https://doi.org/10.1038/s41567-024-02750-3

Different facets of unconventional magnetism

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Recent advances in classifying magnets according to spin-group symmetry have expanded the possibilities of unconventional magnetism. Unconventional magnets – such as collinear spin-split antiferromagnets, also known as altermagnets, noncollinear spin-split antiferromagnets and anomalous-Hall antiferromagnets – combine the advantages of ferromagnetism and antiferromagnetism.

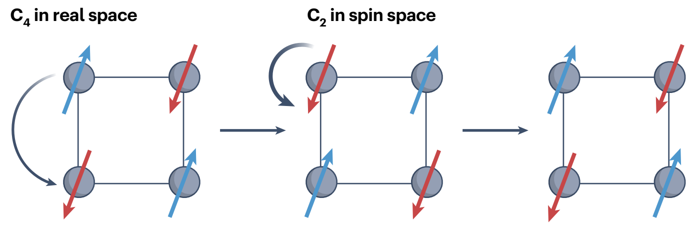

Fig. 1 | A spin group symmetry of an antiferromagnetic lattice. It combines a real-space four-fold rotation C_4 and a spin-space two-fold rotation C_2. In contrast to the framework of magnetic groups where a lattice rotation is accompanied by the same spin rotation, such a spin-group symmetry operation involves separated lattice and spin rotations.

Magnetism is an old field in physics, yet it remains dynamic. Beyond its fundamental importance, it underpins a wide range of industrial applications. Historically, ferromagnets have dominated magnetic applications thanks to their non-zero magnetization, allowing an order parameter to couple with external magnetic fields. However, antiferromagnets (AFMs) also present a vast, rich and diverse landscape. Introduced by Louis Néel, antiferromagnetism describes a magnetic order characterized by symmetry-governed net-zero magnetization. In this arrangement, the magnetic moments of atoms align in a regular pattern with orientations on different symmetry-related sublattices. Early work focused on AFMs with collinear magnetic order, in which sublattices are related by a global lattice translation. In his Nobel lecture, Louis Néel noted that while AFMs were extremely interesting from a theoretical standpoint, they did not seem to have any practical applications[1]. These collinear AFMs (now referred to as conventional AFMs), were once viewed primarily as objects of theoretical interest.

With the advance of antiferromagnetic spintronics, magnetic materials with diverse magnetic structures have garnered widespread attention. Of particular interest are unconventional magnets, which exhibit antiferromagnetic configurations while displaying properties reminiscent of ferromagnets. Thus, unlike conventional AFMs, these materials promise to combine the advantages of both ferromagnets and AFMs, offering high storage capacity, high packing densities, low power consumption, electrical manipulation and read-out, tamper-resistance, high-frequency operation and ultrafast dynamics. These attributes hold immense potential for the development of advanced spintronic devices. Here we introduce some basic properties of different kinds of unconventional magnetism, clarify some key aspects, and discuss diverse functionalities.

Spin-split AFM and anomalous-Hall AFM

One prominent example of an unconventional magnet is an altermagnet[2] – a collinear AFM that exhibits a spin-splitting of the electronic structure, similar to ferromagnets. In these materials, the spin degeneracy – the energy degeneracy of electronic states with opposite spins at a given crystal momentum **k** seen in a conventional AFM – is lifted in momentum space. This spin-splitting originates entirely from the collinear magnetic order and the crystal structure, in particular the positions of non-magnetic atoms, and is independent of spin–orbit coupling (SOC). The collinear nature of altermagnets implies that the spin, or the spin angular momentum S_z, remains a good quantum number in the absence of SOC.

Consequently, the spin–momentum locking, represented by the spin texture in momentum space $\mathbf{S}(\mathbf{k})$, features a common k-independent quantization axis across the Brillouin zone and is one-dimensional. In contrast, noncollinear spin-split AFMs, in which the magnetic moments of atoms on different sublattices are oriented in various symmetry-related directions, can exhibit two- or three-dimensional spin textures in momentum space even without SOC. Overall, the spin-splitting electronic structure facilitates various applications in spintronics, including spin-polarized currents, spin-to-charge conversion, spin torques, magnetoresistance, magnonics and twist engineering of two-dimensional magnetism.

Another fascinating category of unconventional magnetism is often closely intertwined with spin-split antiferromagnetism, especially after the recent advent of altermagnetism. Termed anomalous-Hall antiferromagnetism, it combines AFM with the anomalous-Hall effect (AHE), traditionally considered an exclusive signature of ferromagnets[3]. This property is crucial in spintronics, enabling the read-out of the magnetic states from electrical transport properties. Typically, AHE arises from non-zero magnetization. However, for specific conditions of SOC, certain collinear and coplanar antiferromagnetic configurations exhibit an intrinsic AHE induced by Berry curvature. Such anomalous-Hall AFMs often develop a small ferromagnetic canting caused by the SOC-induced Dzyaloshinskii–Moriya interaction, a phenomenon known as weak ferromagnetism. Additionally, anomalous-Hall AFMs also feature other time-reversal-odd responses, such as orbital magnetization, the anomalous Nernst effect and the magneto-optical Kerr effect.

Symmetry principles of unconventional magnetism

The rapid evolution of unconventional magnetism has inevitably engendered some degree of conceptual ambiguity, misinterpretation and uncertainty, particularly regarding the interplay between spin-split

Unconventional magnetism

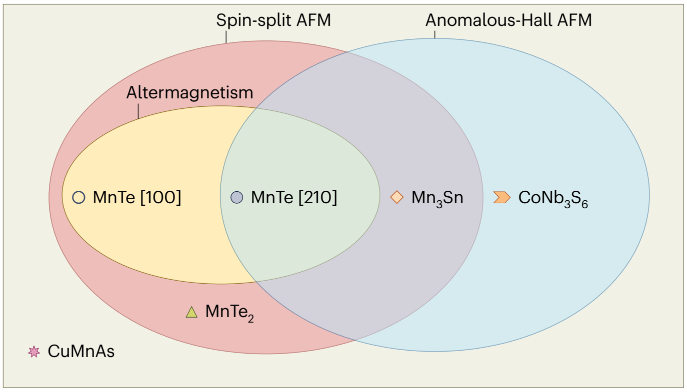

Fig. 2 | Different facets of unconventional magnetism. Spin-split antiferromagnetism is highlighted in pink; anomalous-Hall antiferromagnetism is highlighted in blue; and altermagnetism is highlighted in yellow. Some representative materials are also listed.

AFMs and anomalous-Hall AFMs. Spin-split AFMs and anomalous-Hall AFMs are distinct types of unconventional magnet, although they both manifest 'ferromagnet-like' effects. However, the recent literature often struggles to properly differentiate between the two, and their properties are increasingly intermixed. For example, it is a common misconception to assume that one type of unconventional magnet, such as spin-split AFM, inherently represents other ferromagnet-like effects, such as AHE, or vice versa. Both types of unconventional magnetism can be fully described through symmetry analysis within an appropriate crystallographic group framework without relying on first-principles calculations or experimental characterization.

The primary distinction between these two classes lies in their physical properties. Spin-split antiferromagnetism involves a momentum-dependent spin splitting without SOC, whereas anomalous-Hall antiferromagnetism usually relies on SOC-induced effects. Consequently, their symmetry requirements differ, and the group-theoretical frameworks used to discuss their symmetry properties are distinct. This difference also results in separate pools of material suitable for each type of unconventional magnetism and their respective spintronics applications.

In a spin-split AFM, the absence of SOC means that the symmetry operations of spin and lattice degrees of freedom are only loosely coupled. Unlike the standard framework of the magnetic group, the complete symmetry description of magnetic Hamiltonians with negligible SOC is based on an extended crystallographic group known as the spin group, which separately includes spin and spatial operations[4,5]. For example, in the simple antiferromagnetic order shown in Fig. 1, a spatial four-fold operation followed by a two-fold spin rotation constitutes a spin-group symmetry. For collinear spin-split AFMs, also known as altermagnets, the sublattice-transposing symmetry connecting sublattices with opposite magnetic moments must be neither inversion nor translation. For noncollinear spin-split AFMs, additional symmetry requirements in spin space are necessary to protect the spin degeneracy throughout the Brillouin zone.

In AFMs displaying the SOC-induced AHE, the SOC locks the lattice and spin rotations in a magnetic material, resulting in the application of the magnetic group framework. Of the 122 magnetic groups, 31 correspond to the ferromagnetic point group, which allow AHE, display the magneto-optical Kerr effect and have a net magnetization along a specific direction. Examples include collinear MnTe, which has the Néel order along the [210] direction[5], and noncollinear AFM Mn_3Sn (ref. 6). Following Gell-Mann's totalitarian principle that "anything not forbidden is compulsory", such materials must inevitably exhibit SOC-induced weak ferromagnetism composed of both orbital magnetization and spin magnetization. Conversely, AHE and magneto-optical effects occurring without the assistance of SOC require a noncoplanar magnetic configuration. The spin-space operations of such a configuration break certain symmetries in real space, enabling orbital magnetization. Recent examples include the [111]-strained cubic antiferromagnet γ-FeMn(ref. 7) and the hexagonal-lattice antiferromagnet $CoNb_3S_6$ (ref. 8) with triple-*q* configurations.

Figure 2 illustrates the material pool for spin-split AFMs and its collinear subset, – the altermagnets – highlighting representative materials. It is evident that in general spin-split AFMs and anomalous-Hall AFMs constitute two independent material sets, albeit with some overlapping regions. For instance, the spin-split AFM $MnTe_2$ (which is not an altermagnet owing to its noncoplanar configuration) does not exhibit an AHE[9], whereas neither the anomalous-Hall AFM γ-FeMn (with strain) nor $CoNb_3S_6$ exhibit any spin splitting. In three-dimensional bulk collinear magnets, anomalous-Hall antiferromagnetism forms a subset of spin-split antiferromagnetism thanks to the one-to-one correspondence between the magnetic group and the collinear spin group. For example, the hexagonal altermagnet MnTe allows the AHE when the orientation of its Néel vector is along the [210] direction, but forbids the AHE in the [100] direction. However, two-dimensional collinear AFMs in which the sublattice-transposing symmetry is a mirror reflection along the out-of-plane direction (M_z) manifest spin degeneracy throughout the Brillouin zone. Notably, such AFMs with in-plane magnetic moments do not forbid the AHE.

Discussion and outlook

Thus far, we have discussed two fundamentally distinct types of AFM, each representing a unique facet of unconventional magnetism, though some material candidates overlap (Fig. 2). Neither facet is fundamentally new. For instance, various spin textures can emerge from Fermi surface instabilities in strongly correlated, nonrelativistic systems[10], or from the SOC-induced Rashba and Dresselhaus effects in nonmagnetic solids with structure inversion asymmetry. However, the microscopic origin of spin-split antiferromagnetism, including altermagnetism, lies in a distinct type of spin-momentum locking. In SOC-induced spin splitting, the spin orientation locks with the wavevector; for example, the spin orientation is perpendicular to the wavevector in ideal Rashba spin textures. In contrast, the spin orientation of the itinerant electrons in a spin-split AFM depends on the orientation of the local magnetic moments relative to the crystal lattice. The two- and three-dimensional spin textures in momentum space introduced by noncollinear magnetic order remain largely unexplored. With the recent progress on theories of spin-space groups[11–13], it will be interesting to see how the topology of the electronic structure, of the spin texture, and the magnetization in order-parameter space work together to give rise to new properties.

Unconventional magnetism depends on specific target properties or applications and their associated symmetry requirements. For example, the first experimental realization that a digital bit can be electrically written and read through the manipulation and detection of the Néel order occurred in CuMnAs (ref. 14). This material is an AFM that does not exhibit either spin splitting or the AHE owing to the presence of parity-time inversion symmetry. However, this useful property arises from local spin polarization caused by breaking local inversion symmetry[15], which requires more delicate symmetry analysis.

In summary, the rapid growth of the field of unconventional magnetism underscores its fundamental importance and potential for applications, going beyond the conventional antiferromagnetism of Néel by combining both AFM configuration and ferromagnet-like characteristics. In this context, we highlight the role of symmetry-based classification, which offers a clear distinction between different facets of unconventional magnetism. Although we have discussed only two unconventional magnets here, we encourage the community to explore other classes of unconventional magnet based on different symmetry-related properties, such as quantum geometry, multiferroicity and topological magnons. We expect that the exploration of unconventional magnetism continues to push the boundaries of our understanding and application of magnetic materials.

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Published online: 30 January 2025

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Acknowledgements

We thank Y. Liu, X. Chen and C. Liu for discussions.

Competing interests

The authors declare no competing interests.