Magnetic hopfion rings entangled with skyrmions

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Encoding information through the direction of magnetization constitutes a cornerstone technique for the storage of vast amounts of data, which has fueled the growth of sectors like artificial intelligence. Typically, a uniaxial direction —such as 'up' or 'down'—is employed to encode information. However, magnetization can indeed point in any direction, giving rise to diverse magnetization distributions (also known as spin textures). Some of these textures are irregular and ephemeral, but some of them possess certain symmetries and can be classified by a topological index. Spin texture with a non-zero topological index is identical to another spin texture with the same index, but it cannot be smoothly transformed into spin textures with different topological indices. Recent studies show that topological spin textures are remarkably stable and exhibit particle-like dynamics, which are closely related to their topology. Such stability and dynamical behavior hold potential for innovative information storage solutions.

The study of topological spin textures thrived alongside the discovery of the magnetic skyrmions, which have garnered significant interest due to their intriguing physical properties. For a typical skyrmion configuration, as shown in Figure 1A, the magnetizations form a swirling-like pattern. A skyrmion is a two-dimensional (2D) topological spin texture with its topological index defined on a 2D surface. Its experimental discovery in magnets has inspired researchers to further pursue its three-dimensional (3D) counterpart, known as the magnetic hopfion, whose topological index is defined in a 3D space. A key feature of hopfion's topology is the linking between the equi-spin lines (formed by spins with the same orientation). A skyrmion can be extended to three dimensions as a string, and a magnetic hopfion can be understood as a 2π-twisted skyrmion string with gluing its two ends together (Figure 1A top panel). However, realizing a hopfion in such a way is quite challenging due to the lack of a precise and reliable method to manipulate skyrmion string in three-dimension.

Another way to realize a hopfion is to sew a target skyrmion (see Figure 1A bottom panel). A target skyrmion (also known as skyrmionium) is a central skyrmion wrapped by a circular helical stripe with opposite topological charge. It can be stabilized in chiral magnets, a class of skyrmion-host materials, at a moderate external magnetic field. If a certain boundary condition is applied, the target skyrmion transforms into a hopfion.[1] Even without boundary condition, previous studies have shown that a fractional hopfion can be realized by partially gluing the target skyrmion.[3] Some skyrmion bundles [a combination of (anti)skyrmions surrounded by a skyrmion or target skyrmion] can also be considered as fractional hopfion at specific magnetic field ranges.[2] Their experimental discovery thus provides a foundation for further searching for hopfions in chiral magnets. However, the on-demand creation of hopfion remains a challenge.

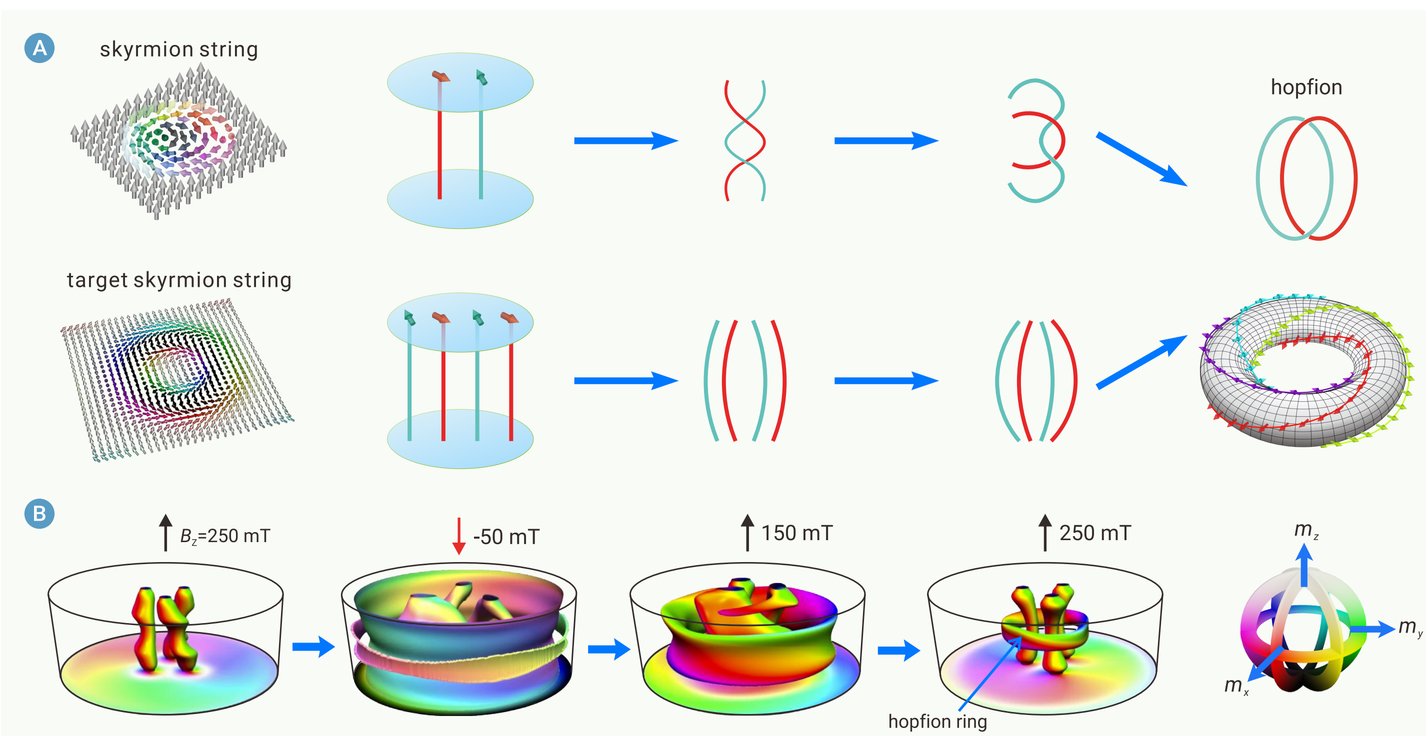

Figure 1. Realization of a magnetic hopfion ring entangled with skyrmion strings (A) Realization of hopfion through a skyrmion string (top process) or a target skyrmion (bottom process). The red and cyan lines represent the equi-spin lines of magnetizations with their x-component equal to +1 and -1, respectively. (B) Field-swapping protocol to create a hopfion ring, adapted from Zheng et al[4]. Surfaces where the magnetizations with their z-components equal to 0 (first, second, and fourth panel) and 0.5 (third panel) are plotted. The hopfion ring is created after the field-swapping process.

Reporting in *Nature*,[4] Zheng and colleagues demonstrate the diversity of the hopfion rings entangled with skyrmion strings in FeGe, a skyrmion-hosting magnetic material. Using advanced microscopes and simulations, the team shows that these hopfion rings can be reliably nucleated in a confined sample via a specific protocol called 'field-swapping'. A similar method has previously been employed to create skyrmion bundles.[2] In this protocol, an external magnetic field is initially applied to one direction to stabilize some skyrmion textures. Next, the field is flipped to the opposite direction with amplitude that is small enough to avoid destroying the skyrmions. Finally, the field is set back to its original direction. During this process, a hopfion ring is created, as shown in Figure 1B. Here the confined geometry plays a vital role in the formation of the hopfion ring as the outer ring (Figure 1B) is generated from the boundary. The research team found that the hopfion rings are always associated with the skyrmion strings. Furthermore, the number of skyrmions inside the hopfion ring is not limited to one, resulting in diverse skyrmion-based configurations therein.

Further micromagnetic simulations suggest that multiple hopfion rings can exist in thicker samples, which are not accessible to the current experimental technique. A wide diversity of hopfion rings is predicted, where they may form stacking structure and even interlinking structure. Simulations of current-induced dynamics also reveal that the skyrmions and hopfion rings are coupled with each other, giving rise to complex dynamical modes such a rotational-translational motion of the hopfion ring along the skyrmion string. These findings can greatly extend the topological classes of 3D spin textures.

These novel findings can play key roles for further studies on the fascinating physical properties proposed for hopfions. For example, the hopfions can induce nonlinear Hall effect and nonreciprocal magnetoresistance; they also exhibit entangled and nonreciprocal dynamics. The exploration of these phenomena could lay a foundation for the development of hopfion-based devices. The current results are identified through combing two-dimensional magnetic imaging and micromagnetic simulations. In the future, fast-developing three-dimensional magnetic imaging tools would be useful to further examine the diverse three-dimensional spin textures. The on-demand creation of hopfion rings may also be useful for device applications based on 3D topological spin textures such as neuromorphic computing.[5]

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DECLARATION OF INTERESTS

The author declares no competing interests.