Qubits based on merons in magnetic nanodisks

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Merons and skyrmions are classical topological solitons. However, they will become quantum mechanical objects when their sizes are of the order of nanometers. Recently, quantum computation based on nanoscale skyrmions has also been proposed [13, 14]. However, the coherence time is yet to be improved.

The simplest example of a qubit is a single spin, where the up spin is assigned to the quantum state $|0\rangle$ and the down spin is assigned to the state $|1\rangle$. The one-qubit gate operation is executed by applying magnetic field, where the Larmor precession changes the direction of the spin. The Heisenberg interaction gives a two-qubit gate operation [9, 12]. However, the problem is that the coherence time is too short in order to execute quantum algorithms.

To overcome this problem, we focus on the core spin in a nanoscale disk made of a chiral ferromagnet. Here, the magnetic dipole-dipole interaction (DDI) and the easy-plane magnetic anisotropy force the spin direction to make a clockwise or anticlockwise circular rotation in the disk plane, forming a vortex-like structure called a meron [15–25], as illustrated in Fig. 1. It is a ground-state texture in disk geometry. The direction of the spin circulation is called the chirality. Besides, the direction of the core spin, which points upward or downward, is called the polarity. Therefore, there are four types of merons depending on the polarity and chirality, as illustrated in Fig. 1. However, the Dzyaloshinskii-Moriya interaction (DMI) in chiral ferromagnets correlates the polarity and the chirality [22]. Hence, only right-handed merons shown in Figs. 1a and b are degenerated ground states [22], which serve as a classical bit. The meron structure is topologically protected when the sample is infinitely large. However, when its size is of the order of 100 nm, it is quite stable and yet it is possible to reverse the core spin. The core-spin direction could be reversed and read out by magnetic field [15–17] or electric current [18–20]. Indeed, a random-access memory has been realized experimentally based on merons [19].

In this work, we propose to use a nanoscale meron in a magnetic nanodisk as a qubit, where it simulates a single spin with a longer coherent time. First, we study numerically how much

![Image](https://example.com/image.png)
the size of a classical meron can be made small. We find that a meron with the radius containing only 7 spins is stable by assuming typical material parameters taken from MnSi. It is of the order of 3 nm as the lattice constant is 0.4 nm. When the radius of the magnetic nanodisk is of the order of nanometers, the quantum effect will be dominant. A nanoscale meron is uniquely specified by the direction of the core spin. Thus, we assign the up-spin state as $|0\rangle$ and the down-spin state as $|1\rangle$. Their superposition is allowed quantum mechanically, which represents the qubit. The coherence time is longer when the number of spins constituting a nanodisk is larger.

The Zeeman effect due to the magnetic field induces the Pauli Z operation to this qubit. By controlling the time duration of the Zeeman field, it is possible to construct an arbitrary phase-shift gate including the $\pi/4$ phase shift gate. Furthermore, by applying magnetic field or electric current, it is possible to flip a spin, which acts as the Pauli X gate. Sequential applications of the Pauli Z and X gates produce the Hadamard gate. Finally, the Ising interaction between layered merons produces the controlled-Z (CZ) gate. Sequential application of the CZ and Pauli Z gates produces the CNOT gate.

**Results**

**Classical meron in a frustrated magnet.** A meron is formed when the spin system has a nanoscale disk geometry. It is a vortex-like circulating structure of spins, where the spins on the circumference lie within the plane while the core spin points upward or downward, forming the Bloch structure due to the DDI, as illustrated in Fig. 1.

A meron is specified by the spin-circulation direction called the chirality $c = \pm 1$ and the core-spin direction called the polarity $p = \pm 1$. Here, $c = 1$ ($c = -1$) for the anti-clockwise (clockwise) rotation, and $p = 1$ ($p = -1$) for the up (down) spin.

The spin texture located at the coordinate center is parametrized as

$$m(x, y) = (\sin \theta(r) \cos \phi, \sin \theta(r) \sin \phi, \cos \theta(r)),$$

with

$$\phi = \varphi + \eta + \pi/2,$$

where $\varphi$ is the azimuthal angle ($0 \leq \varphi < 2\pi$) satisfying $x = r \cos \varphi$, $y = r \sin \varphi$. We note that there is a difference from the conventional definition in Eq. (2) by the angle $\pi/2$, where $\eta = 0$ corresponds to $c = 1$, and $\eta = \pi$ corresponds to $c = -1$. The polar angle $\theta$ is subject to

$$\theta(0) = 0, \pi, \lim_{r \to R} \theta(r) = \pi/2,$$

where $R$ is the radius of the nanodisk, while $\theta(0) = 0$ corresponds to $p = 1$ and $\theta(0) = \pi$ corresponds to $p = -1$. The meron with $cp = 1$ is called right handed and the one with $cp = -1$ is called left handed.

There are two topological numbers defining the meron. One is the skyrmion number,

$$Q \equiv -\frac{1}{4\pi} \int m(r) \cdot (\partial_x m(r) \times \partial_y m(r)) \, dx \, dy,$$

which is given by $Q = p/2$ depending on the polarity $p$. Note that $Q$ is a half integer for the meron.

The other is the winding number defined by

$$\omega \equiv \int \left( m \times \frac{\partial m}{\partial \phi} \right)_z \, d\phi = c,$$

which depends on the chirality $c$.

There are four degenerate merons with $c = \pm 1$ and $p = \pm 1$ in the absence of the DMI. However, the DMI correlates the polarity and the chirality. The DMI is induced by the inversion

![Simulated ground states for the meron for radius n = 3, 4, ..., 12. The mesh size is 0.4nm×0.4nm. The in-plane spin direction is indicated by the arrow. The out-of-plane spin component is color coded: white is in-plane, and red is out of the plane. We have used the material parameters for MnSi [30], where $A_{ex} = 0.32pJ/m$, $D = 0.115mJ/m^2$, $M_s = 152kA/m$ and $K = -0.5MJ/m^3$. See Eq.(9).](image-url)
symmetry breaking due to the interface between the nanodisk and the substrate [22]. As a result, the right-handed merons are energetically favored [22]. We assign the merons with $p = 1$ and $p = -1$ to the classical states $|0\rangle$ and $|1\rangle$, respectively.

It is a nontrivial problem how much the size of a meron can be made small. Let us call it a meron with radius $n$, when its radius contains $n$ spins. We have performed simulations on the stability of a relaxed static meron with radius $n$, $n = 2, 3, \cdots, 9$, by embedding it in the $(2n - 1) \times (2n - 1)$ square lattice, as shown in Fig. 2. The simulations are carried out under the framework of micromagnetics, where we include the ferromagnetic exchange, the DMI, the magnetic DDI, and the easy-plane magnetic anisotropy (see Methods). As a concrete instance, we have used the material parameters for MnSi [30], where $A_{ex} = 0.32 \text{pJ/m}$, $D = 0.115 \text{mJ/m}^2$, $M_s = 152 \text{kA/m}$ and $K = -0.5 \text{MJ/m}^3$. The simulated ground state of a meron is demonstrated in Fig. 2 for $n = 3, 4, \cdots, 12$. We find that a meron is formed for $n \geq 4$. In addition, the radius of the core marked in red is almost identical and contains only 4 spins irrespective of the nanodisk radius $n$ as in Fig. 2.
The stability diagram showing whether the ground state is a meron or a ferromagnetic state is given in Fig. 3, where the exchange energy and the easy-plane magnetic anisotropy energy are varied with the material parameters $D = 0.115 \text{mJ/m}^2$ and $M_s = 152 \text{kA/m}$ being fixed to those of MnSi [30]. The formation of a meron is confirmed by the spin texture as in Figs. 3a−h and by the Pontryagin number as in Figs. 3a′−h′.

There are two features. One is that a small size meron is stabilized for a small value of the exchange interaction. It is understood that the exchange interaction becomes large for a large spin angle between the adjacent spins. The spin angle becomes large and the small exchange interaction has an advantage for a nanoscale meron. The other feature is that the large easy-plane magnetic anisotropy stabilizes a nanoscale meron. It is natural because the meron has an in-plane vortex structure except for the core. The radius can be as small as 7 spins. The requirement of the exchange interaction and the easy-plane magnetic anisotropy is relaxed for a larger size of a meron.

**Control of a meron core spin.** If we apply an external magnetic field along the $z$ axis, the Zeeman effect splits the energy between the up and down spins.

$$H_{B_z} = \alpha_{B_z} B_z \sigma_z = \alpha_{B_z} B_z (|0\rangle\langle 0| - |1\rangle\langle 1|),$$

where $\alpha_{B_z}$ is a constant.

If we apply an external magnetic field along the $x$ axis, where the effective Hamiltonian for the core spin is represented as

$$H_{B_x} = \alpha_{B_x} B_x \sigma_x = \alpha_{B_x} B_x (|0\rangle\langle 1| + |1\rangle\langle 0|),$$

where $\alpha_{B_x}$ is a constant. The flip of the spin is also induced by applying electric current.

We consider a bilayer nanodisk, where two nanodisks are placed vertically (Fig. 4a). The exchange interaction between two spins reads

$$H_{\text{Ising}} = J_{\text{exchange}} \sigma_z^{(1)} \otimes \sigma_z^{(2)}.$$

Another mechanism is to use the DDI, where the two nanodisks are placed vertically or horizontally (Figs. 4a and b). It also produces the Ising interaction because the core spin direction is fixed to be up or down.

**Core-spin qubit.** We focus on the right-handed merons, which have lower energy than the left-handed merons in the presence of the DMI. We consider a nanodisk of the order of nanometers, where a superposition of the up and down spins is a quantum mechanical state. In this regime, the up and down states of the core spin may act as a qubit. We assign the meron with the up core-spin ($p = 1$) as the quantum state $|0\rangle$ and the one with the down core-spin ($p = -1$) as the quantum state $|1\rangle$, as illustrated in Fig. 1.

The phase-shift gate is constructed with the use of $H_{B_x}$. The Hadamard gate is constructed with the use of $H_{B_z}$ and $H_{B_x}$. The CNOT gate is constructed with the by $H_{\text{Ising}}$ and $H_{B_z}$. See Methods for details.

**Coherence time.** The skyrmion-number conservation prohibits the core spin to flip when the sample is infinitely large. Then, the coherence time is infinite. This is the topological protection. Physically, it follows from the fact that it costs infinitely large energy to inverse spin directions in an infinitely large sample. The topological protection is lost when the sample size is small. Indeed, when its size is of the order of 100 nm, it is possible to flip the core spin by applying magnetic field [15–17] or electric current [18–20].

The two merons representing $|0\rangle$ and $|1\rangle$ are obstructed by an energy barrier made of the exchange energy, easy-plane magnetic anisotropy and the DDI. We make an estimation for a small size classical meron based on the energy (9) in Methods. The size dependence of various energies including the total, exchange, DMI, easy-plane magnetic anisotropy and magnetic DDI energies is shown in Fig. 5. The total energy increases as the increase of the meron size as shown in Fig. 5a. The total energy is mainly determined by the exchange energy as shown in Fig. 5b. Roughly speaking, the coherence time is proportional to the total energy because it is necessary to overcome the total energy to flip the core spin. Thus, it is a dynamical problem to optimize the radius of a meron to make the coherent time long enough without losing the quantum mechanical property.

There are several features in the size dependence of the energy. First, the DMI decreases as the increase of the meron size as shown in Fig. 5c. It is understood as follows. The DMI is proportional to the spin angles between the adjacent sites. The spin angle is small for larger size merons because the spin texture becomes smooth. As a result, the DMI energy is smaller for larger size merons. Second, there are cusp structure in the magnetic anisotropy energy and the DDI energy for merons with $n \leq 6$ as shown in Figs. 5d and e. They correspond to the fact that a meron is not formed but the ground state is a ferromagnetic state.

The mean magnetization becomes smaller for larger-size merons as shown in Fig. 5f. It means that the size of the core spin is almost identical and the total spin texture looks more like a vortex structure for larger-size merons.

**Initialization.** We apply magnetic field to the sample and raise the temperature, where the system is a paramagnet. We have numerically checked that the polarity is chosen to be up by applying small external magnetic field. When we cool down the sample, right-handed up-spin merons are nucleated. This is the initialization of the quantum state $|00\cdots0\rangle$.

**Read out.** The polarity can be observed by the full-field soft X-ray transmission microscopy [22, 23], magnetic force microscopy [18, 26] or magnetic tunneling junction [27]. The polarity is fixed to be up or down by the observation. Hence, the quantum state is fixed to be $|s_1 s_2 \cdots s_N\rangle$ with $s_j = 0, 1$.
Discussions

The numerical estimation suggests that the minimum size of a meron is the order of 3 nm. The energy barrier to flip the polarity is of the order of $10^{-21}$ J, which is of the order of 70 K. It is necessary to cool down the temperature lower than 70 K to create such a meron.

We have argued that a nanoscale meron acts as a qubit and that universal quantum computation is possible. It would behave like a single spin with a longer coherence time, being supported by the meron structure. It may solve the problem of short coherence time in qubits.

In the skyrmion-based quantum computations, frustrated magnets are used [13, 14]. On the other hand, an ordinary ferromagnet is enough for the present proposal. It is a merit because there are plenty of ferromagnets compared to frustrated magnets hosting nanoscale skyrmions.

So far, we have discussed to use a meron as a qubit. However, there are four degenerate states in the absence of the DMI. Hence, it is possible to construct a qudit possessing the polarity is of the order of $10^{-23}$ J, which is of the order of 70 K to create such a meron.

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\( \alpha = 0.3, M_x = 580 \text{ kA/m}, D = 0.115 \text{ mJ/m}^2 \) and \( K = 0.1 \text{ mJ/m}^3 \). We have demonstrated that the main conclusion of this work holds for a wide range of sample sizes as in Fig. 3.

**Construction of quantum gates.** The Schrödinger equation for qubits is

\[
i\hbar \frac{d}{dt} \psi = H \psi,
\]

with the Hamiltonian

\[
H = \alpha_B B_z \sigma_z + \alpha_B B_x \sigma_x
\]

for single qubit, and

\[
H_{\text{Ising}} = J_{\text{exchange}} \sigma_x^{(1)} \otimes \sigma_x^{(2)}
\]

for two qubits. We control the coefficient \( B_z, B_x \) and \( J_{\text{exchange}} \) temporally.

We first discuss single-qubit gates. We set \( B_x = 0 \) and

\[
\alpha_B B_z (t) = \hbar \theta / 2t_0
\]

for \( 0 \leq t \leq t_0 \) and \( B_z (t) = 0 \) otherwise. The solution of the Schrödinger equation reads

\[
U_z (\theta) = \exp \left[ -i \hbar \sigma_z \int_0^t \alpha_B B_z (t) \, dt \right]
= \exp \left[ -i \theta \sigma_z / 2 \right].
\]

This is the \( z \) rotation gate by the angle \( \theta \). It gives an arbitrary phase-shift gate.

\[
U_\theta = e^{i\theta / 2} U_z (-\theta),
\]

In the similar way, we set \( B_z = 0 \) and

\[
\alpha_B B_x = \hbar \theta / 2t_0
\]

for \( 0 \leq t \leq t_0 \) and \( B_x (t) = 0 \) otherwise. The solution of the Schrödinger equation reads

\[
U_x (\theta) = \exp \left[ -i \hbar \sigma_x \int_0^t \alpha_B B_x (t) \, dt \right]
= \exp \left[ -i \theta \sigma_x / 2 \right].
\]

This is the \( x \) rotation gate by the angle \( \theta \).

\( \pi / 4 \) **phase-shift gate.** The \( \pi / 4 \) phase-shift gate is realized by the \( z \) rotation (14) by the angle \( -\pi / 4 \) as

\[
U_T = e^{i \pi / 4} U_z \left( -\frac{\pi}{4} \right),
\]

up to the overall phase factor \( e^{i \pi / 8} \).

**Hadamard gate.** The Hadamard gate

\[
U_H = \frac{1}{\sqrt{2}} \begin{pmatrix}
1 & 1 \\
1 & -1
\end{pmatrix},
\]

is realized by a sequential application of the \( z \) rotation and the \( x \) rotation [28] as

\[
U_H = -i U_Z \left( \frac{\pi}{2} \right) U_X \left( \frac{\pi}{2} \right) U_Z \left( \frac{\pi}{2} \right),
\]

with the use of Eq. (14) and Eq. (17). The quantum circuit representation of Eq. (20) is shown in Fig. 6a.

Next, we discuss the two-qubits gate. We manually control \( d_m \) as a function of time. Then, the time evolution is given by

\[
U = \exp \left[ -i \int_0^t \hbar \sigma_z \left( \alpha_B \right) \, dt \right] U_{\text{Ising}} (d_m (t) \, dt)
\]

acting on the 2-qubit in the neighboring layers.

The controlled-Z (CZ) gate \( U_{\text{CZ}} \) is a unitary operation acting on two adjacent qubits defined by

\[
U_{\text{CZ}} = \text{diag} (1, 1, 1, -1)
\]

and constructed as [29]

\[
U_{\text{CZ}} = e^{i \pi / 4} U_Z \left( \frac{\pi}{2} \right) U_Z \left( \frac{\pi}{2} \right) U_{\text{ZZ}} \left( \frac{\pi}{2} \right),
\]

whose quantum circuit representation is shown in Fig. 6b.

The CNOT gate \( U_{\text{CNOT}}^{1 \rightarrow 2} \)

\[
U_{\text{CNOT}}^{1 \rightarrow 2} = \begin{pmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 1 \\
0 & 0 & 1 & 0
\end{pmatrix},
\]

sequential applications of the CZ gate and the Hadamard gate as

\[
U_{\text{CNOT}}^{1 \rightarrow 2} = U_{\text{H}} (2) U_{\text{CZ}} U_{\text{H}} (2),
\]
where the control qubit is the skyrmion in the first layer and target qubit is the skyrmion in the second layer. The corresponding quantum circuit representation is shown in Fig. 6c.

**Code availability.** The micromagnetic simulator MuMax used in this work is publicly accessible at https://mumax.github.io/index.html.

**Data availability.** The data that support the findings of this study are available from the corresponding authors upon reasonable request.

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**Author contributions**

M.E. conceived the idea and conducted the project. J.X. and X.Z. performed numerical simulations in collaboration with X.L. and Y.Z. All authors discussed the results and wrote the manuscript.

**Additional information**

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