Entanglement between photons that never co-existed

E. Megidish, A. Halevy, T. Shacham, T. Dvir, L. Dovrat, and H. S. Eisenberg
Racah Institute of Physics, Hebrew University of Jerusalem, Jerusalem 91904, Israel
hagai.eisenberg@huji.ac.il

We entangle two photons, with the first detected even before the other is created, by using entanglement swapping between temporally-separated polarization-entangled photon pairs. This result shows the nonlocality of quantum mechanics in spacetime.

OCIS codes: (270.4180) Multiphoton processes; (270.5585) Quantum information and processing.

Entanglement between quantum systems is the most puzzling property of quantum mechanics. It results in non-classical correlations between systems that are separated in time and space. Photons are useful realizations of quantum particles as they are easily manipulated and preserve their coherence for long times. Here we demonstrate the creation of entanglement between photons that never interacted, and even more importantly, never co-existed.

A common method for the generation of polarization-entangled photon states is parametric down-conversion (PDC) in nonlinear dielectric crystals[1]. In this process, a high-energy pump photon splits into two lower-energy photons while preserving momentum and energy. With this method it is possible to create bright high quality two photon states in any of the four maximally entangled states, also known as Bell states. For polarized photons these states are

$$|\psi^{\pm}\rangle_{1,2} = \frac{1}{\sqrt{2}}|h_1 v_2\rangle \pm |v_1 h_2\rangle \qquad (1)$$
$$|\phi^{\pm}\rangle_{1,2} = \frac{1}{\sqrt{2}}|h_1 h_2\rangle \pm |v_1 v_2\rangle \ ,$$

where h_1 (v_2) represents a horizontally (vertically) polarized photon in the spatial mode 1 (2).

Entanglement between photons can also be introduced post-selectively by measurement projections onto maximally entangled states[2]. A Bell projecting measurement can be achieved by combining two photons at a polarizing beam-splitter (PBS). The two photons enter individually from each of the ports. In the case where each photon exits the PBS at a different port, the photons must have identical polarizations. If no information is available as to whether they were transmitted or reflected, they are also indistinguishable. An additional 45° polarization rotation (to the P/M polarization basis), enables a projection onto the $|\phi^{\pm}\rangle$ Bell states.

Entanglement swapping is an important protocol in quantum information and computation[3]. It entangles remote photons without any interaction between the photons. In the beginning, two independent entangled photon pairs are created, e.g., from a PDC source. Two photons, one from each of the pairs, are projected onto a Bell state using a PBS. As a result, the two other photons, each from a different pair as well, become entangled even though they may be very distant from each other. Entanglement swapping is the main principle of quantum repeaters that should overcome the limiting effect of absorption in long range quantum communication. Previous demonstrations entangled photons that were separated spatially, but not temporally, i.e., the photons that were entangled existed and were measured at the same time.

In this work we swap the entanglement between temporally separated photons that exist in separate times. A pulsed laser pumps a single PDC polarization-entangled photon source. Two pairs are created at the same source but from different pulses, separated in time by τ:

$$|\psi^-\rangle_{1,2}^{0,0}|\psi^-\rangle_{1,2}^{\tau,\tau} = \frac{1}{2}(|h_1^0 v_2^0\rangle - |v_1^0 h_2^0\rangle)(|h_1^\tau v_2^\tau\rangle - |v_1^\tau h_2^\tau\rangle) \ . \qquad (2)$$

The uppercase designation is for the time-label of the photon. In order to project the second photon of the first pair and the first photon of the second pair onto a Bell state, the former is delayed by τ by a delay line. The same delay is also applied to the second photon of the second pair and the resulting state can be written as:

$$\begin{aligned}|\psi^-\rangle_{1,2}^{0,\tau}|\psi^-\rangle_{1,2}^{\tau,2\tau} = \frac{1}{2}(&|\psi^+\rangle_{1,2}^{0,2\tau}|\psi^+\rangle_{1,2}^{\tau,\tau} - |\psi^-\rangle_{1,2}^{0,2\tau}|\psi^-\rangle_{1,2}^{\tau,\tau} \\ &-|\phi^+\rangle_{1,2}^{0,2\tau}|\phi^+\rangle_{1,2}^{\tau,\tau} + |\phi^-\rangle_{1,2}^{0,2\tau}|\phi^-\rangle_{1,2}^{\tau,\tau}) \ .\end{aligned} \qquad (3)$$

If the photons of time τ are projected onto any Bell state, the first and last photons will also collapse into the same state. The first and last photons, that did not share between them any correlations before, become entangled.

Entanglement between the first and the last photons is created gradually. First, one entangled pair is created, then the second, and finally, the swapping between them is performed. The timing of each photon is merely an additional label to discriminate between the different photons. It is thus clear that the time of the measurement of each photon has no effect on the final outcome. In previous demonstrations, all photons were first created, and only then measured. In our scheme, the first photon from the first pair is measured even before the second pair is created.

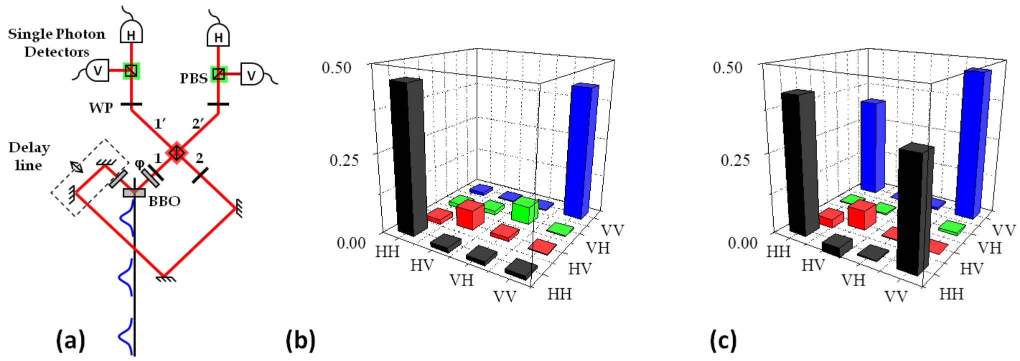

Fig. 1. (a) Experimental setup. (b, c) Real part of the density matrices of the first and last photons, for the case where the middle photons are temporally distinguishable (b) and indistinguishable (c), conditioned on projection of the two middle photons onto the $|\phi^+\rangle$ state.

After the creation of the second pair, the Bell projection occurs by a measurement of a photon from each of the pairs. Only after another delay period, the last photon from the second pair is detected. As entanglement swapping creates correlations between the first and last photons non-locally, the fact that the first photon has been measured even before it was linked to the last photon has no effect on the final outcome. Quantum correlations are only established a posteriori, after measurement of all the photons is completed.

We used the experimental setup presented in Fig. 1a. A doubled Ti:Sapphire laser beam with 400 mW at a wavelength of 390 nm and a repetition rate of 76 MHz pumps a β-BaB_2O_4 (BBO) nonlinear crystal. By type-II non-collinear PDC, polarization entangled pairs are created in the state $|\psi^-\rangle_{1,2}$ with low-power visibility above 90% in the H/V and P/M bases. The free-space delay line is 31.5 m long (105 ns), such that entanglement swapping occurs between pairs created by pump pulses that are 8 pulses apart. The delay time is longer than the single-photon detectors' dead-time (50 ns, Perkin-Elmer SPCM-AQR). This delay time is sufficient to ensure that the first photon detection is completed before the second pair is created.

After the two middle photons have passed through the red PBS, but before they are measured, the four photons are in a GHZ state [4]. These two projected photons are than rotated by wave-plates (denoted WP in Fig. 1a) and measured by the green PBS's in Fig. 1a. The first and last photons though, are already measured when they pass through the red PBS. It would appear that to rotate them without rotating the middle photons that pass through the same paths would require controlled polarization rotators such as fast Pockels cells. Fortunately, we have found that static rotations before the red PBS and a controlled birefringent phase do not affect the middle photons as they pass through the red PBS at the H/V basis, but non-locally rotate the first and last photons.

In order to demonstrate the entanglement created between the first and last photons, we used the non-local rotations to perform quantum state tomography (QST) [5] with a maximal likelihood procedure of these two photons' state, conditioned on the detected state of the two middle photons. The results presented in Figs. 1b and 1c are for the condition that the two middle photons at time τ were projected on the $|\phi^+\rangle_{1,2}^{\tau,\tau}$ state. In Fig. 1b the projected middle photons are temporally distinguishable, as they do not arrive at the PBS simultaneously, while in Fig. 1c this distinguishability is removed. When the projected photons are indistinguishable, the measured state of the first and last photons has fidelity of $77 \pm 1\%$ with a pure $|\phi^+\rangle_{1,2}^{0,2\tau}$ state. When the projected photons are distinguishable, the off-diagonal coherence elements vanish. We also performed QST when the two middle photons were projected on the $|\phi^-\rangle$ state. In this case, the sign of the off-diagonal elements was changed as expected.

In conclusion, we have entangled two photons that never interacted nor co-existed. The first photon was measured even before the entangling projection measurement took place and without knowledge about its outcome. The last photon was detected after the projection measurement occurred, and showed quantum correlations with the first photon, conditioned on the projection result. The delay of the second photon from the first pair until the next pair arrives can be regarded as a quantum memory that keeps a qubit for a later entanglement with another system. This is a required protocol for quantum repeaters, as one qubit may have to be delayed at a node for a successful arrival of a second qubit before they are both projected on a Bell state.

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