18-Qubit Entanglement with Six Photons' Three Degrees of Freedom

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Abstract: Full control of multiple degrees of freedom of multiple particles represents a fundamental ability for quantum information processing. We experimentally demonstrate an 18-qubit Greenberger-Horne-Zeilinger entanglement by simultaneous exploiting three different degrees of freedom of six photons, including their paths, polarization, and orbital angular momentum. We develop high-stability interferometers for reversible quantum logic operations between the photons' different degrees of freedom with precision and efficiencies close to unity, enabling simultaneous readout of 2^{18}=262 144 outcome combinations of the 18-qubit state. A state fidelity of 0.708 ± 0.016 is measured, confirming the genuine entanglement of all 18 qubits.

Quantum information is encoded by different states in certain degrees of freedom (DOF) of a physical system. For example, for a single photon, quantum information can be encoded not only in its polarization [1,2], but also in its orbital angular momentum (OAM) [3], and spatial modes [4]. A central task and challenge in quantum information science is to manipulate more quantum particles as well as their internal and external DOF, maintaining a high level of quantum coherence simultaneously. The ability to create and verify multi-qubit entanglement serves as an important benchmark for quantum technologies.

In linear optical system, the simultaneous entanglement with multiple DOFs, known as hyper-entanglement, offered an efficient route to increase the number of entangled qubits. There are several experiments reported, for instance, genuinely entangled Greenberger-Horne-Zeilinger (GHZ) states with up to five photons and their polarization and path modes [5]. However, it remained a technological challenge for the multi-photon experiments to go beyond 2 DOFs.

In this work, we develop methods to accomplish scalable creation of hyper-entanglement of multiple photon with 3 DOFs, together with reversible conversion and individual measurement of multiple DOFs with near-unity precision and efficiency. With these technologies, we demonstrate and verify 18-qubit maximal entanglement in GHZ state, the largest such state up till now, by manipulating the polarization, spatial modes and OAM of six photons.

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