Skyrmion Qubits: Simplifying a New Class of Quantum Logic Elements

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Term Project
Magnetic & Superconducting Properties of Solids

Contents

Abstract

This term paper reviews the qubit architecture proposed by **Psaroudaki** & **Panagopoulos** (*Phys. Rev. Lett. 127, 067201, 2021*), which uses magnetic skyrmions for solid-state quantum computation. Quantum information is encoded in the skyrmion's helicity, leveraging topological protection and nanoscale structure. Two qubit designs allow coherent control via microwave magnetic field gradients, with tunability through electric and magnetic fields. The paper explores qubit coupling via bilayer exchange, coherence properties, and readout approaches. It outlines theoretical benefits alongside experimental challenges, including material quality, decoherence, and control precision—positioning skyrmion qubits as a promising path for scalable, low-power quantum systems.

1 Introduction and Motivation

The paper introduces a novel approach to quantum information processing by proposing a new type of quantum bit (qubit) based on magnetic skyrmions, which are nanoscale magnetization configurations possessing topological stability. Unlike conventional spin- or charge-based qubits, the proposed scheme encodes quantum information in the helicity of the skyrmion, an intrinsic degree of freedom that characterizes the rotational orientation of the skyrmion's spin texture. By utilizing the helicity as the quantum state variable, the authors suggest that it is possible to achieve robust quantum coherence and control, owing to the inherent protection offered by the skyrmion's topological nature. This method lays the groundwork for an alternative class of qubits that may overcome limitations in existing systems, particularly in terms of stability and scalability.

1.1 Quantum Computing Scope:

Traditional qubit platforms, such as those based on atoms, trapped ions, and superconducting circuits, have achieved significant progress in coherence times and gate fidelities but continue to face persistent challenges when it comes to scalability, integration density, and precise control in large-scale quantum computing architectures. These limitations motivate the exploration of alternative qubit systems that can overcome such constraints.

In this context, **magnetic skyrmions** emerge as promising candidates [1] due to their nanoscale size and topologically protected nature, which grants them inherent robustness against external perturbations, such as thermal fluctuations and structural defects. Furthermore, skyrmions offer versatile control mechanisms, as they can be manipulated effectively using both electric and magnetic fields, making them highly compatible with existing nanofabrication and spintronic technologies. This dual controllability, combined with their stability and compact footprint, positions skyrmion-based qubits as a compelling alternative platform for scalable quantum computing.

1.2 Design and Theoretical Framework:

The paper develops a quantization framework for skyrmion helicity by employing collective coordinate methods, a powerful theoretical approach that simplifies the complex spin field dynamics of the skyrmion into a manageable set of generalized coordinates representing its low-energy excitations. This formalism enables the isolation of the helicity degree of freedom and its treatment as a quantum variable, laying the groundwork for encoding and manipulating quantum information within the skyrmion structure. Building on this foundation, the authors propose two distinct implementations [1] of skyrmion-based qubits:

1. The S_z**-qubit** utilizes quantized spin projections along the z-axis and is conceptually analogous to traditional spin qubits.

2. The **helicity qubit** is based on the quantized rotational states of the skyrmion's spin texture, specifically the helicity angle, which defines the in-plane orientation of spins around the skyrmion core.

These two variants demonstrate the flexibility of the proposed platform and highlight the potential of magnetic skyrmions to host a new class of quantum bits governed by topologically nontrivial and physically accessible internal degrees of freedom.

1.3 Control and Scalability:

The study identifies and analyzes practical methods for manipulating skyrmion-based qubits through the application of external electric and magnetic fields, leveraging the strong coupling between these fields and the skyrmion's internal degrees of freedom.

Electric fields can influence the helicity via magnetoelectric coupling, allowing for precise, localized control without introducing significant thermal noise - a critical advantage for quantum coherence.

Magnetic fields, on the other hand, can be used to tune the energy landscape and stabilize desired skyrmion configurations or transitions between quantum states.

This dual-field control scheme provides a versatile toolbox for implementing quantum gate operations with high spatial and temporal resolution. Furthermore, the paper explores the feasibility of scaling the platform by proposing mechanisms for multiqubit coupling, such as dipolar interactions or mediated exchange through shared magnetic substrates. These coupling schemes pave the way toward constructing entangled qubit networks and implementing two-qubit gates, both of which are essential components for building a scalable quantum processor based on skyrmion helicity.

1.4 Experimental Relevance:

A critical consideration in the proposed skyrmion-based qubit design is the achievement of favorable coherence times, which are necessary for performing reliable quantum operations before decoherence disrupts the system's quantum state. The authors demonstrate that, due to the topological protection and energy barriers associated with skyrmionic configurations, the helicity qubit can achieve coherence times in the microsecond range—comparable to or exceeding those of other solid-state qubit platforms.

This robustness arises from the suppression of local perturbations and thermal noise, which minimally affect the global helicity degree of freedom. In addition to long coherence times, the design offers nonvolatile readout capabilities, leveraging the persistent nature of skyrmion states even in the absence of external power. This nonvolatility enables repeated measurement and storage of quantum information without the need for continuous system initialization, making the skyrmion qubit a strong candidate for stable, energy-efficient quantum memory and processing applications.

2 Theoretical Background and Basic Concepts

2.1 Magnetic Skyrmions

2.1.1 Skyrmion Structure:

A **skyrmion** is a nanoscale spin texture characterized by a swirling pattern of magnetization. It can be mathematically described by the unit vector $\hat{\mathbf{m}}(\mathbf{r}) = (\sin\Theta\cos\Phi, \sin\Theta\sin\Phi, \cos\Theta)$ where Θ and Φ are polar and azimuthal angles, respectively.

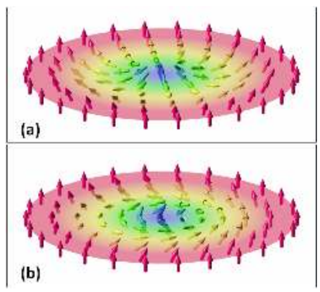

Figure 1: Basic look of a skyrmion

2.1.2 Topological Charge Q:

The skyrmion carries a topological charge defined as :

$$Q = \frac{1}{4\pi}\int d^2r\,\mathbf{m}\cdot\left(\frac{\partial}{\partial x}\mathbf{m}\times\frac{\partial}{\partial y}\mathbf{m}\right) \tag{1}$$

which for a standard skyrmion [3] takes the value $Q = \pm 1$.

2.2 Helicity as a Quantum Degree of Freedom

The **helicity**, denoted by ϕ_0, is a fundamental parameter characterizing the internal spin structure of a magnetic skyrmion. Specifically, it represents the angle of global in-plane rotation of the spin texture around the z-axis, effectively describing how the magnetic moments are twisted within the skyrmion. This angular degree of freedom serves as an internal "phase" of the skyrmion state, analogous to the phase variable in superconducting or photonic qubits, and plays a central role in defining the skyrmion's topological and dynamical properties.

Since the helicity encapsulates a continuous symmetry of the system, it can be quantized under appropriate confinement, making it a viable and tunable candidate for encoding quantum information within a topologically stable platform.

2.2.1 Controllability:

The helicity of a magnetic skyrmion can be effectively tuned using external electric fields and magnetic field gradients, offering dynamic and localized control over the qubit's internal state.

Electric fields influence the helicity through magnetoelectric coupling, whereby an induced electric polarization interacts with the skyrmion's spin texture to rotate its in-plane spin configuration. This mechanism allows for noninvasive, low-power manipulation of the helicity without introducing significant heating or decoherence. Furthermore, applying magnetic field gradients can spatially modulate the local energy landscape, leading to controlled shifts in the helicity angle ϕ_0. Together, these external field controls provide the necessary tools for initializing, manipulating, and driving coherent transitions between helicity states.

2.3 Frustrated Magnets and Competing Interactions

2.3.1 Model Overview:

The theoretical foundation of the paper is based on an inversion-symmetric Heisenberg model that incorporates competing exchange interactions to stabilize complex spin textures, including skyrmions. These competing interactions introduce magnetic frustration, which is essential for the emergence of nontrivial spin configurations. The system's free energy is described by the expression:

$$\text{Free energy } (F) = -\frac{J_1}{2}(\nabla \mathbf{m})^2 + \frac{J_2 a^2}{2}(\nabla^2 \mathbf{m})^2 - H a^2 m_z + K a^2 m_z^2, \tag{2}$$

where $\mathbf{m}$ is the local magnetization vector, J_1 and J_2 represent the strengths of the nearest-neighbor and next-nearest-neighbor exchange interactions respectively, H is the external Zeeman field, K is the magnetic anisotropy constant, and a is the lattice spacing. The negative gradient-squared term encourages spin alignment, while the higher-order gradient term $(\nabla^2 \mathbf{m})^2$ introduces competition that stabilizes finite-size skyrmion textures.

This frustration-driven mechanism permits the formation of small skyrmions, with diameters on the order of a few lattice constants. This frustration ultimately gives rise to a low-energy internal mode - namely, the helicity which becomes a quantizable and controllable quantum degree of freedom, central to the skyrmion qubit proposal.

2.4 Collective Coordinate Quantization

The paper employs the method of collective coordinate quantization to transition from a classical description of skyrmion dynamics to a quantum mechanical framework suitable for qubit applications. In this approach, classical system variables specifically, the helicity ϕ_0, which represents the internal rotational angle - are promoted to quantum operators. These variables are paired with their conjugate momenta, with the helicity's canonical momentum identified as the out-of-plane magnetization component S_z, representing the total spin along the z-axis. The quantization is implemented via the canonical commutation relation:

$$[\hat{\phi}_0, \hat{S}_z] = i/\bar{S} \tag{3}$$

where $\bar{S}$ is an effective spin. In the regime where $\bar{S} \gg 1$, the system behaves classically, while smaller values of $\bar{S}$ enable the emergence of genuine quantum behavior.

3 Skyrmionic Field Quantization

The classical description of a magnetic skyrmion is formulated in polar coordinates (ρ, φ), capturing the rotationally symmetric nature of the spin texture. The magnetization vector $\mathbf{m}(\mathbf{r})$ at position $\mathbf{r}$ is described by two angular functions: the azimuthal angle $\Phi(\mathbf{r})$, which dictates the in-plane orientation of the spins, and the polar angle $\Theta(\rho)$, which defines the out-of-plane component. Specifically, the azimuthal component is given by:

$$\Phi(\mathbf{r}) = -Q\varphi \tag{4}$$

where Q is the skyrmion number or topological charge, representing the winding of spins around the core. The polar angle $\Theta(\rho)$ depends solely on the radial coordinate ρ and determines the radial profile of the skyrmion.

The skyrmion size λ is a key characteristic that quantifies the spatial extent of the spin configuration and is defined through the relation:

$$\lambda \equiv \frac{2a}{\Re^{1/\gamma}} \tag{5}$$

where a is the lattice spacing, $\Re$ is a dimensionless scaling parameter derived from the system's interaction energies, and γ is a phenomenological exponent that encodes the influence of external fields and material-dependent interaction constants.

3.1 Collective Coordinate Approach

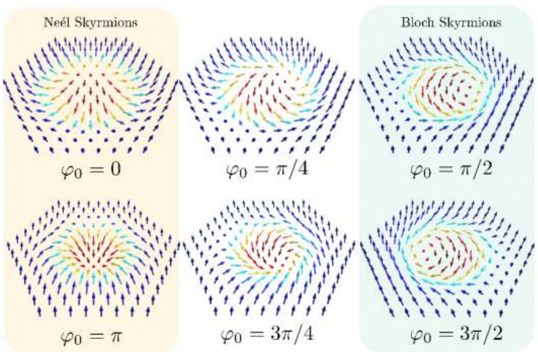

Figure 2: Skyrmions with a fixed topological charge and different helicities

To enable a clear and controllable quantum description of the skyrmion's internal dynamics, the system is spatially confined within a nanodisk. This geometric confinement suppresses the translational modes of the skyrmion i.e its ability to move freely across the plane thereby isolating the internal helicity degree of freedom ϕ_0 as the primary dynamic variable. This simplification ensures that quantum behavior arises only from the helicity, without interference from center-of-mass motion.

The transition from a classical to a quantum mechanical description is then carried out using canonical quantization. The classical helicity ϕ_0 and its conjugate angular momentum S_z are transformed to quantum operators $\hat{\phi}_0$ and $\hat{S}_z$, respectively. The Poisson bracket is thus replaced by the corresponding commutator:

$$\{\phi_0, S_z\} \rightarrow \frac{1}{i}[\hat{\phi}_0, \hat{S}_z] \tag{6}$$

As a result of this quantization, the eigenstates of the system are labeled by discrete values of S_z, representing quantized projections of the spin along the z-axis. These quantized states form a well-defined energy spectrum, providing the basis for defining and manipulating skyrmion-based qubits via the helicity degree of freedom.

3.2 Role of External Fields in Quantization

- **Electric Field Effects:** Electric fields couple to the induced polarization of the skyrmion, directly affecting the helicity potential.
- **Magnetic Field Gradients:** Magnetic field gradients add another tuning parameter, modifying the potential landscape for ϕ_0.

3.3 Hamiltonian for the Helicity Degree of Freedom

In the presence of magnetic anisotropy and externally applied fields, the quantum dynamics of the skyrmion's helicity ϕ_0 is governed by an effective Hamiltonian that encapsulates both the kinetic and potential contributions associated with this internal mode. The Hamiltonian is expressed as:

$$H = \kappa \left(\hat{S}_z - \frac{h}{\kappa} \right)^2 - E_z \cos \hat{\phi}_0, \tag{7}$$

where $\hat{S}_z$ is the angular momentum operator conjugate to $\hat{\phi}_0$, h is the effective magnetic field coupling term, κ denotes anisotropy, and E_z quantifies the strength of the helicity potential induced by electric fields. This Hamiltonian resembles that of a quantum rotor in a periodic potential, where the first term represents the kinetic energy and the second term the potential energy. To determine the quantized energy levels associated with the helicity states, one must solve the corresponding time-independent Schrödinger equation:

$$H\Psi_s(\phi_0) = E_s \Psi_s(\phi_0) \tag{8}$$

where $\Psi_s(\phi_0)$ are the wavefunctions of the helicity qubit in the ϕ_0 basis, and E_s are the associated energy eigenvalues. This formulation allows for the precise determination of the energy spectrum and the characterization of accessible quantum states, laying the theoretical foundation for using helicity as a robust and controllable qubit degree of freedom.

4 Skyrmion Qubit Types: S_z-Qubit and Helicity Qubit

The paper identifies two principal qubit designs based on the quantization of the skyrmion's degrees of freedom [1]. Each type uses different aspects of the skyrmion's dynamics.

4.1 The S_z-Qubit

The S_z-qubit design is built upon the quantization of the S_z operator, which captures fluctuations in the out-of-plane component of the skyrmion magnetization, m_z, relative to its equilibrium configuration. This operator becomes the central degree of freedom for encoding quantum information in this qubit architecture. The full Hamiltonian governing the S_z-qubit is formulated as:

$$H_{S_z} = \kappa \left(\hat{S}_z - \frac{h}{\kappa} \right)^2 - E_z \cos \hat{\phi}_0$$

To isolate a usable two-level quantum system from this continuous spectrum, the Hamiltonian is projected into a reduced two-state subspace, yielding an effective qubit Hamiltonian:

$$H_q = \frac{H_0}{2} \hat{\sigma}_z - \frac{X_c}{2} \hat{\sigma}_x \tag{9}$$

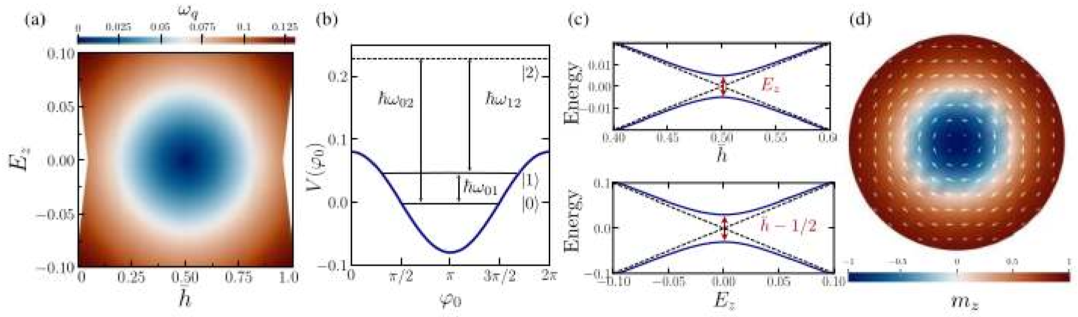

Figure 3: (a) Magnetic field $\hbar$ and electric field E_z dependence of the transition frequency ω_q, close to the degeneracy point $\hbar = 0.5$. The colored surface represents the values of ω_q which satisfy the requirement of high anharmonicity. (b) Nonequidistant quantized energy levels and potential landscape. The qubit states are the ground state $|0\rangle$ and first excited state $|1\rangle$ with level spacing $\hbar\omega_{01} = \omega_q$ smaller than transitions to higher states $\hbar\omega_{02}$,$\hbar\omega_{12}$. (c) Universal energy level anticrossing diagram close to the degeneracy point (dashed lines). The degeneracy is lifted by an electric field (upper panel) or increasing the magnetic field away from $h\hbar = 0.5$ (lower panel). At the degeneracy point, energy eigenstates are symmetric and antisymmetric superpositions of the skyrmion qubit states $(|0\rangle \pm |1\rangle)/\sqrt{2}$. (d) A magnetic skyrmion with a circular profile stabilized in a magnetic nanodisk.

where the effective longitudinal field is given by $H_0 = \kappa(1 - 2\bar{h})/\bar{S}$ (where $\bar{h} = h\bar{S}/\kappa$), and the transverse coupling is $X_c = E_z$. Here, $\hat{\sigma}_z$ and $\hat{\sigma}_x$ are Pauli matrices operating in the two-level qubit basis.

4.2 Energy Spectrum and Anharmonicity

Non equidistant levels : The energy spectrum of the skyrmion qubit is deliberately engineered to be anharmonic, meaning that the spacings between successive energy levels are non-equidistant. Specifically, the energy gap between the ground state and the first excited state, denoted by $\hbar\omega_{01}$, is designed to be significantly smaller than the gaps to higher levels such as $\hbar\omega_{02}$ and $\hbar\omega_{12}$. This spectral structure is a critical design feature that enhances the functionality of the qubit.
Anharmonicity: Anharmonicity provides a key operational advantage. It enables the application of microwave pulses that are resonant only with the qubit transition $|0\rangle \leftrightarrow |1\rangle$, while avoiding unintentional excitations to higher-lying noncomputational states.

4.3 The Helicity Qubit

The helicity qubit encodes quantum information directly in the quantized states of the skyrmion helicity ϕ_0, which serves as an internal rotational degree of freedom of the spin texture. In this design, the helicity potential landscape is engineered into a double-well shape, where each well corresponds to a distinct, stable helicity configuration.

These two minima are identified with the logical basis states $|0\rangle$ and $|1\rangle$ of the qubit. The localization of the wavefunction in one of the wells allows the qubit to represent binary quantum information, while quantum tunneling between the wells introduces coherent superpositions and enables gate operations.

4.3.1 Hamiltonian formulation

The helicity qubit's quantum behavior is governed by an effective Hamiltonian that incorporates both kinetic and potential energy contributions related to the helicity angle $\hat{\phi}_0$ and its conjugate

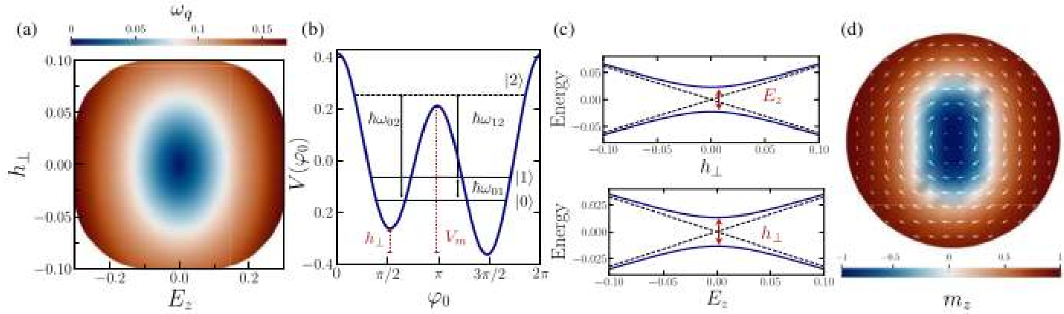

Figure 4: (a) Electric field E_z and magnetic field gradient $h_\perp$ dependence of the transition frequency ω_q, close to the degeneracy point $\bar{h} = 1$. The colored surface represents the values of ω_q which satisfy the requirement of high anharmonicity. (b) Nonequidistant quantized energy levels and double-well potential landscape. The qubit states are the ground state $|0\rangle$ and first excited state $|1\rangle$ with level spacing $\hbar\omega_{01} = \omega_q$ smaller than transitions to higher states $\hbar\omega_{02}$, $\hbar\omega_{12}$. The potential barrier V_m is controlled by E_z and the well difference by $h_\perp$. (c) Universal energy level anticrossing diagram close to the degeneracy point $\hbar = 1$. The degeneracy is lifted by an electric field (upper panel) or a magnetic field gradient (lower panel). (d) A magnetic skyrmion with an elliptical profile stabilized in a magnetic nanodisk. The elliptical profile is essential for realizing the double-well potential.

angular momentum $\hat{S}_z$. The full Hamiltonian is expressed as:

$$H_{\phi_0} = \kappa\hat{S}_z - h\hat{S}_z + V(\hat{\phi}_0) \tag{10}$$

$$V(\hat{\phi}_0) = \kappa_x \cos 2\hat{\phi}_0 - E_z \cos\hat{\phi}_0 + h_\perp \sin\hat{\phi}_0 \tag{11}$$

This potential landscape is engineered to create a double-well structure in the ϕ_0 coordinate. The term $\kappa_x \cos 2\hat{\phi}_0$ is responsible for establishing a symmetric double-well configuration, which supports two localized states corresponding to logical $|0\rangle$ and $|1\rangle$. Additional asymmetry in the potential can be introduced by applying an external electric field E_z or a magnetic field gradient $h_\perp$, which bias the potential to energetically favor one well over the other.

4.3.2 Energy Eigenstates and Tunneling

When the helicity potential wells are nearly equal in depth, the system's two lowest quantum states become symmetric and antisymmetric superpositions of wavefunctions localized in each well. Quantum tunneling between the wells induces a small energy difference—known as tunnel splitting—between these states. This splitting defines the qubit frequency and enables coherent operations between logical states $|0\rangle$ and $|1\rangle$.

Under a two-level approximation, where higher energy levels are neglected, the helicity Hamiltonian reduces to:

$$H_q = \frac{H_0}{2}\hat{\sigma}_z - \frac{X_c}{2}\hat{\sigma}_x,$$

with H_0 representing the energy bias and X_c the tunneling-induced coupling. Here, $\hat{\sigma}_z$ and $\hat{\sigma}_x$ are Pauli matrices. The value of X_c depends on whether control is applied via an electric field E_z or magnetic field gradient $h_\perp$.

4.4 Comparison

S_z**-Qubit**	**Helicity Qubit**
Encodes quantum information in the eigenstates of the out-of-plane spin component S_z, which corresponds to fluctuations in the magnetization along the z-axis. This qubit is sensitive to magnetic field-induced variations in m_z.	Encodes quantum information in the helicity degree of freedom ϕ_0, representing the internal spin rotation angle of the skyrmion. The states are localized in a double-well potential, where each well corresponds to a logical qubit state.
The dynamics are dominated by magnetic anisotropy and Zeeman coupling, with control achieved through variations in the magnetic field h and electric potential E_z.	Control is achieved by tuning the potential wells using external electric fields E_z and magnetic field gradients $h_\perp$, which bias the double-well landscape and modulate tunneling dynamics.
Qubit states are accessed via the quantization of angular momentum in the z-direction, with $S_z = \pm\frac{1}{2}$ forming the logical $\|0\rangle$ and $\|1\rangle$ basis.	The logical basis states $\|0\rangle$ and $\|1\rangle$ correspond to the localization of the helicity wavefunction in the left or right well, respectively. Quantum tunneling between these wells enables coherent qubit operations.
The energy level structure is engineered to be anharmonic by tuning interaction parameters such as κ and external fields, ensuring selective transitions between qubit levels.	Anharmonicity arises naturally due to the shape of the double-well potential, which separates the lowest two energy levels from higher excited states and enables well-defined qubit operations.
Readout is primarily based on detecting the out-of-plane magnetization m_z, which reflects the S_z component of the skyrmion spin configuration.	Readout mechanisms focus on spatially resolved measurements sensitive to the helicity angle ϕ_0, potentially using imaging or field-sensing techniques to distinguish between localized states.

Table 1: Comparison between S_z-Qubit and Helicity Qubit architectures.

5 Qubit Control and Quantum Gate Operations

5.1 Microwave Field Control

Qubit manipulation is facilitated by the application of **microwave magnetic field gradients (MFGs)**, which introduce a time-dependent perturbation into the system's Hamiltonian. The external microwave driving field adds the term:

$$H_{\text{ext}}(t) = b_0 f(t) \cos(\omega t + \phi_{\text{ext}}) \cos \hat{\phi}_0 \tag{12}$$

where b_0 is the field amplitude, $f(t)$ is an envelope function, ω is the microwave frequency, and ϕ_{ext} is the external phase. When projected onto the qubit basis, this interaction reduces to a simpler form:

$$H_{q,\text{ext}} = b_x(t)\hat{\sigma}_x, \tag{13}$$

with $b_x(t) = b_0 f(t) \cos(\omega t + \phi_{\text{ext}})$, where $\hat{\sigma}_x$ acts as the Pauli operator for qubit transitions. To simplify the analysis of the system's dynamics under this time-dependent drive, it is useful to move into a rotating frame of reference. In this rotating frame, the Hamiltonian becomes:

$$H_{\text{rot}} = \frac{\Delta\omega}{2}\hat{\sigma}_z + \frac{\Omega}{2}\left(\cos\phi_{\text{ext}}\,\hat{\sigma}_x + \sin\phi_{\text{ext}}\,\hat{\sigma}_y\right), \tag{14}$$

where $\Delta\omega = \omega_q - \omega$ is the detuning between the qubit transition frequency ω_q and the drive frequency ω, and $\Omega = b_0 \cos\theta$ is the effective Rabi frequency.

5.2 Single Qubit gate operations

Single-qubit gate operations in the skyrmion-based qubit system are implemented through controlled rotations about specific axes of the Bloch sphere, enabled by the microwave magnetic field gradients discussed previously. For rotations about the x-axis, the external microwave drive is applied with phase $\phi_{\text{ext}} = 0$, and the drive is tuned to resonance with the qubit frequency, i.e., $\Delta\omega = 0$. Under these conditions, the qubit evolves according to the time-evolution operator:

$$U_x(t) = \exp\left[-\frac{i}{2}\vartheta(t)\hat{\sigma}_x\right] \tag{15}$$

where the angle of rotation $\vartheta(t)$ is governed by the integral of the pulse envelope and is given by:

$$\vartheta(t) = -\Omega \int_0^t f(t')dt' \tag{16}$$

with Ω representing the Rabi frequency and $f(t')$ the pulse shape function. To achieve rotations about the y-axis, the same microwave pulse is used, but with a phase shift of $\phi_{\text{ext}} = \pi/2$, effectively rotating the field in the control plane.

5.3 Pulse Shaping and Control Parameters

Pulse shaping plays a critical role in the fidelity and efficiency of single-qubit operations. The envelope function $f(t)$, which modulates the amplitude of the microwave drive, is carefully engineered to suppress unwanted excitations to higher energy levels. By minimizing spectral leakage through appropriate pulse design, transitions remain confined to the intended two-level system. In addition to pulse shaping, the choice of control parameters such as the qubit frequency ω_q and Rabi frequency Ω is crucial.

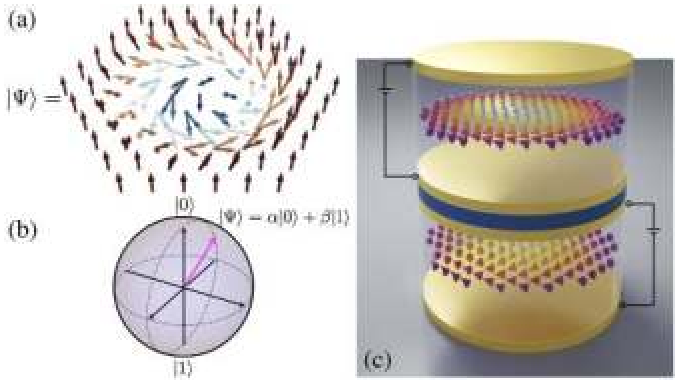

Figure 6: A general quantum state $|\Psi\rangle$ as an arbitrary superposition of skyrmion configurations with distinct helicities φ_0.(b) Bloch sphere representation of general qubit with $|0\rangle$ & $|1\rangle$ denoting the two lowest energy levels of the quantum operator $\hat{\varphi}_0$.(c) A bilayer of magnetic materials as a platform for the skyrmion qubit coupling scheme. The qubit coupling is tuned by a nonmagnetic spacer (blue), and logical states are adjusted by electric fields (yellow plates).

6 Qubit Coupling / Entanglement and Scalable Architectures

6.0.1 Effective Qubit-Qubit Hamiltonian

Mapping the helicity interaction into the qubit basis results in an effective two-qubit Hamiltonian that includes both transverse and longitudinal coupling terms:

$$H_{\text{int}} = -J^x_{\text{int}}\hat{\sigma}^{(1)}_x\hat{\sigma}^{(2)}_x - J^z_{\text{int}}\hat{\sigma}^{(1)}_z\hat{\sigma}^{(2)}_z, \qquad (17)$$

where $\hat{\sigma}^{(i)}_x$ and $\hat{\sigma}^{(i)}_z$ are the Pauli matrices acting on the i-th qubit. The coefficients J^x_{int} and J^z_{int} correspond to the strength of the transverse and longitudinal couplings, respectively.

This dual-coupling structure enables the implementation of various types of two-qubit gates, offering flexibility for scalable quantum computation.

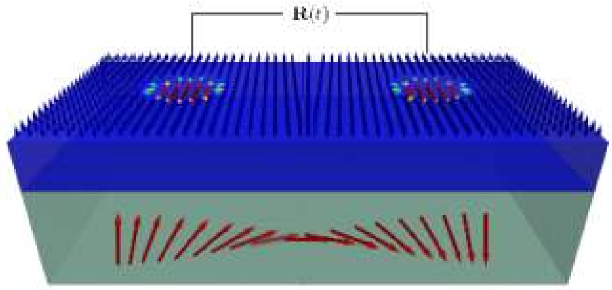

Figure 5: Two skyrmions coupling

6.1 Proposed Coupling Scheme

6.1.1 Magnetic Bi-layer system

The proposed qubit coupling scheme is based on a bilayer system composed of two adjacent magnetic layers. Each layer hosts a skyrmion qubit, and the proximity between layers enables interactions between the skyrmions.

The coupling between the two skyrmion qubits is mediated by an interlayer exchange interaction, described by the following free energy expression:

$$F_{\text{int}} = J_{\text{int}} \int d^2r\, \mathbf{m}_1 \cdot \mathbf{m}_2 \qquad (18)$$

where $\mathbf{m}_1$ and $\mathbf{m}_2$ denote the magnetization fields in the two layers, and J_{int} is the strength of the interlayer coupling.

When expressed in terms of the helicity angles ϕ_1 and ϕ_2 of the two skyrmions, the interaction Hamiltonian becomes:

$$H_{\text{int}} = -J_{\text{int}} \cos(\phi_1 - \phi_2) \tag{19}$$

6.1.2 Tuning the Coupling

1. **Spacer Layer Thickness:** The strength of interlayer coupling between skyrmion qubits, governed by the exchange term J_{int}, can be experimentally modulated through variations in the thickness of the nonmagnetic spacer layer separating the magnetic films. This tunability provides a direct handle over the interaction energy that facilitates qubit-qubit entanglement.

2. **External Field Control:** The longitudinal and transverse coupling components can be independently controlled by external fields: an electric field adjusts the asymmetry in the potential landscape, while a magnetic field gradient can influence tunneling dynamics.

3. **Quantum Annealing applications:** Such dual control is not only essential for gate flexibility but also enables the implementation of quantum annealing protocols, which require both types of interactions to optimize energy landscapes and explore computationally relevant ground states.

7 Noise, Decoherence, and Readout Strategies

7.1 Sources of Noise and Their Impact

- **Environmental Coupling:** Skyrmion qubits, owing to their topological and macroscopic nature, are susceptible to interactions with various environmental degrees of freedom. These include phonons (vibrational modes of the crystal lattice), magnons (spin wave excitations), and conduction electrons. Such couplings serve as primary channels for decoherence, making them critical to consider in the qubit's quantum dynamics.

- **Damping and Fluctuations:** The dissipative behavior of the skyrmion texture is captured by a damping term governed by the Gilbert damping constant α. For the proposed helicity-based qubit platform, ultra-low damping values on the order of $\alpha \sim 10^{-5}$ are assumed. This minimal damping is essential for preserving coherent oscillations and reducing energy loss over time.

- **Quantitative Description:** The influence of environmental noise on the qubit is introduced in the effective Hamiltonian through time-dependent stochastic fields. The full Hamiltonian under noise is given by

$$H_q = \frac{\omega_q}{2}\hat{\sigma}_z + \xi_x(t)\gamma_x\hat{\sigma}_x + \xi_y(t)\gamma_y\hat{\sigma}_y + \xi_z(t)\gamma_z\hat{\sigma}_z \tag{20}$$

  where ω_q is the qubit frequency, and $\xi_i(t)$ are noise terms along each Pauli direction, modulated by coupling strengths γ_i. These fluctuations are characterized by spectral densities $S_i(\omega)$, enabling a quantitative framework to assess and simulate decoherence processes.

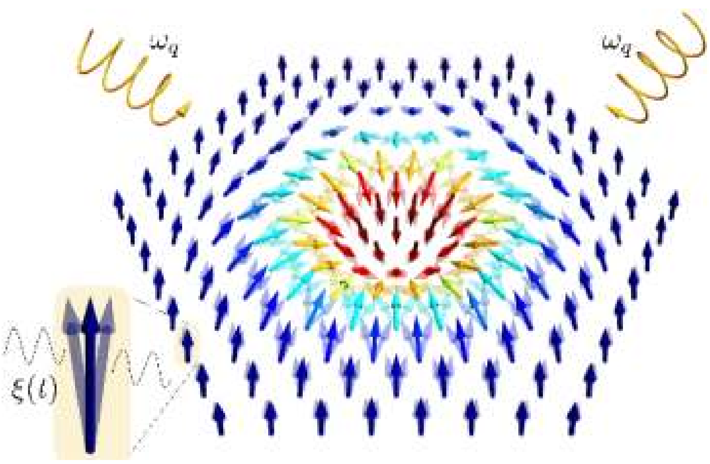

Figure 7: Skyrmions with noise

7.2 Decoherence Time Scales

1. **Longitudinal Relaxation** (T_1) :

   The longitudinal relaxation time T_1 characterizes the time scale over which the excited qubit state $|1\rangle$ decays to the ground state $|0\rangle$ due to energy exchange with the environment. In the skyrmion qubit platform discussed, this relaxation arises from interactions such as magnon or phonon emission. The authors estimate T_1 to lie in the microsecond range, which is promising for practical gate operations and readout fidelity.

2. **Dephasing Time** (T_2) :

   The dephasing time T_2 quantifies how long a quantum superposition state retains its phase coherence in the presence of noise. Even in the absence of energy loss, environmental fluctuations can randomize the phase of the qubit's wavefunction, leading to decoherence. In the proposed scheme, T_2 is also in the microsecond regime. This allows for on the order of 10^5 coherent Rabi oscillations to occur within a single coherence window—sufficient for high-fidelity quantum gate operations.

7.3 Strategies for Readout

Reliable qubit readout is a critical component of any quantum computing platform, and the paper outlines several promising nonvolatile methods tailored to the skyrmion-based system.

- **Quantum sensing via single-magnon detection**, where magnetic excitations associated with the skyrmion helicity state are detected using quantum dots or superconducting qubit sensors.

- **Nitrogen-vacancy (NV) center magnetometry** enabling direct imaging of the skyrmion's helicity through localized magnetic field measurements. The coupling strength in this technique is governed by the spatial proximity between the NV sensor and the skyrmion.

- Additionally, **resonant elastic X-ray scattering (REXS)** provides a direct probe of the underlying spin texture, capturing changes in the skyrmion's configuration with high spatial resolution.

- Lastly, **magnetic force microscopy (MFM)** detects shifts in the resonance frequency of the cantilever due to changes in the magnetic state, offering a mechanical means of helicity readout.

7.4 Minimizing Noise Effects

Skyrmion qubit performance can be enhanced through careful optimization of both material and operational parameters.

1. One key strategy involves optimizing material properties to reduce extrinsic sources of noise. For instance, engineering cleaner interfaces and using high-quality, optimized thin films helps suppress unwanted damping effects.

2. In addition, operating the qubits at cryogenic temperatures, particularly in the sub-Kelvin regime, further diminishes thermal noise, which is a significant contributor to decoherence.

3. Beyond environmental suppression, the design of the qubit potential itself plays a crucial role. The helicity-based qubit is characterized by an engineered anharmonic potential landscape, which inherently minimizes leakage to higher energy levels during gate operations, thus improving fidelity.

8 Experimental Observations and Implications

8.1 Energy-Level Spectra and Transition Frequencies

The paper provides detailed plots illustrating the dependence of the energy-level structure on external control fields. For the S_z-qubit, parameters such as the anisotropy κ, magnetic field h, and electric field E_z are chosen to produce non-equidistant level spacings. This ensures that the logical qubit states $|0\rangle$ and $|1\rangle$ are energetically well isolated from higher levels, minimizing leakage during operations.

A key feature noted in the study is the universal level repulsion that manifests as anticrossing behavior near degeneracy points, where external fields lift the symmetry between coupled states. This level repulsion plays a central role in enabling controlled qubit transitions.

Furthermore, the effective qubit frequency is defined by the relation

$$\omega_q = \sqrt{H_0^2 + X_c^2},$$

where H_0 is the energy bias and X_c the tunneling amplitude. Importantly, this frequency is tunable via the applied electric and magnetic fields, offering significant flexibility in the design and control of skyrmion-based qubits.

8.2 Gate Operation Times and Coherence

The system demonstrates the potential for coherent Rabi oscillations, enabled by microsecond-scale coherence times and GHz-scale Rabi frequencies. This allows for the execution of a large number of coherent oscillations — well above the threshold necessary for fault-tolerant quantum computation.

Additionally, the scalability of this platform is supported by the use of microwave fields for gate operations, which allows for precise and efficient qubit manipulation. Importantly, individual qubits can be controlled using low-power signals, with voltage biases significantly lower than those required for skyrmion creation. This low energy requirement is a key advantage when scaling the architecture to larger qubit arrays.

8.3 Integration with Existing Technologies

The proposed skyrmion qubit platform benefits from a range of suitable material systems, including frustrated magnets and centrosymmetric compounds, in which skyrmions have already been observed under experimental conditions. This existing material base offers a promising foundation for device realization.

Furthermore, the platform aligns well with classical spintronic technologies—since skyrmions are already actively studied in that domain, many experimental tools and fabrication techniques can be directly repurposed for quantum device development.

Beyond material considerations, the architecture also supports scalable quantum processing: the bilayer-mediated multiqubit coupling scheme allows tunability of both transverse and longitudinal interactions, which is essential for implementing complex quantum circuits, executing advanced algorithms, and incorporating error correction protocols.

9 Challenges and Future Directions

9.1 Technical Challenges

1. **Material Quality and Fabrication:** One of the primary challenges in implementing skyrmion-based qubits lies in material quality and fabrication. Achieving magnetic materials with ultra-low Gilbert damping is critical to ensuring long coherence times.

2. **Noise Sources and Decoherence:** Skyrmions, being macroscopic objects, couple to conduction electrons, phonons, and magnons, and these interactions introduce noise that affects qubit stability. Developing detailed microscopic models of these couplings is essential to accurately estimate and reduce decoherence rates.

3. **Precise Qubit Control:** Precise qubit control poses its own set of difficulties. While microwave field-based control enables flexible gate operations, care must be taken to shape the control pulses to minimize leakage into higher energy states.

4. **Anharmonicity:** Maintaining sufficient anharmonicity for qubit isolation, while retaining tunability of the qubit frequency, requires careful optimization of the system parameters.

9.2 Future Research Directions

- **Advanced Material Engineering:** The development of new material platforms, particularly frustrated magnets and centrosymmetric systems, offers promising avenues for enhancing skyrmion-based quantum computing. These materials are expected to exhibit reduced Gilbert damping, which would prolong coherence times and support more pronounced quantum behavior in skyrmion dynamics. Additionally, precise control over magnetic anisotropy—whether intrinsic to the material or engineered through external means such as strain or substrate choice—will be essential for designing stable and anharmonic potential landscapes.

- **Scalable Architectures:** A significant step forward will be the experimental realization of the proposed bilayer coupling scheme, which allows for controlled qubit–qubit interactions via interlayer exchange. Successfully implementing this setup and scaling it to accommodate many qubits on a single chip would mark a critical milestone toward practical skyrmion-based quantum processors. Beyond two-dimensional layouts, exploring three-dimensional architectures and coupling mechanisms could greatly enhance scalability, offering richer connectivity and more flexible design possibilities for future quantum computing platforms.

- **Improved Readout Techniques:** Refining readout techniques like nitrogen-vacancy (NV) center magnetometry and resonant elastic x-ray scattering will be essential for accurate and non-invasive detection of single-qubit states in skyrmion-based systems. These methods enable direct imaging of spin textures and helicity, providing critical information about the qubit state. Additionally, developing hybrid sensors that integrate multiple sensing modalities could further enhance both the sensitivity and spatial resolution, enabling precise characterization and control of individual qubits within larger quantum architectures.

10 Summary and Conclusions

10.1 Summary of the Research

- The paper presents a comprehensive theoretical framework for constructing qubits based on the quantum properties of magnetic skyrmions.
- Two primary qubit designs - the S_z-qubit and the helicity qubit are proposed, each utilizing a distinct quantum degree of freedom of the skyrmion. [1]
- External electric and magnetic fields provide the means to control the qubit's energy-level spectrum, ensuring non-equidistant spacing (anharmonicity) crucial for selective qubit manipulation.
- Microwave magnetic field gradients enable single-qubit gate operations, while a bilayer exchange-coupling scheme is introduced for scalable multi-qubit interactions.
- Noise and decoherence are carefully analyzed, with estimates indicating that the coherence times (in the microsecond range) are competitive with early superconducting qubits, making skyrmion qubits promising candidates for future quantum computing technology. [2]

10.2 Key Points and Theoretical Justifications

- **Quantization and Collective Coordinates:** The transformation of classical skyrmion helicity into a quantum variable is achieved via collective coordinate quantization. The canonical commutation relation $[\hat{\phi}_0, \hat{S}_z] = i/\bar{S}$ forms the theoretical basis for discrete energy levels.
- **Energy-Level Engineering:** By tuning parameters such as the anisotropy constant κ, electric field E_z, and magnetic field gradient $h_\perp$, the potential landscape for ϕ_0 can be engineered to yield a double-well structure with significant anharmonicity.
- **Qubit Operation:** The effective two-level system is represented by the Hamiltonian

  $$H_q = \frac{H_0}{2}\hat{\sigma}_z - \frac{X_c}{2}\hat{\sigma}_x,$$

  with $\omega_q = \sqrt{H_0^2 + X_c^2}$. This forms the basis for designing robust quantum gates via microwave pulses.
- **Control, Coupling, and Readout:** The ability to manipulate skyrmion qubits through microwave fields and tailored coupling schemes (using magnetic bilayers) is critical for scalability.

  Nonvolatile readout strategies using NV magnetometry, x-ray scattering, and MFM ensure that qubit states can be reliably detected.

10.3 Concluding Remarks and Future Outlook

- The paper demonstrates that skyrmion-based qubits have the potential to combine the stability and tunability of classical spin textures with the necessary quantum coherence for information processing.

- Despite the challenges in material quality and noise management, the versatility of skyrmion qubits and the rich control afforded by external fields make them promising candidates for next-generation quantum processors.

- Continued interdisciplinary research in material science, quantum magnetism, and spintronics is expected to address current technical challenges, paving the way for practical applications in quantum computing.

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