SK2300 Quantum Entanglement lab

To prepare for this lab, read pages 1-8 of the attached manual.

Lab tasks:1.

- First, we test out experimental setup. Remove the half-wave plate in front of the pump. Next find the polarizers' setting that minimizes the coincidence counts between the detectors. Can you identify the polarization of the input laser?
- Measure the visibility of the output photons $V=(C_\parallel - C_\perp)/((C_\parallel + C_\perp))$ in the HV basis. Measure the visibility in the Diagonal (D) 45 degrees and Anti-diagonal (A) -45 degrees basis.
- Fix one polarizer to be in the H state, then rotate the second polarizer in steps of 5 degrees. Record the single detector counts and coincidence counts. How do they behave as a function of angle?
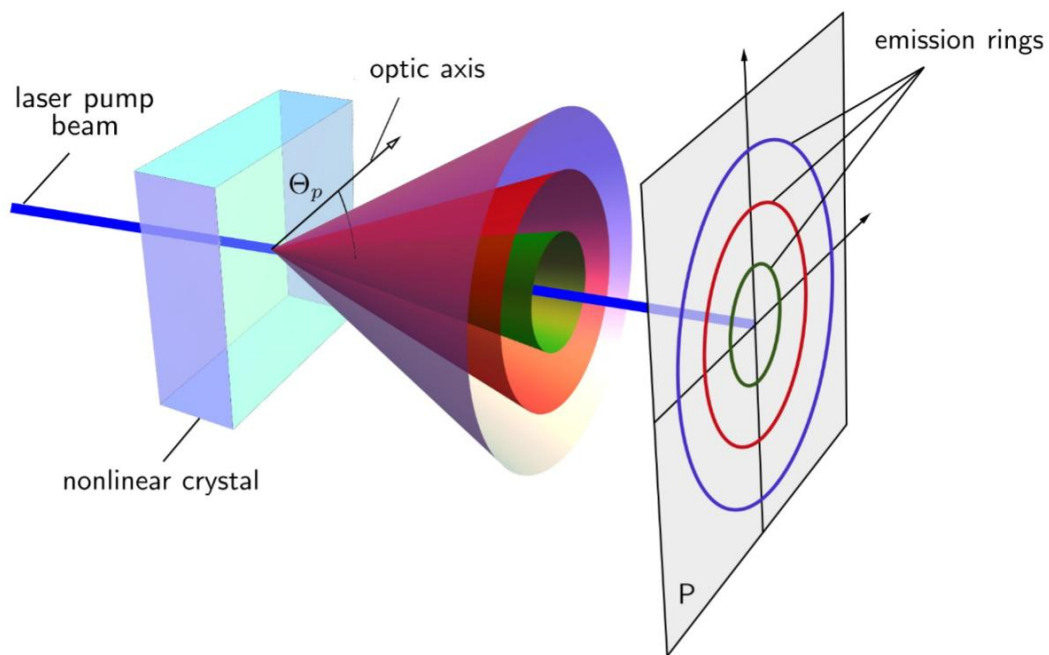
Lab tasks:2

- Insert the half-wave in front of the pump.

- Measure the visibility of the output photons $V=(C_\parallel - C_\perp)/((C_\parallel + C_\perp))$ in the HV basis. Measure the visibility in the Diagonal (D) 45 degrees and Anti-diagonal (A) -45 degrees basis
- Fix one polarizer to be in the H state, then rotate the second polarizer in steps of 5 degrees. Record the single detector counts and coincidence counts. How do they behave as a function of angle? Explain and contrast the result with lab task 1. Would it be possible to obtain such correlations with a source of unpolarized photon pairs, in combination with a set of polarizers and beam splitters?

Lab tasks:3

- The input half wave plate setting can change the output bell state between ϕ^+ and ϕ^-. Note that these states can be expressed in the HV or AD basis as follows.

$$\varphi^+ = \frac{1}{\sqrt{2}}[|HH\rangle + |VV\rangle] = \frac{1}{\sqrt{2}}[|DD\rangle + |AA\rangle]$$

$$\varphi^- = \frac{1}{\sqrt{2}}[|HH\rangle - |VV\rangle] = \frac{1}{\sqrt{2}}[|DA\rangle + |AD\rangle]$$

Record all of the following coincidences in the HV basis

- HH
- HV
- VH
- VV

Record all of the following coincidences in the DA basis

- DD
- DA
- AD
- AA

Rotate the half wave plate in front of the pump by 180 degrees, and repeat the measurements above. Can you identify the created bell state at each setting half wave plate setting?
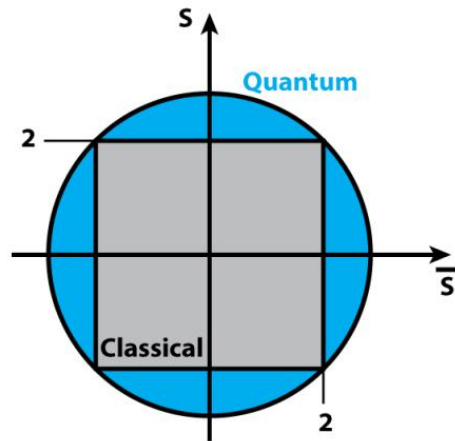
Lab task:4

Select the setting of the half-wave plate that produces the state ϕ^+. In the controller press the middle button until you end up at the CHSH-menu where you can do 16 different measurements. Record coincidences for the 16 different polarizer combinations, by tapping the panel after setting the polarizers. If you cannot reach a value with the polarizer, add or subtract 180degrees, this will do the same. – and + correspond to (A) -45 degrees and (D)+45 degrees. The controlled will automatically calculate the inequality for you, additionally the sheet below gives you more information and how it is calculated.
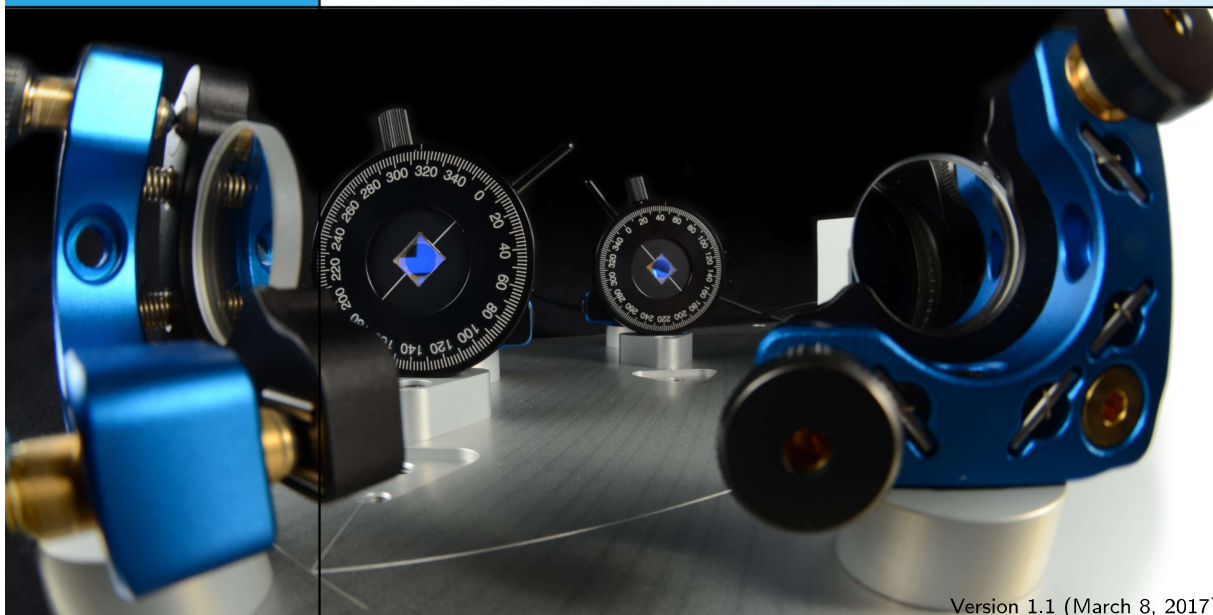
quED Work Sheet – Bell's Inequality

1. Set the source to produce the entangled state $|\phi_+\rangle$. Set the polarizers to the 16 different angle settings below and record the coincidence count rates for each setting. Calculate the expectation values E and the two S values. Mark the corresponding spot in the graph.

$$\frac{\begin{array}{c}\boxed{0° \atop 22.5°}\end{array} - \begin{array}{c}\boxed{0° \atop 112.5°}\end{array} - \begin{array}{c}\boxed{90° \atop 22.5°}\end{array} + \begin{array}{c}\boxed{90° \atop 112.5°}\end{array}}{\begin{array}{c}\boxed{0° \atop 22.5°}\end{array} + \begin{array}{c}\boxed{0° \atop 112.5°}\end{array} + \begin{array}{c}\boxed{90° \atop 22.5°}\end{array} + \begin{array}{c}\boxed{90° \atop 112.5°}\end{array}}$$

E(0°,22.5°) = ☐   E(0°,22.5°) = ☐

+   -

$$\frac{\begin{array}{c}\boxed{45° \atop 22.5°}\end{array} - \begin{array}{c}\boxed{45° \atop 112.5°}\end{array} - \begin{array}{c}\boxed{135° \atop 22.5°}\end{array} + \begin{array}{c}\boxed{135° \atop 112.5°}\end{array}}{\begin{array}{c}\boxed{45° \atop 22.5°}\end{array} + \begin{array}{c}\boxed{45° \atop 112.5°}\end{array} + \begin{array}{c}\boxed{135° \atop 22.5°}\end{array} + \begin{array}{c}\boxed{135° \atop 112.5°}\end{array}}$$

E(45°,22.5°) = ☐   E(45°,22.5°) = ☐

-    -

$$\frac{\begin{array}{c}\boxed{0° \atop 67.5°}\end{array} - \begin{array}{c}\boxed{0° \atop 157.5°}\end{array} - \begin{array}{c}\boxed{90° \atop 67.5°}\end{array} + \begin{array}{c}\boxed{90° \atop 157.5°}\end{array}}{\begin{array}{c}\boxed{0° \atop 67.5°}\end{array} + \begin{array}{c}\boxed{0° \atop 157.5°}\end{array} + \begin{array}{c}\boxed{90° \atop 67.5°}\end{array} + \begin{array}{c}\boxed{90° \atop 157.5°}\end{array}}$$

E(0°,67.5°) = ☐   E(0°,67.5°) = ☐

+   -

$$\frac{\begin{array}{c}\boxed{45° \atop 67.5°}\end{array} - \begin{array}{c}\boxed{45° \atop 157.5°}\end{array} - \begin{array}{c}\boxed{135° \atop 67.5°}\end{array} + \begin{array}{c}\boxed{135° \atop 157.5°}\end{array}}{\begin{array}{c}\boxed{45° \atop 67.5°}\end{array} + \begin{array}{c}\boxed{45° \atop 157.5°}\end{array} + \begin{array}{c}\boxed{135° \atop 67.5°}\end{array} + \begin{array}{c}\boxed{135° \atop 157.5°}\end{array}}$$

E(45°,67.5°) = ☐   E(45°,67.5°) = ☐

=   =

S ☐ $\overline{S}$ ☐

www.qutools.com
info@qutools.com

quED

Entanglement Demonstrator

Version 1.1 (March 8, 2017)

Contents

1 Introduction and General System Description

The quED is a complete system for the generation and analysis of polarization-entangled photon pairs. In its basic version the quED delivers the coincidence counting rate of above 1 kHz with at least 90% visibility of correlation curves in two complementary bases. These parameters guarantee that the genuine two-particle entanglement can be detected and demonstrated, e.g. via measurement of Bell inequalities, within few minutes after the start of the system.

The heart of the quED employs a spontaneous parametric down-conversion process to generate polarization-entangled photon pairs. Fiber coupled single photon detectors in connection with polarizing filters are used to detect the photon pairs, analyze their polarization and verify their non-classical polarization correlations. The quED control unit features a laser diode driver and a multi-channel counter with integrated coincidence logic electronics, which registers single photon detections and photon pair detections. The corresponding counting rates are displayed on an integrated display or can be read out via a network (http) interface.

This document contains user information for the optical unit of quED, i.e. the source of polarization entangled photon pairs. Please read the manual carefully before operating the source. Particular attention should be paid to the section of laser safety. For the details on description and operation of quED control unit users are referred to the document "Down-conversion Controller Manual".
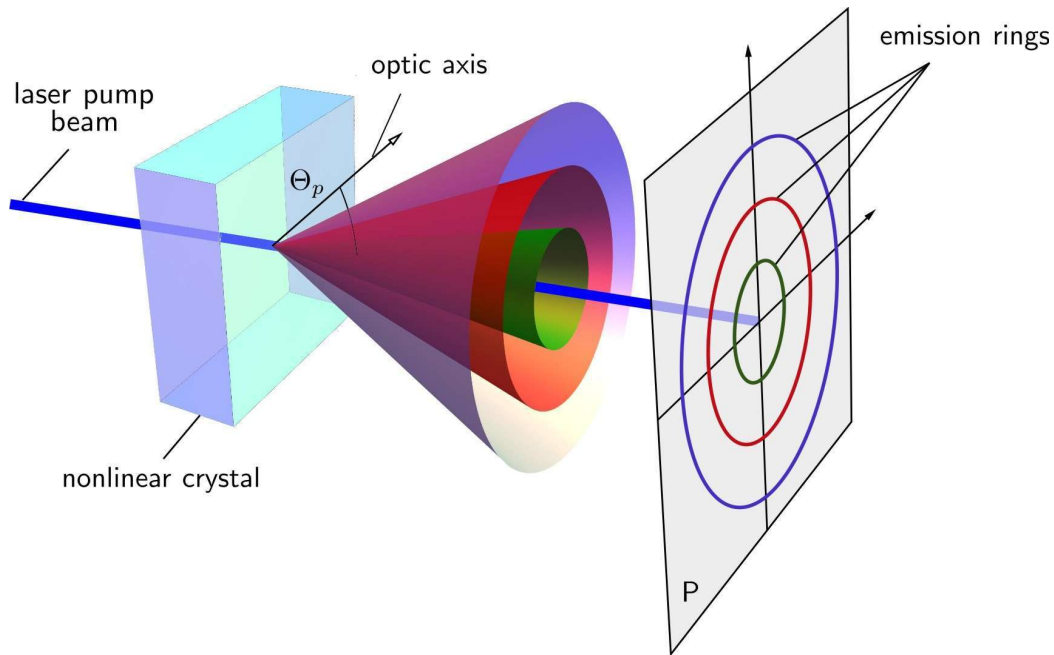
Figure 1: Spatial distribution of the down-conversion emission for type I phase matching. The transverse momentum conservation requires that down-conversion photons have to emerge from the crystal along the directions lying always on exactly opposite sides of the cone.

1.1 Basic Principles of Operation

To generate entangled photon pairs, a second-order nonlinear process, usually referred to as spontaneous parametric down-conversion (SPDC), is used in the quED. In the SPDC process photons of an intense laser pump beam spontaneously convert in a nonlinear crystal with a very low probability ($\approx 10^{-11}$ for standard materials) into pairs of lower-frequency photons. Due to energy and momentum conservation in the nonlinear interaction the possible wavelengths and emission directions of the generated photons are severely constrained. Consequently, the emission pattern is formed by cones, which imprint the characteristic rings in the plane (P) perpendicular to the pump-beam direction. In type I phase matching the cones are concentric around the pump direction, as illustrated in Fig. 1. Every cone corresponds to a distinct emitted wavelength. The opening angles of the emission cones thus depend on the wavelengths of the emitted photons, but also on the angle Θ_p between the pump direction and the optical axis; (the smaller the angle Θ_p, the smaller the opening of the cone with a given wavelength). This allows to angle tune the spatial emission of down-conversion photons as required.

To obtain polarization entanglement from SPDC, the quED utilizes a well-known method of coherent spatial overlap of the emissions from two adjacent type-I crystals. Consider two non-linear crystals, both operated in type-I phase-matching configuration and pumped with linearly polarized light.The otherwise identical crystals are oriented such that their optical axes lie in mutually perpendicular planes. For example, let the optical axis of the first crystal be aligned in the vertical plane and the axis of the second crystal in the horizontal plane. Due to the type-

I coupling, the down-conversion process occurs only in the crystal, where the pump photon is extraordinary polarized, emitting two ordinary polarized down-conversion photons into the characteristic cone. That is, with the vertically-polarized pump the down-conversion process occurs only in the first crystal emitting pairs of horizontally polarized photons, whereas with the horizontally-polarized pump it occurs only in the second crystal producing two vertically-polarized photons. By pumping the crystals with light, linearly polarized at 45° with regard to horizontal and vertical direction, there is an equal probability that a pump photon will be down-converted in either crystal. Provided that the two emission processes are coherent with one another, which is fulfilled as long as there is no way of ascertaining whether a photon pair was produced in the first or the second crystal, the following entangled state is automatically generated:

$$|\Phi\rangle = \frac{1}{\sqrt{2}}\big[|H\rangle_1|H\rangle_2 + e^{i\phi}|V\rangle_1|V\rangle_2\big].$$

The symbols $|H\rangle$ and $|V\rangle$ represent the horizontal and vertical polarization state of photons and the labels "1" and "2" correspond to the two spatial modes, which are in practice selected by e.g. pinholes or fibers. The relative phase ϕ is determined by the details of the phase matching and thickness of the crystals, but can be controlled by adjusting the relative phase between the horizontal and vertical components of the pump light.

The distinguishing information, which might possibly label the emission processes and thereby reduce their mutual coherence, can be either of temporal or spatial character. The latter case occurs whenever the emission modes from the two crystals are spatially distinguishable. To avoid this situation, the nonlinear crystals have to be thin enough and the down-conversion photons have to be collected into spatially single-mode channels, such as a pair of single-mode fibers. The use of thin crystals ensures that the emission cones from the two crystals overlap to a great extent. Moreover, the single-mode nature of the collection modes removes practically all the spatial information the photons may have carried before entering the fiber. Consequently, there is even in principle no way how to spatially distinguish whether the down-conversion photons are coming from the first or the second crystal and therefore pure polarization-entangled photon pairs can be detected.

In the time domain, the crystal birefringence in combination with dispersion lead to an unwanted effect as well. The arrival times of photons at the output face of the second crystal depend on their wavelengths and polarizations, which reveal the actual position of the photon-pair's origin. This leads to a partial loss of coherence between the two emission processes, and thus to the reduced entanglement quality. The detrimental temporal effect is two-fold, which is illustrated in a simplified fashion in Fig. 2. First, it is primarily the group-velocity mismatch between the pump and the down-conversion light, which causes the photon pairs born in the first crystal to be advanced with regard to those originating from the second crystal. This is usually precluded using a continuous-wave pump laser. Since a (spectrally broadband) free-running blue laser diode is used as the pump in the quED, a special birefringent crystal has to be included in the path of the pump beam. It introduces a proper temporal retardation between its horizontally and vertically polarized components and thus effectively pre-compensates the effect. Second, the dispersive delay of the down-conversion
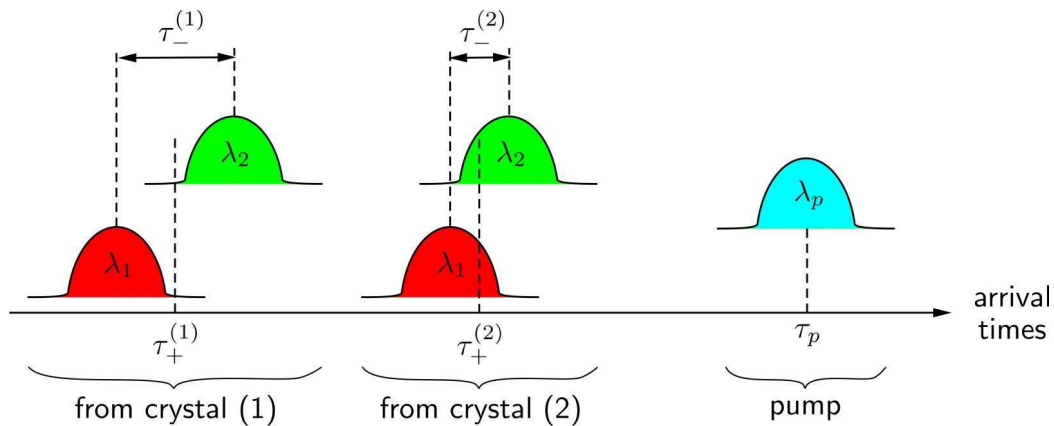
Figure 2: Explanation of the detrimental time effect inherent to SPDC emission in a two-crystal configuration. Due to crystal birefringence and dispersion, the arrival times of non-degenerate photons ($\lambda_1 \neq \lambda_2$) at the output face of the second crystal (2) differ in general for the two emission possibilities. The photon pairs from the first crystal (1) are advanced with regard to photon pairs from the second ($\tau_+^{(1)} < \tau_+^{(2)}$). Moreover, the photons originating from the first crystal experience higher dispersive delay due to their pass through the second crystal ($\tau_-^{(1)} > \tau_-^{(2)}$). Consequently, a compensation using two additional birefringent crystals erasing their temporal distinguishability has to be applied.

photons at non-degenerate wavelengths is different for the two emission possibilities, because the photons generated in the first crystal acquire an extra spread by propagating through the second crystal; (since the type I SPDC emission is spectrally very broadband, the detection of photons with very non-degenerate wavelengths is indeed possible in the quED). Therefore, an additional birefringent crystal has to be put behind the down-conversion crystals to counteract this second effect, too. The described double-crystal compensation technique ensures a complete temporal indistinguishability of the emission processes even though a free-running laser diode as a pump source is used and no spectral filtering of generated photons is applied in the quED.

1.2   Description

Referring to Fig. 3, there is shown the source for the generation of polarization-entangled photon pairs. For convenience, the whole optical set-up mounted on an aluminum breadboard can be divided into two basic blocks: the pump-beam block and the down-conversion block.

All the components of the pump assembly are installed on a rectangular pedestal. This block comprises a laser diode head, two mirrors, beam-shaping optics, two half-wave retarder, a pre-compensation birefringent crystal, and nonlinear down-conversion crystals. The blue laser diode is built in the laser diode mount. The mount features a protective circuit to maximally eliminate laser diode failures due to electrostatic discharge and a thermoelectric module to precisely regulate the operating temperature of the diode. The strongly divergent light from the laser diode is focused using a telescope consisting of a collimating aspheric lens and a
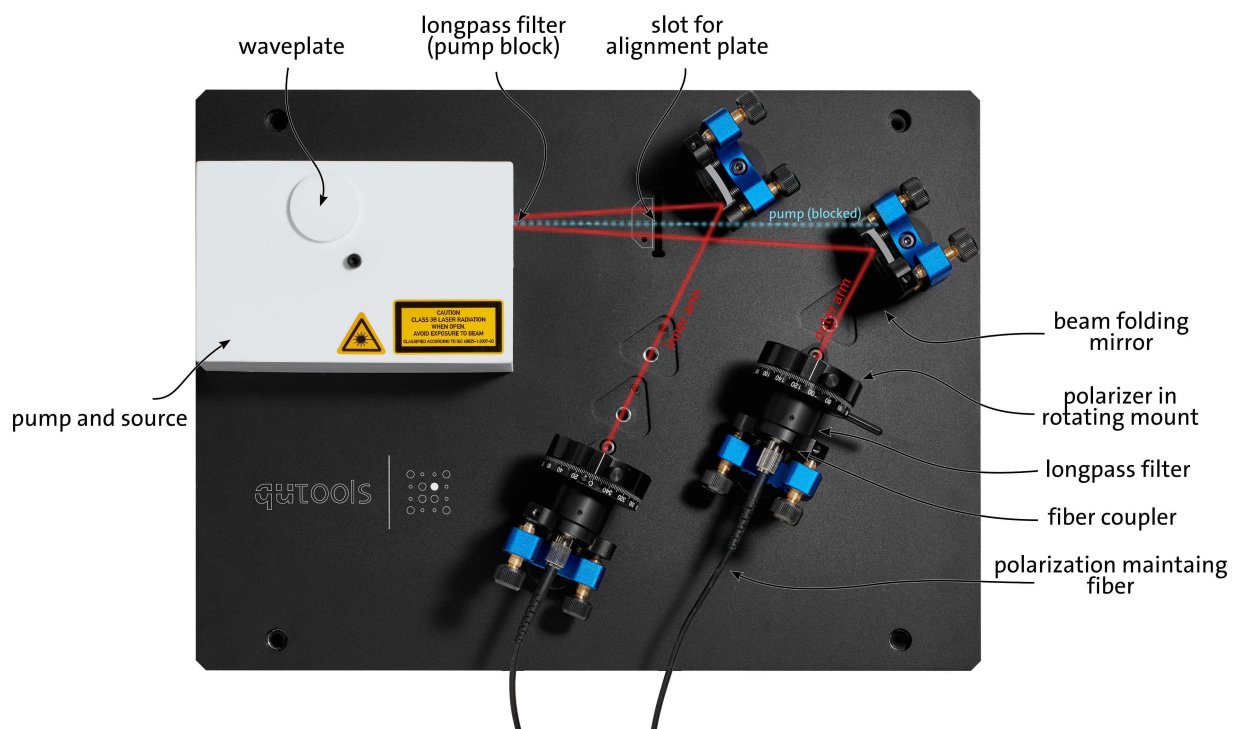
Figure 3: Architecture of the quED optical setup for the generation and collection of polarization-entangled photon pairs. The pump laser and the actual crystal source is hidden under the white cover for laser safety reasons. More details are displayed in figure 4.
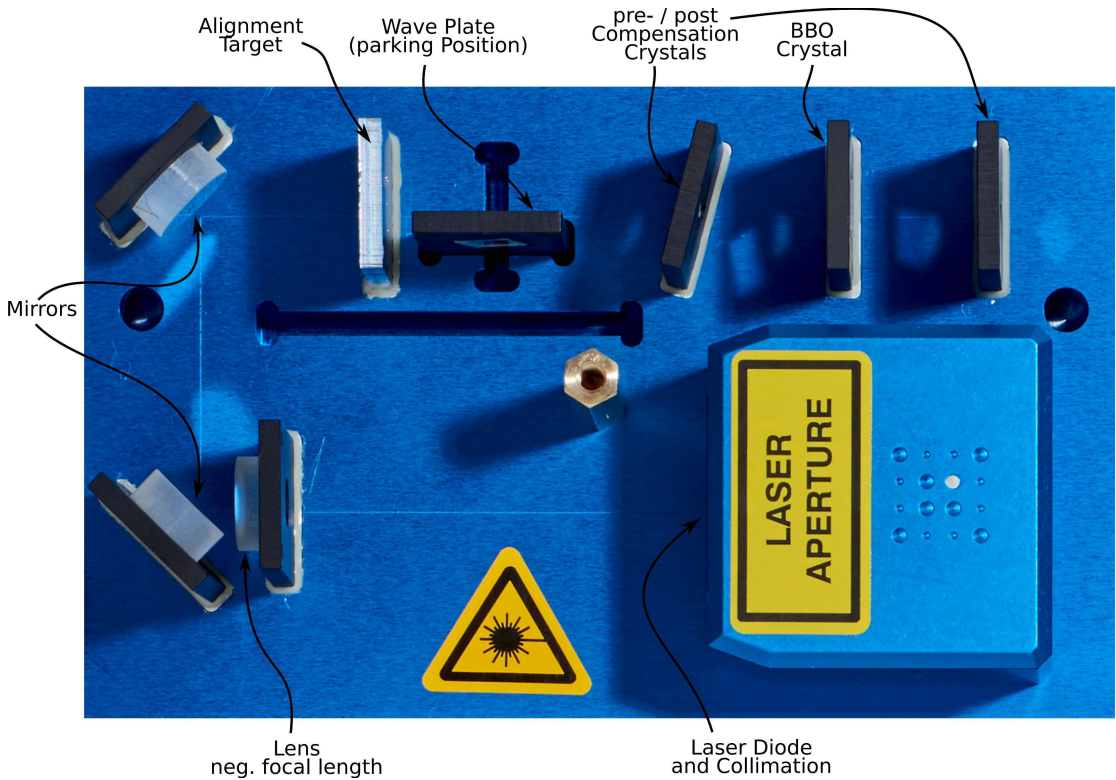
Figure 4: Inner details of the pump assembly with the nonlinear crystal.

negative spherical lens. The angle of linearly polarized laser light emitted from the laser diode is adjusted with the half-wave plate. This have-wave plate can be inserted rotated by 180 ° to manipulate the down-converted state. In the default position the pump laser enters through the circular aperture on the back. The nonlinear down-conversion crystals are mounted at the focus of the laser beam.

Additionally, a pinhole with two adjacent crosses is mounted in the pump beam path. This enables the realignment from scratch in case the couplers completely lost signal (see section. 7).

All the components of the down-conversion block are positioned along the two down-conversion emission directions and form two arms. Either arm comprises a mirror, a rotatable polarizing filter optionally motorized, a long-pass filter, an adjustable optical coupler and a polarization maintaining (PM) single-mode fiber (12). Long-pass filters are inserted into the paths of down-conversion photons to block the residual laser-diode light and stray light. To verify the entanglement of down-conversion photons a pair of polarization filters is used. Both the mirror and the coupler are held in kinematic mounts allowing the fine angular alignment of the coupling mode, which is defined by the single-mode fiber. The full control over the orientation and the divergence of the coupling mode is imperative to achieve high coupling efficiencies of down-conversion photons into single-mode fibers. In either arm the iris diaphragm (8) with adjustable opening is positioned between the mirror and the polarization filter. For additional information on the alignment procedure we refer to sections 3.4.2 and 3.4.3. The fiber-coupled down-conversion photons are detected using passively quenched silicon avalanche photo diodes hidden in the quCR electronic control unit. The corresponding single detection rates in both arms and the coincidence count rate are displayed on the counter panel of this unit.

To prevent the escape of laser radiation and to prevent personnel access to the laser beam during normal operations, the pump assembly is housed in a protective enclosure. The enclosure can be removed when the operator needs to perform maintenance or adjustment tasks. This is required for example during full alignment procedure described in section 3.4.3. The front output aperture of the protective enclosure contains the a long-pass filter which acts as a beam block for the pump laser. Please verify periodically that this filter is in place and intact. Otherwise, high power laser radiation can escape the housing and potentially cause harm or damage.

2 Unpacking and Installation

2.1 Contents of Boxes

When you have received the product, please make sure that the following parts are included:

- Box 1: Optics part
    - Aluminum breadboard with source, mirrors, couplers and polarizers in rotating mount.

- 2 polarization maintaining fibers attached to the couplers. These fibers should never be unplugged.

- 2 long pass filter caps in front of the couplers.

- alignment plate (only to be installed during a full alignment procedure (see figure 8 and section 3.4.3).

- Optical fiber checker

- Cable with with SUB-D9 connectors (to connect down-conversion source with control unit)

2.2　Installation

> ⚠ Before installing the system, make sure that you are familiar with and have obeyed all necessary laser safety precautions. Please refer to paragraph 3.1 for this purpose. Handle the source and all its components very gently. Especially, do not tilt the breadboard too far and be very careful with electrostatic discharges in the immediate vicinity of the laser diode. For additional warnings please see the relevant section (3.2) of the manual.

Please follow these steps:

1. Optionally: Remove the source from the plastics box. It is fastened to the box with four screws in the corners of the aluminum breadboard. Remove the screws from the top. Gently put the breadboard with the source on a stable table. In case you decide to operate the source in the box, make sure to avoid any damage to the fibers when closing the lid.

2. Place the control unit next to the breadboard and connect it to a power socket.

3. Connect the quED with the control unit using the SUB-D9 connector cable.

4. After removing the protective caps, plug and fasten the FC/PC connectors of the single mode fibers into the optical inputs of the control unit (see also fig. 5).

3　Operation

3.1　Laser Safety

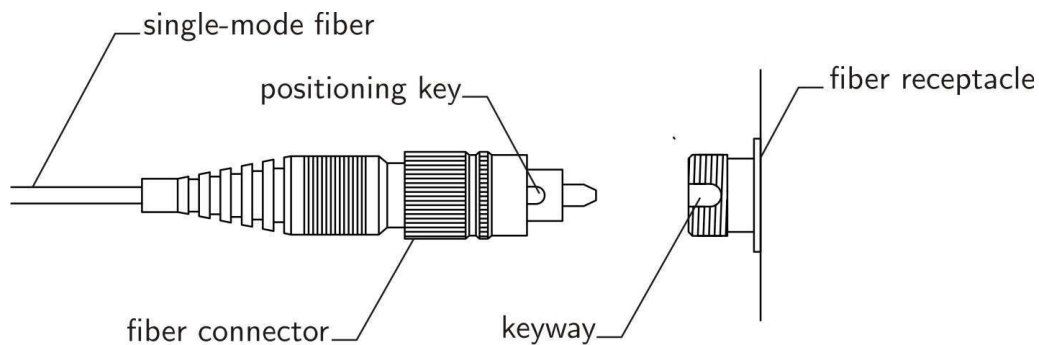This product contains Class 3B laser according to IEC 60825-1 (or EN 60825-1) Safety Standards.

Figure 5: The fiber connector is correctly inserted into the optical fiber input of the twin detection module only if the keyway on the the fiber receptacle mates with the positioning key on the fiber connector.

> Class 3B lasers are hazardous to the eye from direct beam viewing, and from specular reflections even for short and unintentional exposures! Therefore it is absolutely necessary to take overall safety measures when operating the source.

The quED should be operated in a restricted area equipped with post warning signs to alert those present. To ensure adequate warning of hazards associated with the accessible laser radiation, relevant warning signs and labels are conspicuously affixed to the quED. When removing the protective laser enclosure, always wear suitable safety glasses to prevent exposure to laser light. For additional information users should refer to appropriate documents specifying the safety standards such as IEC 60825-1 "Safety of laser products – Part 1: Equipment classification and requirements".

3.2 Additional Warnings

The following precautions should be thoroughly reviewed and followed to avoid the risk of any damage or failure.

- Avoid any back-reflection into the aperture of the laser head. Permanent damage to the laser diode can occur.

- Never connect or disconnect the cable between the control unit and the source while the laser is switched on. These acts can lead to laser hazard for the operator and possible permanent damage to the laser diode.

- The lifetime of the laser diode can be significantly shortened by applying the driving currents higher then the limiting value preset in the control unit. Therefore, the laser diode should be operated strictly below this value.

- ESD (electrostatic discharge) sensitive device! Electrostatic charges as high as several thousand volts might readily accumulate on the human body and equipment and can easily discharge. If this happens in the immediate vicinity of the laser diode, its permanent damage can occur. Therefore, proper ESD precautions are strongly recommended when handling and operating the source. These include avoiding wearing clothes, which easily generate ESD, putting on work gloves to protect against static electricity, maintaining environmental humidity 40–50% or more etc.

- Opening or removing the housing of the laser head might expose the user to the danger of laser radiation, and might cause the laser diode failure.

3.3 Switching On

1. Make yourself familiar with the operation of the quCR Controller for the quED setup which comes with its own "Down-conversion Controller Manual". Switch on the control unit.

2. Switch to the count rate panel. Once stabilized, compare the actual displayed single count rates to dark count rates specified in the inspection data sheet, which is included in the delivery notification. If the actual measured values are significantly higher, the level of stray light in the room has to be lowered. Especially, please try covering the fiber inputs at the control unit by a piece of a black tissue.

3. Switch the laser diode on and increase the input current on the laser driver tab. The laser diode starts lasing at the threshold current specified in the inspection data sheet. By further increasing the input current the source starts generating photon pairs and the coincidence count rate (green "01" number in the counter tab) becomes nonzero. The single count rates rapidly increase above the level of dark counts. After shipping or a longer period of storage there is probably a slight misalignment of the photon coupling into the single-mode fibers. Please choose one of the following possibilities and act accordingly:

   (a) If the displayed single and coincidence count rates reach approximately the values specified in the inspection data sheet, the quED is still perfectly aligned and it is ready to be used for entanglement tests and other experiments.

   (b) If the displayed coincidence count rate is well above zero and single count rates are well above the level of dark counts, but all of them do not reach the regime specified in the inspection data sheet, please try improving the coupling of the down-conversion photons according to description given in section 3.4.2.

   (c) If the displayed coincidence count rate is zero or close to zero and single count rate in one of the source arms is at the dark-count level but in the other arm well above this level, please:

- Try improving the coupling of down-conversion photons in the arm, which shows single count rate above the dark-count level. This arm can be easily identified by blocking the path of down-conversion photons and observing the drop in single count rate. To this end, please follow the instructions given in section 3.4.2.

- Try finding down-conversion photons by angle tuning the adjustable coupler in the arm, which shows single-count rate at the dark-count level. With this aim, please scan angles in a systematic way around the initial position (which should be always remembered), while observing the respective single-count rate at the control unit. As the scanning is performed blindly without any reference, the success comes only if the initial misalignment is small. If the scanning fails and single-count rate does not increase above the level of dark counts, please align the coupling mode in the arm according to steps of the full alignment procedure described in section 3.4.3.

(d) If the displayed coincidence count rate is zero and single count rates in both arms are at the level of dark count rates, please follow the steps of the full alignment procedure described in section 3.4.3.

3.4 Improving the Coupling

3.4.1 Operation of mirror mounts

The setup features a total of four mirror mounts to hold the two folding mirrors as well as the two fiber couplers. They allow for a fine angular alignment of the respective component. The movements of both the mirror and the coupler are controlled using a pair of adjustment screws, one, on the top, providing the control in vertical and the other, close to the breadboard, in horizontal direction.

Please note that all manipulations have to be performed in very small steps. Especially when finalizing the alignment, tiny steps of only a view degree are required.

In any case, you should avoid by all means any adjustments without signal feedback. This means you should never turn any of the screws so far as to loose the single count rate completely. Furthermore, make sure that the count rates you observe are actual down-conversion signal before you make any adjustments. If the laser is accidentally switched off or if the polarizers are set disadvantageous, the dark count rates of the detectors can easily be mistaken for signal.

When improving the coupling and later the entanglement two fundamentally different actions have to be performed:

pointing alignment This first type of adjustment aims to correct for a simple mispointing. In the quED case, this means that one (or both) of the fiber couplers does not point exactly into the pump center within the BBO crystal while it is assumed, that the angle of the coupler axis relative to the pump beam is fine. This is the most common
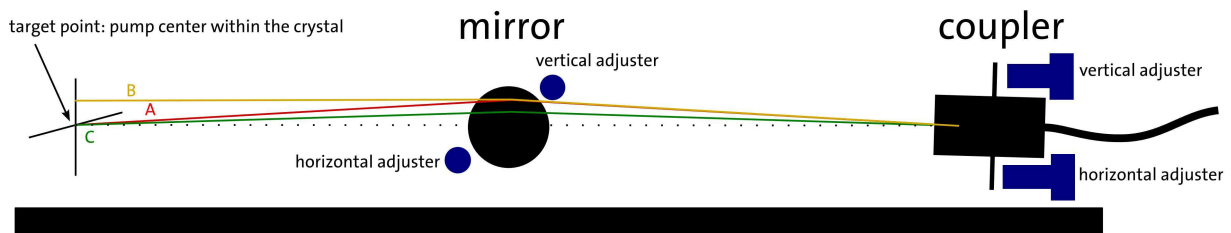
Figure 6: Walking procedure: In the beginning the beam points directly onto the target along path A. The dotted line, however, is the path we are aiming for. To solve this situation, a vertical walk has to be performed: turning (just a little bit) the vertical adjuster of the mirror alone leads to path B. The displacement at the target has now to be compensated with the vertical adjuster of the coupler to arrive at path C. The beam, again, points directly to the target, yet, the path is closer to the dotted line. Each time the procedure is repeated, the path comes closer to the dotted line. Usually one can not tell directly, whether the beam is above or below the dotted line in the beginning and when the perfect path is reached. Therefore, one first has to try one direction of walking and change the direction in case the signal gets worse (or end the procedure when on a maximum). It is essential not to mix up vertical and horizontal directions and to keep good track of the signal values and the direction of the steps already performed.

misalignment to occur with the quED as the overlap of the two coupler modes with the pump center (and each other) is quite sensitive. This is a 2 degree of freedom (DOF) problem which can be addressed using the adjusters of the respective fiber coupler only. (We strongly advice not to change the orientation of the mirrors in this situation despite being theoretically possible).

angle alignment, aka walking This kind of adjustment aims to manipulate the angle under which a target is hit. For the quED this usually means the angle between the coupler mode and the pump beam axis while the overlap with the target − the pump center − is already established. This is a four DOF problem and can in principle concern the horizontal and or the vertical direction. Unfortunately, walking has to be done iteratively. The procedure is explained in figure 6.

3.4.2   Realignment of the setup

After a prolonged time of storage or after shipping often a slight misalignment of the setup only occurs. This, however, only requires realignment of the pointing (2 DOF) to reestablish the overlap of pump and coupler modes within the crystal.

The crucial setting for the entanglement is the diagonal polarization measurement basis. Therefore, set the polarizers for $+45\,^\circ$ and $+45\,^\circ$ (PP). Modify the pointing carefully for a maximum coincidence rate. Check the coincidence rates for vertically- and horizontally-polarized pairs. These should be fairly similar but do not have to be equal.

When these two requirements are accomplished, maximum in PP and similar rates in HH and VV, you can make a quick check of the entanglement quality to be expected as described in 3.5.

3.4.3 Full Alignment Procedure

> For this procedure, the white protective cover on the pump laser assembly has to be removed which gives access to the pump laser power.
>
> Class 3B lasers are hazardous to the eye from direct beam viewing, and from specular reflections even for short and unintentional exposures! Therefore it is absolutely necessary to take overall safety measures when operating the source.

1. If not already turned off, turn off the laser.

2. Remove the long-pass filters, which are positioned right in front of the adjustable fiber couplers (see fig 3).

3. Remove the screw on top of the white cover and lift it off.

4. Disconnect the single mode fibers from the electronic control unit (always use the protective caps to cover fiber ends and optical inputs).

5. Remove the half wave plate from the pump assembly. Remove the polarizers.

6. Connect the fiber checker module to one of the single mode fibers and switch it on. You should see red light coming out of one of the fiber couplers. You can reduce the intensity if you retract the fiber 1 or 2 mm from the fiber checker module. Try to use as little intensity as possible for a more precise alignment. You can reduce the intensity even more if you retract the fiber 1 or 2 mm from the fiber checker module.

7. Turn on the pump laser as faint as possible. Just enough to see the spot on a white piece of paper.

8. In order to align the system you have to make the red beam hit two marks: the left engraved alignment cross (see fig. 7) and − when inserted − the right engraving on the alignment helper plate. Each time you insert the alignment helper plate, move it in the slit to make sure, the blue pump laser hits the central vertical engraving. If the pump is slightly above or below the horizontal marking, adjust the red beam for this same height.

   Note the diagonal beam path, i.e. use the left cross together with the right mark

for one beam and vice versa later for the second arm.

This alignment can only be accomplished iteratively: first, align for the engraving on the helper plate using the two screws of the coupler mount, then remove the plate and align for the small cross using the screws of the mirror mount. Repeat this until both marks are hit simultaneously.

9. Repeat alignment of the coupling mode from step 6 for the second arm of the source.

10. When the coupling modes in both arms of the source are aligned, switch off the pump laser. Switch off the fiber checker, unplug it and connect the fibers to the optical inputs of the controller unit.

11. Remove the alignment helper plate.

12. Place the long-pass filters in front of the fiber couplers and fasten them with the M2 screws.

13. Install the white protective cover back on the pump beam assembly and secure it with the M4 screw on the top.

14. Switch on the laser and increase the input current to the operating value. Observe the detected single- and coincidence-count rates and optimize the pointing of the couplers for maximum single count rates (2 DOF, use only the screws on the coupler).

15. Perform a vertical walk (4 DOF) in *one* arm in order to increase the coincidence rate.

16. Place the half wave plate and the polarizers back in the setup. The coupling is now optimized for one crystal only, thus optimize the coupling as described in section 3.4.2 with diagonal polarizers. You might want to check the HH and VV coincidence rates to be fairly equal for a better entanglement.

17. Check the entanglement as described in section 3.5.

3.5 Checking the Entanglement Quality (quick procedure)

While the contrast between correlation and anticorrelation for the horizontal and vertical polarizations (HH/HV or VV/HV) usually leads to a visibility of well beyond $90\,\%$, the contrast in the diagonal polarizations (PP/PM and MM/PM) is a sensitive measure for the entanglement quality one can expect. It also is much more sensitive then the S-value obtained from a bell inequality and much faster to measure.

1. If not already inserted, put the polarizing filters into the paths of down-conversion photons.
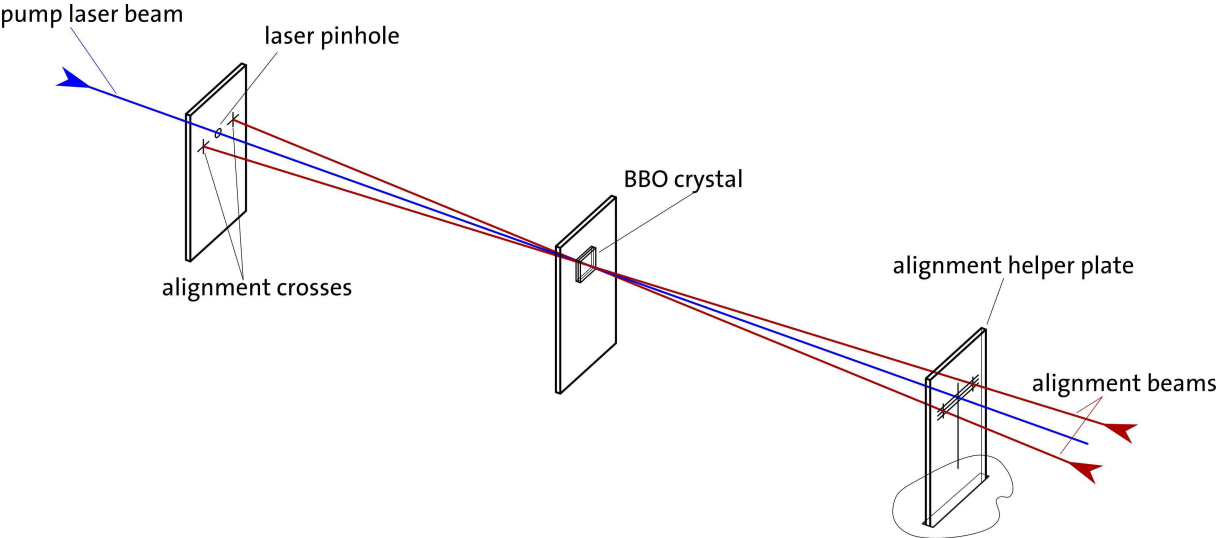
Figure 7: Alignment of the coupling modes using the alignment screen with the pinhole and the engraved pinpoints.
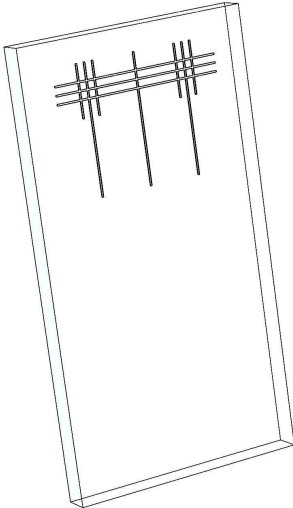

Figure 8: Alignment helper plate. To be used only for a full alignment procedure. Remove for normal quED operation.

2. Verify the existence of correlations in the horizontal-vertical polarization basis (maximum coincidence count rates for the filter combinations "horizontal/horizontal" (HH) and "vertical/vertical" (VV) and minimum coincidence count rates for the filter combinations "horizontal/vertical" (HV) and "vertical/horizontal" (VH)).

3. Rotate the polarizing filters to positions corresponding to polarization analysis in the diagonal basis. Choose the combination of positions, which corresponds to the expected minimum in coincidence count rate for the Bell state Φ^+ (i.e. "+45°/-45°" (PM) or "-45°/+45°" (MP)) and register the coincidence rate.

4. Rotate the polarizing filters to positions corresponding to maximum in coincidence count rate in diagonal polarization basis and register the rate.

5. Calculate visibility of the correlations in the diagonal polarization basis according to $(N_{\max} - N_{\min})/(N_{\max} + N_{\min})$, where $N_{\max}/N_{\min}$ is the maximum/minimum coincidence count rate. If the visibility is lower than expected we refer to section 4.1.

4 Troubleshooting

4.1 Improving the Entanglement Quality

In the following you can find a few issues to be addressed in order to reach a high quality of polarization entanglement.

- In principle the amount of horizontally-polarized photon pairs detected during a time unit should equal approximately the amount of vertically-polarized photon pairs. This situation corresponds to the theoretical maximally-entangled state having equal amplitudes of its two constituting terms, please see also section 1.1. Unfortunately, the polarizers also have a small spatial effect on the modes when rotated due to a very small yet finite wedge angle. Thus, one can not reliably measure the ratio of horizontally- and vertically-polarized photon pairs. If the ratio, however, is very asymmetric (worse then $\approx$60/40) it is advisable to modify the coupling very carefully for more symmetric rates. Geometrically, this means to move the overlap region of pump and collection modes slightly back or forward in the BBO crystal (see fig. 9).

- In case the entanglement quality is still not satisfactory, this indicates that the collection of the down-conversion photons is more or less asymmetric. The emission cones of the two BBO crystals are preadjusted to overlap maximally. Due to the spectral width, however, one can get reasonable coincidence rates from asymmetric collection modes (see fig. 10). The procedure in figure 11 aims to correct this error.
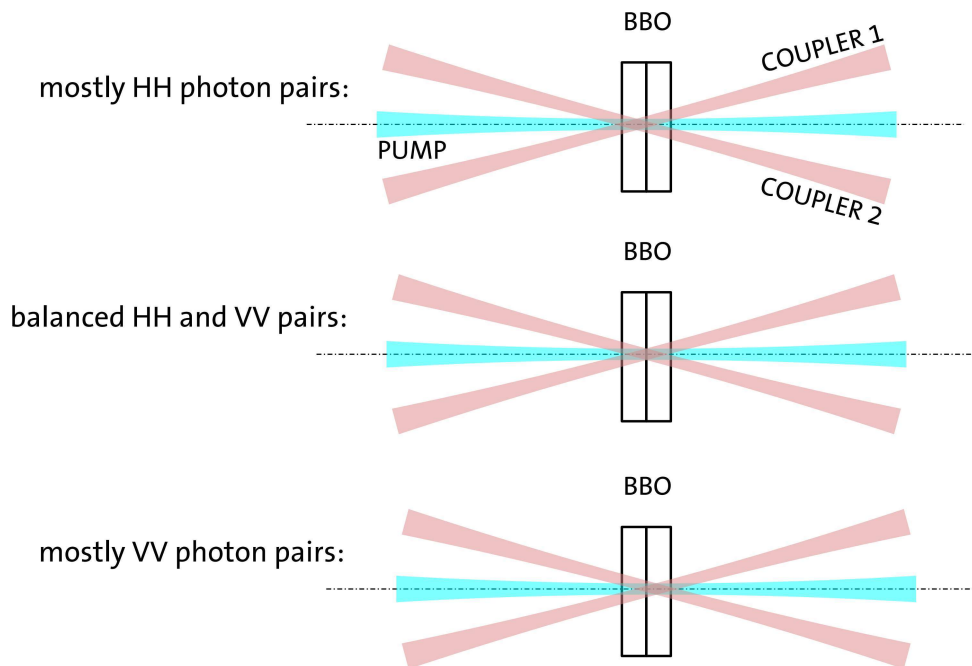
Figure 9: As the BBO is actually made up of two, the exact position of the overlap region (pump, coupler 1 and 2) determines the ratio of horizontally and vertically polarized photon pairs. Only if the overlap region is symmetric relative to the interface of the two crystals HH and VV pairs are collected with the same efficiency. You can easily tune the position with the horizontal pointing of the couplers.
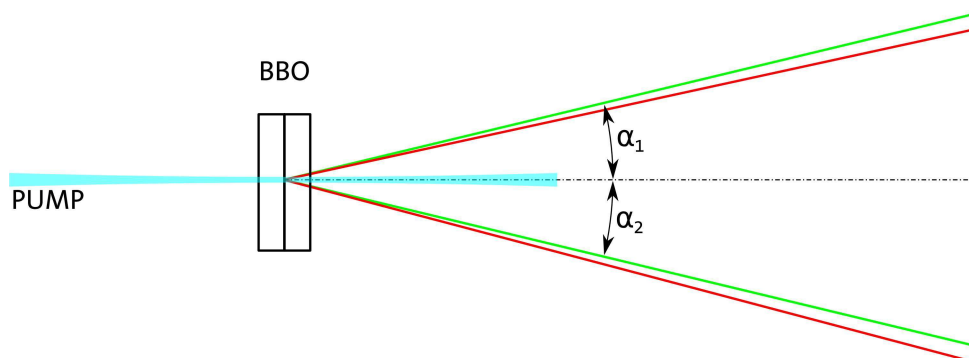

Figure 10: For a good entanglement quality, it is crucial to collect the down-conversion pairs symmetric around the pump beam (green lines, $\alpha_1 = \alpha_2$). From the pre-alignment you might arrive with a situation as indicated with the red lines. While the absolute value of α is not crucial for the entanglement, follow the instructions in section 4.1 to make the coupling symmetric.
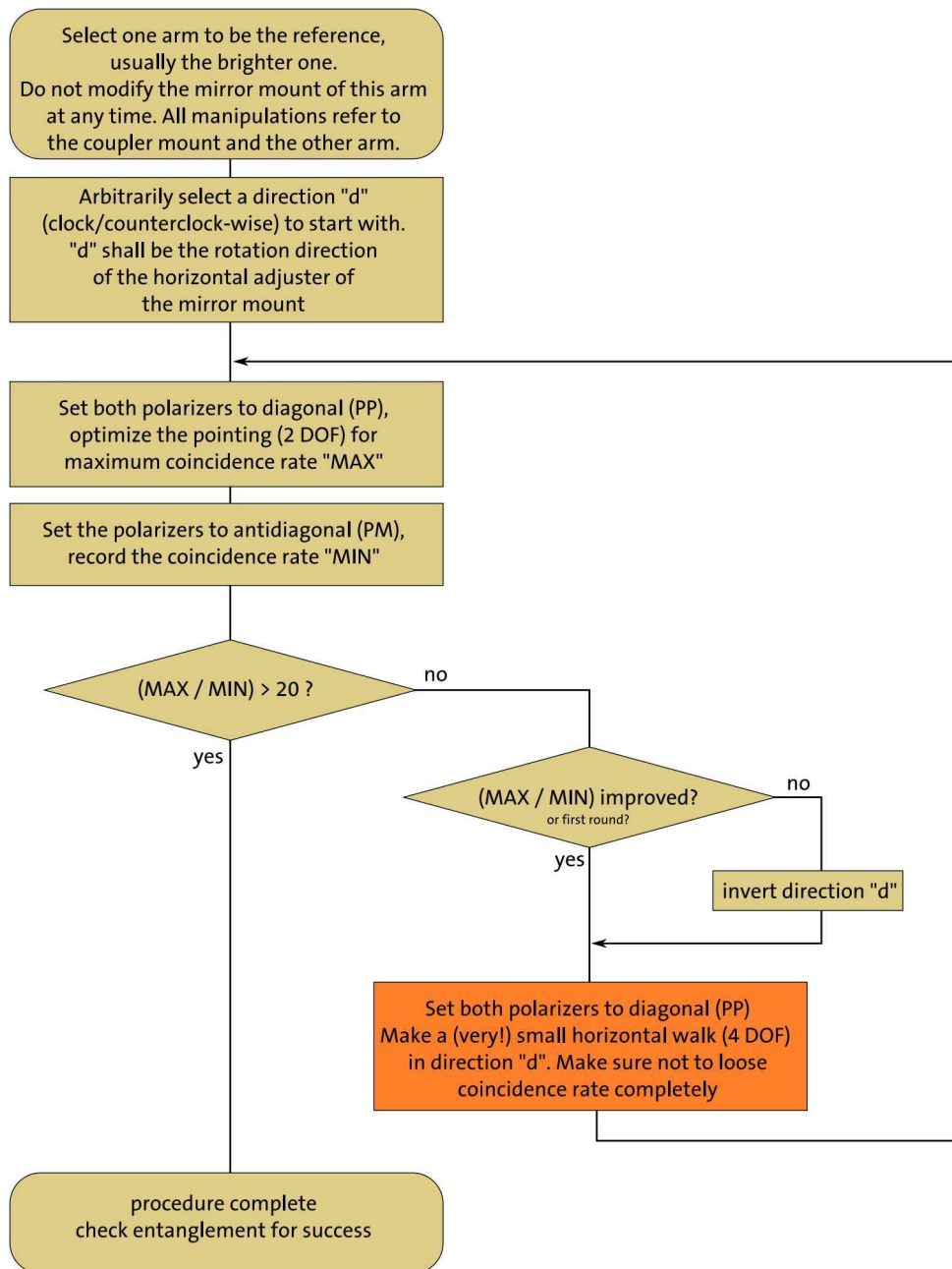
Figure 11: Procedure to eliminate residual asymmetries in horizontal direction. It is assumed, that there is already a reasonable coincidence rate. By selecting one arm as a reference, it is ensured that the procedure does not walk away from the angles prealigned with the red beams.

In the walking step (orange) start by turning the horizontal adjuster of the mirror mount a few degrees in direction "d" (not so far as to loose the coincidence rate completely) and compensate with the horizontal adjuster of the coupler mount.

For fine tuning, this procedure can also be applied to the vertical direction.

4.2   High single count rates but very view coincidences

It sometimes happens that the setup ends up in a state, where both arms receive a high number of single counts but the expected coincidence rate is very low.

It is important to understand that whenever two reasonable high single rates R_1 and R_2 occur, there is a certain probability, that two events from the two rates are accidentally closer together then the coincidence window width $\Delta t = 30\,\text{nm}$ and thus are considered as coincident events. The rate of these accidental coincidences R_a can be estimated by

$$R_a = R_1 \times R_2 \times \Delta t. \tag{1}$$

Especially, when there are very view coincidences, it has to be checked whether they result from actual signal or rather are purely accidental.

If there is actually a true coincidence rate from signal events, the setup is most probably aligned asymmetrically and the fastest solution is the full alignment procedure detailed in section 3.4.3.

If the observed coincidences are entirely accidental, there can be several reasons for this behaviour which can be distinguished in the following way:

1. First make sure, the polarizers are set to actually allow for coincidences. So to check for photon pairs always set the polarizers to be both vertically and subsequently horizontally.

2. If there are still no coincidences, the couplers might actually not collect light from the crystal but be aligned for fluorescence light emitted from the long pass filter in the window of the white housing. Again, this can be checked easily: Remove the wave plate from the pump assembly. Thereby, only one sort of photon pairs are generated in the BBO crystal, both horizontally or vertically polarized. Now, try for each arm separately if there is high contrast visible in the single count rates when turning the polarizer a full revolution. If so, this means the light is polarized and the respective coupler actually collects down-conversion light. If there is no or only very weak contrast, the light is unpolarized which is a hint that the coupler collects fluorescence light from the filter. The procedure for both these cases is explained in the following.

4.2.1   There is polarization contrast in both arms

This means, the single count rates actually are down-conversion signal. If there are no real coincidences at all, the setup is aligned severely asymmetrically and you need to perform the full alignment procedure explained in section 3.4.3.

4.3   There is no polarization contrast in at least one arm

This means, the rates are due to fluorescence in the long pass filter. The situation for both arms is sketched in figure 12.
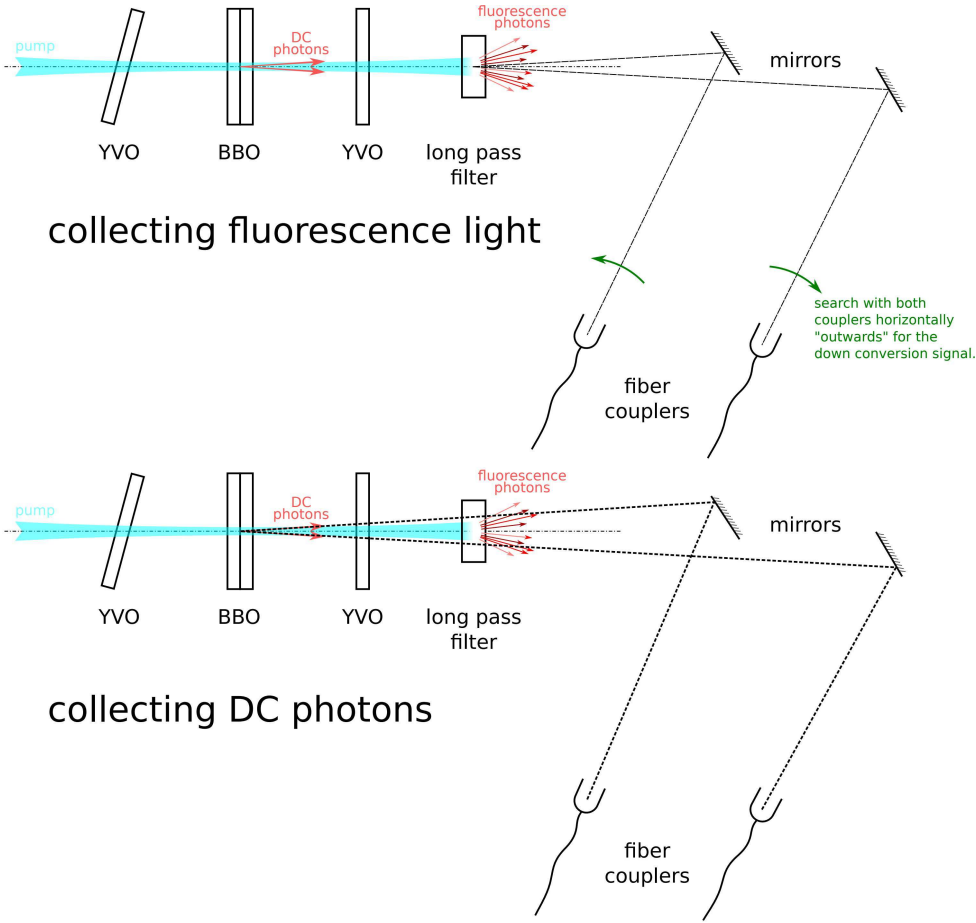
Figure 12: .

A   Experiments with the quED

We suggest and describe a few experiments to be accomplished with the quED, providing the basis for an undergraduate laboratory course on quantum mechanics and quantum optics. In the following the measurement procedures and the interpretation of results are discussed in short for each of the experiments.

A.1   Measurement of correlation curves

The simplest test to verify entanglement of photon pairs generated in the quED involves a measurement of correlation curves in two non-orthogonal complementary bases. This is accomplished by fixing the orientation α of one polarizing filter and continuously changing the orientation β of the other. The two settings $\alpha = 0°$ and $\alpha = 45°$ are usually chosen for convenience, corresponding to the measurement in horizontal/vertical polarization basis and the diagonal basis, respectively; (zero angle corresponds to horizontal polarization). The recorded coincidence count rates for the two settings show the $\sin^2(\beta - \alpha)$ dependencies in analogy to the Malus' law. This observation demonstrates the impossibility of finding a measurement basis, in which the polarization state of the photon pairs is separable - the two-photon state is entangled. On the other hand, the single count rates show no dependence on the orientation β whatsoever. Thus the outcome of a state-measurement on one of the two photons is completely random.

To quantify the quality of the polarization correlations, the visibility V of measured curves can be directly estimated from the formula:

$$V = \frac{C_{\max} - C_{\min}}{C_{\max} + C_{\min}},$$

where $C_{\max}/C_{\min}$ is the maximum/minimum coincidence count rate. The error ΔV on the visibility V is determined by applying the Gaussian error propagation rule:

$$\Delta V = \sqrt{\left(\frac{\partial V}{\partial C_{\max}}\Delta C_{\max}\right)^2 + \left(\frac{\partial V}{\partial C_{\min}}\Delta C_{\min}\right)^2},$$

where

$$\frac{\partial V}{\partial C_{\max}} = \frac{2C_{\min}}{(C_{\max} + C_{\min})^2}, \quad \frac{\partial V}{\partial C_{\min}} = -\frac{2C_{\max}}{(C_{\max} + C_{\min})^2},$$

and the acquired coincidence rates are assumed to be statistically independent Poisson random variables, so that $\Delta C_{\max} = \sqrt{C_{\max}}$ and $\Delta C_{\min} = \sqrt{C_{\min}}$. A more precise determination of the visibility V follows from the best fit to the measured data using the function:

$$f(\beta) = \frac{A}{2}\left[1 - V\sin\left(\frac{\beta - \beta_c}{P}\right)\right],$$

where A, β_c, V, P are the fitting parameters determining the curve amplitude, center, visibility and periodicity, respectively.

A.2 Bell state discrimination

The two Bell states:

$$|\Phi^+\rangle = \frac{1}{\sqrt{2}}\big[|H\rangle_1|H\rangle_2 + |V\rangle_1|V\rangle_2\big], \quad |\Phi^-\rangle = \frac{1}{\sqrt{2}}\big[|H\rangle_1|H\rangle_2 - |V\rangle_1|V\rangle_2\big],$$

can be directly prepared in the quED by rotating the pre-compensation crystal, please see sections 1.1 for more details. They both show correlations in the horizontal/vertical basis, i.e. maximum coincidence count rates are observed for the polarizer combinations $\alpha = 0°/\beta = 0°$, $\alpha = 90°/\beta = 90°$ and minimum coincidence count rates for $\alpha = 0°/\beta = 90°$, $\alpha = 90°/\beta = 0°$. However, in the diagonal basis the two states:

$$|\Phi^+\rangle = \frac{1}{\sqrt{2}}\big[|P\rangle_1|P\rangle_2 + |M\rangle_1|M\rangle_2\big], \quad |\Phi^-\rangle = \frac{1}{\sqrt{2}}\big[|P\rangle_1|M\rangle_2 + |M\rangle_1|P\rangle_2\big],$$

can be easily distinguished by the polarization measurement; here the symbols $|P\rangle$ and $|M\rangle$ represent the diagonal polarization states of photons:

$$|P\rangle = \frac{1}{\sqrt{2}}\big[|H\rangle + |V\rangle\big], \quad |M\rangle = \frac{1}{\sqrt{2}}\big[|H\rangle - |V\rangle\big].$$

Whereas Φ^+ shows correlations in the diagonal basis and the maximum is observed for the polarizer combinations $\alpha = 45°/\beta = 45°$, $\alpha = -45°/\beta = -45°$, the state Φ^- shows anti-correlations and the maximum is observed for the polarizer combinations $\alpha = -45°/\beta = 45°$, $\alpha = 45°/\beta = -45°$.

By inserting the half-wave plate (optionally delivered with the quED) rotated at $45°$ into one of the down-conversion arms one can prepare the two other Bell states $|\Psi^+\rangle$ and $|\Psi^-\rangle$ showing anti-correlations in the horizontal/vertical basis. Analogously to Φ-class Bell states Ψ-states can be distinguished in the diagonal basis.

A.3 Bell experiment

The most widespread version of Bell's inequality used in experimental tests is the one from Clauser, Horne, Shimony and Holt (hereafter referred to as CHSH). The main idea behind the CHSH-Bell inequality is that, in local realistic theories, the absolute value of a particular combination of correlations between two particles is bounded by 2:

$$S(\alpha, \alpha', \beta, \beta') = \big[E(\alpha, \beta) + E(\alpha', \beta) - E(\alpha, \beta') + E(\alpha', \beta')\big] \leq 2,$$

where α (α') and β (β') denote the local measurement settings of two observers, each receiving one of the particles. In our particular experimental configuration with entangled photons α (α') and β (β') are the orientations of polarizing filters positioned in the two arms of the source. Denoting $C(\alpha, \beta)$ the coincidence count rate obtained for the combination of polarizer settings

α and β, the normalized expectation value $E(\alpha, \beta)$ of correlations between the measurements is given by:

$$E(\alpha, \beta) = \frac{C(\alpha, \beta) - C(\alpha, \beta_\perp) - C(\alpha_\perp, \beta) + C(\alpha_\perp, \beta_\perp)}{C(\alpha, \beta) + C(\alpha, \beta_\perp) + C(\alpha_\perp, \beta) + C(\alpha_\perp, \beta_\perp)},$$

where $\alpha_\perp$ and $\beta_\perp$ are the polarization orientations perpendicular - that is rotated by $90°$ - with respect to α and β. The measurement of coincidence count rate with entangled photons shows sinusoidal dependence $C(\alpha, \beta) \propto \sin^2(\beta - \alpha)$ on the difference angle of the polarizer orientations, see section A.1. The same behavior can be predicted for the correlation coefficients $E(\alpha, \beta) = -\cos[2(\beta - \alpha)]$. Therefore, for various combinations of orientations α, α', β, β' the CHSH inequality is violated. The maximum violation is obtained if the following conditions on the polarizer settings are obeyed:

$$(\beta - \alpha) = (\alpha' - \beta) = (\beta' - \alpha') = 22.5° \quad \text{and} \quad (\beta' - \alpha) = 67.5°,$$

giving the upper limit on the violation of the CHSH inequality, $2\sqrt{2}$. Quantum entanglement thus leads to stronger correlations that violate the limit of 2, so that quantum entanglement is experimentally distinguishable from local realistic models, forcing us to abandon at least one of the underlying concepts, locality (meaning that local events cannot be affected by actions in space-like separated regions) or realism (meaning that external reality exists independent of observation).

For the experiment any set of orientations fulfilling the conditions given above can be chosen, e.g. $\alpha = 0°$, $\alpha' = 45°$, $\beta = 22.5°$ and $\beta' = 67.5°$, and four separate experimental runs are conducted, corresponding to the four terms $E(\alpha, \beta)$ in the definition of the value S. Each of the terms $E(\alpha, \beta)$ is calculated from four numbers of coincidences, making together 16 count rates which have to be experimentally taken. The statistical nature of the inequality requires that sufficiently long integration time for collecting the required 16 coincidence rates is chosen. Simple rule for sums is applied to determine the standard deviation of the experimental value S:

$$\Delta S(\alpha, \alpha', \beta, \beta') = \sqrt{\sum_{a=\alpha, \alpha'} \sum_{b=\beta, \beta'} \Delta E(a, b)^2},$$

where the errors $\Delta E(a, b)$ on the individual correlation coefficients are computed via Gaussian error propagation:

$$\Delta E(a, b) = 2 \frac{[C(a, b) + C(a_\perp, b_\perp)] [C(a, b_\perp) + C(a_\perp, b)]}{(C(a, b) + C(a, b_\perp) + C(a_\perp, b) + C(a_\perp, b_\perp))^2}$$
$$\times \sqrt{\frac{1}{C(a, b) + C(a_\perp, b_\perp)} + \frac{1}{C(a, b_\perp) + C(a_\perp, b)}},$$

where we assumed independent errors on the individual measurements and the Poisson photon number statistics[1]. If the experimental value S is numerically greater than 2 it has violated

---

[1]When the individual events are assumed to be independent of each other, the resulting statistics becomes Poissonian. The variance of a Poisson distribution with mean λ is also λ. Hence the standard deviation is $\sqrt{\lambda}$.

the CHSH inequality. The strength of violation is usually defined in terms of the number n_Δ of standard deviations which add up into the gap between the experimental value S and the local realistic bound 2:

$$n_\Delta = \frac{S - 2}{\Delta S}.$$

A.4 Tomographic reconstruction of the two-photon density matrix

The output from real-life entanglement sources like the quED is not truly pure as described by the Bell states in section A.2. In reality we always have to deal with mixed polarization states, which are completely characterized using density matrices. To determine the density matrix ρ of an unknown quantum state, the experimental procedure called state tomography has to be accomplished.

In case of the entangled photon pairs the state tomography requires a set of 16 projective measurements. These are given by all possible permutations of projecting the two photons to horizontal ($|H\rangle$), vertical ($|V\rangle$), plus-diagonal ($|P\rangle$) and right-circular ($|R\rangle$) polarization states; $|R\rangle = 1/\sqrt{2}\,[|H\rangle + \mathrm{i}|V\rangle]$ and $|P\rangle$ is defined in section A.2. The tomography contains measurements in the circular polarization base, which is accessible only with a quarter wave-plate (optionally delivered with the quED). Therefore, to project the photons into any of the four mentioned polarization states, quarter-wave plates preceding the polarizing filters have to be used. For each of the settings the coincidence count rate over a given integration time is recorded and the accumulated experimental data are then evaluated.

Since the evaluation procedure of density matrix from the measured 16 coincidence counts is lengthy and more involved, it is not explicitly described here, but can be found e.g. in D. F. V. James *et al.*, Phys. Rev A 64, 052312. To quantitatively characterize the deviation of the experimental density matrix ρ_exp from the ideal, its overlap with the theoretical density matrix $\rho_\mathrm{th} = |X\rangle\langle X|$, ($X$ is one of the Bell states $\Phi^+, \Phi^-, \Psi^+, \Psi^-$), is calculated:

$$\mathcal{F} = \mathrm{Tr}\left[(\sqrt{\rho_\mathrm{th}}\,\rho_\mathrm{exp}\sqrt{\rho_\mathrm{th}})^{\frac{1}{2}}\right].$$

$\mathcal{F}$ is usually called the fidelity and it takes the values between 0 and 1. The maximum value of 1 is obtained if $\rho_\mathrm{exp} = \rho_\mathrm{th}$, so that the two states are completely indistinguishable. Furthermore, many useful measures to characterize the experimental quantum state can be derived from the reconstructed density matrix; e.g. concurrence or tangle can be computed to quantify the degree of entanglement and entropy to quantify the degree of mixture in quantum state. The definitions of the various measures and their interpretation can be found in a number of quantum mechanics textbooks.

qu⊤ools