm the AHE nature of the low-field anomaly, we carried out a detailed angle-dependent measurements. Figure 3A shows the \( \sigma_{\text{AHE}} \) dependence on the angle of \( \mu_0 H \) relative to the applied electric field, and the inset shows \( \sigma_{\text{AHE}} \) against the \( \cos(\theta) \). The AHC is angle independent until \( \mu_0 H \) is tilted away from the z axis by about 30°, after which it rapidly decreases until it reaches 0 at \( \mu_0 H \parallel E \). The fact that \( \sigma_{\text{AHE}} \) does not linearly scale with the out-of-plane component of \( \mu_0 H \) solidifies its AHE origin and that the AHE extraction is robust. If the OHE was not properly subtracted, then the angle-dependent behavior would be skewed toward the expected linear response. Furthermore, as expected from a real Hall response, the sign of the AHE flips when rotated past 90° (see fig. S3). The extracted \( \sigma_{\text{AHE}} \) for several devices with thicknesses ranging from 30 to 128 nm is plotted against each device’s \( \rho_{\text{xx}} \) (which was varied by changing the temperature) in Fig. 3B. The skew scattering and intrinsic components of the AHE can be fitted to \( \sigma_{\text{AHE}} = \alpha \sigma_{\text{xx}} \sigma_{\text{xy}} + b \), where \( \alpha \) is

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**Fig. 2. Hall effects in KV3Sb5.** (A) The Hall resistivity of KV3Sb5 with the current applied in the ab plane and the magnetic field applied along the c axis. The AHE shows up as antisymmetric S shape in the low-field region for all temperature below 50 K. At low temperatures and high-field regime, the Hall resistivity exhibits a typical two-band behavior. (B) Extracted electron carrier concentration and mobility in the one-band regime. Inset: The Hall response of KV3Sb5 above 75 K. (C) Extracted \( \rho_{\text{xy}}^{\text{AHE}} \) taken by subtracting the local linear ordinary Hall background at various temperatures. The inset shows the converted \( \rho_{\text{xy}}^{\text{AHE}} \) at various temperatures by inverting the resistivity tensor.
skew constant, $\sigma_{xx0}$ is the residual resistivity, and $b$ is the intrinsic AHC (22). Samples 1, 2, and 3 were fabricated from freshly exfoliated crystals, while samples 4, 5, and 6 were fabricated a few weeks after exfoliation. All devices follow a square dependence with $\alpha$ varying from 0.0075(2) to 0.0172(5); more than an order of magnitude larger than Fe and Ni [0.00149 (34) and 0.0007 (36), respectively]. The inset shows the extracted intrinsic $\sigma_{AH}\sigma_{b}$ which average to positive for samples 1 to 3 in the high-conductivity regime and negative 325 $\Omega^{-1}$ cm$^{-1}$ for samples 4 to 6 in the low-conductivity regime. We use an assumed ferromagnetic splitting of the bands to reveal that the intrinsic mechanism cannot account for the markedly larger observed signal in high-conductivity regime. The DFT-calculated intrinsic values (see the Supplementary Materials) represent an upper limit for the intrinsic contribution to the Hall conductivity and, together with the Hall sign change around the Fermi level, are in agreement with the experimentally extracted intrinsic values. This further confirms the robustness of the AHC extraction. The AHR percentages ($\sigma_{AHE}/\sigma_{xx}$ × 100) for various KV$_3$Sb$_5$ devices and for Fe (23) are shown in Fig. 3C. Throughout the measured $\sigma_{xx}$ range, the AHR of KV$_3$Sb$_5$ rises monotonically with $\sigma_{xx}$ unlike Fe, which has a decreasing AHR throughout its intrinsic region until $\sigma_{xx} = 0.6 \times 10^6 \Omega^{-1}$ cm$^{-1}$, at which point its skew scattering mechanism begins to dominate. Because of its smaller skew constant, the rate of increase of its AHR is smaller compared to KV$_3$Sb$_5$ (37, 38).

With an AHE this large, there are few known systems that are comparable to KV$_3$Sb$_5$. It is fundamentally distinct from Fe in that it has both Dirac quasiparticles and a triangular magnetic sublattice. It is also fundamentally distinct from the AHEs recently observed in topological materials (e.g., Co$_3$Sn$_2$S$_2$ and Co$_2$MnGa), which are intrinsically driven by Berry curvature ($\sigma_{AHE} \approx 10^3 \Omega^{-1}$ cm$^{-1}$ (16–18)). To the best of our knowledge, KV$_3$Sb$_5$ is the first material to showcase an enhanced extrinsic AHE in a frustrated system; other frustrated systems, like Mn$_2$Sn and Nd$_2$MnO$_7$, have been shown to be dominated by the intrinsic mechanism (40, 44, 45). KV$_3$Sb$_5$ appears to follow the recently proposed “spin cluster” mechanism by Ishizuka and Nagaosa (25). Here, a triangular spin cluster or tiled clusters as in a Kagome net can act like a “compound magnetic scattering center” when, due to an external field, a distortion of the local order results in a net magnetization and magnetic fluctuations act as scattering centers generating an enhanced skew scattering potential (25). Upon further examination of the AHE shown in the massive Dirac Kagome ferromagnet, Fe$_3$Sb$_2$, we find that its AHC also follows a quadratic scaling with a similar skew constant (0.013) as KV$_3$Sb$_5$, but due to its low longitudinal conductivity, the magnitude is 10 times smaller. However, the spin cluster theory predicts that a $\sigma_{AHE}$ is proportional to $\sigma_{xx}$ relationship, which assumes weak magneto-electron coupling that excludes spin-orbit coupling (SOC) in the derivation. A theoretical treatment of Dirac quasiparticles in spin cluster systems where SOC is included will have additional terms in the scattering potential that may recover the quadratic dependence.

A combination of enhanced skew scattering parameters and the quadratic scaling grant the KV$_3$Sb$_5$-like materials the potential to realize another fascinating effect: to achieve an AHA approaching 90° extrinsically, which has not been previously proposed or observed. Quadratic dependence of $\sigma_{AHE}$ means that the AHA increases quickly with increasing $\sigma_{xx}$, allowing a very large $\sigma_{AHE}$ at reasonable $\sigma_{xx}$. For example, extrapolating the evident quadratic scaling of KV$_3$Sb$_5$ shown in Fig. 4, an AHA = 45° is reached by $\sigma_{xx}$ of $5 \times 10^7 \Omega^{-1}$ cm$^{-1}$. These are very large conductivities but not implausible; the Dirac semimetal Cd$_3$As$_2$ (46), Weyl semimetal NbAs (47), and encapsulated graphene (48) all are known to reach this conductivity regime. A similar extrapolation for Fe would require an unrealistic $\sigma_{xx}$ of >10$^8 \Omega^{-1}$ cm$^{-1}$.

**DISCUSSION**

To compare the observed AHE of KV$_3$Sb$_5$ with that of other materials, $\sigma_{AHE}$ versus $\sigma_{xx}$ for a variety of materials spanning the various AHE regimes from the dirty regime (localized hopping regime) through to the skew scattering regime are plotted in Fig. 4 (23, 39–43). The different scaling relationships for the localized hopping regime ($\sigma_{xx}$) and skew scattering regimes ($\sigma_{xx}$) as well as the quadratic scaling behavior of Fe ($\sigma_{xx}$) are shown by black dotted lines. Purple lines show three AHRs and their corresponding AHA values. The AHE in KV$_3$Sb$_5$, for devices of varying thickness with its scaling shown as the red dotted line, begins its quadratic scaling at $\sigma_{xx} \approx 2 \times 10^5 \Omega^{-1}$ cm$^{-1}$, an order of magnitude before Fe, and dwarfs most materials by $\sigma_{xx} \approx 2 \times 10^7 \Omega^{-1}$ cm$^{-1}$.

**Fig. 3. AHE in KV$_3$Sb$_5$.** (A) Angular dependence of $\sigma_{AHE}$ at 2 K as the $\mu_0$H is tilted from out-of-plane to in-plane. The inset shows the $\sigma_{AHE}$ against $\cos(\theta)$. (B) Extracted $\sigma_{AHE}$ versus $\sigma_{xx}$ for various devices with thickness ranging from 30 to 128 nm. Solid lines are fittings to the equation shown in the inset to extract the skew scattering constant ($\alpha$) and intrinsic AHC ($b$) for each device. The inset shows the extracted intrinsic $\sigma_{AHE}$ for all six devices. Larger error is seen for samples 1 to 3 due to the size of the dominating extrinsic component. (C) The ratio between $\sigma_{AHE}$ and $\sigma_{xx}$ for six KV$_3$Sb$_5$ devices and for Fe. The black lines guide the eye to illustrate the increasing tendency of $\sigma_{AHE}/\sigma_{xx}$ for KV$_3$Sb$_5$ and for Fe.
of the effects of quantum anomalous Hall insulators may be replicated in a highly conductive metal. We conclude that the Kagome sub-lattice in KV₃Sb₅ is acting as tilted spin clusters, giving rise to an enhanced skew scattering effect in accordance with a recent proposal by Ishizuka and Nagaosa (25) but with highly mobile Dirac quasiparticles enhancing the conductivity. This suggests that future theoretical studies on understanding the coupling of relativistic electrons to the magnetic texture with SOC are necessary to reveal the detailed scaling relations. Studies on sister compounds RbV₃Sb₅ and CsV₃Sb₅ could elucidate the effect of increased SOC strength. Since these materials also have weakly bound alkali earth interstitials, the Fermi level can be tuned through intercalation control; ionic liquid gating on few layer samples is an ideal way to vary σₓᵧ and explore the AHE response. In addition, the high exfoliatability of these compounds makes them ideal platforms for thickness-dependent and monolayer exploration of the AHE and observing the cross-over from the extrinsic-dominated AHE to the intrinsic-dominated regime. This combination of exotic band structures with metallic geometrically frustrated systems provides a novel route for the study of extrinsic Hall effects. Also, since the magnetic fluctuations can be tuned with external perturbations, a new type of experiment where the AHE is further enhanced by modifying the skew scattering potential in situ is possible. In addition, the skew scattering SHE arises from a similar mechanism as the skew scattering AHE; therefore, very large spin Hall angles may also be discovered in KV₃Sb₅ and other similar materials. This is another particularly important avenue of research as large spin Hall angles in highly conductive systems (and therefore low power) are extremely sought after for spintronic applications.

**METHODS**

High-quality single crystals of KV₃Sb₅ were synthesized from K (ingot, Alfa 99.8%), V (powder, Sigma 99.9%), and Sb (shot, Alfa 99.999%) via the flux method as described by Ortiz et al. (33). Flux mixtures containing 5 mole percent of KV₃Sb₅ were heated to 1000°C, soaked for 24 hours, and then subsequently cooled at 2°C per hour. KV₃Sb₅ crystals were structurally and chemically characterized by powder x-ray diffraction to confirm bulk purity and scanning electron microscopy energy-dispersive x-ray for chemical analysis.

A Quantum Design physical property measurement system (PPMS) was used for transport measurements with Keithley 6221 and Keithley 2182 electronics. Hall measurements were taken in a five-wire configuration, while the MR of KV₃Sb₅ samples was measured using the four-point method. The rotator insert (Quantum Design) was used to tilt the angle between the magnetic field and the current direction. ARPES measurements were performed at Beamline 105 of the Diamond Light Source using the Scienta R4000 analyzer. The angle and energy resolutions were <0.2° and <15 meV, respectively.

The electronic structure calculations were performed in the framework of DFT using the Vienna Ab initio Simulation Package (VASP) (50) code with a full-potential linearized augmented plane wave (FP-LAPW) basis (51) together with the Perdew Burke Ernzerhof parametrization of the generalized gradient approximation as the exchange-correlation functional. The Fermi surface was plotted with the program XCRYSDen.

**SUPPLEMENTARY MATERIALS**

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/6/31/eabb6003/DC1


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Author contributions: S.-Y.Y. and Y.W. measured the transport data and carried out the analysis. B.R.O. grew the samples and measured the magnetism. D.L. carried out the ARPES measurements. R.G.-H. and L.S. performed and analyzed the ab initio calculations. L.S., J.G., and E.D. carried out DFT analysis and provided theoretical support. S.-Y.Y. and M.N.A. conceived the study. Y.C., S.S.P.P., S.D.W., E.S.T., T.M., and M.N.A. are the principal investigators.

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