Current-induced skyrmion motion on magnetic nanotubes

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Abstract

Magnetic skyrmions are believed to be the promising candidate of information carriers in spintronics. However, the skyrmion Hall effect, due to the nontrivial topology of skyrmions, can induce a skyrmion accumulation or even annihilation at the edge of the devices, which hinders the real-world applications of skyrmions. In this work, we theoretically investigate the current-driven skyrmion motion on magnetic nanotubes which can be regarded as ‘edgeless’ in the tangential direction. By performing micromagnetic simulations, we find that the skyrmion motion exhibits a helical trajectory on the nanotube, with its axial propagation velocity proportional to the current density. Interestingly, the skyrmion’s angular speed increases with the increase of the thickness of the nanotube. A simple explanation is presented. Since the tube is edgeless for the tangential skyrmion motion, a stable skyrmion propagation can survive in the presence of a very large current density without any annihilation or accumulation. Our results provide a new route to overcome the edge effect in planar geometries.

Keywords: skyrmion, magnetic nanotube, spintronics

Supplementary material for this article is available online

(Some figures may appear in colour only in the online journal)
depended by imposing an additional pinning layer at the edge of the track [35]. More recently, Yang et al discovered a novel twisted skyrmion state at the boundary of two antiparallel magnetic domains coupled antiferromagnetically, through which skyrmions with opposite polarities can transform mutually [36]. Under proper conditions, the domain boundary can also act as a reconfigurable channel for skyrmion propagations [36]. All these proposals were aiming to eliminate the skyrmion Hall effect in a planar geometry. Different from a planar strip with two edges, a closed curved geometry, e.g. magnetic spheres and/or cylinders, can be edgeless. In such geometries, the skyrmion cannot vanish at edges any more, even in the presence of the skyrmion Hall effect. Of course, the curvature of the non-planar geometry may induce other interesting consequences like those in domain wall dynamics [37, 38]. These facts motivate us to consider the skyrmion motion on a nanotube that a planar strip is rolled up, as shown in figure 1.

In this work, we show, via micromagnetic simulations, that the skyrmion can be created on magnetic nanotubes and the skyrmion motion exhibits a helical trajectory when it is driven by an electric current along the tube. Further, we demonstrate that the skyrmion can travel over arbitrarily long distances in the presence of a very large current density since the nanotube geometry are edgeless. The skyrmion’s angular speed increases with the increase of the thickness of the nanotube, which is different from the case in planar geometry.

We consider the magnetic energy density in a nanotube,
\[ E = E_{\text{ex}} + Dm \cdot (\nabla \times m) - K(m \cdot \hat{p})^2 + E_{\text{DDI}}, \]
where \( m \) is the unit magnetization vector with a saturation magnetization \( M_s \), \( E_{\text{ex}} \) is the ferromagnetic exchange constant, \( D \) is the bulk Dzyaloshinskii–Moriya interaction (DMI) strength, \( K > 0 \) is the easy-normal anisotropy constant along \( \hat{p} \) direction, and \( E_{\text{DDI}} \) is the energy density of dipole–dipole interaction. \( |\nabla m|^2 \) is short for \( |\nabla m_1|^2 + |\nabla m_2|^2 + |\nabla m_3|^2 \).

To study the current-driven magnetization dynamics, we solve the Landau–Lifshitz–Gilbert equation with the spin transfer torque \( \tau_{\text{stt}} \) associated with the electric current flowing along the tube [39, 40],
\[ \partial_t m = -\gamma m \times H_{\text{eff}} + \alpha m \times \partial_t m + \tau_{\text{stt}}. \]
Here \( \gamma \) is the gyromagnetic ratio, \( \alpha \) is the Gilbert damping constant, and \( H_{\text{eff}} = -\frac{\delta E_{\text{ex}}}{\delta m} \) is the effective field. The spin transfer torque \( \tau_{\text{stt}} \) can be written as
\[ \tau_{\text{stt}} = -(v \cdot \nabla) m + \beta m \times (v \cdot \nabla) m, \]
where \( v = -\mu e j / [\mu B (1 + \beta^2)] \) is a vector with dimension of velocity and parallel to the spin-polarized current density \( j \), \( e \) is the electronic charge, \( p \) is the polarization rate of the current, \( \mu B \) is the Bohr magneton, and \( \beta \) is the dimensionless parameter describing the degree of non-adiabaticity [39].

To visualize the skyrmion motion on magnetic nanotubes, we performed micromagnetic simulations by employing the MuMax3 package [40]. The nanotube for numerical study is defined by fixed outer radius \( R = 50 \text{ nm} \), various thickness \( d = 10–40 \text{ nm} \), and length \( l = 600 \text{ nm} \). The mesh size of \( 2 \times 2 \times 2 \text{ nm}^3 \) is used in our simulations. The magnetic nanotubes are assumed to be made of FeGe and the following material parameters are used [41]: exchange stiffness \( A_{\text{ex}} = 8.78 \text{ pJ m}^{-1} \), saturation magnetization \( M_s = 1.1 \times 10^5 \text{ A m}^{-1} \), bulk DMI parameter \( D \) varying from 0.8 mJ m\(^{-2}\) to 1.5 mJ m\(^{-2}\), easy-normal anisotropy parameter \( K = 2 \times 10^5 \text{ J m}^{-3} \), and Gilbert damping constant \( \alpha = 0.1 \). For the spin transfer torque, we assume \( p = 0.5 \) and \( \beta = 0.5 \). Figure 1 schematically shows a Bloch-type skyrmion (a) in a planar film and (b) in a nanotube. The coordinate system is shown at the lower right corner of figure 1(b). \( \rho, \phi \) and \( z \) represent the radial, tangential, and axial coordinates, respectively. The origin is set to be the center of the tube.

Firstly, in order to see how a skyrmion can exist on magnetic nanotubes, we numerically calculate the phase diagram by tuning parameters \( D \) and \( d \). We initially set \( m_p = -1 \) on the intersection of a 20 nm-diameter cylinder along the half-line \( \phi = 0 \), \( z = 0 \) and the nanotube, and set \( m_p = 1 \) in the rest part, and then relaxed the system from the initial state by minimizing the total energy. Numerical results are shown in figure 2, in which three phases are identified: single domain of \( m_p = 1 \) (rhombuses), ordinary isolated skyrmion (circles), and stretched skyrmion (squares) where the skyrmion is elongated like a spiral reaching the ends of nanotube. The typical magnetization profiles are shown next to the phase diagram. When \( D \) is small, the stable state is a single domain. The phase boundary between the single-domain phase and the ordinary skyrmion phase is mesh-size-dependent. That is because when \( D \) is small, the skyrmion size is also small [42, 43] so that the 2 nm mesh is not small enough to mimic the continuous model. To justify this, we have tested that when the mesh size is 1 nm, the stable state becomes an ordinary isolated skyrmion for \( D = 1 \text{ mJ m}^{-2} \). This mesh-size-related annihilation of skyrmions is well-known and has been studied in detail [44]. For an intermediate \( D \), an isolated skyrmion can exist. The sectional view cut in \( xy \) plane (upper) and the front view after expanding the tube into a plane (lower) are shown for \( D = 1.2 \text{ mJ m}^{-2} \) and \( d = 40 \text{ nm} \). From the inner surface to the outer surface, the skyrmion size is getting larger.
The skyrmion size (or radius) is almost linearly dependent on \( \rho \). It can also be observed that the skyrmion is tilted to the right (see also figure 4(a) below). This is because of the effective DMI induced by the curvature of the tube, which will be explained later. When \( D \) is large enough, the stable state is a stretched skyrmion. The stretched skyrmion forms a right-handed spiral on the tube when \( D > 0 \) as shown in the figure, or a left-handed spiral when \( D < 0 \) (not shown). The phase boundary between the ordinary skyrmion phase and the stretched skyrmion phase depends on the diameter of the tube, similar to the well known fact that the confinement effect of the sample boundary is important in stabilization of the skyrmion in planar films [45]. In planar films, the upper limit of \( D \) for the existence of an isolated skyrmion is larger in a small sample than that in an infinite film [43, 45]. However, the upper limit of \( D \) here in the nanotube is smaller than that in an infinite film, probably because the skyrmion size is larger than the diameter of the nanotube. The skyrmion size increases with \( d \) due to the demagnetizing field, similar to the case in the planar geometry [42, 43].

To investigate the current-driven skyrmion dynamics in infinite long nanotubes, we employ the periodic boundary condition in \( z \)-direction. The DMI is fixed to be \( D = 1.2 \text{ mJ m}^{-2} \). A typical current-driven skyrmion motion in the nanotube is plotted in figure 3(a) for \( d = 20 \text{ nm} \). We have compared the results obtained by using 2 nm and 1 nm mesh sizes and found no observable difference. So in the calculations below, we use 2 nm mesh size. A skyrmion is initially created at one end of the nanotube. Then we inject an electric current along the axis of the nanotube. The current exerts spin transfer torques on the magnetization texture. Similar to the skyrmion motion in planar films [2, 3, 27], the skyrmion moves not only along the current direction, but also in the tangential direction at the same time because of the skyrmion Hall effect. As a result, the skyrmion trajectory follows a helical curve, as shown in the green line of figure 3(a). As a comparison, the trajectory of skyrmion motion in a planar film of the same thickness is shown in figure 3(b). Due to the skyrmion Hall effect, the skyrmion will annihilate at the edge when the current density is large enough. To see more details, we calculate the instantaneous velocity of the skyrmions from the simulation results. Considering the outer surface only, the skyrmion velocity \( \mathbf{v} \) has two components: the component parallel to the direction of the electric current, \( v_\parallel = \mathbf{v} \cdot \hat{z} \), and a perpendicular one, \( v_\perp = \mathbf{v} \cdot \hat{\phi} = R \omega \), where \( \omega \) is the skyrmion’s ‘angular speed’.

Figures 3(c) and (d) show the current dependence of \( v_\parallel \) and \( v_\perp \), respectively. The two velocity components of the skyrmion in planar film are also plotted as comparisons. (It is noted that in planar film the velocity is measured before the skyrmion annihilation at the edge). As the injected current density \( j \) varies from \( 1 \times 10^{10} \text{ A m}^{-2} \) to \( 1 \times 10^{13} \text{ A m}^{-2} \), both \( v_\parallel \) and \( v_\perp \) are proportional to \( j \). In planar film, the skyrmion annihilates when \( j \) is larger than \( 2 \times 10^{11} \text{ A m}^{-2} \), as shown by the vertical grey lines in figures 3(c) and (d). The corresponding longitudinal speed is no more than \( 100 \text{ m s}^{-1} \). However, because the tube is closed in the tangential direction, the skyrmion does not vanish even at a very large current density. The \( v_\parallel \) can reach \( \approx 2000 \text{ m s}^{-1} \) when we inject a very large \( j = 1 \times 10^{13} \text{ A m}^{-2} \). So the skyrmion motion in nanotube geometries possesses the advantages that a stable skyrmion propagation can survive in the presence of a very large current density and the propagation speed can be very fast.

We then fix the current density \( j = 5 \times 10^{12} \text{ A m}^{-2} \), and investigate the \( d \)-dependence of skyrmion velocity at the outer surface of the nanotube. The outer radius of the nanotube is still \( R = 50 \text{ nm} \) as above. Figures 3(e) and (f) show the \( d \)-dependence of \( v_\parallel \) and \( v_\perp \), respectively. For different thickness \( d \), \( v_\parallel \) is almost a constant (blue circles in figure 3(e)), and shows no apparent difference in comparison with that in planar films (green squares in figure 3(e)). However, \( v_\perp \) increases with \( d \) (blue circles in figure 3(f)), which is different from that in planar films, where \( v_\perp \) stays unchanged when \( d \) increases (green squares in figure 3(f)).

See supplementary material MOVIE 1 (stacks.iop.org/JP2/52/225001/mmedia) for skyrmion motions in different thicknesses.
To better understand the numerical findings, we first consider the effect of the curvature of the nanotube. Suppose the nanotube is constructed by many coaxial thin layers of tubes, with their thicknesses much smaller than their radii $\rho$. For each layer, we can express the energy density in local coordinates on the outer surface of the nanotube constructed by basis vectors $(\hat{\rho}, \hat{\varphi}, \hat{z})$ \cite{46, 47}. Intuitively, this means to expand the tube into a planar film. To be more clear in comparison with a planar film, we rename the local basis vectors as $\hat{\rho} \rightarrow \hat{x}'$, $\hat{\varphi} \rightarrow \hat{y}'$, and $\hat{z} \rightarrow \hat{z}'$. In the local coordinates, the energy density is

$$E = A_{\text{ex}} |\nabla' m|^2 + D m \cdot (\nabla' \times m) - Km z'_2 + E_{\text{DMI}}$$

\[\text{(4)}\]

where $\nabla'$ denotes the derivatives in primed coordinates. Compared to a planar film, the curvature induces three extra terms. The first term $2A_{\text{ex}} (m_x' \partial_y m_z' - m_y' \partial_y m_x') / \rho$ comes from the exchange interaction. For a fixed $\rho$, this term has the same mathematical form as an interfacial DMI along $\hat{z}$ direction \cite{48} (the constant term $A_{\text{ex}} / \rho^2$ does not affect the magnetization profile). A left-handed Néel wall \cite{49, 50} is thus preferred along $\hat{z}$ direction. However, it is known that the bulk DMI prefers a Bloch skyrmion. The superposition of this two effects therefore gives a skyrmion tilting to the right, as schematically plotted in the figure 4(a), which is consistent with the numerical observation shown in figure 2. When the sign of $D$ is reversed, the rotation direction of the Bloch skyrmion is also switched, so the orientation of the tilting is flipped consequently. The stretched skyrmion also grows with a certain tilting direction for the same reason. The second term is an effective easy-axis anisotropy along $z'$ direction, due to which the skyrmion is stretched along the axial direction of the tube. Note that $A_{\text{ex}}/2\rho^2$ is smaller than $K$ for the parameters we used so that the easy-normal anisotropy $K$ still dominates. The third term $D m_y m_z' / \rho$ comes from the DMI, and it prefers that $m_y$ and $m_z'$ have opposite signs, which competes with the first term. We note that the first $A_{\text{ex}}$-term is approximately $2A_{\text{ex}} m_y m_z' / (\rho w)$ where $w \approx \pi D / (4K)$ is the skyrmion wall

Figure 3. The trajectory of current-driven skyrmion motion in the nanotube (a) and the planar film (b). The current-dependence of skyrmion velocity, $v_{||}$ (c) and $v_{\perp}$ (d), in which $d$ is fixed to 20 nm and the vertical grey line denotes the annihilation of skyrmion at edges for the case of planar geometry, where the velocity is calculated before the annihilation of skyrmions. (e) and (f) The $d$-dependence of $v_{||}$ and $v_{\perp}$ in both planar and tube geometries, in which $j$ is fixed to $5 \times 10^{12}$ A m$^{-2}$. Symbols are numerical results. Solid lines are analytical results obtained from equations (6) and (7) for planar films and dashed curves are from equation (8).
width [42, 43]. For parameters used in the simulations, $2\lambda_{ex}/w$ is much larger than $D$. Thus, the first $\lambda_{ex}$-term dominates over the $D$-term, and the contribution from the latter term can be safely ignored.

Below, we analytically understand the motion of the skyrmion on the nanotube. Let us first consider a planar film, in which the skyrmion follows the Thiele’s equation [2, 23, 29, 31, 34, 51, 52].

$$\vec{G} \times (\vec{v} - \vec{v}_s) + D(\alpha \vec{v} - \beta \vec{v}_s) = 0,$$

(5)

where $\vec{G} = 4\pi \vec{Q}$ is the gyrovector where $Q = \pm 1$ is the skyrmion number, $D_{ij} = \int \partial_i \vec{m} \cdot \partial_j \vec{m} d\vec{r}$ is the dissipation tensor, and $\vec{v}$ is the skyrmion velocity. For a rotationally symmetric skyrmion, $D$ degenerates to a scalar that can be calculated from the numerical results [29]. In our simulations, the electric current is applied only along $\hat{z}$ direction, and the Thiele’s equation can be easily solved. The parallel component ($z$-component) and the perpendicular component ($y$-component) are

$$v_{\parallel} = \left[ \frac{\beta}{\alpha} + \frac{G^2}{\alpha} \frac{\alpha - \beta}{G^2 + (\alpha D)^2} \right] v_s,$$

(6)

$$v_{\perp} = \frac{(\alpha - \beta)GD}{G^2 + (\alpha D)^2} v_s.$$

(7)

As shown by solid lines in figures 3(c)–(f), our analytical results obtained from equations (6) and (7) are consistent with the micromagnetic simulations.

In the nanotube, for each layer of radius $\rho$ expanded to a planar film, the skyrmion still follows the Thiele’s equation. The gyrovector $\vec{G}$ does not depend on $\rho$. Strictly speaking, the dissipation tensor $D$ is no longer a scalar because the skyrmion is tilted, and its value also depends on the skyrmion size. However, as long as the skyrmion stays in the isolated phase as shown in figure 2, this tilting is small enough. The dependence of $D$ on the skyrmion size is also weak. For the parameter we used in figure 3, it is good enough to adopt the scalar $D$ in the corresponding planar film, as shown by solid lines in figures 3(e) and (e), which show that the parallel velocity components are nearly the same in a planar film and in a tube. Numerically, the planar film gives $D_{xx} = D_{yy} = 15.8$, while the flattened tube at $d/2$ gives $D_{xx} = 17.4$, $D_{xy} = -2.2$ and $D_{yy} = 16.4$. The longitudinal speed calculated with this tensor $D$ is hardly distinguishable from the one with the scalar $D$. However, the perpendicular component $v_{\perp}$ is significantly different due to the curving nature of the tube. This can be understood following the schematic diagrams in figure 4(b): supposing that each layer is independent to each other, the $v_{\perp}$ is the same as that in the planar film. However, for the layer at different $\rho$, the angular speed $\omega(\rho) = v_{\perp}/\rho$ is larger (smaller) for smaller (larger) $\rho$. Since the layers are strongly coupled by exchange interactions and the skyrmion in each layer is closely bounded together, the smaller angular speed in outer layers is dragged to become faster so that all layers share the same angular speed in the end. As a result, $v_{\perp}$ at the outer surface is faster than that in a planar film, and it increases with $d$ in a nanotube. The angular speed $\omega = v_{\perp}/\rho$ also increases with $d$ for fixed outer radius $R$. By fitting with the numerical data, we find that $v_{\perp}$ as well as $\omega$ can be estimated by considering the skyrmion motion at the layer with radius $R - d/2$, i.e. the half-thickness of the tube wall. At $\rho = R - d/2$, the Thiele’s equation gives

$$v_{\perp}|_{\rho=R-d/2} = \frac{(\alpha - \beta)GD}{G^2 + (\alpha D)^2} v_s = \omega(R - d/2).$$

Thus, we obtain

$$v_{\perp}|_{\rho=R} = \frac{(\alpha - \beta)GD}{G^2 + (\alpha D)^2} (R - d/2) v_s.$$

(8)

In figures 3(d) and (f), the above expression for $v_{\perp}$ is plotted in dashed curves, which show excellent agreement with the numerical results.

Magnetic nanotube is the key to test our theoretical predictions. Experimentally, there are several methods to produce the nanotube geometry. Sui et al reported that the nanotubes can be generated by hydrogen reduction in nanochannels of porous alumina templates [53]. Nielsch et al proposed that the nanotubes can be made by electrodeposition [54]. Daub et al reported that the magnetic nanotubes can be synthesized by atomic layer deposition into porous membranes [55]. Although it is still challenging to manufacture patterned nanotubes nowadays, our proposal provides another paradigm to eliminate the drawbacks of skyrmion Hall effect and design the skyrmionic devices.

To conclude, we investigate the static and dynamic properties of skyrmions on magnetic nanotubes. Through micromagnetic simulations, we show that the electric current can drive a skyrmion propagation with a helical trajectory on the tube because of the skyrmion Hall effect. The skyrmion velocity is proportional to the injected current without conventional upper limit. The skyrmion’s angular velocity increases with the thickness of the nanotube, which is different from the fact in the planar geometry. Our proposal of transporting the skyrmion in nanotube geometry will stimulate future design of skyrmionic devices.
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