Quantum Teleportation

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Teleportation - the transmission and reconstruction of objects over arbitrary distances - is a spectacular process, which actually has been invented by science fiction authors some decades ago. Unbelievable as it seems in 1993 a theoretical scheme has been found by Charles Bennett *et al.* that predicts the existence of teleportation in reality - at least for quantum systems. This scheme exploits some of the most essential and most fascinating features of quantum theory, such as the existence of entangled quantum states. Only four years after its prediction, for the first time quantum teleportation has been experimentally realized by Anton Zeilinger *et al.*, who succeeded in teleporting the polarization state of photons. Apart from the fascination that arises from the possibility of teleporting particles, quantum teleportation is expected to play a crucial role in the construction of quantum computers in future.

I. INTRODUCTION

A. Motivation

Teleportation is a term created by science fiction authors describing a process, which lets a person or object disappear while an exact replica appears in the best case immediately at some distant location. The first idea how the dream of teleportation could be realized in practice might be the following: From a classical point of view the object to be teleported can fully be characterized by its properties, which can be determined by measurement. To create a copy of the object one does not need the original parts and pieces, but all that is needed is to send the scanned information to the place of destination, where the object can be reconstructed. Having a closer look at that scheme, we realize that the weak point is the measuring process. If we want to get a perfect replica of the object, it would be inevitable to determine the states of molecules, atoms and electrons - in a word: we would have to measure quantum properties. But according to Heisenberg's uncertainty principle, these cannot be determined with arbitrary precision not even in principle. We see that teleportation is not practicable in this way. And even more: it seems as if the laws of quantum mechanics prohibit any teleportation scheme in general.

It is the more surprising that in 1993 Charles H. Bennett *et al.* have suggested that it is possible to transfer the quantum state of a particle onto another provided one does not get any information about the state in the course of this transformation. The central point of Bennett's idea is the use of an essential feature of quantum mechanics: entanglement [8]. Entanglement describes correlations between quantum systems much stronger than any classical correlation could be. With the help of a so-called pair of entangled particles it is possible to circumvent the limitations caused by Heisenberg's uncertainty principle.

Quite soon after its theoretical prediction in 1997 Anton Zeilinger *et al.* succeeded in the first experimental verification of quantum teleportation. By producing pairs of entangled photons with the process of parametric down-conversion and using two-photon interferometry for analyzing entanglement, they were able to transfer a quantum property (the polarization state) from one photon to another.

Though the prediction and experimental realization of quantum teleportation are surely a great success of modern physics, we should be aware of the differences between the physical quantum teleportation and its science fiction counterpart. We will see that quantum teleportation transfers the quantum state from one particle to another, but doesn't transfer mass. Furthermore the original state is destroyed in the course of teleportation, which means that no copy of the original state is produced. This is due to the no-cloning theorem, which says that it is *impossible* within quantum theory to produce a clone of a given quantum system [1][9]. Finally we will learn that teleporting a quantum state has a natural speed limit. In the best case it is possible to teleport at the speed of light - in accordance with Einstein's theory of relativity.

B. Reminder of Basic Concepts

The theoretical scheme of quantum teleportation necessitates some basic concepts of quantum mechanics. All above we will deal with two-level quantum systems. For instance, such a system can be represented by a spin-$\frac{1}{2}$ particle or the polarization state of a photon. In order to stay in a general setting we call the two basis states $|0\rangle$ and $|1\rangle$. The general wave function of the two-level system is the superposition of these states:

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle, \tag{1}$$

where α and β are two complex numbers satisfying $|\alpha|^2 + |\beta|^2 = 1$. As the next step we want to consider the combination of two two-level systems. The wave function

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of such a system might be the following one:

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|0\rangle_1|1\rangle_2 - |1\rangle_1|0\rangle_2\right), \tag{2}$$

which is a special superposition of states and an example for the so-called *entangled states* or *EPR states* [10]. As already mentioned above, entanglement is an essential feature of quantum mechanics and the reason for this is the following: The entangled state describes a *single* quantum system in an equal superposition of the states $|0\rangle_1|1\rangle_2$ and $|1\rangle_1|0\rangle_2$, and the two particles involved lose their identities in a certain sense. The entangled state contains no information on the individual particles; it only indicates that the two particles will be in opposite states. This means that as soon as a measurement on one particle projects it onto, let's say, $|0\rangle$, the state of the other one must be $|1\rangle$, and vice versa. Noting the fact that Eq. (2) doesn't impose any restrictions on the spatial distance between the two entangled quantum systems, quantum mechanics predicts an instantaneous influence between two particles, which can be arbitrarily far away from each other. This effect seems to be unbelievable and so many distinguished physicists couldn't accept it; Einstein among them even called it a "spooky action at a distance" [11]. Nevertheless experiments have shown that this property of entangled states is reality.

Knowing the special features of entangled EPR states, we want to have a closer look at how entangled systems are put to work in the theoretical scheme of quantum teleportation.

II. THE CONCEPT OF QUANTUM TELEPORTATION

A. Definition of the problem...

Suppose that a sender, whom we call "Alice", has a quantum system such as a spin-$\frac{1}{2}$ particle or a photon prepared in a certain quantum state $|\psi\rangle$. We assume that Alice doesn't know the exact wave function of her state, but she wants to transfer sufficient information to a receiver at a distant location, we call him "Bob", for him to make an exact copy of it. If Alice knew the wave function of her state, this would be sufficient information, but in general there is no way to learn it. To make this point clear, let's consider a two-level system with its general wave function

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle, \tag{3}$$

where α and β are two complex numbers satisfying $|\alpha|^2 + |\beta|^2 = 1$. A measurement on this quantum system would lead to a projection onto an eigenstate of the measured observable. If $|\psi\rangle$ isn't accidentally an eigenstate of the observable, which is extremely unlikely, Alice has no chance to learn the exact wave function. We conclude that measuring $|\psi\rangle$ in general leads to a loss of information and makes a reconstruction of the state impossible.

So we might think that the only possibility for Alice to provide Bob with the whole information on $|\psi\rangle$ would be sending the particle itself. This, of course, is the trivial method, and therefore we want to think of a scenario which doesn't allow sending the particle. Let's say, the communication channel between Alice and Bob is not good enough to preserve quantum coherence. Now, what can Alice's and Bob's strategy be?

An answer to this question has been found by Bennett *et al.* [2] presented in their article "Teleporting an Unknown Quantum State via Dual Classical and Einstein-Podolsky-Rosen-Channels". The title of the article gives an important hind: the information encoded in $|\psi\rangle$ can be divided into two parts, one purely classical and the other one purely nonclassical. These two parts of information are send through different channels, and after having received both, Bob is able to produce an exact replica of $|\psi\rangle$. To understand what is exactly meant by "classical" and "nonclassical" information, we want to have a closer look at Bennett's proposed scheme.

B. ...and its solution!

Alice has a particle 1 in the initial state

$$|\psi\rangle_1 = \alpha|0\rangle_1 + \beta|1\rangle_1. \tag{4}$$

The key role in the teleportation of this state is played by an entangled ancillary pair of particles, because this establishes the nonclassical channel between Alice and Bob. Alice holds particle 2 and Bob particle 3 (see FIG. 1), together being the constituents of an EPR singlet state

$$|\Psi^-\rangle_{23} = \frac{1}{\sqrt{2}}\left(|0\rangle_2|1\rangle_3 - |1\rangle_2|0\rangle_3\right). \tag{5}$$

(Remember the comments on EPR pairs in Sect. I B.)

1. Nonclassical information transmission

We note that the fact, that Alice and Bob share an EPR pair, establishes the possibility of nonclassical correlations between them, but the EPR pair does not yet carry any information about particle 1. This can be seen, when we consider that the entire system of the three particles can be described as a pure product state, $|\psi\rangle_1|\Psi^-\rangle_{23}$. Obviously, performing a measurement on either member of the EPR pair doesn't reveal any information on particle 1. Our aim is now to couple particle 1 with the EPR pair. This can be done, when Alice performs a measurement on the joint system consisting of particle 1 and particle 2 (her EPR particle). This so-called Bell-state measurement should project the system

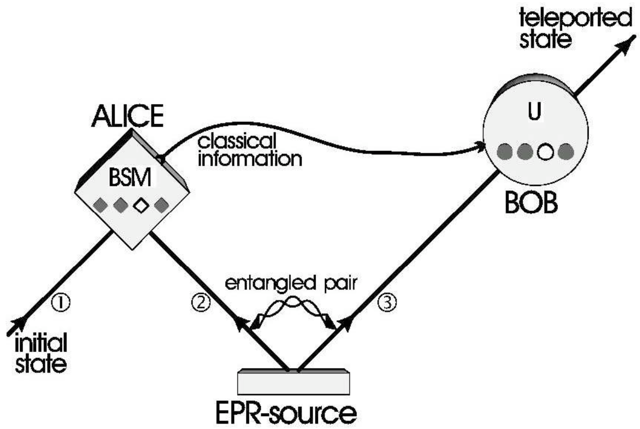

FIG. 1: *Theoretical scheme.* Alice has a quantum system, particle 1, in an initial state, which she wants to teleport to Bob. Alice and Bob also share an ancillary entangled pair, particle 2 and 3, produced by a so-called Einstein-Podolsky-Rosen (EPR) source. Alice performs a joint Bell-state measurement (BSM) on particles 1 and 2, projecting them onto one of the four possible Bell-states. After Alice having sent the outcome of her BSM to Bob as a piece of classical information, he can perform a unitary transformation (U) on particle 3, which changes its state into the initial state of particle 1.

onto one of the four maximally entangled Bell-states:

$$\begin{aligned} |\Psi^{\pm}\rangle_{12} &= \frac{1}{\sqrt{2}}\left(|0\rangle_1|1\rangle_2 \pm |1\rangle_1|0\rangle_2\right), \\ |\Phi^{\pm}\rangle_{12} &= \frac{1}{\sqrt{2}}\left(|0\rangle_1|0\rangle_2 \pm |1\rangle_1|1\rangle_2\right). \end{aligned} \tag{6}$$

These four states form a complete orthonormal basis, the Bell basis, for particles 1 and 2.

The complete state of the three particles before Alice's measurement is

$$\begin{aligned} |\Psi\rangle_{123} = &\frac{\alpha}{\sqrt{2}}\left(|0\rangle_1|0\rangle_2|1\rangle_3 - |0\rangle_1|1\rangle_2|0\rangle_3\right) \\ &+ \frac{\beta}{\sqrt{2}}\left(|1\rangle_1|0\rangle_2|1\rangle_3 - |1\rangle_1|1\rangle_2|0\rangle_3\right). \end{aligned} \tag{7}$$

In this equation, each product $|\ \rangle_1|\ \rangle_2$ can be expressed in terms of the Bell basis, and so we can rewrite Eq. (7) as

$$|\Psi\rangle_{123} = \frac{1}{2}\left[\,|\Psi^-\rangle_{12}\left(-\alpha|0\rangle_3 - \beta|1\rangle_3\right) + |\Psi^+\rangle_{12}\left(-\alpha|0\rangle_3 + \beta|1\rangle_3\right) + |\Phi^-\rangle_{12}\left(\alpha|1\rangle_3 + \beta|0\rangle_3\right) + |\Phi^+\rangle_{12}\left(\alpha|1\rangle_3 - \beta|0\rangle_3\right)\,\right]. \tag{8}$$

From this equation we can conclude that, regardless of the unknown state $|\psi\rangle_1$, the four possible measurement outcomes of Alice's Bell-state measurement are equally likely, each occurring with probability 1/4. Moreover, Bob's particle 3 is influenced by the measurement. Quantum physics predicts that once the particles 1 and 2 are projected onto one of the four Bell-states, particle 3 is instantaneously projected into on of the four pure states superposed in Eq. (8). Denoting

$$|0\rangle \equiv \begin{pmatrix} 1 \\ 0 \end{pmatrix} \qquad \text{and} \qquad |1\rangle \equiv \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

these four pure states are, respectively,

$$\begin{aligned} -|\psi\rangle_3 \equiv -\begin{pmatrix} \alpha \\ \beta \end{pmatrix}, \quad &\begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix}|\psi\rangle_3, \\ \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}|\psi\rangle_3, \quad &\begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}|\psi\rangle_3. \end{aligned} \tag{9}$$

2. Classical information transmission

From Eq. (9) we see that each possible resultant state for Bob's EPR particle is related in a simple way to the original state $|\psi\rangle_1$ which Alice wanted to teleport. In case of the first outcome, Alice measures $|\Psi^-\rangle_{12}$ and Bob's state is the same as the original state except for an irrelevant phase factor, so Bob needs to do nothing further to produce a replica of Alice's unknown state. In the three other cases, Bob must apply one of the unitary transformations given in Eq. (9) to convert the state of particle 3 into the original state of particle 1. The important point now is, that Bob can just apply the right transformation, if he receives the result of the Bell-state measurement performed by Alice. And this piece of information, which is crucial for a successful teleportation, can only be transmitted via a classical communication channel. So the *maximum speed* of quantum teleportation is given by the *speed of light*, as we would have expected. Nevertheless quantum teleportation could happen over arbitrary distances: the nonclassical information transfer happens instantaneously regardless of the distance between the EPR particles; the duration of the classical information transmission depends on the method and the distance.

While Bob, after a successful teleportation, has an exact replica of the initial state $|\psi\rangle_1$, Alice, on the other hand, is left with particles 1 and 2 in one of the states $|\Psi^{\pm}\rangle_{12}$ or $|\Phi^{\pm}\rangle_{12}$, without any trace of the original

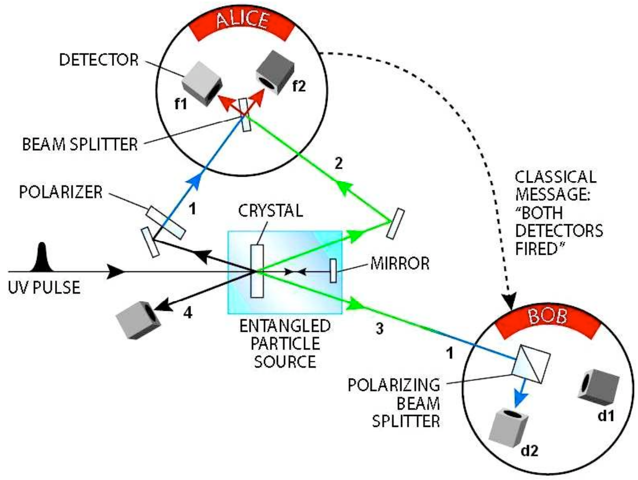

FIG. 2: *Experimental setup.* A pulse of ultraviolet light passes through a non-linear crystal and creates the ancillary pair of entangled photons 2 and 3. The pulse is reflected by a mirror and again passes through the crystal creating another pair of photons. One of them will be prepared in the initial state of photon 1, the other one can serve as a trigger, indicating that a photon to be teleported is on its way. Alice looks for coincidences behind the beam splitter (BS) where the initial photon 1 and photon 2 are superposed. If they are indistinguishable, they interfere. After having received a classical information that Alice measured a coincidence at the detectors f1 and f2 corresponding to the $|\Psi^-\rangle_{12}$ Bell-state, Bob knows that photon 3 has been converted into the initial state of photon 1. He checks this by using polarization analysis with the polarizing beam splitter and the detectors d1 and d2.

state $|\psi\rangle_1$. Therefore particle 3, now being in the state $|\psi\rangle_3 = \alpha|0\rangle_3 + \beta|1\rangle_3$, is not a clone of particle 1, but can be legitimately regarded as the *teleported* particle 1.

We conclude the theoretical discussion of quantum teleportation with the remark that the whole scheme presented above is only possible, because the Bell-state measurement does not reveal any information on the properties of any of the particles. So, we've surmounted the problem we discussed in Sect. II A.

III. EXPERIMENTAL REALIZATION

The core of quantum teleportation is the production and measurement of entangled states; these are the most challenging tasks for an experimental realization limiting the range of possible two-level systems. In 1997 Zeilinger *et al.* [3–6] succeeded in the first experimental demonstration of quantum teleportation transferring polarization states from one photon onto another. At that time there were only very *few* experimental techniques allowing the preparation of entangled states, and there was *no* experimentally realized procedure to identify all four Bell-states for any quantum system. However, entangled pairs of photons could readily be generated by so-called type-II parametric down-conversion and be projected onto at least two of the four Bell-states using two-photon interferometry.

By the time the range of experimental realizations has broadened, because new entanglement techniques have been found (e.g. atom entanglement based on cavity quantum electrodynamics, ion entanglement in electromagnetic Paul traps [6, 7], etc). Some of them even make unconditional teleportation feasible allowing the identification of every Bell-state. Nevertheless we want to report on Zeilinger's experiment in some detail, because this group pioneered the field of experimental quantum teleportation.

A. A Source of Entangled Photons

The process of spontaneous parametric down-conversion provides mechanisms by which pairs of entangled photons can be produced with reasonable intensity and in good purity. In this technique, inside a crystal with nonlinear electric susceptibility, an incoming pump photon can decay with relatively small probability into two photons in a way that energy and momentum inside the crystal are conserved:

$$\omega_p = \omega_1 + \omega_2$$
$$\mathbf{k}_p = \mathbf{k}_1 + \mathbf{k}_2$$

Zeilinger *et al.* used so-called type-II parametric down-conversion. In this process the polarization entangled state is produced directly out of a nonlinear BBO-crystal (beta barium borate). If an incoming pump photon decays spontaneously, the two down-converted photons are polarized orthogonally, but have the same energy [12] (see Fig. 3). Each photon is emitted into a cone such that the momenta of the two photons always add up to the momentum of the pump photon. The essential part of the setting are the intersection lines of the cones, because along these lines, the polarization of neither photon is defined (see Fig. 4). We only know that the two photons have to have *different* polarizations. This is the essential feature to achieve entanglement, for a measurement on each of the photons separately is totally random and gives vertical or horizontal polarization with equal probability. But once a photon, e.g. photon A, is measured, the polarization of the other photon is orthogonal! If we choose $|H\rangle$ and $|V\rangle$ as a basis, we get the following entangled state in the case of type-II parametric down-conversion [13]:

$$|\psi\rangle_{AB} = \frac{1}{\sqrt{2}}\left(|H\rangle_A|V\rangle_B - |V\rangle_A|H\rangle_B\right). \qquad (10)$$

B. The Bell-state Analysis

We can see from Fig. 2 that not only the entangled photon pair is produced in the BBO-crystal, but also another pair of photons. The upper photon of this second

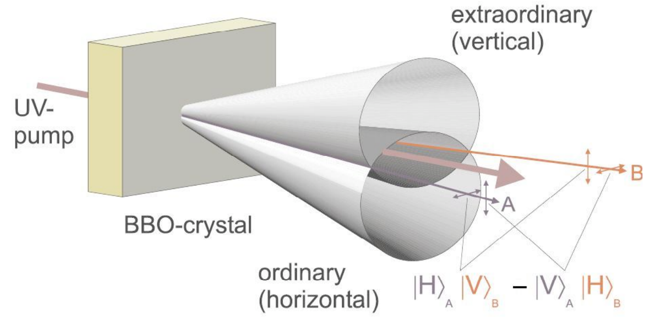

FIG. 3: *Principle of type-II parametric down-conversion.* Inside a nonlinear crystal (here: beta barium borate (BBO)) an incoming pump photon can decay spontaneously into two photons. These photons are polarized orthogonally to each other. Each photon is emitted into a cone and the photon on the top cone is vertically polarized while its counterpart exactly opposite in the bottom cone is horizontally polarized. Along the intersection line of the two cones the polarizations are undefined; all that is known is that they have to be orthogonal, which results in polarization entanglement between the two photons in beams A and B.

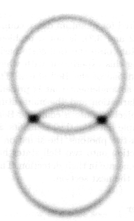

FIG. 4: *Type-II down-conversion light* as seen through a narrow-band filter. The two rings are the ordinary and extraordinary cones of light rays. Along the intersecting directions, which are cut out by irises, we observe unpolarized light.

pair is prepared in a specific polarization state by the polarizer, then being photon 1 to be teleported, whereas the lower one can serve as a trigger, indicating that photon 1 is under way.

Now we arrive at the problem of performing a Bell-state analysis on photon 1 and photon 2. To achieve projection of photons 1 and 2 onto a Bell-state, we have to make them indistinguishable. To achieve this indistinguishability, we exploit the two-photon interference effect at a 50:50 standard beam splitter. The beam splitter has two spatial input modes a and b (see Fig. 5).

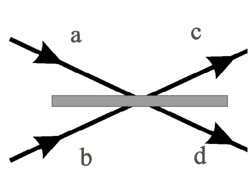

FIG. 5: *Standard beam splitter.* The beam splitter transforms two input spatial modes (a, b) into two output spatial modes (c, d).

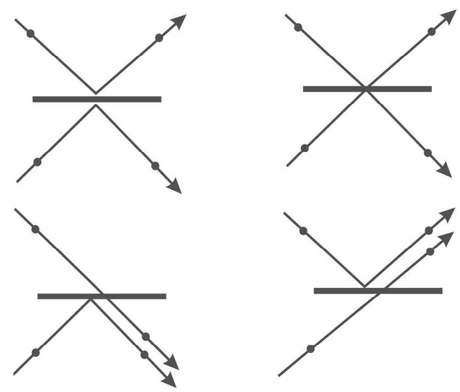

FIG. 6: Two photons incident on the beam splitter, one from each side. There are four possibilities how the two photons can leave the beam splitter.

Quantum mechanically the action of the beam splitter on the input modes can be written as

$$|a\rangle \rightarrow \frac{i}{\sqrt{2}}|c\rangle + \frac{1}{\sqrt{2}}|d\rangle,$$
$$|b\rangle \rightarrow \frac{1}{\sqrt{2}}|c\rangle + \frac{i}{\sqrt{2}}|d\rangle, \tag{11}$$

where, e.g. $|a\rangle$ describes the spatial quantum state of a photon in input mode a. Eq. (11) describes the fact that the photon can be found with equal probability (50%) in either of the output modes c and d, no matter what the input mode was. The factor i corresponds physically to a phase jump upon reflection at the semi-transparent mirror [14].

Now we want to consider what happens at the beam splitter with two incident photons, say, photon 1 in input beam a and photon 2 in input beam b. Suppose that photon 1 is in polarization state $\alpha|H\rangle_1 + \beta|V\rangle_1$ and photon 2 in $\gamma|H\rangle_2 + \delta|V\rangle_2$ (with $|\alpha|^2 + |\beta|^2 = 1$ and $|\gamma|^2 + |\delta|^2 = 1$). Each photon has the same 50:50-probability of being transmitted or reflected. Thus four different possibilities arise (see Fig. 6):

(1) Both photons are reflected, (2) both photons are transmitted, (3) the upper photon is reflected, the lower one is transmitted, and (4) the upper one is transmitted and the lower one is reflected. Each case occurs with the same probability, and one has to investigate now, whether any interference effects are observed. For *distinguishable* photons, which behave therefore like classical particles, no interference arises and we thus arrive at the prediction that in two of the cases, i.e. with probability $p = 0.5$, the two particles end up in different output ports and, with the probability $p = 0.25$, both end up in the upper output beam and, with the same probability $p = 0.25$, they end up in the lower output beam.

Let us now assume that the photons are quantum mechanically *indistinguishable*. Then we can't, not even in principle, decide which of the incident particles ended up in a given output port. Therefore we have to consider coherent superpositions of the amplitudes for these different possibilities. We start with the input state

$$|\psi_i\rangle = (\alpha|H\rangle_1 + \beta|V\rangle_1)\,|a\rangle_1\,(\gamma|H\rangle_2 + \delta|V\rangle_2)\,|b\rangle_2. \quad (12)$$

When passing the beam splitter the spatial modes undergo the transformation given by Eq. (11). So the state in Eq. (12) evolves into

$$\begin{aligned} |\psi_f\rangle_{12} = & \tfrac{1}{\sqrt{2}}\,(\alpha|H\rangle_1 + \beta|V\rangle_1)\,(i|c\rangle_1 + |d\rangle_1) \\ \times & \tfrac{1}{\sqrt{2}}\,(\gamma|H\rangle_2 + \delta|V\rangle_2)\,(|c\rangle_2 + i|d\rangle_2) \end{aligned} \quad (13)$$

Because photons 1 and 2 are indistinguishable after passing through the beam splitter, the total two-photon state, including both the spatial and the polarization part, has to obey bosonic quantum statistics. This means that the outgoing state has to be symmetric under exchange of the labels 1 and 2. So we symmetrize the state $|\psi_f\rangle_{12}$ by writing

$$|\psi_f\rangle = \frac{1}{\sqrt{2}}\,(|\psi_f\rangle_{12} + |\psi_f\rangle_{21}) \quad (14)$$

with

$$\begin{aligned} |\psi_f\rangle_{21} = & \tfrac{1}{\sqrt{2}}\,(\alpha|H\rangle_2 + \beta|V\rangle_2)\,(i|c\rangle_2 + |d\rangle_2) \\ \times & \tfrac{1}{\sqrt{2}}\,(\gamma|H\rangle_1 + \delta|V\rangle_1)\,(|c\rangle_1 + i|d\rangle_1)\,. \end{aligned} \quad (15)$$

After insertion of Eqs. (13) and (15) into Eq. (14) and some calculation, we get

$$\begin{aligned} |\psi_f\rangle = & \tfrac{1}{2\sqrt{2}}\,[(\alpha\gamma + \beta\delta)\,(|H\rangle_1|H\rangle_2 + |V\rangle_1|V\rangle_2)\cdot i\,(|c\rangle_1|c\rangle_2 + |d\rangle_1|d\rangle_2) \\ & + (\alpha\gamma - \beta\delta)\,(|H\rangle_1|H\rangle_2 - |V\rangle_1|V\rangle_2)\cdot i\,(|c\rangle_1|c\rangle_2 + |d\rangle_1|d\rangle_2) \\ & + (\alpha\delta + \beta\gamma)\,(|H\rangle_1|V\rangle_2 + |V\rangle_1|H\rangle_2)\cdot i\,(|c\rangle_1|c\rangle_2 + |d\rangle_1|d\rangle_2) \\ & + (\alpha\delta - \beta\gamma)\,(|H\rangle_1|V\rangle_2 - |V\rangle_1|H\rangle_2)\,\cdot\,(|d\rangle_1|c\rangle_2 - |c\rangle_1|d\rangle_2)]. \end{aligned} \quad (16)$$

Of course, this equation requires some discussion, but we will see that it allows us to easily project the two-photon state onto two of the four Bell-states

$$\begin{aligned} |\Psi^\pm\rangle_{12} &= \frac{1}{\sqrt{2}}\,(|H\rangle_1|V\rangle_2 \pm |V\rangle_1|H\rangle_2)\,, \\ |\Phi^\pm\rangle_{12} &= \frac{1}{\sqrt{2}}\,(|H\rangle_1|H\rangle_2 \pm |V\rangle_1|V\rangle_2)\,. \end{aligned} \quad (17)$$

It is just these states that we find in the middle column of Eq. (16). Having a closer look at the last line of Eq. (16), we see the state $|\Psi^-\rangle_{12}$ and realize that the two photons have this state, if, and only if they proceed in different output modes after the beam splitter. So Bell-state $|\Psi^-\rangle_{12}$ can clearly be identified, if detectors on both sides of the beam splitter fire simultaneously. For a full Bell-state analysis, we need a way to distinguish between the three other states $|\Psi^+\rangle_{12}$, $|\Phi^-\rangle_{12}$ and $|\Phi^+\rangle_{12}$. But we find, that it is only the state $|\Psi^-\rangle_{12}$ which can additionally be identified, because, while emerging on the same side of the beam splitter, the photons still are polarized orthogonally. Thus we have seen that two-photon interference effects allow us to clearly identify two of the four Bell-states via two-fold coincidence analysis at detectors behind the beam splitter.

C. The Experiment

For reasons of practical convenience Zeilinger *et al.* only analyzed the projection onto $|\Psi^-\rangle_{12}$. As we found out in the previous section, this corresponds to detecting a coincidence between the two detectors at the different output ports of the beam splitter (in Fig. 2 see detectors f1 and f2), and due to Eq. (16) this means that in one out of four cases a projection onto $|\Psi^-\rangle_{12}$ takes place. Furthermore, we have already derived in Sect. II B 1 that projecting the photons 1 and 2 onto $|\Psi^-\rangle_{12}$ instantaneously transforms photon 3 into the initial state of photon 1. We note with emphasis that although only one of the four Bell-states is identified in the experiment, teleportation is successfully achieved nevertheless, albeit only in a quarter of the cases.

The experimental Bell-state analysis is an extremely sensitive point, because it relies on the interference of two independently created photons. A projection onto a Bell-state can thus only be successful, if good spatial and temporal overlap at the beam splitter is guaranteed. That means all kinds of Welcher-Weg-information for the photons 1 and 2 must be erased. This is achieved by increasing the coherence times of the interfering photons to become much longer than the time interval within which they are created. In the experiment ultraviolet laser pulses with a duration of 200fs are used to create the photon pairs. In front of the detectors f1 and f2 narrow bandwidth filters ($\Delta\lambda = 4.6$nm) are placed. These

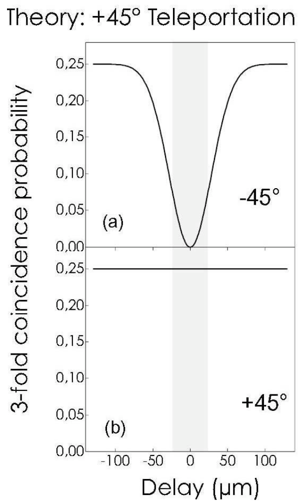

FIG. 7: *Theoretical prediction* for the three-fold coincidence probability between the two Bell-state detectors (f1, f2) and the detectors analyzing the teleported state. The signature of teleportation of a photon polarization state at +45° is a dip to zero at zero delay in the three-fold coincidence rate with the detector analyzing -45° (d1f1f2) (a) and a constant value for the detector analyzing +45° (d2f1f2) (b). The shaded area indicates the region of teleportation.

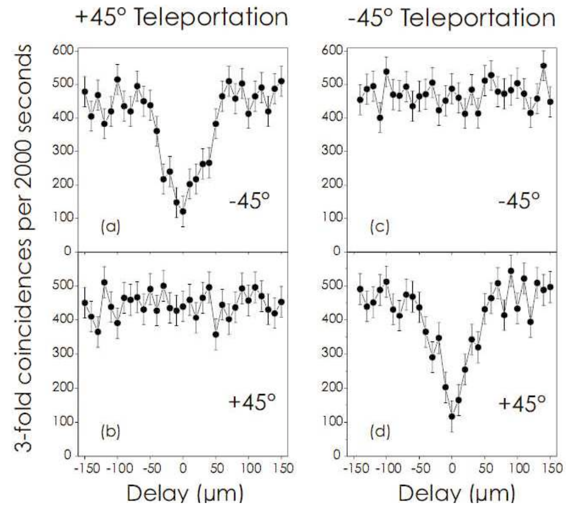

FIG. 8: *Experimental results.* Measured three-fold coincidence rates d1f1f2 (-45°) and d2f1f2 (+45°) in the case that the photon state to be teleported is polarized at +45° ((a) and (b)) or at -45°((c) and (d)). The coincidence rates are plotted as a function of the delay between the arrival of photon 1 and 2 at Alice's beam splitter. These data, compared with Fig. 7, confirm teleportation for an arbitrary state.

produce a coherence time of about 500fs, which is sufficiently longer than the pump pulse duration.

To prove experimentally that an *arbitrary* quantum state can be teleported, one has to show that teleportation works on a complete basis, i.e. a set of states into which any other state can be decomposed. A basis for polarization states has just two components, for example one could choose horizontal and vertical polarization. But because horizontal and vertical polarization are somehow preferred directions in the experimental setup, for the sake of greater generality, Zeilinger *et al.* demonstrated teleportation for the two states linearly polarized at -45° and +45° [15].

D. The Results

In the first experiment photon 1 was polarized at +45°. Teleportation should work as soon as photon 1 and photon 2 are detected in the $|\Psi^-\rangle_{12}$ state, which occurs in one of four cases. The $|\Psi^-\rangle_{12}$ state is identified by recording a coincidence between the two detectors f1 and f2, placed behind the beam splitter (see Fig. 2).

If a f1f2 coincidence is detected, then photon 3 should be polarized at +45°. The polarization of photon 3 is experimentally checked by passing it through a polarizing beam splitter selecting +45° and -45° polarization. To demonstrate teleportation only detector d2 at the +45° output should fire, f1f2 coincidence provided. So, recording a three-fold coincidence d2f1f2 (+45° analysis) together with the absence of a three-fold coincidence d1f1f2 is a proof that the polarization of photon 1 has been teleported to photon 3.

The temporal overlap between photons 1 and 2 is changed in small steps by changing the delay between the first and second down-conversion which is achieved by translating the retroreflection mirror (see Fig. 2). In this way the region of temporal overlap can be scanned.

Outside the region of teleportation photon 1 and 2 each will go either to f1 or to f2 independent from each other. The probability of having a coincidence between f1 and f2 is therefore 50% (as deduced in Sect. III B), which is twice as high as inside the region of teleportation. Then photon 3 should not have a well-defined polarization, because it is part of an entangled pair. Therefore, d1 and d2 both have a 50% chance of receiving photon 3. This yields a 25% probability both for the -45° analysis and for the +45° analysis outside the region of teleportation. On the other hand, *successful* teleportation of the +45° state is characterized by a decrease to zero in the -45° analysis and a constant value in the +45° analysis. The above argument is summarized in Fig. 7 as a theoretical prediction in case teleportation works as expected.

If teleportation didn't work as expected, the prediction would be different. In any case, at zero delay there is a decrease to half in the coincidence rate for the two *detectors f1 and f2* of the Bell-state analyzer. But if the polarization of photon 3 was completely uncorrelated to the others, the graphs of the three-fold coincidence should also show this dip to half in both the -45° and the +45° analysis.

The experimental results of Zeilinger *et al.* are presented in Fig. 8. Comparing the graphs with the theoretical prediction of Fig. 7, we can state a very good agreement. Thus quantum teleportation is experimentally proven.

IV. SUMMARY AND OUTLOOK

In this short review on quantum teleportation we deduced from the basic principles of quantum mechanics that it is possible to transfer the quantum state from one particle onto another over arbitrary distances. To do so, we need an entangled EPR pair of particles 2 and 3 which the sender and the receiver share. The sender has to perform a joint Bell-state measurement on the particle 1 to be teleported and his EPR particle 2. This Bell-state measurement instantaneously influences the EPR particle 3 of the receiver in a nonclassical way. To complete the teleportation the receiver must be informed about the result of the Bell-state measurement via a classical communication channel. Due to this information, he can apply a unitary transformation resulting in his particle 3 being in the state of the original particle. This is the theoretical scheme of quantum teleportation in brief.

As an experimental elaboration of that scheme we discussed the teleportation of polarization states of photons. But quantum teleportation is not restricted to that system at all. One could imagine entangling photons with atoms or photons with ions, and so on. Then teleportation would allow us to transfer the state of, for example, fast decohering, short-lived particles onto some more stable systems. This opens the possibility of quantum memories, where the information of incoming photons could be stored on trapped ions, carefully shielded from the environment. With this application we are in heart of quantum information processing. But quantum teleportation is not only an important and promising ingredient for those tasks. It also allows new types of experiments to check the very basic principles of quantum mechanics. As an arbitrary state can be teleported, so can the fully undetermined state of a particle which is member of an entangled pair. By doing so, one can transfer entanglement between particles (*entanglement swapping*), and, for example, perform a test of Bell's theorem on particles which do not share any common past. This is a new step in the experimental investigation of the features of quantum mechanics.

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[8] English translation of the German word *Verschränkung.*
[9] This is the reason, why we do not use the word "copy", but the word "replica" in this article.
[10] Due to Einstein, Podolsky and Rosen (EPR), who were the first scientists that realized and considered the features and consequences of entangled states in detail.
[11] In German: *spukhafte Fernwirkung.*
[12] In fact, a certain wavelength is cut out using a narrow-band optical-filter behind the BBO-crystal.
[13] We note that in the experiment one has to cope with quite a few obstacles to really achieve an entangled pair as described by Eq. (10). In particular, the photons A and B have to be indistinguishable in any of their properties. To obtain this, just to mention an example, the time delay between photon A and photon B arising from different group velocities for horizontally and vertically polarized light within the crystal have to be compensated.
[14] Note that a standard beam splitter is polarization independent and thus has no effect on the polarization state of the photon.
[15] In fact, Zeilinger *et al.* additionally demonstrated teleportation for circular polarization.