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Altermagnetism: Concept, materials landscape, and future prospects

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CONCEPTUAL FOUNDATIONS

Altermagnetism refers to an unconventional collinear antiferromagnetic phase in which crystalline symmetry enforces momentum-dependent spin splitting despite the absence of net magnetization. The concept was theoretically consolidated by Šmejkal et al.,[1] who demonstrated that such spin splitting is a symmetry-allowed and potentially widespread phenomenon rather than an exotic anomaly. In these systems, opposite spin polarizations are tied to different momenta through specific symmetry operations—typically nonsymmorphic or rotational elements—rather than through spin–orbit coupling. From a group-theoretical perspective, altermagnetism can be regarded as a subset of collinear antiferromagnetic order in which the combined time-reversal and lattice-translation symmetry is broken, yielding characteristic *d*-wave- or *g*-wave-like spin polarization in the Brillouin zone. This viewpoint emphasizes the physical origin of symmetry-enforced spin splitting and avoids unnecessary taxonomic debates over whether altermagnets represent a new magnetic class, as shown in Figure 1A.

The essential distinction lies in their electronic signatures: momentum-selective spin polarization and zero net magnetization. These features set altermagnets apart from both conventional spin-degenerate antiferromagnets and spin–orbit–driven Rashba or Weyl systems. The coexistence of spin-polarized states with compensated magnetization enables spin transport without stray fields, offering functionality naturally compatible with dense device integration. These discoveries have reshaped theoretical frameworks and inspired material searches aimed at exploiting such unconventional spin textures.

MATERIALS LANDSCAPE: VERIFIED SYSTEMS AND CONTROVERSIES

The material basis of altermagnetism, though still limited, has grown rapidly. Early predictions identified several oxides and pnictides as promising candidates. As shown in Figure 1B, MnTe became the first archetypal system in which direct spin splitting was experimentally resolved. Using spin- and angle-resolved photoemission spectroscopy (ARPES), Krempaský et al. demonstrated the lifting of Kramers degeneracy in MnTe,[2] confirming the symmetry-driven band splitting anticipated by theory. Shortly thereafter, Reimers et al. reported altermagnetic band structures in high-quality epitaxial CrSb films,[3] establishing another benchmark.

KV_2Se_2O has recently attracted particular attention. It exhibits *d*-wave altermagnetism that persists up to room temperature, and its relatively high carrier density makes the spin-split states highly responsive to external electric fields.[4] Its van der Waals–bonded layered structure further enhances its usefulness for device integration, enabling fabrication of thin films, heterostructures, and gate-tunable devices. KV_2Se_2O also resonates with the physics of La_2CuO_4 and other correlated layered oxides: all host transition-metal–oxygen planes in which electronic correlations and unconventional orders emerge. If cuprates can indeed harbor altermagnetic states, the interplay between altermagnetism, correlation effects, and superconductivity would open a particularly intriguing frontier.

At the same time, controversies remain. RuO_2, predicted to host robust

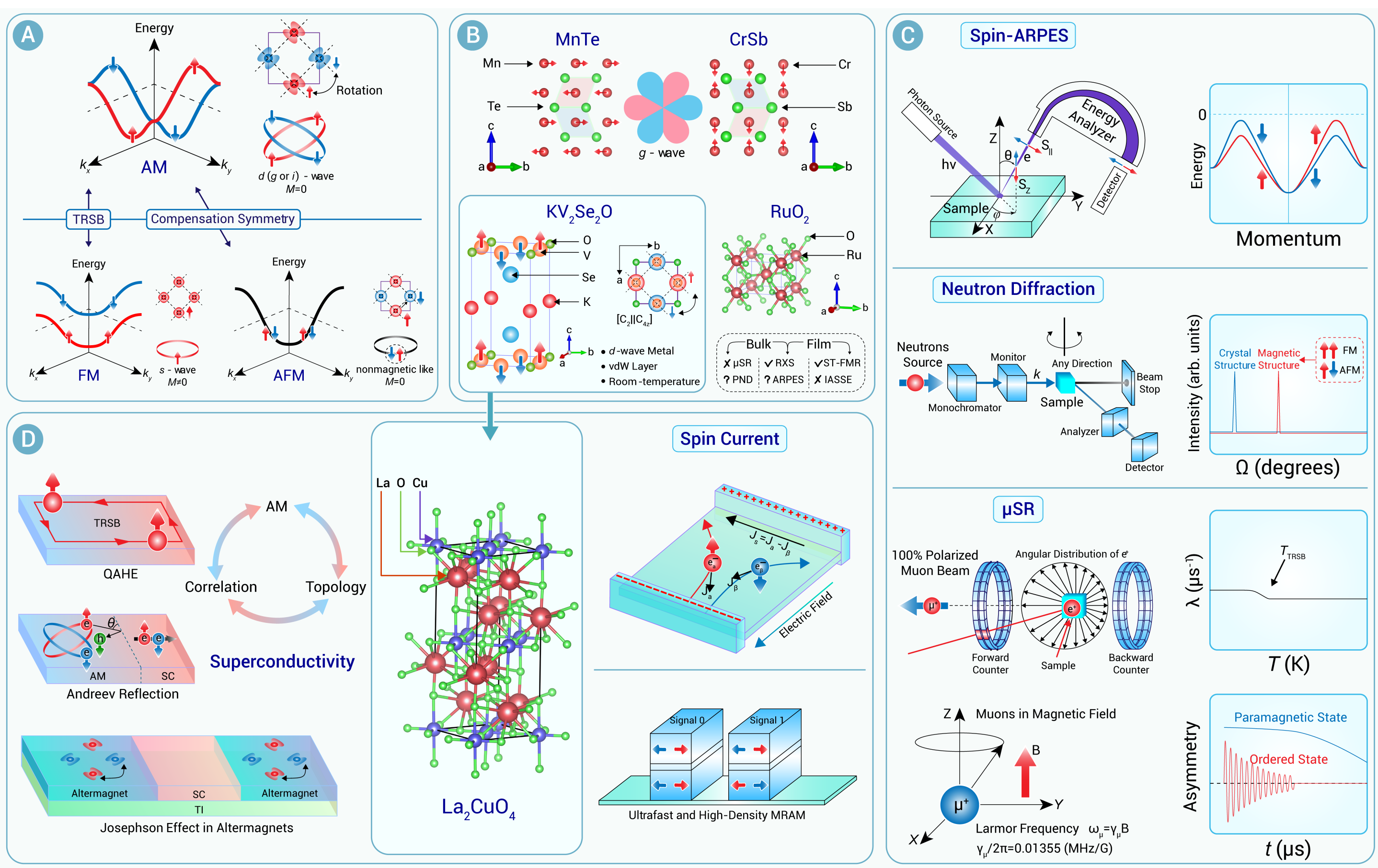

Figure 1. Schematic overview of altermagnetism (A) Illustrating the conceptual foundations, (B) representative materials, (C) key experimental techniques mainly relying on large-scale research facilities, and (D) emerging quantum phenomena and potential applications.

altermagnetic states,[5] has produced conflicting experimental observations. Some studies report signatures consistent with symmetry-enforced spin splitting, while others attribute the apparent effects to disorder, surface reconstructions, or probe limitations. The debate highlights the difficulty of detecting altermagnetism, which lacks macroscopic signatures and requires careful disentanglement of intrinsic features from extrinsic artifacts.

Looking forward, systematic exploration of transition-metal oxides, pnictides, and layered chalcogenides—combined with high-throughput symmetry-guided screening—may reveal additional candidates. Yet reproducibility challenges arising from twinning, disorder, and interface effects remain substantial. Building a reliable materials database is essential both for fundamental understanding and for ultimately identifying technologically relevant systems.

EXPERIMENTAL TECHNIQUES: RECENT ADVANCES AND BEST PRACTICES

Despite rapid theoretical progress, experimental verification of altermagnetism remains challenging, because key signatures fall into two distinct categories: (i) momentum-dependent spin splitting, and (ii) the underlying collinear antiferromagnetic order. Additional probes sensitive to time-reversal symmetry breaking (TRSB) or internal magnetic fields provide important complementary information. No single technique can establish all aspects of altermagnetism, and each method faces intrinsic limitations. Real materials further complicate interpretation through domains, disorder, strain, and surface reconstructions that obscure symmetry-enforced features.

Spin-resolved ARPES provides the most direct access to momentum-dependent spin textures, as shown in Figure 1C. However, its limited count rates and energy resolution often make subtle signatures difficult to resolve. Conventional ARPES maps band dispersions reliably but lacks spin sensitivity; in correlated or magnetically complex systems—where theoretical predictions of band structure are uncertain—identifying altermagnetic spin splitting becomes inherently ambiguous. Transport measurements such as anomalous Hall, spin Hall, or nonlinear responses may offer indirect signatures of spin-polarized currents, but these signals can also arise from disorder, Berry curvature dipoles, or extrinsic mechanisms unrelated to altermagnetism and therefore require careful interpretation.

Determining the magnetic ground state presents a separate challenge. Neutron diffraction remains the benchmark for identifying long-range antiferromagnetic order, yet both polarized and unpolarized neutron experiments require large, high-quality crystals and elements with sufficiently strong scattering cross-sections—constraints that render the technique unsuitable for thin films or nanoscale samples. Element-specific probes such as resonant elastic X-ray scattering and X-ray magnetic circular dichroism (XMCD) help identify sublattice magnetization patterns, though they lack momentum resolution and cannot directly detect spin-split bands. Muon spin rotation/relaxation (μSR) provides exceptional sensitivity to very weak internal magnetic fields and is particularly powerful for identifying TRSB. The appearance of spontaneous fields or enhanced relaxation below the ordering temperature offers evidence of TRSB even in magnetically compensated systems. However, μSR relies on accelerator-based muon sources available only at a few global facilities, making beam time extremely limited. Its interpretation also depends on reconstructing local field distributions rather than resolving momentum-space spin textures directly.

The ongoing debate over RuO_2 illustrates these difficulties: modest differences in growth conditions, crystal orientation, or probe sensitivity can lead to divergent conclusions. Progress therefore depends on methodological rigor, reproducibility across laboratories, and strategic combinations of complementary techniques to ensure that conclusions about altermagnetic order are robust.

POTENTIAL APPLICATIONS

The distinctive characteristics of altermagnets have stimulated broad interest in their potential technological impact. Absence of stray fields allows dense integration without magnetic cross-talk, while the presence of momentum-dependent spin polarization enables efficient coupling to spin currents in semiconductors or two-dimensional materials. These properties suggest conceptual advantages over both ferromagnets and conventional collinear antiferromagnets.

Many proposed applications remain theoretical but promising, as shown in Figure 1D. In spintronics, altermagnets could serve as efficient spin filters, functional layers in magnetic tunnel junctions (MTJ), and magnetic random access memory (MRAM). Their alternating spin texture could also be engineered to interface with materials exhibiting spin–momentum locking, such as topological insulators. Because symmetry-enforced spin splitting is present even without macroscopic magnetization, thermal spin conversion may occur with reduced dissipation, offering opportunities for energy-efficient spin caloritronics.

A particularly intriguing possibility is coupling altermagnetism with superconductivity. Since altermagnets generate spin splitting without spin–orbit coupling, they may support unconventional pairing states or modulated superconducting phases. Similarities between KV_2Se_2O and layered cuprates further motivate exploration of correlated systems in which altermagnetism and superconductivity coexist.

However, practical constraints are significant. Only *d*-wave altermagnets can generate a net spin-polarized current suitable for transport-based devices; higher-order representations (such as *g*-wave) cancel upon momentum averaging. Furthermore, MTJ and MRAM applications require high-temperature metallic magnets capable of delivering out-of-plane spin-polarized currents. To date, only RuO_2 and KV_2Se_2O have been proposed as high-temperature metallic altermagnets; however, the altermagnetic nature of RuO_2 remains under debate, and KV_2Se_2O is a two-dimensional material that poses significant challenges for integration into conventional out-of-plane device architectures. The predicted pool of such materials is extremely limited, representing a key bottleneck for realistic applications.

OUTLOOK AND MAJOR CHALLENGES

Yet major challenges remain. Identifying room-temperature, metallic, and easily synthesized altermagnets is an urgent priority. Experimental verification requires stringent reproducibility across laboratories and complementary use of multiple probes to disentangle intrinsic properties from extrinsic artifacts. Advances in spin-resolved detection, synchrotron instrumentation, and nanoscale magnetic imaging will be essential.

The integration of altermagnetism with other quantum phases provides exciting long-term opportunities. Coupling with superconductivity may stabilize unconventional pairing symmetries, while interfacing with topological materials could yield hybrid states uniting spin control with topological protection. These possibilities highlight the importance of sustained collaboration between theory and experiment.

Ultimately, the promise of altermagnetism lies not only in novelty but in its potential to redefine spin-based functionalities. Translating conceptual opportunities into devices requires reproducible materials, scalable growth, and reliable interfaces. Only through coordinated advances in synthesis, characterization, and engineering can altermagnets move from laboratory curiosities to technological building blocks. The challenges are substantial, but the potential rewards—in both fundamental physics and applied spintronics—are equally significant.

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DECLARATION OF INTERESTS

The authors declare no competing interests.