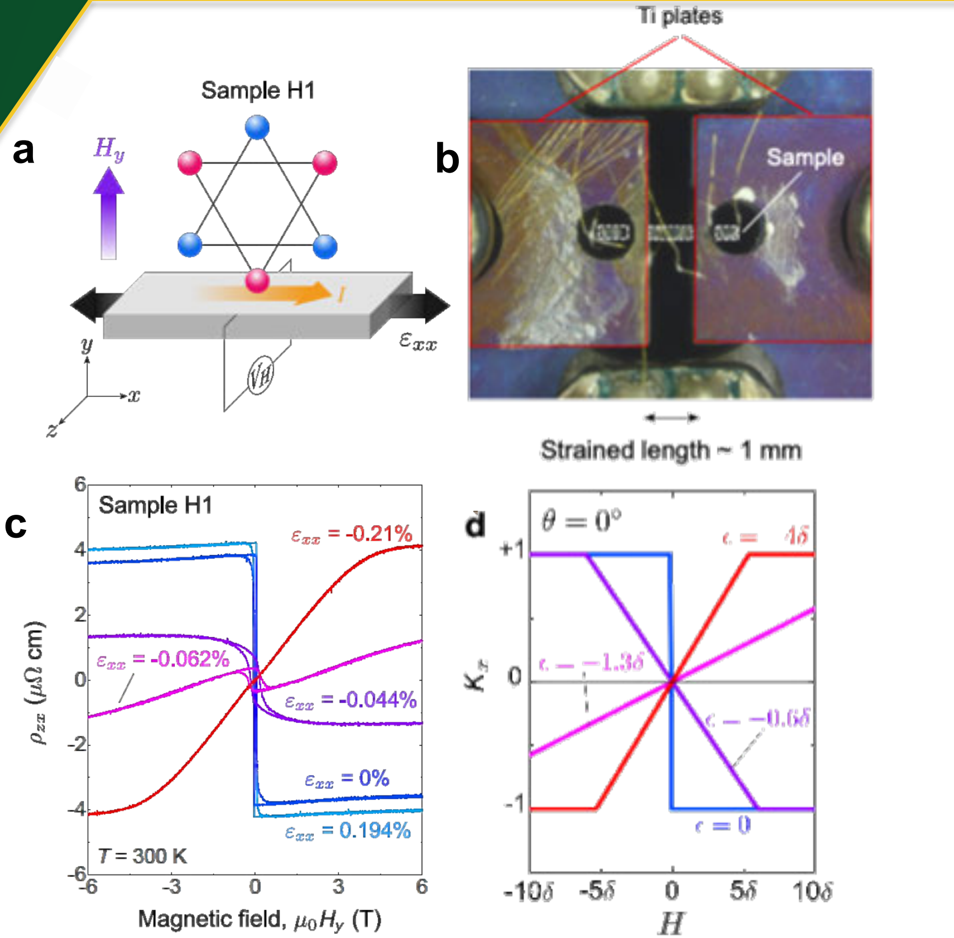
Control of Hall effect by strain in Weyl semimetal Mn_3Sn



a. Schematic of experiment. **b.** Sample and setup. **c.** Hall resistivity v. magnetic field at constant strains (experiment). **d.** Same (theory).

M. Ikhlas, S. Dasgupta, F. Theuss, T. Higo, S. Kittaka, B. J. Ramshaw, O. Tchernyshyov, C. W. Hicks, S. Nakatsuji, Nature Physics (2022).

Scientific Achievement

IQM scientists have shown that the sign and magnitude of the Hall conductivity in Mn_3Sn can be controlled by the application of uniaxial strain.

Significance and Impact

Mn_3Sn is an antiferromagnetic Weyl semimetal exhibiting the anomalous Hall effect (AHE). Its Hall conductivity depends on its magnetic state. Our experiments show that the magnetic state and the Hall conductivity in Mn_3Sn can be manipulated not only by a magnetic field but also by uniaxial strain.

Research Details

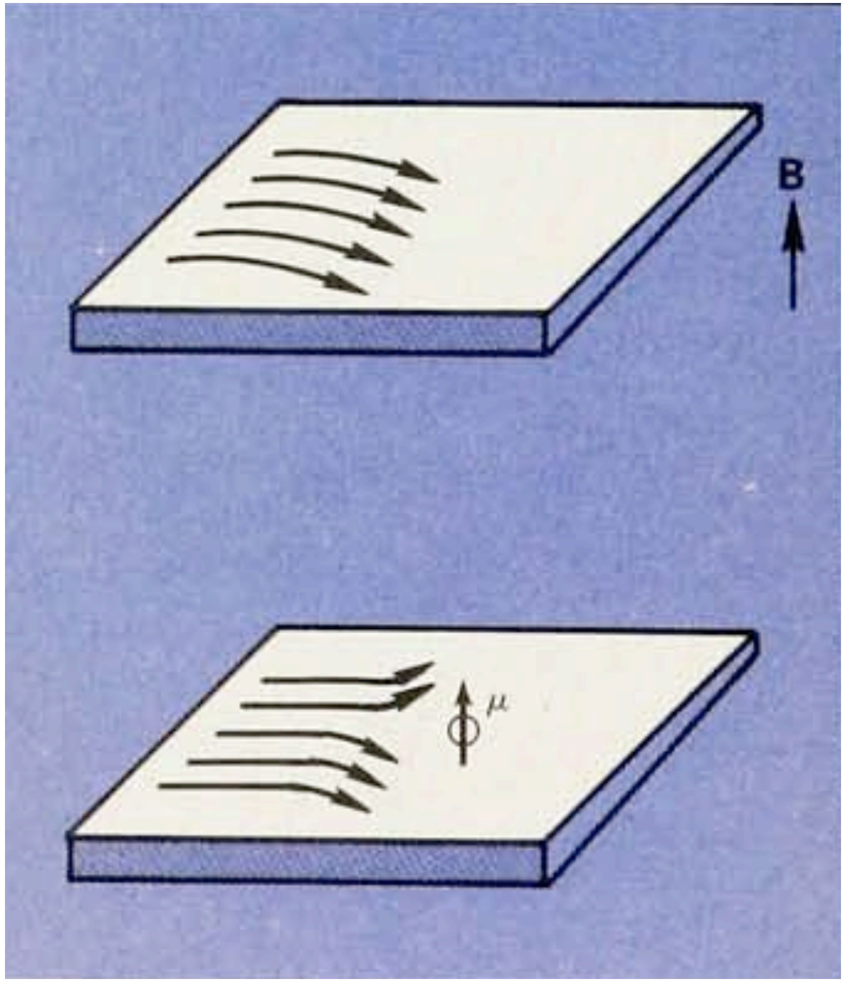
- Common wisdom holds that the anomalous Hall effect is directly related to magnetization.
- Uniaxial strain reverses the Hall conductivity of Mn_3Sn but not magnetization, showing the former is not controlled by the latter.
- Conventional wisdom is thus wrong. The AHE is tied to the electron Berry curvature, not magnetization.
- Our work opens a new mechanical way of controlling the electrical properties of Mn_3Sn.

U.S. DEPARTMENT OF ENERGY | Office of Science

INSTITUTE FOR QUANTUM MATTER

EFRC DE-SC0019331

Background: ordinary and anomalous Hall effects



Ordinary Hall effect (1879)

Caused by the Lorentz force deflecting moving carriers of electric charge. Requires an applied magnetic field **B**.

$$E_x = R_0 j_y B_z$$

Anomalous Hall effect (1881)

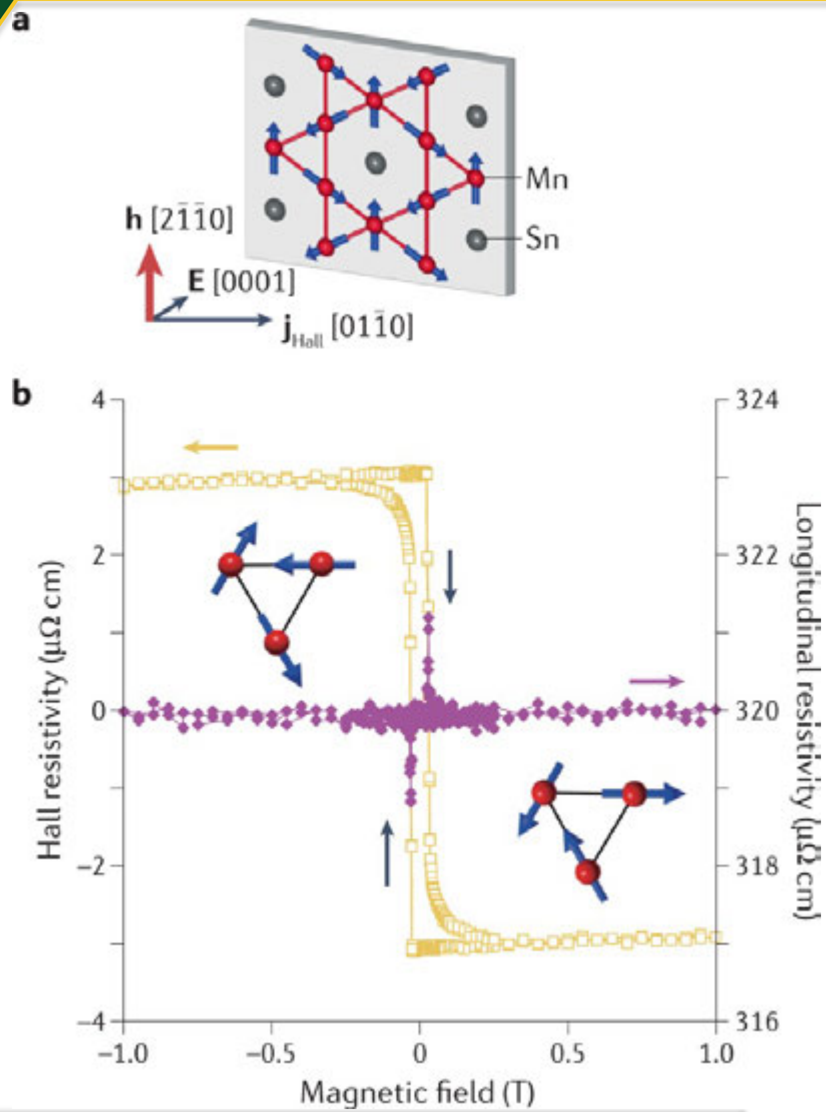
First observed in ferromagnetic metals. Requires a field breaking the time-reversal symmetry such as magnetization **M**.

$$E_x = R_a j_y M_z$$

AHE is an electric read-out for a magnetic state. Modern theory relates AHE to the Hall vector **K,** a "magnetic field" felt by electrons in **k**-space:

$$j_x = (e^2/h) E_y K_z$$

Mn_3Sn: weak ferromagnet with strong Hall effect



Hexagonal antiferromagnet with 3 sublattices

Magnetic order below T_N = 420 K with spins in the *ab* plane with 3 sublattices rotated 120º relative to one another.

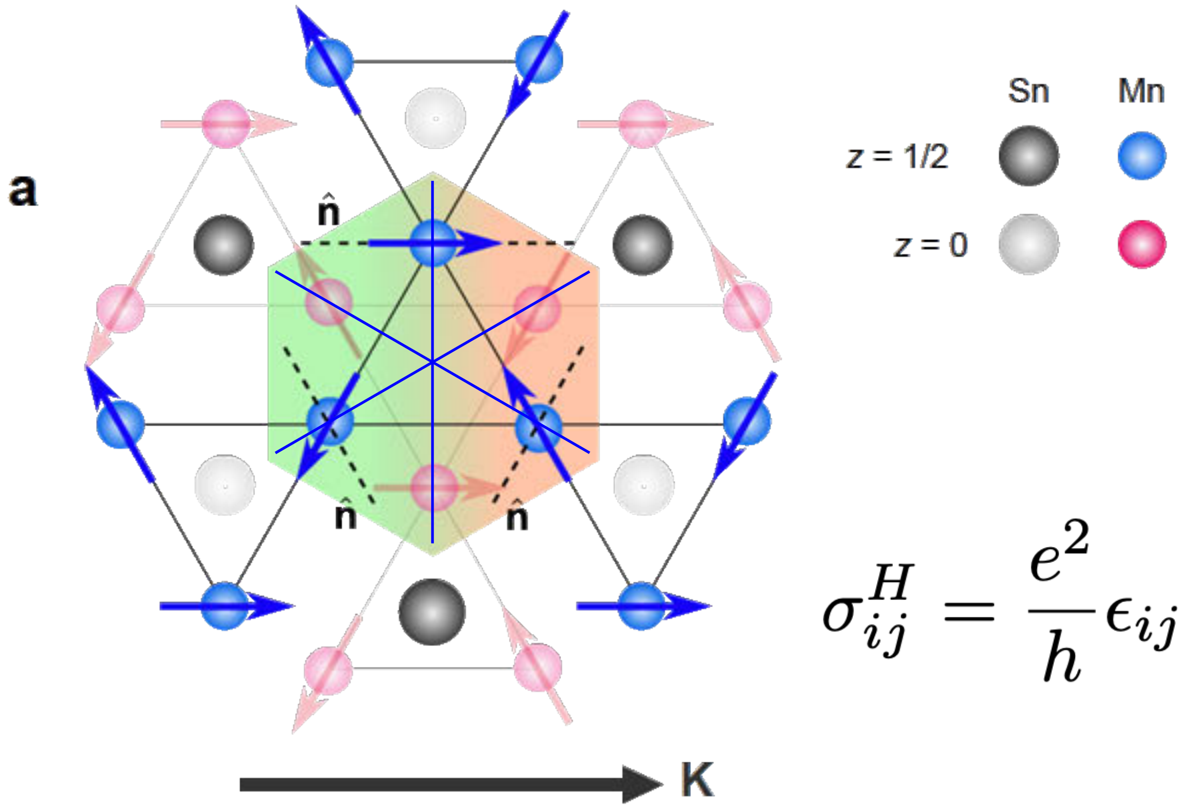
Imperfect 120º alignment creates net magnetization **M** of 0.001 Bohr magneton per Mn, allowing for control of magnetic order with a magnetic field.

AHE with **j** and **E** in the plane orthogonal to **M**. Reversal of **E** in AHE points to the reversal of magnetic order.

S. Nakatsuji *et al.*, Nature **527**, 212 (2015).
T. Šmejkal *et al.*, Nat. Rev. Mater. **7**, 483 (2022).

U.S. DEPARTMENT OF ENERGY | Office of Science

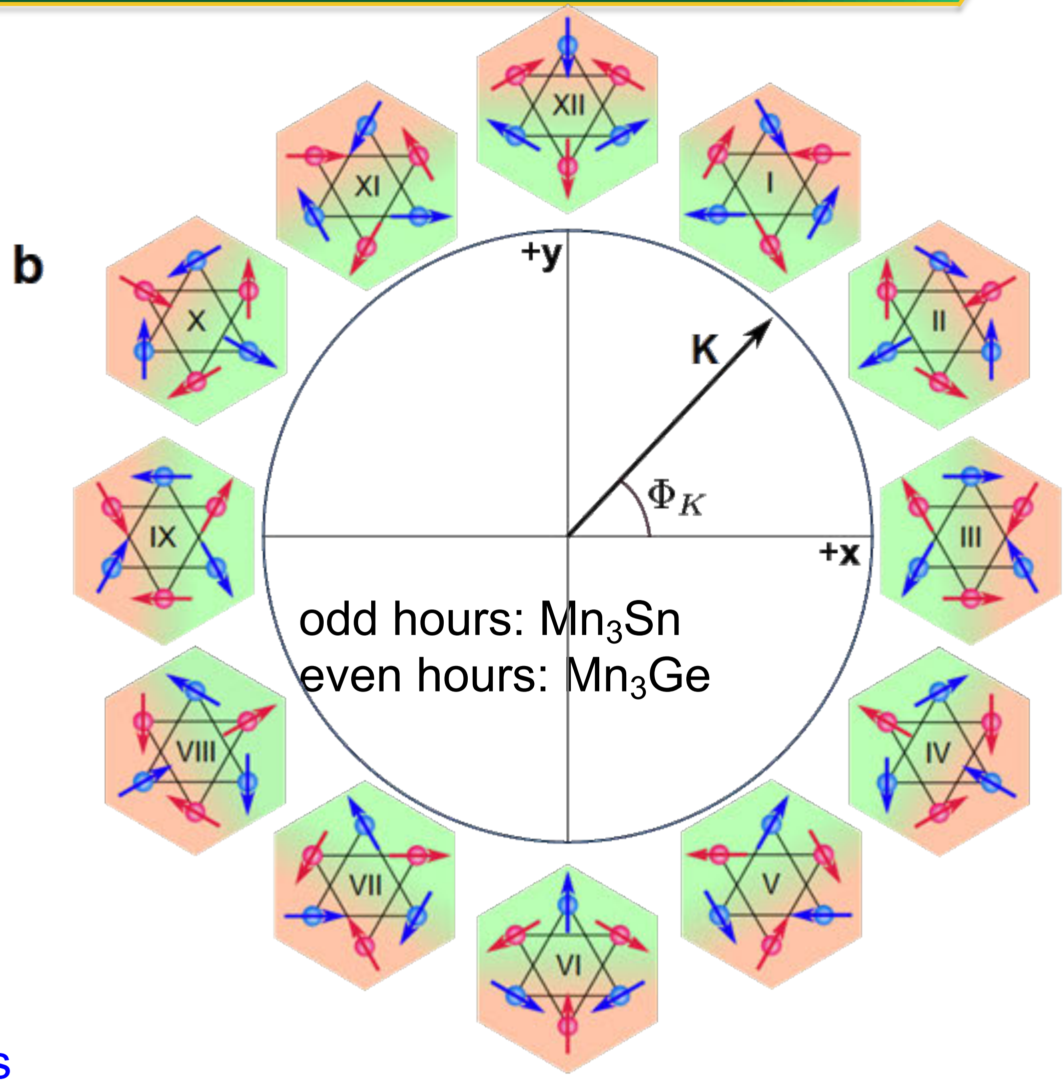
Magnetic order in Mn_3Sn



$$\sigma_{ij}^{H} = \frac{e^2}{h}\epsilon_{ijk}K_k$$

magnetic Hall vector **K** is the order parameter

spins can be obtained from **K** by local mirror reflections



Coupling of the magnetic order to external fields

Magnetic order parameter $\mathbf{K} = (K\cos\Phi_K, K\sin\Phi_K, 0)$

Magnetic field $\mathbf{H} = (H\cos\Phi_H, H\sin\Phi_H, 0)$

Shear strain in the *xy*-plane $\epsilon_{xx} - \epsilon_{yy} = \epsilon\cos 2\Phi_\epsilon, \quad \epsilon_{xy} + \epsilon_{yx} = \epsilon\sin 2\Phi_\epsilon$

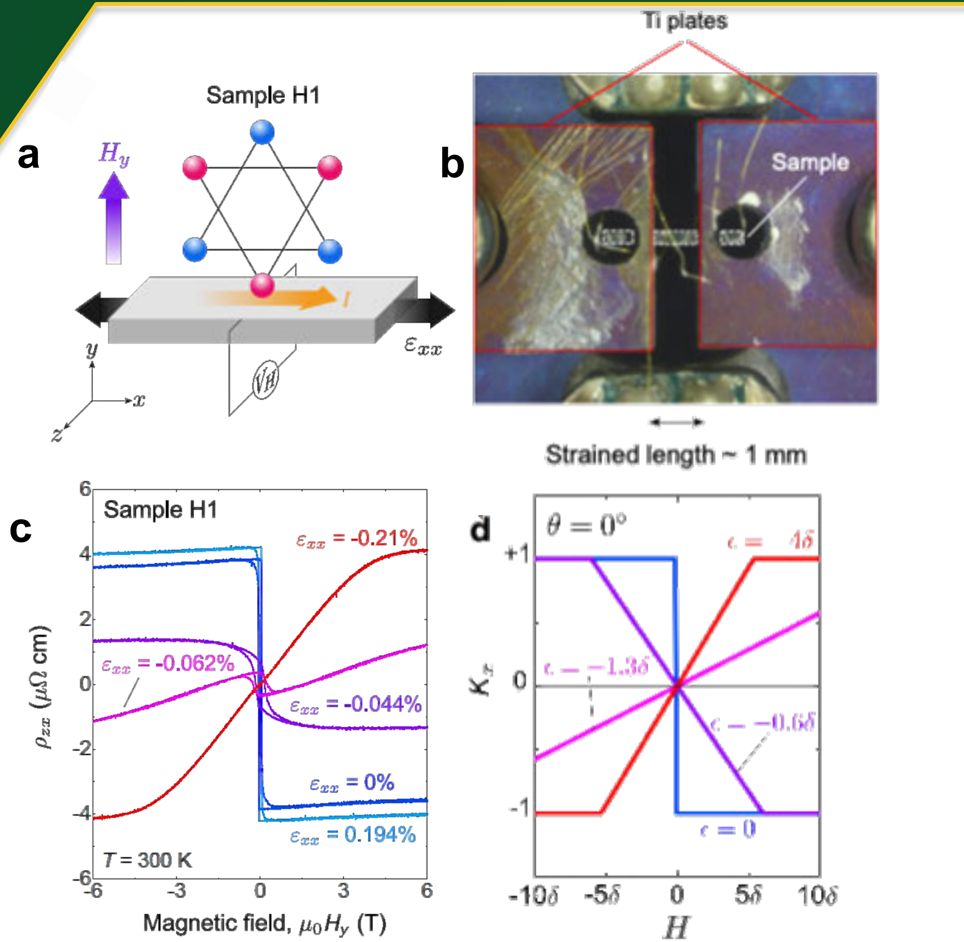
Landau free energy density:

$$U = -\delta HK\cos(\Phi_K - \Phi_H) + \delta\epsilon K^2\cos(2\Phi_K - 2\Phi_\epsilon) + \epsilon HK\cos(\Phi_K + \Phi_H - 2\Phi_\epsilon).$$

"Zeeman" term "magnetostriction" "piezomagnetism"

δ is the strength of local anisotropy (easy axis)

Control of Hall effect by strain in Weyl semimetal Mn_3Sn



a. Schematic of experiment. **b.** Sample and setup. **c.** Hall resistivity v. magnetic field at constant strains (experiment). **d.** Same (theory).

M. Ikhlas, S. Dasgupta, F. Theuss, T. Higo, S. Kittaka, B. J. Ramshaw, O. Tchernyshyov, C. W. Hicks, S. Nakatsuji, Nature Physics (2022).

Scientific Achievement

IQM scientists have shown that the sign and magnitude of the Hall conductivity in Mn_3Sn can be controlled by the application of uniaxial strain.

Significance and Impact

Mn_3Sn is an antiferromagnetic Weyl semimetal exhibiting the anomalous Hall effect (AHE). Its Hall conductivity depends on its magnetic state. Our experiments show that the magnetic state and the Hall conductivity in Mn_3Sn can be manipulated not only by a magnetic field but also by uniaxial strain.

Research Details

- Common wisdom holds that the anomalous Hall effect is directly related to magnetization.
- Uniaxial strain reverses the Hall conductivity of Mn_3Sn but not magnetization, showing the former is not controlled by the latter.
- Conventional wisdom is thus wrong. The AHE is tied to the electron Berry curvature, not magnetization.
- Our work opens a new mechanical way of controlling the electrical properties of Mn_3Sn.