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Experimental quantum teleportation

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Quantum entanglement lies at the heart of new proposals for quantum communication and computation. Here we describe the recent experimental realization of quantum teleportation.

Keywords: quantum physics; teleportation; entanglement; quantum computer; Einstein–Podolsky–Rosen paradox

1. Introduction

Entanglement between quantum systems is a pure quantum effect describing correlations between systems that are much stronger and richer than any classical correlations can be. Originally this property was introduced by Einstein, Podolsky and Rosen and by Schrödinger and Bohr in the discussion on the completeness of quantum mechanics and by von Neumann in his description of the measurement process (see Wheeler & Zurek 1983). Since then entanglement has been seen as just one of the features which makes quantum mechanics so counterintuitive.

However, recently the new field of quantum information theory has shown the tremendous importance of quantum entanglement also for the formulation of new methods of information transfer and for algorithms exploiting the capability of quantum computers (Bennett 1995). While the latter need entanglement between a number of quantum systems, basic quantum communication schemes only rely on entanglement between the members of a pair of particles, directly pointing at a possible realization of such schemes by means of correlated photon pairs as produced by parametric down-conversion. These violently non-classical states of light have proven their usefulness in several experiments on the foundations of quantum mechanics (Greenberger *et al*. 1993; Chiao *et al*. 1994).

In the present work, we report on what we believe is the first experimental realization of how to communicate quantum information itself in the process of quantum teleportation.

2. Quantum teleportation

Classical communication uses two-state systems to encode a single bit of information. If one wants to send a certain amount of information, consequently one has to physically transfer the corresponding number of such systems. The question now arises as to whether one can use quantum systems to communicate classical information more efficiently, and also whether it is possible to transfer quantum information, i.e. the state of a quantum system, itself. In the original proposal of quantum teleportation (Bennett *et al*. 1993) it was realized that the foremost requirement for the sender

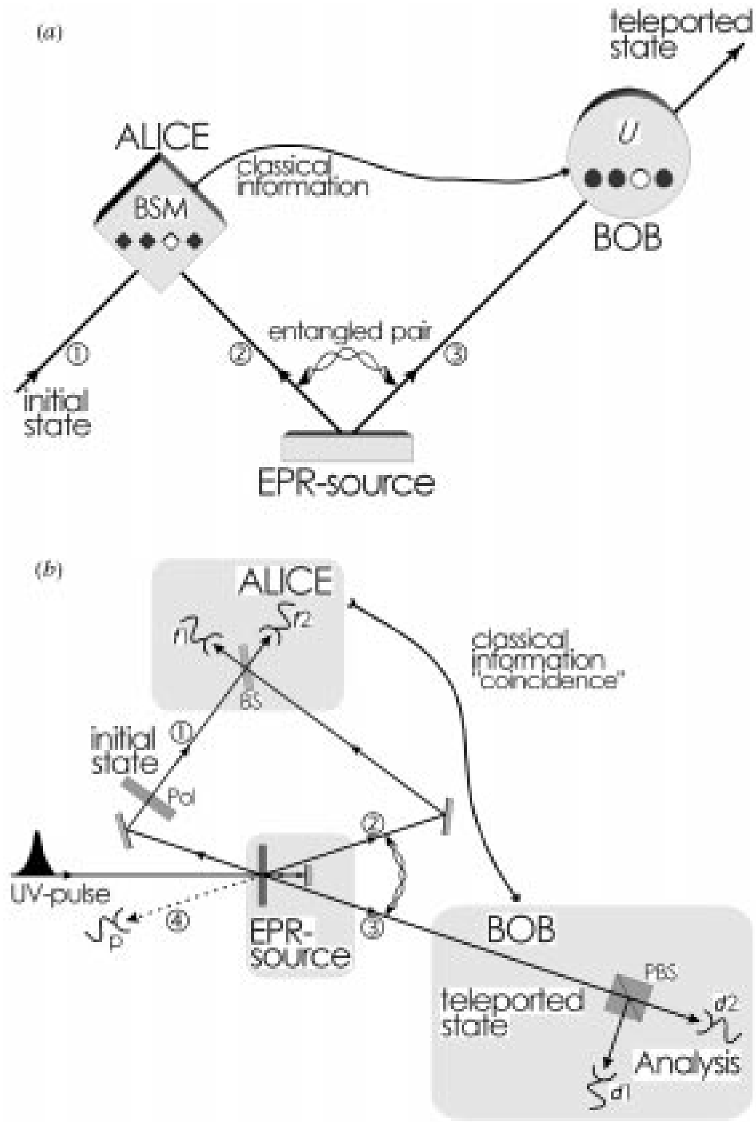

Figure 1. Principle of quantum teleportation: (*a*) scheme; (*b*) experimental set-up.

and the receiver is first to share an entangled pair of particles. As can be seen in figure 1*a*, for quantum teleportation the essential ingredients are (i) the Einstein–Podolsky–Rosen (EPR) source for entangled pairs of particles; (ii) a component (U) performing unitary operations on a two-state quantum particle given one of four classical messages; and (iii) the so-called Bell-state measurement (BSM), where a pair of two-state particles is projected onto the Bell-state basis given by four maximally entangled orthogonal states:

$$|\Psi^{\pm}\rangle = \frac{1}{\sqrt{2}}(|H\rangle|V\rangle \pm |V\rangle|H\rangle), \quad |\Phi^{\pm}\rangle = \frac{1}{\sqrt{2}}(|H\rangle|H\rangle \pm |V\rangle|V\rangle). \tag{2.1}$$

In classical physics 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. Quantum information of a system is given by the state of a quantum system. However, according to Heisenberg's uncertainty relation, one cannot determine the state of a single quantum system by measurement. Any attempt to gain knowledge about quantum information causes a collapse of the quantal wavefunction and thus changes the accessible information. This is closely related to the no-cloning theorem and seems to bring the idea of transferring quantum information to a halt. Surprisingly, it is a measurement which does not give any information about the state of a quantum system at all that gives a solution to the problem.

For the teleportation of a quantum state, Alice first measures one of the entangled particles together with the particle in the state to be transferred. If the measurement projects the state of the two particles onto an entangled state, then the initial properties of each of the two particles can no longer be inferred. However, due to the original quantum correlations the state of the second particle of the pair is now correlated with the result of the measurement. The corresponding unitary transformation can restore the quantum state on Bob's particle once he has received the result via classical communication.

3. Experimental realization

The pairs of polarization-entangled photons were produced by type-II down-conversion in a nonlinear beta-barium-borate crystal (figure 1*b*). A UV beam (pulses with a duration of 200 fs and $\lambda = 490$ nm) was down-converted into pairs of photons with equal wavelength but orthogonal polarization (Kwiat *et al*. 1995).

Bell-state analysis turned out to be the most challenging task to be performed. Conditional state changes, for example due to strong coupling or interaction between two quantum particles, are needed, but are not yet feasible with current technology. Here we employ two-photon interferometry allowing a partial solution of the problem (Weinfurter 1994; Zeilinger *et al*. 1994; Braunstein & Mann 1995).

The two-particle interference which occurs when overlapping at a beam splitter is usually described as giving different results for fermionic (antisymmetric wave function) and bosonic particles (symmetric wave function) (Feynman *et al*. 1965), namely either both particles leaving the beam-splitter via the same output beam for a symmetric wave function or one particle exiting into each output for an antisymmetric state. Photons are bosonic particles; however, what matters is only the spatial part of the wave function at the (polarization-insensitive) beam-splitter, and this spatial part has different symmetry 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 between the different 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 states giving the same, third result.

For quantum teleportation, the interferometric approach to Bell-state analysis requires specific timing conditions for two independent incoming photons at Alice's Bell-state analyser in order to erase any source information (Zukowski *et al*. 1995; Rarity 1995). In order to ensure sufficient visibility of the two-photon interference it is necessary to either detect or to generate the interfering photons within an ultra-coincidence time interval much shorter than their coherence time ($\Delta\tau \ll T_c$). Since

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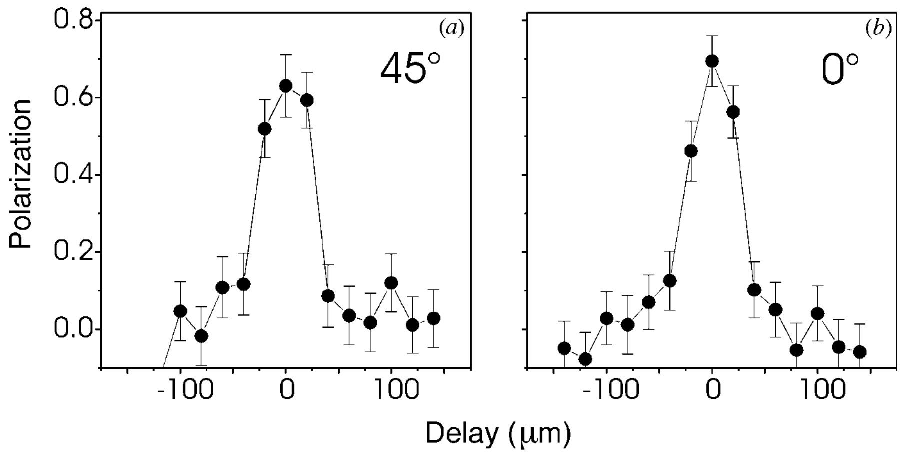

Figure 2. Linear polarization of photons teleported to Bob depending on the relative delay of photons 1 and 2 at the Bell-state analyser (for different initial polarization of photon 1: (*a*) 45°, (*b*) 0°.

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.

Adjusting for perfect overlap of the two photons at the Bell-state analyser, one can transfer the state of the initial photon—in our case the polarization—onto a third photon. Figure 2 shows the degree of polarization of the third photon depending on the delay between photons 1 and 2 at the Bell-state analyser. For zero delay we obtained about 70% polarization along the direction prepared on photon 1 (Bouwmeester *et al*. 1997). The two measurements for non-orthogonal polarizations of photon 1 ((*a*) 45° and (*b*) 0°) prove that any polarization can be teleported.

4. Conclusion

In this paper we presented the proof of principle experiment of quantum teleportation. We demonstrated the possibility of transferring the polarization state from one photon onto another. The experimental techniques developed here also allow one to perform the transfer of any arbitrary quantum state, which in the process of entanglement swapping enables one to create non-classical correlations between particles that never interacted with each other (Zukowski *et al*. 1993; Bose *et al*. 1998). This was recently confirmed experimentally (Pan *et al*. 1998). Moreover, with these experimental techniques, generating entanglement between three out of four particles finally comes within reach (Zeilinger *et al*. 1997).

In principle, any two quantum systems could be entangled with each other, for example atoms or ions in a trap. Then one could also consider schemes where the long coherence time of atomic states allows the storage of quantum states for longer times than would be possible for light; the transfer of quantum information into such a quantum memory would be achieved typically by quantum teleportation.

Quantum memories find use in extensions of the standard quantum cryptography schemes and of course in the new field of quantum computation.

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