The stability of a skyrmion in a nanotube

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Abstract
We study the stability of a skyrmion in a nanotube by using micromagnetic simulations. We find that skyrmions can exist stably in a nanotube within a moderate magnetic field range when the magnetic field is perpendicular to the center axis of the nanotube. In nanotubes the shape of the skyrmion is elliptical. The semimajor and semiminor axes of the ellipse depend on the magnetic field and the angular position of skyrmion. When the skyrmion has an angular displacement from the direction of magnetic field, its shape and size change greatly with the angular position of skyrmion. Also the topological number is dependent on the angular position of skyrmion. When the angular position of skyrmion reaches a critical value, the skyrmion annihilates. The critical angle that skyrmion can survive is not affected by the circular current density, but depends on the radius of nanotube and the strength of magnetic field.

Introduction
Magnetic skyrmions, particle-like spin textures with topological protection [1], have recently been one of the research hotspots in magnetic information memory [2–4], logic circuit [5] and neuromorphic device [6] due to their nanoscale dimension, stable configuration and ultra-low driven energy. Skyrmion [7] as a topologically stable configuration was first presented by the British physicist Tony Skyrme to account for baryons in nuclear physics in 1962. Since then, extensive researches indicated that skyrmion-type textures can exist in different material systems, such as liquid crystals [8], quantum Hall systems [9], Bose–Einstein condensates [10] and thin magnetic films [11]. The theoretical prediction of the existence of magnetic skyrmions in B20-type bulk helimagnets was proposed by Rößler et al [12] and the first experimental confirmation of chiral skyrmions in MnSi was made by Mühlbauer et al [13]. Subsequently, a large number of experimental observations of skyrmions have been reported [14–16].

Relevant studies show that there are many physical mechanisms for the formation of magnetic skyrmions. One of them is Dzyaloshinskii–Moriya interaction (DMI) [17, 18]. Owing to the nanometer size of skyrmions given rise by DMI and the wide material sources with DMI, magnetic skyrmions in this kind of materials are undoubtedly catching more interest. There are two typical types of DM interaction: bulk DMI and interfacial DMI. The former is generally found in non-centrosymmetric chiral magnets, e.g. MnSi [13, 19], FeGe [16, 20] and Cu2OSeO3 [21], which usually induce Bloch-type skyrmions. The latter supporting Néel-type skyrmions is generated from magnetic film/heavy metal, thin film heterostructures and multilayered material systems, e.g. Ir(111)/Fe [15], Pt/Co/MgO trilayers [22] and [Ir/Co/Pt] multilayers [23].

In three-dimensional chiral magnets, the skyrmion phase exits in a narrow region of the temperature-field phase diagram, near Curie temperature [13]. Reducing the dimension of magnetic material can expand the range where skyrmions stably exist [14, 16, 24–29]. However there are two main obstacles to the application of chiral-magnet thin films as the carriers of skyrmions. First, the emergence of skyrmions in chiral magnets is a consequence of the various energy competitions and DMI plays a significant role in the stability of skyrmion. The DMI energy in chiral magnets is intrinsic, so it is difficult to modulate the DMI strength in such materials. Second, the ground state of 2D chiral magnets is the helical state at zero magnetic field. An important condition for generating skyrmions in thin film structures is the presence of a perpendicular symmetry-breaking field,
either external or internal field. Recent theoretical and experimental analyzes reveal that in addition to exchange interaction the 3D curved and torsional magnets can induce two effective magnetic interactions: curvature-induced effective anisotropy and effective DMI [30–32]. So the adjunction of these two energies will have a significant impact on the stability and dynamical properties of skyrmions.

With the development of microstructural technology, 3D magnetic structures with complicated geometry and different size can be fabricated by various chemical and physical approaches. Among the different geometric types of magnetic objects, nanotubes offer three independent geometrical parameters to control the magnetic properties in their design, i.e. the length, the inner radius and the outer radius. Various experiments [33–37] and theoretical studies [38–41] based on nanotubes have also show that this structure has great influence on material properties. More recently, Wang et al reported the current-induced skyrmion motion on magnetic nanotubes [42]. Based on this point, we design a nanotube made of chiral magnets and study the stability of skyrmion in a nanotube utilizing micromagnetic simulations. The research results not only provide a new method to optimize structure of chiral magnets, but also offer a reference for the operation of a single skyrmion in generation, manipulation and deletion.

Model and methods

Our model is a series of nanotubes with different diameters but the same thickness \( t = 10 \text{ nm} \) and length \( L = 400 \text{ nm} \), as shown in figure 1. The outer radius and the inner radius are expressed by \( R \) and \( r \), respectively. The Cartesian coordinates and the cylindrical coordinates used for the analytic study are sketched in the inset of figure 1, where the \( z \)-axis is along the nanotube axis and \( \phi \) is the angular coordinate of the skyrmion center. In the simulation, a single Bloch-type skyrmion is initially set in the nanotube—figure 1, which is based on the special function—initial magnetization of Mumax3. During the simulations, an external magnetic field \( \mathbf{H} = (H_x, 0, 0) \) is applied along \(+x\)-direction. In addition, because our simulations also involve the angular motion driven by a circular current, 10 nm wall was cut off from the nanotube along \( x \)-direction in order to inject a circular spin current. In fact, we have also performed the same simulation experiments in nanotubes without cutting 10 nm wall. The simulation results show that the existence of incision has no obvious influence on the results of the study. This is because the cutting-off part is thin and the distance between the incision boundary and the skyrmion is large. The effect of the repulsive force generated by the incision boundary on the motion of the skyrmion can be neglected.

The study is carried out by means of the finite difference GPU accelerated micromagnetic simulation software Mumax3 [43]. The time-dependent magnetization dynamics is governed by the Landau–Lifshitz–Gilbert (LLG) equation

\[
\frac{d\mathbf{m}}{dt} = -\gamma |\mathbf{m}| \mathbf{m} \times \mathbf{H}_{\text{eff}} + \alpha \left( \mathbf{m} \times \frac{d\mathbf{m}}{dt} \right). \tag{1}
\]

In this equation, \( \mathbf{m} \) is the unit vector of the magnetization, \( \gamma \) is the gyromagnetic ratio, \( \alpha \) is the Gilbert damping constant, and \( \mathbf{H}_{\text{eff}} = -\frac{1}{\mu_0 M_s} \frac{\partial E}{\partial \mathbf{m}} \) is the effective fields (\( E \) is the average energy density). The energy density includes four different sources: the exchange energy, the Zeeman energy, the magnetostatic energy and the bulk DMI energy.
\[ E = A |\nabla \mathbf{m}|^2 - \mu_0 M_s \mathbf{m} \cdot \mathbf{H}_{\text{ext}} - \frac{\mu_B M_s}{2} \mathbf{m} \cdot \mathbf{H}_d + D \mathbf{m} \cdot (\nabla \times \mathbf{m}), \]  

where \( A \) is the exchange constant, \( D \) is the DMI constant. \( \mathbf{H}_{\text{ext}} \) and \( \mathbf{H}_d \) represent the external field and the demagnetizing field.

For simulation of the current injected to the nanotube along the \( \phi \) direction, the spin-transfer torque (STT) including both adiabatic and non-adiabatic terms was added to equation (1), with

\[ \tau_{\text{STT}} = \mu \mathbf{m} \times \left( \frac{\partial \mathbf{m}}{\partial r} \times \mathbf{m} \right) + \beta \mathbf{m} \left( \frac{\partial \mathbf{m}}{\partial r} \times \mathbf{m} \right), \]

where \( \mu = \mu_0 J P / e M_s \), \( M_s \) is the saturation magnetization, \( J \) is the current density, \( P \) is the spin polarization, \( \mu_B \) is the Bohr magneton, \( e \) is the electron charge, \( \beta \) is the non-adiabaticity factor, and \( dr = \sqrt{(dx)^2 + (dy)^2} \). In the simulation, a circular spin-polarized current \( j(p, \phi, z) = Je \) was injected into nanotube to drive a skyrmion to move.

FeGe is one of the most widely studied chiral magnets that host magnetic skyrmions. Nanostructures made of FeGe, such as the wedge-shaped nanostripe [44], nanodisks [45, 46] and nanowires [47], have been experimentally fabricated. Here we consider using chiral magnet FeGe with mesh size of 0.5 T, such geometry, we can apply along \( \phi \) direction. Then we use energy minimization method to obtain the equilibrium deformation of the skyrmion. Figure 2 shows the typical magnetic states that appear in the nanotube, including both adiabatic and non-adiabatic terms was added to equation (1), with

\[ \tau_{\text{STT}} = \mu \mathbf{m} \times \left( \frac{\partial \mathbf{m}}{\partial r} \times \mathbf{m} \right) + \beta \mathbf{m} \left( \frac{\partial \mathbf{m}}{\partial r} \times \mathbf{m} \right), \]

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Results and discussion

First we investigate the stability of skyrmion affected by a magnetic field in nanotubes with different radii. A skyrmion is first prepared in a nanotube at the point \( \phi = 0 \) rad, \( z = 200 \) nm, and an external magnetic field \( H_x \) is applied along \( x \)-direction. Then we use energy minimization method to obtain the equilibrium magnetization distribution of the nanotube with the external magnetic field gradually decreasing from \( H_x = 0.5 \) T to 0 T or increasing from 0.5 to 1.5 T.

Ordinarily, the topological number \( Q \) can be used to evaluate the change of the magnetic states such as creation and annihilation of skyrmions during the system evolution. For a perfect skyrmion, \( Q = \pm 1 \). As is well known, on a two-dimensional plane (yz plane in our model) the topological number is defined as

\[ Q = \frac{1}{4\pi} \int m \cdot \left( \frac{\partial m}{\partial y} \times \frac{\partial m}{\partial z} \right) dy dz. \]

In the current context, the magnetic states reside on a curved film. To calculate the topological number in such geometry, we first screen out the magnetization data in a circular film which satisfy the condition: \( R - 2 \) nm < \( \sqrt{x^2 + y^2} < R \), and then we calculate the topological number as

\[ Q = \frac{1}{4\pi} \int m \cdot \left( \frac{\partial m}{\partial z} \times \frac{\partial m}{\partial r} \right) dz dr, \]

where \( dr = \sqrt{(dx)^2 + (dy)^2} \).

Figure 2(a) shows the topological number as a function of the applied magnetic field in nanotubes with different outer radii. It can be seen that regardless of the outer radius of the nanotubes, the existing magnetic state can be roughly divided into three stages: the multi-topological state in low field, the stable skyrmion state in intermediate magnetic field and the ferromagnetic state in high magnetic field. We take nanotube with \( R = 50 \) nm as an example for detailed analysis. Figure 2(b) shows the typical magnetic states that appear in the nanotube when the magnetic field decreases from 0.5 T to lower field. When the applied external field decreases from the moderate magnetic field to the lower field, after a series of transition states (the purple ellipse in figure 2(a)), a stable skyrmion will evolve into a three topological state with the topological number changes from \( Q = -1.5 \) (\( H_x = 0.15 \) T) to \( Q = -3.1 \) (\( H_x = 0.14 \) T) and finally transforms into similar-helicoid state as the magnetic field decreases further. The skyrmion can stay stable when the magnetic field \( H_x \) is between 0.25 and 1.25 T. When the magnetic field is increased to \( H_x = 1.26 \) T, the skyrmion soon disappears from sight with \( |Q| \) drops to 0, and the magnetizations are all along the \( x \)-direction.

Through the analysis of the simulation results, we find that the skyrmion will be deformed in the process of changing the external magnetic field. As shown the sample in the inset of figure 2(c), we can see that the shape of the skyrmion in nanotube is an ellipse. In fact, [44, 49] have pointed out that geometric constraints and the tilt of the magnetic field can make skyrmions non-circular. In order to better describe the shape of the skyrmion we use ellipse to fit the boundary of the skyrmion (the isoline with \( m_z = 0 \)). The semimajor and semiminor axes of the ellipse are represented by \( a \) and \( b \), respectively. They are used as indicators to measure the size and deformation of the skyrmion. Figure 2(c) shows the dependence of the size of a stable skyrmion on the applied...
magnetic field $H_x$ during the above process. We can see that the difference between $a$ and $b$ is large in low field. For instance, in the nanotube with $R = 40$ nm, when $H_x = 0.25$ T, $a = 27.7$ nm and $b = 16.8$ nm, the value of $a - b = 10.9$ nm. However, as the magnetic field increases to $H_x = 0.45$ T, $a$ and $b$ decrease to 15.3 nm, 12.7 nm and 2.6 nm, respectively. When the magnetic field increases further, $a$ and $b$ are almost equal. This means that the size of the skyrmion is large and the deformation is obvious in low magnetic field. Furthermore,
the skyrmion in the nanotube with larger outer radius has a larger size. The outer radius of nanotube has a mild effect on the size of skyrmion in high field.

Among the various methods of driving the motion of skyrmions, e.g. the temperature gradient [50], the magnetic field gradient [51] or strain [52], utilizing spin-polarized current [53–55] has distinct advantage in terms of the energy usage ratio and the feasibility of the process operation. When a spin-polarized current is injected into a ferromagnetic film, the strong coupling between the electron spins and the local magnetic moments will induce the motion of skyrmions. For the stability of skyrmions in nanostructures, Liang et al have experimentally explored current-driven dynamics of skyrmions stabilized in MnSi nanowires [56]. In a nanotube, if an electrical current flows parallel to the axis of a nanotube, the skyrmion has an angular motion velocity \( v_f \), rotating about the axis of a nanotube in addition to the longitudinal motion velocity \( v_z \), parallel to the electron flow direction as the result of the skyrmion Hall effect [57–59]. When the skyrmion has an angular displacement from the direction of magnetic field, the magnetic field will be no longer perpendicular to the skyrmion. Hence the relationship between its stability and the azimuthal angle \( \phi \) deserves our in-depth exploration. For this purpose, a circular spin-polarized current \( j(\rho, \phi, z) = j e_\phi \) was injected into nanotube to drive a skyrmion to move as far as possible along the tangential direction.

Next we take the case of a skyrmion in a nanotube with \( R = 50 \) nm to illustrate the stability of skyrmion affected by the angular position. Figure 3(a) displays the change of the topological number \( Q \) and the size of the skyrmion with angular position \( \phi \). In our model, the influence of parameter \( z \) can be neglected, because the displacement of the skyrmion in \( z \)-direction is not large and the length of nanotube \( L \) is longer than any other relevant length-scale in the model. From figure 3(a), we can see that \(|Q|\) is close to 1 when \( \phi \) is small in the process of driving the skyrmion by a circular current. However, when \( \phi \) reaches a certain value (the purple circle), \(|Q|\) begins to decrease sharply. The value of \(|Q|\) represents the stability of skyrmion to some extent. The sharp decline in \(|Q|\)

Figure 3. (a) \( Q, a \) and \( b \) as a function of \( \phi \) in the case of \( R = 50 \) nm, where \( H_x = 0.40 \) T and \( j = 1.0 \times 10^{12} \) A m\(^{-2}\). The purple circle corresponds to \( Q = -0.83 \). (b) The \( m_x \)-image of skyrmion at four different positions: \( \phi = 0.11, 0.35, 0.61, \) and 0.80 rad. The blue color represents the magnetization is oriented along +x direction, and the red color represents the magnetization is oriented along -x direction.
implies that the configuration of a skyrmion is unstable at this position. Accordingly, we set a criterion that a skyrmion cannot exist steadily when the value of \(|Q|\) is smaller than a critical value \(Q_c\). Based on the analysis of multiple sets of simulation data, we find that it is appropriate to take \(Q_c = 0.8\). Then we define the value of \(\phi\) when \(|Q| = 0.8\) as the critical angle \(\phi_c\). The critical angle \(\phi_c\) indicates that the skyrmion exist stably when \(\phi \leq \phi_c\), but it cannot exist when \(\phi > \phi_c\). Besides that, we also can see that both \(a\) and \(b\) decrease with increasing of \(\phi\) in movement process. It is interesting that when \(\phi\) near 0.35 rad, \(a\) and \(b\) are almost equal. In other words, the shape of skyrmion is circular.

Figure 3(b) shows the image of the skyrmion at four different angular positions during the motion. When the skyrmion is at \(\phi = 0.11\) rad, \(a = 18.0\) nm, \(b = 14.6\) nm and \(a - b = 3.4\) nm, when \(\phi = 0.35\) rad, \(a \approx b \approx 15\) nm. Since then, the semimajor and semiminor axes have been decreasing with the increase of \(\phi\). We also notice that in the course of the movement, the skyrmion also rotates. At the beginning of the movement, there is a certain angle between the major axis of the skyrmion and the electron flow direction (the vertical direction in the picture). As the position changes, the angle decreases. When \(\phi\) changes from 0.61 to 0.80 rad, the major axis almost parallel to the electron flow direction and there is nearly no rotation of the skyrmion.

Then we analyze the role of the outer radius \(R\) of the nanotube in the process of current-induced skyrmion dynamics. Varing of \(Q\), \(a\) and \(b\) with the angular position parameters \(\phi\) in nanotubes with different outer radii at \(H_x = 0.4\) T and 0.7 T are shown in figure 4, respectively. From figures 4(a) and (b), we find that the variation trends of \(Q\) with \(\phi\) are almost unanimously in nanotubes with different \(R\) when \(\phi\) is small. But the influence of \(R\) on \(Q\) is obvious when \(\phi\) is large. The variation of \(Q\) with \(\phi\) is more rapid in the nanotube with larger \(R\) than that in the nanotube with smaller \(R\). From figure 4(c), we can see that when \(\phi\) is small the skyrmion in the nanotube with a smaller outer radius has smaller \(a\) and \(b\). But when \(\phi\) is large the skyrmion in the nanotube with a larger outer radius has smaller \(a\) and \(b\). It is interesting that when \(\phi\) is close to 0.3 rad, the skyrmion is nearly a circle for different \(R\). For \(H_x = 0.7\) T, it shows the similar trend, but the difference between \(a\) and \(b\) is much smaller.

Finally, we show the motion of the skyrmion under the effect of a circular spin-polarized current density. Figure 5(a) shows the trajectories of skyrmion driven by a circular current with different current densities. When the circular current density is small, the skyrmion will be rebounded (the green line). When the current density is higher than a critical value \(j_c\), the drafting force of current will push the skyrmion to a certain position (\(\phi_c\), \(z\)), and subsequently the skyrmion annihilates. It is interesting that when \(j > j_c\) the current density does not affect

\[ H_x = 0.4, 0.7 \text{ T} \]

\[ a, b, d, \text{ and } \phi \text{ are as shown in figure } 4. \]

\[ \phi_c \text{ indicates that the skyrmion exist stably when } \phi \leq \phi_c, \text{ but it cannot exist when } \phi > \phi_c. \]

\[ Q \text{ is a function of } \phi \text{ for four different outer radii under } j = 1.0 \times 10^{12} \text{ A m}^{-2}, \text{ where (a) } H_x = 0.4 \text{ T and (b) } H_x = 0.7 \text{ T. (c) and (d) The semimajor axis } a \text{ and the semiminor axis } b \text{ as a function of } \phi \text{ for four different outer radii, where (c) } H_x = 0.4 \text{ T and (d) } H_x = 0.7 \text{ T.} \]
the critical angle $f_c$. We also find that the larger magnetic field strength corresponds to a smaller critical current density $j_c$, and the outer radius of nanotube has little effect on $j_c$.

We plot the critical angle $f_c$ that is reachable in skyrmion motion as a function of magnetic field in figure 5(b). It shows that $f_c$ becomes small as the magnetic field increases. We also can see that the effect of $R$ on $f_c$ is obvious in low fields. The skyrmion in the nanotube with larger $R$ has a smaller $f_c$. For example, when $H_x = 0.45$ T, $f_c = 1.21$ rad for $R = 40$ nm, $f_c$ decreases to 1.05 rad for $R = 70$ nm. However, when $H_x = 0.80$ T, $f_c = 0.76$ rad for $R = 40$ nm, it slightly decreases to 0.67 rad for $R = 70$ nm.

**Conclusion**

In summary, we study the stability of skyrmion in a nanotube. With varying of the $x$-direction magnetic field, the existing magnetic state in nanotubes can be roughly divided into three stages: the multi-topological state in low field, the stable skyrmion state in intermediate magnetic field and the ferromagnetic state in high magnetic field. Skyrmions can exist stably in a nanotube within a wide magnetic field range when the magnetic field is along the $x$-direction. In nanotubes the shape of the skyrmion is elliptical, its semimajor and semiminor axes depend on the angular position of skyrmion $\phi$. Also the topological number $Q$ is dependent on the angular position of skyrmion. When $\phi$ reaches a critical value $\phi_c$, $|Q|$ drops remarkably and the skyrmion annihilates. The value of $\phi_c$ is not affected by the circular current density, but it depends on the radius of the nanotube and $H_x$. The nanotube with a larger radius corresponds to a smaller $\phi_c$.

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