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Observation of Three-Photon Greenberger-Horne-Zeilinger Entanglement

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We present the experimental observation of polarization entanglement for three spatially separated photons. Such states of more than two entangled particles, known as Greenberger-Horne-Zeilinger (GHZ) states, play a crucial role in fundamental tests of quantum mechanics versus local realism and in many quantum information and quantum computation schemes. Our experimental arrangement is such that we start with two pairs of entangled photons and register the photons in a way that any information as to which pair each photon belongs to is erased. After detecting a trigger photon, the registered events at the detectors for the remaining three photons exhibit the desired GHZ correlations. [S0031-9007(98)08348-3]

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Since the seminal work of Einstein, Podolsky, and Rosen [1], there has been a quest for generating entanglement between quantum particles. Although two-particle entanglements have long been demonstrated experimentally [2,3], the preparation of entanglement between three or more particles remains an experimental challenge. Proposals have been made for experiments with photons [4] and atoms [5], and three nuclear spins within a single molecule have been prepared such that they locally exhibit three-particle correlations [6]. However, until now there has been no experiment which demonstrates the existence of entanglement of more than two spatially separated particles. Here we report the experimental observation of polarization entanglement of three spatially separated photons.

The original motivation to prepare three-particle entanglements stems from the observation by Greenberger, Horne, and Zeilinger (GHZ) that entanglement of more than two particles leads to a conflict with local realism for nonstatistical predictions of quantum mechanics [7]. This is in contrast to the case of experiments with two entangled particles testing Bell's inequalities, where the conflict only arises for statistical predictions [8].

The incentive to produce GHZ states has been significantly increased by the advance of the fields of quantum communication and quantum information processing. Entanglement between several particles is the most important feature of many such quantum communication and computation protocols [9,10].

The experiment described here is based on techniques that have been developed for our previous experiments on quantum teleportation [11] and entanglement swapping [12]. In fact, one of the main complications in those experiments, namely, the creation of two pairs of photons by a single source, is here turned into a virtue.

The main idea, as was put forward in Ref. [4], is to transform two pairs of polarization entangled photons into three entangled photons and a fourth independent photon. In our experiment the GHZ entanglement is observed only under the condition that both the trigger photon and the three entangled photons are actually detected. Thus, detection plays the double role of both projecting into the GHZ state and performing a specific measurement on the state. This, we submit, in practice will not be a severe limitation because, on the one hand, in any realistic scheme one always has losses, and information is only obtained if the photons are actually observed, as, for instance, in third-man quantum cryptography. On the other hand, many applications explicitly use specific measurement results. For example, the GHZ argument for testing local realism is based on detection events, and knowledge of the underlying quantum state is not even necessary.

Figure 1 is a schematic drawing of our experimental setup. Pairs of polarization entangled photons are

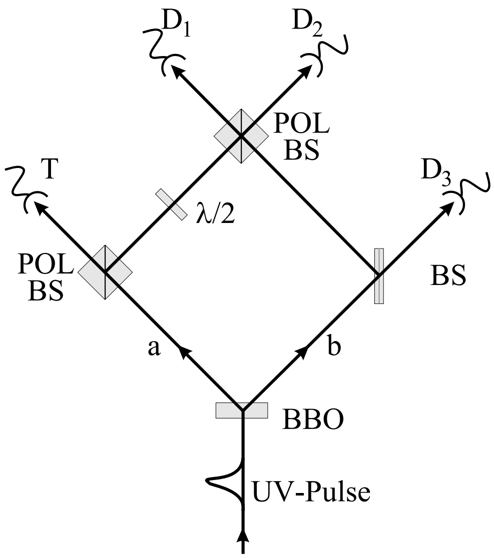

FIG. 1. Schematic drawing of the experimental setup for the demomstration of the Greenberger-Horne-Zeilinger entanglement for spatially separated photons. Conditioned on the registration of one photon at the trigger detector T, the three photons registered at D_1, D_2, and D_3 exhibit the desired GHZ correlations.

generated by a short pulse of ultraviolet (UV) light ($\approx$200 fs, $\lambda = 394$ nm from a frequency-doubled, mode-locked Ti-sapphire laser), which passes through a nonlinear crystal (here, β-barium-borate, BBO). The probability per pulse to create a single pair in the desired modes, selected by irises, about 1.5 mm wide and 25 cm behind the crystal, is low and of the order of a few 10^{-4}. The pair creation is such that the following polarization entangled state is obtained [3]:

$$\frac{1}{\sqrt{2}}(|H\rangle_a|V\rangle_b - |V\rangle_a|H\rangle_b). \tag{1}$$

This state indicates a superposition of the possibility that the photon in arm a is horizontally polarized and the one in arm b is vertically polarized ($|H\rangle_a|V\rangle_b$), and the opposite possibility ($|V\rangle_a|H\rangle_b$). The minus sign indicates that there is a fixed phase difference of π between the two possibilities. For our GHZ experiment this phase factor is actually allowed to have any value, as long as it is fixed for all pair creations.

The setup is such that arm a continues towards a polarizing beam splitter, where V photons are reflected and H photons are transmitted towards detector T (behind an interference filter $\delta\lambda = 4.6$ nm at 788 nm). Arm b continues towards a 50/50 polarization-independent beam splitter. From each beam splitter, one output is directed to a final polarizing beam splitter. In between the two polarizing beam splitters, vertical polarization is rotated to 45° polarization using a $\lambda/2$ plate. The remaining three output arms continue through interference filters ($\delta\lambda =$ 3.6 nm) and single-mode fibers towards the single-photon detectors D_1, D_2, and D_3. Including filter losses, coupling into single-mode fibers, and the Si-avalanche detector efficiency, the total collection and detection probability of a photon is about 10%.

Consider now the case that *two* pairs are generated by a single UV pulse, and that the four photons are all detected, one by each detector T, D_1, D_2, and D_3. Our claim is that, by the coincident detection of the four photons and because of the brief duration of the UV pulse and the narrowness of the filters, one can conclude that a three-photon GHZ state has been recorded by detectors D_1, D_2, and D_3. The reasoning is as follows. When a fourfold coincidence recording is obtained, one photon in path a must have been horizontally polarized and detected by the trigger detector T. Its companion photon in path b must then be vertically polarized, and it has a 50% chance to be transmitted by the beam splitter (see Fig. 1) towards detector D_3 and a 50% chance to be reflected by the beam splitter towards the final polarizing beam splitter, where it will be reflected to D_2. Consider the first possibility, i.e., the companion of the photon detected at T is detected by D_3 and necessarily carried polarization V. Then the counts at detectors D_1 and D_2 were due to a second pair, one photon traveling via path a and the other one via path b. The photon traveling via path a must necessarily be V polarized in order to be reflected by the polarizing beam splitter in path a; thus its companion, taking path b, must be H polarized and, after reflection at the beam spliter in path b, it will be transmitted by the final polarizing beam splitter and arrive at detector D_1. The photon detected by D_2 therefore must be H polarized since it came via path a and had to transit the last polarizing beam splitter. Note that this latter photon was V polarized but after passing the $\lambda/2$ plate it became polarized at 45° which gave it a 50% chance to arrive as an H polarized photon at detector D_2. Thus we conclude that, if the photon detected by D_3 is the companion of the T photon, the coincidence detection by D_1, D_2, and D_3 then corresponds to the detection of the state

$$|H\rangle_1|H\rangle_2|V\rangle_3. \tag{2}$$

By a similar argument one can show that, if the photon detected by D_2 is the companion of the T photon, the coincidence detection by D_1, D_2, and D_3 corresponds to the detection of the state

$$|V\rangle_1|V\rangle_2|H\rangle_3. \tag{3}$$

In general, the two possible states (2) and (3), corresponding to a fourfold coincidence recording, will not form a coherent superposition, i.e., a GHZ state, because they could, in principle, be distinguishable. Besides the possible lack of mode overlap at the detectors, the exact detection time of each photon can reveal which state is present. For example, state (2) is identified by noting that T and D_3, or D_1 and D_2, fire nearly simultaneously. To erase this information it is necessary that the coherence time of the photons is substantially longer than the duration of the UV pulse (approximately 200 fs) [13]. We achieved this by detecting the photons behind narrow bandwidth filters which yields a coherence time of approximately 500 fs. Thus, the possibility to distinguish between states (2) and (3) is no longer present, and, by a basic rule of quantum mechanics, the state detected by a coincidence recording of D_1, D_2, and D_3, conditioned on the trigger T, is the quantum superposition

$$\frac{1}{\sqrt{2}}(|H\rangle_1|H\rangle_2|V\rangle_3 + |V\rangle_1|V\rangle_2|H\rangle_3), \tag{4}$$

which is a GHZ state [14].

The plus sign in Eq. (4) follows from the following more formal derivation. Consider two down-conversions producing the product state

$$\tfrac{1}{2}(|H\rangle_a|V\rangle_b - |V\rangle_a|H\rangle_b)(|H\rangle'_a|V\rangle'_b - |V\rangle'_a|H\rangle'_b). \tag{5}$$

Initially, we assume that the components $|H\rangle_{a,b}$ and $|V\rangle_{a,b}$ created in one down-conversion might be distinguishable from the components $|H\rangle'_{a,b}$ and $|V\rangle'_{a,b}$ created in the other one. The evolution of the individual components of state (5) through the apparatus towards the detectors T, D_1, D_2, and D_3 is given by

$$|H\rangle_a \to |H\rangle_T, \tag{6}$$

$$|V\rangle_b \to \frac{1}{\sqrt{2}}(|V\rangle_2 + |V\rangle_3), \tag{7}$$

$$|V\rangle_a \to \frac{1}{\sqrt{2}}(|V\rangle_1 + |H\rangle_2), \tag{8}$$

$$|H\rangle_b \to \frac{1}{\sqrt{2}}(|H\rangle_1 + |H\rangle_3). \tag{9}$$

Identical expressions hold for the primed components. Inserting these expressions into state (5) and restricting ourselves to those terms where only one photon is found in each output we obtain, after normalization,

$$\tfrac{1}{2}\{|H\rangle_T(|H\rangle'_1|H\rangle'_2|V\rangle_3 + |V\rangle'_1|V\rangle_2|H\rangle'_3) + |H\rangle'_T(|H\rangle_1|H\rangle_2|V\rangle'_3 + |V\rangle_1|V\rangle'_2|H\rangle_3)\}. \tag{10}$$

If now the experiment is performed such that the photon states from the two down-conversions are indistinguishable, we finally obtain the desired state

$$\frac{1}{\sqrt{2}}|H\rangle_T(|H\rangle_1|H\rangle_2|V\rangle_3 + |V\rangle_1|V\rangle_2|H\rangle_3). \tag{11}$$

Note that the total photon state produced by our setup, i.e., the state before detection, also contains terms in which, for example, two photons enter the same detector. In addition, the total state contains contributions from single down-conversions. The fourfold coincidence detection acts as a projection measurement onto the desired GHZ state (11) and filters out these undesirable terms. The efficiency for one UV pump pulse to yield such a fourfold coincidence detection is very low (of the order of 10^{-10}). Fortunately, 7.6×10^7 UV pulses are generated per second, which yields about one double pair creation and detection per 150 seconds, which is just enough to perform our experiments [15]. Triple pair creations can be completely neglected since they can give rise to a fourfold coincidence detection only about once each day.

To experimentally demonstrate that GHZ entanglement has been obtained by the method described above, we first verified that, conditioned on a photon detection by the trigger T, both the $H_1H_2V_3$ and the $V_1V_2H_3$ components can be observed, but no others. This was done by comparing the count rates of the eight possible combinations of polarization measurements, $H_1H_2H_3$, $H_1H_2V_3, \ldots, V_1V_2V_3$. The observed intensity ratio between the desired and undesired states was 12:1. Existence of the two terms as just demonstrated is a necessary but not yet sufficient condition for demonstrating GHZ entanglement. In fact, there could, in principle, be just a statistical mixture of those two states. Therefore, one has to prove that the two terms coherently superpose. This we did by a measurement of linear polarization of photon 1 along $+45°$, bisecting the H and V directions. Such a measurement projects photon 1 into the superposition $|+45°\rangle_1 = \frac{1}{\sqrt{2}}(|H\rangle_1 + |V\rangle_1)$, implying that the state (11) is projected into

$$\frac{1}{\sqrt{2}}|H\rangle_T|+45°\rangle_1(|H\rangle_2|V\rangle_3 + |V\rangle_2|H\rangle_3). \tag{12}$$

Thus photons 2 and 3 end up entangled as predicted under the notion of "entangled entanglement" [16]. Rewriting the state of photons 2 and 3 in the 45° basis results in the state

$$\frac{1}{\sqrt{2}}(|+45°\rangle_2|+45°\rangle_3 - |-45°\rangle_2|-45°\rangle_3), \tag{13}$$

which implies that if photon 2 is found to be polarized along $-45°$ (or along $+45°$), photon 3 is polarized along the same direction. The absence of the terms $|+45°\rangle_2|-45°\rangle_3$ and $|-45°\rangle_2|+45°\rangle_3$ is due to destructive interference and thus indicates the desired coherent superposition of the terms in the GHZ state (11). The experiment therefore consisted of measuring fourfold coincidences between the detector T, detector 1 behind a $+45°$ polarizer, detector 2 behind a $-45°$ polarizer, and measuring photon 3 behind either a $+45°$ polarizer or a $-45°$ polarizer. In the experiment, the difference in arrival time of the photons at the final polarizer or, more specifically, at the detectors D_1 and D_2 was varied.

The data points in Fig. 2(a) are the experimental results obtained for the polarization analysis of the photon at D_3, conditioned on the trigger and on detection of two photons polarized at 45° and $-45°$ by the two detectors D_1 and D_2, respectively. The two curves show the fourfold coincidences for a polarizer oriented at $-45°$ (squares)

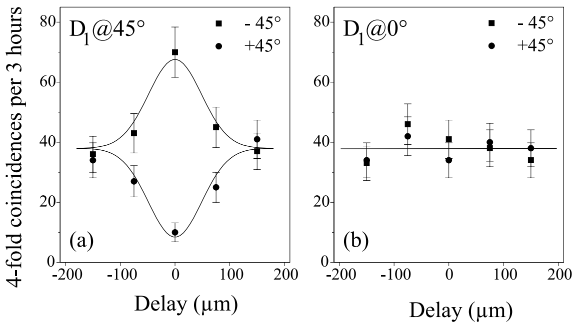

FIG. 2. Experimental confirmation of GHZ entanglement. Graph (a) shows the results obtained for polarization analysis of the photon at D_3, conditioned on the trigger, and the detection of one photon at D_1 polarized at 45° and one photon at detector D_2 polarized at $-45°$. The two curves show the fourfold coincidences for a polarizer oriented at $-45°$ and 45°, respectively, in front of detector D_3 as a function of the spatial delay in path a. The difference between the two curves at zero delay confirms the GHZ entanglement. By comparison [graph (b)] no such intensity difference is predicted if the polarizer in front of detector D_1 is set at 0°. Error bars are given by the square root of the coincidence counts.

and $+45°$ (circles) in front of detector D_3 as a function of the spatial delay in path a. From the two curves it follows that for zero delay the polarization of the photon at D_3 is oriented along $-45°$, in accordance with the quantum-mechanical predictions for the GHZ state. For nonzero delay, the photons traveling via path a towards the second polarizing beam splitter and those traveling via path b become distinguishable. Therefore increasing the delay gradually destroys the quantum superposition in the three-particle state.

Note that one can equally well conclude from the data that, at zero delay, the photons at D_1 and D_3 have been projected onto a two-particle entangled state by the projection of the photon at D_2 onto $-45°$. The two conclusions are only compatible for a genuine GHZ state. We note that the observed visibility was as high as 75% [17].

For an additional confirmation of state (11) we performed measurements conditioned on the detection of the photon at D_1 under 0° polarization (i.e., V polarization). For the GHZ state $(1/\sqrt{2})(|H\rangle_1|H\rangle_2|V\rangle_3 + |V\rangle_1|V\rangle_2|H\rangle_3)$ this implies that the remaining two photons should be in the state $|V\rangle_2|H\rangle_3$ which cannot give rise to any correlation between these two photons in the 45° detection basis. The experimental results of these measurement are presented in Fig. 2(b). The data clearly indicate the absence of two-photon correlations and thereby confirm our claim of the observation of GHZ entanglement between three spatially separated photons.

Although the extension from two to three entangled particles might seem to be only a modest step forward, the implications are rather profound. First, GHZ entanglements allow for novel tests of quantum mechanics versus local realistic models [7,18]. Second, three-particle GHZ states might find a direct application, for example, in third-man quantum cryptography. Third, the method developed to obtain three-particle entanglement from a source of pairs of entangled particles can be extended to obtain entanglement between many more particles [19], which is the basis of many quantum communication and computation protocols. Finally, we note that our experiment, together with our earlier realization of quantum teleportation [11] and entanglement swapping [12], provides necessary tools to implement a number of novel entanglement distribution and network ideas as recently proposed [20].

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