Noncommutative metasurfaces enabled diverse quantum path entanglement of structured photons

We introduce an approach to achieve diverse path entanglement by exploiting the interaction between noncommutative metasurfaces and entangled photons.

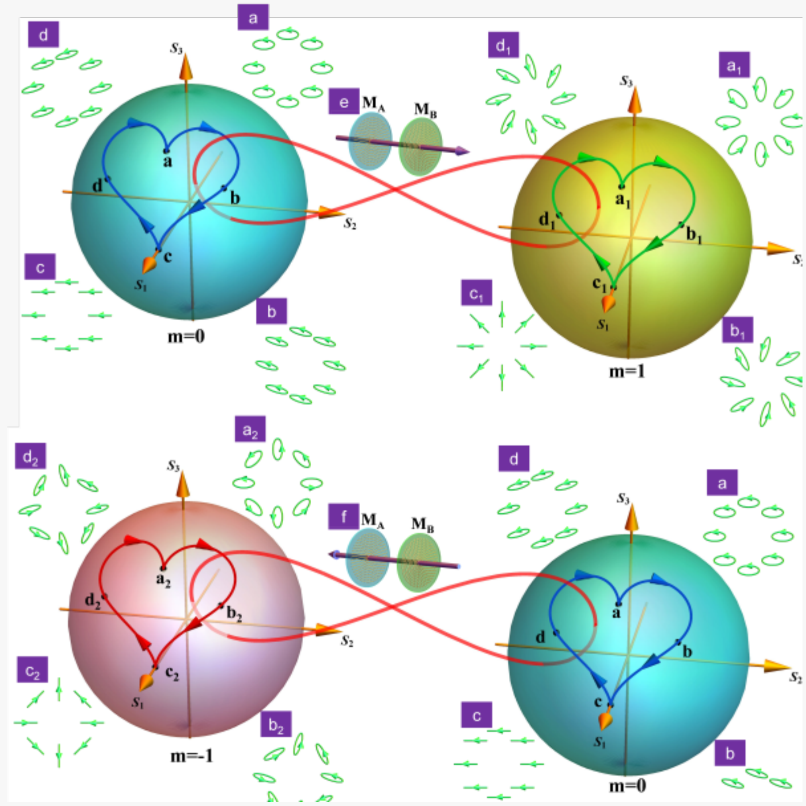

Fig 1. Schematic diagram for noncommutative metasurfaces enabled diverse quantum path entanglement of structured photons. Noncommutative metasurfaces (MAB, MBA) with different combination orders achieve path entanglement switching on HOPS with order.

CHENGDU, SICHUAN, CHINA, August 20, 2025 /EINPresswire.com/ -- Quantum entanglement, a core concept of quantum mechanics, is a key resource for quantum information science and is widely used in quantum communication, quantum computing, and other fields. However, traditional quantum entanglement is mostly based on a single degree of freedom, which limits the efficiency and capacity of quantum information processing. In recent years, progress has been made in the study of quantum entanglement with multiple degrees of freedom, but it remains challenging to generate and control complex quantum entangled states in a more compact and flexible manner. Metasurfaces, as artificial two-dimensional materials, can precisely control the amplitude, phase, and polarization of light to achieve complex optical functions, offering a new way to manipulate quantum entanglement flexibly. Currently, the potential of metasurfaces in the field of quantum entanglement has not been fully explored.

To address these challenges, the team led by Prof. Hailu Luo at Hunan University proposed a method to achieve diverse quantum path entanglement based on the interaction between noncommutative metasurfaces and entangled photons. Unlike traditional physical paths or paths in other degrees of freedom, the quantum path entanglement in this study arises from the evolution path of photons on the Poincaré sphere.

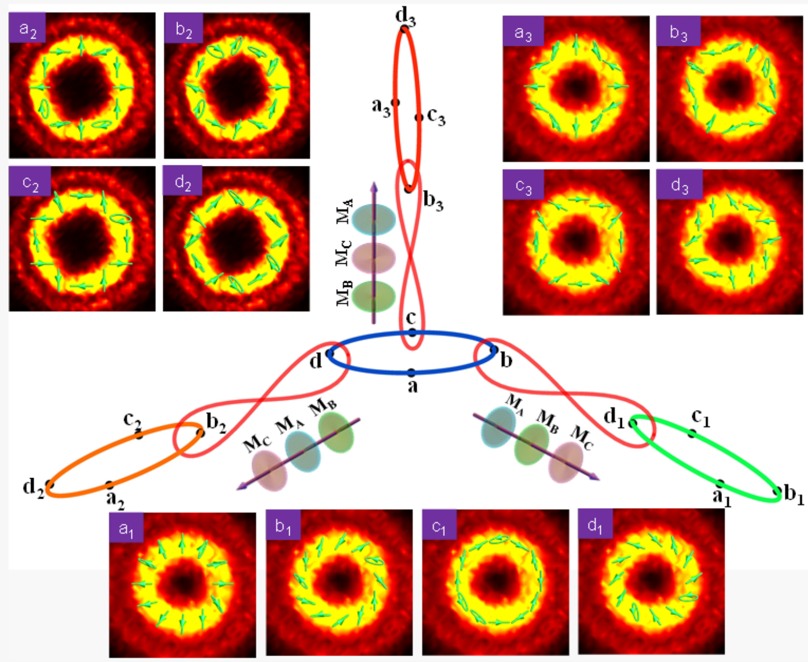

Fig 2. Generation of diverse quantum path entanglement of structured photons across multiple HOPS via noncommutative metasurfaces (m=1 (green), m=3 (orange), m=-1 (red)).

This study leverages the noncommutative property of metasurfaces (i.e., the cascading order of metasurfaces with different functionalities leads to distinct optical responses). By adjusting the combination sequence of metasurfaces, dynamic switching of quantum path entanglement between different higher-order Poincaré spheres (HOPS) can be achieved. As shown in Fig. 1, when signal photons pass through metasurfaces MA and MB in sequence, heart-shaped quantum path entanglement is generated on the HOPS with m=1. Conversely, when the metasurface order is reversed to MB followed by MA, the cardioid quantum path entanglement switches to the HOPS with m=-1. The noncommutativity of metasurfaces provides additional degrees of freedom for quantum entanglement manipulation, expanding the dimensions of quantum information processing.

Based on the ability of noncommutative metasurfaces to switch diverse quantum path entanglement between different HOPS, the researchers further expanded their versatility across a broader range of HOPS. By introducing three metasurfaces to further exploit noncommutative properties, diverse quantum path entanglement can be switched not only between HOPS of opposite orders but also different non-opposite orders. Three special cascaded metasurface sequences: MA-MB-MC, MB-MA-MC and MB-MC-MA were considered, enabling the switching and generation of quantum path entanglement on HOPS of different orders (such as m=1 (green), m=3 (orange), m=-1 (red), etc.) as shown in Fig. 2. This achievement not only validates the flexibility of noncommutative metasurfaces in quantum entanglement manipulation but also provides potential pathway for high-dimensional information encoding in quantum communications and parallel processing in quantum computing.

This study not only provides novel methodologies and insights for the generation and manipulation of quantum entanglement but also lays a solid foundation for the development of future quantum technologies, such as quantum communication and quantum computing. The introduction of noncommutative metasurfaces is expected to propel the field of quantum optics toward greater efficiency and flexibility, offering possibilities for realizing complex quantum protocols and high-dimensional quantum systems. This work was published as "Noncommutative metasurfaces enabled diverse quantum path entanglement of structured photons" in Opto-Electronic Science, Volume 6, 2025.

The research group of Prof. Hailu Luo from School of Physics and microelectronics, Hunan University propose "Noncommutative metasurfaces enabled diverse quantum path entanglement of structured photons".

Introduction of authors’ research group
Dr. Luo Hailu is currently a professor at the School of Physics and microelectronics, Hunan University. In 2007, he obtained his doctorate in theoretical physics from Nanjing University and joined Hunan University in the same year. In 2009, Dr. Luo Hailu established a spin photonics laboratory. Since then, he has carried out systematic and in-depth research in this field and successfully developed precision measurement techniques and differential imaging techniques based on the photonic spin Hall effect. Dr. Luo Hailu's current research interests mainly focus on the fundamental theory of spin photonics and its applications in multiple fields such as optical analog computation, all-optical image processing, quantum measurement, and quantum imaging. He led his group to publish more than 100 papers in academic journals such as Physical Review Letters, PNAS, Science Advances, Reports on Progress in Physics, Opto-Electronic Advances, and Opto-Electronic Science. These papers have been cited more than 10,000 times by domestic and foreign peers, with an h-index of 52 (Google Scholar). In addition, Prof. Luo Hailu has also achieved some results: he won the second prize for natural sciences of the Ministry of Education in 2020; from 2020 to 2024, he was selected as a highly cited scholar in China by Elsevier for five consecutive years.

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Andrew Smith
Charlesworth
+44 7753 374162
marketing@charlesworth-group.com
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