Scattering-dependent transport of $SrRuO_3$ films: From Weyl fermion transport to hump-like Hall effect anomaly

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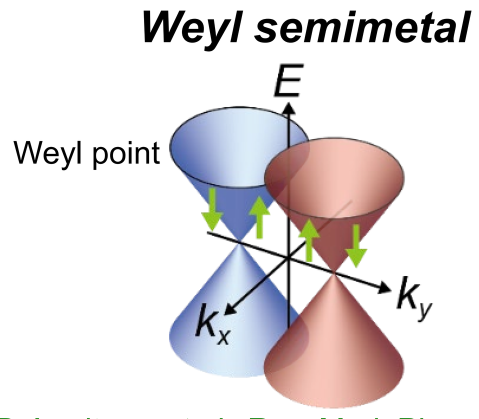
Background

■ $SrRuO_3$ has a variety of topological physics

Weyl semimetal



N. P. Armitage *et al.*, Rev. Mod. Phys. **90** 1551 (2018).

Magnetic Weyl semimetal; Massless Dirac Hamiltonian

+ broken **Time reversal symmetry (TRS)**

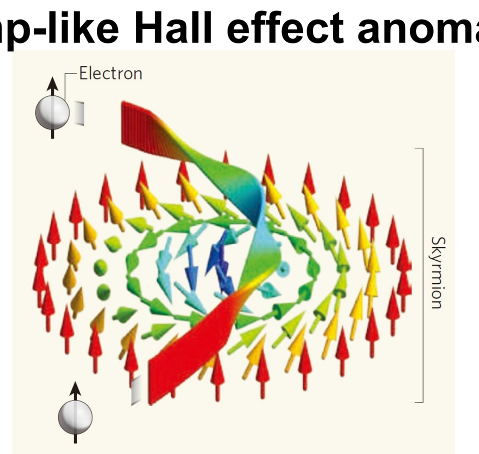
e.g.) $Co_3Sn_2S_2$, Co_2MnGa, $SrRuO_3$

K. Takiguchi *et al.*, Nat. Commun. **11**, 4969 (2020).
S. K. Takada *et al.*, npj. Quantum. Mater. **7**, 102 (2022).

Application : Topoelectrical circuit

C. H. Lee *et al*, Commun. Phys. **1**, 39 (2018).
S. M. Rafi-Ul-Islam *et al*, Commun. Phys. **1**, 72 (2020).

Topological Hall effect (Hump-like Hall effect anomaly)



C. Pfleiderer and A. Rosch, Nature **465**, 880 (2010).

Transverse electron flows via skyrmions

e.g.) MnSi, FeGe, $SrRuO_3/SrIrO_3$

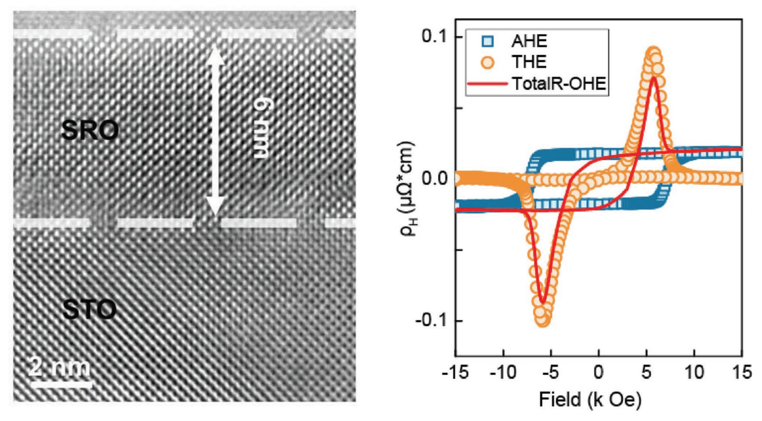
J. Matsuno *et al.*, Sci. Adv. **2**, e1600304 (2016).
Q. Qin *et al.*, Adv. Mater. **31**, 1807008 (2019).

Application : Racetrack memory

R. Tomasello *et al*, Sci. Rep. **4**, 6784 (2014).
X. Zhang *et al*, Sci. Rep. **5**, 7643 (2015).

■ Controversial origins of Hump-like Hall effect anomaly in $SrRuO_3$

➢ Topological Hall effect derived from skyrmions

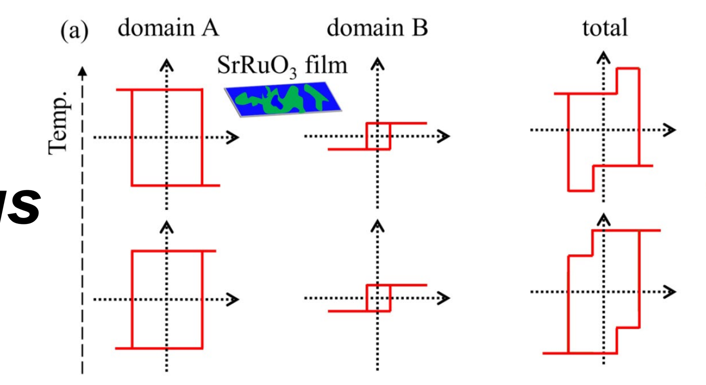


Q. Qin *et al.*, Adv. Mater. **31**, 1807008 (2019).

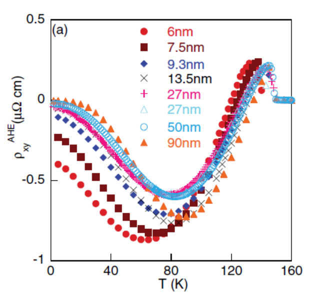
✓ Intrinsic phenomenon
✓ Skyrmions at the $SrRuO_3/SrIrO_3$ interface or the $SrRuO_3$ single layer

Versus

➢ Multi-channel anomalous Hall effect (AHE)



D. Kan *et al.*, Phys. Rev. B **101**, 144405 (2020).



N. Haham *et al.*, Phys. Rev. B **84**, 174439 (2011).

✓ Extrinsic phenomenon
✓ Superposition of AHEs with different signs of hysteresis loops due to the Ru defects
□ Lack of Ru-deficiency dependence experiments due to the difficulty of adjusting the amount of Ru defects.

■ Purpose of this study

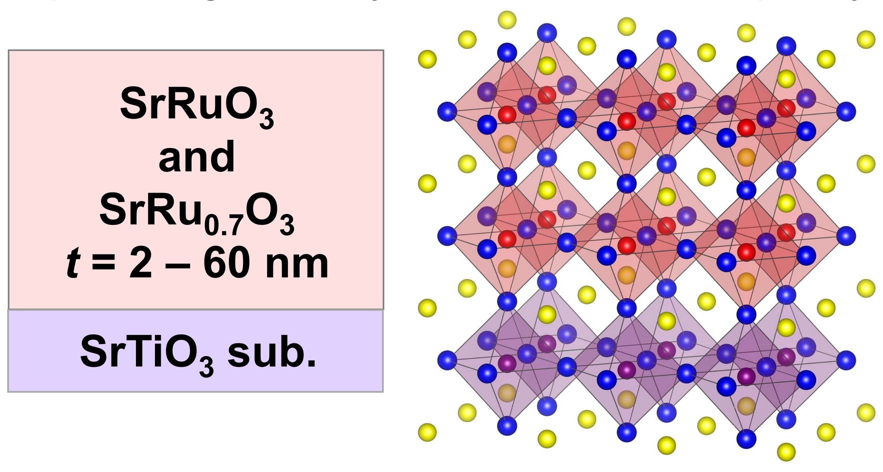
□ Investigate the scattering dependence on the Weyl fermion transport and hump-like Hall effect anomaly, which is governed by the degree of scattering (*i.e.* Ru-deficiency-, interface-driven-defect, and phonon scatterings), in $SrRu_{1-x}O_3$ films

□ Reveal the origin of the hump-like Hall effect anomaly

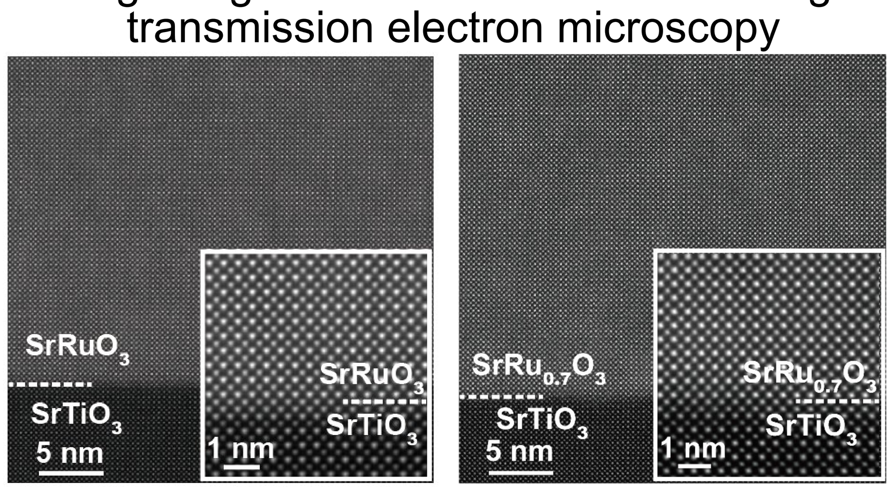
Experiments

■ Sample analysis and transport property

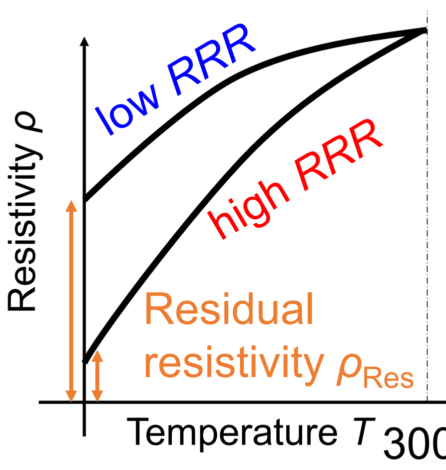
Epitaxial growth by molecular beam epitaxy



High-angle annular dark-field scanning transmission electron microscopy



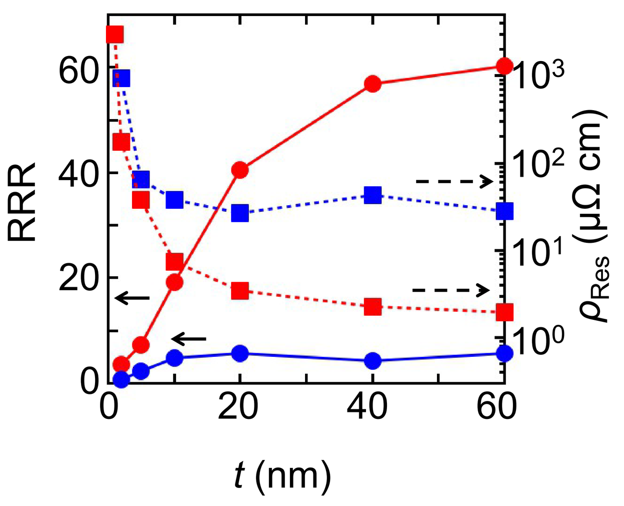
S. Kaneta-Takada, Y. K. Wakabayashi *et al.*, Appl. Phys. Lett. **118**, 092408 (2021).
Y. K. Wakabayashi, S. Kaneta-Takada *et al.*, AIP. Adv. **11**, 035226 (2021).



Residual resistivity ratio (*RRR*) = ρ(300 K) / ρ(T → 0 K)

Expressing the quality and purity of metallic samples.

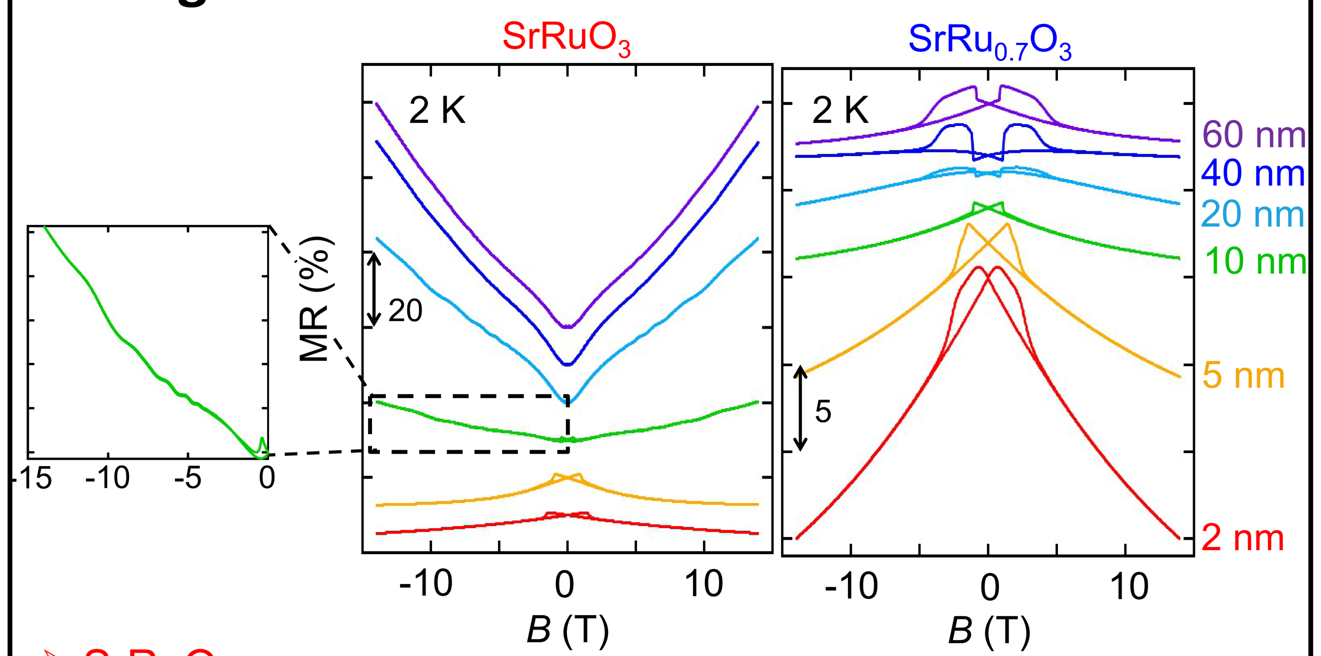
ρ(T → 0 K) is originated from the extrinsic factors: defects, impurities.



ρ_{Res} of $SrRu_{0.7}O_3$ is larger than that of $SrRuO_3$.
→ Ru defects are the scatterers.

ρ_{Res} of $SrRuO_3$ and $SrRu_{0.7}O_3$ increase steeply below 10 nm.
→ Scattering due to disorder at the interface

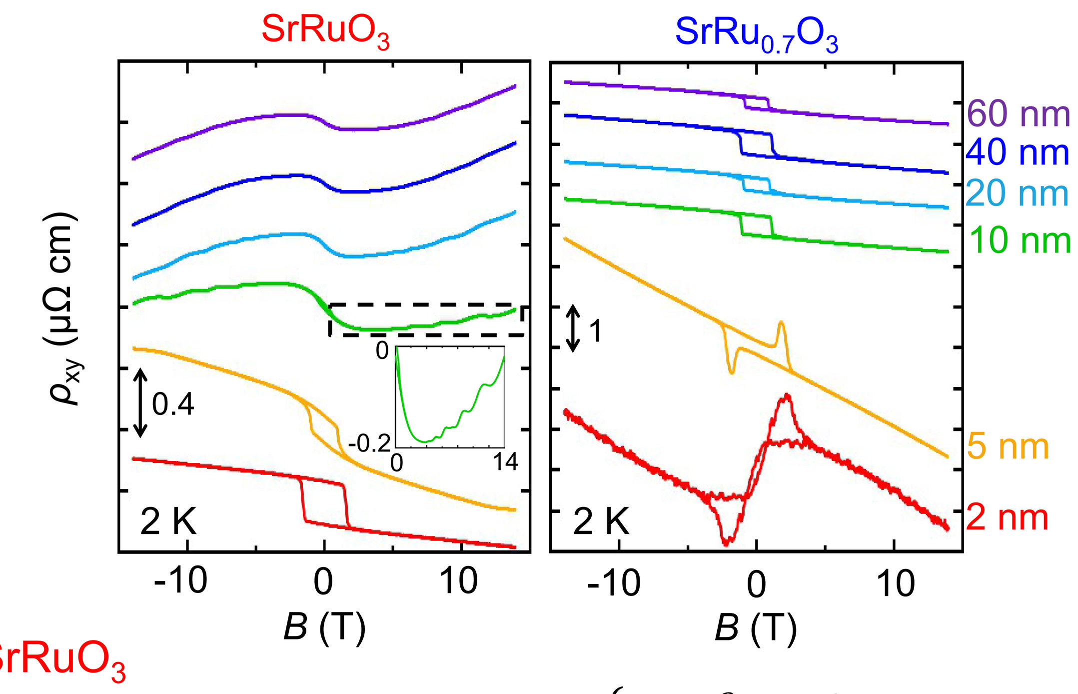
■ Magnetoresistance



➢ $SrRuO_3$
Quantum oscillations and linear positive magnetoresistance of Weyl fermions for t ≥ 10 nm
⇨ Sufficiently long quantum scattering time with a low interfacial disorder

➢ $SrRu_{0.7}O_3$
No linear positive magnetoresistance with quantum oscillations
⇨ Scattering due to Ru defects inhibits observation of quantum transport of Weyl fermions

■ Anomalous Hall effect

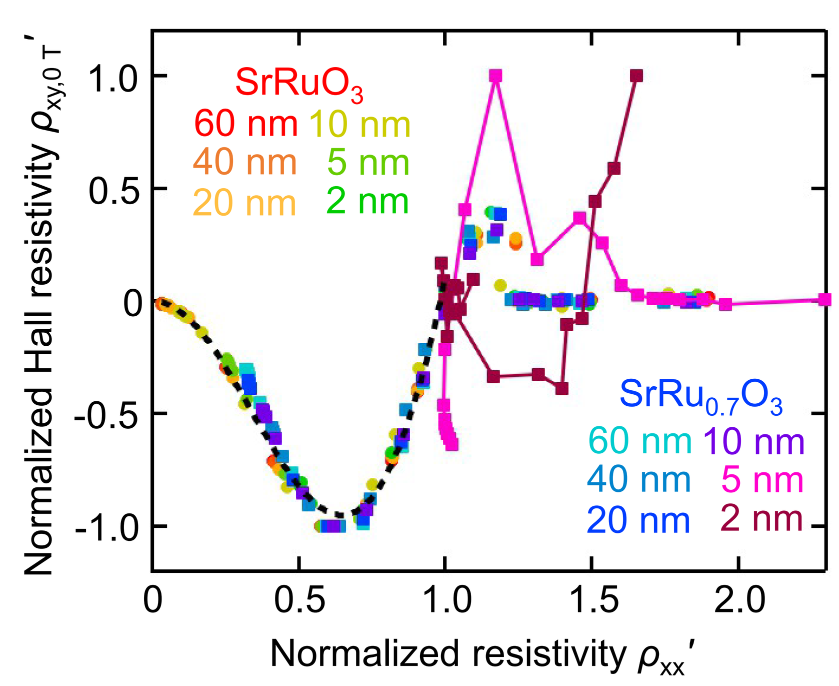


➢ $SrRuO_3$
The carrier type of the Weyl fermion is hole.
The multi-carrier behavior disappears with t ≤ 5 nm

$$\rho_{xy} \approx \begin{cases} \frac{1}{e}\frac{p\mu_h^2 - n\mu_e^2}{(p\mu_h + n\mu_e)^2}B & (B \ll 1) \\ \frac{1}{e}\frac{1}{p-n}B & (B \gg 1) \end{cases}$$

➢ $SrRu_{0.7}O_3$
Humps are found only in the $SrRu_{0.7}O_3$ thin films (t ≤ 5 nm).
⇨ The Ru-defects and interface scattering play an important role in the appearance of the humps.

■ Universal scaling of AHE in $SrRuO_3$



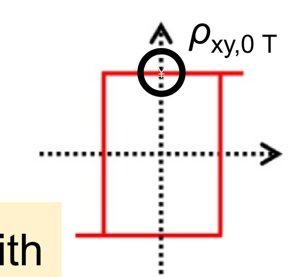
Origins of AHE in $SrRuO_3$

1. side jump — L. Berger, Phys. Rev. **2**, 4559 (1970).
2. skew-scattering — J. Smit, Physica **21**, 877 (1955).
3. Karplus-Luttinger (KL) model — R. Karplus and J. M. Luttinger, Phys. Rev. **95**, 1154 (1954).

Fit by following equation

$$\rho'_{xy,0\,T} = \underbrace{\frac{a_1}{\Delta^2 + a_2(\rho'_{xx})^2}(\rho'_{xx})^2}_{\text{KL mechanism}} + \underbrace{a_3(\rho'_{xx})^2}_{\text{Side jump}}$$

$\rho_{xy,0\,T}' = \rho_{xy,0\,T}$ / |max($\rho_{xy,0\,T}$)|
$\rho_{xx}' = \rho_{xx}(T) / \rho_{xx}(T_S)$
T_S : T at which the sign of the AHE changes.



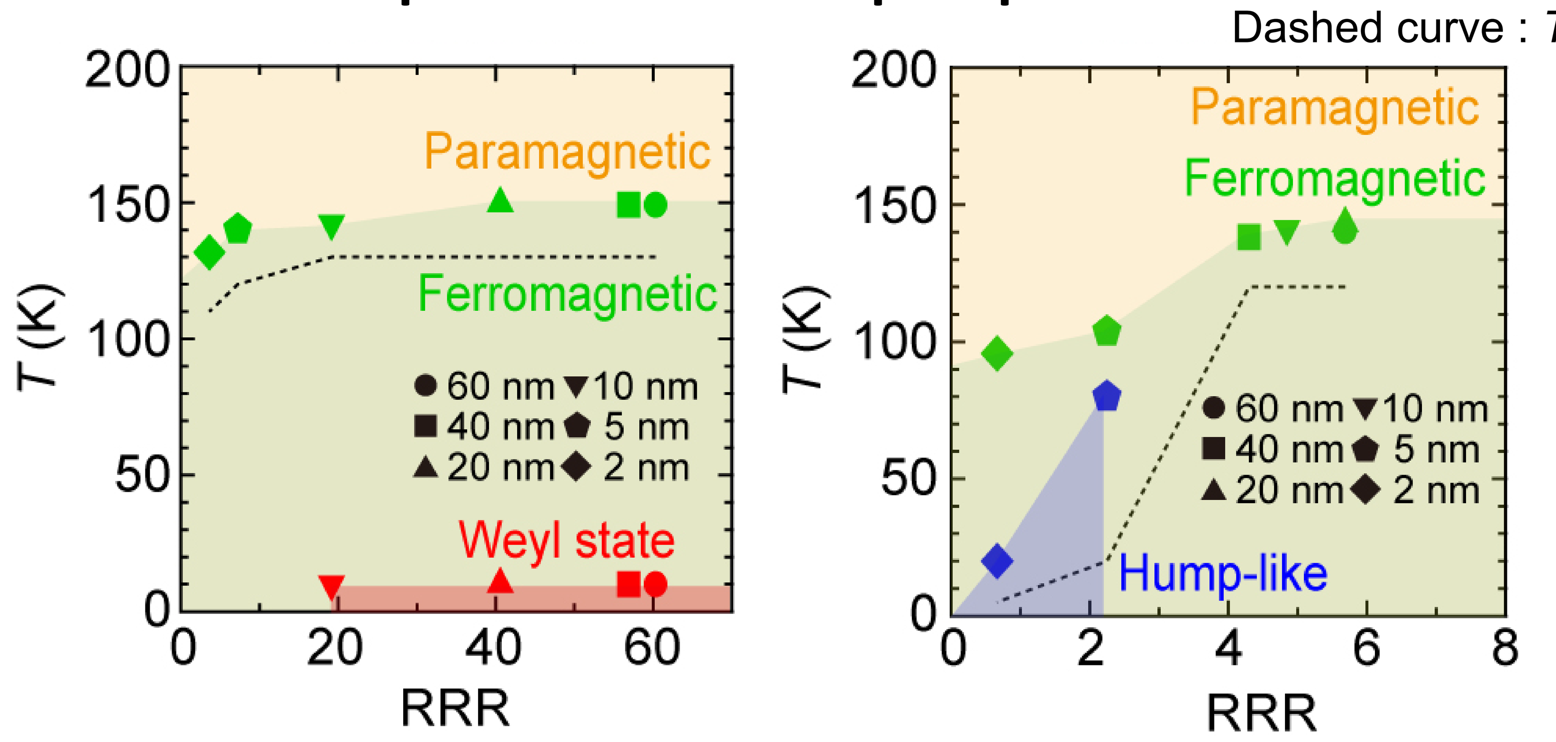
The dashed fitting curve is well consistent with the experimental results.

✓Universal trend in $\rho_{xy,0\,T}'$ vs ρ_{xx}' except for the $SrRu_{0.7}O_3$ films with t = 2 and 5 nm.
✓Only $SrRu_{0.7}O_3$ films with t = 2 and 5 nm do not follow this trend.

⇨ The hump-like Hall effect anomaly does not come from these mechanisms, and is derived from the multi-channel AHEs.

■ RRR and T dependence of transport phenomena

Dashed curve : T_S



✓For the films with RRR higher than ~20, the Weyl fermion transport is observed below ~20 K.
✓For the $SrRu_{0.7}O_3$ films with t ≤ 5 nm, whose RRRs are below ~3.5, the hump-like Hall effect anomaly is observed.

Summary

✓We have investigated the magnetotransport properties of epitaxial stoichiometric $SrRuO_3$ and Ru-deficient $SrRu_{0.7}O_3$ films with various thicknesses (t = 2–60 nm).

✓The $SrRuO_3$ films with t ≥ 10 nm, whose RRR is over ~20, show the Weyl fermion transport at low temperatures below ~20 K. By introducing Ru-defects and/or interface-driven defects, these Weyl fermion transports disappear.

✓By introducing Ru-defects and interface-driven defects further, the Ru-deficient $SrRu_{0.7}O_3$ films with t ≤ 5 nm, whose RRRs are below 2.2, show the hump-like Hall effect anomaly.

✓The hump-like Hall effect anomaly doesn't follow the scaling law incorporating the side-jumps and KL mechanism. This result suggests that the hump-like Hall effect anomaly in the $SrRu_{0.7}O_3$ thin films is derived from the multi-channel AHEs.

S. Kaneta-Takada *et al.*, Phys. Rev. Mater. **7**, 054406 (2023).

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