Proc. Waseda Int. Sympo. on Fundamental Physics —New Perspectives in Quantum Physics—
J. Phys. Soc. Jpn. Vol. 72 (2003) Suppl. C pp. 168–173

Photon Statistics and Quantum Teleportation Experiments

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(Received January 31, 2003)

We present an overview of the method for generating entangled photon pairs via spontaneous parametric down conversion and the experimental method of detecting entangled states or Bell-states with the use of photon statistics, the two key systems required to realize quantum state teleportation and other related experiments. As a proof of the quantum nature of teleportation we performed an entanglement swapping experiment, where the teleported state itself was entangled. The experiment clearly showed that the entanglement survived the teleportation, as the quantum correlations of the teleported photon violated Bell's inequality.

KEYWORDS: quantum entanglement, Bell state, Bell state analyzer, quantum state teleportation, entanglement swapping, quantum repeater, spontaneous parametric down conversion, fiber optics, laser

1. Introduction

Quantum information processing is a new and exciting field which might completely change our ways of handling information. The very fascinating feature of quantum information is, that it emerged from basic and philosophical questions about the foundations of physics, dating back to the EPR-paradox[1)] and the development of Bell's theorem.[2)] Quantum information is an intriguing example where fundamental questions can lead to a new technology. The most important development in this field is the quantum computer, which promises to solve computational problems not achievable with existing classical computers. Another important area of quantum information processing is quantum communication because it offers new means of communication which have no resemblance in the classical world and could one day be a ubiquitous technology. Furthermore, quantum communication is at present the experimentally most advanced aspect of quantum information processing and first experiences using this technology can be performed. Quantum cryptography is already technically feasible and development of commercial systems is pursued at several institutions.

The basic concept of quantum information is to enhance the unit of information, the bit, into the so-called qubit, which also has the two distinct levels just like the classical bit (0 and 1), but here they are represented by two levels $|0\rangle$ and $|1\rangle$ of a two-level quantum system (e.g. spin, electronic states of atoms, etc.). The quantum system can also be in a *coherent superposition* of these two levels. This is a great advancement, since this superposition-principle is a specific feature of quantum-systems with no correspondence in the classical world. In general, the state $|Q\rangle$ of a qubit has the form

$$|Q\rangle = a|0\rangle + b|1\rangle, \tag{1}$$

where a and b are the complex coefficients of the two levels $|0\rangle$ and $|1\rangle$. In the photon experiments presented here the physical representations of the two states $|0\rangle$ and $|1\rangle$ are the polarization states of photons, i.e. $|0\rangle$ is represented by a horizontally polarized photon $|H\rangle$, and $|1\rangle$ is represented by a vertically polarized photon $|V\rangle$. Then the general qubit state $|Q\rangle$ is the general polarization state of a photon, i.e. the superposition of the two basis states $|H\rangle$ and $|V\rangle$.

Based on the EPR-paradox, some very interesting cases for systems of two (or more qubits) were discovered, this is when two or more qubits are entangled. Actually, entanglement is a superposition of joint states for several quantum systems. For the case of two qubits, there are four independent entangled states possible, the four Bell-states:

$$|\Psi^-\rangle = \frac{1}{\sqrt{2}}\Big[|H\rangle_1|V\rangle_2 - |V\rangle_1|H\rangle_2\Big], \tag{2}$$

$$|\Psi^+\rangle = \frac{1}{\sqrt{2}}\Big[|H\rangle_1|V\rangle_2 + |V\rangle_1|H\rangle_2\Big], \tag{3}$$

$$|\Phi^-\rangle = \frac{1}{\sqrt{2}}\Big[|H\rangle_1|H\rangle_2 - |V\rangle_1|V\rangle_2\Big], \tag{4}$$

$$|\Phi^+\rangle = \frac{1}{\sqrt{2}}\Big[|H\rangle_1|H\rangle_2 + |V\rangle_1|V\rangle_2\Big], \tag{5}$$

where the numbers 1 and 2 denote the two qubits respectively. These four Bell-states form a basis for the space of two qubits and are not separable into subparts for particles 1 and 2, and they show such strong non-classical correlations for the polarization measurements on the photons, that a violation of Bell's inequality will be observed. This violation leads to the conclusion that the quantum correlations cannot be described with a local-realistic model (also called local hidden variables model). In an experimental situation the correlations will never be ideal and many of the photon pairs will not be observed due to losses, which necessitates an adapted version of Bell's inequality. Most suitable is the version from Clauser, Horne, Shimony and Holt (CHSH),[3)] which has the form

$$S = |E(\alpha,\beta)+E(\alpha',\beta)|+|E(\alpha,\beta')-E(\alpha',\beta')| \leq 2, \tag{6}$$

where S is the Bell-parameter, $E(\alpha,\beta)$ are the correlation coefficients for the polarization measurement on particle 1 with an analyzer setting α and the polariza-

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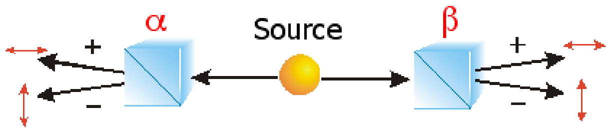

Fig. 1. Schematic arrangement of the correlation measurement for two entangled photons. The source emits the photons in different directions and sends them to polarization analyzers, oriented at α and β respectively. The photons are detected in either the + or − output of the polarizers.

tion measurement on particle 2 with the analyzer setting β, and α, α' are two different values. A schematic setup of a correlation measurement for two entangled photons is shown in Fig. 1. The correlation coefficient is defined as

$$E(\alpha, \beta) = \frac{C_{++} - C_{+-} - C_{-+} + C_{--}}{C_{++} + C_{+-} + C_{-+} + C_{--}}, \qquad (7)$$

where $C_{..}$ are the number of coincidences observed during a measurement run for a particular outcome of the polarization measurements (+1 or −1) for the two photons. For example, C_{++} are the counts of coincidences where each of the photons took the +1-outputs. It turns out, that the quantum mechanical predictions for $E(\alpha, \beta)$ for the Bell-states lead to a maximal value of $S = 2\sqrt{2}$, which clearly violates the limit imposed by local-realistic assumptions.

2. Producing Entangled Photon Pairs

At present, the best method for generating entangled photon pairs is via spontaneous parametric down-conversion (SPDC).[4–6] This is achieved in a nonlinear optical medium, such as a barium-borate crystal (BBO), where a coupling between optical modes with different directions and wavelengths can be achieved. The birefringence of the crystal governs the directions of these modes in respect to each other via the phase-matching condition. When this crystal is pumped with an ultraviolet laser beam, then under the right conditions there will be a coupling of the pump-mode with two other optical modes and spontaneous emission of photons pairs into these two modes will occur. This type of source replaced the earlier atomic-cascade sources,[7–9] since it offers much higher yields of photon pairs combined with a high quality of the entanglement. In order to directly produce polarization entangled photon pairs we use type-2 phase matching, where the polarizations of the two generated photons are different, i.e. one has *ordinary polarization* and the other has *extraordinary polarization* in respect to the optical axis of the crystal. The photons emerge from the crystal on cones with different polarization, which leads to entanglement in the intersection lines of the cones, as shown in Fig. 2. With this source it is possible to generate all Bell-states eqs. (2)–(5) by performing adequate local operations on one of the photons.

In a typical experimental setup, this source is realized with a BBO crystal of 4 mm thickness, pumped with the 351 nm line (UV) of an argon-ion laser at about 300 mW.

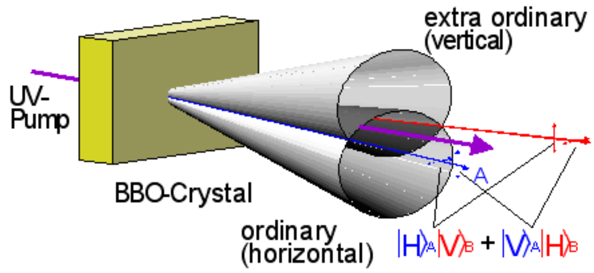

Fig. 2. Schematic view of the generation of polarization entangled photon pairs with type-II down-conversion. The nonlinear crystal (BBO) is pumped via a UV-laser beam and the photon pairs are generated spontaneously. Due to the specific phase matching condition the photons will always have different polarization and are emitted into different sets of cones depending on their wavelength. The photons found on the intersection lines of the cones with the same wavelength are entangled, since whenever one photon came from the H-cone then the other must have come from the V-cone and vice versa, but prior to a measurement it is undecided from which cone a particular photon originated.

The entangled photon pairs will then have a wavelength of 702 nm, and the observed rate of photon pairs can reach up to 300 KHz. The purity of the entangled state of the photon pairs is so good that the correlation visibility measured in the 45°-basis (where the interference of the $|H\rangle_1|V\rangle_2$ and $|V\rangle_1|H\rangle_2$ term is observed) is above 98%. A summary of different sources for entangled photons and also different types of entangled states was written up by Tittel and Weihs.[10] SPDC has been realized for different types of lasers and wavelengths, such as violet laser diodes running continuously at a wavelength of 405 nm and ultra-short laser pulses (200 fs) with a wavelength of 394 nm, all delivering similar photon counts and purity of entanglement. Unfortunately, it turns out from experimental evidence as well as theoretical calculations,[11,12] that the quality of the SPDC is affected when ultra-short pump pulses are used, because of the wide spectral bandwidth of the pulsed laser. But in the first order SPDC pumped with ultra-short laser pulses can be treated in the same way as SPDC pumped with a continuous laser.

SPDC is a clean and stable way to generate entangled photon pairs and conditional single photons [when one photon of the pair is detected as a trigger which tells the presence of the other one (and only one) photon]. Yet one major drawback of this source remains, that is the probabilistic nature of the photon emission, since SPDC is a purely spontaneous process. It is required that the pump power is low-enough to ensure that the probability of generating two photon pairs at the "same time" (depending on the type of experiment and laser this is either the coherence time of the photons, ≈ 500 fs, or the timing window of the detectors ≈ 1 ns) is well below unity. Typically in our experiments using SPDC, the probability of two-pair events within the given coincidence time window of about 1 ns is less than 10^{-2}. Ideally, for realizing quantum information schemes and also improving fundamental experiments, a real "photon on demand" emitter is desirable. There are large efforts undertaken to develop deterministic photon sources such as quantum dots,[13–16] NV-centers in diamond[17,18] or single ions/atoms in cavity QED,[19] just to name a few research programs in this field. Some of these have showed promising results, but a great deal of further development is still ahead.

A good example of the versatility of our source was the experimental demonstration of quantum cryptography system based on the entanglement[20] of two photons sent to different users, Alice and Bob. By observing the photons, Alice and Bob can generate identical random sequences of $+1$ and -1 which they may use as cryptographic keys. The security of the keys can be ascertained via estimating the bit errors in the keys, since any manipulation or eavesdropping of the photons on their way would reduce the quality of the entanglement hence inducing errors in the keys. In our experiment, Alice and Bob were able to securely transmit an image over a distance of 350 m.

3. Bell-State Analysis

An important question in many quantum information and fundamental experiments is how to detect the Bell-states. The first approach is to observe the correlations between the two particles, in our case photons, as described above and perform measurements with several settings of the polarizers, e.g. $\alpha = \beta = 0°, 45°$; $\alpha \neq \beta$; and conclude the state via statistical analysis of the observed data. Alternatively, entanglement can also be identified via a test of Bell's inequality.

The correlation measurements will surely allow to determine the state, but only by averaging over an ensemble of many equally prepared pairs of photons, and necessarily for a single photon pair only very little information is accessible. The tool to do this is a Bell-state analyzer (BSA). This is a measuring device with two inputs for two photons and four outputs, each of them corresponding to a different one of the four Bell-states. When two entangled photons enter the BSA, it will perform some operations with the photons, detect these and give a signal on the output corresponding to the entangled input state of the photons. On paper, the BSA can be designed very easily with some quantum logic by using a combination of a c-not operation and an Hadamard operation. To illustrate this we consider two input qubits, where we let qubit 1 be the control and qubit 2 be the target qubit of the c-not operation. Then an entangled input state will be transformed in the following way

$$\frac{1}{\sqrt{2}}\Big[|0\rangle_1|1\rangle_2 - |1\rangle_1|0\rangle_2\Big] \rightarrow \frac{1}{\sqrt{2}}\Big[|0\rangle_1|1\rangle_2 - |1\rangle_1|1\rangle_2\Big], \quad (8)$$

where the state $|1\rangle_1$ induced a flip of qubit 2. Next, we compress the expression, and then we apply a Hadamard operation to qubit 1

$$\frac{1}{\sqrt{2}}\Big(|0\rangle_1 - |1\rangle_1|\Big)|1\rangle_2 \rightarrow |1\rangle_1|1\rangle_2, \quad (9)$$

which clearly leaves both qubits well defined in state $|1\rangle$ (which corresponds to a $|\Psi^-\rangle$ input state). Note that this small quantum logic circuit would also work in reverse, i.e. the BSA would actually entangle two formerly separate qubits.

As it happens, such a BSA cannot be built with linear optical elements only, it also requires the use of a nonlinear photon-photon interaction. This interaction is naturally very weak, and many ideas have been researched, such as cavity-QED,[21,22] Kerr-nonlinearity[23] or atomic ensembles.[24,25] At present, the candidate systems are technically too demanding or not even realized, as that they could be implemented in a practical BSA system. Incidentally, the research into the design of a full BSA is equivalent to the research for the quantum c-not gate, since once we have a c-not, we can directly implement the BSA.

4. Using Photon Statistics as the Bell-State Analysis

A relatively simple and good way to perform BSA with photons uses only linear optical elements, which can in principle only achieve an efficiency of 50%.[26,27] The concept is to use the statistics of two photons interfering on a 50:50 beam splitter which allows to identify two of the four Bell-states (Fig. 3). The entanglement of the two interfering photons influences the probabilities in which of the two output modes the two photons can be found and detected, and hence allows to detect one of the Bell-states. The $|\Psi^-\rangle$ is asymmetric, which makes it different from the other three Bell-states. This asymmetry leads to a kind of "anti-bunching" of the two photons in the outputs of the beam splitter in that the photons will always take different outputs of the beam splitter. This behavior is shown for entangled photons generated with SPDC by a measurement of the coincidences of the two detectors in the outputs of the beam splitter [Fig. 4(up)]. The delay between the two photons is varied in order to achieve optimal interference and the increasing in the coincidence rate shows this "anti-bunching" effect. In

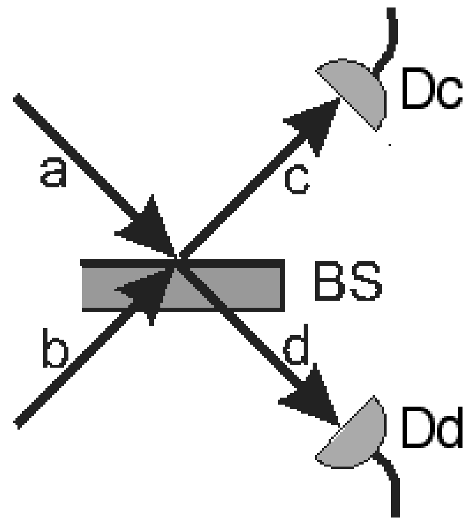

Fig. 3. The scheme for Bell-state analysis with photon statistics. The two photons enter the beam splitter BS in two different modes a and b, and each has a 50% chance of being reflected or transmitted. The interference of the two photons will changes the detection probabilities of detectors Dc and Dd depending on the initial state of the two photons. Only if they are entangled in the $|\Psi^-\rangle$ then they will take separate outputs of the beam splitter.

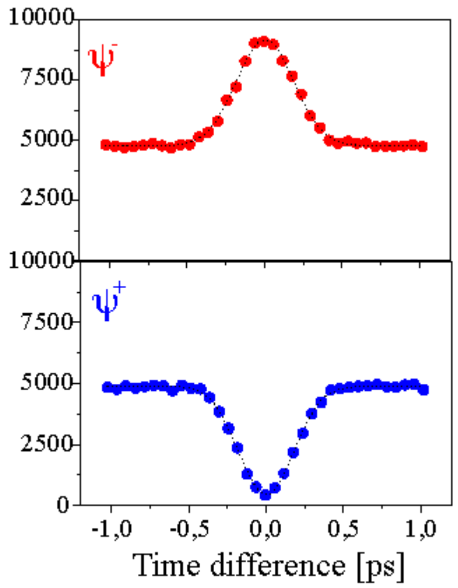

Fig. 4. Measurement of interference of two photons on a 50:50 beam splitter. Shown is the coincidence rate between the two detectors in the outputs of the beam splitter, in dependence of the temporal delay between the two photons (Measurements performed by Markus Operparleiter[28]). (up) "anti-bunching" of the two output photons, when they are prepared in the $|\Psi^-\rangle$ state, and always take different outputs. (down) "bunching" of the two photons occurs when the photons are prepared in a $|\Psi^+\rangle$ state as they will always take the same output.

the case of an optimal temporal overlapping of the two photons, they will become completely indistinguishable, and they will always take different outputs of the beam splitter. On the other hand, if one of the three other Bell-states (symmetric) is present, the two photons will always take the same output and the coincidence rate between the two detectors will drop to zero for optimal temporal overlap of the photons. The measurement in Fig. 4(down) shows this feature for the coincidence rate when the two photons are in a $|\Psi^+\rangle$ entanglement when entering the beam splitter. Note that it is not directly possible to distinguish the three symmetric Bell-states. It is possible though, to tell the $|\Psi^+\rangle$ from $|\Phi^\pm\rangle$ with the help of additional polarizing beam splitters placed in the two output modes, since the photons will take the same output, but still have opposite polarization in the H-V basis. So in total, with linear optical elements, it is possible to detect two Bell-states perfectly ($|\Psi^-\rangle$ and $|\Psi^+\rangle$), and two Bell-states only together ($|\Phi^-\rangle$ and $|\Phi^+\rangle$). This Bell-state analyzer was used in the quantum dense coding experiment,[29] where local operations on only one photon (qubit) of an entangled pair allow to encode more than 1 bit of information.

5. Realization of Quantum State Teleportation

Quantum state teleportation[30] is a quantum communication scheme with relevance to many quantum information schemes, such as quantum computation with linear elements,[31] quantum repeaters,[32] networking of quantum computers and quantum networks in general.[33] Quantum state teleportation allows the transfer of a quantum state from one system to another, without gaining any information on the state whatsoever. Entanglement swapping is a special case of quantum state teleportation, where the transferred state is not even unknown, but actually undefined, since it is part of an entangled pair. However, if the procedure works as predicted by quantum mechanics, then the entanglement will survive this procedure. We recently performed an experimental demonstration of entanglement swapping[34] where we were able to observe that after teleportation the entanglement still violated a Bell-inequality. The experiment was based on entangled photon pairs generated by SPDC and a Bell-state analyzer based on the photon statistics at a 50:50 beam splitter, as described above.

The principles of teleportation are straightforward. The key systems required are quantum channel (entangled pair), a classical channel and a Bell-state analyzer. As we will do entanglement swapping where the input photon is also an entangled photon, our system initially contains two entangled pairs of photons (0–1 and 2–3). Hence the full state of the photons has the form

$$|\Psi_{\text{total}}\rangle = |\Psi^-\rangle_{01}|\Psi^-\rangle_{23}. \tag{10}$$

By expressing $|\Psi^-\rangle$ in its polarization states and rearranging the resulting terms by expressing photon 1 and photon 2 in the basis of Bell states leads to:

$$\begin{aligned}|\Psi_{\text{total}}\rangle = \frac{1}{2}[&|\Psi^+\rangle_{03}|\Psi^+\rangle_{12} - |\Psi^-\rangle_{03}|\Psi^-\rangle_{12} \\ &- |\Phi^+\rangle_{03}|\Phi^+\rangle_{12} + |\Phi^-\rangle_{03}|\Phi^-\rangle_{12}].\end{aligned} \tag{11}$$

When Alice subjects photons 1 and 2 to the measurement in her BSA she could find them e.g. in the state $|\Psi^-\rangle_{12}$, then photons 0 and 3 measured by Bob will be in the entangled state $|\Psi^-\rangle_{03}$. (If Alice observes any of the other Bell-states for photons 1 and 2 with a suitable BSA, photons 0 and 3 will also be perfectly entangled in the corresponding Bell-states.) We stress that photons 0 and 3 will be perfectly entangled for each result of the Bell-state analyzer, and therefore it is not necessary to apply a unitary operation to the teleported photon 3 as in the standard teleportation protocol. But it is certainly necessary for Alice to communicate to Bob her Bell-state measurement result. This will enable Bob to sort the data into subsets, each representing the results for one of the four maximally entangled Bell-states.

Our experimental setup is shown in Fig. 5. It is based on photon pairs generated via SPDC with ultra-short fs-laser pulses, so that the relative timing of the interfering photons 1 and 2, which are independent, is fixed to a time shorter than their coherence time ($\approx$ 500 fs).[35] The laser system is a frequency doubled Ti:SA (pumped by a 10 W green solid state laser) which produces laser pulses with about 200 fs pulse width at a wavelength of 394 nm. The Bell-state analyzer is realized with a 50:50 fiber beam splitter, which ensures perfect mode overlap of the photon wave packets for photons 1 and 2, except for the polarization. The relative delay between the two photons is adjusted via movement of a motorized mirror for the UV-laser pulses. The two "outer photons" 0 and 3 are separately analyzed with polarization analyzers

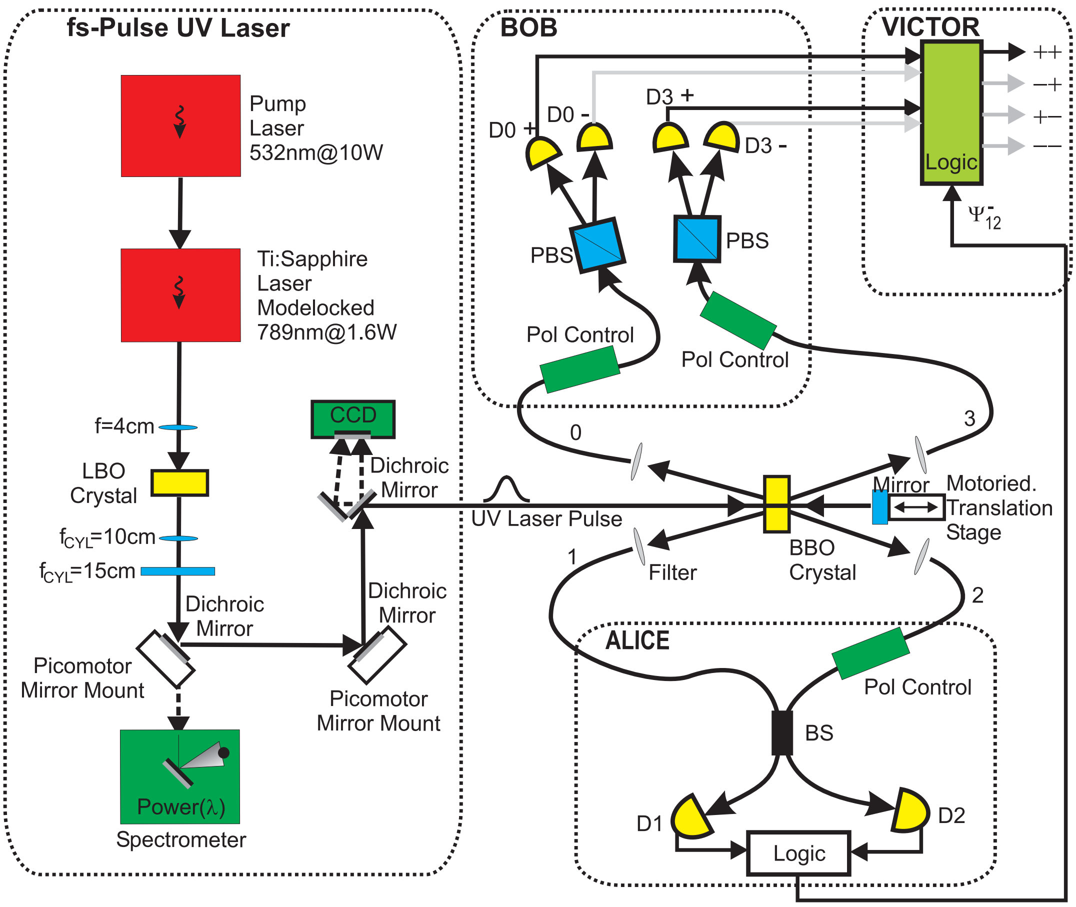

Fig. 5. Experimental setup of entanglement swapping.

which give a $+1$ or -1 result for the specifically aligned basis (α, β), set at e.g. $0°$, $45°$. All photons are detected with Si-avalanche photo diodes (Si-APD), which have a detection efficiency of about 40%. The detection pulses are sent to a special discrimination logic which identifies those cases where four photons where detected, i.e. two in the separate outputs of the BSA and one in each of the polarizers. The final rate of obtaining a 4-photon event from a successful teleportation was 1 in 100 seconds.

The different outputs of the polarization measurements lead to four different combinations which are separately counted, e.g. $+1$ in mode 0 and -1 in mode 3 adds to the count C_{+-}, and from the four possible counts the correlation coefficients $E(\alpha, \beta)$, from eq. (7), are determined. In order to violate the CHSH-inequality (6), the settings of the two polarizers must be $(\alpha, \alpha') = (0°, 45°)$ and $(\beta, \beta') = (22.5°, 67.5°)$. The measured values of these coefficients are $E(0°, 22.5°) = 0.628 \pm 0.046$, $E(0°, 67.5°) = 0.677 \pm 0.042$, $E(45°, 22.5°) = 0.541 \pm 0.045$ and $E(45°, 67.5°) = 0.575 \pm 0.047$, where the given uncertainties are the statistical errors. These measurements add up to $S = 2.421 \pm 0.091$, which clearly violates the local-realistic limit of $S = 2$ by more than four standard deviations.

6. Conclusion

We have revisited the tools necessary for realization of experimental quantum teleportation or entanglement swapping with polarized photons, which requires entangled photons and their Bell-state analysis. The best method of generating entangled photons is via spontaneous parametric down conversion which delivers photons at a high rate and with experimental correlation visibilities reaching more than 98%. The main drawback of this method is that the photon emission is probabilistic, which may be solved in the future with photon-on-demand sources. The Bell-state analysis for polarized photons is best performed via interference of two photons on a 50:50 beam splitter, which allows to identify the $|\Psi^-\rangle$ Bell-state directly with high quality. It is proven that this linear optical system can only work with a maximal efficiency of 50%. The full Bell-state analysis will require some kind of single-photon non-linear interaction, which is currently not available. Combining these systems we were able to realize a high-visibility entanglement swapping experiment, which showed via violation of a Bell-inequality, that photon entanglement remains even after teleportation of one of the photons.

One future enhancement of teleportation schemes will be to include the more-complete Bell-state analysis, which also allows the detection of a second Bell-state, the $|\Psi^+\rangle$. This will make it necessary, that based on Alice's outcome of the BSA, Bob will have to perform a local operation on his photon in order to obtain the correct output state. This local operation will be realized with an actively switched Pockels cell, implemented in an experiment where a distance of about 600 m is covered by the teleportation, which will make compensation of the additional timing delay of the active switching device (several 100 ns) possible.

This work was supported by the Austrian national science fund (SFB1506) and the project "QuComm" (IST-FET) of the European Commission.

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