Experiment 1: Entanglement demonstration

Dayang Li, DTU Fotonik

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Abstract

In this exercise you will prepare entangled photon pairs, gain some experience on the superposition of distinct physical realities (the common notion of "Here and there at the same time"), and evaluate the quality of the entangled state that we prepare.

1 Preparation of entangled photon pairs

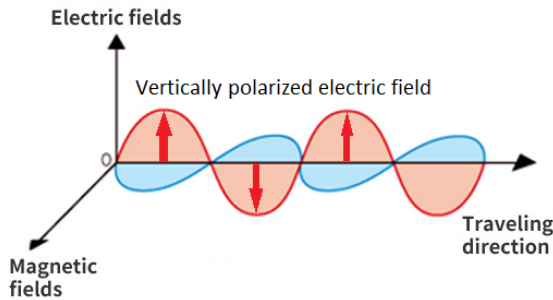To start with, let's ask ourselves a few question.

Figure 1: Electromagnetic field. The electric field is always oscillating in some direction perpendicular to the traveling direction. This oscillation direction is known as the polarization of the electromagnetic field. In the figure we see an electric field polarized in the vertical direction.

1. What is light? Light is a type of electromagnetic wave. An oscillating charged particle will constantly emit electromagnetic wave. When the frequency of oscillation is very high (approx. 100THz), the emitted electromagnetic wave becomes light.

2. What is a photon? Particles of light. If we zoom in on a light beam, we will see individual packets of light instead of a continuous and evenly distributed stream of electromagnetic waves. Just like if we zoom in on a river down to the nanoscale, we will only see individual water molecules. The individual packets of light is what we call photons. For instance a green laser pointer (wavelength 532nm) emitting at 1mW power gives away roughly 10^{15} photons per second. Photons are really small!

3. What is polarization? Direction of vibration of the electromagnetic waves. See Figure 1. Normally we take the optical table as a reference and define the horizontal and vertical polarizations accordingly. For us quantum physicists we write them as ket vectors. So horizontally polarized photon is written as $|H\rangle$ and vertically polarized $|V\rangle$. In addition to the horizontal and vertical polarizations, there could also be (complex linear) combinations of these two, for example diagonal (antidiagonal) polarization where the electric field is oscillating at 45 (-45) degrees with respect to horizontal polarization, written as $|+\rangle = \frac{1}{\sqrt{2}}(|H\rangle + |V\rangle)$ $\left(|-\rangle = \frac{1}{\sqrt{2}}(|H\rangle - |V\rangle)\right)$. If you have not seen or worked with the notations don't worry, it is something good to know but you can still appreciate the experiments without it.

4. What is correlation in general? Being correlated means that two things are likely to happen one after another. An example is a pair of gloves. If we put one each in a box, shuffle them until we don't

remember which glove is in which box, we keep one and send the other far away, by opening the box we kept we found for example a left hand glove, we can immediately tell with certainty which glove is sent away. In this case the information of which glove is in which box is correlated.

5. Then what is entanglement? The short and correct answer is non-classical correlation. But this does not help us understand what it really is. Let us assume for now that there are two parallel universes (or two physical realities). [1] Again we pull out a pair of gloves. We put one in each box, shuffle them and send one box away. But this time in one universe it is the box with the left glove that is sent away, while in the other universe it is the box with the right glove. You, as an observer, cannot tell which universe you are in, unless you open up the box you kept. So before opening the box, you as the observer describes the world as a superposition of two physical realities. So we have a "superposition" of realities, what about entanglement? Entanglment describes that in both of the universes, the two gloves definitely makes up a pair, one left-handed and one right-handed, but which one is which we do not know, since we do not know which universe we are in. Entanglement is the correlation that exists between the pair of gloves (two objects). Only by opening the box we can disrupt this superposition and pin down the handedness of the glove. And the action of opening our box and seeing for example a left hand glove immediately tells us that the glove we sent away is a right hand glove. This kind of correlation involving a superposition of distinctive physical realities is what we call entanglement.

I hope you are not confused (too much)! But no worries, by the end of the exercise, you will understand everything. By asking ourselves these questions, you might already have an idea of what we will do today. We will **entangle photon polarizations**. More precisely, we will prepare pairs of photons, their polarizations are entangled, or in other words, correlated in a way that is "counter-intuitive" or non-classical.

1.1 Experimental setup for the generation of entangled photon pairs

(Section by Lorenzo Leandro)

The quED setup (Figure 2) offers a pair-photons source with fiber outcoupling. The source of paired photons is fully contained in the white box. The two beams are then split in two arms (orange lines) in free space and coupled to polarization maintaining fibers. For the principle of operation of the parametric-down-conversion source refer to the quED manual provided by quTools. Basically it turns one high energy photon from the laser diode travelling down the purple path to a pair of lower energy photons each travelling down one of the orange paths. This source produces two entangled, identical photons coming out of the white protective box.

For students with background in quantum mechanics, the polarization entangled photon pair are in the following state. We call the path leading to the left fiber coupler as path 1 and the arm leading to the right coupler as path 2.

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|H\rangle_1 |H\rangle_2 + |V\rangle_1 |V\rangle_2) \tag{1}$$

From this point on, the paired photons follow two different paths, each of which containing a mirror and a fiber coupler. In each arm, between mirror and fiber coupler, two groves are made on the board in order to eventually include additional pieces in standard quTools rotation stages (such as half- or quarter-wave plates or polarizers). The fiber couplers, if properly aligned, ensure that the light goes effciently into polarization maintaining fibers which are the output of the quED setup.

At the other end of the fiber, there is a detector, Avalanche Photo Detector (APD). When a photon arrives at a detector, it will be detected and produce an electrical signal with a finite probability, this probability is the detector efficiency. In addition, we can measure the coincidence of photon detection events, that is, when two photons arrive at the detectors at the same time. We can also choose which polarization we want to measure by putting a polarization filter (or polarizer in short) to keep only a certain polarization component and block the other. Figure 2 shows the setup and the inside of the laser protective box, with labels for each element. The state prepared by us is a superposition of both photons being horizontally polarized or both vertically polarized.

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[1]Disclaimer: This is not 100% scientifically accurate since the Many-Worlds interpretation of quantum mechanics is not a generally accpeted theory, but I find parallel universe a very suitable tool to explain quantum entanglement.
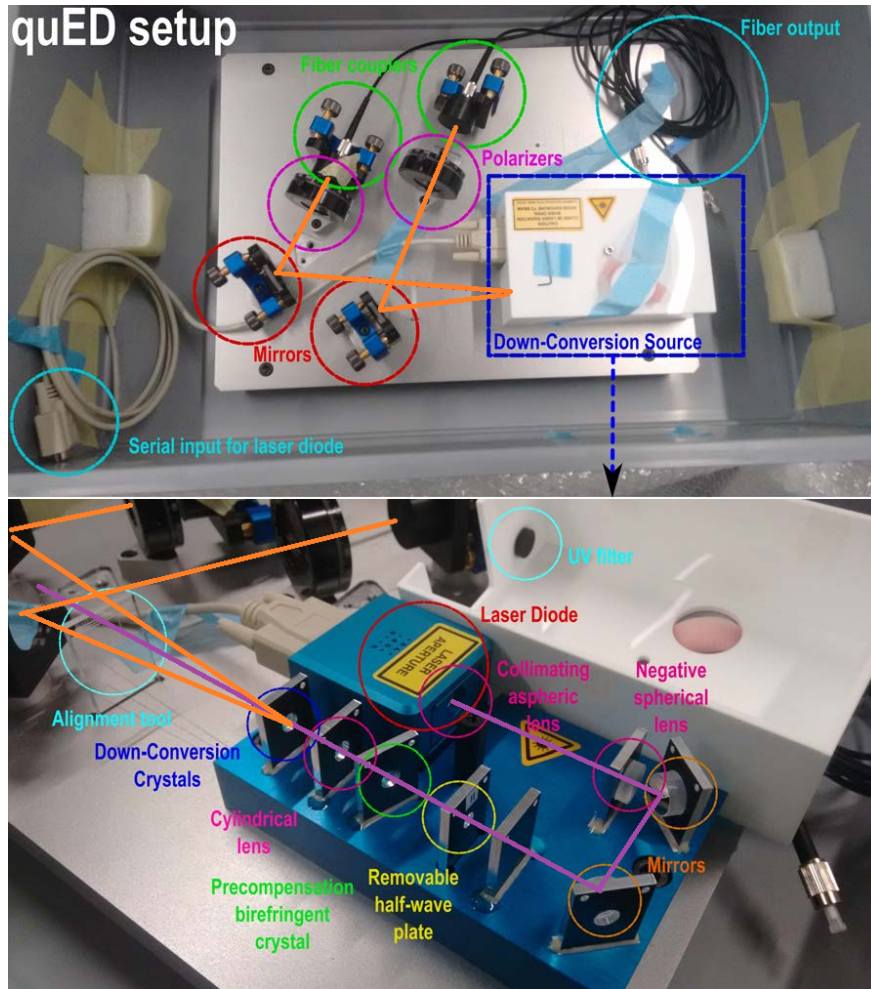
Figure 2: Experimental setup to generate entangled photon pairs. Please read the main text for explanations.

2 Demonstration of entanglement

There are many ways to characterize the prepared entangled state. All of which are based on the measurement of coincidence count rate in different combinations of polarization basis. In other words we rotate both of the polarizers to let f.ex. horizontally polarized photons pass through and measure how many times they arrive at the detector simultaneously in one second, and this is what we call the coincidence count rate in the horizontal/horizontal basis.

In increasing level of experimental complexity the following methods can be used: Measurement of entanglement visibility, violation of Bell's inequality, tomographic quantum state reconstruction. The first two experiments will be mandatory for anyone attending the lab session. The third experiment is optional depending on if time allows and if you feel like a little challenge.

2.1 Entanglement visibility

The entanglement visibility is a quantity between 0 and 1 that tells us how clear we can "see" entanglement in our system. With a good entanglement visibility close to 1, we know that we have prepared an entangled state, and our setup and optical alignment is good enough to measure them. Entanglement visibility V and

its uncertainty ΔV are defined as the following.

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

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

with

$$\frac{\partial V}{\partial C_{\text{min}}} = \frac{2C_{\text{min}}}{(C_{\text{max}} + C_{\text{min}})^2}, \qquad \frac{\partial V}{\partial C_{\text{max}}} = -\frac{2C_{\text{max}}}{(C_{\text{max}} + C_{\text{min}})^2},$$
$$\Delta C_{\text{max}} = \sqrt{C_{\text{max}}}, \qquad \Delta C_{\text{min}} = \sqrt{C_{\text{min}}}$$

where $C_{\text{max}}/C_{\text{min}}$ is the maximum/minimum coincidence count rate in a given basis. We will measure in two bases, horizontal/vertical (H/V) basis and diagonal/antidiagonal (+/−) basis. Measuring in horizontal (H) means that the polarizer in the optical path is set to 0 degree, while measuring in vertical (V) requires the polarizer to be set to 90 degrees. Similarly for diagonal (+) and antidiagonal (−), set to 45 and 135(=-45) degrees respectively.

Before we proceed let us build up some expectations by considering two cases: Perfect visibility of unity contrast, and no visibility with zero contrast. A high visibility indicates good entanglement. What do we expect from the max and min count rates?

2.1.1 Experimental procedure

1. Measure coincidence at the following settings: HH, VV, HV, VH.

Basis	Coincidence count rate C
HH	
VV	
HV	
VH	

Use the definitions to calculate Visibility and its uncertainty.

2. Measure coincidence at the following settings: ++, − −, +−, −+.

Basis	Coincidence count rate C
++	
− −	
+−	
−+	

Use the definitions to calculate Visibility and its uncertainty.

In general for the state we have prepared, a visibilty above 85% in both bases indicates good entanglement, given that the uncertainty is small (approx. 1%).

2.2 Breaking the CHSH inequality

2.2.1 Historical background

The breaking of the CHSH inequality is the experiment that received the Nobel Prize in Physics in 2022. It demonstrated for the first time that quantum mechanics is fundamentally different from classical physics. The principle of entanglement and superposition leads to a brand new picture of the way we should look

at the physical world. Albert Einstein thought that entanglement cannot be real, and proposed that "God does not play dice". In our example with the gloves, Einstein would say that there has been one universe all along, when we shuffle the boxes with gloves, which one is kept by us and which is sent to some other planet is already determined, regardless of what happens afterwards. This point of view is given the formal name of local realism.

In the year of 1964, John Steward Bell proposed the Bell's inequality, stating that if quantum mechanics is a local realistic theory (one universe, everything is determined prior to any measurement), this inequality should be obeyed. Later in 1969, one of the Nobel Prize laureates, John Clauser, togehter with three others (Michael Horne, Abner Shimony, and Richard Holt) adapted the Bell's inequality to make it work with entangled photon pairs. The adapted version is known as the CHSH inequality [1]. Another Nobel Prize laureate Alain Aspect, is the first to experimentally break the CHSH inequality (in 1982) [2, 3], proving to the world that quantum mechanics is fundamentally different from classical physics, entanglement is real. There are however some loopholes to Alain Aspect's experiment that makes the results not fully approved by the critical community. This is fixed by a group from Delft in 2015. Now there is no dispute that Bell's inequality can be broken by quantum systems.

2.2.2 The CHSH inequality

We want to measure a quantity S for our two-photon system. The CHSH inequality sets a bound on the absolute value for S.

$$|S| \leq 2 \tag{2}$$

S is a quantity consisting of 4 terms.

$$S = E(\alpha, \beta) + E(\alpha', \beta) - E(\alpha, \beta') + E(\alpha', \beta') \tag{3}$$

Each of the terms $E(\alpha, \beta)$ is a quantum correlator, basically it represents the expectation value of the product of the measurements when the first particle is measured in a basis defined by angle α and the second particle in the basis β. The rule of the measurement is such that each of the measurement results can be +1 or -1, for example a single shot measurement to distinguish between horizontally (+1) or vertically (-1) polarized photon state in the basis $\alpha = 0$. In reality this is impossible with a single measurement without deterministic photon pair source and perfect single photon detectors, what we can do instead is to measure both in the horizontal basis $\alpha = 0$ and the vertical basis $\alpha = 90°$, then combine the results.

$$E(\alpha, \beta) = \frac{C(\alpha, \beta) - C(\alpha, \beta_\perp) - C(\alpha_\perp, \beta) + C(\alpha_\perp, \beta_\perp)}{C(\alpha, \beta) + C(\alpha, \beta_\perp) + C(\alpha_\perp, \beta) + C(\alpha_\perp, \beta_\perp)} \tag{4}$$

The coincidence counts $C(\alpha, \beta)$ is measured with the first polarizer set to α and the second set to β, while $\perp$ means that the basis angle is added by 90°.

The theoreticians predicted that a set of angles $\alpha = 0°$, $\alpha' = 45°$, $\beta = 22.5°$ and $\beta' = 67.5°$ can break the CHSH inequality to the greatest extent. What remains for us to do is to carry out the coincidence measurements $C(x, y)$, calculate the quantum correlators $E(x, y)$ and finally calculating S.

1. Measure the Quantum Correlator $E(\alpha = 0°, \beta = 45°)$.

Basis	Coincidence count rate C
$\alpha, \beta = 0°, 22.5°$	
$\alpha, \beta_\perp = 0°, 112.5°$	
$\alpha_\perp, \beta = 90°, 22.5°$	
$\alpha_\perp, \beta_\perp = 90°, 112.5°$	

Calculate the quantum correlator $E(\alpha = 0°, \beta = 45°)$ based on the definition.

2. Measure the three other quantum correlators

Basis	Coincidence count rate C
$\alpha', \beta =$	
$\alpha', \beta_\perp =$	
$\alpha'_\perp, \beta =$	
$\alpha'_\perp, \beta_\perp =$	

Calculate the quantum correlator $E(\alpha', \beta)$ based on the definition.

Basis	Coincidence count rate C
$\alpha, \beta' =$	
$\alpha, \beta'_\perp =$	
$\alpha_\perp, \beta' =$	
$\alpha_\perp, \beta'_\perp =$	

Calculate the quantum correlator $E(\alpha, \beta')$ based on the definition.

Basis	Coincidence count rate C
$\alpha', \beta' =$	
$\alpha', \beta'_\perp =$	
$\alpha'_\perp, \beta' =$	
$\alpha'_\perp, \beta'_\perp =$	

Calculate the quantum correlator $E(\alpha', \beta')$ based on the definition.

3. Calculate the S parameter and compare with the CHSH inequality.

Hopefully by now you have found a S value much larger than 2 (approx. 2.6 or higher). This means that the CHSH inequality is broken, quantum entanglement prevails!

2.3 (Optional) Quantum state tomography

Quantum state tomography is yet another way to examine the characterize the two photon state we have prepared. Before proceeding, we need to introduce the concept of a density matrix. It is a more general description of quantum systems compared with the state vector description. A density matrix an describe a quantum system that is not in a pure quantum state, for instance due to decoherence and imperfect measurements. A density matrix is said to carry all the information about a quantum system, and is the most convincing way of demonstrating the presence of entanglement in any system. For a system in an arbitrary pure state $|\psi\rangle$, the density matrix is defined as $\rho = |\psi\rangle\langle\psi|$. For a quantum system in mixed state, the density matrix is a normalized linear combination of pure state density matrices, the coefficients being the probability to find the mixed state in each of the pure state configurations.

To know how it works, I would refer you to the work by D. F. V. James *et.al.* [4]. Here I outline the density matrix reconstruction procedure and the measurements necessary to support the reconstruction.

To perform a quantum state tomography requires us to measure each of the qubits in 4 bases, and we measure in all combination of the single-qubit bases, for instance for two qubits we measure in all 16 bases combinations. In the following table the notation for bases states are consistent with [4]: $|D\rangle = \frac{1}{\sqrt{2}}(|H\rangle+|V\rangle)$, $|L\rangle = \frac{1}{\sqrt{2}}(|H\rangle + i|V\rangle)$, $|R\rangle = \frac{1}{\sqrt{2}}(|H\rangle - i|V\rangle)$. The measurement of linear polarizations $|H\rangle$, $|V\rangle$, $|D\rangle$ are done by rotating the polarizer to the corresponding angles. The measurement of the circular polarization $|L\rangle$ and $|R\rangle$ are achieved by setting the polarizer at horizontal polarization, and putting an extra quarter wave plate in the optical path where circular polarization is measured. To measure $|L\rangle$ one set the angle on the quarter wave plate to $+45°$, and $-45°$ for $|R\rangle$.

Basis	Coincidence count rate C
HH	
HV	
VV	
VH	
RH	
RV	
DV	
DH	
DR	
DD	
RD	
HD	
VD	
VL	
HL	
RL	

The reconstruction procedure is outlined in equation (3.12, 3.15.3.20) in [4]. Basically one needs to find the $B_{\mu,\nu}$ matrix as in Eq. (3.12), the states $|\psi_\nu\rangle$ stand for the two-photon states as in Table I. For instance $\nu = 1$ gives $|\psi_\nu\rangle = |HH\rangle$. The Γ_μ matrices are given in Appendix A, you can directly take the definitions from there. They arethe Kronecker products of the Pauli matrices (multiplied by 1/2). There is a mistake in the article, the indices shown in Eq. (3.12) is $B_{\nu,\mu}$ while it should have been $B_{\mu,\nu}$. Once we have the B matrices, we can proceed to calculate the M_ν matrices as in Eq. (3.15). Again there is a mistake in the article, the index under the summation should be $\mu = 1$ instead of $\nu = 1$. After calculating the B and M matrices taking the index mistakes into consideration, we can calculate the density matrix ρ according to Eq. (3.20). The n_ν that appear in Eq. (3.20) are the coincidence count rates we measured in the table above.

During the exercise, you just need to do the measurements listed above. I have a script that can perform the density matrix reconstruction that you can use. The results can be sent to you after the exercise.

The reconstructed density matrix ρ_{exp} can be compared with the pure state density matrix ρ_{ideal} that we intend to prepare. By calculating a figure of merit named fidelity $F = (\text{Tr}\sqrt{\sqrt{\rho_{ideal}}\rho_{exp}\sqrt{\rho_{ideal}}})^2$, we know how close our prepared state is to the ideal state. Hopefully a fidelity above 0.95 has been found.

References

[1] John F. Clauser, Michael A. Horne, Abner Shimony, and Richard A. Holt. Proposed experiment to test local hidden-variable theories. *Phys. Rev. Lett.*, 23:880–884, Oct 1969.

[2] Alain Aspect. Proposed experiment to test the nonseparability of quantum mechanics. *Phys. Rev. D*, 14:1944–1951, Oct 1976.

[3] Alain Aspect, Jean Dalibard, and Gérard Roger. Experimental test of bell's inequalities using time-varying analyzers. *Phys. Rev. Lett.*, 49:1804–1807, Dec 1982.

[4] Daniel F. V. James, Paul G. Kwiat, William J. Munro, and Andrew G. White. Measurement of qubits. *Phys. Rev. A*, 64:052312, Oct 2001.

Experiment 2: Two-photon interference

Dayang Li, DTU Fotonik

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Abstract

In this exercise you will see how two identical photons interfere with each other at a beam splitter, producing the characteristic dip in coincidence count rate when the optical path lengths are tuned just right. This effect is called Hong-Ou-Mandel effect, a strong prediction made by quantum optics.

1 The Hong-Ou-Mandel effect

1.1 What is the Hong-Ou-Mandel effect?

To answer this question, let us start by considering a simple case. When a light beam travels in air and hits the surface of another material (For instance a beam splitter, see Figure 1), it will be partially reflected and partially transmitted. Even down to the single photon level this is still true. A photon arriving at an interface will either be reflected or transmitted.
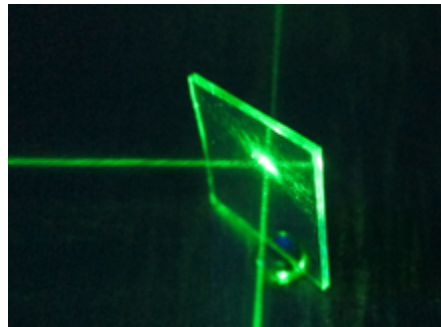

Figure 1: A beamsplitter. A laser beam is launched from the bottom and hits the beam splitter at an angle of incidence of 45 degrees. It is partially reflected (the beam to the left) and partially transmitted (to beam to the top).

So what would happen when we send two of the same photons towards a beam splitter (Figure 1) from the bottom and from the right, at the same time? Quite intuitively we will say that there can be three scenarios, 1) both leave from the left, 2) both leave from the top, or 3) one in each path.

However, the Hong-Ou-Mandel effect predicts that a pair of identical (or in a fancy way, indistinguishable) photons meeting at a beam splitter will constructively and destructively interfere with each other. As a result, both photons should leave the beamsplitter in the same path, there is no way that we can find one photon in each path. In this case, scenarios 1) and 2) originate from constructive interference of two photons, while scenario 3) corresponds to the destructive interference of them.

1.2 Simple explanation of the Hong-Ou-Mandel effect

When a photon arrives at a beam splitter surface, it can either be reflected or transmitted. In most cases, transmission/reflection does not induce a phase change. But being reflected by the back of a beam splitter

gives a phase change of 180° (or π)[1], because light is traveling in a high refractive index material (glass) and is reflected at the interface to a lower refractive index material (air). This means that in the mathematical description the term representing this possibility gets multiplied by a factor of -1.

Now imagine that we have two photons each travelling towards the two input ports of a beam splitter. At the output port we can have the following scenarios. (See also Figure 2)

1. The photon at the upper branch is reflected, the one at the lower branch is transmitted. Both leave the beam splitter from the upper branch.

2. Both photons transmitted. At the exit, one photon leaves at each branch.

3. Both photons reflected. At the exit, one photon leaves at each branch.

4. The photon at the upper branch is transmitted, the one at the lower branch is reflected. Both leave the beam splitter from the lower branch.
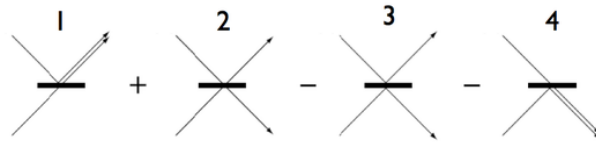
Figure 2: Demonstration of the four possibilities that contribute towards the Hong-Ou-Mandel effect.

In both scenario 2 and 3, one photon leaves each of the exit ports. However, in scenario 3, the photon reflected at the back of the beam splitter gains a 180° phase. Scenario 2 and 3 therefore has opposite phase. And if you still remember from Experiment 1, light is an electromagnetic wave. For waves with opposite phase, we know they destructively interfere, which means that scenario 2 and 3 cancel each other out.

We are therefore left with only scenario 1 and 4, where both photons leave at the same port. If we were to put a detector behind each output port (the upper and lower ports), there will never be simultaneously detection of photons at both detectors.

1.3   (Optional) Quantum optical derivation of the Hong-Ou-Mandel effect

Quantum state at the input
$$|1,1\rangle_{ab} = \hat{a}^\dagger \hat{b}^\dagger |0,0\rangle_{ab}$$

Quantum mechanical beam splitter transformation

$$\hat{a}^\dagger \to \frac{\hat{c}^\dagger + \hat{d}^\dagger}{\sqrt{2}} \quad \text{and} \quad \hat{b}^\dagger \to \frac{\hat{c}^\dagger - \hat{d}^\dagger}{\sqrt{2}}$$

Beam splitter transformation applied on the input state

$$|1,1\rangle_{ab} = \hat{a}^\dagger \hat{b}^\dagger |0,0\rangle_{ab} \to \frac{1}{2} \left(\hat{c}^\dagger + \hat{d}^\dagger \right) \left(\hat{c}^\dagger - \hat{d}^\dagger \right) |0,0\rangle_{cd}$$

$$= \frac{1}{2} \left(\hat{c}^{\dagger 2} - \hat{d}^{\dagger 2} \right) |0,0\rangle_{cd} = \frac{|2,0\rangle_{cd} - |0,2\rangle_{cd}}{\sqrt{2}},$$

$$\frac{1}{2}(c^{\dagger 2} + c^\dagger d^\dagger - c^\dagger d^\dagger - d^{\dagger 2})$$

Figure 3: The input state is the application of one photon creation operator on each of the modes a and b. A mode in quantum optics means light at a specific wavelength, travelling in a specific direction, with a specific polarization etc.. Any operation in quantum mechanics is mathematically a unitary transoformation. The same goes for a beam splitter. When we apply the beam splitter transformation to the input state, we obtain what would emerge from the output ports c and d, namely either two photons in c or two photons in d.

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[1]How do we know which side is the back? When a photon travels into the glass substrate and hits the beam splitting coating then gets reflected, it is reflected by the back.

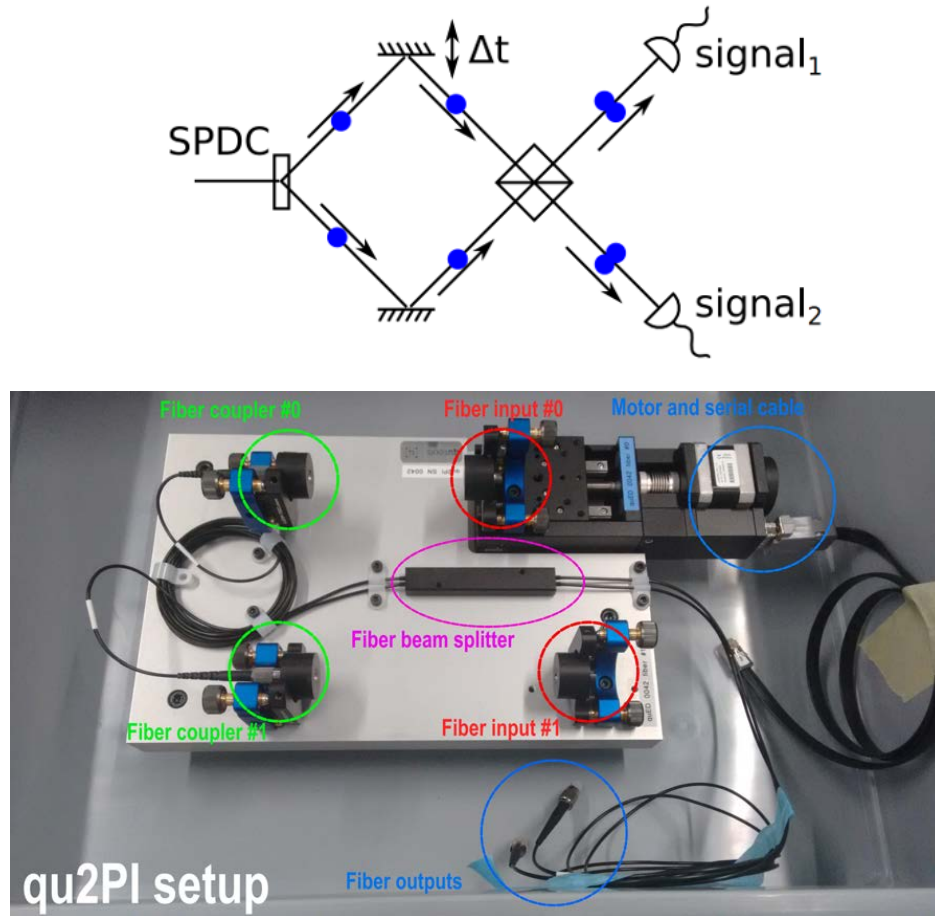# 2 Experimental setup for the demonstration of two-photon interference

Figure 4: The setup we use to demonstrate Hong-Ou-Mandel effect. At the top we have the conceptual schematics, at the bottom we have the actual setup.

To demonstrate the Hong-Ou-Mandel effect, we need a pair of indistinguishable photons, a beam splitter, a variable optical delay line, and a pair of single photon detectors. In Experiment 1 you have already learned how a pair of indistinguishable photons can be generated. Now we just need a Hong-Ou-Mandel interferometer.

The generated photon pairs are sent to this part of the setup in optical fibers, they are connected to the fiber input #0 and #1. As we can see in the setup (Figure 4), the photons then leaves the fibers, travels in free-space, and enters the fiber couplers #0 and #1. After that, the photons travels down the fibers to the left, and interfere at the fiber-based beamsplitter. We are using a fiber based beamsplitter, but the physics is essentially the same as what we have discussed.

The stepper motor in blue circle controls the optical path difference between the two branches, when the distance is set just right, the two indistinguishable photons will be able to arrive at the beam splitter at the same time. At the fiber outputs we expect that both photons emerge from the same fiber. By connecting the fibers to a detector, we can monitor the count rates and especially the coincidence count rate that tells us whether the photons are indistinguishable or not.

3 Experimental procedure

In short, all we need to do is to record the coincidence count rate C as we vary the optical path difference. The key to this demonstration is to find the right optical path delay. On the controller screen (Figure 5), we can set the start and end position of a scan (**Position** and **Target**), the **Stepsize** used in the scan, and how long time we want to measure at each step (**Integration Time**). The absolute values of the **Position** and **Target** are not to be trusted, but the **Stepsize** and width of the dip is meaningful. As a rule of thumb, we need a step size at most half of the width to see a dip at all. Now try and find the dip by yourself!
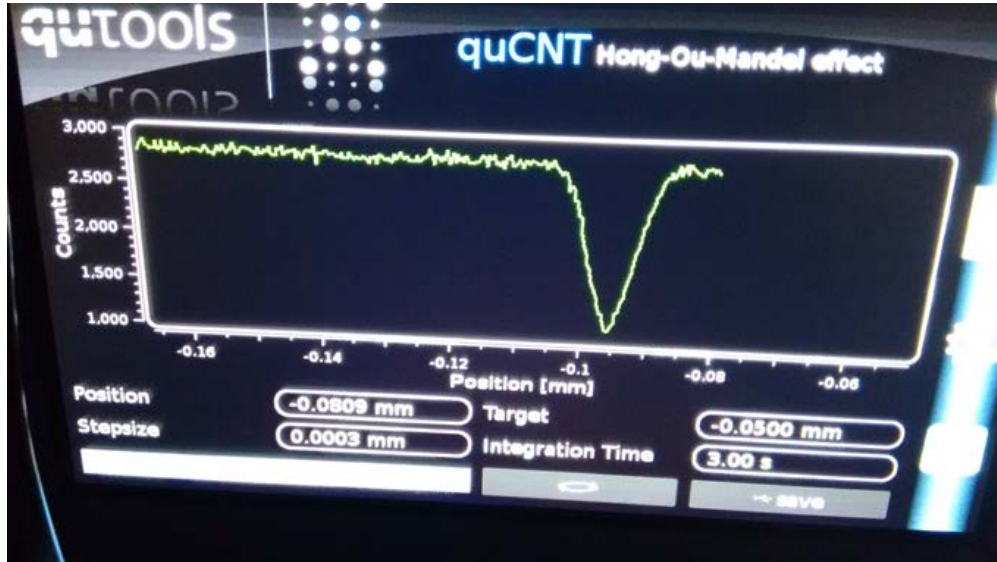

Figure 5: The controller screen that shows the coincidence count rate as a function of the stepper motor position, which is related to the optical path difference.

Actually, the following configurations are all worth trying, and before trying each scenario, please come up with some expectations for the results.

- Both input photons having the same polarization.

- The input photons having the opposite polarizations.

- One photon in horizontal polarization and the other in an even superposition of horizontal and vertical polarization.

3.1 Sources of experimental error

In a perfect world, we can expect Hong-Ou-Mandel effect to give a perfect dip of 0 coincidence when the two photons arrive simultaneously. But why are we seeing a non-zero floor at the minimum?
Hint: Dark count, timing jitter of the detector and the time-tagger (correlator), timing resolution of the time-tagger, imperfections in optical components introducing polarization scattering.