Physicists extend entanglement in Einstein experiment

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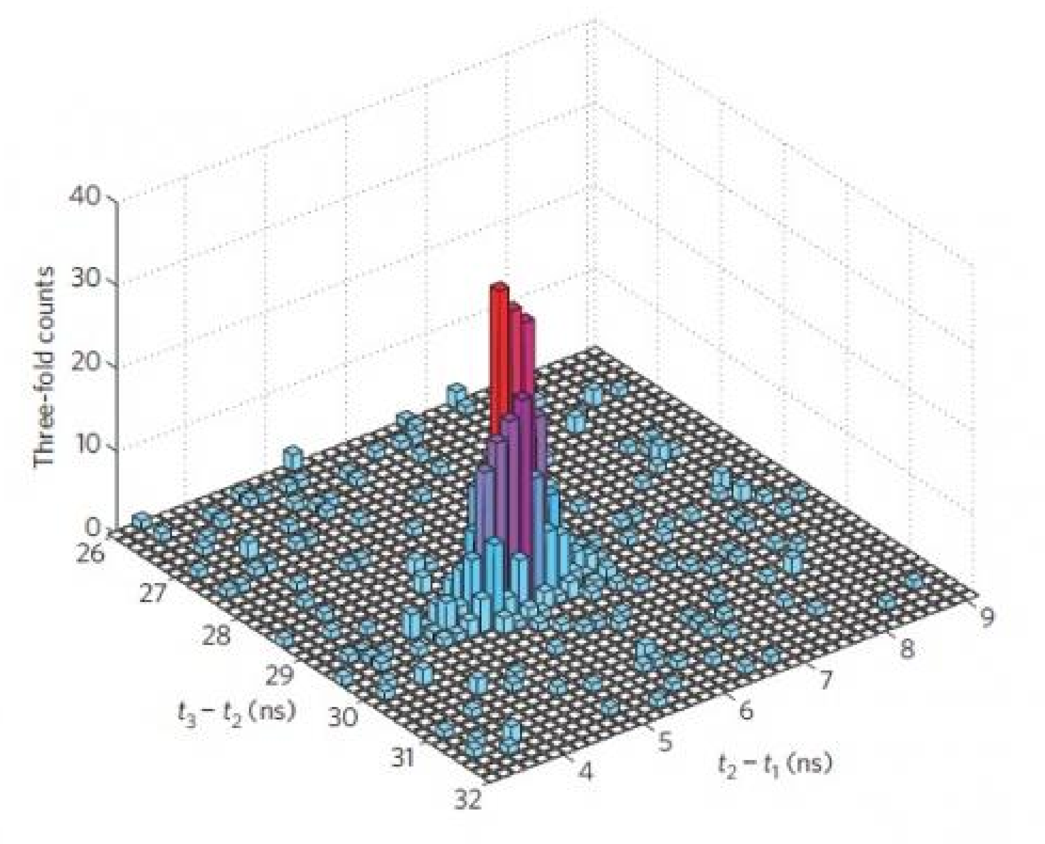

To verify entanglement among the three photons, the physicists measured the times that the photons arrived at a detector. This 2D histogram shows that groups of three photons are all localized to a small region, indicating strong correlations in the arrival times of the three photons. Image credit: L. K. Shalm, et al. ©2012 Macmillan Publishers Limited

(Phys.org)—Using a photon fission process, physicists have split a single photon into a pair of daughter photons and then split one of the daughter photons into a pair of granddaughters to create a total of three photons. All three photons, the scientists showed, share quantum correlations between their energies (corresponding to their momentums) and between their emission times (corresponding to their positions). The study marks the first experimental demonstration of energy-time entanglement of three or more individual particles, building on the original two-particle version proposed by Einstein, Podolsky, and Rosen (EPR) 77 years ago.

The physicists, from the University of Waterloo and the University of Calgary, have published their paper on three-photon energy-time entanglement in a recent issue of Nature Physics.

As the physicists explain, this new form of entanglement is the three-photon version of the famous EPR correlations for continuous variables (e.g., position and momentum) between two particles. The EPR thought experiment, published in 1935, raised questions about the fundamental concepts underlying the young theory of quantum mechanics.

"The Heisenberg uncertainty principle forbids one from simultaneously discovering both the position and momentum of a particle with arbitrary accuracy," lead author Krister Shalm of the University of Waterloo told *Phys.org*. "EPR pointed out that, if you create a pair of entangled particles, it is possible to measure both the position and momentum of both of them with arbitrary precision. It is still impossible to learn both the position and momentum of each of the individual particles, but, instead, we can learn information about the total position and momentum they share. Entangled particles, in some sense, are the ultimate team players. They lose their own individual identity with all the information in the system contained in the correlations."

In the original experiment, EPR tried to demonstrate that the correlations between two particles were so strong that there must be some hidden parameter to explain them that quantum mechanics does not account for. This conclusion seemed to uncover some inadequacies in quantum mechanics.

"The original arguments made by EPR in 1935 were designed to show that quantum mechanics, by itself, is not sufficient to describe reality," Shalm said. "This inspired John Bell, who showed that if you take the arguments of EPR that relied on hidden variables to their logical conclusions, you arrive at a contradiction with quantum mechanics. Since then, much work has been devoted to using Bell's work to test quantum mechanics, and extensions of the work have profoundly shaped our understanding of the quantum world."

Building on these studies over the next several decades, physicists have demonstrated many different types of entanglement, which are defined by the number and type of objects that are entangled and the properties of the objects that are entangled. These properties can fit into one of two categories: discrete or continuous, which describe the variable's domain. For example, spin is a discrete variable since its value can only be an integer or half-integer, while emission time is continuous. Entanglement has previously been demonstrated between the discrete variables of 14 ions and the continuous variables of three light beams, but until now entanglement among the continuous properties of three individual particles has remained an open challenge.

"What is exciting about our work is that we can take the original arguments made by EPR for two particles and extend them to three particles," Shalm said. "The kind of entanglement that EPR first proposed pertained to continuous variables, like position and momentum, as opposed to discrete variables, like polarization or spin. Discrete variables in photons have traditionally been easier to manipulate. With our system we finally have a viable way to explore the entanglement of continuous variables between three particles."

To achieve continuous-variable entanglement among three photons, the physicists split a photon into a pair of daughters using a process called cascaded spontaneous parametric downconversion. Since energy is conserved, each daughter photon has a frequency that is roughly half that of the pump photon. When one of the daughter photons is split, the two granddaughter photons each have a frequency that is about half that of the daughter photons. Although the frequency of each individual photon may vary slightly from exact halving, the total energy of the three photons combined is exactly equal to the energy of the pump photon. In addition, because the splitting process is instantaneous, the three photons must arrive at photon detectors at the same time.

Under these production conditions, the three photons share strong spectral correlations and, in theory, possess genuine tripartite energy-time entanglement. This means that the energy values and the emission times of the three photons share correlations that are stronger than those allowed by classical physics.

To verify that the three photons possess energy-time entanglement, the physicists had to confirm that the three photons violate a set of inequalities that are an extension of the EPR arguments for two particles. These tests require measuring and comparing the arrival times of the three photons at a single-photon detector. One way to do this is to directly measure each photon's frequency; however, current technology doesn't provide sufficient precision for direct frequency measurements. Instead, the scientists measured the frequency of the pump photon and ensured that energy was conserved in the downconversion process. They also used detectors to measure the arrival times of the photons, but noted that the detectors have a timing jitter of several hundred picoseconds that limited the precision.

Even accounting for this uncertainty, the results showed that the three photons do indeed violate the EPR inequalities and are therefore energy-time entangled. Future improvements in detector precision would provide improvements in the measured values of the inequalities by over two orders of magnitude. In addition, new technologies to enhance the observed effects could potentially allow this scheme to be scaled up to larger photon numbers.

In terms of applications, this entanglement scheme could be useful in quantum communications because it provides the opportunity to entangle multiple degrees of freedom, generating "hyper-entanglement." If one of the entangled photons could be interfaced with an atomic storage medium while the other two photons are transmitted over telecom fibers to remote quantum nodes, then scientists could create new possibilities for storing and distributing quantum information. Other modifications of the scheme could lead to new fundamental tests of quantum mechanics.

"Three particle states that are entangled in their continuous degrees of freedom may allow for a new class of tests for quantum mechanics that could further our understanding of quantum theory and entanglement," Shalm said. "This is also an important technological step. It is a system that lets us exploit optical nonlinearities at the single-photon level. This may have important applications in creating the gates needed in a quantum computer, or in distributing quantum information over a network."

In the future, the scientists plan to try to combine the position and momentum entanglement among the three photons with more traditional types of entanglement based on angular momentum and polarization. This kind of combined entanglement could lead to the creation of hybrid quantum systems that possess multiple unique properties of light at the same time.

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