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Topological Light Waves: Skyrmions can Fly

Harnessing an emerging class of structured waves as counterparts of localized topological quasiparticles to revolutionize information technology.

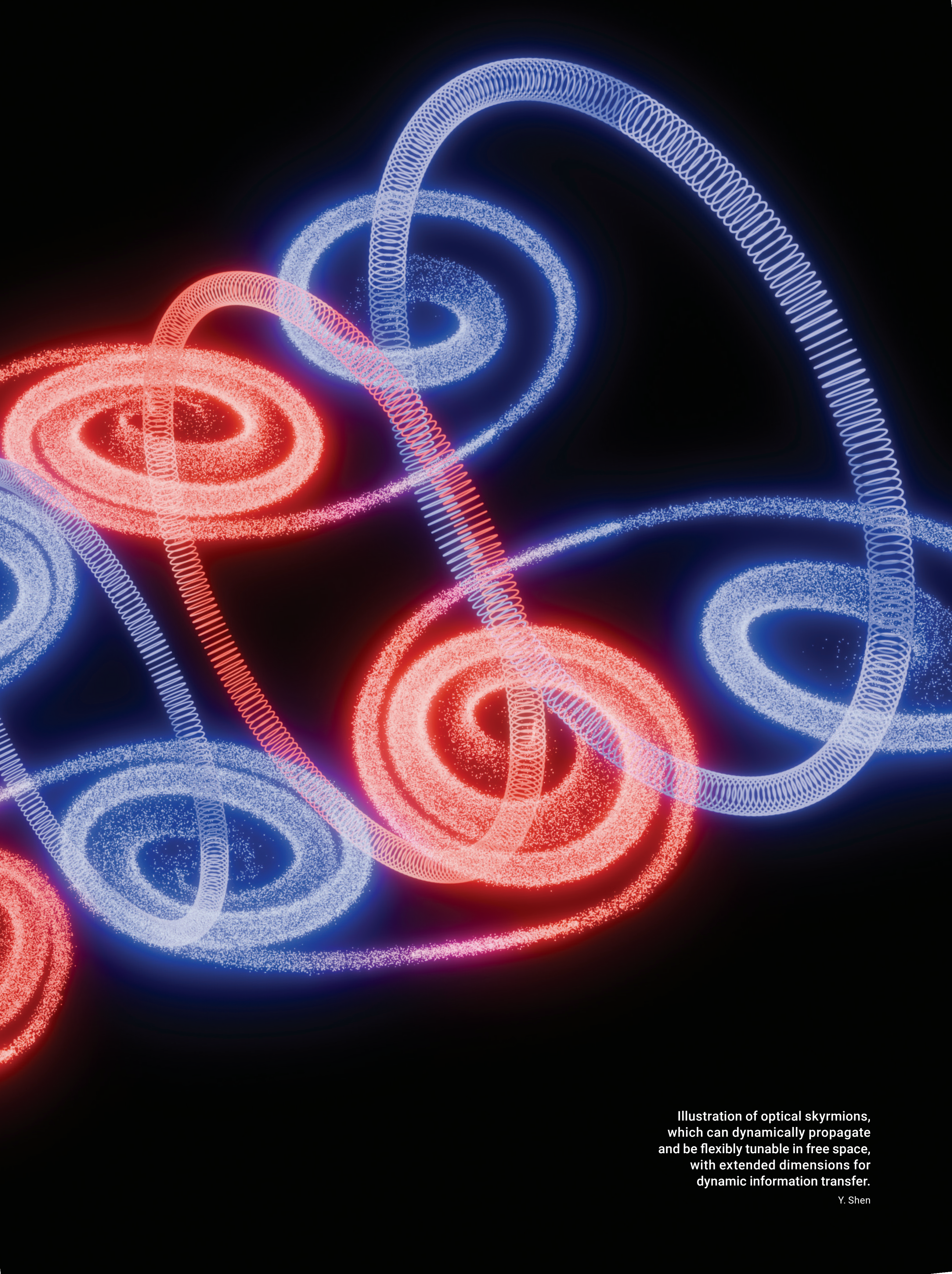

Illustration of optical skyrmions, which can dynamically propagate and be flexibly tunable in free space, with extended dimensions for dynamic information transfer.

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In contemporary textbooks of physics, electromagnetic waves propagating in free space have become the backbone of information and energy transfer. Structured light with multiple degrees of freedom, such as polarization, orbital angular momentum and spatial mode, present great benefits for high-speed and high-capacity information transfer. However, in the current age of information explosion, the pursuit of greater bandwidth, stability and security of data storage and transfer is crucial to societal development. Could tailoring a more intriguing hallmark of light fields—their topologies—become a solution?

Topological defects or textures have already emerged as novel information carriers in material science due to the intrinsic robustness of topological matter states. In magnetic materials, for example, nonlinear spin-spin interactions create stable particle-like swirling textures localized in nanoscale regions, known as magnetic skyrmions. These tiny structures were conceived as one of the most auspicious information carriers for next-generation solid-state data storage, offering improved capacity and stability. However, the spin textures embedded in solid-state magnets primarily support steady information storage technology and data writing, reading and processing rather than dynamic long-range information transfer. Can topologically structured light enable robust, long-distance information transfer?

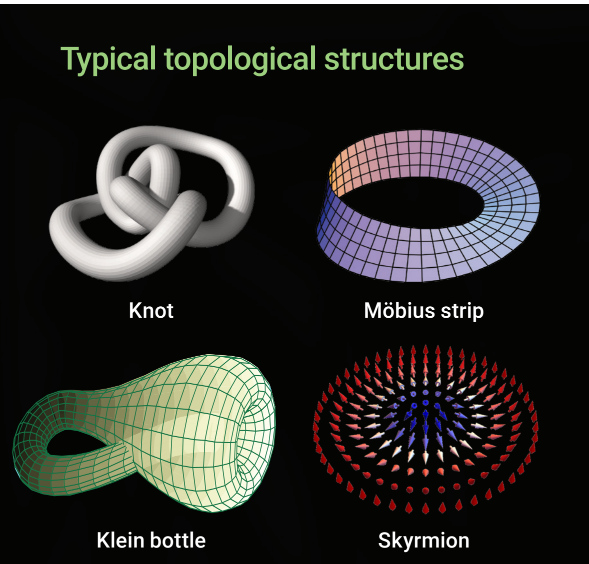
Recent developments in nanophotonics and structured light have led to the creation of similar topological particle-like textures in optical fields, known as optical skyrmions. In contrast to topological spin textures embedded in matter, optical skyrmions can propagate in free space, enabling long-distance information transfer. Creating and controlling free-space topological textures with structured light is an emerging field that will drive conceptual revolutions from solid-state data storage to dynamic long-range information transfer.

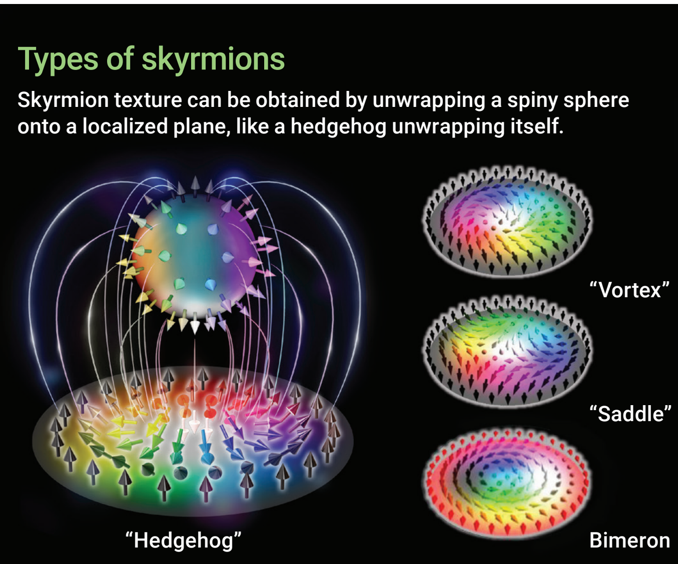
What is a skyrmion?

Topology—the study of properties of objects preserved through continuous deformations, such as twisting and stretching—reveals hidden secrets in nature, from the twisted growth of rattan plants to the double helix in DNA, or the vortex rings in smoke and water. The skyrmion is among the many well-known models of typical topological structures in the scientific community, such as the knot, Möbius strip or Klein bottle.

Proposed in 1961 by the British particle physicist Tony Skyrme, the skyrmion is a spin texture obtained by mapping a spiny sphere onto a localized plane, just like a stereographic projection in cartography. This mapping can also be visualized as a hedgehog unwrapping itself–its geometry changes while the texture preserves a topological invariance. Similar to how hair on our heads can be arranged in different styles, the localized spin texture after Skyrme's mapping can adopt various topological classifications. These topological quasiparticles—all unified within this mathematical model—are what we call skyrmions.

Skyrmion topologies offer a range of parameter spaces to play with. For instance, hedgehog-like textures feature radially oriented vectors; a vortex-like texture can be created by combing a vortex on the parametric hairy sphere, saddle-like textures can emerge from





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The construction of skyrmions has been extended from matter to light waves, and from the classical to the quantum regime.

arranging vector bundles on the sphere, presenting a radically different topology. In addition, we can implement a half stereographic projection, mapping only one hemisphere, with the resultant configuration called a meron. If the mapping starts from other points on the sphere rather than the poles, we obtain a bimeron.

Skyrmions hold very diversified topological states. While Skyrme's model in particle physics was initially not successful, it led to subsequent research in many other contexts, including Bose–Einstein condensates, liquid crystals, magnetic materials and optics.

Particle topologies of vectorial light

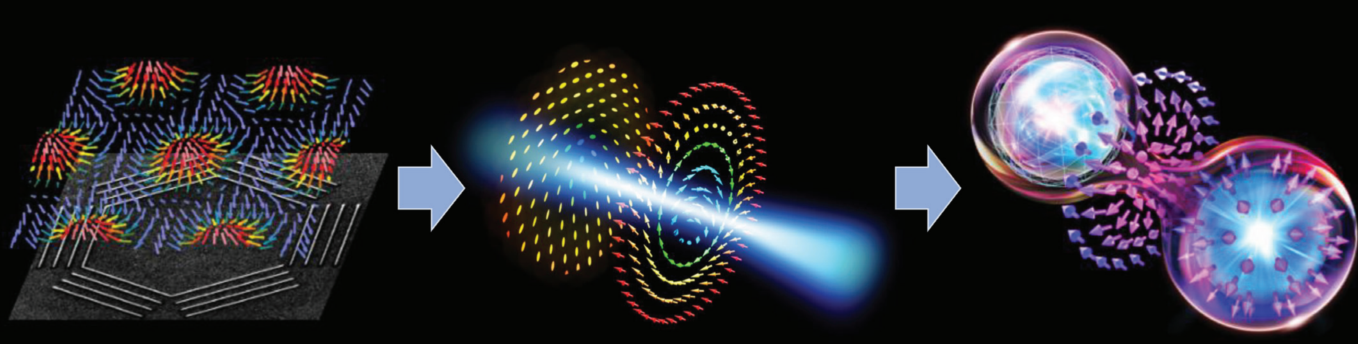
How can we construct a skyrmion using optical fields? Conventional light waves are transverse, meaning their field vectors exist only in-plane; thus, it is challenging to construct a skyrmionic texture that requires a full "spiny sphere" mapping. The pioneering works on optical skyrmions were based on evanescent waves excited by plasmonic effects at metal interfaces, where the electric field presents both in-plane and out-of-plane field components, enabling the formation of skyrmionic textures. Soon, other kinds of optical vectors were used to construct diverse topological textures in evanescent waves—including optical spin and magnetic fields—yielding diverse topologies from skyrmions to merons.

However, this earlier family of optical skyrmions was highly dependent on plasmonic materials, confining them to material surfaces. Before long, researchers turned to free-space structured light shaping to solve this problem. One solution is to exploit spatially variant polarization Stokes vectors in structured vector beams. The oscillation trajectory of the electric field along the transverse plane can have diverse states, known as polarization states—linear, elliptical and circular—all of which can be represented as points on the surface of the Poincaré sphere. By precisely controlling the polarization texture of a light beam, researchers can perform a stereographic projection from the Poincaré sphere to the transverse plane, tailoring on-demand free-space topological textures. A big advantage of free-space Stokes skyrmions is that the topological states can be flexibly generated and transformed with spatial light modulation technology, in sharp contrast to the material-based skyrmions, where the topological state is hardly switchable. Following the generation and observation of Stokes skyrmions, research expanded toward more general topologies with different optical vectors, such as optical spin, momentum and Poynting (energy flow) vectors.

Moreover, the construction of optical skyrmions has extended from the classical to the quantum regime, where topological textures are embedded in the nonlocal correlations of entangled photon pairs, an effect often referred to as "spooky action at a distance." Each photon does not present topological textures on its own,

Skyrmions in diverse vectorial fields

Skyrmions constructred by electric field vectors on evanescent waves of a medium surface (left), polarization vectors of free-space paraxial beams (center) and nonlocal correlations of two structured quantum entangled photons (right).



Evanescent-wave skyrmion **Skyrmionic light beams** **Quantum nonlocal skyrmion**

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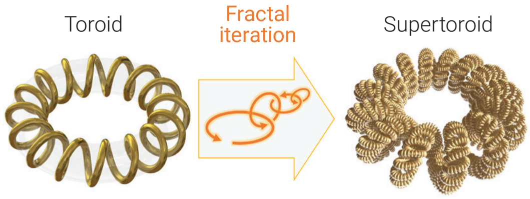
but their correlation fulfills the skyrmion mapping. This suggests that topologies in photon entanglement could lead to resilient quantum information protocols.

Despite this progress, the skyrmions described so far have been spatially generated in steady-state monochromatic light. So another question arises: Can we transport topological structures at the speed of light with dynamic spatiotemporal light pulses?

Skyrmions can fly!

How can we make skyrmions fly—freely propagating in free space at the speed of light? Over the past 15 years, toroidal electrodynamics has emerged as a new research field in electromagnetism and led to the development of flying skyrmions.

In the last decade, experimental and theoretical studies of toroidal electromagnetic excitations in matter and free space fueled numerous seminal discoveries, such as the observation of dynamic toroidal moments, toroidal multipoles, and dynamic anapole non-radiating configurations in metamaterials. Even more exotic physics can be observed when toroidal excitations occur in free space—toroidal electromagnetic pulses carrying skyrmionic topological structures propagating in free space at the speed of light, also known as "flying doughnuts." These pulses were theoretically predicted by space–time nonseparable solution of Maxwell's equations but experimentally observed only in recent years. The first observation of the toroidal light pulse was achieved by transforming a radially polarized ultrashort pulse using a space–time correction carried out by a metasurface. The detection of the pulse's



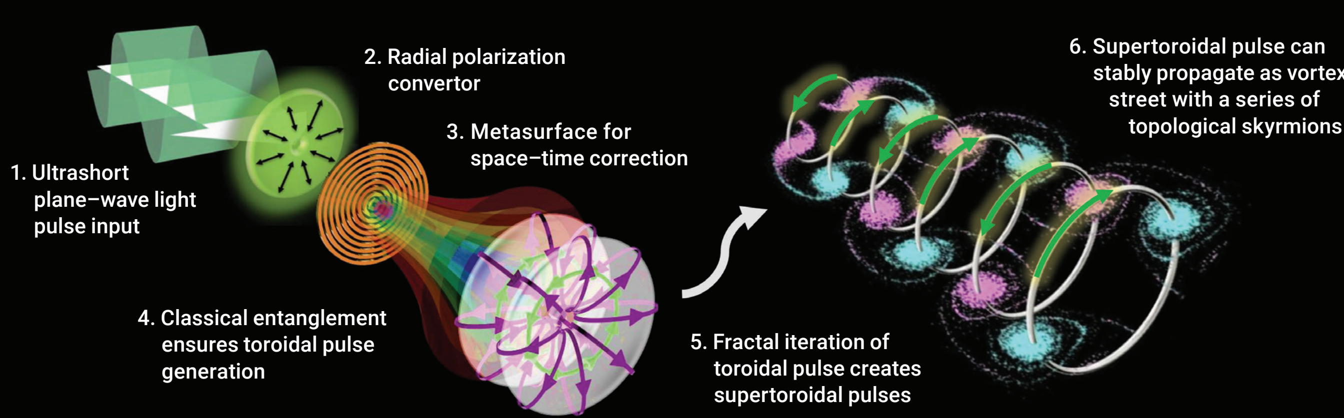
Toroidal structures

Toroidal, doughnut-like structures are a kind of classic topology, ubiquitous in natural phenomena and artificial materials—from smoke rings in air and vortex rings in water to toroidal DNA condensates and nuclear currents. In physics, a toroidal electromagnetic structure always refers to a solenoid that is bent into the shape of a ring, where current flows along the toroidal path. This is a classic configuration used to confine a magnetic field, as a typical toolkit for application in particle acceleration or nuclear fusion devices like the Tokamak. Toroidal structures are closely related to skyrmion structures—when we observe the field distribution at a cross-section of a toroid away from its center, it will show an electromagnetic skyrmion.

Supertoroids refer to various higher-order extensions with fractal iterations of a basic toroid, where a higher-order current wires on a lower-order configuration. The higher-order extension from toroidal to supertoroidal configurations is general, not limiting how the current wires on the lower order can be linked, knotted or nested along diverse directions. Supertoroidal currents also play important roles in modern electrodynamics, especially in electromagnetic shedding, nonreciprocal forces, and so on, in which supertoroidal excitations always exist in artificial materials.

From toroidal to supertoroidal light pulses

The spatiotemporal evolutions of the field structures of a toroidal light pulse carrying skyrmionic structures (left) and a nondiffracting supertoroidal light pulse (right).



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Complex topologies arise from higher-order fractal iterations of toroidal excitations, enabling higher-order toroidal electromagnetic pulses that carry multiple skyrmionic structures.

spatiotemporally localized vector texture also required complex polarization and time-resolved interferometry with a reference probe pulse. This marked the first observation of an electromagnetic skyrmion in an ultrashort pulse, although understanding its propagation dynamics is still a challenge.

From toroidal to supertoroidal electrodynamics

Recent advances also call for a generalization of toroidal to supertoroidal electrodynamics. Complex topologies arise from higher-order fractal iterations of toroidal excitations, enabling higher-order toroidal electromagnetic pulses that carry multiple skyrmionic structures. These pulses exhibit exotic physical effects, such as fractal singularities and nondiffraction, extending at ultrasmall and ultrafast scales.

In these pulses, toroidal features are found as fractal complications at increasingly smaller scales. Researchers have recently proposed a novel supertoroidal excitation family in free space: supertoroidal pulses (STP). STPs include the fundamental toroidal pulse ("the flying doughnut"), but also exhibit more diversified topological skyrmionic structures, multiple singularities in the Poynting vector maps and fractal-like distributions of energy backflow.

However, these exotic physical effects in STPs can only be observed at focus and diffract away rapidly. Can we make STP topological configurations more robust, so they stably propagate in free space? A recent solution has been proposed to upgrade STP into nondiffracting supertoroidal pulses (NDSTP), based on more complex space–time nonseparable solution, with a factor to quantitatively control the nondiffracting effect. In NDSTP, all the prior nontrivial features of skyrmions, including fractal-like singularities and multi-layer energy backflows, become robust over arbitrarily long propagation distances. More intriguingly, the field structure of NDSTPs has a strong similarity with von Kármán vortex streets, a pattern of swirling vortices observed in fluid dynamics that is responsible for the "singing" of telephone lines in the wind.

Toward compact generators

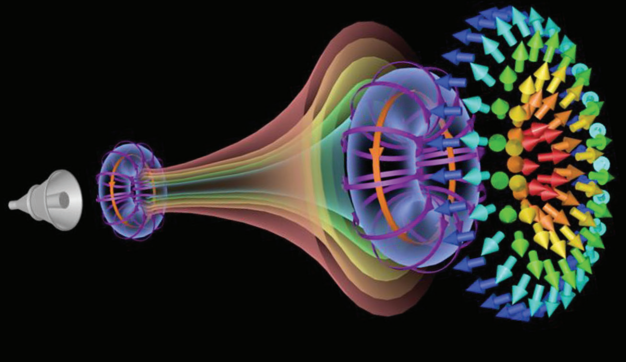
Despite the exciting theoretical work, generating supertoroidal light pulses experimentally is still a challenge. Current methods using complex metasurfaces to create toroidal pulses are limited in demonstrating the propagating properties of skyrmions. A new generation method with a compact, direct-emission source is highly desired.

To illustrate this, consider the air vortex cannon: a device that generates smoke rings—toroidal vortices—when an instantaneous pressure difference forces air through a circular opening. Similarly, dolphins master creating and playing with bubble rings—air-filled vortex rings propagating in water.

Researchers recently demonstrated an "electromagnetic vortex cannon" that directly emits electromagnetic vortex rings. The operational principle of their electromagnetic cannon utilizes ultra-wideband, radially polarized, conical coaxial horn antennas to create a rotating electromagnetic wave structure. When the antenna emits, it generates an instantaneous field signal difference that forms the vortex rings. Although initially limited in finite aperture, they gradually stabilize their topologies over long distances. The uniqueness of this method lies in its ability to easily produce electromagnetic skyrmions that showcase resilience and self-healing properties during propagation.

Electromagnetic skyrmion cannon

Electromagnetic cannons effectively emit self-resilient toroidal pulses with skyrmion topologies, offering unique potential in high-capacity communication, target detection and data encoding.



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Applications and outlook

The potential applications of this technology are vast and exciting. In high-capacity communication systems, vortex pulses could revolutionize how we transmit information by offering efficient and robust data encoding methods. The unique spectral and polarization characteristics of the vortex rings allow them to carry more information compared with traditional waves, making them ideal candidates for next-generation communication networks. Furthermore, their ability to maintain structural integrity even in the presence of environmental disturbances positions them as valuable tools in remote sensing and target detection. By analyzing the unique patterns of vortex pulses, we can develop more precise and reliable methods for detecting and locating objects, whether in defense systems or space exploration.

Additionally, the skyrmion textures embedded within the vortex rings offer intriguing possibilities for topological data storage and processing, potentially leading to more efficient ways of managing and analyzing large datasets in wireless technology, creating opportunities to redefine our understanding of electromagnetic phenomena. While the electromagnetic cannon currently works in the microwave domain, there is potential to extend similar compact flying skyrmion generators into the optical domain to boost more fundamental physical breakthroughs and facilitate practical applications.

Toward higher-dimensional topologies

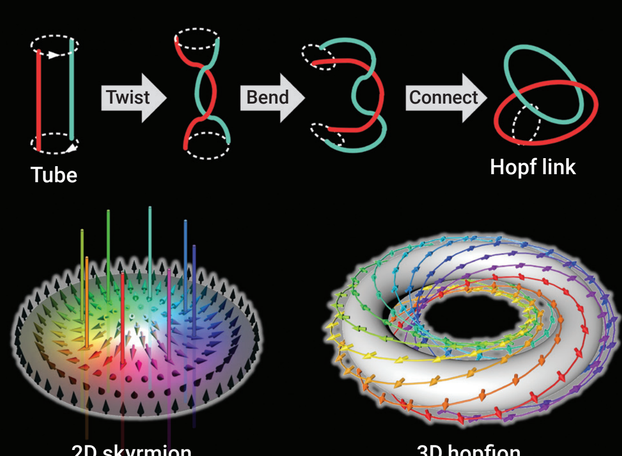
So far, skyrmion textures have been studied in a localized plane, a mapping from 3D parameter spaces to a 2D plane, also called “baby skyrmions.” But higher-dimensional topological textures are possible. An example is the hopfion, a 3D topological quasiparticle that fulfills a mapping from a 4D parametric hypersphere to 3D space, known as the Hopf map.

How can we visualize the hypersphere? For a baby skyrmion, a point in the parametric sphere is mapped to a point in the 2D plane. For a hopfion, a point in the parametric sphere is mapped to a loop in 3D space. After stereographic mapping, a fiber bundle with layer-by-layer toroidal structures will emerge—known as the Hopf fibration—where each loop or fiber acts as an iso-spin counter, resulting in sophisticated spin textures localized in 3D space. Imagine elongating a 2D skyrmion first into a skyrmion tube, then twisting and bending it into a nose-to-tail torus. You’ve now made a hopfion; meaning hopfions host skyrmions in their subspaces. And just as we can manipulate skyrmions using digital spatial light modulation technology, we can also implement tunable topological states to the optical hopfions.

Hopfions allow new topological orders that baby skyrmions do not possess. For instance, one can count how many times a fiber goes through or wraps around the torus, yielding topological numbers induced in 3D knotted fields. Control of high-dimensional hopfions was also experimentally realized—ahead of the magnetic higher-order hopfion, which is still to be found.

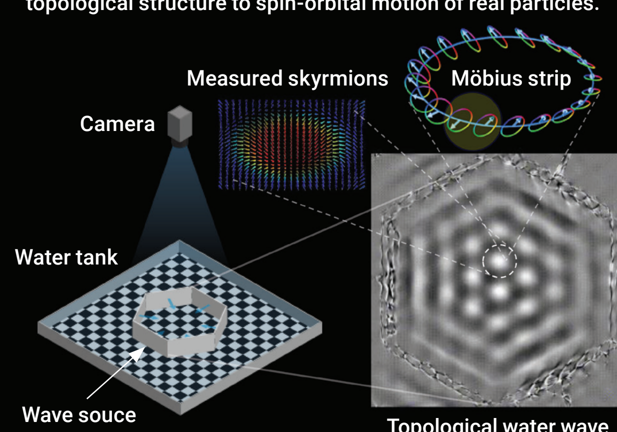
In addition to the individual hopfions, another breakthrough on higher-dimensional topologies is the creation of hopfion crystals, where hopfions can be

From 2D skyrmion to 3D hopfion



Water-wave skyrmions

Manipulating water-wave skyrmions and transferring wave topological structure to spin-orbital motion of real particles.



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In high-capacity communication systems, topological light waves could revolutionize how we transmit information by offering efficient and robust data encoding methods.

tailored into 4D space–time periodic structures. The space–time crystalline structure motivates the exploration of additional hidden dimensions to manipulate topologies of light.

From light to general waves

Inspired by air and fluid vortex rings, researchers have successfully generated their electromagnetic counterparts and observed the skyrmions embedded in them. Surprisingly, skyrmion structures had never been properly explored in the most obvious medium: water waves. This gap was recently filled.

Water surface waves are a natural class of nontransverse waves and allow for many intrinsic physical vectors to be defined related to the motion of water molecules. Spurred by prior theories, the experimental realization of topological water-wave structures was recently achieved, where diverse topologies—including skyrmions, merons, vortices and Möbius strips—were generated and observed by designing interference of multiple plane-wave sources with controlled symmetry. For instance, wave interference from a hexagonal source can induce skyrmion lattices in the water-wave velocity field.

Furthermore, both optical and acoustic structured waves are crucial for manipulating small objects—from atoms to macroscopic biological objects. Recently, the efficient manipulation of subwavelength- and wavelength-order floating particles with topologically structured water waves was demonstrated. This includes trapping of different kinds of particles, from small foam particles to ping-pong balls, in the high-intensity field zones of topological water waves. An existing property of water waves is that their topologies can be controlled and transferred to matter, that is, controllable orbital and spinning particle motions due to the orbital and spin angular momenta of water waves. These results reveal the water–wave counterpart of optical and acoustic fields, especially generalizing light–matter interactions to general wave–matter interactions, which paves the avenue for applications in hydrodynamics, microfluidics and environmental sustainability.

More topologies to explore

The creation of novel topological structures in diverse physical systems is a captivating blend of science and aesthetics. Topological waves are emerging as a topical research direction, expanded from solid-state physics to optics, and now to general waves. There are still many intriguing topological states to be explored, for instance, the links between hopfion rings may open new dimensions for 4D or even 5D topological maps. On the other hand, the higher-dimensional topological mapping can be implemented onto different physical domains by choosing different parametric vectors and physical spaces in which we carry out the topological map. Different choices and combinations of the basis vectors and different physical systems can promise topological textures with radically different fundamental properties.

So, how close are we are to implementing these optical topologies in practical information technologies? Researchers have already built compact topological light generators; however, the development of effective detectors for these topologies is the next challenge. In the next decade, both topological light generator and detector technologies are expected to mature, serving as the "sender" and "receiver," respectively, in future optical communication systems. Once achieved, topological light could be directly integrated into these systems, thereby enhancing their resilience by topological encoding and projection.

Finally, the dawn of topological waves offers a timely and broad research platform for the demonstration of new physics with diverse potential applications in communications, light–matter interaction, microscopy and spectroscopy with complex topologies. OPN

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For references and resources, go online: **optica-opn.org/link/0525-skyrmion**.

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