

Magnetic skyrmions: A new frontier for quantum computing

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Nanoscale, topologically protected whirlpools of spins have the potential to move from applications in spintronics into quantum science.

Chirality, a geometric property that distinguishes an object from its mirror image, is a foundational concept in physics. It appears in the asymmetry of a hand, in the spiral of DNA, in the helicity of neutrinos in the standard model of particle physics, and even in the structure of galaxies. Chirality also organizes fields, such as circularly polarized light, and excitations in matter, such as graphene's low-energy electronic quasiparticles, effectively massless fermions whose handedness is tied to the direction of motion. In each case, chirality is more than just a visual feature; it affects how particles interact, limits their behavior, and produces measurable effects.

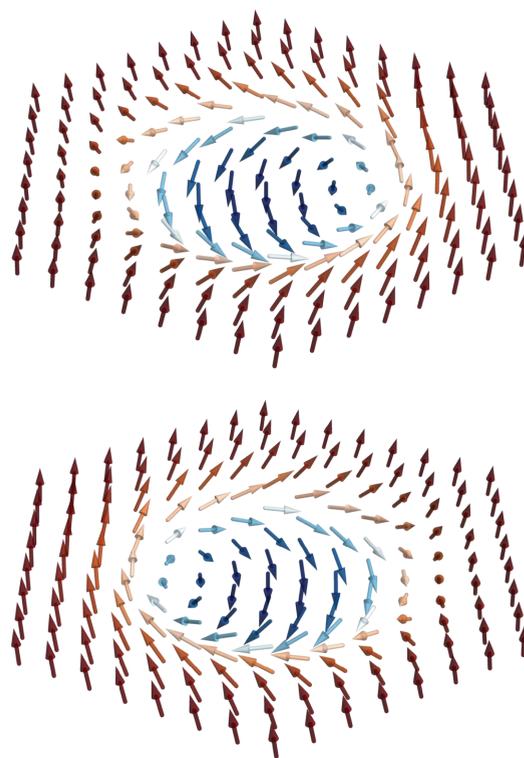
In condensed-matter physics, chirality is also manifested in magnetic skyrmions, illustrated in figure 1, which are nanoscale spin textures characterized by smooth spatial winding and topology that protects them against small perturbations. (See the 2020 *PT* article “The emergence of magnetic skyrmions,” by Alexei Bogdanov and Christos Panagopoulos.) First proposed in particle physics and later identified in magnetic systems, skyrmions bridge abstract mathematics and real materials. Recognized for their robustness, small size, and efficient response to tiny currents, magnetic skyrmions have been explored in the past decade for ultradense memory, reconfigurable logic, and neuromorphic devices in the field of spintronics.

Chirality can also act as a quantum variable. Circularly polarized photons already serve as qubits in optical platforms.¹ Nanophotonic waveguides—tiny structures that guide light on a chip—enable directional emission and spin–photon conversion. Chiral electronic channels, such as quantum Hall edge states, enable one-way signal routing and support devices like microwave circulators in superconducting circuits. Magnetic skyrmions offer a geometric path to similar functionality. Their internal twist, known as helicity, indicates the handedness of the spin rotation. In suitable materials, that degree of freedom can be promoted from a continuous angle to a quantized two-state system. Helicity itself becomes the information carrier, which opens a route toward scalable quantum architectures rooted in magnetism and topology.

Topological textures in magnetism

Magnetic skyrmions are nanoscale whirlpools of spins whose orientation winds smoothly from core to edge. At the core, the spins point opposite the ambient magnetization. As you move outward from the center, the magnetization rotates within the 2D plane of the skyrmion until it aligns with the ambient magnetization at the perimeter, as shown in figure 1.

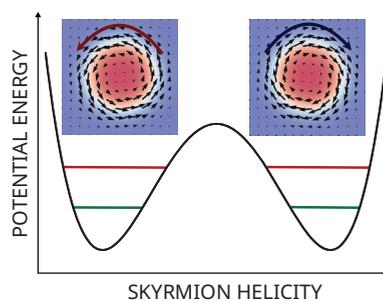
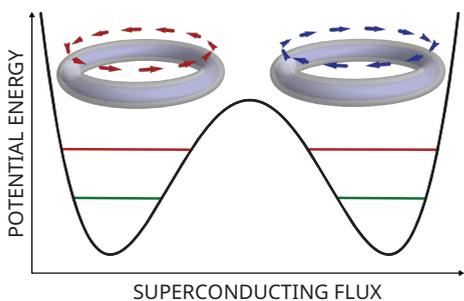
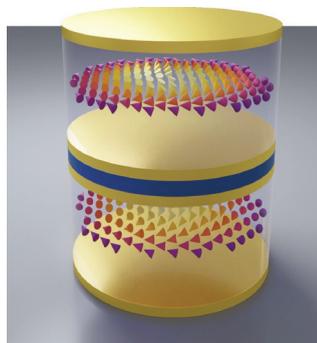
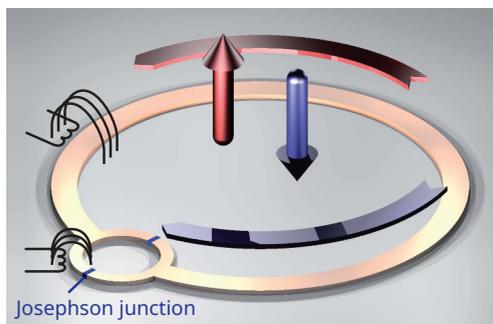
That winding is captured quantitatively by the skyrmion number, a topologically invariant integer



▲ Figure 1. Magnetic skyrmions. These nanoscale whirls of spins are characterized by central spins that point opposite the surrounding magnetization. Colors indicate the local spin direction, which rotates within the plane as an observer moves outward from the center. The skyrmions shown have a skyrmion number of 1, corresponding to a single robust topological twist. Skyrmions are chiral, meaning that they are not identical to their mirror images.

that counts how the spin directions evolve across the texture. In a skyrmion, the spins point in all possible directions as an observer moves from the center to the edge; the full range of orientations is covered once. That topological characteristic endows skyrmions with an unusual kind of robustness against defects and disturbances: A skyrmion texture may be perturbed, stretched, or translated, but it cannot be unwound without introducing a discontinuity, and that makes skyrmions exceptionally stable.

The stabilization of skyrmions in materials depends on competing magnetic interactions and material symmetry.² In systems that lack inversion symmetry, such as certain chiral magnets, spin–orbit coupling gives rise to the interactions that favor chiral spin arrangements and can stabilize skyrmions that have a fixed helicity. Skyrmions were first observed in those systems, in materials such as MnSi and FeGe. They appear in a narrow temperature and magnetic field range near the magnetic-ordering transition—the point at which a material's spins collectively settle into an ordered state.



◀ **Figure 2.** Chiral qubits. In a superconducting loop (**top left**) interrupted by Josephson junctions, clockwise and counterclockwise circulating currents form the two states of a flux qubit. In magnetic skyrmions (**top right**), helicity can be promoted from a continuous variable to a quantized two-state system that can be used as a qubit. In both cases, the double-well potential illustrates how chirality provides a natural two-level structure for quantum information. Green and red lines mark the lowest and first-excited quantized energy levels, respectively, and they are split by quantum tunneling between the two wells. (Figure adapted from refs. 6 and 12.)

More recently, skyrmions have also been realized in a novel category of centrosymmetric frustrated magnets, which includes materials such as Gd_2PdSi_3 and $\text{Gd}_3\text{Ru}_4\text{Al}_{12}$. In those materials, competing quantum mechanical exchange interactions and spin–spin couplings that favor incompatible spin alignments create conditions in which skyrmion helicity is no longer fixed but instead can vary continuously at low energy. That continuous variation makes it easy to manipulate dynamically using external fields.

Some of the compelling advantages of skyrmions have been demonstrated in classical information technologies.^{3,4} Their small scale, from tens of to a few hundred nanometers, suits high-density storage, and the low currents needed to move them imply energy-efficient operation. In classical spintronics, those qualities have motivated the vision of racetrack-memory devices, in which skyrmions act as mobile bits whose interactions can also implement logic operations.

A separate line of work proposes to exploit the nonlinear dynamics and multistability of skyrmions for neuromorphic (brain-inspired) and certain neural-network functionalities. Such proposals further illustrate the versatility of the textures in classical systems. This article examines a different application: skyrmions as a controllable quantum state in magnetic materials with weak energy loss, the conceptual foundation for skyrmion-based qubits.

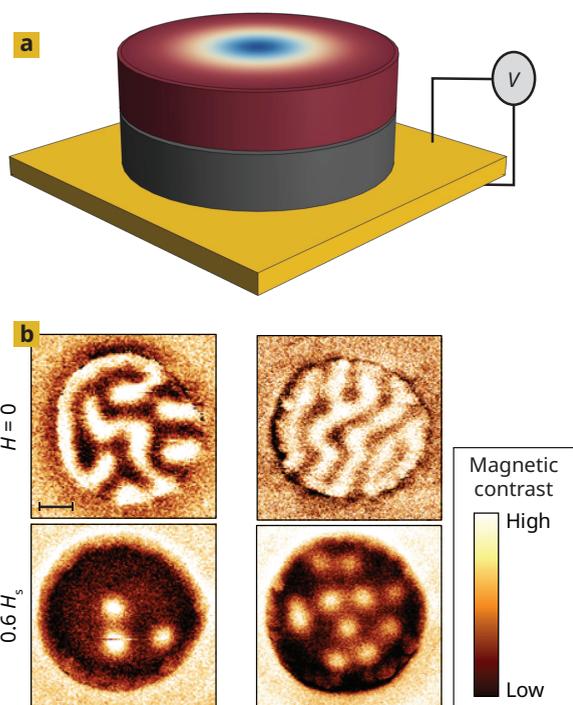
Quantizing helicity

The discovery of stable atomic-scale skyrmions at temperatures of a few kelvin has highlighted the limits of classical micromagnetism. Quantum signatures

appear in the spectra of magnons (quantized spin-wave excitations), in texture dynamics, and in phase transitions, and theory shows that even skyrmions comprising thousands of spins can display such behavior, which blurs the line between classical and quantum particles. Together with advances in quantum-sensitive magnetometry and materials with low ohmic dissipation, those developments have given rise to a research direction focused on the quantum properties of skyrmions.⁵

At the heart of that line of investigation is the realization that internal degrees of freedom in skyrmions can be quantized and used as qubits. Among them, helicity, the sense of in-plane spin rotation along a radial path from the center of the skyrmion outward, is a promising candidate because it can support coherent and controllable two-level dynamics.⁶

Unlike the skyrmion's topological charge, which is always quantized and robust, helicity can remain continuous in systems without strong spin–orbit coupling or crystalline constraints. In such environments, often realized in centrosymmetric magnets, helicity can be dynamically excited by external fields, anisotropies, or pinning potentials and, under the right conditions, quantized. By engineering the potential-energy landscape, researchers can create a bistable system in which the skyrmion occupies one of two energetically favorable states, clockwise or counterclockwise in-plane spin swirlings, as illustrated in figure 2. Classically, those states are distinct, stable configurations. But in the quantum regime, tunneling between them gives rise to superpositions and enables qubit behavior.



▲ Figure 3. Skyrmion devices. **(a)** A conceptual sketch of a skyrmion-hosting nanodisk, consisting of a magnetic multilayer stack (cylinder) combined with a piezoelectric layer (gold) and a voltage electrode for local electrical control. **(b)** Experimental realization of confined magnetic textures in nanodots fabricated from multilayer stacks of iridium, iron, cobalt, and platinum, and imaged by magnetic force microscopy (scale bar is 100 nm). As the applied magnetic field H is increased toward the saturation field H_s , stripe domains evolve into isolated, stable skyrmions, demonstrating controlled skyrmion confinement. (Panel (b) adapted from ref. 13.)

Quantized helicity leads to discrete energy levels that naturally form a two-level system. Thus, the helicity states readily map onto the familiar language of quantum computing. Left- and right-handed helicities form the two logical states of a qubit, while their coherent superpositions mirror the quantum states used in today's qubit platforms. Like other qubits, the system can be prepared in either state or in a quantum superposition of both, and external fields can be used to drive transitions between them. (For more information about different qubit platforms, see the box on page 53.)

The parallels between superconducting flux qubits and skyrmion helicity-based qubits are depicted in figure 2. For both, chirality provides a natural double-well potential that enables two-level quantum dynamics. For helicity-based skyrmion qubits, the energy splitting is typically in the gigahertz range and is directly compatible with standard microwave technologies already employed in superconducting and spin-based qubits. At cryogenic temperatures, where thermal excitations are suppressed, the coherent dynamics of helicity qubits become experimentally viable.

Skyrmion qubits offer an operating regime that's complementary to but distinct from superconducting and semiconducting platforms. Their quantum states are encoded in collective spin textures rather than charge, so they are intrinsically less sensitive to electric field noise, charge fluctuations, and dielectric loss, which are dominant decoherence channels in charge-based architectures.

In magnetic insulators, the absence of conduction electrons removes ohmic dissipation. The remaining sources of dissipation are magnetic and phononic baths, which are typically weaker and more controllable. Although the helicity states themselves are not topologically protected, the underlying skyrmion texture is a robust, spatially extended object, which provides resilience to disorder and to local fluctuators that would strongly affect single-spin qubits.

Architecturally, skyrmions occupy 20–50 nm disks. Even with local control structures such as near-field microwave lines, nanoscale gates, or magnonic waveguides, the practical qubit spacing lies in the 10–100 nm range, which is three to four orders of magnitude denser than superconducting circuits. Perhaps most importantly, the same mechanisms that allow classical skyrmions to be moved, written, and erased via electric currents or magnetic fields can be employed in the quantum regime to manipulate and read out qubit states. Thus, skyrmions benefit from full compatibility with the mature spintronics ecosystem, including thin-film multilayers, nanodisk patterning, and on-chip microwave or gating architectures already established in magnetoresistive random-access memory (MRAM) and nanomagnonics.

Several recent works have outlined how skyrmion qubits could be created, manipulated, and even entangled in tailored thin-film or multilayer environments, but those concepts remain theoretical at present. Examples of experimental skyrmion confinement are shown in figure 3. But the quantization of the helicity mode, the appearance of discrete helicity levels, and the coherent manipulation and readout of that internal degree of freedom remain to be observed. Those key experimental milestones would elevate the skyrmion from a classical information carrier to a genuine solid-state qubit. The control, readout, and coupling approaches discussed below should be viewed as prospective pathways, grounded in known skyrmion dynamics, the mature spintronics-fabrication ecosystem, and quantum sensing tools. The vision is clear: qubits that combine stability, scalability, and seamless compatibility with spintronic technologies.

Control, readout, and decoherence

A robust qubit must support reliable initialization, coherent manipulation, accurate readout, and long co-

herence lifetimes. For helicity-based skyrmion qubits, the control of skyrmion helicity is rooted in the same physics that governs classical skyrmion manipulation.

The helicity qubit can be initialized by biasing the system into a chosen helicity state using static electric or magnetic fields, or by relying on thermal relaxation to reach the ground-state orientation. Oscillating external fields can drive transitions between helicity states and provide the basis for quantum gates. Magnetic systems also offer a diverse toolkit for fine-tuned manipulation: Electric fields can modify anisotropies through magnetoelectric coupling, strain can alter exchange interactions, and spin-transfer torques or local gating can shape the helicity potential.⁷

A skyrmion-based qubit approach is particularly appealing for quantum information applications because the relevant excitations emerge from the collective motion of many spins. In the helicity mode, the dynamics are not confined to a single spin but instead involve the coordinated motion of many spins across the entire skyrmion texture. That delocalization provides some degree of protection against local noise sources and defects, and that protection enhances coherence. At the same time, the collective nature of helicity makes it more vulnerable to global fluctuations and dissipative processes in the host lattice, both of which can drive decoherence and the loss of quantum information.

Primary decoherence channels include thermal spin-wave excitations, lattice vibrations, and material imperfections. Achieving coherence times sufficient for quantum gate operations within the microsecond regime demands high-purity materials, low-loss dielectrics, clean interfaces, and precisely engineered heterostructures. Operating at cryogenic temperatures reduces the thermal population of magnons and phonons, which helps to maintain the delicate energy splitting that defines helicity levels.

Readout at the quantum level has not been realized, but several strategies have been proposed. Magneto-optical techniques, such as Kerr or Faraday effects, may register changes in magnetization associated with distinct helicity states. Spectroscopic approaches, such as Brillouin light scattering and ferromagnetic resonance, offer the possibility of detect-

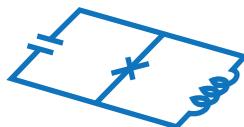
ing transitions in the gigahertz regime. Electronic detection might exploit helicity-dependent skyrmion motion driven by spin-transfer torques or other current-induced effects. That motion could produce measurable electrical signatures, for example, through spin pumping or a helicity-dependent contribution to the Hall response. Each readout scheme requires optimization for quantum sensitivity and minimal disturbance.

Coupling and scaling up

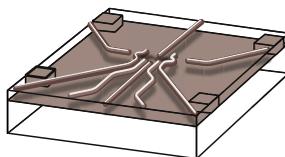
Quantum computation depends on entangling qubits, which in turn relies on coherent coupling mechanisms.

Diverse qubits serve diverse purposes

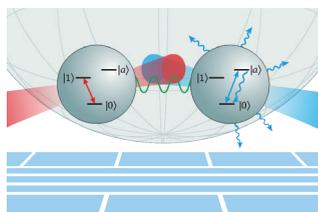
Superconducting circuits



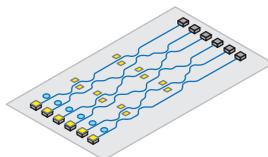
Solid-state spins



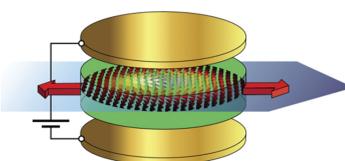
Trapped ions



Photonic circuits



Magnetic skyrmions



Researchers developing various quantum computing platforms, such as superconducting circuits and trapped ions, have made remarkable progress in recent decades. Yet each platform faces unavoidable trade-offs in performance and design flexibility. A diversity of approaches is key to overcoming trade-offs in coherence, scalability, and control. That has motivated the search for alternative realizations that can introduce new physical advantages.

Different architectures bring complementary strengths: Superconducting circuits enable fast gate operations and scalable chip integration, solid-state spins promise dense integration, trapped ions offer exceptional coherence and high-fidelity control, and photonic circuits excel at long-distance communication. In that landscape, skyrmion-based qubits stand out as candidates that could unify several transformative features such as nanoscale dimensions, compatibility with thin-film technologies, and the exceptional robustness of topologically protected spin textures. Advancing the skyrmion platform not only diversifies the quantum hardware toolkit but also opens pathways that may complement the capabilities of today's leading approaches.

(From the top down, figures are adapted from ref. 14; adapted from ref. 15; adapted from ref. 16; courtesy of Galan Moody; and adapted from ref. 17.)

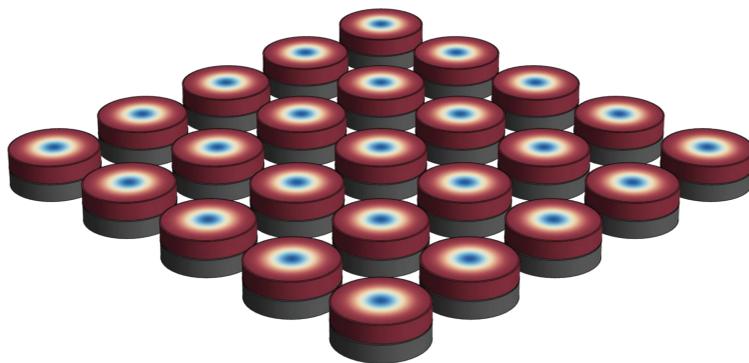
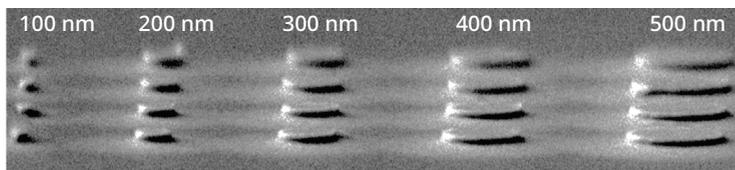


Figure 4. Scalability of skyrmion qubits. Skyrmions can be confined in lithographically defined nanodisk arrays, as shown schematically in the top panel. The nanodisk diameters are on the order of 20–50 nm. Skyrmions have been generated in arrays of layered nanodots of different sizes. One such array is shown in the lower panel. Optimized fabrication processes continue to improve the scalability of such materials. (Lower panel adapted from ref. 13.)



In multilayer magnetic films, skyrmions can couple via exchange interactions if the textures are aligned closely or via dipolar magnetic interactions when the distances are slightly larger.⁶ Inter-skyrmion coupling can be engineered to depend on helicity, because the relative position of two skyrmions sets their interaction energy. That helicity–helicity interaction can be harnessed to implement two-qubit gates, fundamental building blocks for universal quantum computation.

Engineers can tune coupling strengths through materials engineering, such as the use of magnetic multilayers with spacer layers that control direct skyrmion–skyrmion interactions. Another strategy is hybrid coupling via microwave cavities. If skyrmion-hosting films were embedded in electromagnetic resonators, qubits could interact through virtual photons, and that would enable long-range entanglement and integration into larger quantum networks. Growing research interest in cavity optomagnonics and quantum magnonics is reflected in work that couples spin excitations to cavity photons.⁸

From a fabrication standpoint, skyrmion qubits would benefit from compatibility with planar nanofabrication and could be used with techniques already common in the magnetic memory and spintronics industries. Figure 4 highlights the scalability of lithographically defined skyrmion arrays. Skyrmion-based devices inherit the same degree of CMOS compatibility as established spintronic platforms such as spin-orbit torque MRAM, where thin-film magnetic stacks and on-chip microwave structures are routinely integrated with silicon.⁹ Lithographically defined patterns in thin films can guide skyrmion positioning, while local gates or current lines enable individual addressability, allowing for the fabrication of 2D skyrmion-qubit arrays.

Although large-scale skyrmion-based processors remain a long-term objective, researchers have already stabilized, transported, and controlled multi-skyrmion arrays in nanotracks and sub-100-nm dots using established fabrication techniques. Scalability in quantum devices is not just about fitting many qubits together. It also requires that each qubit can be operated and read out reliably, without interference from its neighbors, and that the system can be kept cold enough to preserve quantum coherence. Achieving that across a large array of skyrmions is challenging, since it demands uniform materials and precise control of their spacing and interactions. Encouragingly, research in skyrmionics has already made progress in patterning, controlling pinning sites, and tuning interactions, and that work has provided a strong foundation for future quantum designs.

The road ahead

Despite an elegant theoretical framework, skyrmion-based quantum computing is still in its infancy. The first decisive milestones will be the experimental demonstration of helicity quantization in a solid-state system and the detection of coherent superpositions of helicity states. Showing that a collective spin texture can host a quantized internal degree of freedom would not just validate the idea of a helicity qubit—it would represent a breakthrough for condensed-matter physics by revealing new ways in which geometry and quantum mechanics intertwine.

Reaching that point will require advances on several fronts. Materials optimization is critical to hosting stable, long-lived skyrmions that remain coherent at cryogenic temperatures. The helicity degree of freedom must be tunable yet robust, and maintaining that balance demands precise control over

interfaces, defects, and anisotropies. At the same time, researchers need tools capable of detecting and manipulating helicity with high fidelity. Hybrid approaches that link skyrmions to superconducting circuits, optomechanical resonators, or spin defects may provide the sensitivity and control needed to take those first steps.

That road map echoes the early days of other qubit platforms. Superconducting qubits, now a leading platform, began with crude Josephson junctions and evolved over two decades into mature systems with coherence times exceeding 100 μs .¹⁰ Similarly, nitrogen–vacancy centers in diamond grew from spectroscopic curiosities to precision quantum sensors.¹¹ Progress in all cases has been driven by a nonlinear feedback loop between theory, materials development, and advances in experimental design. Skyrmion-based quantum systems may follow a similar trajectory.

Beyond their technological promise, skyrmion qubits raise deeper scientific questions. They challenge us to see topological spin textures not as static curiosities but as dynamic, quantum-coherent objects. If realized, skyrmion qubits could both expand the practical toolkit of quantum information science and reshape

how we think about the quantum potential hidden within condensed-matter textures.

A twist in quantum technology

Spin patterns remind us that some of the most notable advances in quantum science arise directly from the geometry of matter itself. Magnetic skyrmions mark a striking new frontier in the search for robust and scalable quantum platforms. Their properties make them particularly suited for both conceptual insight and practical innovation. Although challenges remain in materials, control, and coherence, the combination of robustness and quantum behavior suggests a path to devices that go beyond incremental advances. It points to new ways of processing information rooted in the geometry of condensed matter.

Chirality links phenomena as diverse as the double helix of biology and the handedness of particle physics. Skyrmion-based qubits would use that geometric property to encode and manipulate quantum states in collective spin textures and represent an intersection of topology and quantum information science. Should we succeed in guiding these textures into coherent superpositions, the future of quantum computing may rest on the graceful twist of a spin vortex. **PT**

References

1. J. L. O'Brien, "Optical quantum computing," *Science* **318**, 1567 (2007).
2. Y. Tokura, N. Kanazawa, "Magnetic skyrmion materials," *Chem. Rev.* **121**, 2857 (2021).
3. G. Finocchio, C. Panagopoulos, eds., *Magnetic Skyrmions and Their Applications*, Woodhead Publishing (2021).
4. A. Fert, N. Reyren, V. Cros, "Magnetic skyrmions: Advances in physics and potential applications," *Nat. Rev. Mater.* **2**, 17031 (2017).
5. A. P. Petrović et al., "Colloquium: Quantum properties and functionalities of magnetic skyrmions," *Rev. Mod. Phys.* **97**, 031001 (2025).
6. C. Psaroudaki, C. Panagopoulos, "Skyrmion qubits: A new class of quantum logic elements based on nanoscale magnetization," *Phys. Rev. Lett.* **127**, 067201 (2021).
7. C. Psaroudaki, E. Peraticos, C. Panagopoulos, "Skyrmion qubits: Challenges for future quantum computing applications," *Appl. Phys. Lett.* **123**, 260501 (2023).
8. H. Y. Yuan et al., "Quantum magnonics: When magnon spintronics meets quantum information science," *Phys. Rep.* **965**, 1 (2022).
9. V. D. Nguyen et al., "Recent progress in spin-orbit torque magnetic random-access memory," *npj Spintron.* **2**, 48 (2024).
10. M. Kjaergaard et al., "Superconducting qubits: Current state of play," *Annu. Rev. Condens. Matter Phys.* **11**, 369 (2020).
11. S. Esmaili et al., "Evolution of quantum spin sensing: From bench-scale ODMR to compact integrations," *APL Mater.* **12**, 040901 (2024).
12. M. W. Johnson et al., "Quantum annealing with manufactured spins," *Nature* **473**, 194 (2011).
13. P. Ho et al., "Geometrically tailored skyrmions at zero magnetic field in multilayered nanostructures," *Phys. Rev. Appl.* **11**, 024064 (2019).
14. T. D. Ladd et al., "Quantum computers," *Nature* **464**, 45 (2010).
15. R. Hanson, D. D. Awschalom, "Coherent manipulation of single spins in semiconductors," *Nature* **453**, 1043 (2008).
16. K. R. Brown et al., "Materials challenges for trapped-ion quantum computers," *Nat. Rev. Mater.* **6**, 892 (2021).
17. C. Psaroudaki, C. Panagopoulos, "Skyrmion helicity: Quantization and quantum tunneling effects," *Phys. Rev. B* **106**, 104422 (2022).

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