

Spin-Splitting Magnetoresistance in Altermagnetic RuO₂ Thin Films

Hongyu Chen, Zi-An Wang, Peixin Qin,* Ziang Meng, Xiaorong Zhou, Xiaoning Wang, Li Liu, Guojian Zhao, Zhiyuan Duan, Tianli Zhang, Jinghua Liu,* Ding-Fu Shao,* Chengbao Jiang,* and Zhiqi Liu*

The recently discovered altermagnets, featured by the exotic correlation of magnetic exchange interaction and alternating crystal environments, have offered exciting cutting-edge opportunities for spintronics. Nevertheless, the altermagnetism of RuO₂, one of the earliest-discovered altermagnets, is currently under intense debate. Here, this controversy is attempted to be resolved by demonstrating a spin-splitting magnetoresistance (SSMR) effect that is driven by a spin current associated with the giant nonrelativistic spin splitting of an altermagnet. Compared to the spin Hall magnetoresistance induced by a conventional relativistic spin current, the SSMR is characterized by unusual angular dependence with a phase-shift feature underpinned by the Néel-vector orientation and pronounced temperature dependence caused by its susceptibility to electron scattering. Through systematical investigations on the magnetoresistance of (101)-RuO₂/Co bilayers, a sizable SSMR is disentangled and hence a Néel vector along [001] direction is unveiled. This work not only demonstrates a simple electric avenue for probing the Néel vector of altermagnets, but also indicates long-range magnetic order in thin films of RuO₂.

dubbed altermagnetism.^[1–3] It is worth noting that altermagnetism in fact represents a special case of unconventional magnetism (Pomeranchuk instability) in the even partial wave channels that was proposed by Wu and Zhang in the pioneering works in the 2000s.^[4,5] Altermagnets are typically composed of two opposite magnetic sublattices that are connected by crystal rotation symmetries. Such alternating magnetic structures break both *PT* and *T τ* symmetry (*P*, *T*, and τ denote the operation of space inversion, time reversal, and half-unit-cell translation, respectively), thus engendering sizable spin splitting with alternating spin polarization in momentum space even in the absence of relativistic spin–orbit coupling (SOC).^[1–3] Consequently, altermagnets naturally combine the virtues of both ferromagnets and conventional antiferromagnets for spintronics—they are endowed with various *T*-symmetry-breaking responses^[6–10]

and charge–spin interconversion phenomena^[11–14] that are ubiquitous in ferromagnets despite their symmetry-enforced vanishing net magnetic moment.

Among these exotic properties, the spin-splitting effect (SSE) has received a surge of interest recently.^[11,15–18] Taking a *d*-wave altermagnet (Figure 1a) as an example, the SSE describes the generation of a net nonrelativistic spin current along [100] by an electric current applied along [010] due to the anisotropic spin-split Fermi surfaces, as illustrated in Figure 1b.^[11] Remarkably, such a spin current is highly tunable as the spin angular momentum in reciprocal space is closely related to the Néel vector in real space.^[11] For instance, an out-of-plane spin current with unconventional spin polarization can be engendered in an altermagnetic thin film through proper epitaxial/Néel-vector orientation design.^[15,17–22] On the other hand, the inverse spin-splitting effect (ISSE)—the reciprocal process of the SSE—can convert a spin current with spin polarization parallel to the Néel vector into a transverse charge current.^[18–23] Consequently, the SSE and ISSE constitute a novel route to realizing charge–spin interconversion—the core of spintronics—without resort to SOC.

The SSE was first proposed in rutile RuO₂, a system widely used to discuss altermagnetism and the associated

1. Introduction

Recent theoretical and experimental studies on some unconventional antiferromagnets have unveiled an exotic magnetic phase

H. Chen, P. Qin, Z. Meng, X. Zhou, X. Wang, L. Liu, G. Zhao, Z. Duan, T. Zhang, J. Liu, C. Jiang, Z. Liu
School of Materials Science and Engineering
Beihang University
Beijing 100191, China
E-mail: qinpeixin@buaa.edu.cn; 09077@buaa.edu.cn;
jiangcb@buaa.edu.cn; zhiqi@buaa.edu.cn

Z.-A. Wang, D.-F. Shao
Key Laboratory of Materials Physics
Institute of Solid State Physics
HFIPS
Chinese Academy of Sciences
Hefei 230031, China
E-mail: dfshao@issp.ac.cn

Z.-A. Wang, D.-F. Shao
Science Island Branch of Graduate School
University of Science and Technology of China
Hefei 230026, China

The ORCID identification number(s) for the author(s) of this article can be found under <https://doi.org/10.1002/adma.202507764>

DOI: 10.1002/adma.202507764

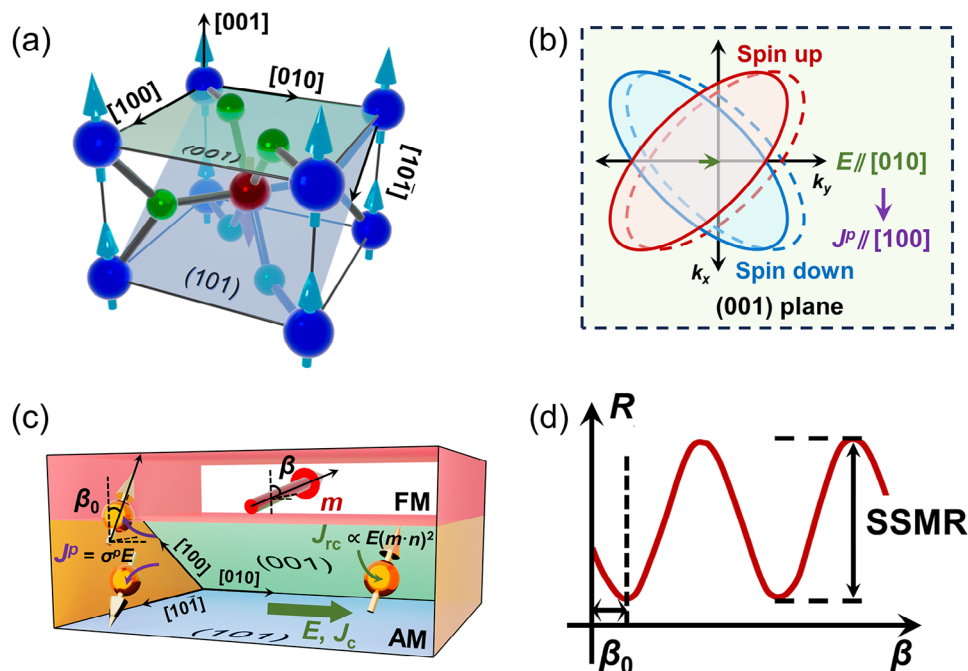


Figure 1. a) Crystal structure of a rutile-structured d -wave altermagnet (AM). The green and blue shadowed regions are the (001) and (101) plane, respectively. The dark blue and dark red balls represent the magnetic atoms with opposite magnetic moment as indicated by the light blue and light red arrows, respectively. The green balls denote the nonmagnetic atoms. b) Schematic of the spin-splitting effect (SSE). An electric field E applied along [010] shifts the anisotropic spin-split Fermi contours (the red and blue shadowed ellipses), resulting in a net nonrelativistic spin current J^p along [100] with polarization p . p is parallel to the Néel vector n . c) Schematic of the SSMR in a (101)-oriented AM/ferromagnet (FM) bilayer. An applied E (charge current J_c) along [010] engenders an out-of-plane $J^p = \sigma^p E$ through the spin conductivity σ^p of the SSE, illustrated by the movement of electrons (orange balls) with their spin moment (yellow arrows) parallel to n . β_0 is the out-of-plane tilting angle of n . J^p is reflected by the AM/FM interface, leading to a longitudinal charge current J_{cr} that lowers the resistance of the heterostructure. The magnitude of J_{cr} is dictated by the squared product of n and the magnetization unit vector m of the FM [$J_{cr} \propto E(m \cdot n)^2$]. d) Envisaged longitudinal resistance R as a function of β in the SSMR.

spin-dependent transport properties.^[11,15–26] Nevertheless, its magnetic ground state has been under intense debate recently. Although early neutron diffraction,^[27] X-ray scattering,^[28] and spin- and angle-resolved photoemission spectroscopy studies^[29] have indicated the altermagnetism for RuO_2 , recent first principle calculations^[30] and experiments^[31–39] question this conclusion, particularly for bulk RuO_2 . Moreover, the situation is much more intricate for thin films of RuO_2 . Latest theoretical studies highlight the fragility of the altermagnetism in RuO_2 ,^[30,40–42] suggesting that RuO_2 could be near a quantum critical transition and the long-range magnetic order could be stabilized possibly by proper doping, epitaxial strain, and surface/interface symmetry breaking. The remarkable differences between thin-film and bulk RuO_2 materials based on these aspects are elaborated in Note S2 (Supporting Information). Such claims are indeed supported by the aforementioned early studies and recent experiments including the T -symmetry breaking observed by angle-resolved photoemission spectroscopy,^[43] optical second harmonic generation,^[44] X-ray magnetic linear dichroism,^[45] optical excitation of spin polarization,^[46] the anomalous Hall effect,^[47] and tunneling magnetoresistance effect^[48] in thin films.

In order to solve this controversy, here we first propose that the SSE can lead to a nonrelativistic magnetoresistance parallel to the celebrated spin Hall magnetoresistance (SMR) of a relativistic origin,^[49–51] which we dub spin-splitting magnetoresistance (SSMR). We show that the SSMR can be differentiated from

the SMR according to their distinct angular and temperature dependence. We next employ the SSMR to explore the possible altermagnetism in epitaxial RuO_2 thin films. It is found that the magnetoresistance of (101)- RuO_2/Co bilayers contains comparable contributions from the SSMR and the SMR, with the former suggesting a Néel vector along approximately [001] direction. Our work not only demonstrates an unexplored nonrelativistic magnetotransport property of altermagnets, but also indicates the existence of long-range magnetic order in epitaxial RuO_2 thin films.

2. Results and Discussions

For simplicity, we consider a bilayer composed of a ferromagnet (FM) and a d -wave altermagnet with its Néel vector $n \parallel [001]$, as shown in Figure 1c, to elaborate on the mechanism and characteristics of the SSMR. For a (101)-oriented altermagnetic thin film, an electric field E along [010] generates a spin current $J^p = \sigma^p E$ along [100], where σ^p is the associated spin conductivity with the spin polarization p . In the absence of SOC, J^p is solely engendered by the SSE and p is collinear with n (Figure 1b). Since [100] direction is oblique to the (101) plane, J^p flows toward the FM on the top and is then reflected by the altermagnet/FM interface, with the reflection strength modulated by the relative orientation between p and the magnetization direction m of the FM. When p is perpendicular (parallel) to m , the reflection is

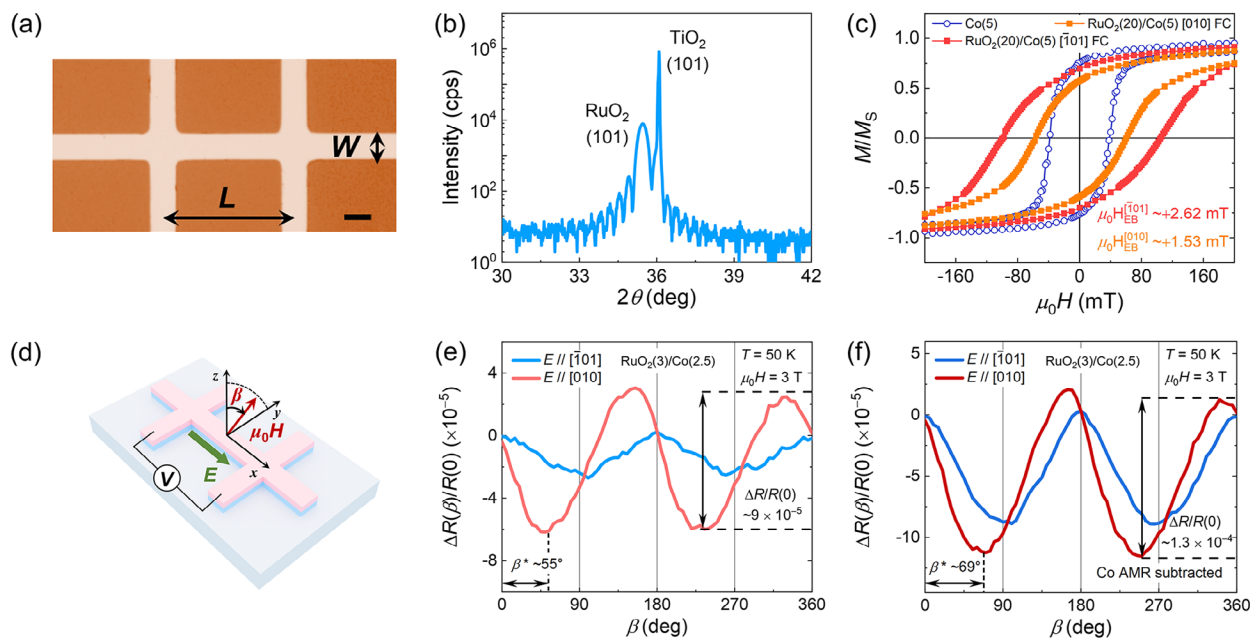


Figure 2. a) Optical image of a typical Hall bar device with width W and length L . The scale bar is $3\ \mu\text{m}$. b) Enlarged X-ray diffraction pattern of a thick RuO_2 epilayer on a (101)- TiO_2 substrate. The full-range pattern can be found in the Supporting Information. c) Normalized magnetization M/M_S as a function of external magnetic field $\mu_0 H$ at 50 K of a single Co layer and a RuO_2 (20 nm)/Co (5 nm) bilayer. In order to establish exchange bias, both samples are postannealed at 393 K for 0.5 h in a magnetic field of $-1.5\ \text{T}$ applied along RuO_2 $[\bar{1}01]$ or $[010]$. The measurements are conducted after field cooling (FC) in the same magnetic field. d) Schematic of the coordinate system and the rotation angle β of $\mu_0 H$ in the magnetoresistance measurements. The longitudinal voltage V is detected with E (a current) applied along the x axis. e, f) β -dependent magnetoresistance $\Delta R(\beta)/R(0)$ of the RuO_2 (3 nm)/Co (2.5 nm) bilayer measured at 50 K along RuO_2 $[010]$ and RuO_2 $[\bar{1}01]$ in a magnetic field of 3 T. The data collected before and after the subtraction of the ferromagnetic anisotropic magnetoresistance (AMR) contribution from Co are shown. $R(0)$ denotes the resistance R of the bilayer at $\beta = 0^\circ$.

minimized (maximized) due to the strong (weak) absorption of J^p by the FM. The reflected spin current thus has the intensity proportional to $(\mathbf{m} \cdot \mathbf{n})^2$, which converts into an additional longitudinal charge current $J_{\text{rc}} = \theta_{\text{SSMR}} J^p (\mathbf{m} \cdot \mathbf{n})^2 \propto E(\mathbf{m} \cdot \mathbf{n})^2$. Here, we qualitatively introduce θ_{SSMR} as the SSMR efficiency about the conversion of the reflected J^p to J_{rc} . Consequently, with $\mathbf{m}$ rotating in a plane perpendicular to E , the longitudinal resistance minimizes at a rotation angle $\beta = \beta_0$ wherein $\mathbf{m}$ is parallel to $\mathbf{n}$. Therefore, in the absence of SOC, β_0 is exactly the out-of-plane tilting angle θ_n of $\mathbf{n}$.

The underlying physics of the SSMR can be compared with that of the SMR in nonmagnet/FM heterostructures:^[49–54] 1) both effects are underpinned by the modification of the charge–spin interconversion processes in the spin-current source layer by $\mathbf{m}$; 2) The SMR stems from the relativistic spin Hall effect (SHE) and (or) the Rashba–Edelstein effect (REE) while the SSMR is of a nonrelativistic origin and is thus in principle more prominent.

On the other hand, the characteristics of the SSMR are distinct from those of the conventional SMR.^[49–54] Taking the bilayer shown in Figure 1c as an example: 1) for E applied along $[010]$, the β -dependent magnetoresistance minimizes at $\beta_0 \approx 90^\circ$ in the SMR whereas it minimizes at $\beta_0 = \theta_n$ in the SSMR; 2) for measurements with varied E directions, β_0 almost remains a constant of 90° in the conventional SMR, but it significantly changes in the SSMR as imposed by the interfacial reflection strength of J^p and the anisotropy of the SSE; therefore, the SSMR can serve as a simple electric method for characterizing the $\mathbf{n}$ of altermagnets; 3) the SSMR typically exhibits enhanced temperature de-

pendence compared to the SMR since the Fermi-surface-driven SSE is more susceptible to electron scattering.^[11,15,18,23,55,56] These features allow the disentanglement of SSMR and SMR in realistic systems.

We next systematically study the magnetoresistance in (101)- RuO_2 /Co bilayers to ascertain the possible magnetism of the RuO_2 thin films. If RuO_2 is altermagnetic, the nonrelativistic SSE would lead to the magnetoresistance in concert with the relativistic SHE and REE (denoted as SHE hereafter for simplicity), i.e., the SSMR would coexist with the SMR. Notably, the contribution from the SSE to the out-of-plane spin-current generation/conversion is much more pronounced when E is applied along $[010]$ than along $[\bar{1}01]$ according to Figure 1b and our first principle calculations (Note S6, Supporting Information). Moreover, the SSMR would yield a $\beta_0 \approx 35^\circ$ (θ_n of the RuO_2 thin films) in the former case. On the other hand, if RuO_2 is nonmagnetic, only the SMR with β_0 close to 90° would be detected regardless of the direction of E . Consequently, distinct angular- and temperature-dependence of the magnetoresistance for E applied along $[010]$ and $[\bar{1}01]$ would unambiguously demonstrate the existence of the SSMR and thus the long-range antiferromagnetic order in RuO_2 .

The detailed preparation processes of the samples can be found in the Supporting Information. Figure 2b shows the X-ray diffraction pattern of a thick RuO_2 thin film deposited onto a (101)-oriented TiO_2 substrate. The sharp diffraction peaks of RuO_2 (101) together with the clear Kiessig fringes indicate the high epitaxy quality of the sample. It is worth noting that the

bilayers exhibit observable exchange bias after post annealing in a magnetic field and subsequent field cooling [Figure 2c and Note S2 (Supporting Information)], indicating the antiferromagnetic order of the RuO₂ thin films. In addition, according to an X-ray scattering study,^[28] the **n** of RuO₂ thin films lies in a direction nearly parallel to the *c* axis. Therefore, for (101)-oriented epilayers, the in-plane projection of **n** is larger along $\bar{1}01$ than along 010 . As shown in Figure 2c, for a RuO₂ (20 nm)/Co (5 nm) heterostructure with exchange bias established along RuO₂ $\bar{1}01$ and 010 , both the magnetic coercivity and the exchange bias field are much smaller in the latter case, which suggests a close-to- 001 orientation of **n** and is consistent with the previous study.^[28]

Hall bars as shown in Figure 2a are patterned to investigate the magnetoresistance of a RuO₂ (3 nm)/Co (2.5 nm) bilayer. The definitions of the coordinate system and the rotation angle β of the applied magnetic field are illustrated in Figure 2d. The current is applied along the *x* axis and the applied field is 3 T in the measurements unless otherwise specified. As depicted in Figure 2e, the longitudinal resistance $R(\beta)$ measured along RuO₂ 010 at 50 K reaches a minimum at $\beta^* \approx 55^\circ$ following $\Delta R(\beta)/R(0) \propto \sin^2(\beta - \beta^*)$, in sharp contrast to that measured along RuO₂ $\bar{1}01$ wherein $\beta^* \approx 90^\circ$ and $\Delta R(\beta)/R(0) \propto \cos^2\beta$. Here $\Delta R(\beta) = R(\beta) - R(0)$, and $R(0)$ denotes the longitudinal resistance of the sample at $\beta = 0^\circ$. As the phase-shifted angular dependence is unusual, we perform a series of control experiments and confirm that it is an intrinsic property of the bilayer, presumably induced by the (S)SMR-like mechanisms rather than artifacts due to angular offset, the Co layer, or the RuO₂ layer. We also find that magnon excitations play a negligible role in leading to the abnormal $\Delta R(\beta)/R(0)$. A detailed discussion can be found in Note S4 (Supporting Information). According to the (S)SMR scenario, β^* describes the out-of-plane tilting angle of the **p** of the engendered spin current. Therefore, the anisotropic $\Delta R(\beta)/R(0)$ indicates that the **p** contains sizable out-of-plane *z*-components for $E \parallel \text{RuO}_2[010]$ but only consists of in-plane *y*-components for $E \parallel \text{RuO}_2[\bar{1}01]$. In addition, we define the difference between the maximum and the minimum of $R(\beta)$ as ΔR and the magnetoresistance ratio as $\Delta R/R(0)$. Note that the $\Delta R/R(0)$ measured along RuO₂ 010 and RuO₂ $\bar{1}01$ are both on the order of 10^{-5} , at least one order of magnitude smaller than those for heavy metal/FM bilayers.^[49,51–54] Therefore, the underlying physics of the unusual $\Delta R(\beta)/R(0)$ in Figure 2e entails discreet analyses.

We first ascertain the role of Co. We consider a situation according to the SMR scenario wherein the spin current underpinning the anisotropic behavior of the $\Delta R(\beta)/R(0)$ is generated by the Co layer. Generally, the SMR describes the magnetoresistance induced by the modulation of the spin distribution and the spin-charge interconversion processes in the bilayers. According to the SMR theories,^[49–51] the magnitude of such magnetoresistance is determined by 1) the spin Hall angle of the spin-source layer, 2) the spin transport properties of the spin-source layer, and 3) the dissipation of the spin current by the other layer. Note that both the magnitude $\Delta R/R(0)$ and the angular dependence $\Delta R(\beta)/R(0)$ of the magnetoresistance are distinct for the measurements along RuO₂ 010 and RuO₂ $\bar{1}01$ (Figure 2e). We thus examine whether the factors 1–3) can lead to such anisotropy when the spin current is generated by Co.

We first explore the effect of factor 1), the spin Hall angle θ_{SH} of Co. We have confirmed that the Co layer deposited at room

temperature in our study is polycrystalline in nature via X-ray diffraction. As a result, the θ_{SH} of Co, as an averaged property of various tiny crystalline grains with stochastic orientations, is supposed to be isotropic and cannot lead to current-direction-dependent $\Delta R/R(0)$. In addition, Co can engender a spin current with the anomalous Hall effect. In this case, the θ_{SH} changes with β . For the generation of an out-of-plane spin current, θ_{SH} reaches a maximum at $\beta = 90^\circ$ and a minimum at $\beta = 0^\circ$. Therefore, the β -dependent θ_{SH} of Co cannot lead to the phase shift of the $\Delta R(\beta)/R(0)$ curves measured along RuO₂ 010 . We next explore the effect of factor 2), the spin transport properties of Co. Similar to 1), we note that 2) is supposed to be isotropic for polycrystalline Co. Also, although 2) of Co could change with β , it cannot result in the phase shift of the $\Delta R(\beta)/R(0)$ curves measured along RuO₂ 010 . We subsequently explore the effect of factor 3), the dissipation (absorption and reflection) of the Co-generated spin current by the antiferromagnetism of RuO₂. Since epitaxial RuO₂ thin films are utilized in our study, 3) could be anisotropic. On the other hand, 3) is supposed not to vary with β because the small magnetic field used in our study cannot notably change the property of a nonmagnet or an antiferromagnet with strong magnetic anisotropy. This is supported by the almost identical $\Delta R(\beta)/R(0)$ curves of RuO₂ in different magnetic fields (Figure S5, Supporting Information). We also replace the Co layer in the sample with a 3-nm-thick Pt layer to further exclude this possibility. As the θ_{SH} of Pt is much larger than that of Co, the substitution would lead to more pronounced magnetoresistance if the observed $\Delta R/R(0)$ was related to the β -dependent 3) of RuO₂. Nevertheless, as shown in Figure 3a,b, the $\Delta R/R(0)$ is negligibly small compared to that in Figure 2c, and no phase-shift feature can be found.

We finally point out that the experimentally measured efficiency for spin-current generation is subtle for Co compared to that for Ni, NiFe, etc.,^[57,58] due to its weak SOC. Note that the magnitude of the SMR is proportional to the squared θ_{SH} of the spin-current source. This further magnifies the incapability of Co of leading to sizable SMR, as is confirmed with a control sample of Cu (1 nm)/Co (2.5 nm). Cu is a light metal with a θ_{SH} that we expect to be much smaller than that of RuO₂. Therefore, the role of Co in generating $\Delta R(\beta)/R(0)$ in the bilayer would be highlighted in this sample. As displayed in Figure 3c, only the ferromagnetic anisotropic magnetoresistance (AMR) induced by the geometrical-size effect,^[59] i.e., $\Delta R(\beta)/R(0) \propto \sin^2\beta$, can be found. Therefore, the anisotropic behavior of $\Delta R(\beta)/R(0)$ in Figure 2e cannot originate from the spin current generated by Co, and the Co layer contributes to the $\Delta R(\beta)/R(0)$ with the ferromagnetic AMR effect. Moreover, as depicted in Figure 2f, the subtraction of the AMR contribution from Figure 2e changes the β^* and the $\Delta R/R(0)$ measured along RuO₂ 010 to $\approx 69^\circ$ and $\approx 1.3 \times 10^{-4}$, respectively (see Note S5 in the Supporting Information for detailed discussions and the AMR subtraction processes).

We subsequently investigate the effect of the spin current produced by the RuO₂/Co interface with a control sample of RuO₂ (3 nm)/Cu (1 nm)/Co (2.5 nm). It is found that the insertion of a thin Cu layer reduces the $\Delta R/R(0)$ (Figure S8, Supporting Information). Note that a similar phenomenon has also been reported in a previous study.^[49] This can derive from the deteriorated spin-transport efficiency along the out-of-plane direction due to the formation of an additional interface between RuO₂ and Cu.

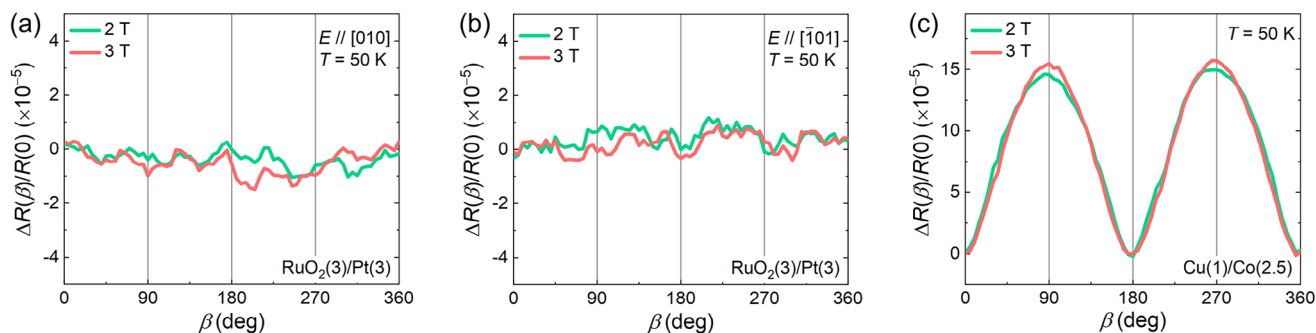


Figure 3. a,b) $\Delta R(\beta)/R(0)$ measured at 50 K along $\text{RuO}_2[010]$ and $\text{RuO}_2[101]$ in different magnetic fields of a (101)- RuO_2 (3 nm)/Pt (3 nm) bilayer. c) $\Delta R(\beta)/R(0)$ measured at 50 K in different magnetic fields of a Cu (1 nm)/Co (2.5 nm) bilayer.

Moreover, the $\Delta R(\beta)/R(0)$ measured along $\text{RuO}_2[010]$ exhibits a β^* of $\sim 75^\circ$ after subtracting the AMR of Co. Here the β^* is slightly larger than that in Figure 2e, probably due to the distinct antiferromagnetic domain population/distribution of RuO_2 in this sample. Therefore, the robust existence of the phase-shift feature in the samples with and without Cu insertion clearly demonstrates that interfacial spin-current generation plays a negligible role in leading to the abnormal $\Delta R(\beta)/R(0)$.

We thus conclude that the unusual $\Delta R(\beta)/R(0)$ is related to the spin current produced by the RuO_2 layer. As we have discussed, the SSE is in good accordance to the anisotropic spin-current-generation/conversion behavior entailed by the β^* in Figure 2f. In addition, the SHE of a (101)-oriented (nonmagnetic) thin film with a rutile structure can, in principle, exhibits a similar feature too due to the low symmetry.^[60] Nevertheless, we notice that such a relativistic mechanism is incapable of yielding considerable out-of-plane spin polarization (see Note S6 in the Supporting Information for detailed discussions). Therefore, we deduce that the remarkable phase-shifted $\Delta R(\beta)/R(0)$ is related to the existence of the SSE. Further support for this inference can be found in the anisotropic temperature dependence of the $\Delta R/R(0)$. As depicted in Figure 4a, the $\Delta R/R(0)$ measured along $\text{RuO}_2[010]$ after subtracting the AMR increases more rapidly with decreased temperature compared to that measured along $\text{RuO}_2[101]$. This is well consistent with the fact that the temperature-susceptible SSE plays a more important role in the out-of-plane spin-current generation for $E // \text{RuO}_2[010]$ than for $E // \text{RuO}_2[101]$.

According to the SSMR scenario illustrated in Figure 1c,d, the β^* is anticipated to be exactly the θ_n ($\approx 35^\circ$) of RuO_2 when the SSE dominates the charge–spin interconversion in the bilayer. The notable deviation from this value indicates that sizable SMR coexists with SSMR in the sample. This is reasonable since the SSE of different magnetic domains in the RuO_2 layer can compensate each other due to its T -odd nature, leading to a small net effect (see Note S6 in the Supporting Information for a detailed discussion). Moreover, we notice that the β^* measured along $\text{RuO}_2[010]$ gradually increases with raised temperature (Figure 4b), indicating that the $\mathbf{p}$ becomes closer to the γ axis. This can also be interpreted by the competition between the coexisting SSE and SHE—the SHE plays a more important role in the charge–spin interconversion at high temperature due to the weakening of the SSE by enhanced electron scattering.

We subsequently try to disentangle the SSMR from the measured $\Delta R(\beta)/R(0)$ through a ternary - variable fitting process (see

Note S7 in the Supporting Information for detailed discussions on its effectiveness). According to the SMR theories,^[49–51] for a transparent interface

$$\Delta R/R(0) = \theta_{\text{SH}}^2 \frac{\lambda_{\text{sf}}}{t_{\text{AF}}} \frac{\tanh\left(\frac{t_{\text{AF}}}{2\lambda_{\text{sf}}}\right)}{1 + \frac{\rho_{\text{AF}} t_{\text{F}}}{\rho_{\text{F}} t_{\text{AF}}}} \left[1 - \frac{1}{\cosh\left(\frac{t_{\text{AF}}}{\lambda_{\text{sf}}}\right)} \right] \quad (1)$$

wherein θ_{SH} and λ_{sf} are the spin Hall angle and spin diffusion length of the RuO_2 layer, respectively; t_{AF} and ρ_{AF} are the thickness and longitudinal resistivity of the RuO_2 layer, respectively; t_{F} and ρ_{F} are the thickness and longitudinal resistivity of the Co layer, respectively. Note that

$$\theta_{\text{SH}}^2 = \rho_{\text{AF}}^2 [(\sigma^y)^2 + (\sigma^z)^2] \quad (2)$$

wherein σ^y and σ^z are the components of the spin conductivity tensor for generating spin currents with γ - and z -direction polarization, respectively. Among these quantities, σ^y , σ^z , λ_{sf} , ρ_{AF} , and ρ_{F} vary with temperature T , leading to the temperature dependence of $\Delta R/R(0)$. In order to highlight the role of the SSE and the SHE, we rewrite Equation (1) with Equation (2) as

$$\Delta R/R(0) = [(\sigma^y)^2 + (\sigma^z)^2] [\rho(T) SF(T)]^2 \quad (3)$$

wherein $\rho(T)$ and $SF(T)$ are the components of the right-hand side of Equation (3) that are related to the resistivity and λ_{sf} , respectively. Since the β^* is the out-of-plane tilting angle of the spin polarization, we have

$$\sin(\beta^*) \sqrt{\Delta R/R(0)} = \sigma^y \rho(T) SF(T) \quad (4)$$

$$\cos(\beta^*) \sqrt{\Delta R/R(0)} = \sigma^z \rho(T) SF(T) \quad (5)$$

For E applied along $\text{RuO}_2[010]$, we assume that σ^y contains contributions from both the SSE and the SHE ($\sigma_{010}^y = \sigma_{\text{SSE},010}^y + \sigma_{\text{SHE},010}^y$) while σ^z is only related to the SSE ($\sigma_{010}^z = \sigma_{\text{SSE},010}^z$). Note that temperature can remarkably influence $\sigma_{\text{SSE},010}^y$ and $\sigma_{\text{SSE},010}^z$ but not $\sigma_{\text{SHE},010}^y$. Therefore, we have

$$\begin{aligned} \sin(\beta^*) \sqrt{\Delta R/R(0)}_{010} &= \sigma_{\text{SSE},010}^y(T) \rho_{010}(T) SF_{010}(T) \\ &+ \sigma_{\text{SHE},010}^y \rho_{010}(T) SF_{010}(T) \end{aligned} \quad (6)$$

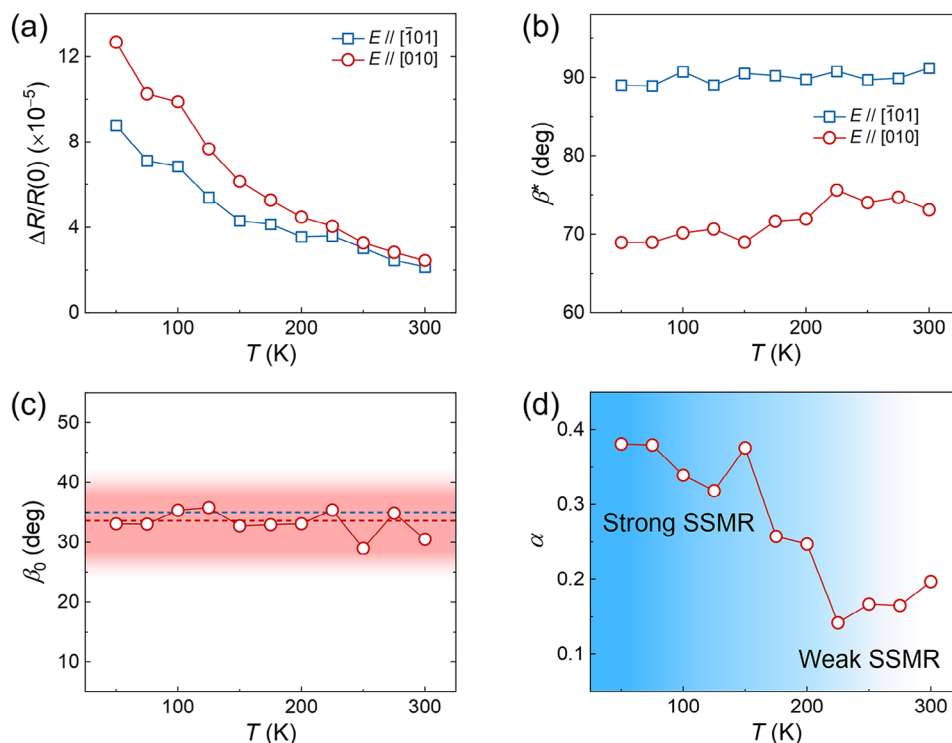


Figure 4. a) Temperature (T)-dependent magnetoresistance ratio $\Delta R/R(0)$ and b) phase-shift angle β^* of the RuO_2 (3 nm)/Co (2.5 nm) bilayer measured along $\text{RuO}_2[010]$ and $\text{RuO}_2[\bar{1}01]$ in a magnetic field of 3 T after subtracting the AMR contribution. c) Temperature-dependent out-of-plane tilting angle β_0 of the Néel vector and d) the relative strength α of the pure SSMR with respect to the pure spin Hall magnetoresistance as deduced through a ternary-variable fitting process to (a) and (b). The blue dashed line in (c) denotes the out-of-plane tilting angle ($\approx 35^\circ$) of the $[001]$ -directional Néel vector indicated by a previous X-ray scattering study.^[26] The red dashed line and shaded region in (c) represent the fitted β_0 value of $\approx 33.6^\circ$ and the corresponding 95% confidence interval, respectively. The red curve in (c) denotes the β_0 calculated with Equation (14).

$$\cos(\beta^*) \sqrt{\Delta R/R(0)}_{010} = \sigma_{\text{SSE},010}^z(T) \rho_{010}(T) SF_{010}(T) \quad (7)$$

We define

$$\beta_0 = \tan^{-1} \left(\frac{\sigma_{\text{SSE}}^y}{\sigma_{\text{SSE}}^z} \right) \quad (8)$$

According to the SSE scenario, β_0 is supposed to be θ_n .

On the other hand, for E applied along $\text{RuO}_2[\bar{1}01]$, there is only finite σ^y since $\beta^* \approx 90^\circ$. Note that the calculated $\sigma_{\text{SSE},\bar{1}01}^y$ is much smaller in this case (even smaller than the $\sigma_{\text{SHE},\bar{1}01}^y$) (Table S1, Supporting Information). Moreover, the multidomain state of RuO_2 can further decrease the realistic $\sigma_{\text{SSE},\bar{1}01}^y$. We thus assume a negligible $\sigma_{\text{SSE},\bar{1}01}^y$ compared to $\sigma_{\text{SHE},\bar{1}01}^y$, and we have

$$\sqrt{\Delta R/R(0)}_{\bar{1}01} = \sigma_{\text{SHE},\bar{1}01}^y \rho_{\bar{1}01}(T) SF_{\bar{1}01}(T) \quad (9)$$

Since we find a subtle difference between the sample resistance measured along $\text{RuO}_2[010]$ and $\text{RuO}_2[\bar{1}01]$, we have

$$\rho_{010}(T) \approx \rho_{\bar{1}01}(T) \quad (10)$$

Although the values of $SF(T)$ along $\text{RuO}_2[010]$ and $\text{RuO}_2[\bar{1}01]$ can be different, its relative change with varied temperatures (from 50 to 300 K) is expected to be nearly identical, because

the spin diffusion processes are underpinned by the same mechanisms. In addition, the σ_{SHE}^y can be anisotropic along $\text{RuO}_2[010]$ and $\text{RuO}_2[\bar{1}01]$. We thus utilize a constant η to describe the anisotropy of σ_{SHE}^y and $SF(T)$ along $\text{RuO}_2[010]$ and $\text{RuO}_2[\bar{1}01]$

$$\eta = \frac{\sigma_{\text{SHE},010}^y SF_{010}(T)}{\sigma_{\text{SHE},\bar{1}01}^y SF_{\bar{1}01}(T)} \quad (11)$$

Thus, we have

$$\eta \sqrt{\Delta R/R(0)}_{\bar{1}01} = \sigma_{\text{SHE},010}^y \rho_{010}(T) SF_{010}(T) \quad (12)$$

Taking Equations (7), (8), and (12) into Equation (6), we have

$$\sin(\beta^*) \sqrt{\Delta R/R(0)}_{010} = \tan(\beta_0) \cos(\beta^*) \sqrt{\Delta R/R(0)}_{010} + \eta \sqrt{\Delta R/R(0)}_{\bar{1}01} \quad (13)$$

Equation (13) is the core of our method, with which we can fit the measured relation between $\sqrt{\Delta R/R(0)}_{010}$, $\sqrt{\Delta R/R(0)}_{\bar{1}01}$, and β^* utilizing two parameters, β_0 and η . We can check the fitting

effectiveness through recalculating β_0 with η according to

$$\begin{aligned}\beta_0 &= \tan^{-1} \left(\frac{\sigma_{SSE}^y}{\sigma_{SSE}^z} \right) \\ &= \tan^{-1} \left[\frac{\sin(\beta^*) \sqrt{\Delta R/R(0)_{010}} - \eta \sqrt{\Delta R/R(0)_{101}}}{\cos(\beta^*) \sqrt{\Delta R/R(0)_{010}}} \right] \quad (14)\end{aligned}$$

In addition, we can determine the relative strength of the pure SSMR with respect to the pure SMR as

$$\begin{aligned}\frac{(\sigma_{SSE,010}^y)^2 + (\sigma_{SSE,010}^z)^2}{(\sigma_{SHE,010}^y)^2} &= \\ \frac{[\tan(\beta_0) \cos(\beta^*) \sqrt{\Delta R/R(0)_{010}}]^2 + [\cos(\beta^*) \sqrt{\Delta R/R(0)_{010}}]^2}{[\eta \sqrt{\Delta R/R(0)_{101}}]^2} \quad (15)\end{aligned}$$

The best fitting gives $\beta_0 \approx 33.6^\circ$ and $\eta \approx 0.84$. Note that the calculated β_0 values at different temperatures with the obtained η according to Equation (14) are all close to 33.6° (Figure 4c), confirming the reliability of the fitting. Moreover, the β_0 is close to the out-of-plane tilting angle of the Néel vector,^[28] which further corroborates the existence of the SSE. In addition, the pure SSMR is comparable to the pure SMR in the sample (Figure 4d), with its relative strength decreasing with raised temperature. This indicates that the SSMR is more sensitive to electron scattering compared to the SMR, also consistent with the Fermi-surface origin of the SSE.

Our magnetoresistance measurements, together with the exchange-bias effect, provide compelling evidence for the altermagnetism in the epitaxial RuO₂ thin films. In addition, we note the fact that the SSMR is strongly suppressed at high temperature also offers an implication that high-temperature detections of altermagnetism might be tricky, due to the spin-splitting of Fermi surface being largely smeared out at high temperature. In this sense, our results could also be beneficial for resolving the current controversy of different measurements on the altermagnetism of RuO₂.

3. Conclusion

In summary, we propose a nonrelativistic magnetoresistance effect termed the SSMR for altermagnets. The existence of the SSMR is unambiguously demonstrated for (101)-RuO₂/Co bilayers, indicating the presence of altermagnetism in epitaxial RuO₂ thin films. The unique phenomenology of the SSMR makes it a simple electric probe for detecting the Néel vector of altermagnets without resort to complex magnetic tunnel junctions^[61–64] or lock-in techniques.^[65–68] Finally, we point out that the SSMR can also exist in other unconventional antiferromagnets with momentum-dependent spin splitting.^[69–75] Therefore, our work opens an avenue to studying the emerging materials with unconventional spin degeneracy lifting.

4. Experimental Section

Sample Fabrication: The RuO₂ thin films in this study were fabricated by a pulsed laser deposition system with a base pressure of 1.5×10^{-8} Torr and a target–substrate distance of ≈ 60 mm following a recipe developed in the previous work.^[7] The laser fluence and repetition rate were set to be ≈ 1.6 J cm^{−2} and 10 Hz, respectively. During deposition, the substrate temperature and the oxygen pressure were 550 °C and 1 mTorr, respectively. After deposition, the samples were in situ annealed for ≈ 0.5 h in the chamber under the same conditions (temperature and oxygen pressure) as in the deposition process and then cooled down to room temperature at a ramp rate of ≈ 10 °C min^{−1}. The samples were subsequently transferred into a d.c. magnetron sputtering system with a base pressure of 7.5×10^{-9} Torr and a sample–target distance of ≈ 245 mm. The Co and Al layers were grown at room temperature with a sputtering power of 60 and 30 W, respectively. The Ar pressure during deposition was 3 mTorr. The as-deposited thin films were then patterned into Hall bars through optical lithography and Ar ion milling. The channel width of the Hall bars was 3 μ m and the distance between two longitudinal voltage probes was 15 μ m.

X-Ray Diffraction: The X-ray diffraction measurement was performed with a Panalytical MRD X’Pert 3 diffractometer using Cu K α radiation.

Magnetic and Electrical Measurements: The magnetic properties of the samples were examined by a Quantum Design VersaLab system with a vibrating sample magnetometer module. The transport properties of the samples were measured by the Quantum Design VersaLab system with a horizontal rotator module. A Keithley 6221 source meter and a Keithley 2182A nanovoltmeter were additionally employed to detect weak electrical signals. For each set of β^* and $\Delta R/R(0)$, at least two independent β -dependent magnetoresistance measurements were performed under the same conditions with β rotated from 0° to 360° and from 360° back to 0°. The averaged $R(\beta)$ curve was employed to extract β^* and $\Delta R/R(0)$ according to a $\sin^2(\beta)$ fitting.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

Acknowledgements

H.C. and Z.W. contributed equally to this work. P.Q. acknowledges funding from the National Natural Science Foundation of China (Grant No. 52401300). Z.L. acknowledges funding from the National Natural Science Foundation of China (Grant No. 52425106). C.J. and Z.L. acknowledge funding from the National Natural Science Foundation of China (Grant No. 52121001). Z.L. acknowledges funding from the National Natural Science Foundation of China (Grant No. 52271235) and from the National Key R&D Program of China (Grant Nos. 2022YFA1602700 and 2022YFB3506000). D.S. acknowledges funding from the National Natural Science Foundation of China (Grant Nos. 12274411, 12241405, and 52250418), from the Basic Research Program of the Chinese Academy of Sciences Based on Major Scientific Infrastructures (Grant No. JZHKYPT-2021-08), and from the CAS Project for Young Scientists in Basic Research (Grant No. YSBR-084). Z.L. acknowledges funding from the Beijing Natural Science Foundation (Grant No. JQ23005). P.Q. acknowledges funding from the China National Postdoctoral Program for Innovative Talents (Grant No. BX20230451) and from the China Postdoctoral Science Foundation (Grant No. 2024M754058). D.S. acknowledges Hefei Advanced Computing Center. This work was also supported by “the Fundamental Research Funds for the Central Universities”. Z.M. acknowledges financial support from the National Natural Science Foundation of China (Grant No. 524B2003). This work was also supported by the Academic Excellence Foundation for Ph.D. students of the Beihang University.

Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

altermagnets, spin-splitting magnetoresistance, RuO₂

Received: April 23, 2025
Revised: May 19, 2025
Published online: June 10, 2025

- [1] L. Šmejkal, J. Sinova, T. Jungwirth, *Phys. Rev. X* **2022**, 12, 031042.
- [2] L. Šmejkal, J. Sinova, T. Jungwirth, *Phys. Rev. X* **2022**, 12, 040501.
- [3] J. Krempaský, L. Šmejkal, S. W. D'Souza, M. Hajlaoui, G. Springholz, K. Uhlířová, F. Alarab, P. C. Constantinou, V. Strocov, D. Usanov, W. R. Pudenko, R. González-Hernández, A. Birk Hellenes, Z. Jansa, H. Reichlová, Z. Šobáň, R. D. Gonzalez Betancourt, P. Wadley, J. Sinova, D. Kriegner, J. Minár, J. H. Dil, T. Jungwirth, *Nature* **2024**, 626, 517.
- [4] C. Wu, S.-C. Zhang, *Phys. Rev. Lett.* **2004**, 93, 036403.
- [5] C. Wu, K. Sun, E. Fradkin, S.-C. Zhang, *Phys. Rev. B* **2007**, 75, 115103.
- [6] L. Šmejkal, R. González-Hernández, T. Jungwirth, J. Sinova, *Sci. Adv.* **2020**, 6, aaz8809.
- [7] Z. Feng, X. Zhou, L. Šmejkal, L. Wu, Z. Zhu, H. Guo, R. González-Hernández, X. Wang, H. Yan, P. Qin, X. Zhang, H. Wu, H. Chen, Z. Meng, L. Liu, Z. Xia, J. Sinova, T. Jungwirth, Z. Liu, *Nat. Electron.* **2022**, 5, 735.
- [8] A. Hariki, A. Dal Din, O. J. Amin, T. Yamaguchi, A. Badura, D. Kriegner, K. W. Edmonds, R. P. Campion, P. Wadley, D. Backes, L. S. I. Veiga, S. S. Dhesi, G. Springholz, L. Šmejkal, K. Výborný, T. Jungwirth, J. Kuneš, *Phys. Rev. Lett.* **2024**, 132, 176701.
- [9] A. Hariki, Y. Takahashi, J. Kuneš, *Phys. Rev. B* **2024**, 109, 094413.
- [10] O. J. Amin, A. Dal Din, E. Golias, Y. Niu, A. Zakharov, S. C. Fromage, C. J. B. Fields, S. L. Heywood, R. B. Cousins, F. Maccherozzi, J. Krempaský, J. H. Dil, D. Kriegner, B. Kiraly, R. P. Campion, A. W. Rushforth, K. W. Edmonds, S. S. Dhesi, L. Šmejkal, T. Jungwirth, P. Wadley, *Nature* **2024**, 636, 348.
- [11] R. González-Hernández, L. Šmejkal, K. Výborný, Y. Yahagi, J. Sinova, T. Jungwirth, J. Železný, *Phys. Rev. Lett.* **2021**, 126, 127701.
- [12] D.-F. Shao, S.-H. Zhang, M. Li, C.-B. Eom, E. Y. Tsymlal, *Nat. Commun.* **2021**, 12, 7061.
- [13] L. Šmejkal, A. B. Hellenes, R. González-Hernández, J. Sinova, T. Jungwirth, *Phys. Rev. X* **2022**, 12, 011028.
- [14] D.-F. Shao, Y.-Y. Jiang, J. Ding, S.-H. Zhang, Z.-A. Wang, R.-C. Xiao, G. Gurung, W. J. Lu, Y. P. Sun, E. Y. Tsymlal, *Phys. Rev. Lett.* **2023**, 130, 216702.
- [15] A. Bose, N. J. Schreiber, R. Jain, D.-F. Shao, H. P. Nair, J. Sun, X. S. Zhang, D. A. Muller, E. Y. Tsymlal, D. G. Schlom, D. C. Ralph, *Nat. Electron.* **2022**, 5, 267.
- [16] H. Bai, L. Han, X. Y. Feng, Y. J. Zhou, R. X. Su, Q. Wang, L. Y. Liao, W. X. Zhu, X. Z. Chen, F. Pan, X. L. Fan, C. Song, *Phys. Rev. Lett.* **2022**, 128, 197202.
- [17] S. Karube, T. Tanaka, D. Sugawara, N. Kadoguchi, M. Kohda, J. Nitta, *Phys. Rev. Lett.* **2022**, 129, 137201.
- [18] Y. Guo, J. Zhang, Z. Zhu, Y.-y. Jiang, L. Jiang, C. Wu, J. Dong, X. Xu, W. He, B. He, Z. Huang, L. Du, G. Zhang, K. Wu, X. Han, D.-f. Shao, G. Yu, H. Wu, *Adv. Sci.* **2024**, 11, 2400967.
- [19] Y. Fan, Q. Wang, W. Wang, D. Wang, Q. Huang, Z. Wang, X. Han, Y. Chen, L. Bai, S. Yan, Y. Tian, *ACS Nano* **2024**, 18, 26350.
- [20] Z. Li, Z. Zhang, Y. Chen, S. Hu, Y. Ji, Y. Yan, J. Du, Y. Li, L. He, X. Wang, J. Wu, R. Zhang, Y. Xu, X. Lu, *Adv. Mater.* **2025**, 37, 2416712.
- [21] Y. Zhang, H. Bai, L. Han, J. Dai, C. Chen, S. Liang, Y. Cao, Y. Zhang, Q. Wang, W. Zhu, F. Pan, C. Song, *arXiv:2412.17013* **2024**.
- [22] B. Sekh, H. Rahaman, R. Maddu, P. K. Mishra, T. Jin, S. N. Piramanayagam, *arXiv:2501.12593* **2025**.
- [23] H. Bai, Y. C. Zhang, Y. J. Zhou, P. Chen, C. H. Wan, L. Han, W. X. Zhu, S. X. Liang, Y. C. Su, X. F. Han, F. Pan, C. Song, *Phys. Rev. Lett.* **2023**, 130, 216701.
- [24] Y. Liu, H. Bai, Y. Song, Z. Ji, S. Lou, Z. Zhang, C. Song, Q. Jin, *Adv. Opt. Mater.* **2023**, 11, 2300177.
- [25] X. Feng, H. Bai, X. Fan, M. Guo, Z. Zhang, G. Chai, T. Wang, D. Xue, C. Song, X. Fan, *Phys. Rev. Lett.* **2024**, 132, 086701.
- [26] C.-T. Liao, Y.-C. Wang, Y.-C. Tien, S.-Y. Huang, D. Qu, *Phys. Rev. Lett.* **2024**, 133, 056701.
- [27] T. Berlijn, P. C. Snijders, O. Delaire, H. D. Zhou, T. A. Maier, H. B. Cao, S. X. Chi, M. Matsuda, Y. Wang, M. R. Koehler, P. R. C. Kent, H. H. Weitering, *Phys. Rev. Lett.* **2017**, 118, 077201.
- [28] Z. H. Zhu, J. Stremper, R. R. Rao, C. A. Occhialini, J. Pellicari, Y. Choi, T. Kawaguchi, H. You, J. F. Mitchell, Y. Shao-Horn, R. Comin, *Phys. Rev. Lett.* **2019**, 122, 017202.
- [29] Z. L. Lin, D. Chen, W. Lu, X. Liang, S. Feng, K. Yamagami, J. Osiecki, M. Leandersson, B. Thiagarajan, J. Liu, C. Felser, J. Ma, *arXiv:2402.04995* **2024**.
- [30] A. Smolyanyuk, I. I. Mazin, L. Garcia-Gassull, R. Valentí, *Phys. Rev. B* **2024**, 109, 134424.
- [31] P. Keßler, L. Garcia-Gassull, A. Suter, T. Prokscha, Z. Salman, D. Khalyavin, P. Manuel, F. Orlandi, I. I. Mazin, R. Valentí, S. Moser, *npj Spintron.* **2024**, 2, 50.
- [32] L. Kiefer, F. Wirth, A. Bertin, P. Becker, L. Bohatý, K. Schmalzl, A. Stunault, J. A. Rodríguez-Velamazán, O. Fabelo, M. Braden, *J. Phys. Condens. Matter* **2025**, 37, 135801.
- [33] J. Liu, J. Zhan, T. Li, J. Liu, S. Cheng, Y. Shi, L. Deng, M. Zhang, C. Li, J. Ding, Q. Jiang, M. Ye, Z. Liu, Z. Jiang, S. Wang, Q. Li, Y. Xie, Y. Wang, S. Qiao, J. Wen, Y. Sun, D. Shen, *Phys. Rev. Lett.* **2024**, 133, 176401.
- [34] T. Osumi, K. Yamauchi, S. Souma, P. Shubhankar, A. Honma, K. Nakayama, K. Ozawa, M. Kitamura, K. Horiba, H. Kumigashira, C. Bigi, F. Bertran, T. Oguchi, T. Takahashi, Y. Maeno, T. Sato, *arXiv:2501.10649* **2025**.
- [35] M. Hiraiishi, H. Okabe, A. Koda, R. Kadono, T. Muroi, D. Hirai, Z. Hiroi, *Phys. Rev. Lett.* **2024**, 132, 166702.
- [36] M. Wenzel, E. Uykur, S. Rößler, M. Schmidt, O. Janson, A. Tiwari, M. Dressel, A. A. Tsirlin, *Phys. Rev. B* **2025**, 111, L041115.
- [37] F. Pawula, A. Fakhri, R. Daou, S. Hébert, N. Mordvinova, O. Lebedev, D. Pelloquin, A. Maignan, *Phys. Rev. B* **2024**, 110, 064432.
- [38] Z. Q. Wang, Z. Q. Li, L. Sun, Z. Y. Zhang, K. He, H. Niu, J. Cheng, M. Yang, X. Yang, G. Chen, Z. Yuan, H. F. Ding, B. F. Miao, *Phys. Rev. Lett.* **2024**, 133, 046701.
- [39] X. Peng, Z. Liu, S. Zhang, Y. Zhou, Y. Sun, Y. Su, C. Wu, T. Zhou, L. Liu, Y. Li, H. Wang, J. Yang, B. Chen, Y. Li, C. Xi, J. Du, Z. Jiao, Q. Wu, M. Fang, *arXiv:2412.12258* **2024**.
- [40] S. Brahimi, D. P. Rai, S. Lounis, *arXiv:2412.15377* **2024**.
- [41] Z. Qian, Y. Yang, S. Liu, C. Wu, *Phys. Rev. B* **2025**, 111, 174425.
- [42] D. Q. Ho, D. Q. To, R. Hu, G. W. Bryant, A. Janotti, *arXiv:2502.03751* **2025**.
- [43] O. Fedchenko, J. Minár, A. Akashdeep, S. W. D'Souza, D. Vasilyev, O. Tkach, L. Odenbreit, Q. Nguyen, D. Kutnyakhov, N. Wind, L. Wenthau, M. Scholz, K. Rossnagel, M. Hoesch, M. Aeschlimann, B. Stadtmüller, M. Kläui, G. Schönhenne, T. Jungwirth, A. B. Hellenes, G. Jakob, L. Šmejkal, J. Sinova, H.-J. Elmers, *Sci. Adv.* **2024**, 10, adj4883.

- [44] S. G. Jeong, I. H. Choi, S. Nair, L. Buiarelli, B. Pourbahari, J. Y. Oh, N. Bassim, A. Seo, W. S. Choi, R. M. Fernandes, T. Birol, L. Zhao, J. S. Lee, B. Jalan, *arXiv:2405.05838* **2024**.
- [45] Z. Yi-Chi, B. Hua, C. Chong, H. Lei, L. Shi-Xuan, C. Rui-Yue, D. Jian-Kun, P. Feng, S. Cheng, *Chin. Phys. Lett.* **2025**, 42, 027301.
- [46] M. Weber, S. Wust, L. Haag, A. Akashdeep, K. Leckron, C. Schmitt, R. Ramos, T. Kikkawa, E. Saitoh, M. Kläui, L. Šmejkal, J. Sinova, M. Aeschlimann, G. Jakob, B. Stadtmüller, H. C. Schneider, *arXiv:2408.05187* **2024**.
- [47] S. G. Jeong, S. Lee, B. Lin, Z. Yang, I. H. Choi, J. Y. Oh, S. Song, S. w. Lee, S. Nair, R. Choudhary, J. Parikh, S. Park, W. S. Choi, J. S. Lee, J. M. LeBeau, T. Low, B. Jalan, *arXiv:2501.11204* **2025**.
- [48] S. Noh, G.-H. Kim, J. Lee, H. Jung, U. Seo, G. So, J. Lee, S. Lee, M. Park, S. Yang, Y. S. Oh, H. Jin, C. Sohn, J.-W. Yoo, *Phys. Rev. Lett.* **2025**, <https://doi.org/10.1103/nrk5-5zrj>.
- [49] H. Nakayama, M. Althammer, Y. T. Chen, K. Uchida, Y. Kajiwara, D. Kikuchi, T. Ohtani, S. Geprägs, M. Opel, S. Takahashi, R. Gross, G. E. W. Bauer, S. T. B. Goennenwein, E. Saitoh, *Phys. Rev. Lett.* **2013**, 110, 206601.
- [50] Y.-T. Chen, S. Takahashi, H. Nakayama, M. Althammer, S. T. B. Goennenwein, E. Saitoh, G. E. W. Bauer, *Phys. Rev. B* **2013**, 87, 144411.
- [51] M. Althammer, S. Meyer, H. Nakayama, M. Schreier, S. Altmannshofer, M. Weiler, H. Huebl, S. Geprägs, M. Opel, R. Gross, D. Meier, C. Klewe, T. Kuschel, J.-M. Schmalhorst, G. Reiss, L. Shen, A. Gupta, Y.-T. Chen, G. E. W. Bauer, E. Saitoh, S. T. B. Goennenwein, *Phys. Rev. B* **2013**, 87, 224401.
- [52] S. Cho, S.-H. C. Baek, K.-D. Lee, Y. Jo, B.-G. Park, *Sci. Rep.* **2015**, 5, 14668.
- [53] J. Kim, P. Sheng, S. Takahashi, S. Mitani, M. Hayashi, *Phys. Rev. Lett.* **2016**, 116, 097201.
- [54] H. Nakayama, Y. Kanno, H. An, T. Tashiro, S. Haku, A. Nomura, K. Ando, *Phys. Rev. Lett.* **2016**, 117, 116602.
- [55] Y. Ou, C.-F. Pai, S. Shi, D. C. Ralph, R. A. Buhrman, *Phys. Rev. B* **2016**, 94, 140414.
- [56] A. Nomura, T. Tashiro, H. Nakayama, K. Ando, *Appl. Phys. Lett.* **2015**, 106, 212403.
- [57] Y. Omori, E. Sagasta, Y. Niimi, M. Gradhand, L. E. Hueso, F. Casanova, Y. Otani, *Phys. Rev. B* **2019**, 99, 014403.
- [58] W. Wang, T. Wang, V. P. Amin, Y. Wang, A. Radhakrishnan, A. Davidson, S. R. Allen, T. J. Silva, H. Ohldag, D. Balzar, B. L. Zink, P. M. Haney, J. Q. Xiao, D. G. Cahill, V. O. Lorenz, X. Fan, *Nat. Nanotechnol.* **2019**, 14, 819.
- [59] W. Gil, D. Görlitz, M. Horisberger, J. Kötzler, *Phys. Rev. B* **2005**, 72, 134401.
- [60] M. Patton, D. A. Pharis, G. Gurung, X. Huang, G. Noh, E. Y. Tsymlal, S.-Y. Choi, D. C. Ralph, M. S. Rzchowski, C.-B. Eom, *Adv. Mater.* **2025**, 37, 2414267.
- [61] P. Qin, H. Yan, X. Wang, H. Chen, Z. Meng, J. Dong, M. Zhu, J. Cai, Z. Feng, X. Zhou, L. Liu, T. Zhang, Z. Zeng, J. Zhang, C. Jiang, Z. Liu, *Nature* **2023**, 613, 485.
- [62] X. Chen, T. Higo, K. Tanaka, T. Nomoto, H. Tsai, H. Idzuchi, M. Shiga, S. Sakamoto, R. Ando, H. Kosaki, T. Matsuo, D. Nishio-Hamane, R. Arita, S. Miwa, S. Nakatsuji, *Nature* **2023**, 613, 490.
- [63] D.-F. Shao, E. Y. Tsymlal, *npj Spintron.* **2024**, 2, 13.
- [64] J. Shi, S. Arpaci, V. Lopez-Dominguez, V. K. Sangwan, F. Mahfouzi, J. Kim, J. G. Athas, M. Hamdi, C. Aygen, H. Arava, C. Phatak, M. Carpentieri, J. S. Jiang, M. A. Grayson, N. Kioussis, G. Finocchio, M. C. Hersam, P. Khalili Amiri, *Adv. Mater.* **2024**, 36, 2312008.
- [65] J. Godinho, H. Reichlová, D. Kriegner, V. Novák, K. Olejník, Z. Kašpar, Z. Šobáň, P. Wadley, R. P. Campion, R. M. Otxoa, P. E. Roy, J. Železný, T. Jungwirth, J. Wunderlich, *Nat. Commun.* **2018**, 9, 4686.
- [66] D.-F. Shao, S.-H. Zhang, G. Gurung, W. Yang, E. Y. Tsymlal, *Phys. Rev. Lett.* **2020**, 124, 067203.
- [67] H. Liu, J. Zhao, Y.-X. Huang, W. Wu, X.-L. Sheng, C. Xiao, S. A. Yang, *Phys. Rev. Lett.* **2021**, 127, 277202.
- [68] C. Wang, Y. Gao, D. Xiao, *Phys. Rev. Lett.* **2021**, 127, 277201.
- [69] S. Hayami, Y. Yanagi, H. Kusunose, *J. Phys. Soc. Jpn.* **2019**, 88, 123702.
- [70] L.-D. Yuan, Z. Wang, J.-W. Luo, E. I. Rashba, A. Zunger, *Phys. Rev. B* **2020**, 102, 014422.
- [71] Y.-P. Zhu, X. Chen, X.-R. Liu, Y. Liu, P. Liu, H. Zha, G. Qu, C. Hong, J. Li, Z. Jiang, X.-M. Ma, Y.-J. Hao, M.-Y. Zhu, W. Liu, M. Zeng, S. Jayaram, M. Lenger, J. Ding, S. Mo, K. Tanaka, M. Arita, Z. Liu, M. Ye, D. Shen, J. Wrachtrup, Y. Huang, R.-H. He, S. Qiao, Q. Liu, C. Liu, *Nature* **2024**, 626, 523.
- [72] P.-X. Qin, H. Yan, X.-N. Wang, Z.-X. Feng, H.-X. Guo, X.-R. Zhou, H.-J. Wu, X. Zhang, Z.-G.-G. Leng, H.-Y. Chen, Z.-Q. Liu, N. Spintronics, *Rare Met.* **2020**, 39, 95.
- [73] H. Chen, L. Liu, X. Zhou, Z. Meng, X. Wang, Z. Duan, G. Zhao, H. Yan, P. Qin, Z. Liu, *Adv. Mater.* **2024**, 36, 2310379.
- [74] H. Yan, X. Zhou, P. Qin, Z. Liu, *Appl. Phys. Lett.* **2024**, 124, 030503.
- [75] L.-D. Yuan, A. B. Georgescu, J. M. Rondinelli, *Phys. Rev. Lett.* **2024**, 133, 216701.