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Experimental quantum teleportation of arbitrary quantum states

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Abstract. Quantum teleportation enables one to transfer any arbitrary quantum state from one particle to another. In the experiments presented here we use parametric down-conversion to produce entangled photon pairs and two-photon interferometry to perform the necessary projection onto entangled states, the so-called Bell state analysis. This allows us to teleport the polarization state from one photon to the other and to entangle photons that have never interacted with one another in the past.

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Suppose Alice has some object at hand and wants to send this to Bob. Suppose further that at this moment, she cannot send the object itself, only a simple communication line is available, e.g., for sending binary information. In classical physics this is not a problem, since any object is fully determined by its properties which can be determined by measurement. If one knows all these properties, in principle, one can make a copy at a distant location and thus does not need to send the object.

But how precisely can this be a true copy of the original? What about the object's electrons, atoms and molecules? What happens to their individual quantum properties?

The state of a quantum system, which is just the information on the system's properties, cannot be determined by a single measurement. Any attempt to gain knowledge about the quantum state causes a reduction of this state randomly to one of the states associated with the measurement procedure, and thus irreversibly erases the original information. This is intrinsically related to the no-cloning theorem and seems to bring the idea of transferring quantum information to a halt. It was realized by Bennett et al. [1] that, surprisingly, it is a measurement which does *not* give any information about the state of a quantum system at all, which shows the way out. During the process of quantum teleportation Alice will destroy the quantum state at hand while Bob receives the quantum state with neither Alice nor Bob obtaining information about it. A key role in the teleportation scheme is played by an entangled ancillary pair of particles which will be initially shared by Alice and Bob.

In the present work we report on experiments showing that it is possible to transfer any arbitrary, in principle undefined quantum state. By producing pairs of entangled photons by the process of parametric down-conversion and using two-photon quantum interferometry for analyzing entanglement, we were able to transfer a quantum state (in our case the polarization state) from one photon to another [2]. This experiment demonstrates the new features and extended capabilities of quantum communication systems [3].

1 Quantum teleportation – the idea

Assume the following initial situation (Fig. 1a). Particle 1, which is given to Alice is in the quantum state $|\Psi\rangle_1 = \alpha|H\rangle_1 + \beta|V\rangle_1$, where, as is the case in our experiment, H and V denote horizontal or vertical polarization of a photon. Alice now has to teleport the state of particle 1 to Bob, with the help of an entangled pair of particles 2 and 3 shared by Alice and Bob in the state

$$\left|\Psi^-\right\rangle_{23} = \frac{1}{\sqrt{2}}\big(|H\rangle_2|V\rangle_3 - |V\rangle_2|H\rangle_3\big)\,. \qquad (1)$$

This entangled pair is a single quantum system in an equal superposition of the states $|H\rangle_2|V\rangle_3$ and $|V\rangle_2|H\rangle_3$. The entangled state contains no information on the specific polarization of the individual particles; it only indicates that the two particles will be in opposite polarization states, independently of the measurement basis. The properties of entangled states have now been demonstrated by numerous experiments [4] in the realm of the Einstein-Podolsky-Rosen paradox, but only recently has it been shown that these strictly nonclassical features can be utilized for quantum information processes.

The teleportation scheme is now as follows. Alice has the particle 1 in the initial state $|\Psi\rangle_1$ and particle 2, which is entangled with particle 3 in the hands of Bob. The essential point is to perform a specific measurement on particles 1 and

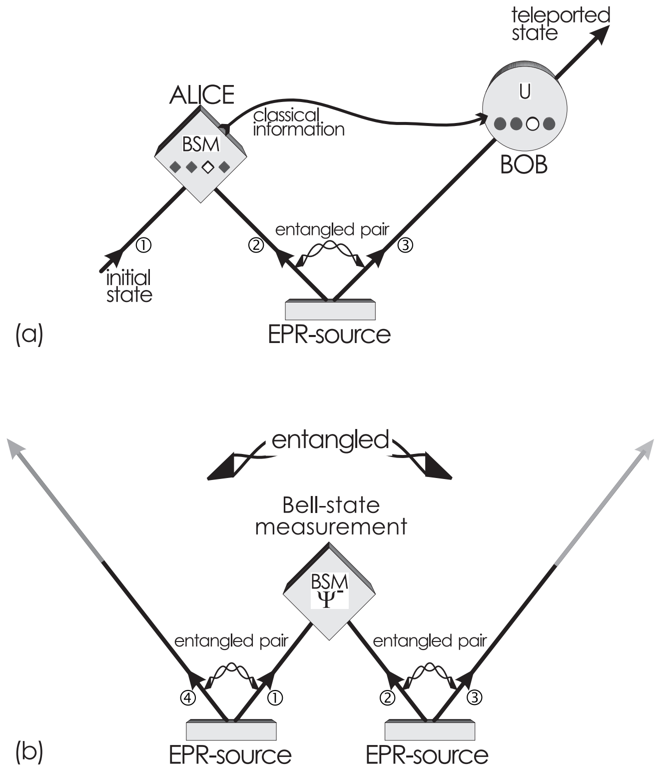

Fig. 1. a Principle of quantum teleportation. **b** Teleporting the undefined state of a photon entangled with yet another one in the process of entanglement swapping proves the ability to transfer any arbitrary quantum state. (Classical information about the result of the Bell-state measurement (BSM) has to be sent to the observers of photons 3 and 4)

2 which can project them onto the entangled state

$$\left|\Psi^-\right\rangle_{12} = \frac{1}{\sqrt{2}}\big(|H\rangle_1|V\rangle_2 - |V\rangle_1|H\rangle_2\big)\,. \tag{2}$$

This is only one of four possible maximally entangled states (the Bell states) into which any state of two particles can be decomposed. The projection of an arbitrary state of two particles onto the basis of the four states is called a Bell-state measurement.

Quantum physics predicts [1] that once particles 1 and 2 are projected onto $\left|\Psi^-\right\rangle_{12}$, particle 3 is in the initial state of particle 1. The reason for this is as follows. Because we observe particles 1 and 2 in the state $\left|\Psi^-\right\rangle_{12}$ we know that whatever the state of particle 1 is, particle 2 must be in the opposite state, i.e. in the state orthogonal to the state of particle 1. But we had initially prepared particles 2 and 3 in the state $\left|\Psi^-\right\rangle_{23}$, which means that particle 2 is also orthogonal to particle 3. This is only possible if particle 3 is in the same state as particle 1 was initially! The final state of particle 3 is therefore

$$|\Psi\rangle_3 = \alpha|H\rangle_3 + \beta|V\rangle_3\,. \tag{3}$$

Note that after the Bell-state measurement one cannot infer the initial states of particles 1 and 2. The state $|\Psi\rangle_1$ is destroyed on Alice's side during teleportation. Moreover, after projecting a pair of particles onto a Bell state one can not infer the original states of any of the particles. Thus no information about the original quantum state of particle 1 is revealed and quantum teleportation escapes the verdict of the no-cloning theorem [5].

A projection onto the Bell-state basis can not only give the result that the two particles are in the state $\left|\Psi^-\right\rangle_{12}$, but with equal probabilities of 25% we could find them in any one of the 3 other entangled states.

$$\left|\Psi^+\right\rangle_{12} = \frac{1}{\sqrt{2}}\big(|H\rangle_1|V\rangle_2 + |V\rangle_1|H\rangle_2\big)$$

$$\left|\Phi^\pm\right\rangle_{12} = \frac{1}{\sqrt{2}}\big(|H\rangle_1|H\rangle_2 \pm |V\rangle_1|V\rangle_2\big)\,. \tag{4}$$

When this happens particle 3 is left in one of three different states. It can then be brought by Bob into the original state of particle 1 by an accordingly chosen transformation, after receiving via a classical communication channel the information about the result of the Bell-state measurement obtained by Alice. Still, if we choose to identify only one of the four Bell states as discussed above, teleportation is successfully achieved, albeit only in a quarter of the cases.

The scheme is not confined to the transfer only of pure states, but it is also capable of teleporting a mixed and even an undefined quantum state. This is best illustrated by the process of entanglement swapping [6]. Suppose particle 1 itself is entangled with yet another particle 4 (Fig. 1b). Then, on its way to Alice's Bell-state analyzer, it has no well-defined properties of its own before any measurement on either itself or its entangled partner particle is performed. After the Bell-state measurement on particles 1 and 2, Bob can transform his particle 3 into the state of particle 1 using information about Alice's result, irrespective of the state of 1. Thus, entanglement between particle 3 and 4 is created, although the two particles neither interacted nor were they coupled together in their past. The demonstration of this effect fully proves the capability of quantum teleportation.

2 Experimental realization

In the experiment, polarization entangled photons were produced by type-II down-conversion in a nonlinear BBO crystal (see Fig. 2a). A UV-beam (pulses with a duration of 200 fs and $\lambda = 394$ nm) is down-converted into pairs of photons with equal wavelength but orthogonal polarization [7]. The entangled pair of photons 2 and 3 is produced in the first passage of the UV-pulse through the nonlinear crystal, and the pair 1 and 4 after reflecting the pulse at a mirror back through the crystal. Mirrors and beamsplitters (BS) are used to steer and to overlap the light beams. Polarizers (Pol) and polarizing beamsplitters (PBS) together with half-wave plates ($\lambda/2$) prepare and analyze the polarization of the photons. All single photon detectors indicated (Silicon-avalanche photodiodes operated in the Geiger-mode) are equipped with narrow band interference filters.

Bell-state analysis turned out to be the most crucial task to be performed. Conditional state changes, e.g., due to strong coupling or interaction between two quantum particles, would be needed, but are unfortunately not yet feasible with current technology. Here we employ two-photon interferometry allowing a partial solution of the problem [8].

The two-particle interference which occurs when overlapping them at a beam splitter is usually described as giving

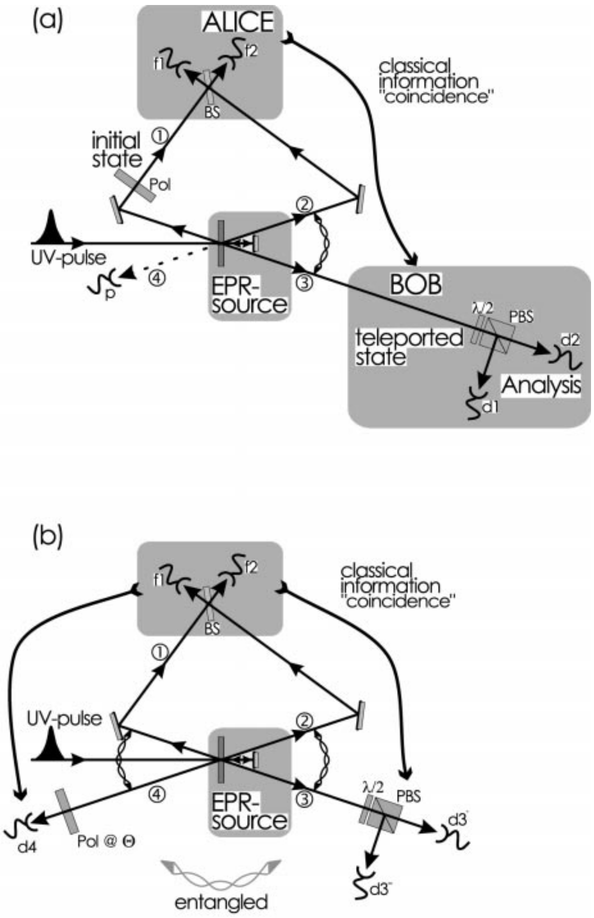

Fig. 2a,b. Set-up of the experiments for quantum teleportation (**a**) and entanglement swapping (**b**)

different results for fermionic (antisymmetric wave function) and bosonic particles (symmetric wave function) [9], namely either both particles leaving the beam splitter via the same output beam for a symmetric wave function or one photon exiting into each output for an antisymmetric state. Photons are bosonic particles, yet what matters is only the spatial part of the wave function at the (polarization insensitive) beam-splitter, and this is different for the various Bell-states. Since only the state $|\Psi^-\rangle$ has an antisymmetric spatial part, only this state will be registered by coincidence detection behind the two outputs of the beam splitter. With additional polarization analysis in the outputs, we can uniquely identify two of the four states with the other two giving a third result. In this work we confined ourself to registering only the $|\Psi^-\rangle$ state. In such a case, one also does not need to perform any unitary transformation on Bob's side, since photon 3 is already in the correct state if Alice detects the characteristic coincidence.

For quantum teleportation, the interferometric approach to Bell-state analysis requires specific timing conditions for two independent incoming photons at Alice's Bell-state analyzer to erase path information [10]. In order to ensure sufficient visibility of the two-photon interference it is necessary either to detect or to generate the interfering photons within a time interval much shorter than their coherence time ($\Delta\tau \ll T_c$). Since there are currently no photon detectors with such a high time resolution available, we decided to use pulsed down-conversion radiation together with narrow filtering at the detectors. Observing the down-converted photons at a wavelength of 788 nm and a bandwidth of 4 nm results in a coherence time of 520 fs, which compared to the 200 fs source-pulses is sufficiently long in principle to achieve high interference visibility.

For the first demonstration of quantum teleportation [11] we prepared particle 1 in various nonorthogonal polarization states using a polarizer and quarter wave plate (not shown). Bob performed polarization analysis to prove the dependence of the polarization of photon 3 on the polarization of 1. (In this case we used the registration of photon 4 only to define the appearance of photon 1.)

To prove that any arbitrary quantum state can be transferred we carefully aligned the paths of photons 1 and 4 to obtain entanglement for this pair, too (Fig. 2b). After removing the polarizer from arm 1 and putting it into arm 4, the state of 1 was not defined anymore, but still could be teleported to photon 3, what was proven by showing that now the entanglement has swapped to photons 3 and 4.

3 Results

The first task is to prove that there is no information on the state of photon 1 revealed during the Bell-state measurement of Alice. Figure 3 shows the coincidence rate between detectors f1 and f2 when varying the overlap of photons 1 and 2 at the beam splitter (for this we changed the position of the mirror reflecting the pump beam back into the crystal). The characteristic interference effect, a reduction of the coincidence rate, occurs only around zero delay. Outside this region, which is on the order of the coherence length of the detected photons, no reduction occurs, and the two photons are detected in coincidence with 50% probability. Besides statistics, there is no difference in the two data sets, although particle 1 was prepared in two mutually orthogonal states (+45° and −45°). Obviously, Alice has no means to determine which of the two states particle 1 was in after the projection into the Bell-state.

Figure 4 shows the polarization of photon 3 after performing the teleportation protocol, again when varying the delay between photons 1 and 2. Once interference occurs at the beam splitter, the polarization of photon 3 is given by the settings for photon 1. The reduction in the polarization to

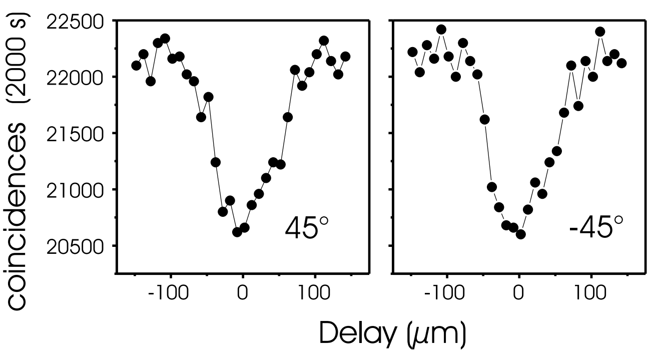

Fig. 3. Coincidence rate between the two detectors of Alice's Bell-state analyzer depending on the delay between the two photons 1 and 2. The data for +45° and −45° polarization of photon 1 are equal within statistics, which shows that no information about the state of photon 1 is revealed to Alice

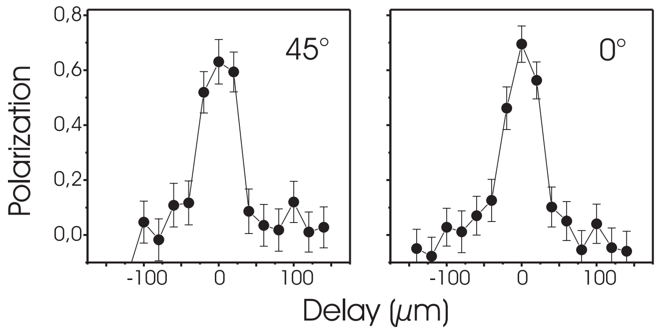

Fig. 4. Polarization of photon 3 after teleportation. Bob's analyzer was set parallel to the polarization prepared at photon 1. The degree of polarization (about 65%) is limited by alignment considerations

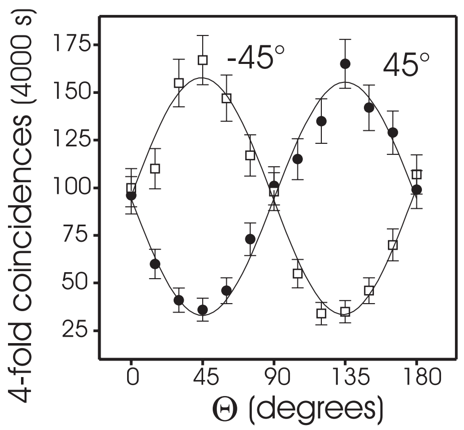

Fig. 5. Verification of the entanglement between photons 3 and 4. The sinusoidal dependence of the 4-fold coincidence rate on the orientation Θ of the polarizer in arm 4 for $\pm 45°$ polarization analysis of photon 3 proves the possibility of teleporting any arbitrary quantum state

about 65% is due to the limited degree of entanglement between photons 2 and 3 (85%), and by the reduced contrast of the interference at the beam splitter due to the relatively short coherence time of the detected photons. Of course, better beam definition by narrow pinholes and more stringent filtering could improve this value, however, this causes further, unacceptable loss for the four-fold coincidence rates. Each of the polarization data points shown was obtained from about 100 four-fold coincidence counts in 4000 s.

Finally, in order to prove the ability to teleport any arbitrary quantum state of a single particle, entanglement was adjusted also between photons 1 and 4 (also roughly 85%) and the polarizer moved from arm 1 to arm 4. This enables one to demonstrate that entanglement between particles 1 and 4 can be swapped to particles 3 and 4 [12]. Figure 5 verifies the entanglement between photons 3 and 4, conditioned on coincidence detection of photons 2 and 3. Varying the angle Θ of the polarizer in arm 4 causes a sinusoidal variation of the count rate, here with the analyzer of photon 3 set to $\pm 45°$.

4 Conclusion

With these experiments we present the first demonstration of quantum teleportation. It was shown that any arbitrary, even undefined quantum state can be transferred from one photon to the other. Crucial for the measurements was the generation and determination of entanglement between photon pairs. This of course is also important for further quantum communication experiments like entanglement purification and for the realization of quantum memories [13]. Quantum teleportation might serve as a link between quantum computers, but to really benefit from all these new ideas one first needs to perform Bell-state analysis and simple quantum logic operations for all possible states. Recent advances in experiments with high-finesse cavities [14] indicate that such goals could be achieved soon. The experiments reported here however also indicate that generating entanglement between three or four photons has now finally come within reach of experiments [15].

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