Physicists detect entanglement of one photon shared among four locations

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Scientists at the California Institute of Technology (Caltech) have developed an efficient method to detect entanglement shared among multiple parts of an optical system. They show how entanglement, in the form of beams of light simultaneously propagating along four distinct paths, can be detected with a surprisingly small number of measurements. Entanglement is an essential resource in quantum information science, which is the study of advanced computation and communication based on the laws of quantum mechanics.

In the May 8 issue of the journal *Science*, H. Jeff Kimble, the William L. Valentine Professor and professor of physics at Caltech, and his colleagues demonstrate for the first time that quantum uncertainty relations can be used to identify entangled states of light that are only available in the realm of quantum mechanics. Their approach builds on the famous Heisenberg uncertainty principle, which places a limit on the precision with which the momentum and position of a particle can be known simultaneously.

Entanglement, which lies at the heart of quantum physics, is a state in which the parts of a composite system are more strongly correlated than is possible for any classical counterparts, regardless of the distances separating them.

Entanglement in a system with more than two parts, or multipartite entanglement, is a critical tool for diverse applications in quantum information science, such as for quantum metrology, computation, and communication. In the future, a "quantum internet" will rely on entanglement for the teleportation of quantum states from place to place (for a recent review see H. J. Kimble, *Nature* 453, 1023 (2008)).

"For some time physicists have studied the entanglement of two parts—or bipartite entanglement—and techniques for classifying and detecting the entanglement between two parts of a composite system are well known," says Scott Papp, a postdoctoral scholar and one of the authors of the paper. "But that hasn't been the case for multipartite states. Since they contain more than two parts, their classification is much richer, but detecting their entanglement is extremely challenging."

In the Caltech experiment, a pulse of light was generated containing a single photon—a massless bundle, with both wave-like and particle-like properties, that is the basic unit of electromagnetic radiation. The team split the single photon to generate an entangled state of light in which the quantum amplitudes for the photon propagate among four distinct paths, all at once. This so-called W state plays an important role in quantum information science.

To enable future applications of multipartite W states, the entanglement contained in them must be detected and characterized. This task is complicated by the fact that entanglement in W states can be found not only among all the parts, but also among a subset of them.

To distinguish between these two cases in real-world experiments, coauthors Steven van Enk and Pavel Luogovski from the University of Oregon developed a novel approach to entanglement detection based on the uncertainty principle. (See also the recent theoretical article by van Enk, Lougovski, and the Caltech group, "Verifying multi-partite mode entanglement of W states" at xxx.lanl.gov/abs/0903.0851.)

The demonstration of the detection of entanglement in multipartite W states is the key breakthrough of the Caltech group's work.

The new approach to entanglement detection makes use of non-local measurements of a photon propagating through all four paths. The measurements indicate whether a photon is present, but give no information about which path it takes.

"The quantum uncertainty associated with these measurements has allowed us to estimate the level of correlations among the four paths through which a single photon simultaneously propagates, by comparing to the minimum uncertainty possible for any less entangled states," says Kyung Soo Choi, a Caltech graduate student and one of the authors of the paper.

Correlations of the paths above a certain level signify entanglement among all the pathways; even partially entangled W states do not attain a similar level of correlation. A key feature of this approach is that only a relatively small number of measurements must be performed.

Due to their fundamental structure, the entanglement of W states persists even in the presence of some sources of noise. This is an important feature for real-world applications of W states in noisy environments. The Caltech experiments have directly tested this property by disturbing the underlying correlations of the entangled state. When the correlations are purposely weakened, there is a reduction in the number of paths of the optical system that are entangled. And yet, as predicted by the structure of W states, the entanglement remains amongst a subset of the paths.

"Our work introduces a new protocol for detecting an important class of entanglement with single photons," Papp explains. "It signifies the ever-increasing degree of control we have in the laboratory to study and manipulate quantum states of light and matter."

Next, the researchers plan to apply their technique to entangled states of atoms. These efforts will build upon previous advances in the Caltech Quantum Optics Group, including the mapping of photonic entanglement to and from a quantum memory (www.physorg.com/news124034968.html), and the distribution of entanglement amongst the nodes of a quantum network (www.physorg.com/news95349862.html).

More information: The paper, "Characterization of Multipartite Entanglement for One Photon Shared Among Four Optical Modes," appears in the May 8 issue of *Science*.

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