Dense Coding in Experimental Quantum Communication

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Classically, sending more than one bit of information requires manipulation of more than one two-state particle. We demonstrate experimentally that one can transmit one of three messages, i.e., 1 "trit" ≈ 1.58 bit, by manipulating only one of two entangled particles. The increased channel capacity is proven by transmitting ASCII characters in five trits instead of the usual 8 bits. [S0031-9007(96)00478-4]

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While the strikingly nonclassical properties of entangled states lead to more and more novel demonstrations of fundamental properties of quantum mechanical systems [1], the young field of quantum information exploits such entangled quantum states for new types of information transmission and information processing [2]. In the present paper, we report the first experimental realization of quantum communication, verifying the increased capacity of a quantum information channel by "quantum dense coding." The scheme, theoretically proposed by Bennett and Wiesner [3], utilizes two entangled two-state systems. Suppose that, as was the case in our experiment, the two states are horizontal (H) and vertical (V) polarizations of a photon. Then, classically, the four possible polarization combinations for a pair of photons are $HH, HV, VH,$ and VV. Identifying each with different information implies that we can encode two bits of information by manipulating both photons.

Quantum mechanics allows one to encode the information also in superpositions of the classical combinations, an appropriate basis is formed by the maximally entangled Bell states

$$\begin{aligned}
|\Psi^+\rangle &= (|H\rangle|V\rangle + |V\rangle|H\rangle)/\sqrt{2}\,,\\
|\Psi^-\rangle &= (|H\rangle|V\rangle - |V\rangle|H\rangle)/\sqrt{2}\,,\\
|\Phi^+\rangle &= (|H\rangle|H\rangle + |V\rangle|V\rangle)/\sqrt{2}\,,\\
|\Phi^-\rangle &= (|H\rangle|H\rangle - |V\rangle|V\rangle)/\sqrt{2}\,.
\end{aligned} \tag{1}$$

The Hilbert space spanned by these orthogonal states is still four dimensional, implying that using the two particles we again can encode 2 bits of information, yet, now by manipulating only *one* of the two particles. This is achieved in the following quantum communication scheme for transmitting 2 bits of information per two state: Initially, Alice and Bob each obtain one particle of an entangled pair, say, in the state $|\Psi^+\rangle$. Bob then performs one out of four possible unitary transformations on his particle alone. For polarized photons, four such transformations are (i) identity operation; (ii) polarization flip ($|H\rangle \rightarrow |V\rangle$ and $|V\rangle \rightarrow |H\rangle$, changing the two-photon state to $|\Phi^+\rangle$); (iii) polarization-dependent phase shift (differing by π for $|H\rangle$ and $|V\rangle$ and transforming to $|\Psi^-\rangle$); and (iv) rotation and phase shift together (giving the two-photon state $|\Phi^-\rangle$). Since the four manipulations result in the four orthogonal Bell states, four distinguishable messages, i.e., 2 bits of information, can be sent via Bob's two-state particle to Alice, who finally reads the encoded information by determining the Bell state of the two-particle system.

This scheme enhances the information capacity of the transmission channel to 2 bits compared to the classical maximum of 1 bit [4]. The problem clearly is how to identify the four Bell states. Unique determination of the state would be possible by coupling the two particles in a similar way as in certain quantum logic operations. However, reversing the process of down-conversion and combining two photons conditionally in a nonlinear crystal [3] has to fail due to low efficiency ($\approx 10^{-6}$). Also, cavity-QED techniques [5] still lack the necessary strong coupling, and the recently developed ion-trap quantum logic gates [6] impose other severe restrictions for the present application. On the other hand, two-particle interferometry can provide a solution to this problem [7]. Different interference effects allow one to identify two of the four Bell states, with the other two giving the same, third, measurement signal. Such an interferrometric state analyzer therefore allows Alice to read three different messages sent via Bob's particle.

In this Letter we report the realization of quantum dense coding transmission with entangled photon pairs as produced by parametric down-conversion. We choose polarization entanglement [8] because of the higher stability and the more reliable methods for manipulating polarized beams, as opposed to experimental Bell-state analysis of momentum-entangled photons [9]. The reduction of phase drifts, and especially the simpler configuration of the Bell-state analyzer, results in better interference visibility.

The experiment consists of three distinct parts (Fig. 1): the EPR source generating entangled photons in a well-defined state; Bob's station for encoding the messages by a unitary transformation of his particle; and, finally, Alice's Bell-state analyzer to read the signal sent by Bob. The polarization-entangled photons were produced by

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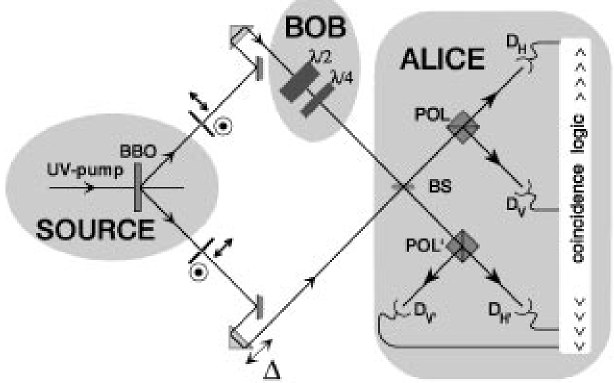

FIG. 1. Experimental setup for quantum dense coding. Because of the nature of the Si-avalanche photodiodes, the extension shown in the inset of Fig. 4 is necessary for identifying two-photon states in one of the outputs.

degenerate noncollinear type-II down-conversion in a nonlinear BBO crystal. A UV beam ($\lambda = 351$ nm) from an argon-ion laser is down-converted into pairs of photons ($\lambda = 702$ nm) with orthogonal polarization. We obtained the entangled state $|\Psi^+\rangle$ after compensation of birefringence in the BBP crystal along two distinct emission directions (carefully selected by 2 mm irises, 1.5 m away from the crystal [10]). One beam was first directed to Bob's encoding station, the other directly to Alice's Bell-state analyzer; in the alignment procedure optical trombones were employed to equalize the path lengths to well within the coherence length of the down-converted photons ($\ell_c \approx 100\ \mu$m), in order to observe the two-photon interference.

For polarization encoding, the necessary transformation of Bob's particle was performed using a half-wave retardation plate for changing the polarization and a quarter-wave plate to generate the polarization-dependent phase shift [11]. The beam manipulated in this way in Bob's encoding station was then combined with the other beam at Alice's Bell-state analyzer. It consisted of a single beam splitter followed by two-channel polarizers in each of its outputs and proper coincidence analysis between four single photon detectors.

Such a configuration allows one to distinguish between the Bell states due to the different outcomes of the interference at the beam splitter and the subsequent polarization analysis. The spatial part of the state determines the photon statistics behind the (polarization insensitive) beam splitter. This results either in both photons leaving the beam splitter via the same output beam for a symmetric spatial part or in one photon exiting into each output for an antisymmetric spatial component of the state [12]. Since only the state $|\Psi^-\rangle$ has an antisymmetric spatial part, only this state will be registered by coincidence detection between the different outputs of the beam splitter (i.e., coincidence between detectors D_H and $D_{V'}$ or between $D_{H'}$ and D_V). For the remaining three states, both photons exit into the same output port of the beam splitter. The state $|\Psi^+\rangle$ can easily be distinguished from the other two due to the different polarizations of the two photons, giving, behind the two-channel polarizer, a coincidence between detectors D_H and D_V or between $D_{H'}$ and $D_{V'}$. The two states $|\Phi^+\rangle$ and $|\Phi^-\rangle$ both result in a two-photon state being absorbed by a single detector and thus cannot be distinguished. Table I gives an overview of the different manipulations and detection probabilities of Bob's encoder and Alice's receiver.

The experiments were performed by first setting the output state of the source such that the state $|\Psi^+\rangle$ left Bob's encoder when both retardation plates were set to vertical orientation, the other Bell states could then be generated with the respective settings (Table I). To characterize the interference observable at Alice's Bell-state analyzer, we varied the path length difference Δ of the two beams with the optical trombone. For $\Delta \gg \ell_c$ no interference occurs, and one obtains classical statistics for the coincidence count rates at the detectors. For optimal path-length tuning ($\Delta = 0$), interference enables one to read the encoded information. Figures 2 and 3 show the dependence of the coincidence rates C_{HV} (●) and $C_{HV'}$ (○) on the path length difference for $|\Psi^+\rangle$ and $|\Psi^-\rangle$, respectively (the rates $C_{H'V'}$ and $C_{H'V}$ display analogous behavior; we use the notation C_{AB} for the coincidence rate between detectors D_A and D_B). At $\Delta = 0$, C_{HV} reaches its maximum for $|\Psi^+\rangle$ (Fig. 2) and vanishes (aside from noise) for $|\Psi^-\rangle$ (Fig. 3). $C_{HV'}$ displays the opposite dependence and clearly signifies $|\Psi^-\rangle$. The results of these measurements imply that, if both photons are detected, we can identify the state $|\Psi^+\rangle$ with a reliability of 95% and the state $|\Psi^-\rangle$ with 93%.

The performance of the dense coding transmission is influenced not only by the quality of the interference

TABLE I. Overview of possible manipulations and detection events of the quantum dense coding experiment with correlated photons (we use h to denote the state of a photon in the mode towards detector D_H, etc.).

Bob's setting $\lambda/2$	Bob's setting $\lambda/4$	State sent	State at output of Bell-state analyzer	Alice's registration events
0°	0°	$\|\Psi^+\rangle$	$\{hv + h'v' + vh + v'h'\}/2$	Coincidence between D_H *and* D_V or $D_{H'}$ *and* $D_{V'}$
0°	90°	$\|\Psi^-\rangle$	$\{hv' - h'v' + v'h - vh'\}/2$	Coincidence between D_H *and* $D_{V'}$ or $D_{H'}$ *and* D_V
45°	0°	$\|\Phi^+\rangle$	$\{hh + vv + h'h' + v'v'\}/2$	2 photons in either D_H, D_V, $D_{H'}$, or $D_{V'}$
45°	90°	$\|\Phi^-\rangle$	$\{hh - vv + h'h' + v'v'\}/2$	2 photons in either D_H, D_V, $D_{H'}$, or $D_{V'}$

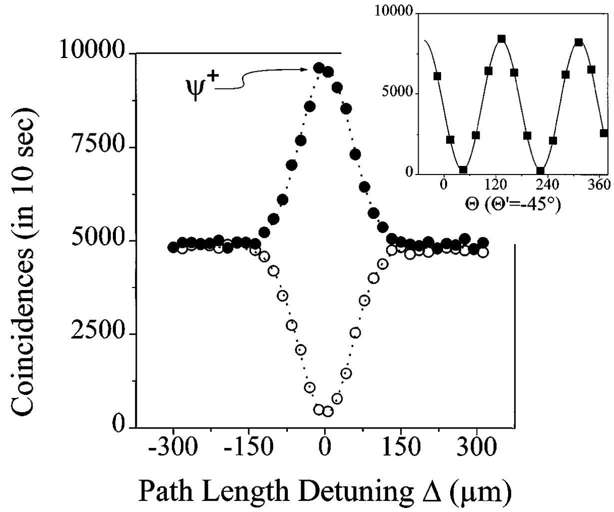

FIG. 2. Coincidence rates C_{HV} (●) and $C_{HV'}$ (○) as functions of the path length difference Δ when the state $|\Psi^+\rangle$ is transmitted. For perfect tuning ($\Delta = 0$), constructive interference occurs for C_{HV}, allowing identification of the state sent. The inset shows a correlation measurement with the beam splitter of the Bell-state analyzer removed to check the quality of the transmitted state. (θ, θ' are the orientations of half-wave plates, not shown in Fig. 1, in front of the polarizers POL or POL$'$.)

alignment, but also by the quality of the states sent by Bob. In order to evaluate the latter the beam splitter was translated out of the beams. Then an Einstein-Podolsky-Rosen-Bell–type correlation measurement (using additional half-wave plates with orientation θ and θ', not shown in Fig. 1, in front of the polarizers) analyzed the degree of entanglement of the source as well as the quality of Bob's transformations (typical scans of the half-wave plate orientation θ relative to V are shown in the insets of Figs. 2 and 3 for $\theta' = 45°$). The correlations were only (1–2)% higher than the visibilities with the beam splitter in place, which means that the quality of this experiment is limited more by the quality of the entanglement of the two beams than by that of the achieved interference.

When using Si-avalanche diodes in the Geiger mode for single-photon detection, a modification of the Bell-state analyzer is necessary, since then one also has to register the two photons leaving the Bell-state analyzer for the states $|\Phi^+\rangle$ or $|\Phi^-\rangle$ via a coincidence detection [13]. One possibility is to avoid interference for these states by introducing polarization-dependent delays $\gg \ell_c$ before Alice's beam splitter, e.g., using thick quartz plates, retarding $|H\rangle$ in one beam and $|V\rangle$ in the other (the analog technique for momentum-entangled photon pairs is described in [9]). Another approach is to split the incoming two-photon state at an additional beam splitter and to detect it (with 50% likelihood) by a coincidence count between detectors in each output (inset of Fig. 4). For the purpose of this proof-of-principle demonstration we put such a configuration only in place of detector D_H. Figure 4 shows the increase of the coincidence rate $C_{H\overline{H}}$ (□) at path length difference $\Delta = 0$, with the rates C_{HV} and $C_{HV'}$ at the background level, when Bob sends the state $|\Phi^-\rangle$. Note, however, that for both methods half of the time both photons still are absorbed by one detector; therefore, and since we inserted only one such configuration, the maximum rate for $C_{H\overline{H}}$ is about a quarter of that of C_{HV} or $C_{HV'}$ in Figs. 2 and 3.

Since we now can distinguish the three different messages, the stage is set for the quantum dense coding transmission. Figure 5 shows the various coincidence rates (normalized to the respective maximum rate of the transmitted state) when sending the ASCII codes of "KM°" (i.e., codes 75, 77, 179) in only 15 trits instead of

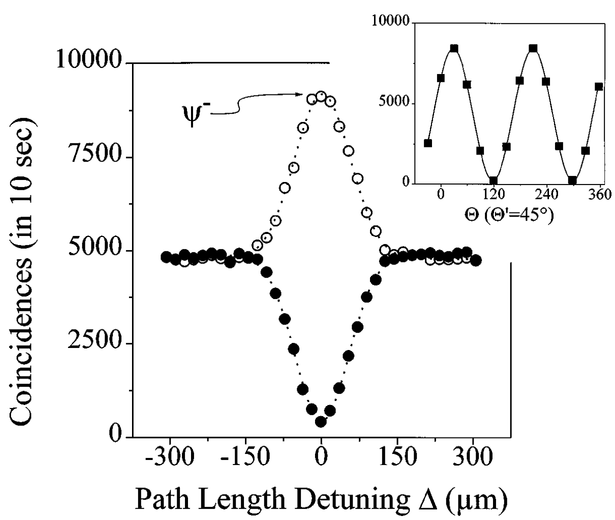

FIG. 3. Coincidence rates C_{HV} (●) and $C_{HV'}$ (○) depending on the path length difference Δ, for transmission of the state $|\Psi^-\rangle$. The constructive interference for the rate $C_{HV'}$ enables one to read the information associated with that state.

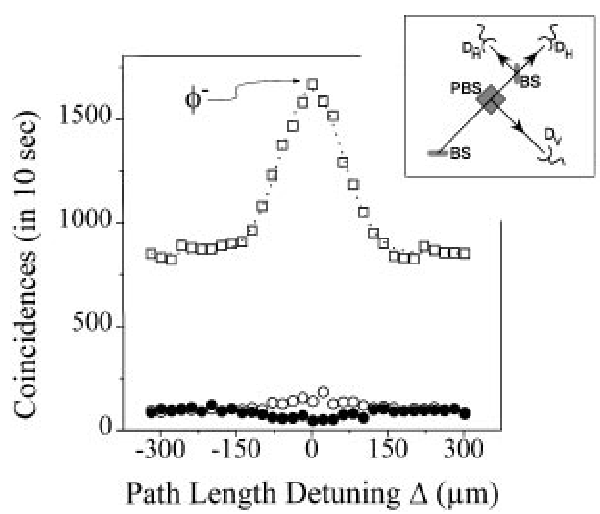

FIG. 4. Coincidence rates $C_{H\overline{H}}$ (□), C_{HV} (●), and $C_{HV'}$ (○) as functions of the path-length detuning Δ. The maximum in the rate $C_{H\overline{H}}$ signifies the transmission of a third state $|\Phi^-\rangle$ encoded in a two-state particle. The addition to the Bell-state analyzer is shown in the inset. $C_{H\overline{H}}$ is smaller by a factor of 4 compared to the rates of Figs. 2 and 3 due to a still reduced registration probability of $|\Phi^-\rangle$, see text.

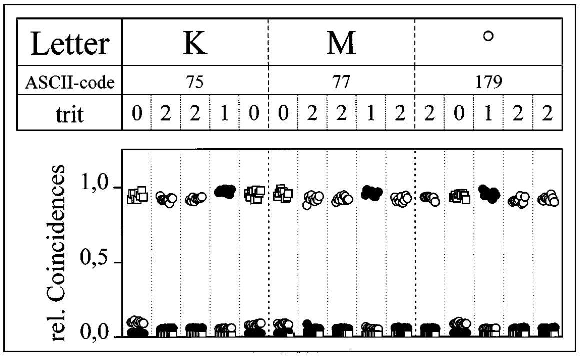

FIG. 5. "1.58 bit per photon" quantum dense coding: The ASCII codes for the letters "KM°" (i.e., 75, 77, 179) are encoded in 15 trits (with "0" $\equiv$ $|\Phi^-\rangle \,\widehat{=}\, \square$, "1" $\equiv$ $|\Psi^+\rangle \,\widehat{=}\, \bullet$, and "2" $\equiv$ $|\Psi^-\rangle \,\widehat{=}\, \bigcirc$) instead of the 24 bits usually necessary. The data for each type of encoded state are normalized to the maximum coincidence rate for that state.

24 classical bits. From this measurement, one also obtains a signal-to-noise ratio by comparing the rates signifying the actual state with the sum of the two other registered rates. The ratios for the transmission of the three states varied due to the different visibilities of the respective interferences and were $S/N_{|\Psi^+\rangle} = 14.8$, $S/N_{|\Psi^-\rangle} = 13.0$, and $S/N_{|\Phi^-\rangle} = 8.5$.

In this Letter we have reported the realization of a quantum dense coding transmission using polarization-entangled photons. The transmission of three messages per two-state photon becomes possible by utilizing interferrometric Bell-state analysis and enables an increase of the channel capacity by a factor of 1.58 [14]. The high quality of the observed interference encourages us to proceed to other quantum communication methods, such as the teleportation of quantum states, or the transfer and manipulation of entanglement in many-particle systems.

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[4] While it is clear that this scheme enhances the information capacity of the transmission channel accessed by Bob to 2 bits, we have to notice that the channel carrying the other photon transmits 0 bits of information, thus the total transmitted information does not exceed 2 bits.

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[10] The interference effects at the Bell-state analyzer showed a high sensitivity on the size and position of the irises. The reason might be that the irises still are within the Rayleigh length of the source. Fresnel diffraction has therefore to be considered [R. Chiao (private communication)].

[11] The component polarized along the axis of the quarter-wave plate is advanced only by $\pi/2$ relative to the other. Reorienting the optical axis from vertical to horizontal causes a net phase change of π between $|H\rangle$ and $|V\rangle$.

[12] A photon state has to be bosonic, i.e., symmetric upon exchange of the particles. Thus the symmetry of the spatial part of the wave function will be changed together with the spin part. This is the case when switching to and from $|\Psi^-\rangle$. For changing between the other three Bell states the spatial part of the wave function remains unchanged, giving the characteristic interference effects [C. K. Hong, Z. Y. Ou, and L. Mandel, Phys. Rev. Lett. **59**, 2044 (1987); A. Zeilinger, H. J. Bernstein, and M. A. Horne, J. Mod. Opt. **41**, 2375 (1994)].

[13] Because of our limited detection efficiency ($\approx$30%), a special identification of the two-photon state is necessary. However, Si-avalanche photodiodes give the same output pulse for one or more photons, thus only a coincidence detection allows the registration of the two-photon state. Special photomultipliers can distinguish between one- and two-photon absorption, but are too inefficient at present.

[14] The achieved signal-to-noise ratio results in an actual channel capacity of 1.13 bit. This value is, of course, further reduced when using Si-avalanche single photon detectors due to their mentioned deficiencies and the limited efficiency.