

Bending electrons get hot

Evgeny Y. Tsymlal & Ding-Fu Shao

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A spontaneous Hall effect has been observed in a collinear antiferromagnet at room temperature.

When an electric field is applied to a conductor, electrons are forced to flow, generating a charge current along the electric field. In the presence of magnetic field, this electron flow bends. Such bending of electrons leads to a transverse charge current known as the Hall effect¹. In ferromagnetic metals, the Hall effect emerges even in the absence of magnetic field and thus is referred to as anomalous or spontaneous². The spontaneous (anomalous) Hall effect (AHE) is commonly associated with the spontaneous magnetization of ferromagnets. However, recently, this effect has been predicted³ and then demonstrated⁴ in antiferromagnetic (AFM) metals, despite their vanishingly small net magnetization. This discovery is important because antiferromagnets with their zero stray fields and ability of ultrafast switching can be efficiently employed in spintronics – a vigorously developing research field promising to revolutionize data processing and storage^{5,6}. So far, however, only non-collinear antiferromagnets have revealed AHE at room temperature, while their collinear counterparts, which are arguably promising for spintronics, have not. Now, writing in *Nature Materials*, Rina Takagi and colleagues experimentally demonstrate AHE in a collinear antiferromagnet at room temperature⁷.

Modern theories predict that AHE originates from the geometrical property of the crystal's energy bands known as the Berry curvature⁸. The Berry curvature is a fictitious magnetic field bending electron trajectories like a real magnetic field. The Berry curvature and hence AHE are controlled by the magnetic group symmetries of a crystal. For example, time reversal T turns over the Hall current and flips a magnetic

moment, because it is intrinsically linked to the motion of electric charges. Consequently, AHE does not occur in non-magnetic materials, because they obey T -symmetry, so that the Hall current equals to its negative and thus vanishes. On the contrary, in ferromagnetic materials, where T -symmetry is broken due to their magnetization, AHE is non-zero.

In collinear antiferromagnets, T -symmetry transforms two AFM-aligned magnetic sublattices to each other. The T -transformed state is supposed to have a reversed Hall current. However, if this new state can be transformed back by some crystal symmetry operation O , the two states appear to be identical, and the Hall current vanishes. Equivalently, if a magnetic crystal has a combined TO -symmetry, AHE is forbidden. Among such crystal symmetries O are space inversion P , half-a-unit-cell translation t and in-plane mirror reflection M_z . Figure 1a–c illustrates typical examples of AFM structures holding these symmetries.

Most conventional antiferromagnets possess one or more of these symmetries that prohibit AHE. However, there is a group of antiferromagnets with all these symmetries broken. Figure 1d shows an example where the TO -symmetries are destroyed, and thus AHE is permitted⁹. It is noteworthy that collinear antiferromagnets with broken TO -symmetries exhibit an exchange-split electronic structure and belong to the class of collinear antiferromagnets now known as 'altmagnets'¹⁰.

Recently, efforts have been made to observe AHE in nominal altermagnets RuO₂ (ref. 11) and MnTe (ref. 12). However, owing to magnetic symmetry of RuO₂ that is incompatible with AHE, the Hall response was observed only at high magnetic field¹¹, while in MnTe, AHE was weak and detectable only at low temperature¹². Observing a robust spontaneous Hall response at ambient conditions has remained a challenge – until now.

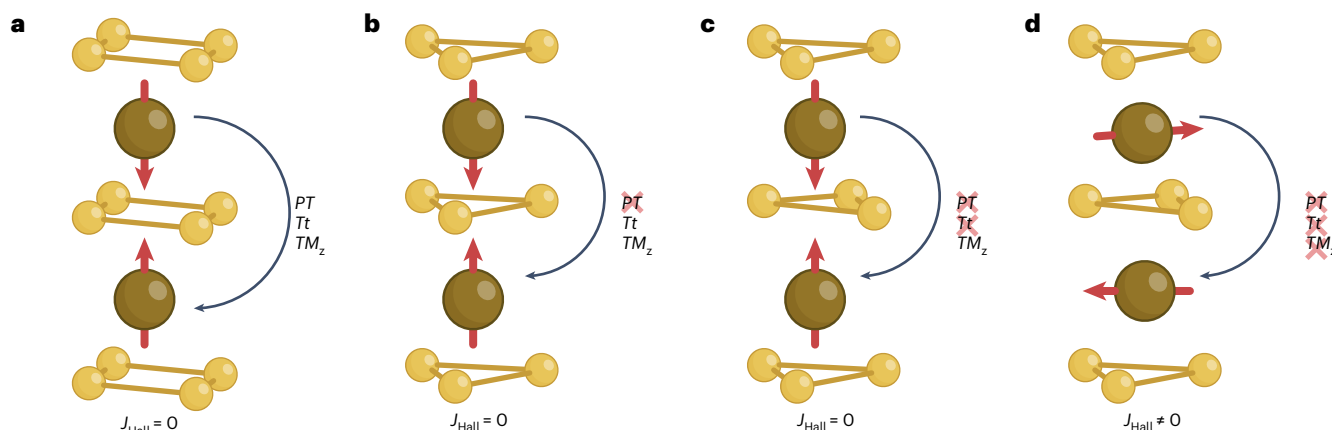


Fig. 1 | AFM structures with different magnetic group symmetries.

a–d, Examples of atomic and magnetic structure of collinear antiferromagnets with vanishing (**a–c**) and non-vanishing AHE (**d**). Red arrows show the direction of magnetic moments on two magnetic sublattices. Panels **c** and **d** represent the

structure of FeS, the antiferromagnet studied by Takagi et al.⁷, for the easy-axis (**c**) and easy-plane (**d**) AFM states. Symmetries transforming magnetic sublattices to each other are shown. Crosses indicate broken symmetries. J_{Hall} denotes the Hall current.

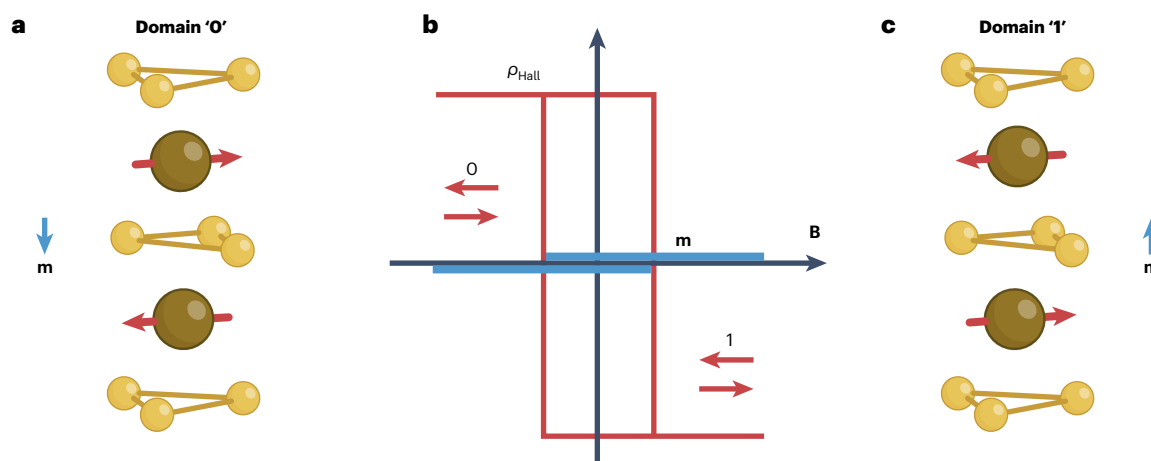


Fig. 2 | Switching of collinear antiferromagnet FeS between two AFM domains '0' and '1' at room temperature. a, c, AFM domains '0' (a) and '1' (c) exhibiting opposite magnetization on two magnetic sublattices. Red arrows show the magnetic moments on two magnetic sublattices. Blue arrows indicate a tiny

net moment $\mathbf{m}$ whose direction is perpendicular to the plane and opposite for the two domains. b, Schematic hysteresis curve showing the switching of Hall resistivity ρ_{Hall} and net magnetic moment $\mathbf{m}$ between AFM domains '0' and '1' under applied external out-of-plane magnetic field $\mathbf{B}$.

Takagi and colleagues rise to this challenge and succeed in demonstrating AHE in the collinear antiferromagnet FeS at room temperature⁷. As confirmed by their X-ray diffraction measurements and shown in Fig. 1d, the atomic structure of FeS consists of magnetic Fe atoms sandwiched by oppositely oriented triangular plaquettes of S atoms. Their magnetic susceptibility and neutron scattering studies indicate that FeS hosts easy-plane AFM order at room temperature (Fig. 1d), which alters to easy-axis below 220 K (Fig. 1c). Thus, the symmetry conditions for non-vanishing AHE in FeS are fulfilled at room temperature but not below 220 K.

To observe the effect, Takagi and colleagues measure the Hall resistivity as a function of magnetic field at different temperatures. Strikingly, for out-of-plane applied field, they observe a pronounced spontaneous Hall signal at room temperature. Its sign reverses at positive or negative fields, resulting in a hysteresis loop schematically shown Fig. 2b. In contrast, no AHE is observed below 220 K.

The hysteretic behaviour of the Hall resistivity is driven by switching the AFM order between domains '0' (Fig. 2a) and '1' (Fig. 2c). This switching is mediated by the out-of-plane net magnetic moment, which originates from small out-of-plane canting of AFM-aligned moments allowed by the broken TO -symmetries. While the net moment is tiny, it interacts with the applied out-of-plane magnetic field and switches simultaneously with the AFM order. The measured hysteresis loops reveal switching of the magnetic moment and Hall resistivity at the same field, as depicted in Fig. 2b. The observed anomaly in the Hall resistivity is much more pronounced than that in the magnetic moment, suggesting that AHE is not simply induced by this tiny moment, but rather driven by the Berry curvature associated with the TO -symmetry-broken AFM order.

Overall, Takagi and colleagues make an important step towards implementing the concept of AFM spintronics to utilize an AFM order parameter as a state variable in spintronic devices. Their work shows the complete switching of the AFM order between two non-volatile states, which can serve as '0' and '1' in magnetic memories with readout

provided by AHE. Their findings indicate that even relatively simple, both structurally and magnetically, collinear antiferromagnets can be employed in AFM spintronics. Among the outstanding challenges is demonstrating reversible AHE in collinear easy-axis antiferromagnets and realizing current-induced switching by spin torques. Also, demonstration of functional AFM tunnel junctions based on collinear TO -symmetry-broken antiferromagnets would be appealing¹³. On the whole, the work by Takagi and colleagues represents an important milestone in the developing field of AFM spintronics.

Evgeny Y. Tsymbal ¹ & **Ding-Fu Shao** ²

¹Department of Physics and Astronomy & Nebraska Center for Materials and Nanoscience, University of Nebraska, Lincoln, NE, USA.

²Key Laboratory of Materials Physics, Institute of Solid State Physics, HFIPS, Chinese Academy of Sciences, Hefei, China.

e-mail: tsymbal@unl.edu; dfshao@issp.ac.cn

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References

- Hall, E. Amer. J. Math. **2**, 287–292 (1879).
- Hall, E. H. Proc. Phys. Soc. Lond. **4**, 325–342 (1880).
- Chen, H., Niu, Q. & MacDonald, A. H. Phys. Rev. Lett. **112**, 017205 (2014).
- Nakatsuji, S., Kiyohara, N. & Higo, T. Nature **527**, 212–215 (2015).
- Baltz, V. et al. Rev. Mod. Phys. **90**, 015005 (2018).
- Tsymbal, E. Y. & Žutić, I. (eds) *Spintronics Handbook: Spin Transport and Magnetism* 2nd edn (CRC Press, 2019).
- Takagi, R. et al. Nat. Mater. <https://doi.org/10.1038/s41563-024-02058-w> (2024).
- Nagaosa, N., Sinova, J., Onoda, S., MacDonald, A. H. & Ong, N. P. Rev. Mod. Phys. **82**, 1539–1592 (2010).
- Šmejkal, L., González-Hernández, R., Jungwirth, T. & Sinova, J. Sci. Adv. **6**, eaaz8809 (2020).
- Šmejkal, L., Sinova, J. & Jungwirth, T. Phys. Rev. X **12**, 040501 (2022).
- Feng, Z. et al. Nat. Electron. **5**, 735–743 (2022).
- Gonzalez Betancourt, R. D. et al. Phys. Rev. Lett. **130**, 036702 (2023).
- Shao, D.-F. & Tsymbal, E. Y. npj Spintronics **2**, 13 (2024).

Competing interests

The authors declare no competing interests.