

Review

Altermagnetism and Altermagnets: A Brief Review

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Abstract

Recently, a new class of magnetic material, termed altermagnets, has caught the attention of the magnetism and spintronics community. The magnetic phenomenon arising from these materials differs from traditional ferromagnetism and antiferromagnetism. It generally lacks net magnetization and is characterized by unusual non-relativistic spin-splitting and broken time-reversal symmetry. This leads to novel transport properties, such as the anomalous Hall effect, the crystal Nernst effect, and spin-dependent phenomena. Spin-dependent phenomena such as spin currents, spin-splitter torques, and high-frequency dynamics emerge as key characteristics in altermagnets. This paper reviews the main aspects pertaining to altermagnets by providing an overview of theoretical investigations and experimental realizations. We discuss the most recent developments in altermagnetism and prospects for exploiting its unique properties in next-generation devices.

Keywords: altermagnets; non-relativistic spin-splitting; broken time-reversal symmetry; crystal symmetry



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1. Introduction

During the past few decades, there has been a notable shift in focus from traditional ferromagnetic spintronics to antiferromagnetic systems, driven by the increasing demand for energy-efficient and scalable devices [1–3]. The ferromagnets (FMs) are often associated with stray fields, which can cause device malfunction [1]. To overcome this challenge, the robustness of the antiferromagnets (AFMs) against external perturbation appears promising in the realm of spintronics. However, AFMs exhibit degenerate bands in momentum space, and time-reversal symmetry (TRS) combined with translation or inversion is also preserved in AFMs; hence, they lack spin-polarized currents. In this context, altermagnets (AMs) emerge as a new class of magnetic materials that leverage the advantages of both conventional magnetic phases (FMs and AFMs) [4–6].

Altermagnetism is associated with the breaking of TRS and the lifting of Kramers' degeneracy, characterized by the distinct symmetries of spin and real space (discussed in Section 2), without requiring relativistic spin–orbit coupling (SOC). Such symmetry leads to a nonrelativistic spin splitting (NRSS) of the band structure. The model band structures of AMs are compared with FMs and AFMs in Figure 1b, illustrating the distinct electronic structures of AMs, where spin splitting alternates in momentum space and can reach large

magnitudes on the order of a few electron volts (eV). The two main phases of magnetism have been previously understood as follows: antiferromagnetism, in which spin alignment is antiparallel and cancels out net magnetization, and ferromagnetism, characterized by parallel spin alignment producing net magnetization [7] (see Figure 1a).

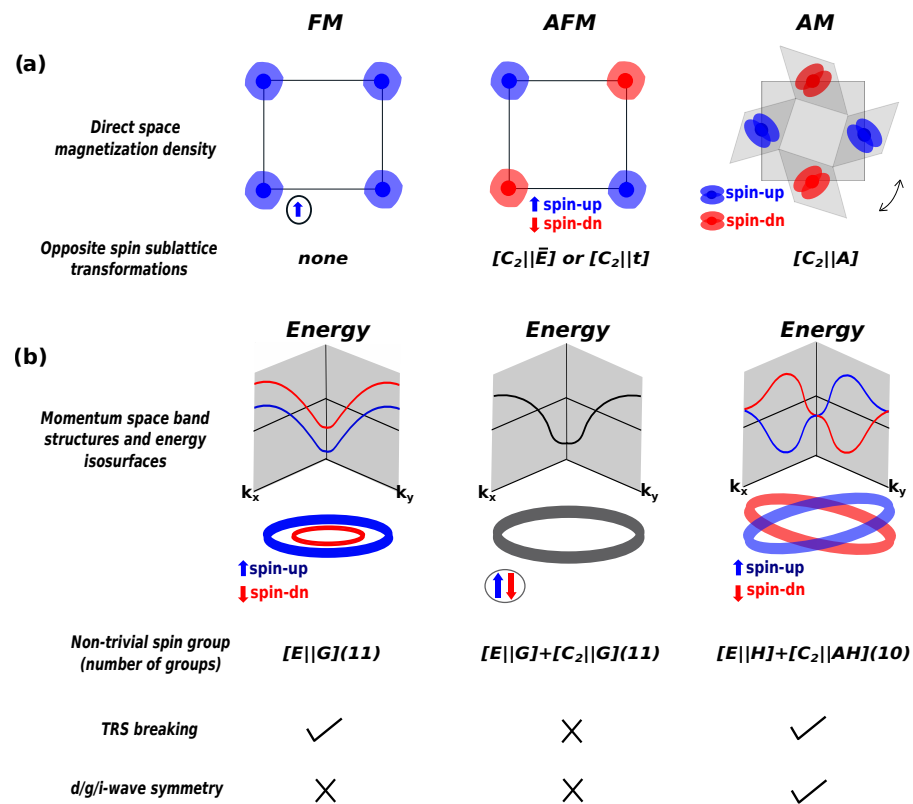


Figure 1. (a) Schematic comparison of spin densities in FM, AFM, and AM. FM and AFM have isotropic spin densities. Rutile AM with anisotropic spin density of magnetic atoms (red and blue); the double-headed arrow indicates that two opposite spin sub-lattices are connected by rotation only ($[C_2||C_{4z}t]$). (b) Comparison of the schematic band structures of FMs, AFMs, and AMs, followed by the iso-surface depicted at the bottom of the diagram. FMs show constant spin-splitting in the momentum space, whereas AFMs show no spin-splitting. However, the band structure corresponding to AMs shows significant alternating spin-splitting. These figures are reproduced from Refs. [4,5] under CC BY 4.0 International license. Published by APS, copyright 2022.

In conventional ferromagnets (FMs), the spin density (the difference between spin-up and spin-down electron densities) is isotropic within each magnetic sublattice. Correspondingly, the spin splitting in momentum space resembles an isotropic s-wave character, as illustrated in Figure 1a,b. In contrast, altermagnets (AMs) exhibit anisotropic spin densities [refer to Figure 1a], and the corresponding spin splitting in momentum space is reminiscent of d-, g-, or i-wave parity, as shown in Figure 2 [4,5]. The latter can be regarded as the magnetic counterparts of unconventional superconductors [5] and as realizations of nematic states in both real and spin spaces. The origin of spin-splitting in the band structure of ferromagnetic materials can be attributed to either relativistic SOC or exchange coupling (Zeeman effect) in the non-relativistic limit [8]. Historically, spin splitting in non-centrosymmetric, high-Z compounds was attributed to SOC, as demonstrated in the seminal works of Rashba and Dresselhaus [9,10]. However, these materials often suffer from chemical instability [11], necessitating alternative pathways for achieving spin splitting in centrosymmetric, thermodynamically stable, low-Z antiferromagnets. One such example is MnF_2 , a rutile-structured AFM material, where conventional SOC-driven mechanisms cannot account for the observed spin splitting [11].

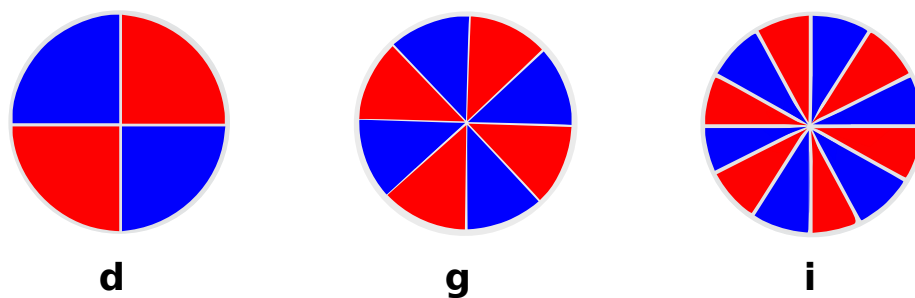


Figure 2. Schematic d-, g- and i-even-parity waveform of AMs depicted in 2D. The figure is adapted from ref. [5] under CC-BY 4.0 International license. Published by American Physical Society (APS).

From a chemist's viewpoint, local distortion in each opposite spin sublattice environment, and the bonding between magnetic and non-magnetic atoms, play a crucial role in shaping spin-splitting properties in AMs, as comprehensively discussed in Ref. [12]. The systematic distortion of the local environment from a hypothetical high-symmetry phase can lead to distorted phases depending on the second-rank symmetric tensor $\hat{U}$'s, potentially resulting in altermagnetism when the magnetization is compensated [13], as illustrated in Figure 3. The underlying mechanism may be linked to the spin-polarized even-parity wave Pomeranchuk instability—a purely electronic instability of the correlated Fermi liquid that distorts the Fermi surface [14,15]. A wide range of materials, including metals, semiconductors, insulators, and superconductors, can intrinsically exhibit altermagnetism [4]. Additionally, material design concepts can be used to induce it, as discussed in Section 4.4.

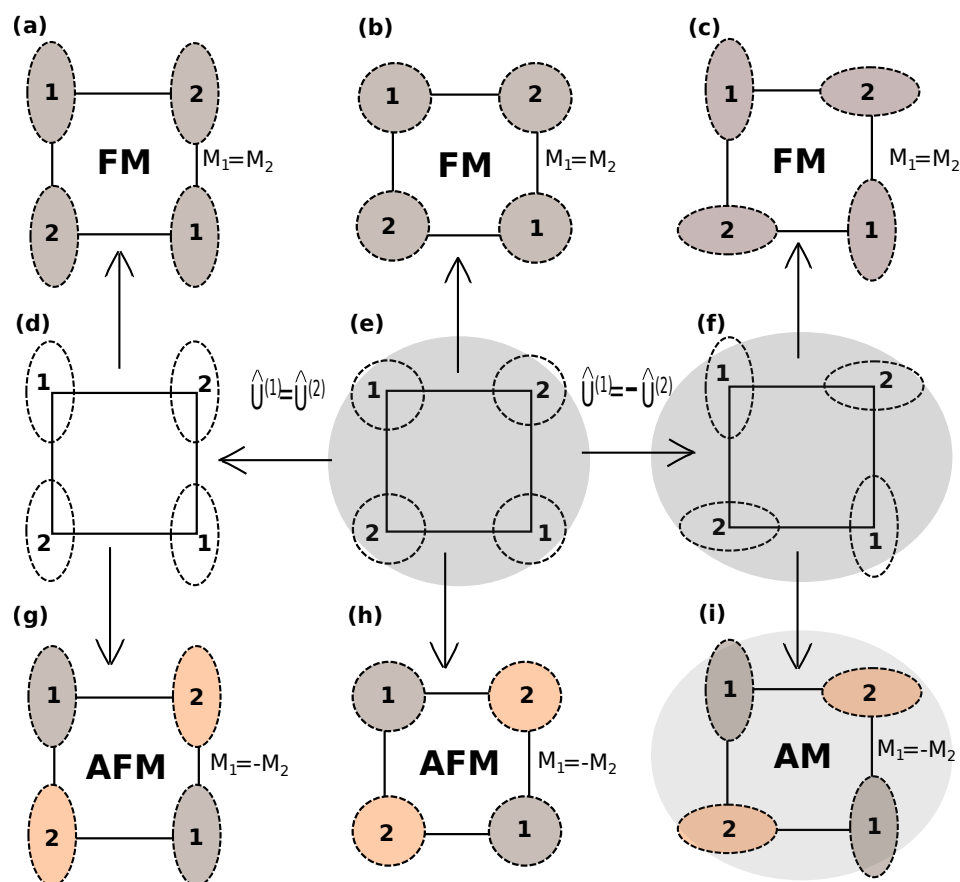


Figure 3. (a–c) represent the ferromagnetic phases (FM with $M_1 = M_2$), while (g–i) represent the staggered magnetic phases (AFM or AM with $M_1 = -M_2$), and (d,f) are structural phases. Any magnetic phase can

be derived from the highly symmetric hypothetical phase demarcated in (e) with no magnetic order and an isotropic local environment of magnetic atoms (shown with circles). The distortion of the local environment leads to two different structural phases with equal ($\hat{U}^{(1)} = \hat{U}^{(2)}$) or a distorted ($\hat{U}^{(1)} = -\hat{U}^{(2)}$) local environment (U 's are second rank symmetric tensors illustrating the feasible distortion of the sublattices). Combining the staggered environment with the staggered order gives altermagnetism. The sign of the exchange coupling between atoms 1 and 2 determines whether the magnetic order results in staggered ($M_1 = -M_2$) or ferromagnetic ($M_1 = M_2$) structures. This figure is reproduced from Ref. [13] under CC-BY 4.0 International License. Published by Springer Nature, copyright 2024.

To identify AMs, Smejkal et al. [4] proposed the following theoretical criteria:

- The number of magnetic atoms in a unit cell is even.
- The magnetic atoms with opposite spin in AMs are not related by inversion symmetry.
- The presence of inequivalent local environments surrounding each oppositely aligned spin sublattice leads to non-interconvertible local motif–pair spin anisotropy, a key distinguishing feature of altermagnetic order.
- The opposite-spin sublattices are connected by rotation (in spin and real spaces) or combined with translation or inversion symmetry, mirror, glide, or screw.

Such an identification is automated and can be readily found using a computational tool developed by Smolyanyuk et al. [16] using a Crystallographic Information File as input. First-principle computations demonstrated NRSS in various materials, with more than 200 compounds in bulk and 2D predicted as candidate AMs [17]. Using a machine-learning-based approach, potential candidates have been identified based on their electronic structures [18]. However, only a limited number have been experimentally investigated (as shown in Table 1), resulting in the discovery of only a few material candidates. Indeed, advanced experimental methods such as neutron scattering, magnetic resonance, and advanced spectroscopic techniques can probe the unique spin structures of AMs. This paves the way for exploring a wide range of two-dimensional (2D) and bulk materials that could potentially host altermagnetism.

Table 1. NRSS on various altermagnetic materials from multiple forms of ARPES experiments.

Space Group	Materials	$[C_2 A]$
$P6_3/mmc$	CrSb [19–22] MnTe [23–25] CoNb ₄ Se ₈ [26,27] Co _{1/4} NbSe ₂ [28,29]	$[C_2 C_{6z}]$
$P4/mmm$	KV ₂ Se ₂ O [30] Rb _{1-δ} V ₂ Te ₂ O [31]	$[C_2 C_{4z}]$
$I4_1/md$	GdAlSi [32]	$[C_2 C_{4z}]$
$P4_2/nmm$	RuO ₂ [33–35]	$[C_2 C_{4z}]$

Beyond their fundamental interest, AMs hold immense potential for spintronic applications due to the emergence of spin currents [36–39], spin-splitter torques [40,41], efficient spin-to-charge conversion [42,43], giant/tunnel magnetoresistance [44–49] effects, exotic phenomena linked to superconductivity [50–75], high-frequency dynamics (THz) [76,77], and distinct topological states [51,78–80]. In general, these properties promote AMs as promising materials for information technology [4,5,8,12,17,81,82]. Spintronic devices would switch faster and operate at lower power compared to conventional charge-based

electronics [83,84]. Although theoretical studies have advanced rapidly in the field of AMs, experimental verification and material realization remain in their early stages. This review aims to provide a concise overview of recent developments, clarify fundamental concepts, and highlight potential applications, along with methods for inducing altermagnetism. We begin by discussing the spin group theory used to understand the formation of altermagnets from a symmetry perspective. Next, we review the experimental and theoretical techniques employed to explore the emergence of altermagnets, followed by an examination of the materials studied in this context. We then discuss magnetotransport phenomena and promising applications before concluding with key insights.

2. Spin Group Theory Description

In Landau theory, traditionally applied to ferromagnets and antiferromagnets, the coupling between spin and real space is inherently a relativistic effect [12]. The primary order parameter is the Néel vector (the difference between magnetic dipole moments of the opposite spin sublattice); it fails to distinguish AFM and AM [85]. As a result, higher-order magnetoelectric multipoles may be suitable for the discussion of AMs, which break TRS. McClarty et al. [86] extended this framework by introducing a set of TRS-odd multipolar secondary order parameters that bridge the gap between ideas about spin symmetries and the observed NRSS. This approach has been effective in explaining NRSS and TRS breaking in rutile MnF_2 , owing to the ferroic ordering of magnetic octupoles [85] (discussed in Section 4.1). The approach used by Smejkal et al. [4,5] to explain NRSS in AMs uses a description of nonrelativistic spin group theory, where spin and space symmetries are decoupled. A symmetry operation is denoted as $[C_i | C_j]$, where the transformation on the left of the double vertical line acts in spin space, and the one on the right acts in real space. In the case of the rutile family ($\text{RuO}_2, \text{MnF}_2, \text{MnO}_2$, etc.), the related spin group symmetry is $[C_2 || C_{4z} t]$ (see Figure 1a) [4]. Here, twofold (C_2) rotation in spin space and fourfold rotation (C_{4z}) are merged with the translation (t) in real space. If r_s corresponds to a spin-only group containing the transformation solely in the spin space, and R_s is the nontrivial spin group containing the transformation like $[C_i || C_j]$, then the spin group can be expressed as the direct product $r_s \times R_s$ [87,88]. The spin-only group is defined as $r_s = C_\infty + \bar{C}_2 C_\infty$, where C_∞ is the group containing all the spin space rotational transformations about the spins' common axis and $\bar{C}_2$ is the two-fold rotation about an axis orthogonal to the spin, followed by reversal of spin space. C_∞ makes spin a good quantum number; hence, the band structure of the collinear magnets does not mix the spin-up and spin-down channels [5]. Time reversal symmetry ($\mathcal{T}$) operation is equivalent to spin space inversion followed by flipping of the crystal momentum (k) direction [87,88] in the nonrelativistic limit. The symmetry operation $[\bar{C}_2 || \mathcal{T}]$ forms the symmetry of a collinear system. While the spin-only group r_s is common to all the nonrelativistic collinear magnets. The nontrivial spin group (R_s) is constructed using an isomorphic coset decomposition between the spin-space transformation group and the real-space crystallographic transformation group.

The three types of nontrivial spin groups can describe different types of magnetic materials. The foremost kind is for ferromagnetic materials, where the group is represented by $R_s^I = [E || G]$, where E is a spin-space identity transformation and G specifies the Laue group. R_s^I defines the non-trivial spin group corresponding to conventional ferromagnetism (spin-split band structure with broken TRS symmetry). The second type of non-trivial spin group is $R_s^{II} = [E || G] + [C_2 || G]$. The group R_s^{II} also describes conventional antiferromagnetism and the related opposite spin sublattice symmetry is $[C_2 || \bar{E}]$ or $[C_2 || t]$, where $\bar{E}$ is the real space inversion and t denotes translation. $R_s^{III} = [E || H] + [C_2 || AH]$ gives the nontrivial spin group that characterizes the AMs. H is the Halving subgroup possessing half elements of the real space transformation of the nonmagnetic Laue group G , which

includes the identity element of real space. The $G - H = AH$ contains the residual half of the transformation, where A is a real-space rotation (proper or improper, symmorphic or non-symmorphic), but excludes the identity and inversion operations. Only real space transformations that exchange atoms between sublattices of the same spin are contained in H , and exclusive real space transformations that exchange atoms between sublattices of opposite spin are present in $G - H$. The non-trivial spin subgroup $[E||H]$ determines the anisotropic spin densities in real space. In contrast, $[C_2||AH]E(k,\sigma)=E(k',-\sigma)$; this implies that $E(k,\sigma) \neq E(k',-\sigma)$, indicating that $[C_2||AH]$ is responsible for broken TRS and non-relativistic spin splitting of bands. Together, there are ten nontrivial spin Laue groups categorizing d-, g-, and i-wave AMs [4,5].

3. Experimental Techniques and a Theoretical Approach to Explore Altermagnetism

The field of altermagnetism has been driven by theoretical predictions. There is currently a large database of materials predicted to host an altermagnetic behavior. Here, we review the techniques used experimentally and theoretically to address altermagnetism (see, for example, Table 1).

Various experimental methods have been employed to confirm NRSS in AMs, with angle-resolved photoemission spectroscopy (ARPES) being a key technique. ARPES operates on the principle of the photoelectric effect [89,90], where a spectrometer records the intensity I of emitted photoelectrons based on their kinetic energy E_k and emission angle $\alpha + \beta$. A schematic of the experimental ARPES basic setup is shown in Figure 4. This technique directly maps a material's energy-momentum (E - k) relationship [91].

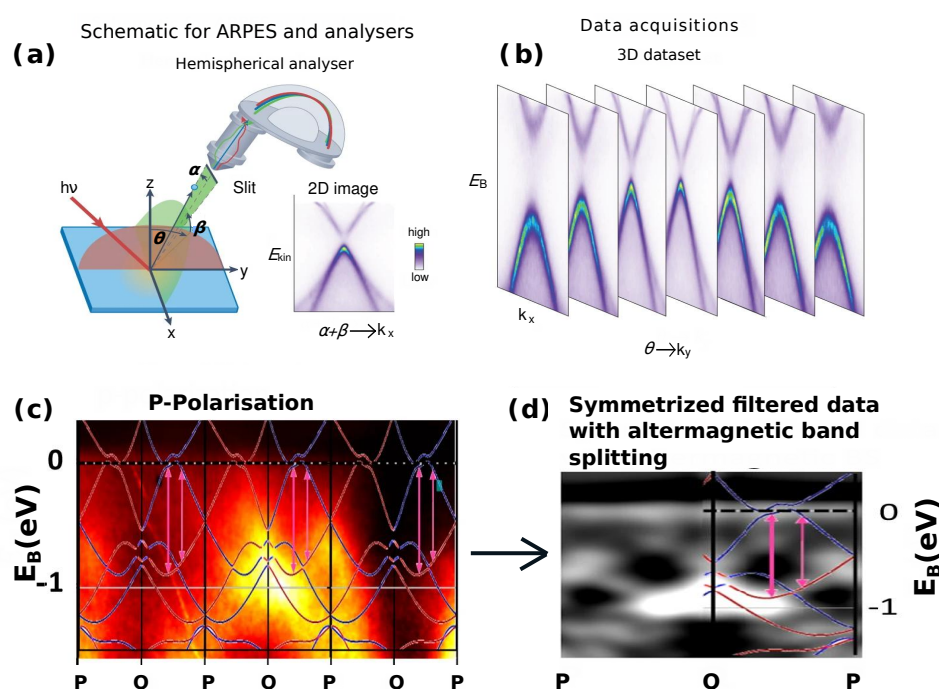


Figure 4. (a) Schematic ARPES experimental setup. (b) ARPES mapped band structure at different sample θ values. (a,b) are reproduced with permission [91]. Copyright 2022, Springer Nature. (c,d) The spin-integrated SX-ARPES intensity just below the Fermi energy, showing distinct spin splitting: (c) High-symmetry P-Q path with p-polarized photons. (d) Symmetrized filtered data using the Laplacian filter. (c,d) are reproduced from Ref. [20] under CC BY 4.0 International license. Copyright 2024, published by Springer Nature.

The pioneering work of Lee et al. [23] marked the first application of ARPES in AMs, using epitaxial thin films of MnTe synthesized in situ to conduct temperature-dependent ARPES studies. Their findings revealed the lifting of Kramers' degeneracy and confirmed that NRSS vanishes above the Néel temperature, signifying a magnetic phase transition [23]. Over the past few decades, ARPES has undergone remarkable advancements, both in technology and scientific applications. The development of advanced light sources, particularly third-generation synchrotrons [92–97], has significantly enhanced its capabilities. Ding et al. [19] utilized synchrotron-based high-resolution ARPES to successfully detect NRSS in CrSb, highlighting the technique's growing sophistication and increasing relevance in uncovering novel electronic properties. Additionally, extending ARPES into the soft and hard X-ray range [92,96,98,99] has broadened its application spectrum. The ARPES signal is strongly influenced by photon energy and polarization, as dipole matrix elements shape the photoemission process [100]. Soft X-ray ARPES (SX-ARPES), with its deeper probing capabilities, is particularly advantageous for studying buried interfaces and capped surfaces [91]. By resonantly probing valence d- and f-states, it provides crucial insights into strongly correlated systems, including Mott insulators, superconductors, and magnetic materials [101,102]. Additionally, the use of high photon energies in SX-ARPES enhances penetration through complex surface structures, reducing the impact of relativistic spin splitting [8]. This technique has also been instrumental in investigating oxide-based heterostructures [103] and superlattices [104], further expanding our understanding of quantum materials. Recent studies have employed angle-dependent SX-ARPES to examine the altermagnetic characteristics of thin epitaxial CrSb films [19–22]. The measurements reveal a significant spin splitting of approximately 0.6 eV below the Fermi level [20] (see Figure 4c), aligning well with theoretical predictions for AMs [4]. Moreover, CrSb exhibits a high Néel temperature of 703 K, making it a promising candidate for room-temperature applications [22].

Another significant advancement is spin-resolved ARPES (Spin-ARPES), which extends the technique by resolving the spin vector direction of electrons with high energy and momentum precision [105–107]. However, its efficiency is lower, leading to longer data acquisition times [91]. Despite this limitation, various forms of ARPES have been successfully employed in multiple AMs to detect NRSS, further reinforcing its importance in the study of novel magnetic materials [19–25,30,31,33,108]. Although ARPES provides direct evidence of NRSS, measuring spin splitting using ARPES is challenging. Foremost, spin polarization in the measured band structure can cancel out due to contributions from mixed domains, as separating altermagnetic domains is often difficult [23]. For example, a helium discharge lamp with mm-scale beam spot is much larger than individual magnetic domains, and the signals from multiple domains blend together, canceling out any net polarization [23]. To address this issue, spin-resolved micro- or nano-ARPES, with a micro- or nanometer-scale beam spot, can be a desirable approach for determining NRSS [25,91].

Besides ARPES, various experimental techniques have been employed to investigate AMs, supported by first-principles calculations, as summarized below.

- High field torque magnetometry applied on FeSb₂ to map the Fermi surface [109].
- Neutron scattering and Muon spin rotation/relaxation (μ SR) techniques: used for RuO₂ [110] and α -MnTe [111].
- XMCD: X-ray magnetic circular dichroism on MnF₂, RuO₂ [112,113] and MnTe [114,115].
- DFT (Density Functional Theory): First-principles investigations can be efficiently performed at a low computational cost without including SOC on altermagnets. First-principles calculations were performed to provide theoretical predictions to motivate and compare with experimental findings, focusing on various materials including RuO₂ [33,116,117], CrSb [19,20], MnTe [23–25], MnF₂ [85,118], and others [119].

4. Examples of Explored Altermagnetic Materials

4.1. MnF_2 and Octupole Moments

In MnF_2 , the fluorine octahedra around the manganese atom at the structure's center are rotated 90° around the z-axis compared to those surrounding the manganese atom at the structure's corner, favoring the formation of altermagnetic order with opposite spin sublattice symmetry [$C_2 \mid C_{4z}t$] (refer Figure 1a). Altermagnetism may emerge in any rutile family of AFMs possessing such symmetry. The examples may include CoF_2 , NiF_2 , ReO_2 , etc. [17]. The computational study by Bhowal et al. [85] explored the role of magnetic octupoles, identifying their potential for tuning via alterations to the fluorine environment around the Mn sites without affecting the spin configuration. This tuning capability demonstrates that flipping the Mn spin arrangements reverses the sign of the octupole moment, highlighting magnetic octupoles as a natural-order parameter for NRSS antiferromagnetism. Magnetic Compton profile measurements were proposed as a tool to detect associated magnetic octupoles [85]. These findings suggest promising research directions, particularly the investigation of other magnetic materials with a centrosymmetric tetragonal rutile structure. The potential role of magnetic octupoles as order parameters in these systems warrants further detailed exploration.

4.2. Marcasite(M)- FeSb_2 with Doping

Doped FeSb_2 received significant attention due to the emergence of the anomalous Hall effect phenomenon (discussed in Section 5.1) owing to the anti-Kramers nodal surfaces. First-principles calculations revealed a non-relativistic spin splitting (NRSS) on the order of ≈ 0.2 eV [120]. Phillips et al. experimentally measured the Fermi surface oscillation of FeSb_2 supported by a first-principles study consistent with metallic conductivity and altermagnetic order [109]. The underlying rotational symmetry in FeSb_2 is [$C_2 \mid C_{2y}$], which connects the opposite-spin sublattices when combined with translation. Another compound in the marcasite family that shares this symmetry and may host altermagnetism is M-CrSb_2 [17]. These theoretical predictions warrant further experimental investigation through techniques such as anomalous Hall conductivity measurements and angle-resolved photoemission spectroscopy (ARPES).

4.3. Contradicting Reports on the Magnetic Ordering of RuO_2

Although RuO_2 stands out as the most explored material for altermagnetism, its magnetic properties have been the subject of conflicting results, with some suggesting Pauli paramagnetism [121] in the past. In contrast, others indicate an antiferromagnetic order [122,123]. Assuming a Hubbard-U of 2 eV [116], the first principles simulations, confirmed experimentally, revealed significant NRSS in RuO_2 [33–35]. However, consider that zero U or a realistic value leads to a non-magnetic state, as shown in the detailed study as a function of U for stoichiometric RuO_2 in Ref. [124]. The study was also carried out for non-stoichiometric RuO_2 , proposing that Ru vacancies could facilitate a magnetic state. This hypothesis is supported by the observation that hole-doped RuO_2 modeled by varying the electron counts in the DFT calculations can exhibit magnetic properties. Hence, the occurrence of altermagnetism depends on the sample's stoichiometry, with nonstoichiometric samples showing potential for magnetism due to Ru vacancies or hole doping. Such an observation could potentially clarify the significant variability in experimental observations, which may be due to differences in sample conditions, underscoring the need for a more detailed characterization of RuO_2 stoichiometry in future studies. The study of Brahimi et al. [125], on the other hand, indicates that the output of the measurements depends on the surface sensitivity of the experimental techniques. First-principles calculations have predicted that altermagnetism can be stabilized in ultrathin RuO_2 films even

without the inclusion of a Hubbard-U term [125]. In these thin films, strong layer relaxations significantly modify the electronic states, effectively mimicking the effects typically induced by a finite U. This observation is consistent with recent studies highlighting the role of strain in thin films in inducing altermagnetism [126–129].

The magnetic characteristics of RuO₂ were investigated by combining a variety of cutting-edge spectroscopy techniques, including neutron diffraction and muon spin spectroscopy (μ SR). It was demonstrated that the previously found magnetic signals are probably the result of experimental errors, such as multiple scattering at defects rather than intrinsic magnetic features of the material, therefore challenging prior assertions of magnetic order in RuO₂. The thoroughness of the methodology ensures high reliability in the results, particularly in ruling out magnetic order in RuO₂ [110,130]. Furthermore, Liu et al. [108] directly analyzed the band structures and spin polarization of single-crystal and thin-film rutile RuO₂ samples using ARPES and SX-ARPES. The electronic structure of RuO₂ is reported to be reasonably consistent with non-magnetic conditions, as evidenced by the lack of k-dependent spin-splitting. An alternative approach for investigating altermagnetism in RuO₂ may involve Fermi surface mapping, as demonstrated in recent experimental studies [109]. This method could offer valuable insights into the electronic structure and magnetic characteristics of RuO₂, complementing existing spectroscopic and theoretical investigations.

Gomonay et al. [13] studied RuO₂'s magnon spectra and domain wall dynamics, developing a phenomenological model for altermagnets (AMs). Their framework extends micromagnetic models, revealing lifted magnon degeneracy [131,132], anisotropic spin stiffness, and domain wall properties distinct from antiferromagnets. The model predicts a Ponderomotive force enabling domain wall manipulation via magnetic force microscopy. Additionally, AMs exhibit anisotropic Walker breakdown at high velocities, with sublattice stiffness differences causing domain wall deformations. Based on Landau–Lifshitz equations, the model incorporates anisotropic exchange stiffness to describe altermagnetic behavior. Tunable domain walls hold potential for novel data storage and neuromorphic computing applications [133].

4.4. Two-Dimensional AMs and Methods for Designing AMs

Various two-dimensional (2D) materials have been proposed to exhibit altermagnetism [17]. Liu et al. [134] identified the 2D altermagnetic semiconductors FeS and FeSe as the thinnest known examples, exhibiting strong magnetic order, low exfoliation energy, and good chemical stability. Both materials feature A-type antiferromagnetic structures with notable spin-splitting magnitudes, 193 meV for FeS and 103 meV for FeSe. Furthermore, magnetic anisotropy energy (MAE) calculations suggest their ability to sustain long-range magnetic order [134]. Monolayer RuF₄ has also been found to exhibit altermagnetism. The inclusion of spin–orbit coupling (SOC) in calculations introduces weak ferromagnetism due to a slight canting of Ru spins [135]. In weak ferromagnets, the Néel vector can be manipulated by a small external magnetic field [136], which offers a potential means of controlling the direction of spin-polarized currents in altermagnets. Expanding upon these control mechanisms, it has been demonstrated experimentally in altermagnetic CrSb that the altermagnetic order can be tuned via the controlled manipulation of crystal symmetry, enabling a designable anomalous Hall effect (AHE) and field-free 180° switching of the Néel vector—features that hold significant promise for next-generation spintronic applications [137].

In addition to the above, various stacking, twisting, and sliding techniques can be used to induce AM (shown in Figure 5), particularly in antiferromagnetic bilayers [138]. An effective approach involves Van der Waals (vdW) stacking, where a magnetic vdW monolayer is stacked into a bilayer with the upper layer flipped, introducing an in-plane

two-fold rotation (see Figure 5a). A subsequent twist operation breaks the inversion symmetry, thus inducing altermagnetism [139]. This method applies broadly to magnetic vdW bilayers that exhibit interlayer antiferromagnetic order across all five 2D Bravais lattices, for example, materials such as transition metal oxyhalides [140,141], antiferromagnetic van der Waals materials [142–144], and hexagonal lattice MnBi_2Te_4 [139]. These techniques have enabled the realization of altermagnetism in materials such as VOBr [139]. In this system, a tight-binding model predicts a giant spin Hall angle, $\Theta = 1.4$, which quantifies the efficiency of converting charge currents into spin currents. This tunability, achieved through variations in the twist angle, opens new avenues for efficient spin-current generation [139]. Pan et al. [145] proposed a General Stacking Theory (GST) to predict altermagnetism in bilayers based on the symmetry of monolayer components, provided there is antiferromagnetic coupling between the layers. The stacking operator ($\hat{P}$) transforms a monolayer (L) into another layer (L') through a series of symmetry operations, translations, or rotations, forming a bilayer (B) directly. Stacking followed by sliding demonstrated an effective method for inducing altermagnetism [146] as illustrated in Figure 5e.

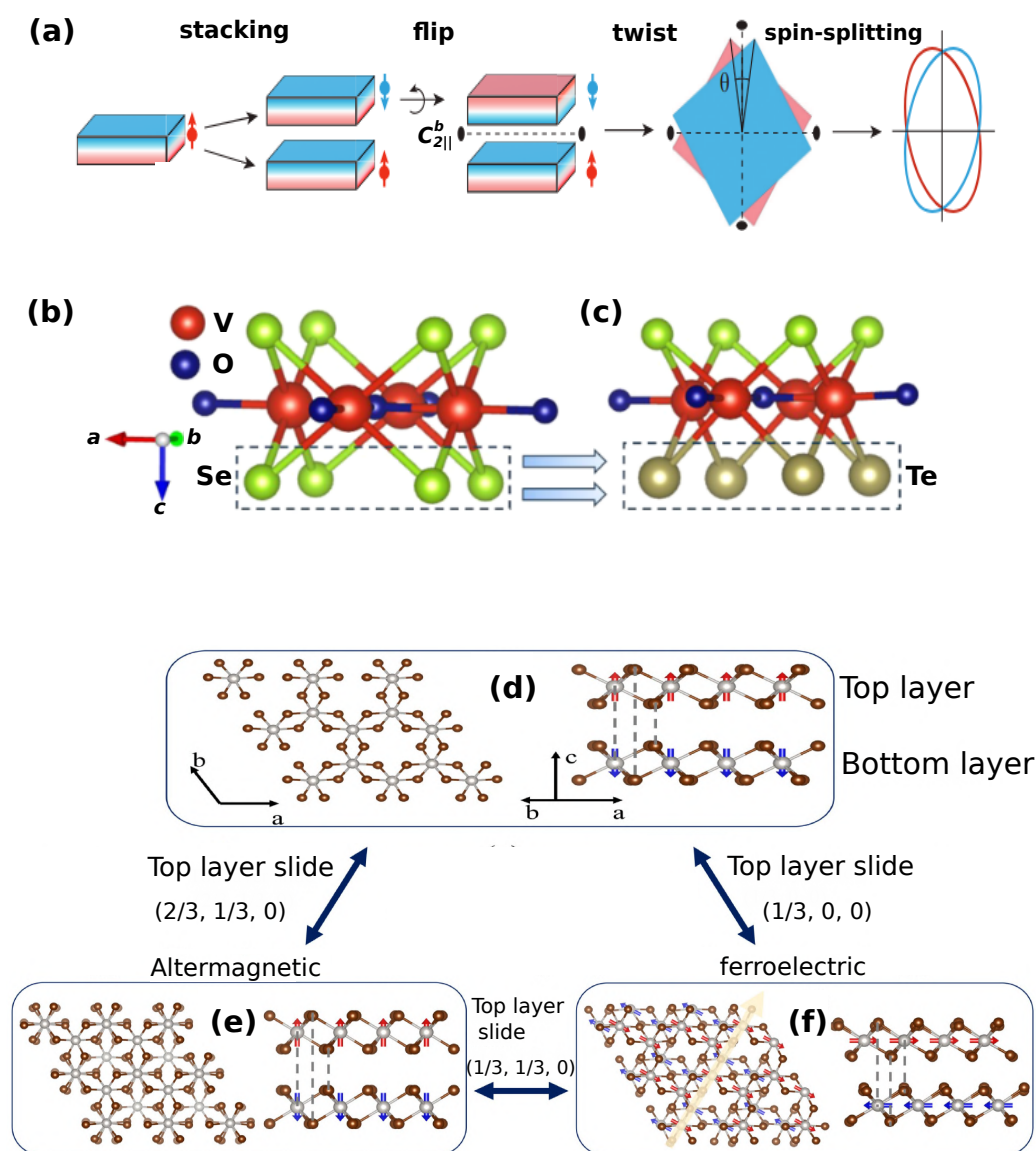


Figure 5. Strategies for inducing altermagnetism: (a) Twisting of Van der Waals bilayer enabled identification of new AMs (e.g., VOBr , Co_2S_2 , MnBi_2Te_4). (a) is reproduced with permission [139].

Copyright 2024, American Physical Society. (b,c) Janus AM V_2SeTeO formed by replacing the bottom Se layer with Te atoms. (b,c) are reproduced with permission [147]. Copyright 2023, American Chemical Society. (d) Monolayer and bilayer of $PtBr_3$. With suitable sliding of the top layer, either an altermagnetic (e) or a ferroelectric (f) material can be obtained. (d–f) is reproduced with permission [146]. Copyright 2024, American Physical Society.

Furthermore, modulating coordination modes enables the tunability of spin-related properties in 2D metal–organic frameworks (MOFs) [148–150]. These materials exhibit high spin–charge conversion ratios, reaching 56.85% for $Ca(\text{pyrazine})_2$ and 86.04% for $Sr(\text{pyrazine})_2$, alongside high spin Hall conductivity. Their ability to control spin currents via electric fields presents exciting opportunities for spintronics applications [149]. A recent study proposes an altermagnetic Janus monolayer [147,151,152]. Janus V_2SeTeO , created by substituting the Se atoms in the bottom layer of V_2Se_2O with Te atoms (see Figure 5b), exhibits enhanced piezoelectricity, strain-induced valley polarization, and doping-controlled piezomagnetism, making it a highly promising material for applications in nanoelectronics, spintronics, and valleytronics. First-principles calculations confirm that these properties can be independently tuned via mechanical strain, offering new possibilities for designing multifunctional 2D materials. These advancements highlight the versatility of 2D altermagnetic materials, demonstrating that approaches such as twisting, stacking, and atomic substitution can effectively engineer spintronic and multifunctional properties across diverse material classes.

The strain has also been identified as a viable method for inducing and modulating altermagnetism by modifying crystal symmetry [126,153–155]. For example, bulk ReO_2 typically adopts an antiferromagnetic monoclinic α phase but transitions to a tetragonal R phase under pressure, exhibiting altermagnetic behavior [153]. Murnaghan fitting data further suggest that the altermagnetic R- ReO_2 phase is more stable than its monoclinic counterpart. Furthermore, a first-principle study shows that external hydrostatic pressure can significantly tune the magnitude of spin splitting in altermagnets (AMs). This tunability arises from pressure-induced variations in bond lengths, which subsequently modify the orbital contributions in both the valence and conduction bands [154,155]. In addition, a recent study suggests that the coexistence of staggered antiferromagnet and orbital order (OO) is capable of producing robust altermagnetism, giving rise to significant spin-splitting and spin-splitter conductivity. Electron correlations can generate a phase in which Néel AFM and staggered OO coexist, producing a d-wave altermagnet [156]. Various experimental studies have identified staggered orbital ordering on the surface of $CeCoIn_5$ [157], as well as in transition-metal oxides with a perovskite structure, such as $LaMnO_3$ [158–160], and in cubic vanadate compounds [161]. The right size of the simulation unit cell plays an important role in predicting the presence of altermagnetism. As demonstrated in the theoretical study by Jaeschke et al. [162], enlarging the unit cell of $MnSe_2$ reveals d-wave altermagnetism, as shown in Figure 6. Several candidates have been identified for d- and g-wave altermagnetism; for example, supercells of perovskites $CsCoCl_3$, $RbCoBr_3$, and $BaMnO_3$ exhibit g-wave altermagnetism.

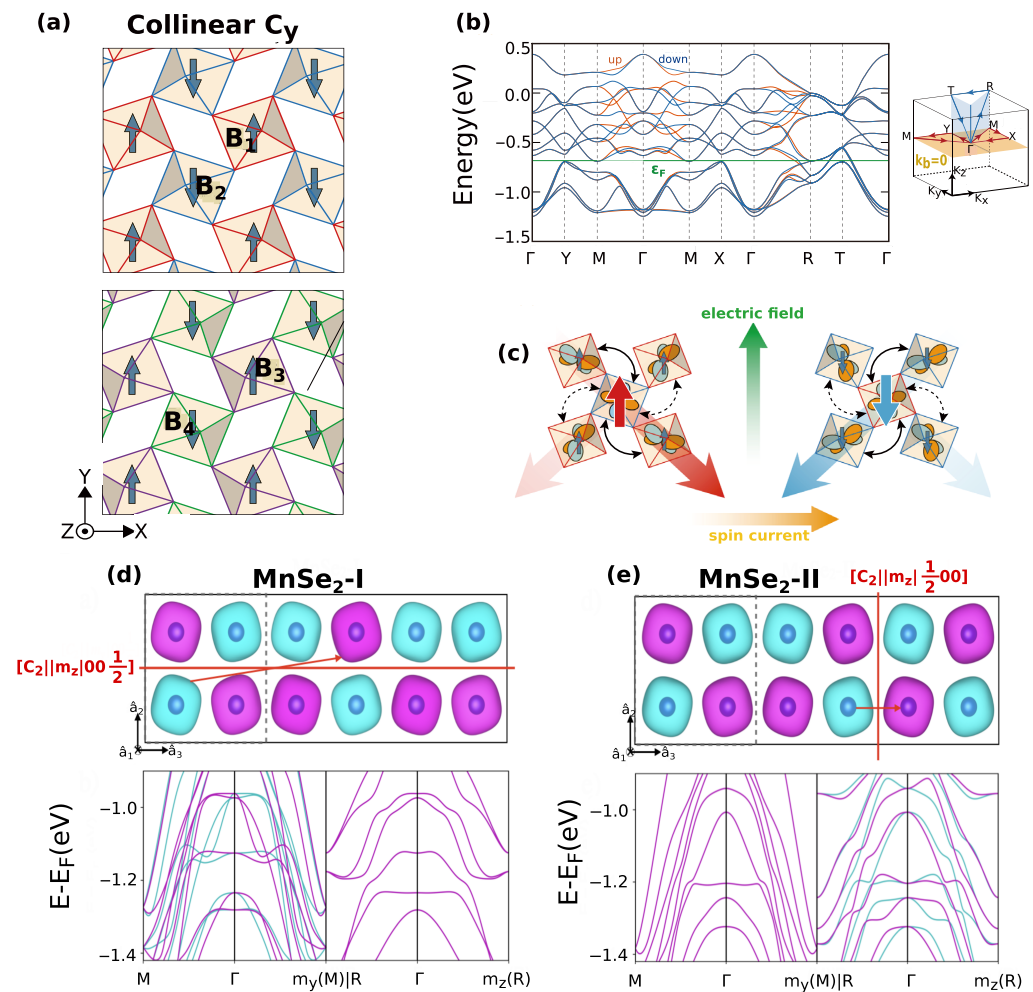


Figure 6. Perovskite and supercell altermagnets: (a) C-type AFM ordering with $GdFeO_3$ type lattice distortion parameterized by ϕ . (b) Corresponding band structure of t_{2g} orbital and high symmetry path. (c) Schematic representation of spin current generation. (a–c) have been adapted from Reference [163] licensed under CC-BY-NC-ND 4.0. (d,e) Supercell AMs with opposite spin sublattices connected by glide symmetry and corresponding band structures at the bottom. (d,e) are reproduced with permission [162]. Copyright 2024, American Physical Society.

4.5. Perovskites

Perovskite is a class of materials with the chemical stoichiometry ABX_3 . They have a diverse range of applications, including photodetectors, solar cells, LEDs, magnetoelectric effects, optoelectronic devices, superconductivity, photovoltaic effects, etc. [164–167]. The combination of antiferromagnetic ordering and $GdFeO_3$ -type lattice distortions (see Figure 6a) leads to the emergence of altermagnetic properties, the anomalous Hall effect, and spin currents in perovskites [39,163,168]. Ruddlesden–Popper phases and their related perovskite structures also serve as material candidates for altermagnets [163,169]. Perovskites with diverse electron configurations (d^n) offer promising candidates for spin current generation and the anomalous Hall effect (AHE). Among them, $CaCrO_3$ ($3d^2$), exhibiting a C-type AFM order below 90 K and maintaining metallic conduction, stands out as a potential material [170]. Similarly, a C-type AFM order is present in AVO_3 ($A = La-Y$), which can transition to a metallic state through doping of the A-site carrier [171–173]. The spin splitting mechanism may also extend to d^4 systems, such as $R_xA_{1-x}MnO_3$, due to e_g-e_g and e_g-t_{2g} electron hoppings [174,175]. Furthermore, A- and G-type AFM orders could exhibit spin splitting if metalized through carrier doping or proximity effects [168,176]. Beyond these, d^3 systems, including $LaCrO_3$ and $YCrO_3$, dis-

play AFM states that potentially support AHE [177–179]. Mn-based perovskites, such as CaMnO_3 and LaMnO_3 [163,180,181], exhibit various AFM phases that may be conducive to spin current generation and AHE, while Fe-based perovskites, including LaFeO_3 , and YFeO_3 , feature G-type AFM ordering [181–184]. Fluoride-based perovskites, such as NaMnF_3 , and KMnF_3 , also emerge as promising candidates, expanding the range of potential materials for altermagnetic applications [185–187].

Recent first-principle studies by Sattigeri et al. [188] highlight the emergence of surface states exhibiting altermagnetic behavior, with spin-splitting believed to be highly dependent on magnetic space groups. The properties of the magnetic surface state have been investigated in three exemplary space groups: orthorhombic ($Pbnm(62)$), hexagonal ($P6_3/mmc(194)$), and tetragonal ($P4_2/mmm(135)$). It was found that the altermagnetic properties on certain surfaces are preserved but annihilated on others because of certain spin-splitting characteristics in the Brillouin zone (BZ). For example, for LaMnO_3 (Space group-62) belonging to the perovskite family with A-type antiferromagnetism, surfaces (010) and (001) are devoid of AM, whereas surface (100) hosts AM with spin splitting of about 30 meV. Furthermore, it was shown that the electric field could have significant control over the surface states and trigger altermagnetism on the otherwise blind surface [188].

4.6. Superconductivity and Altermagnets

The observation of altermagnetism in La_2CuO_4 , which exhibits high-temperature superconductivity, has generated significant research interest in the association of superconductivity with AM. [5]. Conventional s-wave superconductivity maintains a uniform Cooper-pair phase around the Fermi surface, akin to ferromagnetism with a single-spin orientation. In contrast, unconventional d-wave superconductivity features a sign-changing Cooper-pair phase, analogous to d-wave magnetism with a sign-changing spin orientation around the Fermi surface [4]. Altermagnetism is suggested to be compatible with spin-triplet superconductivity [189], presenting a valuable opportunity to explore unconventional superconductors that maintain zero stray fields [8]. The unique altermagnetic property enables novel superconducting phenomena in superconductor/altermagnet junctions, including $0-\pi$ oscillations, multi-nodal current-phase relations, and spin-polarized Andreev levels [50,58,63]. The Josephson effect in AMs differs qualitatively from ferromagnetic junctions, with the decay length and oscillation period influenced by crystallographic orientation [50,63]. AMs also enable tunable superconducting states, such as finite-momentum Cooper pairing and mixed s-wave and p-wave pairings, driven by d-wave altermagnetic order [51,52,58]. They support gapless superconductivity, mirage gaps, and Majorana corner modes under strain or Néel vector rotation, making them promising for cryogenic memory devices and dissipationless superconducting diodes [53,61,68]. The spin-polarized band structure of AMs enables precise control over charge and spin conductance at superconductor interfaces, enhancing functionalities for quantum computing, spintronics, and topological superconductivity [56,64,73].

5. Emerging Magneto-Transport Phenomena and Promising Applications

5.1. Magneto-Transport Phenomena

The anomalous Hall effect (AHE) arises from breaking time-reversal symmetry in magnetic materials, typically due to intrinsic (owing to Berry curvature) and extrinsic (due to skew scattering and side jump) contributions, and is observed in FMs [190]. The AHE is also coined as the spontaneous Hall effect, which surprisingly was predicted and observed to occur in non-collinear antiferromagnets [191–197] and, particularly, in AMs [120,168,198–207]. The spontaneous Hall voltage is a phenomenon in which the application of an electric field

causes electrons to gain transverse velocity without an external magnetic field. This effect is related to the antisymmetric dissipation-free portion of the conductivity tensor, which is represented by the Hall pseudovector and controls the Hall current [116]. In collinear AFMs, the simplified magnetic structure defined solely by the spin orientations and spatial arrangement of magnetic atoms does not produce a spontaneous Hall conductivity. The necessary asymmetry emerges only when additional atoms, often nonmagnetic, occupy noncentrosymmetric sites. In AMs, the arrangement of non-magnetic atoms induces an asymmetry in the magnetization density between the two opposite spin sublattices. The inclusion of relativistic SOC generates anisotropic Berry curvature [120]. Anomalous transport coefficients can be obtained by integrating the Berry curvature within the BZ [116,208]. Smejkal et al. [116] initially calculated anomalous transport coefficients in RuO₂ using first-principles and coined the term crystal Hall effect (CHE). After initial predictions of an AHE in RuO₂ [116], experiments followed quickly with a confirmation [198,202] shown in Figure 7. Furthermore, AHE has been observed in altermagnetic thin films of Mn₅Si₃ [201] and hexagonal MnTe [209]. In the thin film of RuO₂, one can observe the reorientation of the Néel vector from the [001] easy plane to the [110] hard plane caused by the application of an electric field, allowing for the observation of AHE [188,196,202].

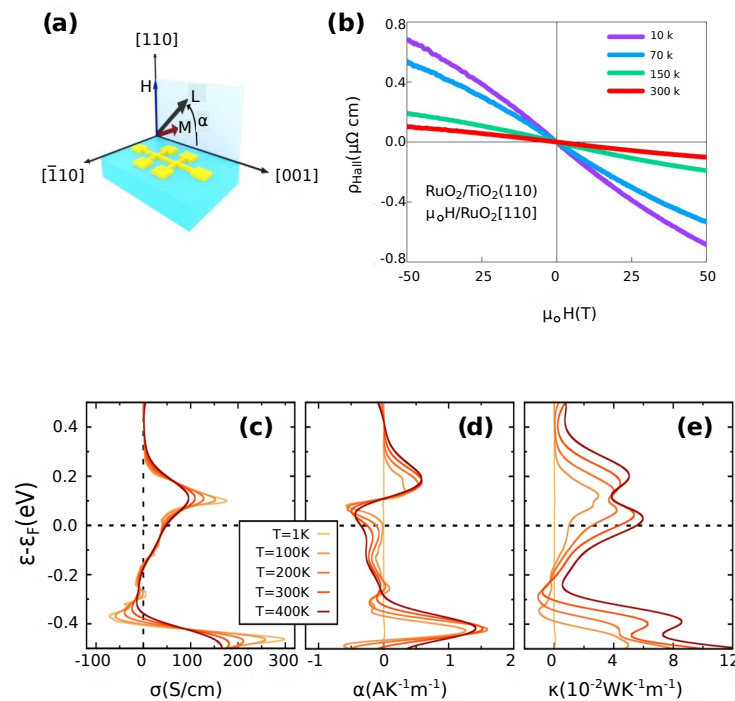


Figure 7. Magneto transport measurements. (a) Orientation of the sample along the [110] direction. The red, brown, and black arrows represent the magnetization, Néel vector, and applied field, respectively. (b) Experimental measurement of Hall resistivity with the sample oriented along the [110] direction, respectively. (a,b) are reproduced with permission [198]. Copyright 2022, Springer Nature. (c–e) First-principles simulations of anomalous Hall conductivity σ , anomalous Nernst conductivity α , and anomalous thermal Hall conductivity κ in a [110]-oriented RuO₂ film at different temperatures. (c–e) are reproduced with permission [208]. Copyright 2024 APS.

The Nernst effect, analogous to the AHE, is a fundamental phenomenon in which a longitudinal temperature gradient in a material gives rise to a transverse voltage, without the application of an external magnetic field. Similar to the AHE, in conventional collinear antiferromagnets, the anomalous Nernst effect (ANE) and the anomalous thermal Hall effect (ATHE) are expected to vanish. However, theoretical work conducted by Zhou et al. [208] revealed that significant thermal transport effects exist in RuO₂ (magnetotransport mea-

measurements are shown in Figure 7), specifically known as the crystal Nernst effect (CNE) and the crystal thermal Hall effect (CTHE). These effects resemble the ANE and ATHE but are unique to the crystal structure of RuO₂. The study suggests that the sporadic thermal and electrical transport coefficients in RuO₂ adhere to an extended Wiedemann–Franz law in a wide temperature range of (0–150 K) [208], a range much wider than what is typically expected for traditional magnetic materials.

The detection of the AHE and CTHE in antiferromagnets, and consequently in AM, offers new possibilities for designing spintronic and spin caloritronics devices that leverage these materials' robustness and unique properties. Potential applications include high-speed, low-power, and low-dissipative electrical devices as well as innovative quantum computer elements [1–3,210].

5.2. Spintronics

A memory device must efficiently read, write, and store data, with magnetoresistance playing a crucial role in ensuring reliable reading. Achieving high magnetoresistance is essential for improving magnetoresistive random access memory (MRAM) reliability, and writing methods typically involve magnetic field-assisted switching or spin-transfer torque (STT)-based writing. Data retention in MRAM is maintained through magnetic anisotropy in the storage layer. Magnetoresistance was first observed in 1856 [211], and its significant enhancement emerged with the introduction of a sandwich structure comprising a free layer, a fixed layer, and a thin non-magnetic spacer. This structure led to the discovery of giant magnetoresistance (GMR) [212,213], where resistance is high when ferromagnetic layers are antiparallel and low when they are parallel, resulting from spin-dependent scattering. A related effect, tunneling magnetoresistance (TMR), was identified in magnetic tunnel junctions (MTJs) at room temperature [214,215]. Unlike GMR, TMR arises from spin-dependent tunneling rather than scattering.

Early MRAM designs relied on magnetic field-induced switching, but this method faced scalability issues since the switching field is inversely proportional to the storage element's size. This limitation was addressed by introducing STT, which enabled field-free switching and improved scalability [216,217]. In STT, as electrons pass through the fixed layer, minority electrons scatter while majority electrons continue to the free layer, creating polarization. These polarized electrons exert a spin torque on the free layer's magnetization, thereby changing the orientation of the magnetization. Enhancing STT efficiency can be achieved by increasing the spin polarization of materials. Despite its advantages, such as fast switching and non-volatility, STT-MRAM faces challenges like high energy consumption and potential reliability issues. To mitigate these concerns, spin-orbit torque MRAM (SOT-MRAM) was introduced, which separates the read and write paths, significantly improving read reliability and reducing power consumption [218]. However, SOT-MRAM faces material compatibility and fabrication issues [219]. Also, SOT-MRAM relies on relativistic effects, which are spin non-conserving and weaker compared to exchange coupling [37]. In ferromagnets, spin-polarized currents allow spin-dependent effects like STT and GMR/TMR, with resistive changes up to 100% in commercial devices [220–222]. Antiferromagnets, due to their T-invariant spin-degenerate structure, rely on weaker relativistic effects like spin-orbit torque [3,223–226]. Moreover, the 180° SOT-assisted switching of the Néel vector (i.e., switching from a high-resistance state to a low-resistance state and vice versa) in the spin split antiferromagnets is now within our reach [129,137]. With the observation of spin and valley polarization in unconventional AFM materials, significant interest has grown in the AFM spintronics [44]. Ultimately, this has led to interest in a new class of materials, AMs, which exhibit a completely different symmetry compared to conventional antiferromagnets [4,5].

AMs exhibit strong nonrelativistic T-symmetry breaking and spin splitting despite zero net magnetization. Their spin-dependent anisotropic conductivity enables out-of-plane spin-polarized currents, leading to a GMR effect in altermagnetic multilayers, theoretically reaching $\sim 100\%$ GMR [44]. Additionally, they act as efficient spin splitters, achieving a high charge–spin conversion ratio, surpassing known relativistic spin Hall materials [37,149,227]. This efficiency supports a proposed spin-splitter torque (SST) [37], free from relativistic limitations, with experimental backing [38,40,41]. Altermagnetic tunnel junctions exhibit a TMR effect, with giant TMR predicted with an altermagnetic electrode [36,45,46,49,228–230] shown in Figure 8. Unlike ferromagnets, AMs eliminate stray fields, reducing magnetic cross-talk and enabling simpler device architectures [220,231]. Their high-frequency (THz-range) spin dynamics facilitate ultrafast, low-energy switching, approaching the Landauer energy limit, allowing for denser integration and better data security [12,232–237].

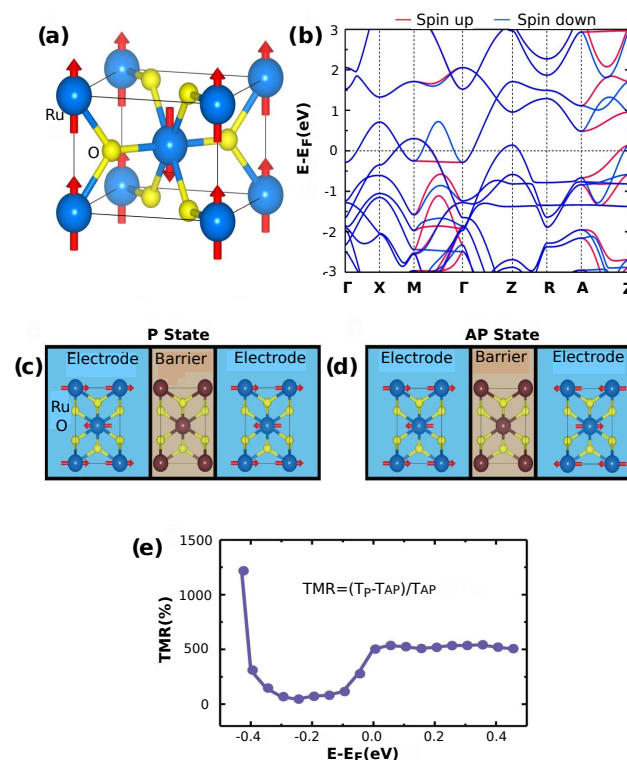


Figure 8. (a) Tetragonal rutile structure of altermagnetic RuO₂. (b) Band structure of altermagnetic RuO₂ with first principles calculation. (c,d) Magnetic tunnel junctions with altermagnetic electrodes. (c) Low resistance parallel (P) state. (d) Anti-parallel (AP) high resistance state. (e) TMR reaching $\sim 500\%$ around the Fermi level. This figure is reproduced from Ref. [36] under CC-BY 4.0 International License. Published by Springer Nature, copyright 2024.

6. Conclusions

To summarize, altermagnets are an appealing, novel, and distinct class of magnetic materials possessing zero net magnetization and strong time-reversal symmetry-breaking responses. They expand the traditional understanding of magnetism, which was previously limited to ferromagnetism and antiferromagnetism. The theoretical framework based on symmetry principles to classify and describe altermagnetism offers a clear distinction between ferromagnetic, antiferromagnetic phases.

Candidate altermagnetic materials range from insulators to superconductors, as initially predicted by Smejkal et al. [4] and were followed by several subsequent studies (see, e.g., Refs. [23,25,85,119,153]). Such predictions associated with state-of-the-art experiments are essential for guiding future research activities and exploring the technological

application of altermagnetic materials in information technology by harnessing emerging spintronics phenomena, ultrafast photomagnetism, and thermoelectrics [36,71,238]. There is a need for more experimental investigations to identify altermagnetic materials. Various stacking and twisting of van der Waals systems can be experimentally achieved [239–245]. Techniques such as nano/micro ARPES enable the direct probing of the electronic properties of twisted van der Waals layers [91,246,247], while the magneto-optic Kerr effect (MOKE) provides a reliable method for detecting time-reversal symmetry breaking [248–250]. The special properties of altermagnetism, including strong NRSS and high magnetic ordering temperatures, make them promising candidates for next-generation devices. AMs can operate in the THz range and exhibit nondegenerate magnonic chirality without external fields [131], offering potential for the development of energy-efficient magnon spintronics devices [251]. Despite growing interest in their potential applications, further research is essential to bridge the gap between theoretical predictions and practical implementation.

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