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Experimental Entanglement Swapping: Entangling Photons That Never Interacted

Jian-Wei Pan, Dik Bouwmeester, Harald Weinfurter, and Anton Zeilinger

Institut für Experimentalphysik, Universität Innsbruck, Technikerstrasse 25, A-6020 Innsbruck, Austria

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We experimentally entangle freely propagating particles that never physically interacted with one another or which have never been dynamically coupled by any other means. This demonstrates that quantum entanglement requires the entangled particles neither to come from a common source nor to have interacted in the past. In our experiment we take two pairs of polarization entangled photons and subject one photon from each pair to a Bell-state measurement. This results in projecting the other two outgoing photons into an entangled state. [S0031-9007(98)05913-4]

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Entanglement is one of the most fundamental features of quantum mechanics. It is at the heart of the Einstein-Podolsky-Rosen paradox, of Bell's inequalities, and of the discussions of the nonlocality of quantum mechanics. Thus far, entanglement has been realized either by having the two entangled particles emerge from a common source [1], or by having two particles interact with each other [2]. Yet, an alternative possibility to obtain entanglement is to make use of a projection of the state of two particles onto an entangled state. This projection measurement does not necessarily require a direct interaction between the two particles: When each of the particles is entangled with one other partner particle, an appropriate measurement, for example, a Bell-state measurement, of the partner particles will automatically collapse the state of the remaining two particles into an entangled state. This striking application of the projection postulate is referred to as entanglement swapping [3–5], and in this Letter we report its first experimental realization.

Consider two EPR sources, simultaneously emitting each a pair of entangled particles (Fig. 1). In anticipation of our experiments we assume that these are polarization entangled photons in the state

$$|\Psi\rangle_{1234} = \frac{1}{2}(|H\rangle_1|V\rangle_2 - |V\rangle_1|H\rangle_2) \times (|H\rangle_3|V\rangle_4 - |V\rangle_3|H\rangle_4). \quad (1)$$

Here $|H\rangle$ or $|V\rangle$ indicates the state of a horizontally or a vertically polarized photon, respectively. The total state describes the fact that photons 1 and 2 (3 and 4) are entangled in an antisymmetric polarization state. Yet, the state of pair 1-2 is factorizable from the state of pair 3-4; that is, there is no entanglement of any of the photons 1 or 2 with any of the photons 3 or 4.

We now perform a joint Bell-state measurement on photons 2 and 3; that is, photons 2 and 3 are projected onto one of the four Bell states which form a complete basis for

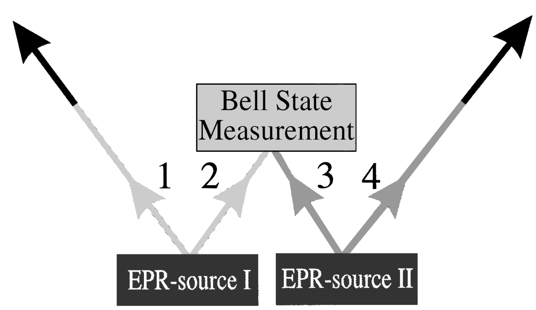

FIG. 1. Principle of entanglement swapping. Two EPR sources produce two pairs of entangled photons, pair 1-2 and pair 3-4. One photon from each pair (photons 2 and 3) is subjected to a Bell-state measurement. This results in projecting the other two outgoing photons 1 and 4 onto an entangled state. Change of the shading of the lines indicates the change in the set of possible predictions that can be made.

the combined state of photons 2 and 3

$$|\Psi^{\pm}\rangle_{23} = \frac{1}{\sqrt{2}}(|H\rangle_2|V\rangle_3 \pm |V\rangle_2|H\rangle_3),$$
$$|\Phi^{\pm}\rangle_{23} = \frac{1}{\sqrt{2}}(|H\rangle_2|H\rangle_3 \pm |V\rangle_2|V\rangle_3). \quad (2)$$

This measurement projects photons 1 and 4 also onto a Bell state, a different one depending on the result of the Bell-state measurement for photons 2 and 3. Close inspection shows that for the initial state given in Eq. (1) the emerging state of photons 1 and 4 will be identical to the one photons 2 and 3 collapsed into. This is a consequence of the fact that the state of Eq. (1) can be rewritten as

$$|\Psi\rangle_{1234} = \frac{1}{2}(|\Psi^+\rangle_{14}|\Psi^+\rangle_{23} + |\Psi^-\rangle_{14}|\Psi^-\rangle_{23} + |\Phi^+\rangle_{14}|\Phi^+\rangle_{23} + |\Phi^-\rangle_{14}|\Phi^-\rangle_{23}). \quad (3)$$

In all cases photons 1 and 4 emerge entangled despite the fact that they never interacted with one another in the past. After projection of particles 2 and 3 one knows about the entanglement between particles 1 and 4.

In the experiment we decided to analyze only the projection onto $|\Psi^-\rangle_{23}$. This projection is realized by interfering the two photons, 2 and 3, at a beam splitter and detecting a coincidence between the two detectors at the output ports of the beam splitter. Here we exploit the fact that $|\Psi^-\rangle_{23}$ is antisymmetric under exchange of labels 2 and 3 which gives the two photons fermionic statistics in their spatial behavior [6] in the sense that they will emerge from different output ports of the beam splitter [7]. The components of the combined state of photons 2 and 3 along the other three Bell states are symmetric under exchange of labels 2 and 3 which results in bosonic statistics; that is, the two photons will emerge at the same output port of the beam splitter. Therefore, detecting coincidences between the two detectors after the beam splitter acts as a projection onto $|\Psi^-\rangle_{23}$. Since originally the polarization states of photons 2 and 3 are completely undetermined, their combined state is in an equal superposition of the four Bell states. As a result, in one out of four cases on average a coincidence will be recorded by the two detectors behind the beam splitter; that is, a projection onto $|\Psi^-\rangle_{23}$ takes place.

Note that the Bell-state analysis relies on the interference of two independently created photons. One, therefore, has to guarantee good spatial and temporal overlap at the beam splitter and, above all, one has to erase all kinds of path information for photon 2 and for photon 3. Especially the high time and frequency correlations of two photons created by parametric down-conversion can give rise to Welcher-Weg information for the interfering photons [8]. However, there are two possibilities for quantum erasure. In the first one, Welcher-Weg information is erased by detecting photons 2 and 3 within time intervals much shorter than their coherence time [4]. Then, such ultracoincident registrations are too close in time to discriminate which of the detected photons shares the source with photon 1, or with photon 4, respectively. Yet, this method cannot be used in practice due to the poor time resolution of existing single-photon detectors (typically 0.5 ns for Si-avalanche photodiodes as compared to typical coherence times of about 500 fs).

The second possibility involves increasing the coherence times of the interfering photons to become much longer than the time interval within which they are created [9]. Then again, one cannot infer anymore which of the detected photons was created together with photon 1, or with photon 4, respectively. In our experiment UV pulses with a duration of 200 fs are used to create the photon pairs. We then choose narrow bandwidth filters ($\Delta\lambda = 4$ nm) in front of the detectors registering photons 2 and 3. The resulting coherence time of about 500 fs is sufficiently longer than the pump pulse duration. Furthermore, single mode fiber couplers acting as spatial filters were used to guarantee good mode overlap of the detected photons.

Figure 2 is a schematic drawing of the experimental setup. UV pulses are produced by frequency doubling the pulses of a commercial mode locked Ti:sapphire laser from 780 to 390 nm using a nonlinear LBO crystal (LiB_3O_5).

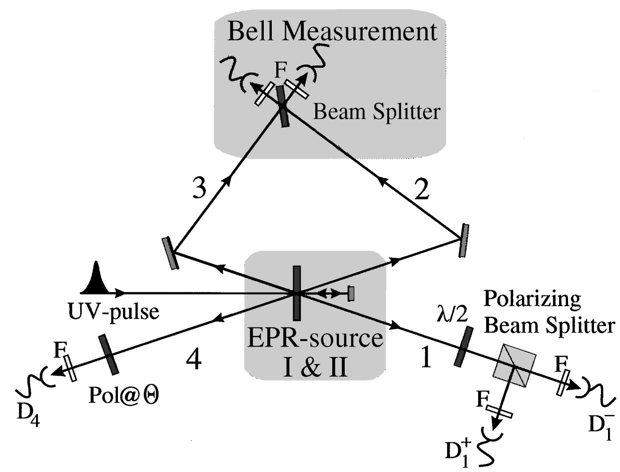

FIG. 2. Experimental setup. A UV pulse passing through a nonlinear crystal creates pair 1-2 of entangled photons. Photon 2 is directed to the beam splitter. After reflection, during its second passage through the crystal the UV pulse creates a second pair 3-4 of entangled photons. Photon 3 will also be directed to the beam splitter. When photons 2 and 3 yield a coincidence click at the two detectors behind the beam splitter, they are projected into the $|\Psi^-\rangle_{23}$ state. As a consequence of this Bell-state measurement the two remaining photons 1 and 4 will also be projected into an entangled state. To analyze their entanglement we look at coincidences between detectors D_1^+ and D_4, and between detectors D_1^- and D_4, for different polarization angles Θ. By rotating the $\lambda/2$ plate in front of the two-channel polarizer we can analyze photon 1 in any linear polarization basis. Note that, since the detection of coincidences between detectors D_1^+ and D_4, and D_1^- and D_4 are conditioned on the detection of the Ψ^- state, we are looking at fourfold coincidences. Narrow bandwidth filters (F) are positioned in front of each detector.

For a repetition rate of 76 MHz we obtained an averaged power of 500 mW. Passing the UV pulses through a BBO crystal (β-BaB_2O_4) creates via type-II down-conversion a pair of photons, 1 and 2, in the entangled state $|\Psi^-\rangle_{12}$ [10]. Yet, birefringence of the BBO crystal causes longitudinal separation of H and V polarized photons inside the crystal which again would give a means to distinguish which of the two possible states was emitted, resulting in an incoherent mixture of these states. Compensation with two extra crystals [10] is only partially possible for a pulsed pump and makes narrow band filtering of both photons, 1 and 2, necessary to achieve a high degree of entanglement [11]. For a BBO crystal of 1.5 mm thickness we obtained, again using filters with $\Delta\lambda = 4$ nm, a polarization correlation of about 0.9 [12].

After reflection, the pump pulse passes the crystal again and produces the second pair of photons, 3 and 4 (after compensation and filtering), in the state $|\Psi^-\rangle_{34}$. Note that the two pairs are created independently of one another, although the same pulse and the same crystal are used twice.

According to the entanglement swapping scheme, upon projection of photons 2 and 3 into the $|\Psi^-\rangle_{23}$ state, photons 1 and 4 should be projected into the $|\Psi^-\rangle_{14}$ state. To verify that this entangled state is obtained, we have to analyze the polarization correlations between photons 1 and 4 conditioned on coincidences between the detectors of the Bell-state analyzer. If photons 1 and 4 are in the $|\Psi^-\rangle_{14}$ state, their polarizations should be orthogonal upon measurement in any polarization basis. Using a $\lambda/2$ retardation plate at 22.5° and two detectors (D_1^+ and D_1^-) behind a polarizing beam splitter, we choose to analyze the polarization of photon 1 along the +45° axis (D_1^+) and the −45° axis (D_1^-). Photon 4 is analyzed by detector D_4 at the variable polarization direction Θ.

If entanglement swapping happens, then the twofold coincidences between D_1^+ and D_4, and between D_1^- and D_4, conditioned on the $|\Psi^-\rangle_{23}$ detection, should show two sine curves as a function of Θ which are 90° out of phase. The $D_1^+D_4$ curve should, in principle, go to zero for $\Theta = 45°$, whereas the $D_1^-D_4$ curve should show a maximum at this position. Figure 3 shows the experimental results for the coincidences between D_1^+ and D_4, and between D_1^- and D_4, given that photons 2 and 3 have been registered by the two detectors in the Bell-state analyzer. Note that this method requires detection of fourfold coincidences. The result clearly demonstrates the expected sine curves, complementary for the two detectors (D_1^+ and D_1^-), registering photon 1 along orthogonal polarizations. We verified by additional measurements that the sine curves are independent of the detection basis of photon 1, that is, independent of the rotation angle of the $\lambda/2$ retardation plate. In other words, the observed sinusoidal behavior of the coincidence rates depends only on the relative angle between the polarizers in beams 1 and 4. The experimentally obtained fourfold coincidences have been fitted by a joint sine function

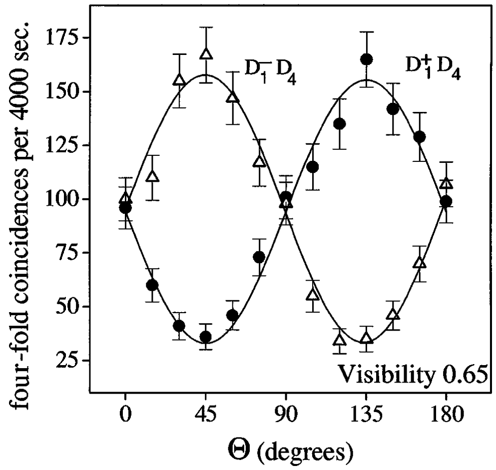

FIG. 3. Entanglement verification. Fourfold coincidences, resulting from twofold coincidence $D1^+D4$ and $D1^-D4$ conditioned on the twofold coincidences of the Bell-state measurement, when varying the polarizer angle Θ. The two complementary sine curves with a visibility of 0.65 ± 0.02 demonstrate that photons 1 and 4 are polarization entangled.

with the same amplitudes for both curves. Note that the observed visibility of 0.65 clearly surpasses the 0.5 limit of a classical wave theory. A visibility of 0.72 ± 0.04 was observed in a few initial measurements for analysis along 45°. A future experiment for showing a significant violation of Bell's inequalities requires a stable visibility better than 0.71. We expect to improve the very low fourfold coincidence rate, the main difficulty of the present experiment, by using a new laser system currently being installed, leading to a better overall performance of the experiment.

The experiment can also be interpreted as teleportation of the unknown state of, say, photon 2 onto photon 4 [3]. In that case, one could consider Alice performing the Bell-state measurement on photons 2 and 3, telling Bob, who is in possession of photon 4, the result of the Bell-state measurement. Then, by performing one out of a fixed set of four unitary operations on photon 4 Bob obtains a teleported replica of photon 2. It is conceptually most interesting to realize that in this case the teleported photon state does not have any well-defined polarization, because it is entangled with photon 1. We note that here we do not teleport some unknown state of a photon but rather its in principle undefined state. The state of photon 2, and, therefore, also of the teleported photon 4, is certainly undefined before any measurements are performed on photons 1 or 4.

In Ref. [4] it was pointed out that the process of entanglement swapping gives a means to define that an entangled pair of photons, 1 and 4, is available. As soon as the result of the Bell-state measurement on particles 2 and 3 yields the $|\Psi^-\rangle_{23}$ state we know that photons 1 and 4 are on their way ready for detection in an entangled state. This now gives, for the first time, the possibility to perform so called "event-ready detections" of the entangled particles, a concept suggested by Bell [13].

We mention that, obviously, registration of a coincidence in the two detectors behind the beam splitter could also have been caused by two pairs created in either source. That possibility could clearly be ruled out by sophisticated detection procedures. It certainly does not have any implication on those events in our experiment where we indeed obtain four registration events.

Various generalizations of the present scheme are at hand [5]. One could have many different kinds of entanglements to begin with, perform various different measurements, and obtain various kinds of entanglement for the emerging particles. A first clear possibility [9] is to project three particles, each from an entangled pair, into a GHZ state [14]; whenceforth the other three emerging particles are also projected into a GHZ state. This again requires pulsed pump technology, with pulses of even higher power than in the present experiment, yet in principle achievable with current technology.

We might also remark that the present results, taken together with those of our recent verification of quantum teleportation [15], are easily understood in the framework of the Copenhagen interpretation of quantum mechanics [16]. They cause no conceptual problems if one accepts that information about quantum systems is a more basic feature than any possible "real" properties these systems might have [17].

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