

# Quantum Mechanics Laboratory Kit



## Experiment Manual

Revision 4.0, December 2020

# Quantum Mechanics Laboratory Kit

## A Word to Users

Quantum mechanics is a field of physics that describes how particles and energy behave when they are observed on a very small scale (i.e. the scale of atoms). Because we spend our lives experiencing physics on a much larger scale, many of these quantum properties will seem strange - or even impossible - when first encountered. Although the theory of quantum mechanics can give us a mathematical means to describe these behaviors and predict future results, direct experimental interaction with quantum phenomena is needed to prove their existence and to reinforce the physical experiences that help to build a researcher's or student's "intuition."

This kit was developed to provide exactly that type of direct experimental interaction. The kit is intended for multiple audiences, including:

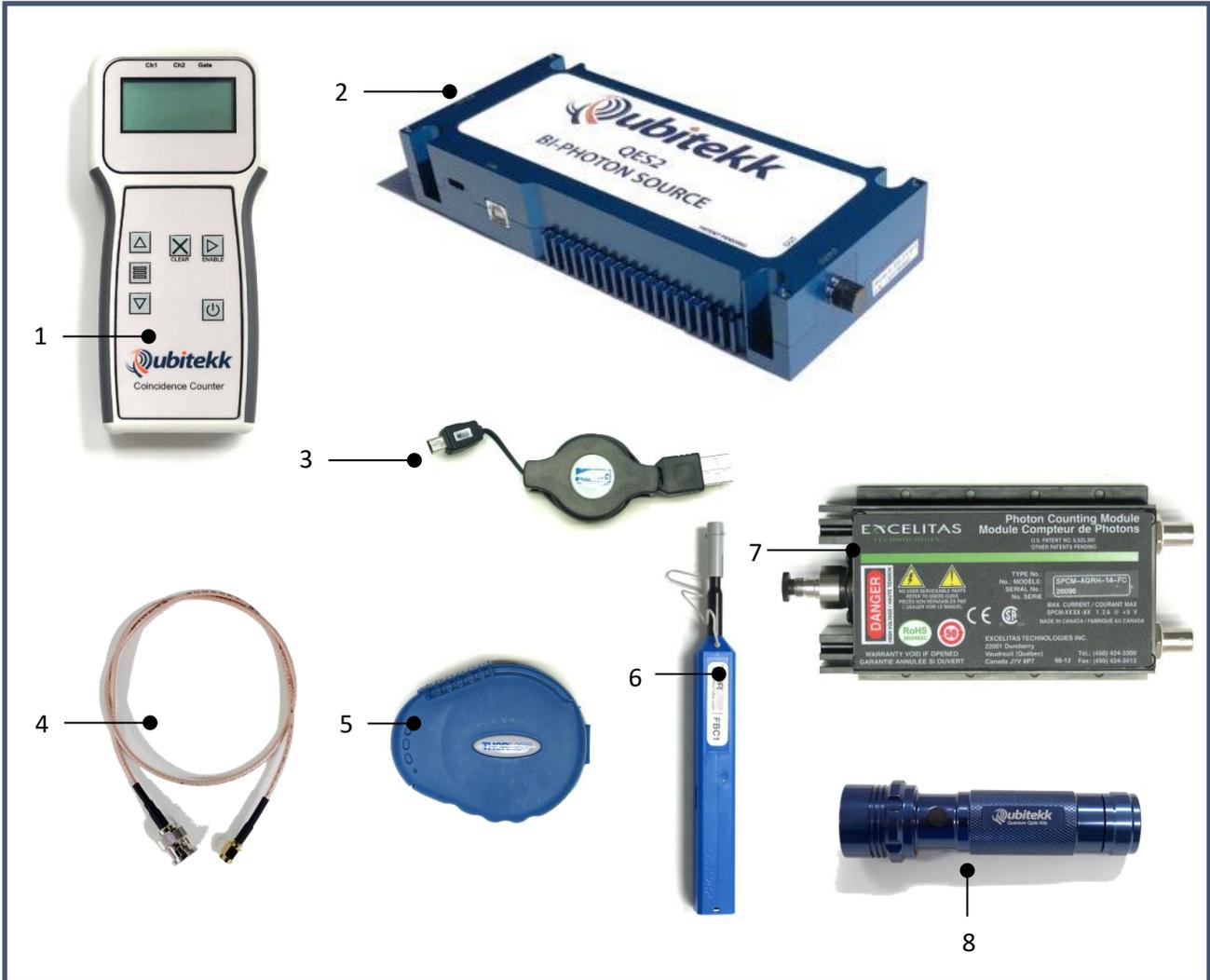
- undergraduate and graduate physics students
- researchers already actively engaged in quantum R&D
- Interested parties with minimal prior exposure to quantum mechanics

Every experiment in this manual has been designed to be understandable to users with minimal prior experience with quantum mechanics. However, inserts have been added that allow for more in-depth study and understanding of the various phenomena depending upon the particular user's background. Inserts shown in blue boxes are intended for graduate physics students while inserts shown in red boxes are aimed at professional researchers.

Regardless of your background, we are confident that you will find this kit useful to gaining a better understanding and comfort with quantum mechanics. Everything needed to perform each of the experiments in the manual has been included in the Quantum Mechanics Lab Kit. Each experiment introduces the user to new aspects of the equipment and theory involved in quantum measurements and builds upon previous experiments. As such, we strongly recommend doing the experiments in the order they appear to get a proper introduction to the equipment and theory involved. Enjoy!

# Quantum Mechanics Laboratory Kit

## Kit Contents

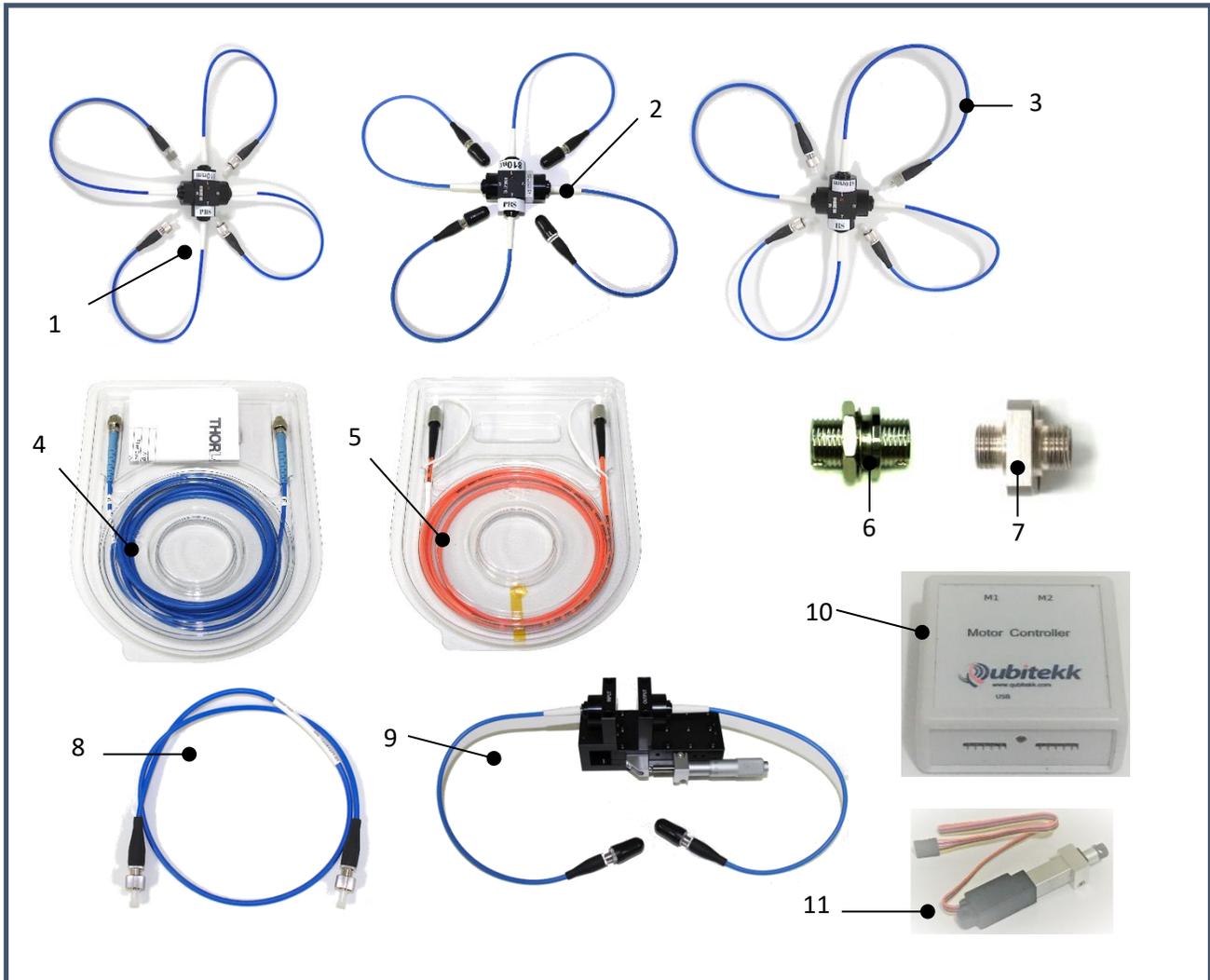


- 1. Coincidence Counter (1)
- 2. QES2 (1)
- 3. Coincidence counter prog. cable (1)
- 4. BNC-to-SMA cables (2)

- 5. Fiber Tip Cleaner (1)
- 6. Fiber Insertion Cleaner (1)
- 7. Single Photon Counting Module (2)
- 8. Flashlight (1)

# Quantum Mechanics Laboratory Kit

## Kit Contents – Continued

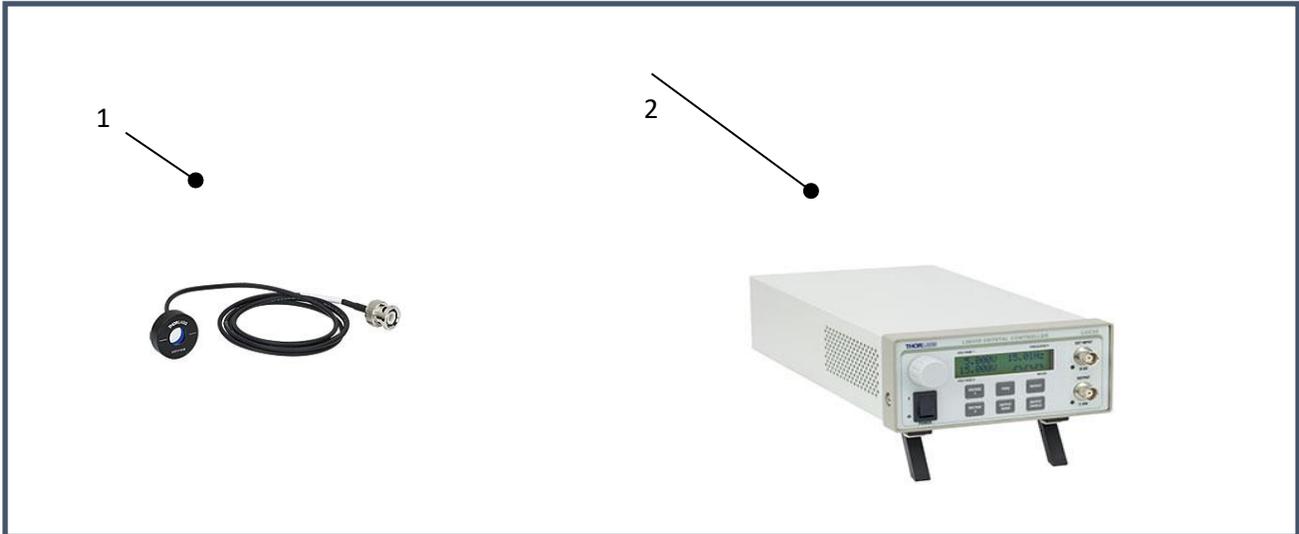


1. 810nm Fiber Optic 2x2 PBS (1)
2. 810nm Fiber Optic 2x2 PBS with 45° leg (2)
3. 810nm Fiber Optic 2x2 BS (1)
4. 810nm Polarization Maintaining Fiber (2)
5. 2m Multimode Fiber (1)
6. Straight Fiber Coupler (7)

7. Rotated Fiber Coupler (3)
8. Fixed Delay Line (1)
9. Variable Delay Line (1)
10. Motor Controller (1)
11. Actuator (1)

# Quantum Mechanics Laboratory Kit

## Kit Contents – Continued



1. Liquid Crystal Variable Retarder (LCVR)  
(1)

2. LCVR Controller

# Quantum Mechanics Laboratory Kit

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# Quantum Mechanics Laboratory Kit

## Notes on Component Handling

When handling the components in the Quantum Mechanics Lab Kit, special care should be taken with the optical fibers and Single Photon Counting Modules (detectors). The following procedures should be used when handling these components:

### OPTICAL FIBER HANDLING AND CARE

Nearly all of the optical fibers in the Quantum Mechanics Lab Kit have FC/PC fiber optic connectors at their ends. The face of these connectors has a precision polish that ensures efficient coupling of light when two connectors are mated together. These connectors must remain clean and must be properly inserted into mating connections to work properly. Failure to clean the fiber connectors before use can, in some situations, permanently damage the optical connector and result in high optical loss. When handling the optical fibers in the QES2 kit, please remember these four rules:

1. Don't Kink
2. Clean Frequently
3. Check Your Rotation
4. Store Properly

#### *Don't Kink*

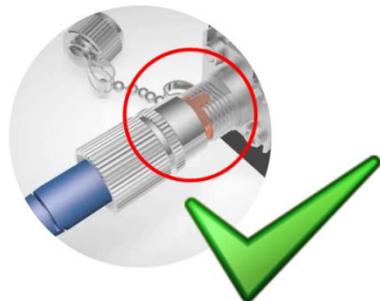
Care should be taken to never bend the optical fiber around a radius of less than one inch. If you "kink" the fiber, or pinch it, this may result in the fiber breaking.

#### *Clean Frequently*

It is recommended to clean optical connectors prior to every insertion into a mating sleeve. This can seem tedious but, if followed, will ensure that your connectors operate at their maximum efficiency. More importantly, it will also ensure that dirt doesn't get introduced into your mating sleeves. See the following section for details on how to clean connectors and mating sleeves using the tools provided with the kit.

#### *Check Your Rotation*

Each fiber optic connector possesses a small metal alignment feature, or **key**. To properly insert a connector into a mating sleeve, the connector's alignment key must be properly rotated to align with the mating sleeve's keyway.



**IMPROPER ALIGNMENT OF THE KEY AND KEYWAY IS THE NUMBER ONE CAUSE OF POOR CONNECTIONS!**

Always check that the connector's key is rotated so that it is aligned with the corresponding keyway.

*Store Properly*

All fiber optic cables are provided with protective end caps and hard-cased containers for long-term storage. Whenever a cable is not in use, immediately replace the protective end caps and, when possible, store them in their proper storage containers.

**CLEANING FIBER OPTIC CONNECTORS AND MATING SLEEVES**

Two tools are provided for keeping your fiber optic connections clean. One tool is used for cleaning fiber optic connectors while the other is used for cleaning fiber optic mating adapters.

To clean fiber optic connectors, follow the instructions below:

- Using the FCC-7020 Fiber Cleaning Cloth Spool (Figure 1), tear off one perforated section of cloth to position a clean section in the Thumb Slide window. Then open Thumb Slide as shown in Figure 2.
- Remove protected End Cap (Figure 3) from fiber cable and gently place fiber end at 10° angle onto cloth window.
- While applying very light pressure, gently swipe fiber end inside cloth window with a motion of two to three consecutive figure eight patterns (see Figure 4). Immediately place into pre-cleaned port (see instructions that follow for fiber port cleaning)



Figure 1



Figure 2

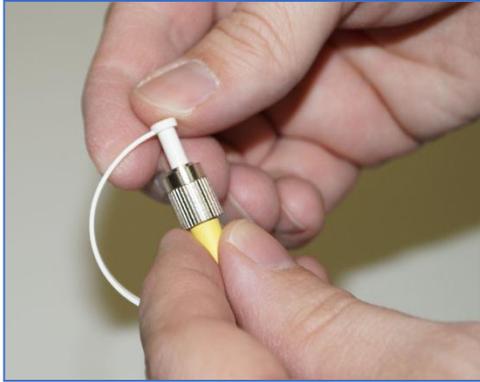


Figure 3



Figure 4

To clean fiber optic mating sleeves, use the FBC-1 insertion cleaner (Figure 5). Fiber optic mating sleeves are found on the Single Photon Counting Modules, and the Fixed and Variable Delay Lines.

To clean fiber optic mating sleeves, follow the instructions below:

- Remove dust cap from FBC-1 (Figure 5). Leave nozzle (sliding extender tab) in “Standard” position unless port depth is difficult to reach.
- Insert FBC-1 into Optic Port (Figure 6) and apply medium pressure until a click is heard. The port should now be clean.



Figure 5



Figure 6

### DETECTOR HANDLING AND CARE

The Single Photon Counting Modules (SPCM) are very high sensitivity optical detectors that are sensitive to levels of light below what the human eye can detect. As such, they can be damaged if they are exposed to high light levels while powered on. To protect the SPCMs, observe the following four rules:

1. Keep room lighting at a minimum
2. Do not apply power to the SPCMs until the experiment is completely set up

3. Before removing a fiber from the SPCM's front adapter, make sure the power is off
4. When possible, cover the detectors with a dark cloth material to reduce background noise and limit the possibility of accidental over-exposure

The fiber optic adapter on the front of the SPCM should always have an optical fiber attached to it when powered on. NEVER leave the SPCM's front ports open or uncapped in a fully lit room when power is applied.

**DO NOT EXPOSE SPCM TO  
HIGH LEVELS OF LIGHT!**

**DIM OR TURN OFF AMBIENT ROOM  
LIGHTING WHEN SPCM IS IN USE.**

# Quantum Mechanics Laboratory Kit

## Laser Operation and Safety

The QES2 bi-photon source included in your Quantum Mechanics Lab Kit includes a laser that is designed to produce a very stable and precise wavelength, or color, of light. The laser has special electronics that ensure that the output wavelength does not vary over time, an important requirement for the experiments in this manual. More technical details on the laser can be found in the “Matchbox 2 Manual” included with your kit. In this section, we will provide an abbreviated description of the basic operation and safety aspects of the laser.

### Laser Safety

The laser embedded in the QES2 is capable of producing up to 15mW of continuous blue (405nm) light. Based solely on this output level, the laser is categorized (and labeled) as a Class 3B laser – meaning it can damage your eye or retina if the laser light shines into your eye. For this reason, **users should not attempt to open the QES2 under any circumstances**. If problems arise with the QES2, it should be returned to Qubitekk for assessment and repair. As long as the integrity of the QES2 is maintained, the device is categorized as a Class 1 laser device and no special laser safety precautions are needed.

### How to Operate the Laser

When power is provided to the QES2, the laser is automatically switched on. Once powered, a short “warm-up” period of 45 seconds is recommended in order for the temperature to stabilize.

# Quantum Mechanics Laboratory Kit

## 01 Experiment

### Measuring Single Photons: Light as a Particle

#### → What you will learn

Quantum mechanics describes the behavior of particles and energy at the very small scale. One of the easiest particles to work with in exploring quantum phenomena is the photon. In this experiment you will learn how to detect and measure single photons and how to statistically characterize the noise in a measurement. You will specifically learn how to:

- Operate photon counting detectors
- Measure coincident photons
- Configure a coincidence counter
- Measure dark noise
- Compute accidentals
- Set up a fiber optic apparatus

These are fundamental skills that will be used in all experiments throughout this manual.

#### → What you will need

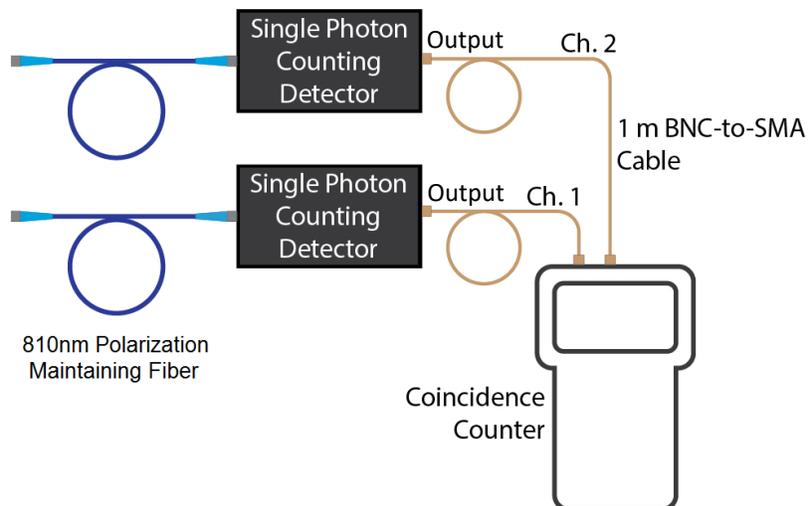
The following experimental components will be needed:

- Flashlight
- Single Photon Counting Modules (2)
- 810nm Polarization maintaining fiber (2)
- 1 meter BNC-to-SMA cable (2)
- 5 meter BNC-to-BNC cable
- 1 BNC-to-BNC Coupler
- Coincidence Counter

#### → Initial Setup

**IMPORTANT:** If you haven't already, read the "Notes on Component Handling" prior to beginning work. The Single Photon Counting Modules should not be plugged in until all fibers are connected and the room lights are dimmed.

Assemble the experimental components as shown in the figure below. Remember to always clean the fiber optic cable tips prior to inserting them into any mating sleeves or devices.



# Quantum Mechanics Laboratory Kit

## → *What you need to know...*

Welcome to the world of Quantum Mechanics! This first experiment is going to explore what light is and how we measure it in quantum experiments. Light is all around us. Some of it we can see (i.e. visible light) and some of it we cannot (i.e. infrared, x-rays, radiowaves, etc.). Scientists have been studying light for a long time. What have they learned after hundreds of years of study and numerous experiments? That a true comprehension of the nature of light is elusive and complex.

Fundamentally, light can behave in two distinctly different ways. On one hand, light behaves like an electromagnetic wave. A “light wave” is a propagating oscillation of electric and magnetic fields in space. Light waves can be split and combined, they can diffract around edges, they can be spread over large expanses of space. On the other hand, light can behave as a particle. A particle of light – or a **photon** – has momentum and a fixed amount of energy. **It cannot be split or divided.** It is localized to a specific location in space and time.

Is light a particle or a wave? These behaviors are contradictory, yet both have been separately verified through competing experiments. If we want to successfully predict the behavior of light, it would seem we must prove it is EITHER a particle or a wave.

This confounding difference – referred to as the **wave-particle duality of light** – is, in part, what spurred the development of quantum mechanics. In the experiments that follow, we will not resolve the question of whether light is a particle or a wave. In fact, in some experiments we will refer to light’s wave-like properties while in others we will refer to its particle-like properties. The goal of these experiments, however, is to demonstrate that light appears to behave as BOTH a particle and a wave. Most importantly, there is a theory - **quantum theory** - that can represent and model this strange contradiction in a way that successfully predicts experimental results.

In this first experiment, we will be treating light as a particle - a photon. Many, many billions of photons make up the visible light that we see around us every day. To study quantum mechanics, however, we will need to examine the behavior of only a few photons at a time. One can easily produce billions of photons with a flashlight. Producing single photons reliably, however, is much more challenging.

There are many ways to produce single photons and one of these techniques will be covered in the next experiment. However, in this experiment we want to first learn how to detect and measure single photons. To do this, we will be using a single photon counting module (or **SPCM**). This type of detector produces an electrical pulse every time a photon is absorbed by the detector’s sensor.

Einstein was awarded the Nobel prize for explaining that an optical detector can only detect a whole photon (not a half, quarter, etc. of a photon). His work led to the recognition that light is made up of tiny photons that each have a fixed, quantized, amount of energy. Bright light is made up of many, many

individual photons, while dimmer light has fewer individual photons. Although the number of photons may change, the energy in any one photon is always the same.

When one of these photons is launched into a SPCM, the SPCM converts the photon into an electrical pulse. As shown below, a 10ns 2.2 volt electrical pulse is produced by the SPCM whenever a photon is detected.



This detector provides a convenient method for detecting photons. However, the device has limitations. While the 10ns pulse is being produced, the SPCM is unable to produce another pulse – even if additional photons are absorbed. Furthermore, after the 10ns electrical pulse is emitted, the SPCM requires an additional 12ns to “reset” before it can measure another photon. The total “deadtime” for the SPCM - or the amount of time between subsequent photon measurements – is therefore 10ns + 12ns = 22ns. Because of this deadtime, the SPCM can only measure and resolve a maximum of 37,000,000 photons per second.

**What if two photons hit the detector at exactly the same time?** Unfortunately, this event would still result in only one pulse being produced. The SPCM is unable to resolve whether one, two, or many photons reach the detector, or are **incident**, at the same time. Because of this limitation, many quantum experiments require a photon source that only produces a very small number of photons per second. This reduces the probability that a SPCM will encounter two photons simultaneously.

The electronic output from an SPCM can be read by various digital devices. For this experiment, we will use a “coincidence counter” to count the pulses emitted from an SPCM. This experiment will demonstrate how to use SPCMs and a coincidence counter to detect and measure single photons.

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→ *Experimental Procedure*

### Measurement 1: Measuring Dark Counts

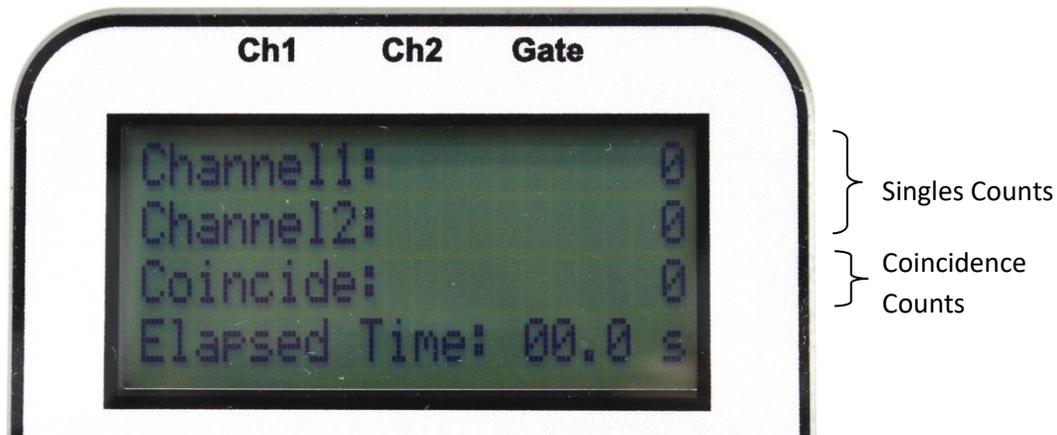
Assemble the initial experimental setup as shown on the first page of this experiment. Remember to clean the optical fiber tips before inserting them into the Single Photon Counting Modules (SPCMs). Do

not provide power to the SPCM units until the optical fibers are fully connected and the room lights are dimmed. Apply power to the coincidence counter by plugging in its USB cable and associated USB power adapter (as shown below).



With the setup configured and power supplied to the coincidence counter and SPCMs, you are now ready to start counting photons.

The coincidence counter has two main channels – Channel 1 and Channel 2. High-speed electronics inside the device count the number of electrical pulses received on each channel over a certain period of time (called the “dwell time”). For a given dwell time, the received pulses on a particular channel will be counted and displayed. This is called the “singles count.” As shown below, the coincidence counter displays a singles count for Channel 1 on line 1 and another singles count for Channel 2 on line 2.



Occasionally, an electrical pulse might be received on Channel 1 while another electrical pulse is received on Channel 2 at exactly – or nearly exactly – the same time. This would be called a “**coincident**” event, and a coincidence measurement would be registered. The number of coincident events detected between two channels (in a given dwell time) is called the “coincidence count” and is displayed on line 3 of the coincidence counter.

**How close do a pulse on Channel 1 and a pulse on Channel 2 have to be before they are considered a coincident pulse?** That depends on how the coincident counter is configured. The “coincidence window” can be adjusted on the device to be anywhere from 1ns to 8 ns. The larger the coincidence window, the more likely coincidence events will be detected.

Coincident pulses can occur by accident or by design. If the pulses on Channel 1 and Channel 2 occur randomly and are unrelated, then any coincident pulses that are detected will be by “accident.” The probability of accidentally detecting two random pulses at the same time is given by the following formula:

$$\text{Accidentals} = \frac{2(\text{Coincidence Window (sec)})(\text{Channel \#1 Singles})(\text{Channel \#2 Singles})}{\text{dwell time (sec)}} \quad (\text{Equation 1})$$

“Accidentals” are a result of statistics and can be calculated based on the singles counts on Channel 1, the singles counts on Channel 2, the dwell time, and the coincidence window.

Sometimes, the detection of a photon on Channel 1 and a photon on Channel 2 is not an accident. In later experiments, we will generate bi-photons. **Bi-photons** are two photons created at exactly the same point in space and time. Experiments with bi-photons often result in coincidence counts. These “coincidences” are quite intentional and they will help us to measure certain quantum effects.

When measuring single photons, it is important to be able to differentiate between accidental coincidences and intentional ones. This experiment will help you know the difference.

By default, when the coincidence counter is first turned on, it will have a dwell time of 2.0 sec and a coincidence window of 1ns. **The counts can be updated by pressing the “START/STOP” button on the front panel.**

Depending on how bright your room is, it is typical to see single counts on Channel 1 and Channel 2 between 1,000 and 20,000 counts. This means that photons in the room are finding a way into the detectors. The most likely way is through the open ends of the optical fibers, which transmit light to the detector.

Remove the fiber end caps and point the fiber ends toward different bright spots in the room to see the number of detected photons increase or decrease. (Don’t point the fibers at anything too bright or it will **saturate** your detectors – which can damage them if prolonged. Make sure the counts never read “Overflow”.)

Now turn off all the lights in the room and try to make the detectors see as few photons as possible. You might even want to cover the detectors and optical fibers with a jacket or a cardboard box. Notice that no matter how dark you make the room, it is not possible to make the singles counts go to zero. There are always some detector pulses. If your room is completely dark, this level is called the “**dark count**” for the detector. These dark counts are phonon-induced avalanches in the detector itself and can be reduced removed by cooling the detector to very low temperatures. Make a note of the approximate dark counts for Channels 1 and 2 and then divide them by 2. Because the coincidence counter is making measurements

every 2.0 seconds, we have to divide by 2 to calculate the counts per second. Record the results in the following table:

Channel 1 Dark Counts/Second	
Channel 2 Dark Counts/Second	

### Measurement 2: Measuring Coincidence Counts

Turn the room lights back on and try to increase the singles counts to levels somewhere between 10,000 and 50,000 counts. You might need to point the fiber ends at a bright section of room or even use the flashlight that is included with the kit. Once you have singles values in the tens of thousands, continue to the next step.

For this measurement, we need to configure the coincidence counter to make more precise measurements. We're going to set the coincidence window to 1 nsec, and the dwell time to 2 seconds. To do this, click on the menu button (  ) on the front of the coincidence counter. Your LCD should look as follows:



Use the up and down arrows on the coincidence counter to move the arrow to the "Coin Window" line. Once there, press the "SELECT" button on the coincidence counter. Use the up and down arrows to select and set the coincidence window to "1 ns" on the menu display. To accept this value, press the "SELECT" button again on the coincidence counter. Perform a similar operation for the "Dwell Time" line and set it to "02 s". When finished, press the menu button again to return to the startup screen.

With the coincidence counter configured, press the "START/STOP" button on the coincidence counter to trigger a measurement. The coincidence counter will begin accumulating counts for 2 seconds. When complete, it will pause and display the final counts indefinitely (or until the power button is pressed again, thereby triggering a new measurement. Depending on your room lighting, you should have measured around 10,000 – 50,000 photons on channels 1 and 2. Record these values on the next page, plus the coincidence count rate:

Channel 1 Singles Count	
Channel 2 Singles Count	
Coincidence Counts	

Because room lighting is random, the photons being detected by one detector should rarely correspond – or be correlated with – photons detected by the other detector. Any coincident events are most likely just “**accidental**” coincidences. Given the singles counts on Channels 1 and 2, and the Dwell Time and Coincidence Window configured on the coincidence counter, calculate the Accidental counts using Equation 1, described earlier. Record the calculated accidentals here:

Calculated Accidentals	
------------------------	--

The calculated accidentals and the measured coincidences should be similar.

Next, change the coincidence window to 8 ns and record the measured singles and coincidence counts with these settings:

Channel 1 Singles Count	
Channel 2 Singles Count	
Coincidence Counts	

The singles counts should not have changed much from our previous measurement. The coincidence counts, however, should now be nearly eight times larger. This makes sense since any two pulses that occur within 8 ns (versus 1 ns) are now being counted as coincident events.

With the new 8 ns coincidence window, calculate the expected accidental rate again.

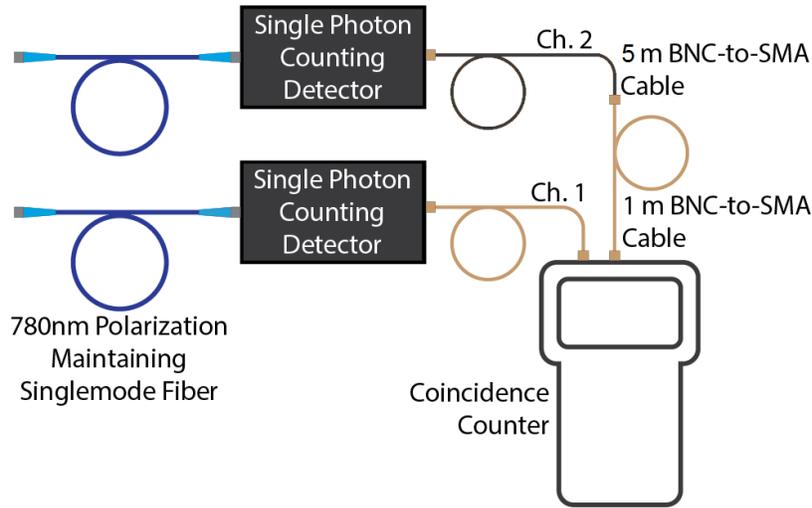
Calculated Accidentals	
------------------------	--

The calculated accidental rate should again be very similar to the measured coincidence rate.

### Measurement 3: Measuring Temporal Sensitivity

Leave the coincidence counter configured as it was in the last experiment. However, this time take the 1m BNC-to-SMA cable on Channel 2 and add a 5 meter BNC-to-BNC cable to it. Use the BNC-to-BNC coupler to join the cables together. Because the cable on Channel 2 is five meters longer than the cable on Channel 1, this will introduce a delay between the pulses generated on Detector 1 and Detector 2.

Specifically, every one meter of coaxial cable introduces 5 nsec of delay. So, the added five-meter cable will cause a delay of roughly 25 nsec.



Record the singles and coincidence counts with this configuration in the following table:

Channel 1 Singles Count	
Channel 2 Singles Count	
Coincidence Counts	

Notice that the coincidence counts are the same with or without the delay. This is typical of accidental counts or uncorrelated photon emissions. As we will see in future experiments, this measurement is a good way to test for bi-photon activity.

An even more accurate measurement of the temporal sensitivity of any coincidence activity is to measure the coincidence counts for increasing delays between Channels 1 and 2. Because this would be tedious to do by continually changing out cable lengths, a delay parameter has been built into the coincidence counter.

Remove the 5m BNC-to-BNC cable on Channel 2, leaving just the 1m BNC-to-SMA cable connected to Channel 2 on the coincidence counter. Adjust the coincidence counter to have a Dwell Time of 1 second and a coincidence window of 1 ns. In addition, verify that the parameter labeled "Ch 1 Delay" is set to 0 ns. Measure and record the coincidence counts with these settings. Repeat the measurement with the Delay set to 2 ns. Continue this for all Delay settings from 0 ns to 14 ns. Chart the variation in coincidence counts in the graph below, and scale your Y-axis as needed. (Note, when making subsequent measurements, be careful not to vary the room lighting or variably shade your setup, the singles counts on Ch 1 and 2 should stay constant.)

SPDC Photon Arrival Time					
Delay (ns)	Channel 1	Channel 2	Coincidences	Accidentals	Coincidences – Accidentals
0 ns					
2 ns					
4 ns					
6 ns					
8 ns					
10 ns					
12 ns					
14 ns					

**Temporal Sensitivity**



You should see a graph that is relatively flat – meaning there is little to no temporal sensitivity in your coincidences. Another way to say this is that the coincidence counts have been confirmed to be completely accidental. They are the result of the accidental, simultaneous detection of random photons and - whether an electronic delay is present or not – will still occur with the same frequency.

As we will see in future experiments, coincidence counts associated with quantum phenomena will be strongly dependent on delays. If we had been measuring bi-photons, for example, then we would expect to see a strong peak in the coincidence counts for a specific delay (typically around 0 nsec).

### **What is a Measurement**

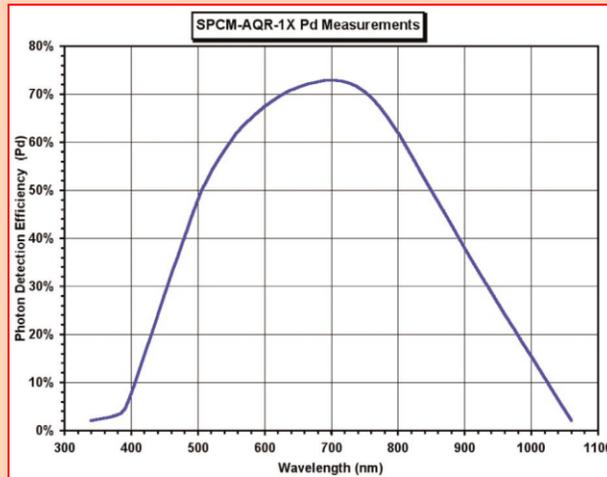
When a photon gets absorbed by a detector, the photon is converted into an electrical charge through the photoelectric effect and its arrival and “capture” by the detector is recorded. When used inside of a particular optical apparatus, this detection event can be used to “strongly” measure the properties of the photon (such as its polarization, wavelength, etc.). These types of measurements are called “strong” measurements. In the process of measuring the photon, it should be noted that the photon is destroyed.

However, what if a measurement apparatus was developed that was purposely “bad” at making measurements? For example, imagine an apparatus that was designed to measure photon polarization but it only worked one in a hundred times. This type of measurement would be called a “weak” measurement and its impact on the properties of the photon would be more difficult to describe.

For delicate quantum experiments (which will be discussed in more detail in Experiment #5), weak measurements may provide a way to measure quantum properties without influencing them. Research into “weak measurements” is pushing the boundaries of how scientists define a measurement and may one day provide a way to observe and probe complex quantum phenomena more completely.

## Detector Efficiency

The Single Photon Counting Modules used in this kit are Silicon-based avalanche photodiode detectors (or Si-APDs) that are sensitive to light in the 350nm to 1050nm range. The photon detection efficiency of these detectors varies with wavelength as shown below:



At their best, commercial Si-APDs are 73% efficient at around 700nm. Unfortunately, for some applications - such as quantum computing - higher detection efficiencies are needed. For other applications - such as quantum cryptography - detectors sensitive to longer wavelengths are needed. Si-APDs represent a very convenient and affordable detector for some experimental work and demonstrations but, for many applications, are unsuitable.

For telecommunication applications, wavelengths around 1550nm are more common because of the minimal optical absorption of optical fibers at these wavelengths. The detectors included in this kit are obviously not sensitive and/or suitable at these wavelengths. For researchers doing quantum cryptography at telecom wavelengths, InGaAs/InP detectors (sometimes referred to simply as “in-gas” detectors) are more commonly used. These detectors can detect photons between 1100nm and 1700nm but, at best, have a detection efficiency between 10% and 25%. This can introduce significant errors into communication schemes that must be carefully addressed and compensated for.

Recently, Superconducting Nanowire Single Photon Detectors (or SNSPDs) have provided an exciting new avenue for detector development. SNSPD detectors are now available commercially that deliver photon detection efficiencies greater than 90%. However, these detectors are significantly more expensive and require sophisticated cryogenic systems to cool the detectors to temperatures often below 1 K. Nonetheless, SNSPDs can deliver very low dark noise, can measure many photons per second, and can even distinguish between single and multiple detected photon events. In addition, they work over a very, very wide wavelength range (500nm to 5000nm).

Developing efficient, reliable, and affordable single photon detectors represents a significant technological hurdle that must be overcome to realize many quantum applications.

# Quantum Mechanics Laboratory Kit

## 02 Experiment

### Generating Bi-Photons

#### → What you will learn

In this experiment, you will learn how to generate and measure bi-photons. You will specifically learn how to:

- Understand SPDC variables
- Measure/calculate coincidence ratio
- Perform temporal tests for bi-photons
- Configure a bi-photon source to produce degenerate or non-degenerate photons
- Use a polarizing beam splitter to separate Type II bi-photons

Bi-photons have applications in many areas of quantum research and will be used in all subsequent experiments in this manual.

#### → What you will need

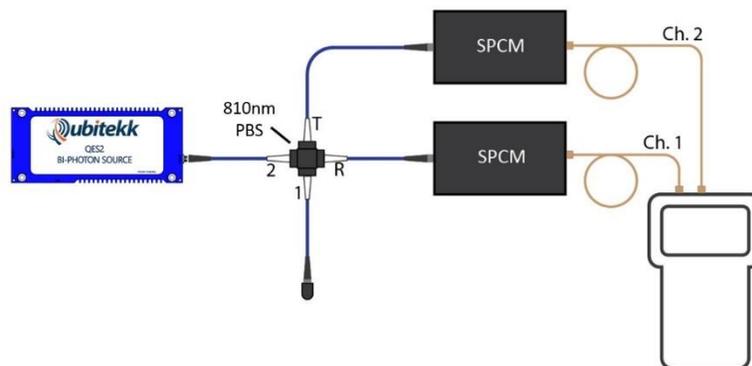
The following experimental components will be needed:

- QES2 Bi-Photon Source (1)
- 810nm Fiber Optic PBS (1)
- Single Photon Counting Modules (2)
- 1 meter BNC-to-SMA cables (2)
- 5 meter BNC-to-BNC cable (1)
- 1 BNC-to-BNC Coupler (1)
- Coincidence Counter

#### → Initial Setup

**IMPORTANT:** The Single Photon Counting Modules should not be plugged in until all fibers are connected and the room lights are dimmed.

Assemble the experimental components as shown in the figure below. Remember to always clean the fiber optic cable tips prior to inserting them into any mating sleeves or devices.

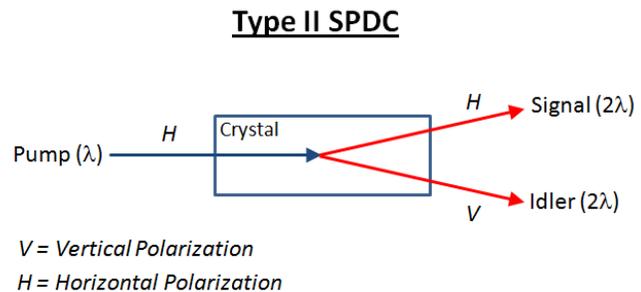


# Quantum Mechanics Laboratory Kit

## → What you need to know...

In the previous experiment, we measured single photons randomly produced by light sources within the room. In this experiment, we want to produce small amounts of photons from a well-defined location and with a very specific wavelength and polarization.

There are many ways to produce single photons but this experiment will focus on a technique called “spontaneous parametric down-conversion,” or SPDC. When light of a particular wavelength ( $\lambda$ ) is focused into a certain crystal, the light can be absorbed by the crystal atoms and re-emitted as two photons at twice the wavelength ( $2\lambda$ ) – a process called **down-conversion**. The light coming into the crystal is called the “pump” beam, while the two photons produced are called the “**signal**” and “**idler**” beams (see figure at right).



For example, if a pump photon of blue light (405nm) is focused into a properly cut crystal, it can be absorbed and re-emitted by the crystal as a red (810nm) signal and a red (810nm) idler photon. Because the energy of a photon is inversely proportional to its wavelength, each red photon has half the energy of the original blue pump photon. **Therefore, the energy of the pump photon has been converted downward – or “down-converted” – into two lower energy photons.** Physicists studying this process noted that the process was driven by fluctuations in quantum vacuum fields and was dependent on the phase relationship between the input/output fields (topics outside the scope of this kit) and this was the origin of the more complete name we use today of Spontaneous Parametric Down-Conversion (or SPDC).

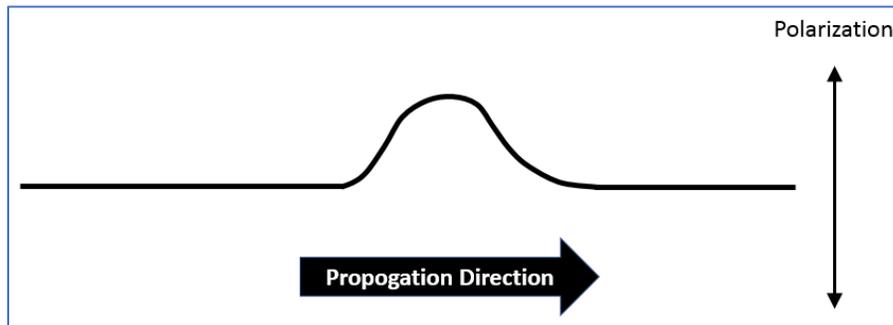
Spontaneous Parametric Down-Conversion is not an efficient process. If 100 billion pump photons enter a crystal, only one or two might actually be down-converted into a signal and idler pair. The rest simply pass through the crystal without undergoing any change. This inefficiency is advantageous when trying to produce single photons. It provides a controllable way of generating very low numbers of photons at a very precise wavelength. Plus, it produces these photons in pairs (or bi-photons) – a feature that is very valuable for quantum optics research and applications. For example, when two photons are produced at exactly the same time, one can be detected and used as an indicator that the pair was produced. This leaves the other undetected photon undisturbed and available for other measurements. Using one photon to signal the presence of another photon is called “**heralding**.”

The efficiency of SPDC depends on a number of parameters, including:

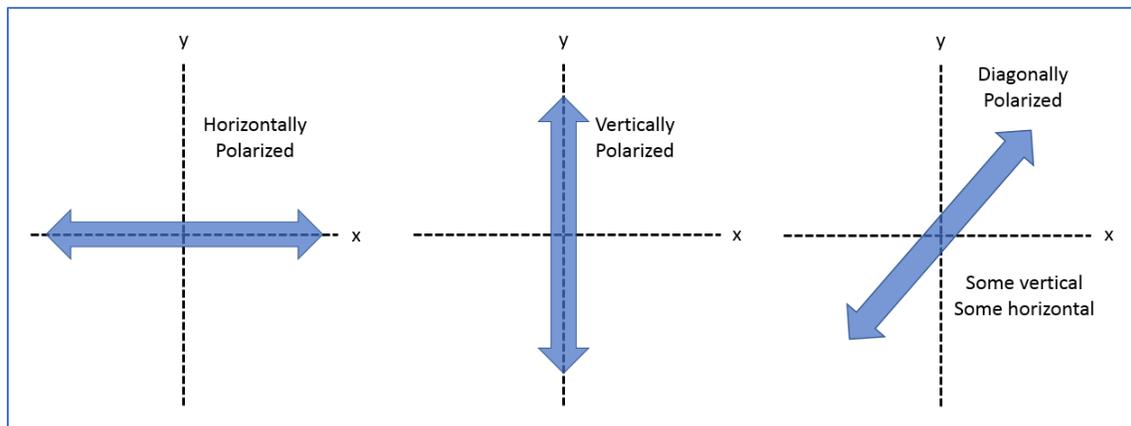
- the intensity of the pump beam

- the wavelength of the pump beam
- the polarization of the pump beam

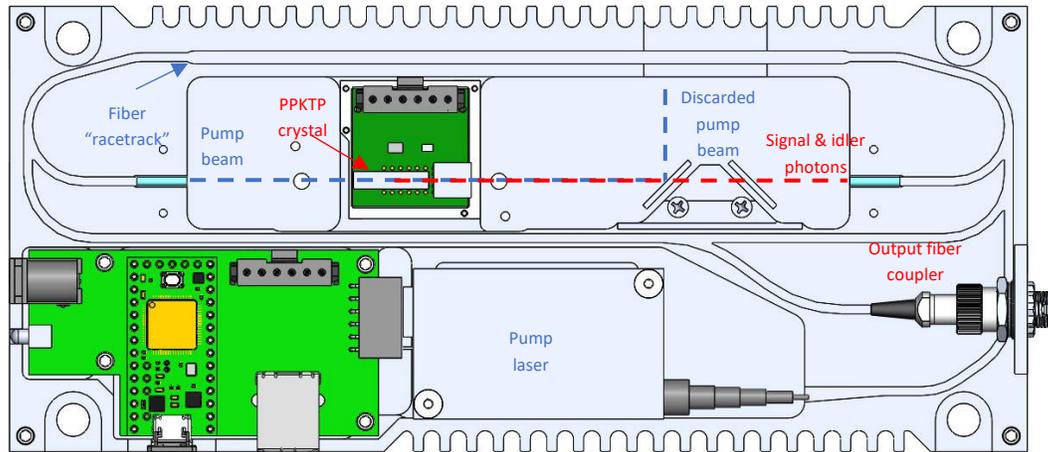
In addition, how the crystal is cut determines the “polarization” of the signal and idler photons. If we think of light as an electromagnetic wave, polarization is the direction in which the electrical field is oscillating. Just as a wave on a string has a particular direction in which the string oscillates, so too does a photon’s electric field - and we call this oscillation direction its **polarization**.



At a very simple level, a photon’s electric field can be oscillating parallel to the horizon (horizontally polarized) or perpendicular to the horizon (vertically polarized), as shown in the figure below. We will represent a horizontally polarized photon with the letter **H** and a vertically polarized photon with the letter **V**. Polarization can even be at some angle between horizontal and vertical (commonly called diagonal).



A crystal cut for Type-I SPDC will produce bi-photons with the same polarization (i.e. both H or both V). In contrast, Type II SPDC produces bi-photons with perpendicular polarizations (one H, one V). The QES2 in your experimental kit has been designed for **Type-II SPDC**. The figure below shows a simplified view of what is inside the QES2.



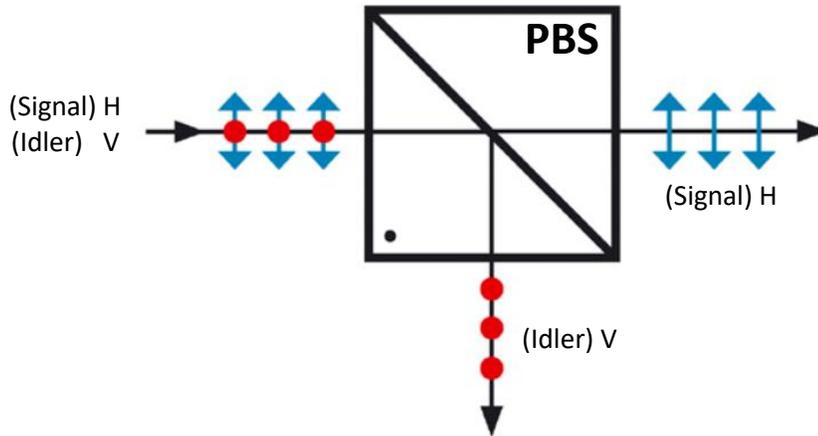
A long crystal made out of a **periodically-poled Potassium Titanyl Phosphate** (or PPKTP) is needed to create the SPDC output. This crystal down-converts an H-polarized blue (405nm) pump photon into an H-polarized “red” (810nm) signal photon and a V-polarized “red” (810nm) idler photon. The pump light is delivered to the PPKTP crystal via an optical fiber, and a second fiber carries the signal and idler photons to the output fiber coupler. A dichroic mirror before the second fiber separates the two colors of photons and ensures that only the red signal and idler photons get collected by the output optical fiber (thereby eliminating the pump photons).

The QES2 also has a small heater which can change the temperature of the crystal. As the temperature of the crystal is changed, the wavelengths of the emitted signal and idler photons will change. For a given pump wavelength, there is a unique crystal temperature that will produce signal and idler photons with exactly the same wavelength. When the two photons have the same wavelength we call the photons **degenerate**. When the signal and idler photons have different wavelengths, we call them **non-degenerate**.

**SAME Wavelengths = DEGENERATE**  
**DIFFERENT Wavelengths = NON-DEGENERATE**

The QES2 is designed to produce at least 10,000 signal and idler photon pairs per second for every 1mW of pump beam. The QES2 collects BOTH the signal and idler photons into a single outgoing fiber. In this experiment and others, we don't want both photons to be in the same fiber. Therefore, we must find a way to separate the photons.

To do this, we can use a fiber optic **polarizing beamsplitter** (or a PBS). A polarizing beamsplitter transmits H-polarized light and reflects V-polarized light. As such, it can be used to separate horizontally polarized signal photons and vertically polarized idler photons into separate paths, as shown in the following figure:



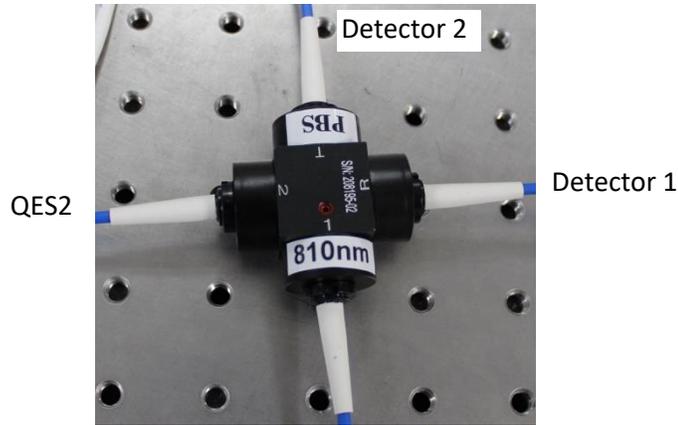
Being able to separate our bi-photons based on their polarization will allow us to manipulate each photon separately and will be useful for later experiments.

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→ *Experimental Procedure*

### Measurement 1: Measuring Temporal Sensitivity

Assemble the setup as shown at the beginning of the experiment. Make sure to use a straight coupler between fibers, not a rotated coupler, and orient the PBS as shown below. Remember to clean the optical fiber tips before inserting them into the Single Photon Counting Modules (SPCMs) or the fiber coupler. Do not provide power to the SPCM units until the optical fibers are fully connected and the room lights are dimmed. Do not yet turn on the QES2.



With the QES2 off, dim the room lights and supply power to the SPCM detectors. Configure the coincidence counter with the following settings (review Experiment #1 if you need help configuring the coincidence counter):

Coincidence Counter Settings	
Window Size	3 ns
Dwell Time	0.1 s
Gate Chan.	Disabled
Delay	0 ns

Using the coincidence counter, measure the number of singles and coincidences in one second. These counts correspond to your dark noise. Record these counts below:

Dark Counts	
Channel 1 Counts/Second ( $\text{Dark}_{\text{CH1}}$ )	
Channel 2 Counts/Second ( $\text{Dark}_{\text{CH2}}$ )	
Coincidence Channel Counts/Second ( $\text{Dark}_{\text{COIN}}$ )	

The **dark count rate** is the registered counts without any incident light. These counts are not due to external photons being detected. There are several different mechanisms that lead to dark counts and the most prominent one here is phonon-induced avalanches. When the detector is lit, a photon can reach the detector surface and convert into an electron. The electron goes through a gain stage in the detector which multiplies it up to a measurable current, similar to a snowball starting an avalanche. Phonons present in the detector from thermal energy can also kick-start this avalanche process. The detectors have built-in coolers to minimize the dark count rate but a small number of thermal events always occur.

Next we will turn on the QES2 Bi-Photon source. To turn on the QES2, simply plug it in, making sure to use the power supply labeled “QES Power Supply”. Wait a couple minutes to allow the unit to power up and stabilize before taking measurements. Without modifying the settings on the coincidence counter, re-measure the number of singles and coincidence counts again with the QES2 on. Record these counts in the following table:

<b>Counts with Laser On</b>	
Channel 1 Counts/Second	
Channel 2 Counts/Second	
Coincidence Channel Counts/Second	

The singles and coincidences should be considerably higher now that the pump laser is on and the QES2 is producing bi-photons. The photons that are being detected now are 810nm bi-photons produced by the SPDC of the 405nm pump laser.

Since the polarizing beamsplitter is transmitting the H-polarized photons into its “R” port and reflecting the V-polarized photons into its “T” port, we can easily determine how many of our produced photons are H or V polarized. Record the singles counts associated with the SPCM connected to the “R” port of the PBS in the following table in the row labeled “H-Polarized.” Similarly, record the singles counts for the “T” port in the row labeled “V-Polarized.” From your measurements earlier, record the corresponding dark counts for each channel. Finally, subtract the dark counts from each singles counts to get the actual number of H and V polarized photons detected. Record this value in the column labeled “Number of Photons (/s)”

	<b>Single Counts</b>	<b>Dark Counts</b>	<b>Number of Photons (/s)</b>
H-Polarized (T Port)			
V-Polarized (R Port)			

Because the photons are produced by a Type II SPDC source, the H and V polarized photons should be roughly equal. If we had a Type I SPDC source, all of the photons would be either H or all would be V polarized.

As we did in Experiment #1, let’s measure and record the coincidence counts as we change **only** the delay time between Channels 1 and 2. Repeat these measurements for a “Delay” setting from 0 ns to 14 ns.

SPDC Photon Arrival Time					
Delay (ns)	Channel 1	Channel 2	Coincidences	Accidentals	Coincidences – Accidentals
0 ns					
2 ns					
4 ns					
6 ns					
8 ns					
10 ns					
12 ns					
14 ns					

Use the following formula to calculate the accidental coincidence counts for each of the measurements in the table above (see Experiment 1 for a reminder of what accidentals are):

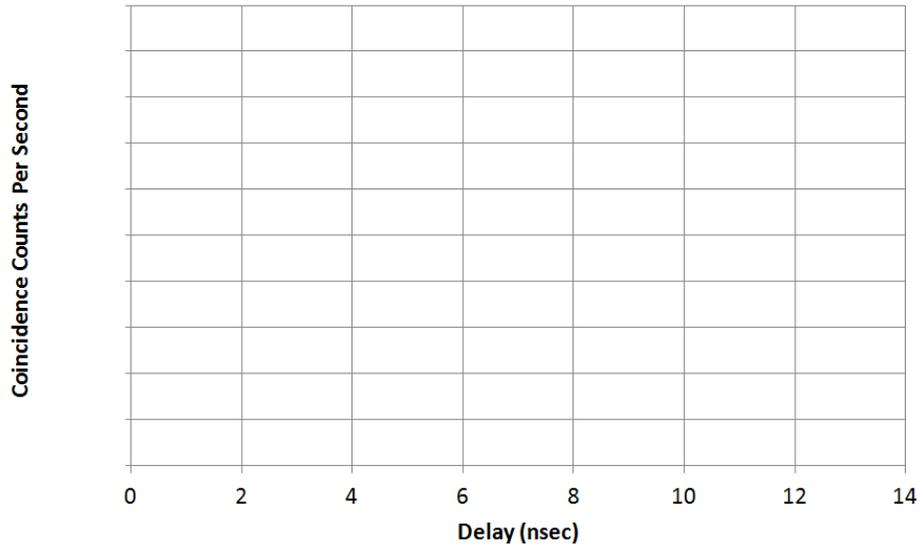
$$\text{Accidentals} = \frac{2(\text{Coincidence Window (sec)})(\text{Channel \#1 Singles})(\text{Channel \#2 Singles})}{\text{dwell time (sec)}}$$

Record your calculations in the column labeled “Accidentals.”

Finally, subtract the Accidental Counts from the Coincidence Counts to get the number of detected bi-photon pairs being produced by the QES2. Record these calculations in the column labeled “Coincidences – Accidentals.”

Chart the “Coincidences – Accidentals” values in the graph below.

## Temporal Sensitivity



You should see a graph that has a well-defined peak that disappears as the delay between Channel 1 and Channel 2 is increased. If each photon was being produced randomly in time then the graph above would not have a peak. This is what we found in Experiment #1 when we looked at the output from room lighting. In this experiment, conversely, you should be seeing a strong peak which indicates that two photons are being detected at the same time and, therefore, are likely being produced by a common bi-photon source.

### Measurement 2: Calculating the Coincidence Ratio

As mentioned earlier, bi-photon pairs can be used to produce “heralded” photons. By detecting just one of the photons in a bi-photon pair, a detected photon can “herald” the presence of another photon in a separate path. How reliably the detection of one photon signals the presence of another photon is termed the “**heralding efficiency**” of the source. A 100% heralding efficiency means that the detection of one photon in one path indicates the presence of another photon in a separate path with 100% certainty.

The output from the PBS in the last experiment is an example of a heralded source. The detection of a photon on the “R” port of the PBS indicates the likelihood of a corresponding photon on the “T” port. However, due to fiber losses and poor detector efficiency, this is not always true. Sometimes a bi-photon pair will be produced by the QES2 only to have one of the photons absorbed or lost on its way to the detector. These lost photons result in a photon in one path but not the other. As a result, these systems can produce “**false heralding**” or “missed heralding.” In these situations, the heralding efficiency would be much lower than 100%.

Unfortunately, it is difficult to accurately measure the heralding efficiency of our current setup using only the equipment in this kit. However, we can measure a related statistic; the Coincidence Ratio. The Coincidence Ratio tells us what fraction of our produced bi-photon pairs actually survives and is measured as a pair by our two SPCM detector. With the coincidence counters “Delay” setting set to 0ns, measure

your counts again. Record these in the table. Use the singles counts on Channel 1 and Channel 2 to calculate the “Accidental Counts” and record this value in the table as well.

<b>Calculating Coincidence Ratio</b>	
Channel 1 Singles Counts	
Channel 2 Singles Counts	
Coincidence Counts (Coincidences)	
Channel 1 Detector Efficiency (DET <sub>1eff</sub> )	0.5 (i.e. 50%)
Channel 2 Detector Efficiency (DET <sub>2eff</sub> )	0.5 (i.e. 50%)
Calculated Accidental Rate (Accidentals)	
Coincidence Ratio	
Coincidence Ratio (for Ideal Detectors)	

The coincidence ratio of the system can be approximated using the following formula:

$$\text{Coincidence Ratio} = \frac{(\text{Coincidences} - \text{Accidentals})}{\left[ \frac{\text{Channel 1} + \text{Channel 2}}{2} \right]}$$

Use the data in the previous table to calculate and record the coincidence ratio.

If we had been using ideal detectors (with an efficiency of 1, or 100%), our coincidence ratio would have been much higher. However, our SPCM detectors have an efficiency closer to 50%. This means that when a photon is incident on the SPCM, there is only a 50% chance that the detector will actually record the photon. The other 50% of the time, the detector will not record the photon.

It is possible to approximate our coincidence ratio if we had ideal detectors. The Coincidence Ratio (for Ideal detectors) can be calculated using the following formula:

$$\text{Ideal Coincidence Ratio} = \frac{(\text{Coincidences} - \text{Accidentals})}{\left[ \frac{\text{Channel 1} + \text{Channel 2}}{2} \right]} \cdot \text{DET}_{\text{eff}}$$

Use the data in the table to calculate and record the ideal coincidence ratio for the QES2.

Notice that the coincidence ratio, even with ideal detectors, is still not 100%. This is due to optical losses within the beamsplitter, fibers, and QES2 device. Furthermore, it is quite possible that the QES2 and beamsplitter may be sampling different regions of the SPDC output. Non-overlapping regions of the SPDC output will result in reduced coincidence ratio. Because of its importance to quantum cryptography and

computing, achieving bi-photon sources with ever increasing heralding efficiencies is an ongoing area of scientific research.

### Measurement 3: Source Flux

A simple way to categorize a bi-photon source is to measure its **flux**. The flux is the total number of bi-photon pairs produced for every 1 milliwatt of pump laser. Based on the measurements already performed, we know that the peak number of bi-photon pairs we detected from the QES2. This was previously recorded in the “**Counts with Laser On**” table (p. 24) in the row labeled “Coincidence Channel Counts/Second.” Record this value again in the following table under “Detected Coincidence Counts (counts/sec)”.

<b>Calculating Source Flux</b>	
Pump Laser Power (mW)	
Detected Coincidence Counts (counts/sec)	
Detected Bi-Photon Flux (pairs/sec·mW)	
Channel 1 Detector Efficiency (DET1 <sub>eff</sub> )	0.5 (i.e. 50%)
Channel 2 Detector Efficiency (DET2 <sub>eff</sub> )	0.5 (i.e. 50%)
Actual Bi-Photon Flux (pairs/sec·mW)	

The flux of the QES2 source can be calculated using the following formula:

$$\text{Detected Bi-Photon Flux} = \frac{\text{Detected Coincidence Counts}}{\text{Pump Power (mW)}}$$

The pump power was measured during the QES2 assembly process and is recorded on the data sheet provided with the kit. Retrieve the factory-measured pump laser power and record it (in milliwatts) in the table. Calculate the flux and record the result in the table next to “Detected Bi-Photon Flux”. This value tells you the total number of bi-photons pairs that you would detect if you pumped the QES2 with only 1 mW of pump laser.

As before, our measurements are heavily influenced by the efficiency of our SPCM detectors. Since our detectors are not 100% efficient, the detected source flux is must lower than the actual source flux. Therefore, the QES2 is actually producing more bi-photon pairs than we are measuring.

To determine the actual bi-photon flux of the QES2, use the following formula:

$$\text{Actual Bi-Photon Flux} = \frac{\text{Detected Coincidence Counts}}{\text{Pump Power (mW)} \cdot \text{Det1}_{\text{eff}} \cdot \text{Det2}_{\text{eff}}}$$

Record the Actual Bi-Photon Flux in the previous table.

#### **Measurement 4: Controlling the QES2 Source Degeneracy**

As mentioned previously, the QES2 source uses Type-II spontaneous parametric down-conversion and absorbs one 405nm horizontally polarized photon and emits two 810nm photons, one horizontal and one vertical. The two emitted photons do not always have the same wavelength. Due to conservation of energy, the frequencies of the emitted photons must sum to the frequency of the pump photon. As wavelength is inversely proportional to the frequency, the wavelengths of the emitted photons near degeneracy will average to 810nm. If the source is detuned for heavily nondegenerate output, then the wavelength splitting about 810nm will be unequal. However, most of the time one photon's wavelength will be only slightly higher and the other will be only slightly lower. By adjusting the temperature of the QES2's crystal we can adjust the wavelength of the emitted photons.

For many experiments, we want the emitted photons to have the same wavelength, a scenario we call "degenerate". In this experiment, we will learn how to adjust the QES2 to produce either degenerate or non-degenerate bi-photons.

Plug in the power cable to the QES2. Make sure to use the cable labeled "QES2." If this is the first time connecting the QES2 to a computer, you will need to install **QES Control** on a Windows 7 or higher OS computer.

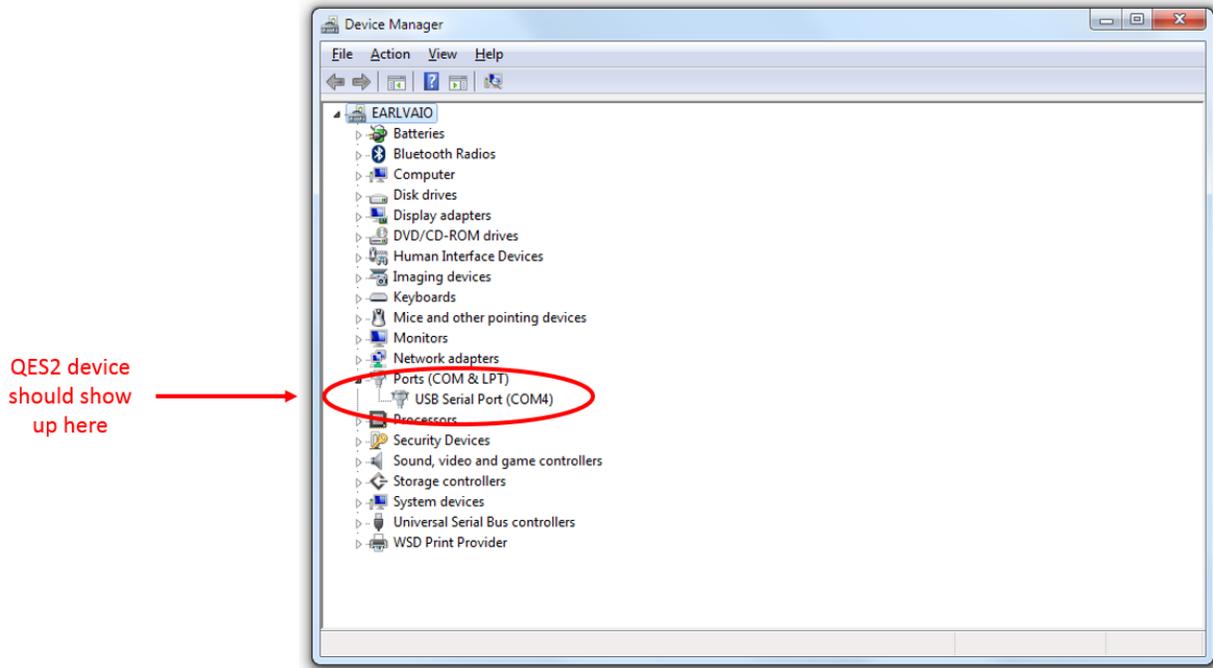
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#### **Installing the QES2.4 User Interface**

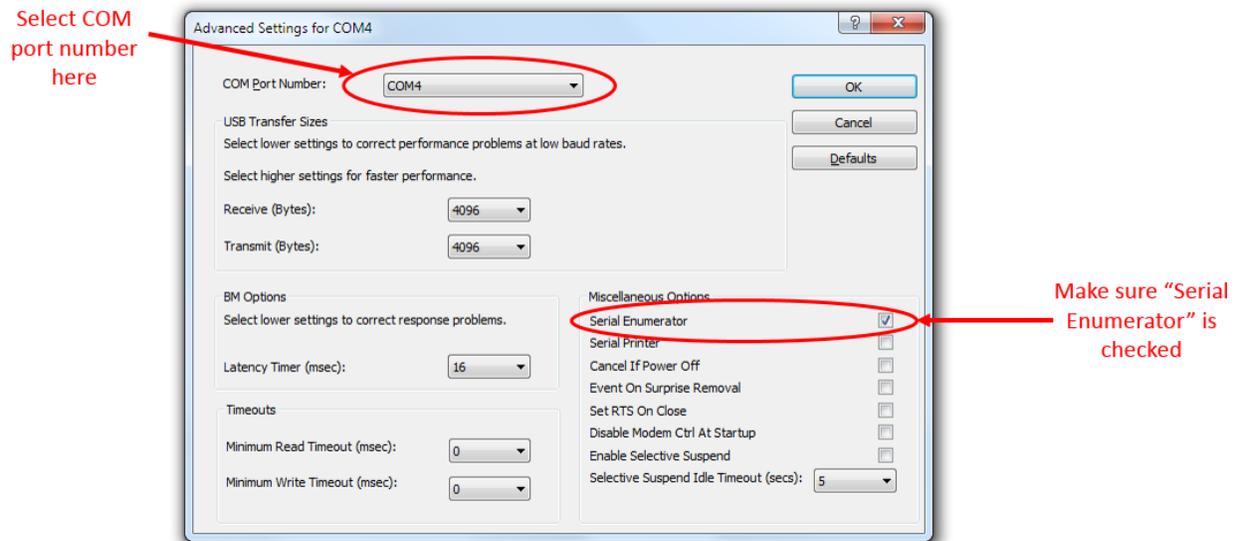
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To install **QES Control**, double-click the "QES-Control\_1.4.exe" file on the thumb drive included with the kit. Follow the prompts from the program to install **QES Control** on your computer. This program will be used to communicate over a USB port and configure the QES2.

Once the program is installed, connect the included USB A to B cable between the computer and the QES2. Once the USB cable is connected, the Windows OS will automatically begin installing drivers for the QES2. This may take a minute or two to complete. Once completed, the QES2 will show up in the Windows Device Manager (accessible through Control Panel -> Device Manager) as shown in the following figure:



When the QES2 is first installed, Windows OS will automatically select a COM port number for the device. In the previous figure, the assigned COM port can be seen to be COM4. If the assigned COM port number is 16 or less, then nothing further must be done. However, if the COM port number is greater than 16, it must be reassigned to a value of 16 or less. To change the assigned COM port number, right mouse click on the “USB Serial Port” entry and select “Properties” from the drop down menu. In the “Properties” window, select the “Port Settings” tab. In the “Port Settings” window, click on the “Advanced...” button. This will open the “Advanced Settings” window as shown in the following figure:

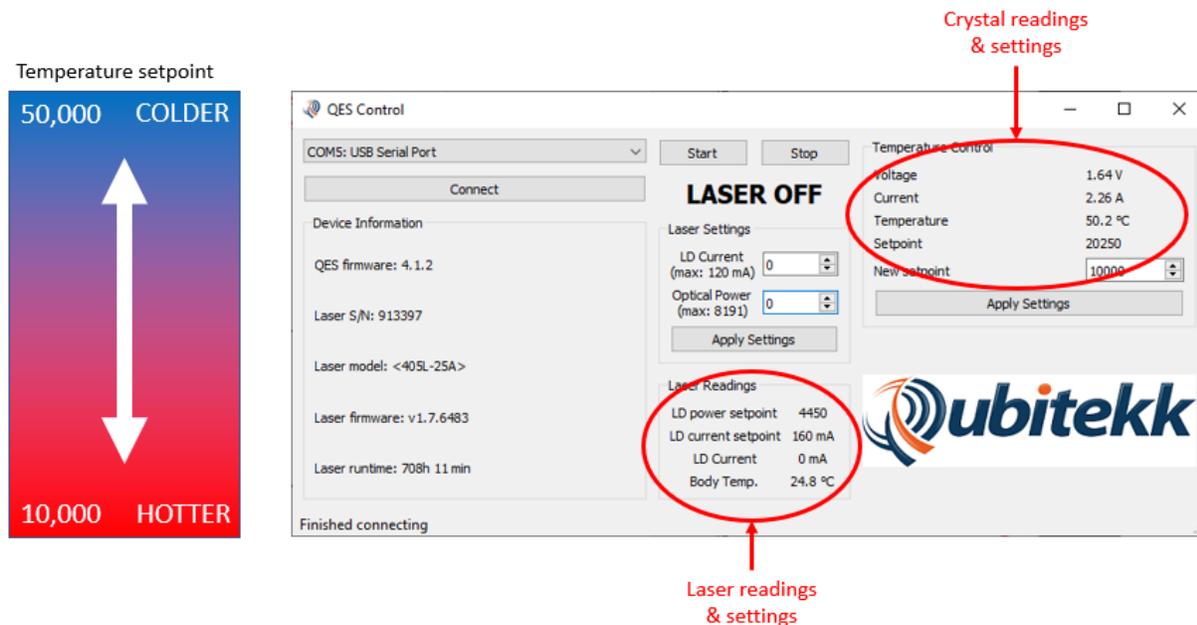


Use the first drop down box to select a new COM port. In some cases, it may be necessary to select a COM port that is already in use. Under most circumstances, this will not cause any issues. With the COM port

selected, ensure that the “Serial Enumerator” option is checked, as shown in the previous figure. Once all settings are made, click the OK button to close all windows.

If the QES2 appears as an unknown device in Device Manager, then run “CDM21228\_Setup.exe” from the USB drive to install the virtual COM port driver.

Once the QES2 software is installed and the COM port setup, run **QES Control**. The program should look as follows (note: you will not see the “Temperature setpoint” graph):



There are three columns in the program. The left column shows device information, the middle column shows the laser control, and the right column shows the crystal control.

At the top of the first column, there is a dropdown to select the COM port of the QES and a button to connect. Under the “Device Information” heading, the QES model number, serial number, and firmware version are listed. Below the QES information we see the integrated laser model number, serial number, firmware version, and runtime. As shown in the figure, this particular laser shows a runtime of “708h 11 min.”

In the middle column, we can control the laser settings and view its readings. After entering a value in the “LD Current” or “Optical Power” fields, clicking the “Apply Settings” button will immediately apply those values to the laser. The laser diode current is entered as milliamps of current, whereas the power is an integer up to 8191. The maximum recommended current is 120 mA, though values up to 180 mA are possible. The power value controls the setpoint of a DAC internal to the laser.

Similar to a power supply operating in constant-current or constant-voltage modes, the laser will operate at whichever of the two settings is more restrictive. For example, a low current setpoint will prevent the laser from reaching a high enough power to satisfy the power setting, so it will operate in constant-current mode. An example of this would be a current of 30 mA and a power DAC of 6000. Conversely, a low power setpoint will prevent the laser from reaching a high enough current to satisfy the current setting, so it will operate in constant-power mode. An example of this would be a current of 120 mA and a power DAC of 500. The recommended mode of operation is constant-power.

In the final column we find the crystal readings and temperature setpoint. Besides the voltage and current driving the Peltier cooler, we see the measurement of the crystal temperature in degrees-Celsius as well as the setpoint. To change the setpoint, enter a new value in the entry box and click “Apply Settings.” As illustrated in the figure, the lower the setpoint, the higher the temperature. Conversely, the higher the setpoint, the lower the temperature. After applying a new setpoint, the crystal will be driven to a new temperature and will take a couple minutes to stabilize.

The QES2 is shipped with default settings that produce a degenerate output (these settings can also be found on the QES2 Datasheet included with your kit). We will want to return to these settings at the end of this experiment so **write down the “Temperature Set Point” and the current temperature reading in the following table:**

QES2 Degenerate Temperature Settings	
Temperature Setpoint Value	
Temperature (°C)	

Try changing the setpoint to various values and note the corresponding change in temperature. Use the following table and fill in the data as you evaluate the QES2 output at various setpoints.

QES2 Temperature						
Set Point	20,000	25,000	30,000	35,000	40,000	45,000
Temperature (°C)						
Channel 1 Singles						
Channel 2 Singles						
Coincidence Counts						

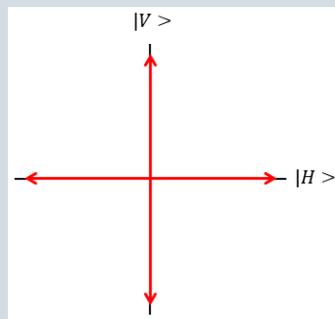
As mentioned, the change in crystal temperature will cause the wavelengths of the bi-photons emitted by the QES2 to change slightly. For this setup, the change in wavelength has little impact on our results. At most, you may see the coincidence counts increase or decrease slightly as the temperature is increased.

However, in future experiments, a change in crystal temperature from a degenerate output to a non-degenerate output will have a major impact on our results. This, in turn, will reveal some interesting aspect of the nature of light at the single photon scale.

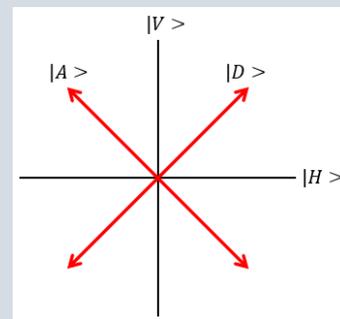
**When you have completed your measurements, set the Temperature Set Point back to the initial value you wrote down at the beginning of this section.**

## Polarization and Quantum States

For future experiments, it will be necessary to represent the polarization of a single photon using quantum mechanical notation. In quantum mechanics, a horizontally polarized photon is said to be in a horizontally polarized state. The state of the particle is then described using the “ket” vector,  $|H\rangle$ . To describe polarization, we will use two measurement reference frames, or bases, which we call the “rectilinear” and “diagonal” basis. The rectilinear basis is made up of horizontal and vertical polarization states,  $|H\rangle$  and  $|V\rangle$ . The diagonal basis is made up of  $+45^\circ$  (D for diagonal) and  $-45^\circ$  (A for anti-diagonal) polarization states,  $|D\rangle$  and  $|A\rangle$ . We call these “measurement bases” because the measurement of the photon’s polarization is constrained to be either  $|H\rangle$  or  $|V\rangle$  (in the rectilinear basis) or  $|D\rangle$  or  $|A\rangle$  (in the diagonal basis), and these bases are shown below.



Rectilinear Basis



Diagonal Basis

Any arbitrarily polarized photon in the rectilinear basis can be written as a “superposition” of the  $|H\rangle$  and  $|V\rangle$  states, as shown below.

$$|\psi\rangle = c_H |H\rangle + c_V |V\rangle,$$

where  $c_H$  and  $c_V$  are complex numbers. Likewise, any polarization in the diagonal basis can be written as a superposition of the  $|D\rangle$  and  $|A\rangle$  states. Furthermore,  $|D\rangle$  and  $|A\rangle$  states can be represented in the rectilinear basis using a superposition, as shown below.

$$|D\rangle = \frac{1}{\sqrt{2}} |H\rangle + \frac{1}{\sqrt{2}} |V\rangle$$

$$|A\rangle = \frac{1}{\sqrt{2}} |H\rangle - \frac{1}{\sqrt{2}} |V\rangle.$$

If we wish to measure a photon that is in the  $|D\rangle$  state, we can choose to measure the photon in either the diagonal or rectilinear basis. If we measure  $|D\rangle$  in the diagonal basis, we see  $|D\rangle$  100% of the time. However, if we measure  $|D\rangle$  in the rectilinear basis, 50% of the time we see  $|H\rangle$  and 50% of the time we see  $|V\rangle$ . In the rectilinear basis, the photon is in a superposition state of  $|H\rangle$  and  $|V\rangle$ . In quantum mechanics, we interpret this to mean that the photon is actually in both  $|H\rangle$  and  $|V\rangle$  simultaneously, until it is measured. Upon being measured, the state “collapses” into one of the two states, not both. We cannot predict which state the photon will collapse to, but the measurement will confirm the final state.

As we will see in Experiment 3, a polarizing beamsplitter can be used to measure the polarization of a single photon. Depending on the orientation of the beamsplitter, we can measure a photon’s polarization

in either the rectilinear or diagonal basis. Since a single photon cannot be split in two, this will create some interesting experiments and phenomena that cannot be adequately explained using classical physics. In the experiments that follow, we will use the notation of quantum theory and its underlying explanation to predict our experimental results. One of the goals of this kit is for the reader to become more comfortable with the notation and quantum physics model in properly predicting experimental results.

## Non-Linear Crystals

Many different types of non-linear crystals can be used to produce bi-photons. PPKTP, BBO, KDP, etc. are all commonly used crystal materials in quantum research. In general, these non-linear materials can be categorized into two groups; bulk crystals (see figure below) and waveguides.



Bulk crystals have traditionally been used to study SPDC and are still widely in use today. The QES2 included with this kit utilizes bulk crystals. Although common, some bulk crystals are not very bright and most require tuning (either angular or thermal) to produce a desired output. Efficiently coupling the output from these bulk crystals into optical fibers is often a challenging process.

Because researchers are constantly looking for new materials and techniques to increase the brightness and control of SPDC emissions, many researchers are exploring waveguides constructed of non-linear material. Some of the brightest SPDC sources have been created with waveguide-based non-linear materials. These devices typically involve a very narrow channel of non-linear material (often only a few microns wide) that might be 20 to 30 mm long. Because the pump beam is tightly focused into the waveguide, the high optical intensity achieved at the focus of the pump is coupled into and maintained over the full length of the non-linear waveguide material. This result is the generation of very high numbers of bi-photons. Since these photons are already generated within a guided waveguide structure, coupling the output into an optical fiber is often very efficient.

Whatever the non-linear material, the pump wavelength, pump power, whether the pump beam is pulsed or continuous, and the target spectral and polarization requirements for the signal and idler photons are all critical parameters influencing the design of a non-linear crystal. Crystal manufacturers typically help researchers to identify and determine the proper specification for a crystal based on these variables.

# Quantum Mechanics Laboratory Kit

## 03 Experiment

### Quantum States and Measurement Bases

#### → What you will learn

In this experiment, you will learn about quantum states and measurement bases. You will specifically learn how to:

- Measure photons in the rectilinear and diagonal bases
- Understand deterministic versus non-deterministic processes
- Understand the function of a non-polarizing beamsplitter
- Understand superposition

Understanding and measuring a photon's state in a particular basis will be critical for understanding future applications.

#### → What you will need

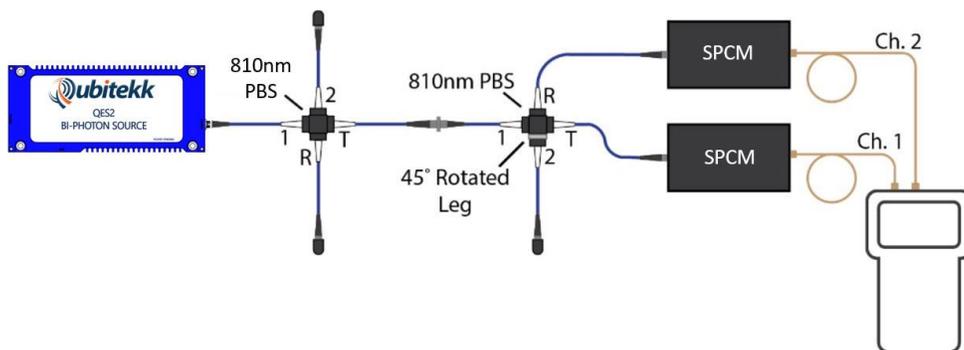
The following experimental components will be needed:

- QES2 Bi-Photon Source (1)
- Straight Coupler (2)
- 90° Coupler (1)
- 810nm Fiber Optic PBS (1)
- 810nm Fiber Optic PBS with 45° leg (1)
- 810nm Fiber Optic BS
- Coincidence Counter
- Single Photon Counting Modules (2)
- 1 meter BNC-to-SMA cables (2)

#### → Initial Setup

**IMPORTANT:** If you haven't already, read the "Notes on Component Handling" prior to beginning work. The Single Photon Counting Modules should not be plugged in until all fibers are connected and the room lights are dimmed.

Assemble the experimental components as shown in the figure below. Remember to always clean the fiber optic cable tips prior to inserting them into any mating sleeves or devices.

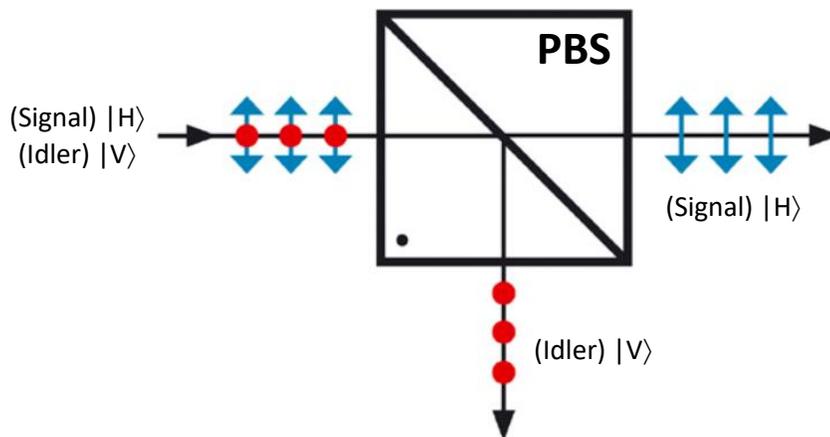


# Quantum Mechanics Laboratory Kit

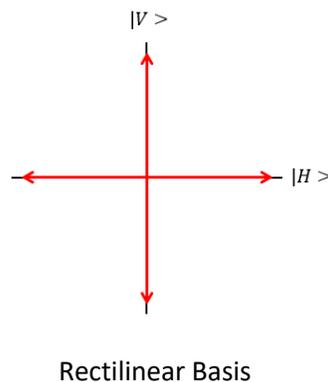
→ *What you need to know...*

In the previous experiment, we used a polarizing beamsplitter (or PBS) to separate bi-photons. A polarizing beamsplitter will transmit or reflect a photon based upon its polarization. In the last experiment, we used a PBS to separate the horizontally (H) polarized signal photons from the vertically (V) polarized idler photons emitted from a QES2.

Beginning with this experiment, we want to start referring to the polarization of a photon using quantum mechanical notation. In quantum mechanics, a horizontally polarized photon is said to be in a horizontally polarized state. The state of the particle is then described using the “ket” vector,  $|H\rangle$ . Similarly, a vertically polarized photon is said to be in a vertically polarized state and is represented as  $|V\rangle$ . The operation of a PBS is to separate photons into these two different states (and only these two states) as shown below:



When we defined polarization previously, we defined it as being relative to the horizon. Horizontal was parallel to the horizon and vertical was perpendicular to the horizon. This reference frame in quantum mechanics is called the “rectilinear” basis and the rectilinear basis is usually represented as shown below:



Note that the  $|H\rangle$  state defines the X-axis and the  $|V\rangle$  state defines the Y-axis. In this rectilinear basis, the  $|H\rangle$  and  $|V\rangle$  states are the only two states that can exist. In the rectilinear basis, no other polarization state is possible.

We know, however, that linearly polarized light can be oriented in any direction. We can have a lightwave polarized at 45 degrees to the horizon, or 22 degrees, or at whatever angle we want. How do we, therefore, represent a diagonally polarized photon's state in the rectilinear basis if there are only the two polarization states  $|H\rangle$  and  $|V\rangle$ ?

To represent a photon that is diagonally polarized at a 45 degree angle to horizontal in the rectilinear basis, we will need to use a "superposition" of states. A 45 degree, diagonally polarized photon in the rectilinear basis would be in the following superposition state:

$$|\psi\rangle = C_H|H\rangle + C_V|V\rangle$$

This equation should be interpreted to mean that the photon is sometimes in the  $|H\rangle$  state and sometimes in the  $|V\rangle$  state. The numbers,  $C_H$  and  $C_V$ , in front of the  $|H\rangle$  and  $|V\rangle$  states will help us to determine how often the photon will be found in the  $|H\rangle$  state versus the  $|V\rangle$  state.

It is important to pause here and consider the implications of what is being suggested with this new notation. This quantum mechanical notation is saying that, in the rectilinear basis, we can use a PBS to measure whether a photon is in either the  $|H\rangle$  or  $|V\rangle$  state. These two states are the only two states that a photon can be measured to be in. If an incoming photon is in the  $|H\rangle$  state, then it will transmit through the PBS 100% of the time. If an incoming photon is in the  $|V\rangle$  state, it will reflect at the PBS 100% of the time. This is a "deterministic" statement that can be used to fully determine what an H-polarized or V-polarized photon will do when it encounters the PBS.

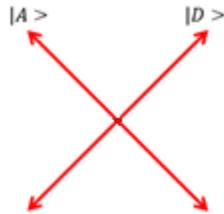
However, if the incoming photon is in a superposition state, the photon – which cannot be split in two – will sometimes reflect and sometimes transmit through the PBS. Or, to state it another way, the photon will be measured by the PBS to be in the  $|H\rangle$  state a percentage of the time and it will be measured to be in the  $|V\rangle$  state another percentage of the time. That is NOT a "deterministic" statement. This statement cannot be used to predict what a specific photon will do when it encounters the PBS. We only know that it will reflect a percentage of the time and transmit another percentage of the time. But, for a given photon, we cannot predict what it will actually do at any given moment.

Accepting this new notation, and its potential implications, is the first step in adopting quantum theory. With this notation, we are conceding that we cannot predict what a specific photon in a superposition state will do at a PBS. Will the photon reflect or transmit? We don't know. How does the photon decide to reflect or transmit? We don't know. But this notation will provide us a mechanism for predicting the average behavior of a group of photons in a superposition state. Plus, more importantly, it will allow us to predict how photons in a superposition state interact and interfere with one another.

One interpretation of quantum mechanics holds that a photon in a superposition state is actually in both  $|H\rangle$  and  $|V\rangle$  states simultaneously, until it is measured (i.e. until it encounters the PBS). Upon being

measured, the state is said to “collapse” into one of the two states. We cannot predict which state the photon will collapse to, but the measurement confirms the final state.

The rectilinear basis isn’t the only reference frame that we can use to describe polarization states. With the rectilinear basis, we arbitrarily chose the horizon as our reference axis for polarization. We could have easily have chosen a 45 degree angle with the horizon as our reference. This is called the “diagonal basis” and it is shown in the following figure:



Diagonal Basis

In the diagonal basis, the  $|D\rangle$  state defines the X-axis and the  $|A\rangle$  state defines the Y-axis. In this basis, a photon with a polarization oriented at +45 degrees to the horizon is defined to be in the diagonal state  $|D\rangle$ . A photon with a polarization oriented at -45 degrees to the horizon is defined to be in the anti-diagonal state  $|A\rangle$ . The  $|D\rangle$  and  $|A\rangle$  states are the only two states that can exist in the diagonal basis. Just as with the rectilinear basis, no other polarization states are possible.

To measure a photon in the diagonal basis, we would again use a PBS. However, the PBS would need to be rotated 45 degrees to the horizon in order to separate photons into the  $|D\rangle$  and  $|A\rangle$  states.

In the diagonal basis, how do we represent horizontally polarized or vertically polarized photons? Again, we must use a superposition of the allowed states  $|D\rangle$  and  $|A\rangle$ , as shown below:

$$|H\rangle = \frac{1}{\sqrt{2}}|D\rangle + \frac{1}{\sqrt{2}}|A\rangle$$

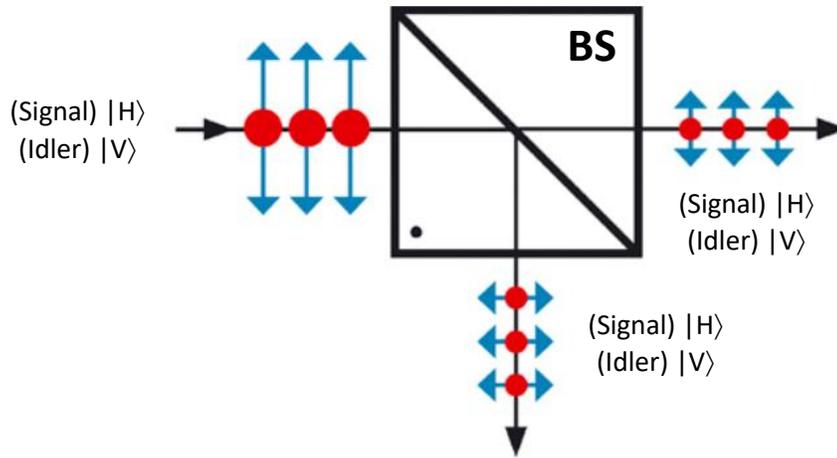
$$|V\rangle = \frac{1}{\sqrt{2}}|D\rangle - \frac{1}{\sqrt{2}}|A\rangle$$

Notice here that we have used real numbers in front of the  $|D\rangle$  and  $|A\rangle$  states. By taking the magnitude squared, these numbers can be used to compute an average probability of finding a photon in either the  $|D\rangle$  or  $|A\rangle$  state (50%).

The rectilinear and diagonal bases are called “measurement bases” because they define the reference frame for any measurements. Experimentally, the rotation of your PBS determines whether you are measuring in the rectilinear or diagonal basis.

One final point to cover is the operation of a non-polarizing beamsplitter (or BS). A BS will reflect or transmit photons at random. A photon’s polarization has no impact on whether or not the photon gets

reflected or transmitted. Therefore, a non-polarizing beamsplitter will send both the signal and idler photons from a QES2 in the same direction 50% of the time and in different directions the other 50% of the time. The operation of a BS is illustrated in the following figure.



→ *Experimental Procedure*

**Measurement 1: Measuring Photon Polarization in the Rectilinear Basis**

Assemble the setup as shown at the beginning of the experiment. Make sure to start with a straight coupler between fibers, not a rotated coupler. Remember to clean the optical fiber tips before inserting them into the Single Photon Counting Modules (SPCMs) or the fiber couplers. Do not provide power to the SPCM units until the optical fibers are fully connected and the room lights are dimmed. Do not yet turn on the QES2.

With the QES2 off, dim the room lights and supply power to the SPCM detectors. Configure the coincidence counter with the following settings (review Experiment #1 if you need help configuring the coincidence counter):

Coincidence Counter Settings	
Dwell Time	0.1 s
Window Size	3 ns

In the first part of this experiment, we will be looking more in depth at how photons of different polarizations behave when they encounter a polarizing beamsplitter (PBS). In the previous experiment, we reviewed how the QES2 source emitted bi-photon pairs, with the signal photon in the  $|H\rangle$  state and the idler photon in the  $|V\rangle$  state. When we sent both photons through a PBS, the photons in the  $|H\rangle$  state were transmitted and the photons in the  $|V\rangle$  state were reflected.

In this experiment, we will connect a second PBS to the first PBS and confirm that we are indeed seeing only one polarization of light coming out of a specific port of the first PBS. To start, we will connect the second PBS to the “T” port of the first PBS using a fiber optic coupler. For our setup, the “T” port of the first PBS should contain the photons that transmitted through the PBS. As we mentioned previously, only the photons in the  $|H\rangle$  state should transmit through the PBS. Therefore, 100% of the photons exiting the first PBS through the “T” port should be in the  $|H\rangle$  state.

To test this assumption, we connect a second PBS to the “T” port and we measure the number of photons transmitting and reflecting from the second PBS. With the QES2 turned, and given a few minutes to stabilize, use the SPCMs and coincidence counter to measure the number of singles and coincidence counts in one second (for a coincidence window of 3ns). Record these counts in the table below, under the heading “no rotation”:

<b>Counts Through Polarizing Beamsplitter</b>		
	<b>No Rotation</b>	<b>90° Rotation</b>
Channel 1 Counts		
Channel 2 Counts		
Coincidence Channel Counts		

You should have observed that Channel 1 – which corresponds to the photons that transmitted through the second PBS - had many counts and while Channel 2 has significantly less. This indicates that most of the photons exiting the “T” port of the first PBS are in the  $|H\rangle$  state, as we expected.

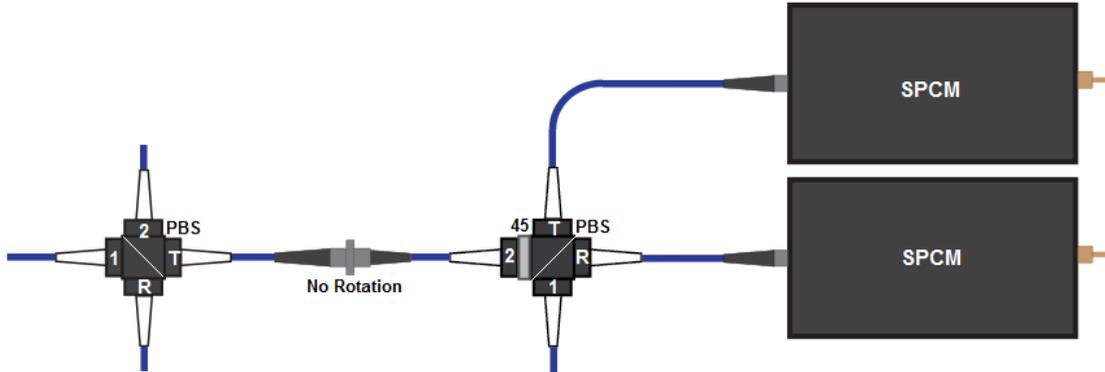
Now, replace the coupler between the two PBS with a 90° rotated coupler and repeat the measurement. Record the results in the table above. By rotating the fibers by 90° relative to each other, we have rotated the polarization of the photon exiting the “T” port from horizontal to vertical. As our photons are now vertically polarized, they should reflect at the PBS and we should see high counts on Channel 2 and low counts on Channel 1.

In this set-up, our photons are behaving deterministically, we know their polarization when entering the PBS, so we know what they will do when they exit the PBS. We could have easily determined what each photon would do without running the experiment. Note that our coincidence counts are nearly zero since the photons are all being deterministically channeled into one detector.

### **Measurement 2: Changing Measurement Bases**

Disconnect the two PBS and reconnect them using a straight coupler with leg “T” from the first PBS connected to leg “2” of the second PBS (as shown in the following figure). Leg “2” of the second PBS has an aluminum insert that reads “45 Degrees.” This labeled insert indicates that this fiber leg has been

rotated 45 degrees relative to the internal PBS. This connection can be thought of as rotating the axis of the PBS by 45 degrees relative to our QES2 source. By doing this, we are rotating our measurement device (i.e. the PBS) into the diagonal basis. Our measurements, therefore, will measure if an incoming photon is in either a diagonal,  $|D\rangle$ , or anti-diagonal,  $|A\rangle$ , state.



*Measurement in the Diagonal Basis*

Using the coincidence counter, measure the number of singles and coincidences in one second. Record these counts in the table below, under the heading “no rotation”:

<b>Counts Through Polarizing Beamsplitter at 45°</b>		
	<b>No Rotation</b>	<b>90° Rotation</b>
Channel 1 Counts		
Channel 2 Counts		
Coincidence Channel Counts		

You should observe that Channel 1 and Channel 2 have roughly the same singles counts. The photons exiting the “T” port of the first PBS were previously demonstrated to be in the  $|H\rangle$  state, however, the  $|H\rangle$  state does not exist in the diagonal basis in which we are now measuring. In the diagonal basis, we must describe the  $|H\rangle$  state as the superposition state:

$$|H\rangle = \frac{1}{\sqrt{2}}|D\rangle + \frac{1}{\sqrt{2}}|A\rangle$$

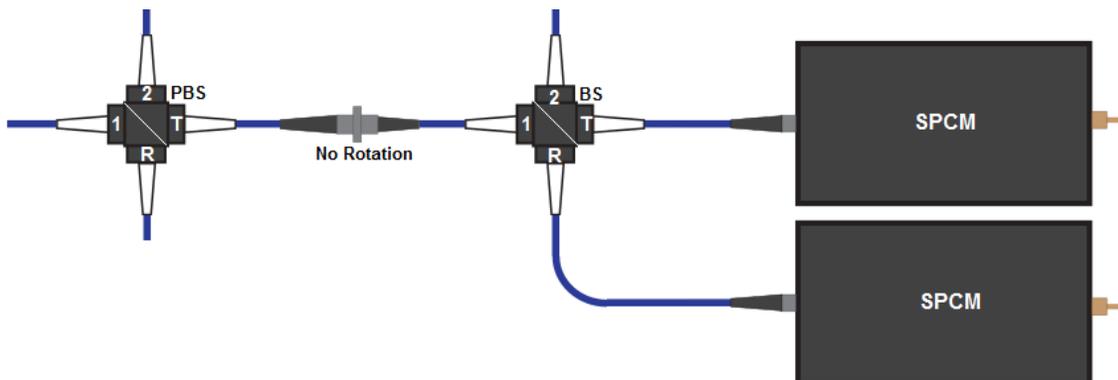
In this state, the photons will be measured to be diagonal (i.e. transmitted from the second PBS) half of the time ( $\frac{1}{\sqrt{2}} * \frac{1}{\sqrt{2}} = \frac{1}{2}$ ) and anti-diagonal (reflected from the second PBS) the other half of the time. Consequently, there will be counts on both channels and they will be roughly equal.

Now, replace the coupler between the two PBS with a 90° rotated coupler and repeat the measurement and record the results in the table above. By rotating the fibers by 90° relative to each other, we have rotated the polarization from diagonal to anti-diagonal. In this case, the rotation should not affect the singles counts as the probabilities still stay the same.

As opposed to the previous experiment, we say this experiment is “nondeterministic” because we don’t know what each individual photon will do at the second PBS. We know that if we send thousands of photons through the second PBS, on average half will transmit and half will reflect, but when it gets down to the individual photon, we have no idea what it will do until it “chooses” whether it will transmit or reflect the instant it hits the PBS. Once a photon “chooses” a path, we say its state has “collapsed.” So, a photon comes into the PBS as a superposition of both the  $|D\rangle$  and  $|A\rangle$  states, but after the PBS, “collapses” into either the  $|D\rangle$  or  $|A\rangle$  state.

### Measurement 3: Measurements with a Non-Polarizing Beamsplitter

Turn off power to the two SPCMs. Replace the second PBS with an 810nm non-polarizing beamsplitter (BS) in the port configuration (1, 2, T, R) shown in the figure below. Again, make sure to use a straight coupler between fibers, not a rotated coupler. Do not provide power to the SPCM units until the optical fibers are fully connected and the room lights are dimmed.



For the remaining measurements in this experiment, we will compare the difference in photon behavior at a BS versus the PBS tested earlier. Because each photon incident on a BS will have a 50% chance of either reflecting or transmitting, the results will look very similar to the previous measurements with the 45° rotated leg on the PBS, with some slight – but important - differences.

Using the coincidence counter, measure the number of singles and coincidences in one second. Record these counts in the table below, under the heading “no rotation”:

Counts Through Non-Polarizing Beamsplitter		
	No Rotation	90° Rotation
Channel 1 Counts		
Channel 2 Counts		
Coincidence Channel Counts		

Now, replace the coupler between the PBS and the BS with a 90° rotated coupler and repeat the measurement and record the results in the table above. By rotating the fibers by 90° relative to each other, we have rotated the input polarization by 90°. In this case, the rotation should not affect the singles counts as the beamsplitter is not sensitive to photon polarization.

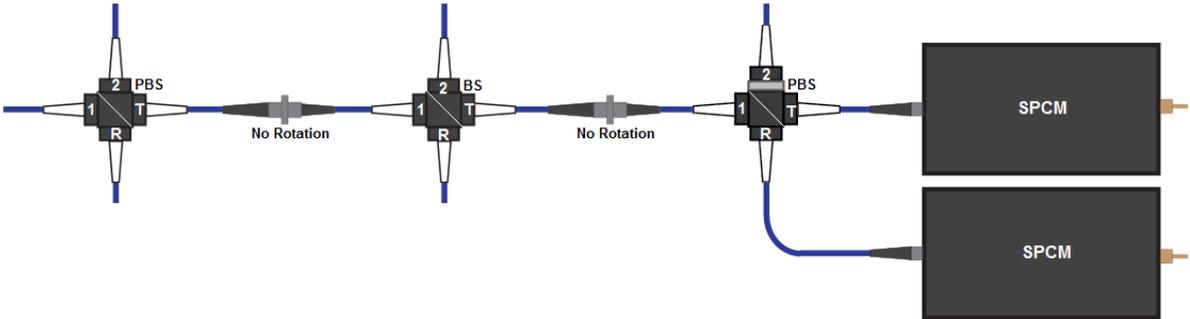
This experiment is also nondeterministic because we don't know what each individual photon will do at the BS. We know that if we send thousands of photons through the beamsplitter, on average half will transmit and half will reflect, but when it gets down to the individual photon, we have no idea what it will do until it "chooses" whether it will transmit or reflect the instant it hits the BS. Since photons are indivisible, they must take one path *or* the other, they cannot take both paths.

Notice that this result is different from what we found in Measurement 1. A polarizing beamsplitter always measures a photon's polarization (in a particular basis). After the PBS, the photon remains in that state as long as it is measured in the same basis. In contrast, a non-polarizing beamsplitter does not measure the polarization of a photon or force it to remain in a particular state. A non-polarizing beamsplitter merely transmits half of the photons and reflect half of the photons, regardless of polarization.

This distinction between the operation of a PBS and a BS will be critical for future experiments.

**Measurement 4: Characterizing the Output of the Non-Polarizing Beamsplitter**

Turn off power to the two SPCMs. Add a second PBS to the experiment by using a straight coupler to connect the "1" port of the new PBS to the "T" output port of the BS (as shown in the figure below). Connect the "R" and "T" outputs of the second PBS to the two SPCMs and apply power.



As we predicted in the last exercise, the photons exiting the BS will not be separated by polarization, however, the photons **entering** the beamsplitter were already separated by polarization in the first PBS. Therefore, the “T” output port of the BS should contain 100% horizontal photons from the “T” output port of the first PBS. By connecting a second polarizing beamsplitter, we can test this prediction.

Using the coincidence counter, measure the number of singles and coincidences in one second. Record these counts in the table below, under the heading “no rotation”:

<b>Output Ports of Non-Polarizing Beamsplitter</b>		
	<b>“T” Output</b>	<b>“R” Output</b>
Channel 1 Counts		
Channel 2 Counts		
Coincidence Channel Counts		

Now, disconnect the BS and second PBS and connect the “R” port of the BS to the “1” port of the second PBS. Repeat the measurement and record the results in the table above. If the beamsplitter is not separating the photons by polarization, you should see very similar results in both cases.

You should have seen many counts on one channel but little to no counts on the other. When you connected the other leg of the beamsplitter, the polarization was still the same. This verifies that the beamsplitter is separating the photons randomly, 50% reflect and 50% transmit, and not based on their polarization.

## What is a Superposition State?

To predict how photons in a superposition state will behave, we must introduce a new notation, called a “bra”. Just like every column vector has an associated row vector, every ket has an associated bra,  $\langle\psi|$ , where the bra is simply  $\langle\psi| = c_H^* \langle D| + c_V^* \langle A|$  and  $*$  denotes a complex conjugate. We can combine a column vector and a row vector to form an inner product, and we do the same with the bra on the left and the ket on the right in a “bracket” (bra-ket? Get it?) to get the inner product:

$$\langle\psi_1|\psi_2\rangle = c,$$

where  $c$  is a complex number. As we are dealing with an orthonormal basis set, we must have

$$\langle H|H\rangle = \langle V|V\rangle = 1,$$

and  $|H\rangle$  and  $|V\rangle$  are orthogonal so,

$$\langle H|V\rangle = \langle V|H\rangle = 0.$$

So, to find  $c_H$  and  $c_V$  we project the basis states onto  $|\psi\rangle$  to find the inner product:

$$\begin{aligned}\langle H|\psi\rangle &= \langle H|(c_H|H\rangle + c_V|V\rangle) \\ &= c_H\langle H|H\rangle + c_V\langle H|V\rangle \\ &= c_H\end{aligned}$$

and similarly,  $\langle H|\psi\rangle = c_V$ .

To find the normalization condition on  $c_H$  and  $c_V$  we can take the inner product  $\langle\psi|\psi\rangle = 1$  and find that  $|c_H|^2 + |c_V|^2 = 1$ . In this way, we assign physical meaning to the coefficients on our state. We know that all probabilities must sum to 1, so it becomes clear that the magnitude squared of our coefficients,  $|c_H|^2$  and  $|c_V|^2$ , give us the probabilities of being in  $|H\rangle$  and  $|V\rangle$ , respectively. With this in mind, we call  $c_H$  and  $c_V$  “probability amplitudes”, as they are not the probabilities themselves but help determine them.

So, what does that mean about superposition? Let’s say we have the state

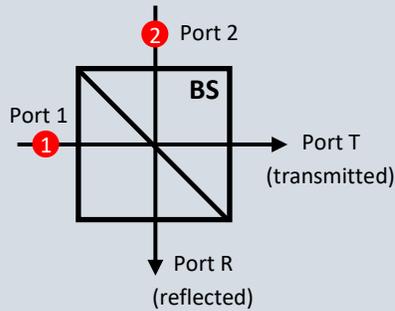
$$|\psi\rangle = |D\rangle = \frac{1}{\sqrt{2}}|H\rangle + \frac{1}{\sqrt{2}}|V\rangle.$$

If we were to measure this state in the *diagonal* basis (which measures a photon to be either  $|D\rangle$  or  $|A\rangle$ ), 100% of the time we would measure the state to be  $|D\rangle$ , and we would never measure it as  $|A\rangle$ .

What if we wish to measure the state in the rectilinear basis (which measures a photon to be either  $|H\rangle$  or  $|V\rangle$ )? We can take the magnitude squared of our probability amplitudes to find that there is a probability of  $\frac{1}{2}$  to be in state  $|H\rangle$  and probability  $\frac{1}{2}$  to be in state  $|V\rangle$ . So, in the  $|H\rangle$  and  $|V\rangle$  basis, 50% of the time we would measure  $|H\rangle$  and 50% of the time we would measure  $|V\rangle$ . This is because the photon is actually in *both* states at once, but when it is measured it “chooses” a state, or “collapses” into that state and is no longer in a superposition. This is different than a classical probability, where your photon would be in either  $|H\rangle$  or  $|V\rangle$  with 50% probability from the instant it is produced; in a quantum superposition, you do not know which state it will be in until you measure it, and the measurement fundamentally changes the state.

## Quantum Operators

When photons interact with polarizing and non-polarizing beamsplitters, the beamsplitters “operate” on the photons and modify the state they are in. We can express this operation as a matrix that converts the input into the output. To understand the matrix, we first must decide on our basis vectors. We have the following 2x2 beamsplitters,



where we have photons coming in each port. Each port could have an  $|H\rangle$  or  $|V\rangle$  (or both), and these may behave differently at the beamsplitter. We call Port 1 and Port T the UD (up-down) ports, and Port 2 and Port R the LR (left-right) ports. So, we will have the basis vector:

$$\begin{bmatrix} H_{LR} \\ H_{UD} \\ V_{LR} \\ V_{UD} \end{bmatrix}$$

as we must account for both polarizations in both ports.

We first look at how the BS operates on our quantum state. We know that 50% from each path will transmit and 50% will reflect, and there will be a  $\pi$  phase shift on leg 2's reflection. We can write this in matrix form as:

$$\text{Beam Splitter} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & -1 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & -1 \\ 0 & 0 & 1 & 1 \end{bmatrix}$$

The PBS operation is even more simple than the BS: the horizontally polarized left-right and up-down inputs will stay the same (transmit), the vertically polarized inputs will switch (reflect).

$$\text{PBS} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

These operators will help us understand what is going on in future experiments.

# Quantum Mechanics Laboratory Kit

## 04 Experiment

### Photon Bunching and Indistinguishability

#### → What you will learn

In this experiment, you will observe a quantum phenomenon called photon bunching. This experiment demonstrates that photons can behave in a manner that is indeterminate – meaning it is not always possible to predict the exact behavior of an individual photon. Even given all information about the photon and the environment, there are still some behaviors that are random. However, when two photons are identical in every way, or indistinguishable, their random behaviors can be correlated. Observing this phenomenon and examining its implications will start us down the road to building intuition about quantum processes.

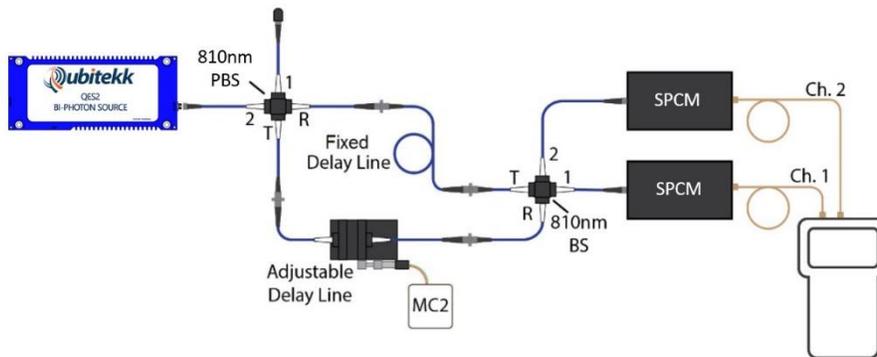
#### → What you will need

The following experimental components will be needed:

- QES2 Bi-Photon Source (1)
- Straight Coupler (4)
- 810nm Fiber Optic PBS (1)
- 810nm Fiber Optic BS (1)
- Adjustable Delay Line
- Fixed Delay Line
- MC2 Motor Controller
- Coincidence Counter
- Single Photon Counting Modules (2)
- 1 meter BNC-to-SMA cables (2)

#### → Initial Setup

Assemble the experimental components as shown in the figure below. Make sure the labeled legs of the fiber optic beamsplitters are connected exactly as shown in the figure below.

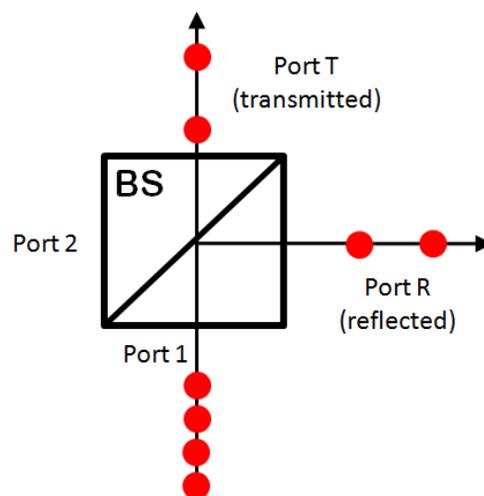


# Quantum Mechanics Laboratory Kit

## → What you need to know...

In previous experiments we generated bi-photons using the QES2. In this experiment, we will use the QES2 bi-photon source, a PBS, and a BS to demonstrate an interesting quantum mechanical phenomena.

As we learned in the previous experiment, when a photon encounters a non-polarizing beamsplitter (BS), it gets randomly reflected or transmitted, as shown in the following figure. Even with knowledge of the photon's properties, it is not clear why one photon transmits and another reflects. Even if we had as much information as possible about each photon's properties, the beamsplitter's properties, and the environment's properties, quantum theory postulates that it is still impossible to calculate whether a particular photon will reflect or transmit. The behavior of the individual photons and the underlying physical process is said to be "indeterminate."



For scientists today, this is still a challenging assumption – and not one that is easily adopted. Some scientists still believe that there may be other explanations, or previously uninvestigated variables, that could bring order to what appears to be random processes. These alternate theories to quantum mechanics are classified as “hidden variable” theories. Although intriguing, these theories are beyond the scope of this kit.

If we cannot determine whether a photon will be reflected or transmitted by a BS, then how can we mathematically describe the photon after the BS? As we saw in the previous experiment, this starts by representing the photon as being in a particular state. For a photon incident on a polarizing beamsplitter, we represented the exiting photons as being in either a horizontally  $|H\rangle$  or vertically  $|V\rangle$  polarized state.

A BS, however, does not separate photons based on polarization. Therefore, we must describe the photons exiting the BS as being in a different type of state. For this experiment, we will describe the photons as leaving the BS in either the reflected state ( $|R\rangle$ ) or the transmitted state ( $|T\rangle$ ).

Since we know that there is a 50% chance the photon might be in the  $|R\rangle$  state and a 50% chance it might be in the  $|T\rangle$  state then we can write the state of the photon after the beamsplitter as a superposition of those states. Namely,

$$|\psi\rangle = \frac{1}{\sqrt{2}}|R\rangle + \frac{1}{\sqrt{2}}|T\rangle$$

As mentioned previously, the coefficients before  $|R\rangle$  and  $|T\rangle$  are the “probability amplitudes” of each and capture the 50% likelihood of finding the photon in either state. These coefficients are written as  $\frac{1}{\sqrt{2}}$  because these coefficients must later be squared to calculate the probability of a measurement (and  $(\frac{1}{\sqrt{2}})^2 = \frac{1}{2}$ ).

As we saw in the last experiment, this representation creates some confusion. It is saying that the photon – which is a “whole” particle – is in both the  $|R\rangle$  and  $|T\rangle$  state or paths simultaneously. How can a single, indivisible, quanta of energy - a particle - be in the reflected and transmitted path simultaneously? If it were a wave (instead of a particle) then this would make sense. A wave can be split in half and sent in different directions. But, as we showed in the past three experiments, a photon is always treated by a beamsplitter and measured by our SPCMs as a whole. In fact, when placing single photon counting modules after a BS, the “whole” photon are observed to be randomly reflected or transmitted. Never our two “half” photons measured as being simultaneous in both paths.

This, again, is the compromise of quantum theory. The superposition of states essentially treats the photon as a wave (a probability wave) that can be split, exist in multiple paths, and can even be made to interfere with itself. On the other hand, the actual physical measurement of the photon requires that the photon be regarded as a whole and indivisible particle. Balancing these two competing concepts within a singular model is the innovation, and the challenge, of quantum theory. The purpose of this experiment is to demonstrate how quantum mechanics simultaneously addresses these two very different pictures of reality and how quantum theory successfully predicts a phenomenon that cannot be explained using classical physics.

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→ *Experimental Procedure*

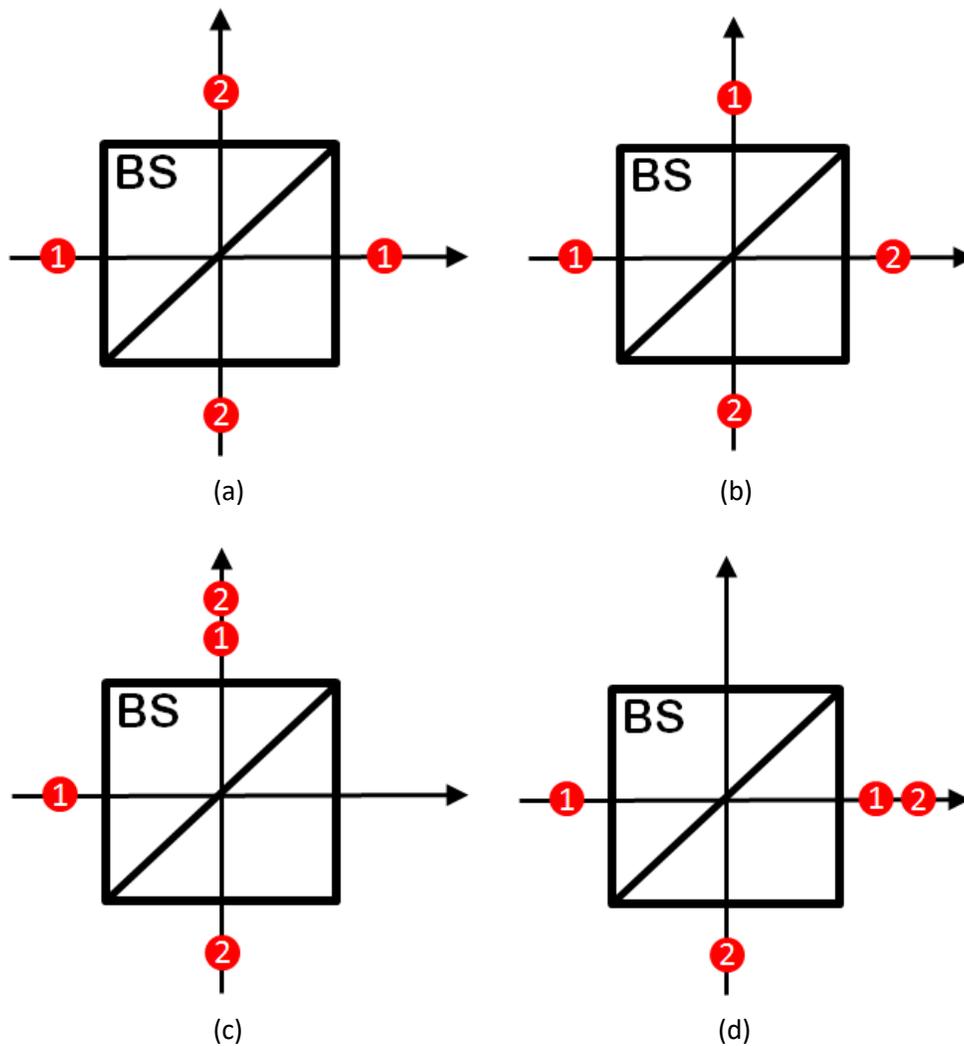
**Measurement 1: Two Photons Interacting with a Beamsplitter**

In the previous experiment we spent a considerable amount of time investigating what happens to a single photon when it encounters a non-polarizing beamsplitter (BS). In this experiment, we are going to investigate the more interesting question of what happens to two photons when they encounter a BS at exactly the same time.

Configure your setup similar to the diagram at the beginning of this write-up. At the heart of this experiment are two optical delay lines. A delay line is a device that collimates light from an optical fiber, sends it across a short air gap (creating a delay), and then couples the light back into another optical fiber. For this experiment, one delay line is a fixed-length fiber while the other delay line can be varied by manual or motorized actuator.

As you can see in the setup, we are using a QES2 to create a bi-photon pair. We are then using a polarizing beamsplitter (PBS) to separate the two bi-photons based on their differing polarization. The two photons then travel down separate paths before encountering a common BS. What will happen if the two photons encounter the BS at the same time? Will the BS treat them the same or will we still get random results for each photon? This is the basic question that we want to examine in this experiment.

Basically, if two photons are incident on a 50/50 non-polarizing beamsplitter at the same time, we could anticipate the following four possible outcomes:



*Four Possible Scenarios for Bi-Photon Interaction*

For scenarios (c) and (d), only one detector will register a “hit.” Therefore, no coincidence counts will be recorded for these scenarios. For scenarios (a) and (b), two detectors will register a “hit” simultaneously, resulting in a coincidence count. If each photon is treated randomly by the beamsplitter, then each scenario has an equal 25% chance of occurring.

For measuring this interaction, we’re going to require that the two incident photons be identical in every way. Rotations have already been made in the delay lines in your kit to ensure that the polarization of the photons are the same. Therefore, the photons incident on port R and port T of the BS have the same polarization (both are horizontally polarized). To ensure that their wavelengths are exactly the same, we need to set the temperature of the crystal inside the QES2 to a specific temperature. The QES2 is shipped with a default setting that ensures the signal and idler photons have identical (or degenerate) wavelengths. If you made changes to these default settings in Experiment #2, be sure to change the settings back to their default values (which are listed on the QES2 datasheet).

Plug in the QES2 and allow three minutes for the crystal temperature to stabilize. With the QES2 at the proper operating temperature, ensure that the variable delay line is unobstructed. This will result in photons entering both Ports 1 and 2 of the BS. Depending on how the variable delay line is configured, one photon in the bi-photon pair may be arriving at the BS before or after the other photon. By adjusting the micrometer on the variable delay line, it is possible to change the delay of one of the photons. Therefore, there exists a micrometer setting that produces equal delays between the fixed and variable delay lines. Once this micrometer setting is found, both photons will arrive at the BS at exactly the same time.

*Note: For this experiment, we are going to describe using a manual micrometer to vary the delay of one of the photons. However, the kit is equipped with a motor and motor controller (the MC2) which can be used to replace the manual micrometer. Details on using the motor and MC2 controller for performing this experiment are available in the MC2 Motor Controller Manual.*

Configure the coincidence counter with the following values:

<b>Coincidence Counter Settings</b>	
Window Size	3 ns
Dwell Time	1.0 s
Gate Chan.	Disabled
Delay	0 ns

Move the micrometer to 0.00 mm. Record the singles and coincidence rates in the following table (or, preferably, in a computer spreadsheet). Move the motor by 0.25 mm and record the singles and coincidence rates again. Repeat this process for the actuator’s full travel range.

<b>Coincidence Counts vs. Delay</b>					
Micrometer (mm)	Channel 1	Channel 2	Coincidences	Accidentals	Coincidences – Accidentals
0.00					
0.25					
0.50					
0.75					
1.00					
1.25					
1.50					
1.75					
2.00					
2.25					
2.50					
2.75					
3.00					
3.25					
3.50					
3.75					
4.00					
4.25					
4.50					
4.75					
5.00					
5.25					

<b>Coincidence Counts vs. Delay</b>					
Micrometer (mm)	Channel 1	Channel 2	Coincidences	Accidentals	Coincidences – Accidentals
5.50					
5.75					
6.00					
6.25					
6.50					
6.75					
7.00					
7.25					
7.50					
7.75					
8.00					
8.25					
8.50					
8.75					
9.00					
9.25					
9.50					
9.75					
10.00					
10.25					
10.50					
10.75					

<b>Coincidence Counts vs. Delay</b>					
Micrometer (mm)	Channel 1	Channel 2	Coincidences	Accidentals	Coincidences – Accidentals
11.00					
11.25					
11.50					
11.75					
12.00					
12.25					
12.50					
12.75					
13.00					
13.25					
13.50					
13.75					
14.00					
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15.00					
15.25					
15.50					
15.75					
16.00					
16.25					

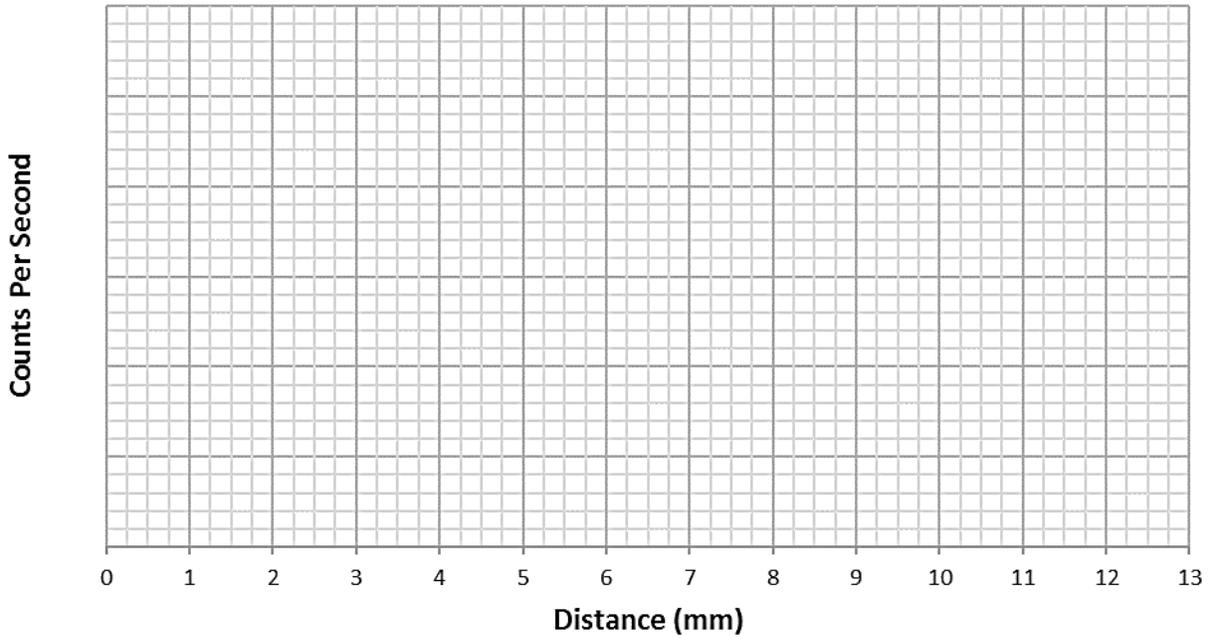
<b>Coincidence Counts vs. Delay</b>					
Micrometer (mm)	Channel 1	Channel 2	Coincidences	Accidentals	Coincidences – Accidentals
16.50					
16.75					
17.00					
17.25					
17.50					
17.75					
18.00					
18.25					
18.50					
18.75					
19.00					
19.25					
19.50					
19.75					
20.00					
20.25					
20.50					
20.75					
21.00					
21.25					
21.50					
21.75					

<b>Coincidence Counts vs. Delay</b>					
Micrometer (mm)	Channel 1	Channel 2	Coincidences	Accidentals	Coincidences – Accidentals
22.00					
22.25					
22.50					
22.75					
23.00					
23.25					
23.50					
23.75					
24.00					
24.25					
24.50					
24.75					
25.00					

With all the data recorded, calculate the accidentals for each measurement and record them in the data table. Finally, subtract the accidental counts from each coincidence count value and record these values in the data table.

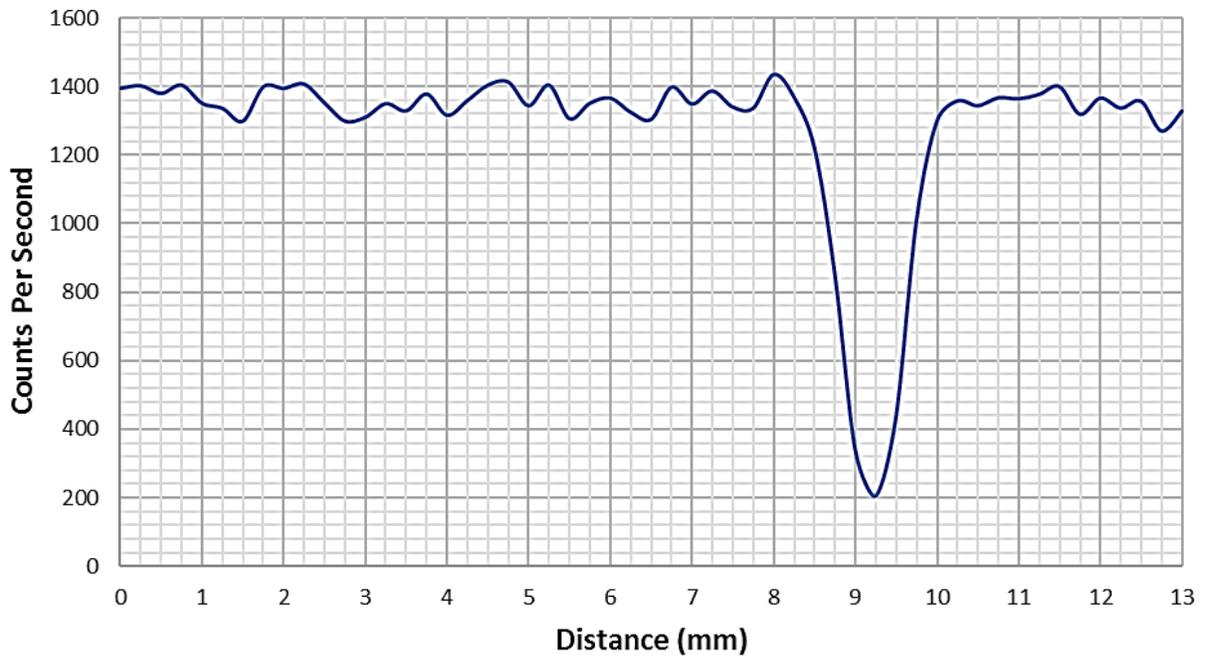
Plot the data in the “micrometer” column versus the “Coincidence – Accidentals” column on the following chart:

### Coincidence - Accidental



Although the location of the “dip” may vary, the data plot should look similar to the figure below:

### Coincidence - Accidental



The dip in the data represents a point where only one SPCM is detecting a photon. Ergo, no coincidence counts are being recorded because both SPCMs are not detecting a photon. At this point, the two photons must be exiting the BS from the same port. Ergo, both photons are traveling to the same detector.

To reiterate this, the bottom of the dip represents the condition where the two photons emerging from the BS must both be exiting the same output port (either Port 1 or Port 2), otherwise they would be in separate ports and would be measured as a coincidence event. A careful measure of each fiber and air-gap lengths would show that the location of the dip also corresponds to the point where both the fixed delay path and the variable delay path have exactly the same lengths. Hence, at the dip location, the two bi-photons are arriving at the BS at exactly the same time.

If we had perfectly aligned all our polarization optics, more precisely tuned the QES2 crystal temperature, and acquired data in finer steps, we would have found that the dip could be made to go to zero coincidence counts. This was the finding made by scientists Hong, Ou, and Mandel in the late 1990s. It was the first recorded measure of the quantum phenomena called “photon bunching.” The dip in the coincidence count data is commonly referred to as the Hong-Ou-Mandel dip.

This dip corresponds to a point where the two incident photons are “indistinguishable” from one another. At this point, the photons are arriving at the BS at exactly the same time, with the same wavelength, and with the same polarization. As they leave the beamsplitter, it is not possible to determine whether the exiting photon came from the variable delay line path or the fixed delay line path.

When photons are indistinguishable we observe that they have a correlated behavior. In this experiment, that means that they bunch together and always leave out the same port. Which port they leave out of is random, but it is always the same for both photons.

When one photon is delayed relative to another, then it is possible to “distinguish” between the two photons and their respective paths based on their arrival time. In this scenario, photon bunching is not observed and each photon is individually and randomly directed into either the transmitted or reflected path.

How does quantum theory explain this result? The blue sections on the following pages will explain the mathematics behind predicting this result, but this explanation does not provide much intuition into the phenomena. A more physical description or model of the behavior can be described if we assume that the photons exist in some other “realm” prior to being measured. This realm may have many dimensions and it is not one that we can easily visualize. In this realm, the photon behaves like waves and their probability of projecting onto our three-dimensional world can be thought of as a type of “probability wave” that governs when and where the photon could project into our world.

When we measure a photon, we force the photon to leave its wave-like realm and project, or collapse, into a well-defined position within our three-dimensional space. In quantum mechanics, we try to crudely capture this concept by saying that measuring a photon collapses its wave function. Therefore, before measurement, the photon is free to act as a wave – where, again, this wave refers to its probability of existence in our three-dimensional world as opposed to its electromagnetic oscillations. For the case

where the two photons are indistinguishable, their probability waves are indistinguishable and, therefore, can interfere with one another. Because both paths are equally possible, a constructive interference occurs between the two probability waves only for the scenario where both photons are detected in the same output port. A destructive interference occurs for the scenario where both photons leave out different ports.

Clearly, trying to physically explain quantum phenomena is much harder than simply using the mathematics of quantum theory to predict results. Nonetheless, for experimentalists, observing the various quantum phenomena and struggling to grasp a somewhat self-consistent, albeit limited, model is a necessary step toward acceptance, application, and eventual progression of quantum theory.

**Measurement 2: Effect of Source Degeneracy on Dip Visibility**

In Experiment 2, we changed the QES2 crystal temperature and looked at the resulting coincidence counts to see if we could observe a difference between degenerate and non-degenerate temperatures. Now that we have a Hong Ou-Mandel dip, we can much more clearly see the effect of changing the crystal temperature. If the crystal temperature is too hot or cold, the signal and idler photons emitted will be two different wavelengths (non-degenerate) and will be distinguishable. Because the Hong-Ou-Mandel dip is the interference of two indistinguishable photons, the dip should reduce in visibility as the output is made non-degenerate.

Begin by moving the micrometer on the variable delay line to the point that produced the lowest dip in your coincidence data. As we did in Experiment #2, connect the QES2 to a computer using the USB A to B cable. Open **QES Control** and try changing the temperature setpoint to various values while noting the corresponding change in temperature.

**Write down the “Temperature Set Point” and the current temperature reading in the following table:**

<b>QES2 Degenerate Temperature Settings</b>	
Temperature Setpoint Value	
Temperature (°C)	

Use the table on the next page to fill in the data as you evaluate the QES2 output at various setpoints.

As mentioned, the change in crystal temperature will cause the wavelengths of the bi-photons emitted by the QES2 to change slightly. For this setup, you should see the singles counts remain relatively unchanged as the temperature of the crystal increases. However, the coincidence counts should change considerably. When the crystal temperature is at the default temperature for producing a degenerate output, the coincidence counts should be at their lowest.

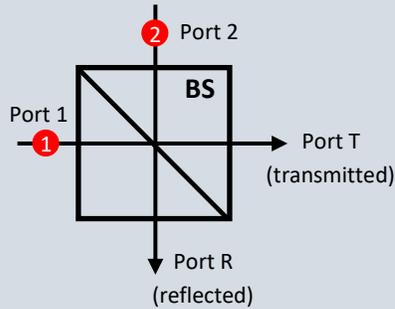
QES2 Temperature						
Set Point	20,000	25,000	30,000	35,000	40,000	45,000
Temperature (°C)						
Channel 1 Singles						
Channel 2 Singles						
Coincidence Counts						

As we were positioned at the location of the deepest part of the dip, you should observe that the singles counts don't change, but as the temperature gets farther from the initial, degenerate temperature, the coincidence counts increase, which means the visibility of the dip is being reduced. The temperature of the crystal affects the wavelength of the photons, and therefore the distinguishability of the photons. You have now demonstrated indistinguishability and distinguishability and its effect on photon bunching!

**When you have completed your measurements, set the Temperature Set Point back to the initial value you wrote down on the previous page.**

## Photon Bunching

The quantum theory explaining why indistinguishable photons “bunch” is fairly straightforward. If we consider the scenario we encountered in the second measurement of this experiment, where two photons are entering the input ports of a 50/50 non-polarizing beamsplitter at exactly the same time, then we have the following initial condition:



These two photons can either reflect or transmit at the BS. To predict how these photons will behave, we start by first writing a quantum state that captures all possible output scenarios (e.g. all combinations of how the two photons could emerge from the beamsplitter).

For example, one possibility is that one photon reflects at the BS and exits out Port R, while the other photon reflects from the BS and exits out Port T. This possible outcome can be denoted as  $|1\rangle_T|1\rangle_R$ , where the numbers indicate how many photons exit through each port. Obviously, there are many possible outcomes (four to be exact). Therefore, the full quantum state vector is written as:

$$|\psi\rangle = |1\rangle_T|1\rangle_R + |2\rangle_T|0\rangle_R + e^{i\pi}|0\rangle_T|2\rangle_R + e^{i\pi}|1\rangle_T|1\rangle_R$$

Where the phase shift  $e^{i\pi}$  has been added for the reflected photon from Port 1 to Port R to conserve energy. The need for a  $\pi$  phase shift upon reflection on **one** leg of a beamsplitter was established long ago as a function of a traveling wave and is critical to include to correctly compute constructive and destructive interference in waves (see beamsplitter matrix on page 46).

Since  $e^{i\theta} = \cos \theta + i \sin \theta$ , then  $e^{i\pi} = -1$ , therefore:

$$|\psi\rangle = |1\rangle_T|1\rangle_R + |2\rangle_T|0\rangle_R - |0\rangle_T|2\rangle_R - |1\rangle_T|1\rangle_R$$

If photon 1 and photon 2 are indistinguishable, then the outcome  $|1\rangle_T|2\rangle_R$  (i.e. the case where photon 1 exits the T port and photon 2 exits the R port) cannot be distinguished from  $|1\rangle_R|2\rangle_T$ . Therefore, the first and last terms in the state vector are equivalent and will cancel.

For indistinguishable photons, this leaves the normalized state:

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|2\rangle_T|0\rangle_R - |0\rangle_T|2\rangle_R)$$

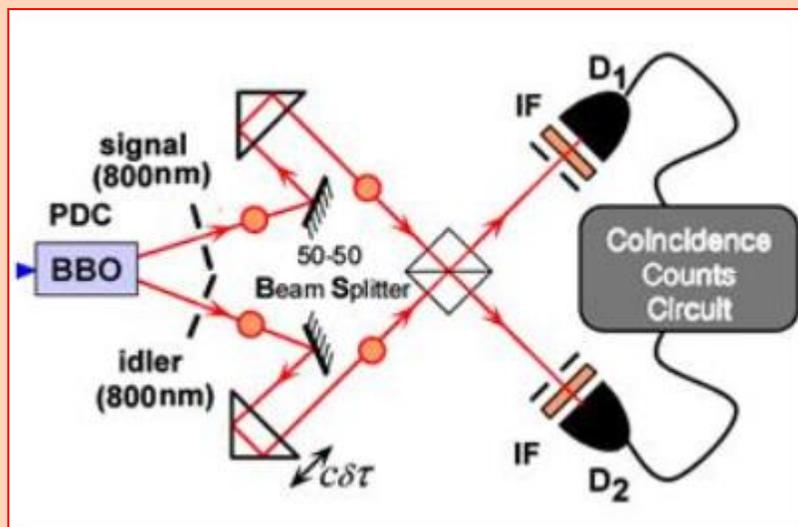
Ergo, the output state represents either two photons leaving port T or two photons leaving port R. This is exactly the photon bunching that we observed experimentally. It can be noted that if the two photons

were not indistinguishable then the canceling of the first and last terms would not have occurred, and no bunching would have been predicted. This, too, is what we observed experimentally.

In general, predicting the behavior of a photon at an optical element (i.e. a beamsplitter, a waveplate, etc.) is going to be more complicated than this example. For more general problems, we will need to describe the quantum state as a vector and the optical components and processes as operators. The operators will take the form of matrices and we will combine them using the tensor product of the operator matrices. This process will be described in more detail in later experiments.

## Hong-Ou-Mandel Interferometer

The Hong-Ou-Mandel dip measured in this experiment is actually a form of quantum interferometry that can be used for very precise timing resolution of optical pulses. As one leg of the interferometer is scanned, a very precise timing profile of the interfering pulses can be constructed.



The original interferometer setup (shown above) used a slightly different setup. Many variations have been developed for the Hong-Ou-Mandel interferometer and some focus on the use of this interferometer for alternate sensing applications.

Historically, this interferometer has been a challenging experiment to setup and conduct. It is not uncommon for graduate students to spend six months or longer trying to see the elusive Hong-Ou-Mandel dip. The setup used in this experiment simplified the interferometer by using singlemode fibers to eliminate any possibility of non-overlapping spatial modes. More complex free space Hong-Ou-Mandel interferometers have been built which can yield much higher count rates than the fiber optic design utilized in this experiment but require greater care in the optical alignment.

# Quantum Mechanics Laboratory Kit

## 05 Experiment

### Non-Locality & Local Realism

#### → What you will learn

In this experiment, you will create entangled photon states and measure their polarization properties. You will measure the properties of single photons (as in Experiment 3), as well as the *joint properties* of the photon pairs. In doing so, you will learn how entangled photons differ from the bi-photons that we have studied thus far.

#### → What you will need

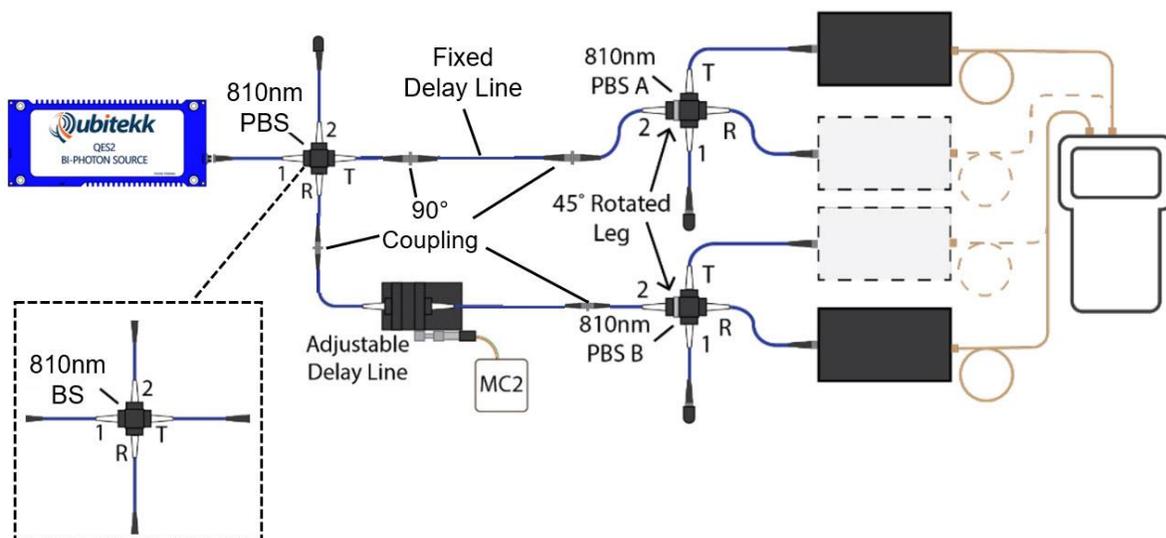
The following experimental components:

- Straight Coupler (4)
- QES2 Bi-Photon Source (2)
- 810nm Fiber Optic PBS (1)

- 810nm Fiber Optic PBS with 45° leg (2)
- Adjustable Delay Line
- Fixed Delay Line
- Liquid crystal variable retarder (LCVR) and controller
- Coincidence Counter
- Single Photon Counting Modules (2)
- 1 meter BNC-to-SMA cables (2)

#### → Initial Setup

Assemble the experimental components as shown in the figure below. Note that the first component after the QES2 will be switched between a PBS and BS. The first measurements will use the PBS. Make sure the labeled legs of the different fiber optic beamsplitters are connected exactly as shown in the figure below. Also make sure to use 90° couplers in the locations shown.



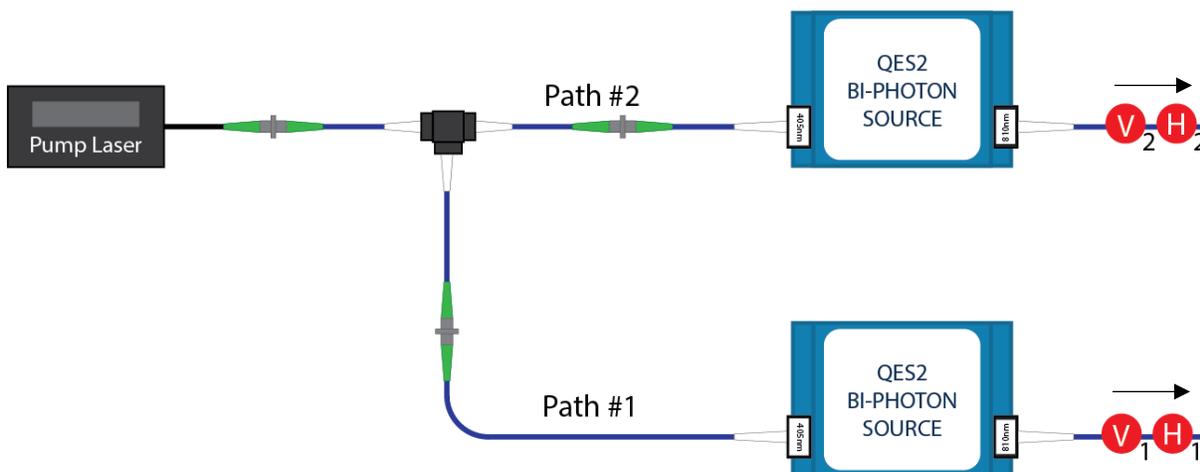
# Quantum Mechanics Laboratory Kit

## → What you need to know...

In the previous experiment, we produced bi-photon pairs using spontaneous parametric down conversion from a single QES2. These photon pairs could be made indistinguishable from one another allowing us to investigate correlations in their behavior when they encountered a 50/50 non-polarizing beamsplitter. The result, the phenomena we called photon bunching, provided an example of how the quantum world can give us results that are not initially what we would predict. Mathematically, it demonstrated how quantum amplitude superposition of two indistinguishable photon states could explain and predict these results.

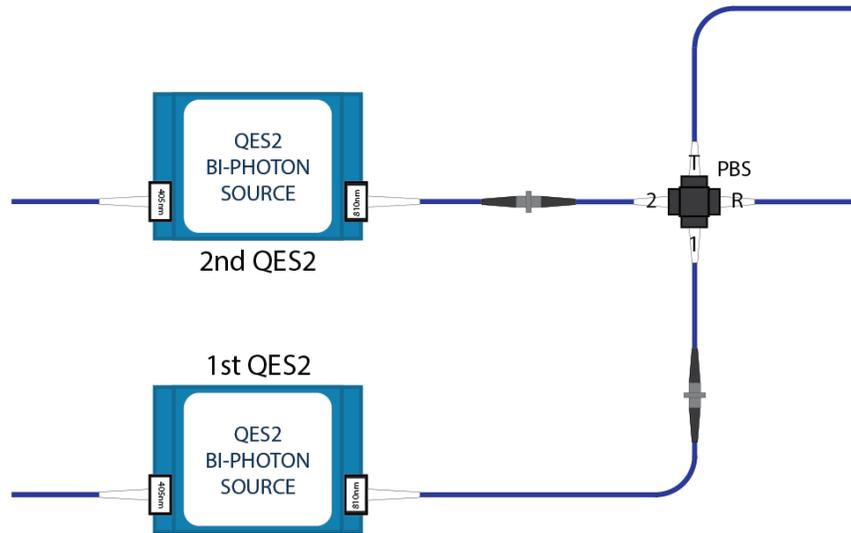
In the past experiment, the two photons existed in “separable” states, meaning that the properties of one photon did not depend on the properties of the other. In this experiment, we will go a step further and create “entangled” photon pairs. Entangled photons exhibit a “shared” state. By “shared” we mean that the properties of one photon depend on the properties of the other photon. This is a complicated idea and, to best illustrate it, we will work through an example.

Let’s imagine we had a pump laser providing pump photons to a beamsplitter (for this discussion, we are imagining the pump laser to be outside the QES2 housing). The beamsplitter can either reflect the pump photons into a fiber (path #1) that leads to a first QES2 or it can transmit the pump photons into a fiber (path #2) that leads to a second QES2, as shown in Figure 1.

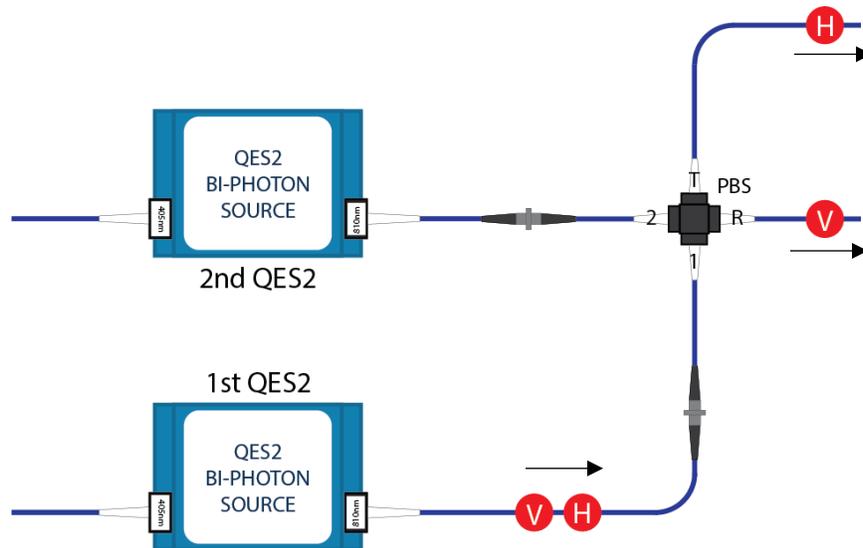


Because the beamsplitter is a 50/50 splitter, there is an equal probability that a pump photon will travel down the first path or the second path. Therefore, there it is equally likely that we will produce bi-photons from either the first QES2 or the second QES2. If we keep the intensity of the pump laser low, we can ensure that rarely will both QES2 units produce bi-photons simultaneously.

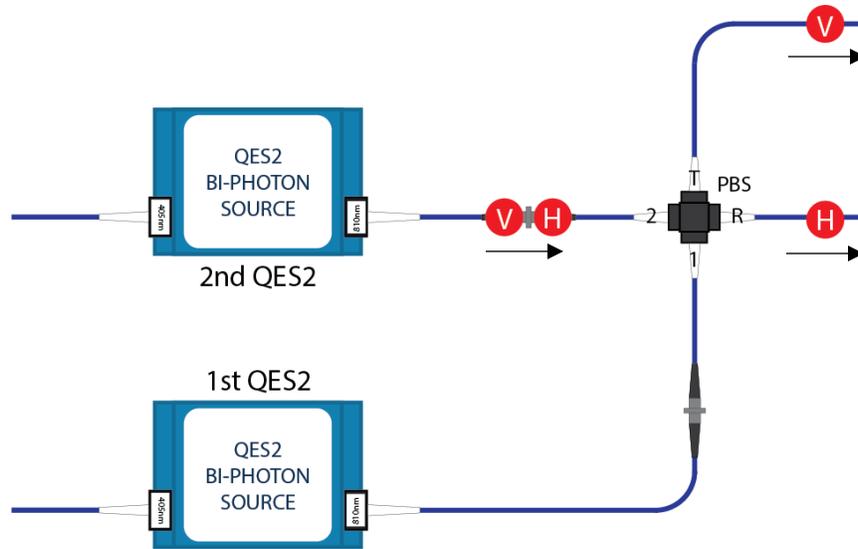
If the outputs of both QES2s are then brought together at a polarizing beamsplitter (PBS), as shown in the next figure, then the output from the PBS becomes uncertain.



For example, if bi-photons are produced from the first QES2, then we should expect the horizontally polarized photon to transmit through the PBS into the upper output fiber as shown below. Likewise, we should expect the vertically polarized photon to reflect from the PBS into the lower output fiber.



However, if bi-photons are produced by the second QES2, then we should expect to get a horizontally polarized photon in the lower output fiber and a vertically polarized photon in the upper output fiber, as shown in the following figure.



Without knowing whether the first or the second QES2 produced the photon pair, we cannot know whether the photon in the upper output fiber is horizontally or vertically polarized. Likewise, we cannot know whether the photon in the lower output fiber is horizontally or vertically polarized. But we can say, with certainty, that whatever the polarization of the photon is in the upper fiber, the photon in the lower fiber must have the opposite polarization. In this way, the properties of one photon are tied, or *entangled*, with the properties of the other photon. This “entangled state” is written as:

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|H_{top}V_{bottom}\rangle + e^{i\theta}|V_{top}H_{bottom}\rangle) = \frac{1}{\sqrt{2}}(|HV\rangle + e^{i\theta}|VH\rangle),$$

where the term  $e^{i\theta}$  reflects any slight phase difference between the two QES2 sources due to their different distances from the beamsplitter (this will be described in more detail later).

At first glance, the common sense interpretation of the physics is that – even though we cannot predict the polarization of the photons in each arm - these two photons must still be exiting the beamsplitter with some well-defined and fixed polarization value. The fact that we can’t predict their values is just a reflection of our own shortcomings. Hence, despite our ignorance, it would seem logical that the photons themselves must “know” their polarization values as they leave the PBS and this value must be fixed and well-defined. As we will see in this experiment, that explanation does not accurately reflect or predict what we observe experimentally.

The surprising behavior of entangled photons is best revealed in their *joint properties*. For that reason, we will be measuring the probabilities of finding the two photons in particular polarization states, *e.g.*, photon 1 with polarization  $X$  and photon 2 with polarization  $Y$ . In the state given above, it is easy to see that the probability of finding the “top” photon with  $H$  polarization and the “bottom” photon with  $V$  polarization is expected to be  $\frac{1}{2}$  (recall that the probability is the square of the magnitude of the  $|HV\rangle$  coefficient). Likewise, the probability of a  $V_{top}H_{bottom}$  coincidence detection is also  $\frac{1}{2}$ , while the  $H_{top}H_{bottom}$  and  $V_{top}V_{bottom}$  probabilities are zero. But what if we detect the photons in the diagonal polarization bases? What is the probability of detecting, say, one photon with diagonal ( $D$ ) polarization

and the other with anti-diagonal (A) polarization? The answer will depend on whether the photons are entangled, as well as *how* they are entangled. To illustrate this behavior, we will first make joint polarization measurements on (not entangled) bi-photons, followed by the same measurements on entangled photons.

---

→ *Experimental Procedure*

## **Bi-photon Configuration**

Configure the fiber optic setup as shown in the *Initial Setup* section. The figure shows that the first beamsplitter to be either a polarization beamsplitter or a nonpolarizing beamsplitter. The PBS is used for the bi-photon setup (this one), and the BS is used for the entangled photon setup. The PBS has two input fibers. For the first set of measurements, connect the bi-photon source to **Leg 1**.

### **Measurement 1: Bi-photons in the rectilinear basis**

Connect **Leg 1** on PBS A and B to the two outputs from the first PBS. This configuration measures both photons in the rectilinear basis. The measurements needed for this experiment are very similar to the measurements made in Experiment 3. In that experiment, the photons were split at a polarization beamsplitter and one of the photons was studied in both the rectilinear (H/V) and diagonal (D/A) polarization bases (the other photon was discarded). Because the polarization beamsplitters are outfitted with a 45 degree rotation in one of the inputs (**Leg 2**), switching between bases is as simple as switching inputs. The biggest difference between Experiment 3 and this one is that the polarization measurements will be made on *both* photons in this experiment, instead of just one. [Because the two polarization beamsplitters have a total of four output ports, the two detectors will need to be moved around quite a bit in this experiment.] The other big difference is the presence of a phase retarder in the path of one of the photons. More on this later.

Note: Be careful when configuring this experiment to ensure that the key on the optical fiber connector does indeed go into the correct slot in the 90 degree coupler. The key on the fiber optic connector can often be difficult to see so connecting the 90 degree coupler is something that should be done carefully and with the room lights elevated.

With the experimental setup configured, turn on the bi-photon source and allow a few minutes for the laser and crystal temperature to stabilize. Configure the coincidence counter with the following settings:

Coincidence Counter Settings	
Dwell Time	1.0 s
Window Size	3 ns
Trigger?	Start/Stop

For this experiment we have four PBS outputs that we want to measure coincidence rates for with our two detectors. This means that we will need to switch between the port R and port T legs on PBS A and PBS B. A total of four combinations are possible. Make the following measurements in the table below:

Bi-photon source in Leg 1 of first PBS (0° rotation   H/V Basis)				
		Singles		
<i>Det 1</i>	<i>Det 2</i>	Coincidences	<i>Ch. 1 (K)</i>	<i>Ch. 2 (K)</i>
PBS A(R)	PBS B(R)			
PBS A(R)	PBS B(T)			
PBS A(T)	PBS B(R)			
PBS A(T)	PBS B(T)			

Your data should show that only one measurement combination produces a high coincidence rate. In addition, the variation between the max and min coincidence rate for that combination should be small (you can verify this by making several repeated observations). This makes sense since the polarizations of the photons exiting the first PBS are known and fixed.

Disconnect the bi-photon source from **Leg 1** of the first PBS and connect it to **Leg 2**. Repeat the above measurement for this new configuration and record your results in the table below:

Bi-photon source in Leg 2 of first PBS (0° rotation   H/V Basis)				
		Singles		
<i>Det 1</i>	<i>Det 2</i>	Coincidences	<i>Ch. 1 (K)</i>	<i>Ch. 2 (K)</i>
PBS A(R)	PBS B(R)			
PBS A(R)	PBS B(T)			
PBS A(T)	PBS B(R)			
PBS A(T)	PBS B(T)			

As before, your data should show that only one measurement combination produced a high coincidence rate and the variation between the max and min coincidence rate for that combination should be small. This makes sense since, again, the polarizations of the photons exiting the PBS are known and fixed. The combination that produced the high coincidence count, however, should be different from before.

### Measurement 2: Bi-photons in the diagonal basis

For this experiment, change the input legs on PBS A and PBS B to **Leg 2** (45° angle). This will project the H/V photons in each path into the diagonal measurement basis.

With the experimental setup configured, verify that the QES is turned on. Once again, configure the coincidence counter with the following settings:

Coincidence Counter Settings	
Dwell Time	1.0 s
Window Size	3 ns
Trigger?	START/STOP

With the system stabilized, connect the QES to **Leg 1** of the first PBS. Begin making continuous measurements with the coincidence counter and record your measurements in the table below:

Bi-photon source in Leg 1 of first PBS (45° rotation   +/- Basis)				
		Singles		
<i>Det 1</i>	<i>Det 2</i>	Coincidences	<i>Ch. 1 (K)</i>	<i>Ch. 2 (K)</i>
PBS A(R)	PBS B(R)			
PBS A(R)	PBS B(T)			
PBS A(T)	PBS B(R)			
PBS A(T)	PBS B(T)			

Your data should show roughly equal coincidence rates for the various combinations with minimal variation in min and max values. This result is very different from the exact same measurement made in the rectilinear basis. In the rectilinear basis, our earlier measurements showed that both photons always had opposite polarizations. When these two photons are measured in the diagonal basis, that correlation has disappeared.

Once again, connect the QES to **Leg 2** of the first PBS and repeat the measurements for this second configuration. Record your results in the table below:

Bi-photon source in Leg 2 of first PBS (45° rotation   +/- Basis)				
		Singles		
<i>Det 1</i>	<i>Det 2</i>	Coincidences	<i>Ch. 1 (K)</i>	<i>Ch. 2 (K)</i>
PBS A(R)	PBS B(R)			
PBS A(R)	PBS B(T)			
PBS A(T)	PBS B(R)			
PBS A(T)	PBS B(T)			

As before, your data should show roughly equal coincidence rates for the various combinations and minimal variations in min and max values. Again, this result is very different from the exact same measurement made in the rectilinear basis. In the rectilinear basis, our earlier measurements showed that both photons always had different polarizations. When these two photons are measured in the diagonal basis, that correlation has again disappeared.

At this point, we have collected enough data to imagine what might happen in the thought experiment discussed in the *What you need to know...* section. There, it was suggested that we could create entangled photon pairs by connecting two bi-photon sources to the two inputs of a PBS. We have done something similar—we connected one source to each of the inputs and studied the combinations of polarizations observed at the two polarization analyzers. Here is a summary of what we observed:

- Strong correlations were seen in the rectilinear basis:
  - One input yielded high  $HV$  rates and low  $VH$  rates;
  - The other input yielded low  $HV$  rates and high  $VH$  rates;
  - Neither input yielded high  $HH$  or  $VV$  rates.
- The polarizations were essentially uncorrelated in the diagonal basis:
  - All four outcomes ( $DD$ ,  $DA$ ,  $AD$ , and  $AA$ ) were equally likely.

If we now imagine connecting two bi-photon sources, one to each of the PBS inputs, we might imagine that the result would be a combination of the two cases we just studied. That is, we might expect:

- Strong correlations in the rectilinear basis:
  - Each analyzer could see either  $H$  or  $V$  ( $H$  from one input and  $V$  from the other);
  - But we would still have low  $HH$  and  $VV$  rates (since these rates were low for both inputs).
- Essentially uncorrelated results in the diagonal basis:
  - All four outcomes ( $DD$ ,  $DA$ ,  $AD$ , and  $AA$ ) equally likely.

Instead of thinking about it, we can actually do the experiment using the configuration described below. We will find that the results differ from the hypothesis above. That is, entangled photons behave quite differently than simple bi-photons.

## **Entangled Photon Configuration**

The “two-source” method described above for generating entangled photons turns out to be somewhat impractical. The biggest problem is that, with two separated bi-photon sources, it is difficult to control the phase between the two downconversion processes. But the principle of combining photons from two sources is quite sound and most entangled photon sources do exactly that, albeit in more compact (and stable) configurations. Because we have only a single bi-photon source, we will have to use a different approach—and the state we end up with will not be truly entangled. The technically correct term is a “post-selected” entangled photon state. To see how we will generate this state and to explain why we use the term “post-selected,” let’s discuss the setup.

The configuration for entangled photon state is the same as the configuration we just studied, except that the first PBS is replaced with a nonpolarizing beamsplitter. When a pair is generated, the two photons—one horizontally polarized, and one vertical—enter the beamsplitter assembly. Because the beamsplitter

is not sensitive to polarization, each photon can be transmitted or reflected. The result is that there are four possible outcomes: i) the  $H$  photon is reflected and the  $V$  photon is transmitted; ii) the  $H$  photon is transmitted and the  $V$  photon is reflected; iii) both photons are reflected; or iv) both are transmitted. In the language of our earlier thought experiment, that state can be described as

$$|\psi\rangle = \frac{1}{2}(|H_{top}V_{bottom}\rangle + e^{i\theta}|V_{top}H_{bottom}\rangle + |H_{top}V_{top}\rangle + |H_{bottom}V_{bottom}\rangle).$$

There are a couple of things to note here. First, the normalization factor is different, reflecting the fact that there are four equally weighted terms instead of two. Also, the phase factors for the third and fourth terms are not shown. It will be clear in a moment why that is not important. But the most important thing to note about this expression is that the first two terms look exactly like our earlier expression for an entangled photon state. So, if we can somehow ignore the third and fourth terms, the remaining expression should act like an entangled state.

Fortunately, there is an easy “experimental” way to ignore those terms. Note that, in each of those terms, both photons go to the same polarization analyzer, whereas the first two terms have one photon going to the “top” analyzer and one to the “bottom.” All of the measurements that we have made so far have been coincidence measurements, in which we detect one photon at each analyzer. So the third and fourth terms in our expression lead to outcomes that are never detected in our experiment. If we “select” only the outcomes in which one photon is seen at each analyzer, then we can safely ignore the other two terms. Thus, our “post-selected” state is the same expression that came out of our thought experiment:

$$|\psi\rangle_{post-selected} = \frac{1}{\sqrt{2}}(|H_{top}V_{bottom}\rangle + e^{i\theta}|V_{top}H_{bottom}\rangle) = \frac{1}{\sqrt{2}}(|HV\rangle + e^{i\theta}|VH\rangle).$$

Even though the post-selected state is not a true entangled state, the behavior is exactly the same as an entangled state, as long as we restrict ourselves to outcomes in which one photon is detected at each analyzer. With that brief explanation, we can begin our study of the polarization properties of (post-selected) entangled photons. Begin by replacing the first PBS in the previous configuration with a nonpolarizing beamsplitter.

### Measurement 3: Entangled photons in the rectilinear basis

As before, we will first make measurements in the rectilinear basis. Ensure that the fibers from the beamsplitter are connected to **Leg 1** for both PBS A and PBS B. Repeat the set of measurements, just as in the previous configuration. Be careful not to contact or disturb the optical fibers during your measurement. Record your results in the table below:

Entangled Photons (0° rotation   H/V Basis)				
			Singles	
<i>Det 1</i>	<i>Det 2</i>	Coincidences	<i>Ch. 1 (K)</i>	<i>Ch. 2 (K)</i>
PBS A(R)	PBS B(R)			
PBS A(R)	PBS B(T)			
PBS A(T)	PBS B(R)			
PBS A(T)	PBS B(T)			

No surprises here. The data for the entangled photons should show two combinations in the rectilinear basis that produce high coincidence counts with minimal variation in max and min values.

#### Measurement 4: Entangled photons in the diagonal basis

For this last set of measurements, change the input legs on PBS A and PBS B to **Leg 2** (45° angle). This will project the H/V photons in each path into the diagonal measurement basis. The measurements will proceed as before, with one small change. When you have the detectors in place for the first measurement, note the stability of the coincidence rates by taking several subsequent readings. Are the coincidences changing from one reading to the next? If not, gently grasp the fiber between the nonpolarizing beamsplitter and one of the polarization analyzers (you may want to use a short dwell time and ‘Continuous’ trigger for this observation). The warmth of your hand is often enough to cause big swings in the coincidence rates. You are seeing the effect of the phase term in the expression for the entangled photon state. That phase arises from the fact that the two polarizations propagate differently in the nonlinear crystal, the optical elements, and especially the polarization-maintaining fibers. In effect, the peaks and troughs of the *H* and *V* waves line up differently at the end of the fiber than at the beginning. These phase differences are affected by temperature and by even the smallest movements of the fibers. All of the accumulated phase differences can be collected into the single phase term shown above.

You may be wondering why we did not see this behavior in our earlier measurements. The reason is related to the polarization-maintaining (PM) fiber that we are using. As its name implies, PM fiber preserves the polarization of light as it propagates through the fiber. But this is true only for light that is linearly polarized either parallel or perpendicular to a special direction in the fiber. Light launched with polarization in one of these directions will emerge with its polarization intact. For most of our configurations, these directions correspond to *H* and *V* polarization. In fact, that is the reason that we did not observe the same type of coincidence rate fluctuations in our earlier measurements (Measurements 1-3): in Measurements 1 and 2, the light leaving the first PBS was linearly polarized *H* or *V*; and in Measurement 3, we were measuring *H* and/or *V* polarizations. Feel free to go back to the earlier

configurations and quickly confirm that the coincidence rates are relatively insensitive to temperature changes (the “warm hand” test).

While PM fiber is great when we deal with only  $H$  or  $V$  polarized light, it is not so great when carrying other polarizations or, as is the case here, when the *phase* between the  $H$  and  $V$  polarizations is important. As noted above, the two different polarizations accumulate different amounts of phase as they propagate through the fiber, and the overall phase difference is affected by tiny stresses in the fiber and by temperature. Fortunately, we have a device that will allow us to adjust the phase in a controllable way: a liquid crystal variable retarder (LCVR). The LCVR includes a transparent cell filled with liquid crystals that can be reoriented via an applied voltage. The result is that it is possible to very precisely adjust the relative amounts of phase accumulated by  $H$  and  $V$  polarized light passing through the cell. For this last set of measurements, we will adjust the LCVR to see the effect that it has on the coincidence rates for the four detector combinations.

Install the LCVR in the adjustable delay line shown in the figure in the *Initial setup* section. We will not be using the delay line as we did in previous experiments—we need it here simply because it provides a convenient way to mount the LCVR. Place the LCVR in the air gap and gently close the gap until the LCVR does not slide freely. Be careful not to clamp the LCVR assembly too tightly, as this will cause the air gap to misalign slightly, leading to a drop in count rates. Ensure that the Liquid Crystal Controller is powered off and connect the LCVR cable to the ‘Output Port.’ If you have not already done so, change the input legs on PBS A and PBS B to **Leg 2** ( $45^\circ$  angle). This will project the H/V photons in each path into the diagonal measurement basis. Once the LCVR is in place and all of the fibers have been connected, it is important to minimize fiber movements, especially between the beamsplitter and the two PBSs. In addition, allowing the setup to “relax” for a few minutes will give better results.

With the experimental setup configured, turn on the bi-photon source and allow a few minutes for the laser and crystal temperature to stabilize. Configure the coincidence counter with the following settings:

<b>Coincidence Counter Settings</b>	
Dwell Time	1.0 s
Window Size	3 ns
Trigger?	START/STOP

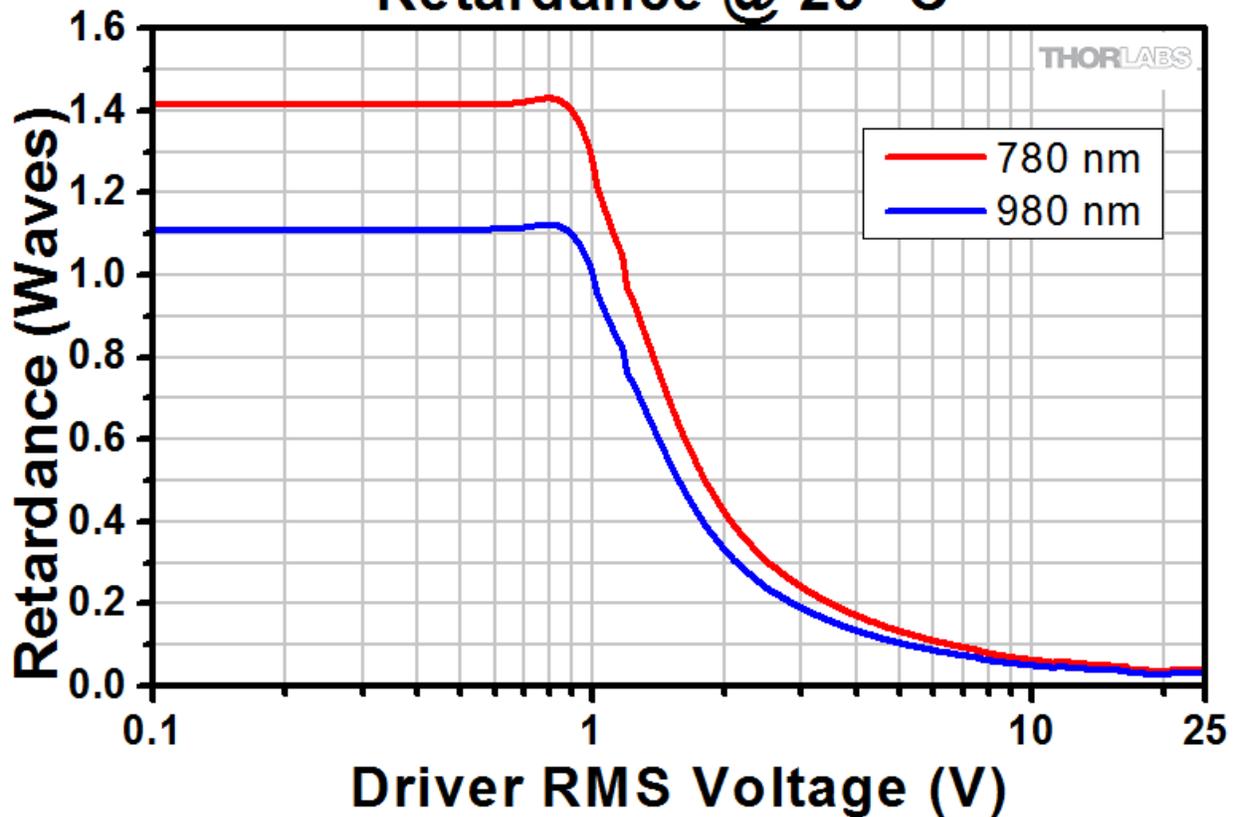
In the previous measurements, the coincidence rates were relatively stable. With this setup, we know that the coincidence rates can be influenced by temperature or mechanical changes—we will see large swings if we simply wait long enough. Our goal in this set of measurements is to show the effect of the LCVR phase adjustment while the rest of the fiber setup is relatively stable. Depending on the conditions in your lab, this period of stability should last at least a couple of minutes. Thus, it is important to work efficiently without disturbing the setup.

For operation of the Liquid Crystal Controller, please refer to the manual included with your kit. Turn on the controller and configure it with the following settings:

<b>Liquid Crystal Controller Settings</b>	
Output Mode	Voltage 1
INT/EXT	INT
V1	See below

The other settings (V2 and Frequency) are not important for these measurements. For the following measurements, we will be measuring singles and coincidences for several different V1 settings. In order to determine a useful range and increment for the V1 settings, it is useful to refer to the retardance curve provided by the LCVR vendor. As seen in the graph below, the retardance shows almost no change for voltages below 0.8V. Then, it changes rapidly with voltage, before leveling off for higher voltages. We will want to scan through about one wave of retardance. But taking equal steps doesn't make much sense, as it will lead to many measurements without much change (for the lower and higher voltages). And since we want to complete our measurements while the fiber is 'stable', we will want to choose our voltages carefully. A reasonable increment schedule is the following: 0.2V steps from 0.8V to 2V; 0.5V steps from 2V to 4V; and 2.0V steps above 4V.

## LCC1113-B & LCC1223-B Retardance @ 25 °C



A couple of other tips for operating the Liquid Crystal Controller:

- The voltage is not applied to the LCVR until you press the OUTPUT ENABLE button. When the output is 'ON', the LED next to the output port will be illuminated.
- It is difficult to dial in an exact voltage. It is possible, but time-consuming. You don't have to stick to an exact 'set' of voltages. Just get close and record the voltage values in the table below.
- The knob 'times out.' To change the voltage, press V1 and then turn the knob. But be aware that the knob will be unresponsive if it is untouched for a period of time.

With the LCVR power supply turned on and the output enabled, set the voltage to (near) 0.8V and record the voltage setting, coincidence count, and singles counts in the table below. Increase the voltage as described above and repeat. Continue until reaching 10-15V. Be sure to note whether the detectors were connected to the "R" or "T" legs of PBS A and PBS B.



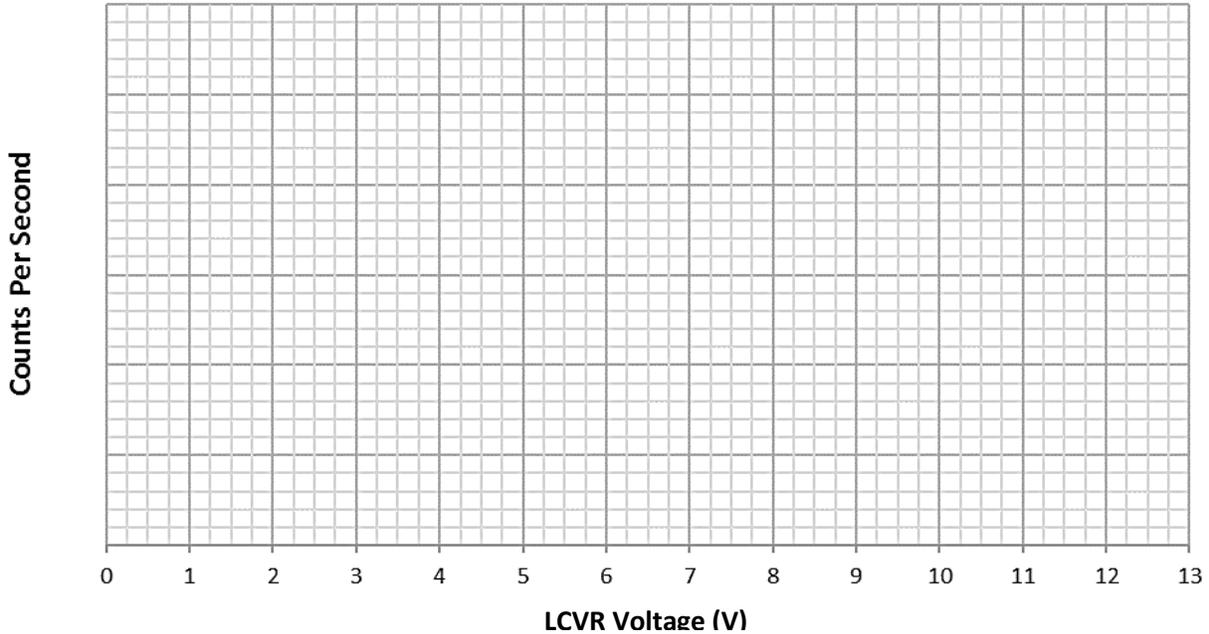






If the fiber setup was “stable” enough, we the coincidence rates should have risen and fallen in a regular pattern as the LCVR voltage was varied. We are interested in the LCVR settings that maximize and

### Coincidence Counts vs. Voltage



minimize the coincidence rates for each detector combination. In the graph below, plot the coincidence counts for the four detector combinations.

Do the Max and Min observations occur at the same LCVR settings for the different detector combinations? If this is not the case, it is an indication that the phase in the fiber setup drifted on its own faster than the total data collection time. If you found that the LCVR settings for the Max and Min were quite different from one detector setting to the next, you might want to try repeating the measurements but only recording the settings corresponding to the Max and Min coincidence counts. With the dwell time at 0.1 s, you should be able to “zero in” on the correct settings by watching the counts while turning the knob on the LCVR controller.

If the fiber setup is stable long enough to find the Max and Min LCVR settings then the observations should have shown that there is an LCVR setting that maximizes coincidence counts for two detector combinations while minimizing the counts for the other two combinations. Moreover, there is a second LCVR setting that does just the opposite. Because we are measuring in the diagonal basis (we are using **Leg 2** for both PBS A and PBS B), this means that one LCVR setting corresponds to the case that the photons always have orthogonal polarizations (*DA* and *AD* are maximized; *DD* and *AA* are minimized), while the other LCVR setting corresponds to the case that the polarizations are always the same (*DD* and *AA* are maximized; *DA* and *AD* are minimized). It is worth noting that the correlations observed in the diagonal basis are probably not as strong as observed in the rectilinear basis. This can be attributed to imperfections in the setup. For example, the walk-off discussed above is almost certainly not corrected

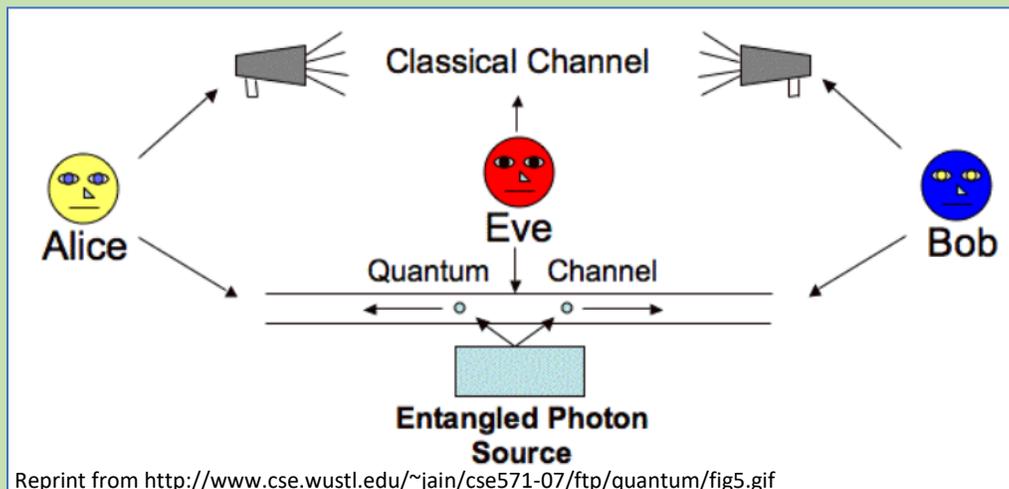
exactly; the two photons may be slightly nondegenerate; and the splitters often exhibit unwanted polarization effects. These imperfections tend to affect the diagonal basis more than the rectilinear basis. In experiments in which these effects are more carefully accounted for, the correlations will be quite strong in both measurement bases.

Let's take a minute to compare the entangled photon result to the result from the bi-photon observations. There, we found that polarizations were correlated in the rectilinear basis, but not the diagonal basis. Here, we find that the polarizations are correlated in both the rectilinear and diagonal bases. Moreover, we can "switch" the correlation in the diagonal basis from "orthogonal polarizations" to "same polarizations." This behavior is even more curious when we recall that any individual result is possible at PBS A and at PBS B. For the purposes of this discussion, assume that the LCVR knob is dialed in to the setting that gives "orthogonal polarizations" in the diagonal basis. Regardless of whether a PBS is set to measure in the rectilinear or diagonal basis, the photon arriving at that PBS is equally likely to exit either port (this can be confirmed by looking at the singles rates for the entangled photon data). Yet, if photon A is found to have, say, diagonal polarization, then photon B will definitely have anti-diagonal polarization. Photon B seems to "know" what photon A did at PBS A, even though there is not really a means for this kind of information to travel from PBS A to PBS B. It is tempting at this point to imagine that the photon pairs exit the beamsplitter with a set of "instructions" that tell each photon what to do at its respective PBS. Because the correlations are found in both the rectilinear and diagonal bases, the instructions for one photon would have to look something like this: *if the PBS is configured for the rectilinear basis, go to H; and if it is configured for the diagonal basis, go to D*. The other photon would have the opposite instructions; and the instructions would be different for each pair of photons leaving the beamsplitter. The problem with this idea is that photons do not behave like that. We can prepare a photon in a definite polarization state, *i.e.*, we can prepare *H* or *V*, and we can prepare *D* or *A*. But we cannot prepare a photon that is both definitely *H* and simultaneously definitely *D*. We saw this with the bi-photon setup. Photons left the first PBS with polarizations that were correlated in the rectilinear basis. But no correlations were seen in the diagonal basis. Yet entangled photons display this odd behavior of being correlated in different measurement bases. Albert Einstein once referred to this behavior as "spooky action at a distance" because the photons act as if they are able to communicate with one other and decide which way to exit their separate polarizing beamsplitters. However, if you were to extend the legs between the polarizing beamsplitters miles apart such that "communication" between the two would take several seconds - even at the speed of light - the behavior would still be instantaneous and exactly the same. By the property of entanglement, the photons - even though separated by great distances - still exhibit a correlated behavior.

## Application: Quantum Cryptography

As was shown in this experiment, entangled photons can exhibit correlated polarizations in two different bases. Measuring two photons to always have opposite polarization, regardless of the measurement basis, is a feature unique to entangled photons (specifically, entangled photons in the singlet state). As we demonstrated, non-entangled photons will not maintain their correlations in different measurement bases. This feature of entangled photons is particularly useful for cryptography applications.

Imagine an application where you need to securely distribute a string of random bits (0s and 1s) between two parties, Alice and Bob. Sending entangled photon pairs is a powerful way to create and distribute a random bit string. In such an application, an H-polarized photon might be considered a “0” while a V-polarized photon might be considered a “1.” Because the polarization of each entangled photon is random yet correlated with one another, sending one entangled photon to Alice and one to Bob allows both parties to receive a photon and measure its polarization.



If both Alice and Bob make measurements in the same measurement basis (for example, either H/V or +/-), then – as we just showed in this experiment - they will always get measurements that are anti-correlated. By making polarization measurements on the photons they receive and then communicating over a classical channel which measurement bases they used, each party can identify the times when measurements were made in the same basis and, therefore, would have produced reliably anti-correlated results. In this manner, Alice and Bob do not need to share their specific measurements, only their various basis choices. This allows Alice and Bob to construct a shared random bit string without needing to transmit any of the actual bits. A random bit string is the basis of a cryptographic “key” and it has many applications in secure communications.

Imagine now that an eavesdropper is trying to intercept one of the distributed entangled photons so that they can learn the key and spy on Alice and Bob’s communications. In this scenario, the eavesdropper, we’ll call her Eve, will need to intercept and measure the polarization of one of the transmitted entangled photons. Let’s say Eve intercepts one of the entangled photons being sent to Alice. Eve then measures the

photon's polarization in the H/V basis and finds it to be V-polarized. Performing the measurement destroys the photon so, to cover her tracks, Eve has to generate a new V-polarized photon to send to Alice. Unfortunately, for Eve, this new photon will not be entangled with the photon traveling to Bob.

If Bob receives his photon and measures it in the H/V basis then he will get an H-polarized photon. If Alice receives the photon from Eve and measures it in the H/V basis, then she will get a V-polarized photon. When Alice and Bob compare their measurements and measurement bases, they will conclude that they have each received one half of an entangled pair (since the measurements are anti-correlated, as expected).

However, if Bob and Alice choose to measure their photons in the +/- basis, then there is only a 50% chance that the detected photons will show the anticipated anti-correlated behavior. The other 50% of the time, the two photons will not be anti-correlated (something that should not be encountered if the two photons are in the singlet state). By sharing a portion of the resulting key, Alice and Bob can quickly detect if Eve is present and influencing their measurements.

Because Eve cannot reliably predict the measurement basis that Alice and Bob will choose, 25% of the time she will end up generating and sending a photon to Alice that is not properly correlated with Bob's photon. If Alice and Bob detect that their correlations are incorrect by 25%, then they will know that Eve is attempting to eavesdrop, and they can stop communications. In practice, even a much smaller error in the measurement correlations would trigger Alice and Bob to stop communicating. In this way, quantum cryptography using entangled photons is being applied to deliver "tamper indicating" communication channels that are protected by the laws of quantum physics.

**Appendix:**  
**Warranty**

# Quantum Mechanics Laboratory Kit

## Warranty

Qubitekk, Inc. (Qubitekk) warrants the Quantum Mechanics Laboratory Kit ("Kit") to be free of defects in materials and workmanship for a period of twelve (12) months from date of delivery. The warranty covers defects in material and workmanship and is limited to replacement of parts and materials.

In the event that the Kit fails to conform, purchaser shall not later than fourteen (14) days after the error occurs, advise Qubitekk of such failure in writing. Depending on the nature of the failure, Qubitekk will decide if a replacement part can be shipped or if the Kit must be returned to the factory with seal on the QES devices intact for evaluation. In case of a necessary return, Qubitekk's Customer Service Department will issue an Authorized Return (AR) number immediately upon phone or written request. Upon examination by Qubitekk, if the Kit is found to be defective it will be repaired or replaced at no charge. Qubitekk's WARRANTY does not apply to damages resulting from any action of the purchaser, including but not limited to mishandling, improper interfacing, operation outside of design limits, improper repair, or unauthorized modification. This WARRANTY is VOID if the unit shows evidence of having been tampered with or shows evidence of being damaged as a result of mishandling; misapplication; misuse or other operating conditions outside of Qubitekk's control.

### LASER

Qubitekk conducts an extensive test and quality control plan that each Kit has to go through before its being shipped. It is imperative that the matching laser is being used for these proceedings. The laser therefore will already have a certain number of hours of usage when it is being delivered. This minimal usage has no impact on the performance of the laser. Qubitekk warrants that the laser will be free from defects in material and workmanship for twelve (12) months from the date of shipment. This limited warranty covers only those defects that arise as a result of normal use of the product, and does not cover any other problems, including those that arise as a result of: (i) improper handling, maintenance or modification, (ii) operation outside the product's specifications; or (iii) unauthorized modification or misuse.

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### Matchbox Laser Specifications and Warranty

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<b>Warm-up time</b>	< 5 min
<b>Power Stability (over 8 hrs)</b>	< 2%
<b>Laser Class</b>	Class 3B (maximum power and wavelength listed on warning labels of unit)
<b>Environmental Temperature (operating)</b>	+15°C - +30°C
<b>Environmental Temperature (storage)</b>	-10°C - +50°C
<b>Humidity</b>	Non condensing
<b>Operating Voltage</b>	5 V DC
<b>Operating Current</b>	5 A max
<b>Laser Dimensions</b>	30 x 50 x 16 mm
<b>Laser Weight</b>	< 1 lb
<b>Warranty</b>	12 month from the date of shipment

## CONSUMABLES

The following item is considered a consumable and intended to be replaced by the purchaser:

- Units received after Dec. 2017: FC/APC to FC/APC PM Cable, P1-780PM-FC-2



A replacement part can be purchased here:

<https://www.thorlabs.com/thorproduct.cfm?partnumber=P1-780PM-FC-2>

## LIMITATION OF LIABILITY

The remedies of purchaser set forth herein are exclusive and the total liability of Qubitekk with respect to this order, whether based on contract, warranty, negligence, indemnification, strict liability or otherwise, shall not exceed the purchase price of the component upon which liability is based.

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