Entanglement Swapping between Photons that have Never Coexisted

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The role of the timing and order of quantum measurements is not just a fundamental question of quantum mechanics, but also a puzzling one. Any part of a quantum system that has finished evolving can be measured immediately or saved for later, without affecting the final results, regardless of the continued evolution of the rest of the system. In addition, the nonlocality of quantum mechanics, as manifested by entanglement, does not apply only to particles with spacelike separation, but also to particles with timelike separation. In order to demonstrate these principles, we generated and fully characterized an entangled pair of photons that have never coexisted. Using entanglement swapping between two temporally separated photon pairs, we entangle one photon from the first pair with another photon from the second pair. The first photon was detected even before the other was created. The observed two-photon state demonstrates that entanglement can be shared between timelike separated quantum systems.

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Entanglement between spatially separated quantum systems is one of the most distinctive results of quantum mechanics. It results in nonclassical correlations between distant systems. Einstein, Podolsky, and Rosen claimed that these instantaneous correlations give rise to a paradox which demonstrates the incompleteness of quantum mechanics [1]. Only after the realization of an experiment suggested by Bell [2–4] was the nonlocal nature of quantum mechanics widely accepted. Nevertheless, the properties of entanglement still puzzle many researchers.

Single photons are used as quantum particles in many experimental realizations, as they are easily manipulated and preserve their coherence for long times. A common method for generating polarization entangled photon states is using the nonlinear optical process of parametric down-conversion (PDC) in dielectric crystals [5]. In this process, a 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 the Bell states. For polarized photons these states are

$$\begin{aligned} |\phi^{\pm}\rangle &= \frac{1}{\sqrt{2}}(|h_a h_b\rangle \pm |v_a v_b\rangle), \\ |\psi^{\pm}\rangle &= \frac{1}{\sqrt{2}}(|h_a v_b\rangle \pm |v_a h_b\rangle), \end{aligned} \tag{1}$$

where $h_a(v_b)$ represents a horizontally (vertically) polarized photon in spatial mode a (b).

Photons can also be entangled by projection measurements onto maximally entangled states [6]. Bell state measurements with linear optical elements require postselection. They can discriminate simultaneously only between two of the four Bell states [7,8]. Complete Bell projection of polarized photons can be achieved using nonlinear optics [9], hyperentanglement [10], and auxiliary photons [11]. Bell projection is a key ingredient in quantum computation and communication protocols such as teleportation [12] and entanglement swapping [13].

Entanglement swapping is the central principle used in quantum repeaters [14], whose purpose is to overcome the limiting effect of photon loss in long-range quantum communication. Previous demonstrations of entanglement swapping [15] and multistage entanglement swapping [16], entangled photons that were separated spatially, but not temporally, i.e., all the photons that were entangled, existed and were measured at the same time.

In this work we demonstrate how the time at which quantum measurements are taken and their order has no effect on the outcome of a quantum mechanical experiment, by entangling two photons that exist at separate times. This is achieved by first creating one photon pair (1–2) and right away measuring photon 1 (see Fig. 1). Photon 2 is delayed until a second pair (3–4) is created and photons 2 and 3 are projected onto the Bell basis. This projection swaps entanglement onto photons 1 and 4. When photon 1 is measured in a certain basis, it does not "know" that photon 4 is going to be created, and in which basis it will be measured. Nevertheless, photons 1 and 4 exhibit quantum correlations despite the fact that they never coexisted. Entanglement swapping of time-bin encoded photons, where each photon is superimposed over more than a single time slot, has also been demonstrated [17]. Nevertheless, the possible time slots of both photons in this case overlap in time.

The idea of quantum correlations in time goes back a long way [18]. Recently, it was suggested to study causality using such correlations [19]. Possible scenarios were discussed theoretically in a system of atoms and photons [20], and in a system where superconducting qubits are coupled to a vacuum mode [21,22]. The consequent emission of two Raman photons from quantum memories made

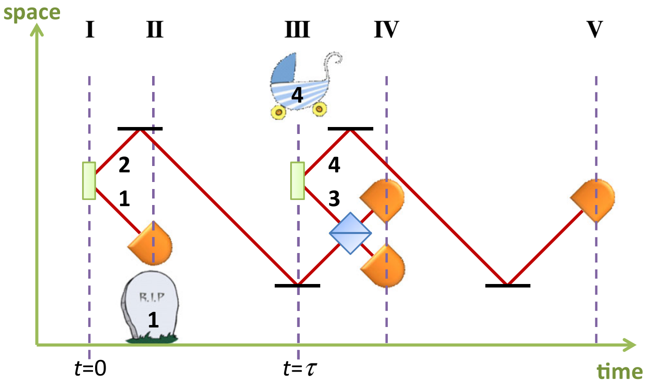

FIG. 1 (color online). Time line diagram. (I) Birth of photons 1 and 2, (II) detection of photon 1, (III) birth of photons 3 and 4, (IV) Bell projection of photons 2 and 3, (V) detection of photon 4.

of a single atom or an atomic ensemble has been previously used to demonstrate the coherence time of the quantum register [23,24]. As these two photons reflect the quantum state of the memory, they exhibit quantum correlations over a long period of time. Before the emission of the second photon (the memory readout), the memory is already entangled with the first photon. Thus, there is no moment in time when the two photons are not entangled, and their observed state is always the same. Recently, entanglement swapping was demonstrated with a delayed choice. Unlike our demonstration, in the first stage of this experiment, all four photons were created, and thus coexisted. Photons 1 and 4 were then measured simultaneously. The choice whether to entangle them or not, by changing the measurement of photons 2 and 3, was done only in the last stage [25].

The scenario of time and space separation we create should be compared to the standard two particle entangled state, where the particles are only spatially separated. In the standard entanglement case, the measurement of any one of the particles instantaneously changes the physical description of the other. This result was described by Einstein as "spooky action at a distance." In the scenario we present here, measuring the last photon affects the physical description of the first photon in the past, before it has even been measured. Thus, the "spooky action" is steering the system's past [26]. Another point of view that one can take is that the measurement of the first photon is immediately steering the future physical description of the last photon. In this case, the action is on the future of a part of the system that has not yet been created. As in the Einstein-Podolsky-Rosen case, this result raises no paradox and does not violate causality.

In order to generate consecutive photon pairs at well-defined times, a pulsed laser is used to pump a single PDC polarization entangled photon source [5]. It is a probabilistic source, and thus there is a probability that two pairs will be created, each pair from one of two consecutive pulses, separated by the laser period time τ. The four-photon state is

$$|\psi^-\rangle^{0,0}_{a,b} \otimes |\psi^-\rangle^{\tau,\tau}_{a,b} = \frac{1}{2}(|h^0_a v^0_b\rangle - |v^0_a h^0_b\rangle) \otimes (|h^\tau_a v^\tau_b\rangle - |v^\tau_a h^\tau_b\rangle), \quad (2)$$

where the subscripts are the spatial mode labels and the superscripts are the time labels of the photons. 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 in a delay line. The same delay is also applied to the second photon of the second pair and the resulting state can be reordered and written as

$$|\psi^-\rangle^{0,\tau}_{a,b} \otimes |\psi^-\rangle^{\tau,2\tau}_{a,b} = \frac{1}{2}(|\psi^+\rangle^{0,2\tau}_{a,b}|\psi^+\rangle^{\tau,\tau}_{a,b} - |\psi^-\rangle^{0,2\tau}_{a,b}|\psi^-\rangle^{\tau,\tau}_{a,b} - |\phi^+\rangle^{0,2\tau}_{a,b}|\phi^+\rangle^{\tau,\tau}_{a,b} + |\phi^-\rangle^{0,2\tau}_{a,b}|\phi^-\rangle^{\tau,\tau}_{a,b}). \quad (3)$$

When the two photons of time τ (photons 2 and 3) are projected onto any Bell state, the first and last photons (1 and 4) collapse also into the same state and entanglement is swapped. The first and last photons, that did not share between them any correlations, become entangled.

According to this description, the timing of each photon is merely an additional label to discriminate between the different photons, and the time in which each photon is measured has no effect on the final outcome. The first photon from the first pair (photon 1) is measured even before the second pair is created (see Fig. 1). After the creation of the second pair, the Bell projection occurs and only after another delay period is the last photon from the second pair (photon 4) detected. Entanglement swapping creates correlations between the first and last photons nonlocally not only in space but also in time. Quantum correlations are only observed *a posteriori*, after the measurement of all photons is completed.

We realized this scenario with the experimental setup presented in Fig. 2 [27]. Polarization entangled photon pairs are created by noncollinear type-II PDC [5]. A pulsed Ti:sapphire laser source with a 76 MHz repetition rate is frequency doubled to a wavelength of 390 nm and an average power of 400 mW. The laser beam is corrected for astigmatism and focused on a 2 mm thick β-BaB$_2$O$_4$ (BBO) crystal (see Fig. 2). Compensating crystals (CC) correct for temporal walk-offs. In addition, tilting of the compensating crystal in path a is used to control the phase φ of the state; e.g., for $\varphi = \pi$ the resulting state is $|\psi^-\rangle$. Half wave plates (HWP) are used to analyze the photons in a rotated basis. The 780 nm wavelength down-converted photons are spatially filtered by coupling them into and out of single-mode fibers and spectrally filtered by using 3 nm wide bandpass filters.

One photon from the first pair is delayed until another pump pulse arrives at the generating crystal by a 31.6 m (105 ns) free-space delay line. The delay is built from high reflecting dielectric mirrors, with an overall transmittance higher than 90% after 10 reflections. Less than 10% of the signal is sampled into a single-mode fiber as a feedback

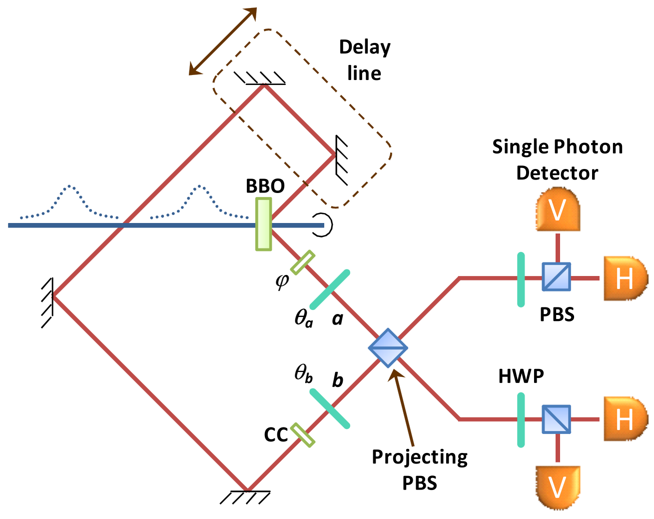

FIG. 2 (color online). The experimental setup (see text for details).

signal that is used to stabilize the delayed beam's spatial properties, by tilting a piezomounted mirror in the middle of the delay line. We chose the delay length to be the time between eight consecutive laser pulses, in order not to lose signal due to the dead time of the single-photon detectors (Perkin Elmer SPCM-AQ4C), and to provide enough time for the measurement of the first photon before the second pair is created.

The delayed photon of the first pair and the nondelayed photon of the second pair are projected onto a Bell state by combining them at the projecting polarizing beam splitter (PBS) (see Fig. 2) [6]. We postselect the cases where each photon exits this PBS at a different port. We ensure that the photons are indistinguishable; i.e., no information is available as to whether both were transmitted or both were reflected. After passing through the PBS, the photons are rotated by HWPs to the $|p/m\rangle = 1/\sqrt{2}(|h\rangle \pm |v\rangle)$ polarization basis. When the polarizations of the middle photons are correlated (hh or vv) they are projected onto a $|\phi^+\rangle^{\tau,\tau}_{a,b}$ state. When they are anticorrelated (hv or vh) they are projected onto a $|\phi^-\rangle^{\tau,\tau}_{a,b}$ state.

In order to fully characterize the first and last photons' state, a quantum state tomography procedure is required [28]. Generally, such a procedure involves independent polarization rotations of each of the photons involved. We have used a set of nonlocal rotations to achieve this (see the Supplemental Material [29] for more details). The density matrix of the first and last photons was constructed, conditioned on the outcome of the projection of the two photons of time τ. If the projected photons were measured in the $|\phi^+\rangle^{\tau,\tau}_{a,b}$ state, the first and last photons were entangled in the $|\phi^+\rangle^{0,2\tau}_{a,b}$ state [see Fig. 3(a)]. Alternatively, if the projected photons were measured in the $|\phi^-\rangle^{\tau,\tau}_{a,b}$ state, the first and last photons were entangled in the $|\phi^-\rangle^{0,2\tau}_{a,b}$ state [see Fig. 3(b)].

Entanglement is demonstrated when the observed fidelity is above 50%. The fidelity between the measured and the theoretical density matrices is $(77 \pm 1)\%$. We calculated other entanglement measures from the measured matrices. The concurrence of this state is 0.57 ± 0.03 (entangled state should have any positive number [30]), the Peres criterion is -0.28 ± 0.01 (should be negative [31]), and the sum of three mutually unbiased visibilities is 2.09 ± 0.06 (should be larger than 1 [32]). Nonlocal steering between photons 1 and 4 is also possible, as the steering parameter S_3 of the measured state is 0.70 ± 0.02 (should be larger than $1/\sqrt{3}$ [33]). The Clauser-Horne-Shimony-Holt inequality value is 2.04 ± 0.04 [4]. This is only a marginal violation of Bell-like nonlocality. Thus, photons 1 and 4 are shown to be entangled and can exhibit nonlocal steering.

The fidelity of the measured entanglement is not perfect as a result of two kinds of imperfections: the entanglement quality of the original photon pairs and the quality of the projection of photons 2 and 3 on a Bell state. The PDC process produces some spectral distinguishability between the photons that reduces the quality of pair entanglement [34], which in turn limits the maximal quality of the swapped entanglement. In addition, the pair quality affects

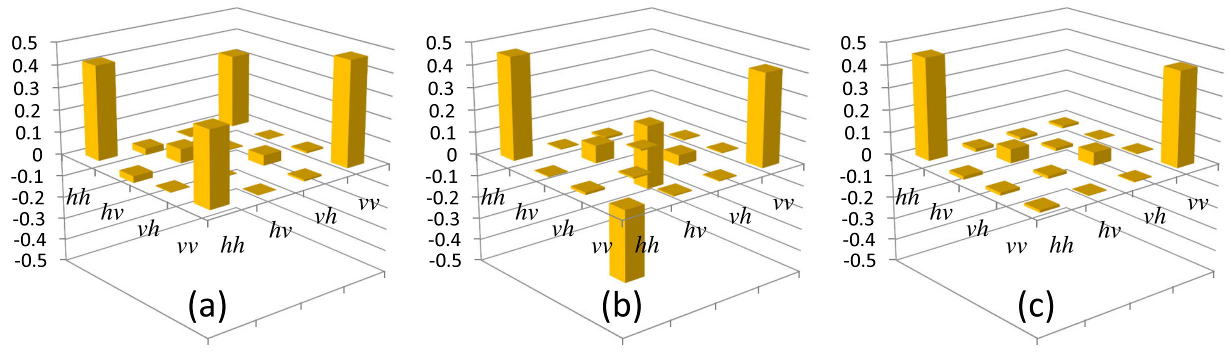

FIG. 3 (color online). Real parts of the density matrices of the first and last photons. (a) The two middle photons are projected onto the $|\phi^+\rangle$ state, (b) the two middle photons are projected onto the $|\phi^-\rangle$ state, and (c) the projection fails due to temporal distinguishability. The total fourfold count rate was 12 Hz and each polarization setting was integrated over 6 min. For errors, see Fig. 1 of the Supplemental Material [29].

the nonlocal rotations that are used in the quantum state tomography procedure. The photon pair fidelity is further reduced after passing through the delay line by 1%–2%. Another cause for reduced fidelity is the presence of higher order events. We estimate this effect to reduce the fidelity by ~2%. Thus, before the projection this fidelity is 93.7%. For good projection, perfect indistinguishability between photons 2 and 3 is required. Although we are shaping the beam from the delay line with a telescope, there is still some beam shape distinguishability between the delayed and the nondelayed beams. The delayed beam position is also changing slowly because of minute ambient temperature changes. We do have a closed loop active stabilization of two of the mirror mounts in the delay, but some distinguishability cannot be avoided.

One can also choose to introduce distinguishability between the two projected photons. In this case, the phase between the two terms of the $|\phi\rangle$ projected state is undefined, resulting in a mixture of $|\phi^+\rangle$ and $|\phi^-\rangle$ in the projected state, and the first and last photons do not become quantum entangled but classically correlated. We observed this when we introduced a sufficient temporal delay between the two projected photons [see Fig. 3(c)]. It is also evidence that the first and last photons did not somehow share any entanglement before the projection of the middle photons.

The scenario we have created is very likely to occur in future quantum repeater realizations [14]. When only one entangled photon reaches a node, it is delayed or stored in a quantum memory until a second photon from another entangled pair arrives. During this waiting period, the distant photon from the first pair can already be used. Only after the arrival of a photon from the second pair are the two photons projected onto a Bell state and entanglement is generated *a posteriori* between the other two distant photons.

In conclusion, we have demonstrated quantum entanglement between two photons that do not share coexistence. Although one photon is measured even before the other is created, their quantum state is inseparable, as is shown by the measured density matrix of the two photons, conditioned on the result of the projecting measurement. This is a manifestation of quantum entanglement not only in space, but also in time. The inductive nature of the setup that was used suggests that it is possible, in principle, to use it to observe multiple stage entanglement swapping.

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[29] See Supplemental Material at http://link.aps.org/supplemental/10.1103/PhysRevLett.110.210403 for the quantum state tomography by nonlocal polarization rotations and for the full density matrix of Fig. 3(a) real, imaginary, and errors.

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