Researchers demonstrate that quantum entanglement and topology are inextricably linked

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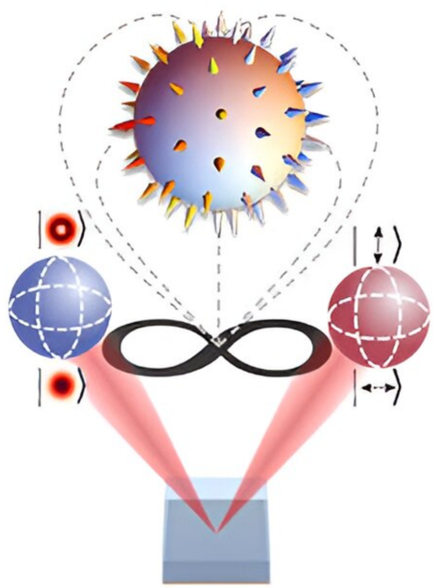

Conceptual illustration of the entangled Skyrmion topology. Each photon contributes to the emerging topology that only exists as a combined entity of the two photons. Credit: Wits University

For the first time, researchers have demonstrated the remarkable ability to perturb pairs of spatially separated yet interconnected quantum entangled particles without altering their shared properties.

The team includes researchers from the Structured Light Laboratory (School of Physics) at the University of the Witwatersrand in South Africa, led by Professor Andrew Forbes, in collaboration with string theorist Robert de Mello Koch from Huzhou University in China (previously from Wits University).

"We achieved this experimental milestone by entangling two identical photons and customizing their shared wave-function in such a way that their topology or structure becomes apparent only when the photons are treated as a unified entity," explains lead author, Pedro Ornelas, an MSc student in the structured light laboratory.

This connection between the photons was established through quantum entanglement, often referred to as "spooky action at a distance," enabling particles to influence each other's measurement outcomes even when separated by significant distances. The research was published in *Nature Photonics* on 8 January 2024.

The role of topology and its ability to preserve properties, in this work, can be likened to how a coffee mug can be reshaped into the form of a doughnut; despite the changes in appearance and shape during the transformation, a singular hole—a topological characteristic—remains constant and unaltered. In this way, the two objects are topologically equivalent. "The entanglement between our photons is malleable, like clay in a potter's hands, but during the molding process, some features are retained," explains Forbes.

The nature of the topology investigated here, termed Skyrmion topology, was initially explored by Tony Skyrme in the 1980s as field configurations displaying particle-like characteristics. In this context, topology refers to a global property of the fields, akin to a piece of fabric (the wave-function) whose texture (the topology) remains unchanged regardless of the direction in which it is pushed.

These concepts have since been realized in modern magnetic materials, liquid crystals, and even as optical analogs using classical laser beams. In the realm of condensed matter physics, skyrmions are highly regarded for their stability and noise resistance, leading to groundbreaking advancements in high-density data storage devices. "We aspire to see a similar transformative impact with our quantum-entangled skyrmions," says Forbes.

Previous research depicted these Skyrmions as localized at a single location. "Our work presents a paradigm shift: the topology that has traditionally been thought to exist in a single and local configuration is now nonlocal or shared between spatially separated entities," says Ornelas.

Expanding on this concept, the researchers utilize topology as a framework to classify or distinguish entangled states. They envisage that "this fresh perspective can serve as a labeling system for entangled states, akin to an alphabet," says Dr. Isaac Nape, a co-investigator.

"Similar to how spheres, doughnuts, and handcuffs are distinguished by the number of holes they contain, our quantum skyrmions can be differentiated by their topological aspects in the same fashion," says Nape. The team hopes that this might become a powerful tool that paves the way for new quantum communication protocols that use topology as an alphabet for quantum information processing across entanglement-based channels.

The findings reported in the article are crucial because researchers have grappled for decades with developing techniques to preserve entangled states. The fact that topology remains intact even as entanglement decays suggests a potentially new encoding mechanism that utilizes entanglement, even in scenarios with minimal entanglement where traditional encoding protocols would fail.

"We will focus our research efforts on defining these new protocols and expanding the landscape of topological nonlocal quantum states," says Forbes.

More information: Pedro Ornelas et al, Non-local skyrmions as topologically resilient quantum entangled states of light, *Nature Photonics* (2024). DOI: 10.1038/s41566-023-01360-4