A Frustrated Bimeronium: Static Structure and Dynamics

Xichao Zhang,1, a) Jing Xia,2, a) Motohiko Ezawa,3, b) Oleg A. Tretiakov,4, 5 Hung T. Diep,6 Guoping Zhao,2 Xiaoji Liu,7 and Yan Zhou1, c)

1) School of Science and Engineering, The Chinese University of Hong Kong, Shenzhen, Guangdong 518172, China
2) College of Physics and Electronic Engineering, Sichuan Normal University, Chengdu 610068, China
3) Department of Applied Physics, The University of Tokyo, 7-3-1 Hongo, Tokyo 113-8656, Japan
4) School of Physics, The University of New South Wales, Sydney 2052, Australia
5) National University of Science and Technology “MISIS”, Moscow 119049, Russia
6) Laboratoire de Physique Théorique et Modélisation, Université de Cergy-Pontoise, 95302 Cergy-Pontoise Cedex, France
7) Department of Electrical and Computer Engineering, Shinshu University, 4-17-1 Wakasato, Nagano 380-8553, Japan

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We show a new topological spin texture called “bimeronium” in magnets with in-plane magnetization. It is a topological counterpart of skyrmionium in perpendicularly magnetized magnets. The bimeronium carries a zero net topological charge but can be seen as a combination of two bimerons with opposite topological charges. We report the static structure and spin-orbit-torque-induced dynamics of an isolated bimeronium in a magnetic monolayer with frustrated exchange interactions. We study the anisotropy and magnetic field dependences of a static bimeronium. We also explore the bimeronium dynamics driven by the damping-like spin-orbit torque. We find that the bimeronium shows steady rotation when the spin polarization direction is parallel to the easy axis. Moreover, we demonstrate the annihilation of the bimeronium when the spin polarization direction is perpendicular to the easy axis. Our results are useful for understanding fundamental properties of bimeronium structures and may offer an approach to build bimeronium-based spintronic devices.

Topological magnetism and spin frustration are important and hot topics in the fields of magnetism and spintronics1–13. The link between topological magnetism and spin frustration lies in the fact that many topological spin textures can be stabilized in frustrated spin systems14–37. For example, the magnetic skyrmion is an exemplary topological spin texture12, which can be regarded as a quasi-particle and shows novel dynamics3–13. The magnetism and spintronics community has focused on skyrmions stabilized by the Dzyaloshinskii-Moriya (DM) interaction38–42, however, recent progress in the field revealed that skyrmions and other topological spin textures can be found in a different system, where topological spin textures are stabilized by exchange frustration14–37. Typical frustrated topological spin textures include the skyrmion14–36, the skyrmionium17, and the bimeron20,34,36. Indeed, skyrmioniums and bimeron can also be stabilized by the DM interaction34,43–48. In principle, all of these particle-like topological spin textures can be used to carry information4,5,7–11,13, and thus are promising for building future information storage and logic computing devices4,5,7–11,13.

In this Letter, we report that the topological counterpart of skyrmioniums, which is called the bimeronium [Fig. 1(a)], can be stabilized in an in-plane frustrated magnetic system with competing exchange interactions. We study the static structure of an isolated bimeronium with a topological charge of zero at different conditions of anisotropy and magnetic field. We also investigate the dynamic properties of an isolated bimeronium induced by the damping-like spin-orbit torque (SOT). Our results suggest that the frustrated bimeronium could be used as a special building block for spintronic applications, however, it cannot move like the frustrated bimeron6 due to its more complex and non-circular symmetric spin structure that could be annihilated by the SOT at certain conditions.

Our simulated system is a $J_1$-$J_2$-$J_3$ classical Heisenberg model on a simple monolayer square lattice4,12,16,21,30,36,37,49, where the nearest-neighbor (NN) exchange interaction $J_1$ is ferromagnetic (FM), while the next-NN (NNN) $J_2$ and next-NNN (NNNN) $J_3$ exchange interactions are antiferromagnetic (AFM). The Hamiltonian $\mathcal{H}$ includes the FM and AFM exchange interactions, in-plane easy-axis magnetic anisotropy ($K$), and applied magnetic field ($B$), given as

$$\mathcal{H} = -J_1 \sum_{\langle i,j \rangle} m_i \cdot m_j - J_2 \sum_{\langle\langle i,j \rangle \rangle} m_i \cdot m_j - J_3 \sum_{\langle\langle\langle i,j \rangle \rangle \rangle} m_i \cdot m_j - K \sum_i (m_i^x)^2 - \sum_i B \cdot m_i,$$

where $m_i$ represents the normalized spin at the site $i$, $|m_i| = 1$. $\langle i,j \rangle$, $\langle\langle i,j \rangle \rangle$, and $\langle\langle\langle i,j \rangle \rangle \rangle$ run over all the NN, NNN, and NNNN sites in the magnetic monolayer, respectively. $K$ is the easy-axis magnetic anisotropy constant, and the easy axis direction is aligned along the $x$ axis. $B$ is the applied magnetic field.

The spin dynamics is simulated by using the Object Oriented MicroMagnetic Framework (OOMMF)50 with periodic boundary condition (PBC) and our extension modules for the $J_1$-$J_2$-$J_3$ classical Heisenberg model16,21,30,36,37. We also use the OOMMF conjugate gradient minimizer for obtaining relaxed spin structures, which is a method that locates local minima in the energy surface through direct minimization techniques50. The spin dynamics is governed by the Landau-

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a)X.Z. and J.X. contributed equally to this work.
b)Email: ezawa@ap.t.u-tokyo.ac.jp
c)Email: zhouyan@cuhk.edu.cn
Lifshitz-Gilbert (LLG) equation

\[
\frac{dm}{dt} = -\gamma_0 m \times h_{\text{eff}} + \alpha \left( m \times \frac{dm}{dt} \right),
\]

where \(|m| = 1\) represents the normalized spin, \(h_{\text{eff}} = -\frac{1}{m_0 M_s} \frac{dH}{dt}\) is the effective field, \(t\) is the time, \(\alpha\) is the Gilbert damping parameter, \(\gamma_0\) is the absolute value of the gyromagnetic ratio, and \(M_s\) is the saturation magnetization.

For the spin dynamics driven by the SOT, we consider the damping-like SOT \(\tau_d\) expressed as\(^4\) \(\tau_d = \frac{u}{\gamma_0} (m \times p \times m)\), where \(u = |(\gamma_0 / \mu_0 e) \cdot (j \theta_{SH}/2M_s)|\) is the spin torque coefficient. \(\mu_0\) is the reduced Planck constant, \(e\) is the electron charge, \(\mu_0\) is the vacuum permeability constant, \(a\) is the thickness of the FM monolayer (i.e., the lattice constant here), \(j\) is the applied current density, \(\theta_{SH}\) is the spin Hall angle. \(p\) denotes the spin polarization direction. \(\tau_d\) is added to the right-hand side of Eq. (2) when the damping-like SOT is turned on.

In this work, we define the topological charge \(Q\) in the continuum limit by the formula\(^6\) \(Q = \frac{1}{2\pi} \int m(r) \cdot (\partial_r m(r) \times \partial_\theta m(r)) d^2 r\). We parametrize the bimeronium [Fig. 1(b)] and bimeron [Fig. 1(c)-(d)] as \(m(r) = m(\theta, \phi) = (\cos \theta, \sin \theta \sin \phi, -\sin \theta \cos \phi)\), and we parametrize the skyrmion [Fig. 1(e)] and skyrmion [Fig. 1(f)-(g)] as \(m(r) = m(\theta, \phi) = (\sin \theta, \cos \phi, \sin \theta \sin \phi, \cos \theta)\). We define \(\phi = Q_0 \varphi + \eta\), where \(\varphi\) is the azimuthal angle in the y-z plane \((0 \leq \varphi < 2\pi)\). For the bimeron and skyrmion, we assume that \(\theta\) rotates \(\pi\) for spins from the texture center to sample edge\(^8\). For the bimeronium and skyrmionium, we assume that \(\theta\) rotates \(2\pi\) for spins from the texture center to sample edge\(^8\). Hence, \(Q_0 = \frac{1}{2\pi} \int \varphi d\phi\) is the vorticity and \(\eta\) is the helicity defined mod \(2\pi\). Note that \(\eta = 0\) is identical to \(\eta = 2\pi\).

The default simulation parameters are\(^{16,21,30,36,37}\): \(J_1 = 30\) meV, \(J_2 = -0.8\) (in units of \(J_1 = 1\)), \(J_3 = -0.9\) (in units of \(J_1 = 1\)), \(K = 0.02\) (in units of \(J_1/a^3 = 1\)), \(B = 0\) (in units of \(J_1/a^3 M_s = 1\)), \(\alpha = 0.3\), \(\gamma_0 = 2.21 \times 10^5\) m \(A^{-1} s^{-1}\), \(\theta_{SH} = 0.2\), and \(M_s = 580\) kA m\(^{-1}\). The lattice constant is \(a = 0.4\) nm (i.e., the mesh size is \(0.4 \times 0.4 \times 0.4\) nm\(^3\)). We have simulated the metastability diagram showing that the frustrated bimeron can be a metastable state for a wide range of \(J_2\) and \(J_3\) (see supplemental material). The minimum required value of \(J_3\) for stabilizing bimeronium decreases with increasing \(J_2\).

We first study the static structures and properties of a relaxed isolated bimeron in the magnetic monolayer with competing exchange interactions and in-plane easy-axis anisotropy, where we set \(J_2 = -0.8, J_3 = -0.9, K = 0.02\) and \(B = 0\). Figure 1 shows the top views of both relaxed bimeronium and bimeron structures. For the purpose of comparison, we also show the relaxed solutions of skyrmionium and skyrmion obtained with the same parameters but an easy-axis aligned along the z axis. The given skyrmionium with \(Q = 0\) [Fig. 1(e)] consists of an inner skyrmion with \(Q = -1\) [Fig. 1(f)] and an outer skyrmion with \(Q = +1\) [Fig. 1(g)]. Similarly, the corresponding bimeronium with \(Q = 0\) [Fig. 1(b)] exists as a combination of an inner bimeron with \(Q = -1\) [Fig. 1(c)] and an outer bimeron with \(Q = +1\) [Fig. 1(d)]. Namely, the bimeron in in-plane magnetized magnets can be seen as a topological counterpart of the skyrmionium in out-of-plane magnetized magnets.

The total energy as well as different energy contributions for a relaxed bimeron are given in Fig. 2(a). It can be seen that the competition among the FM NN, AFM NNN, and AFM NNNN exchange interactions is considerable. The magnetic anisotropy energy is positive, which means larger anisotropy constant could raise the total energy of a bimeron and may reduce its stability. A controllable degree of freedom of topological spin textures in frustrated magnetic systems is the helicity \(\eta\). It is found that the bimeronium energy is independent of its helicity \(\eta\) [Fig. 2(b)].

As the magnetic anisotropy can be adjusted experimentally, we study the bimeronium structure for different anisotropy constants \(K\), as shown in Fig. 3. By increasing \(K\) from 0 to 0.095, while keeping the easy-axis orientation aligned along the \(x\) direction, the size of relaxed bimeronium decreases obviously. The spin component \(m_x\) reduces with increasing \(K\), while \(m_y\) and \(m_z\) do not depend on \(K\) [Fig. 3(a)]. The total energy [Fig. 3(b)], anisotropy energy [Fig. 3(c)], AFM NNN
As the bimeronium size is related to its spin component along the easy-axis orientation, which is $m_x$ in this work [Fig. 3(a)], we apply a magnetic field along the $x$ direction with a strength of $B_z$. Within a reasonable range of $B_z$ that does not destroy the bimeronium (i.e., in this work $B_z/1000 = -0.2 \sim 0.8$ in units of $J_1/a^3 M_S = 1$), it is found that the bimeronium size is not sensitive to $B_z$. The spin component $m_x$ increases with $B_z$, while $m_y$ and $m_z$ are independent of $B_z$ (see supplemental material). The total energy, anisotropy energy, and FM NN exchange energy are proportional to $B_z$, while the AFM NNN and NNNN exchange energies are inversely proportional to $B_z$ (see supplemental material).

As shown in Fig. 4, we continue by investigating the dynamic properties of an isolated bimeronium driven by the damping-like SOT $\tau_d$. We assume that $\tau_d$ is generated by the spin Hall effect in a heavy-metal substrate layer underneath the magnetic monolayer. We first consider that the direction of spin polarization is aligned along the easy-axis direction, i.e., $p = +\hat{x}$. A recent report suggested that the frustrated bimeron shows SOT-induced rotation when the spin polarization direction is parallel to the easy-axis direction. Similarly, we find that the bimeronium also shows steady rotation induced by the damping-like SOT when $p = +\hat{x}$. The rotation period decreases with increasing driving current density [Fig. 4(a)] and the rotation frequency is proportional to the driving current density [Fig. 4(b)]. At a given current density, the rotation frequency decreases with increasing damping parameter $\alpha$. For the rotating bimeronium, its total energy [Fig. 4(c)] and spin components [Fig. 4(d)] are independent of time when the steady rotation state is reached. It is worth mentioning that the bimeronium rotation depends on both the intrinsic properties of the bimeronium as well as the spin polarization direction. As shown in Fig. 4(e), when the bimeronium consists of an inner bimeron with $Q = -1$ and an outer bimeron with $Q = +1$, it shows counterclockwise rotation driven by the damping-like SOT with $p = +\hat{x}$. If the initial bimeronium structure consists of an inner bimeron with $Q = +1$ and an outer bimeron with $Q = -1$, it may show clockwise rotation driven by the damping-like SOT with $p = -\hat{x}$ (see supplemental material).

As reported in Ref. 36, the frustrated bimeron could show SOT-induced translational motion when the spin polarization direction is perpendicular to the easy-axis direction. However, we find that the frustrated bimeronium cannot be driven into steady motion when the spin polarization direction is perpendicular to the easy-axis direction, i.e., $p = \pm \hat{y}$. Instead, the damping-like SOT leads to the deformation and annihilation of the bimeronium structure, as shown in Fig. 5. The total energy [Fig. 5(a)] and spin component $m_x$ [Fig. 5(b)] decreases significantly during the SOT-induced annihilation of the bimeronium. The spin components $m_y$ and $m_z$ also show certain fluctuations during the annihilation process. Note that the initial bimeronium structure in Fig. 5 consists of an inner bimeron with $Q = -1$ and an outer bimeron with $Q = +1$. For the bimeronium structure consisting of an inner bimeron with $Q = +1$ and an outer bimeron with $Q = -1$, it also shows deformation and annihilation when the damping-like SOT with $p = \pm \hat{y}$ is applied (see supplemental material).

FIG. 2. (a) Different energy contributions for a relaxed bimeronium with $\eta = 0$. The energies are given in units of $J_1 = 1$. (b) The total energy of a relaxed bimeronium as a function of $\eta$. Top views of relaxed bimerions with (c) $\eta = 0$, (d) $\eta = \pi/2$, (e) $\eta = \pi$, and (f) $\eta = 3\pi/2$ are given. Here, $J_2 = -0.8$, $J_3 = -0.9$, $K = 0.02$, and $B = 0$. The arrows represent the spin directions. The out-of-plane spin component ($m_z$) is color coded. The displayed area is of $10 \times 10$ nm$^2$.

FIG. 3. (a) Spin components as functions of $K$. A bimeronium with $\eta = 0$ is relaxed at the center of a monolayer with $J_2 = -0.8$, $J_3 = -0.9$, and $B = 0$. (b) Total energy $E_{\text{total}}$ as a function of $K$. The energies are given in units of $J_1 = 1$. (c) Anisotropy energy $E_K$ as a function of $K$. (d) NN exchange energy $E_{\text{NN}}$ as a function of $K$. (e) NNN exchange energy $E_{\text{NNN}}$ as a function of $K$. (f) NNNN exchange energy $E_{\text{NNNN}}$ as a function of $K$. Top views of relaxed bimerions with $\eta = 0$ at (g) $K = 0.01$, (h) $K = 0.02$, (i) $K = 0.04$, and (j) $K = 0.08$ are given. The arrows represent the spin directions. The out-of-plane spin component ($m_z$) is color coded. The displayed area is of $12.4 \times 12.4$ nm$^2$.

exchange energy [Fig. 3(e)], and AFM NNN exchange energy [Fig. 3(f)] increase with $K$, while the FM NN exchange energy [Fig. 3(d)] decreases with increasing $K$. When $K$ is larger than certain threshold (i.e., 0.1 in this work), the bimeronium structure becomes unstable and cannot exist in the system. We also study the effect of an external in-plane magnetic field on the bimeronium structure (see supplemental material).
FIG. 4. (a) Bimeronium rotation period $T$ as a function of driving current density $j$ for different damping parameters $\alpha$. The spin polarization direction $p = +\hat{x}$. (b) Bimeronium rotation frequency $f$ as a function of $j$ for different $\alpha$. (c) Time-dependent total energy of a typical rotating bimeronium. (d) Time-dependent spin components of a typical rotating bimeronium. (e) Top views of a typical rotating bimeronium at selected times. The arrows represent the spin directions. The out-of-plane spin component ($m_z$) is color coded. Here, $J_2 = -0.8$, $J_3 = -0.9$, $K = 0.02$, and $B = 0$. The initial bimeronium state consists of an inner bimeron with $Q = -1$ and an outer bimeron with $Q = +1$.

In conclusion, we have studied the static structures and SOT-induced dynamics of an isolated bimeronium in a frustrated magnetic monolayer with competing FM and AFM exchange interactions. Note that the small FM NN and large AFM NNN exchange interactions could be realized in low-dimensional compound Pb$_2$VO(PO$_4$)$_2$ with frustrated square lattice. The bimeronium structure carries a topological charge of $Q = 0$ but it can be regarded as a combination of two bimerons with opposite topological charges. Namely, it may consists of an inner bimeron with $Q = -1$ and an outer bimeron with $Q = +1$, and it may also consists of an inner bimeron with $Q = +1$ and an outer bimeron with $Q = -1$.

It is found that the frustrated bimeronium energy is independent of its helicity in the in-plane magnetized system, however, the size and energy of a bimeronium is subject to the easy-axis magnetic anisotropy. A larger anisotropy will lead to a smaller compact bimeron with higher total energy. Indeed, extremely large anisotropy may result in the instability of the bimeronium structure. On the other hand, the bimeronium energy can be subtly adjusted by an external in-plane magnetic field, however, the bimeronium size is insensitive to the magnetic field.

In this work, we have also numerically demonstrated that the bimeronium can be driven into steady rotation by the damping-like SOT, of which the spin polarization direction is parallel to the easy-axis direction. It is found that the rotational dynamics depends on both the internal bimeronium structure and the spin polarization direction. In particular, when the spin polarization direction is perpendicular to the easy-axis, the bimeronium is annihilated by the damping-like SOT.

We point out that the rotational feature of a bimeronium may be used for building multi-state memory devices, where bimeronums with different helicity values stand for different information bits. The current-controlled rotation of a bimeronium could also be useful for future spin-wave applications, where arrays of bimeroniums serve as reconfigurable spin wave guides. We believe our results are important for understanding the frustrated bimeronium structures, and can provide guidelines for the design of spintronic devices based on bimeronums.

See supplemental material for additional simulation results.

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DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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