ELEC4605 Photon Lab

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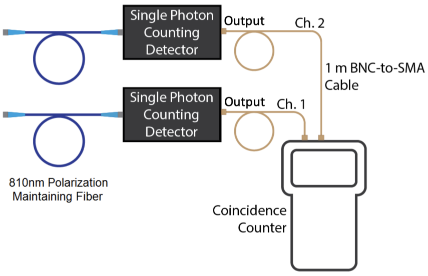
1 Measuring Single Photons

In this experiment we will explore the particle nature of light by detecting and measuring single photons and statistically characterize noise in the environment. Initially we set up the equipment as shown



We want to measure the photons generated randomly by light sources in the room.

1.1 Dark Counts

Before doing so, we must measure the photon counts that is unrelated to our light sources, i.e., the thermal photons emitted by the detector itself.

Channel 1 Dark Counts/Second	1265.5
Channel 2 Dark Counts/Second	247.5

We can then subtract this value from our measurements later.

1.2 Coincidence Counts

Coincidence counts are when we detect photons arriving from CH1 and CH2 within a time period known as the coincidence window. Also, the time in which we take measurements in is called the dwell time. We used a window of 1 ns, and a dwell time of 2 s.

Channel 1 Singles Count	1260152
Channel 2 Singles Count	933028
Coincidence Count	1805

Since room lighting is random, we don't expect any correlation which produce the coincidence counts. They are merely due to accidentals. The accidental counts can be found using

$$\text{accidentals} = \frac{2(\text{Coincidence Window})(\text{CH1 Counts})(\text{CH2 Counts})}{\text{Dwell Time}}. \tag{1}$$

Using this, the calculated accidentals are 1175.76 counts which roughly resemble our coincidence counts.

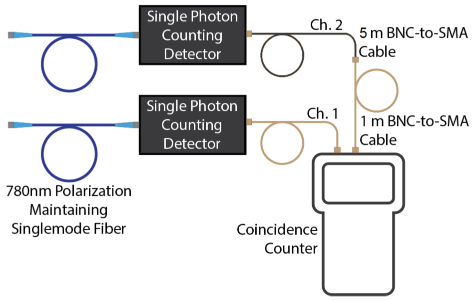
Now we set our coincidence window to 8 ns to get the following data:

Channel 1 Singles Count	11357261
Channel 2 Singles Count	993078
Coincidence Count	8736

where the accidental counts are 9406.1. We see that our singles count haven't changed much but the coincidence interval increased by the same factor as we have increased the coincidence interval.

1.3 Measuring Temporal Sensitivity

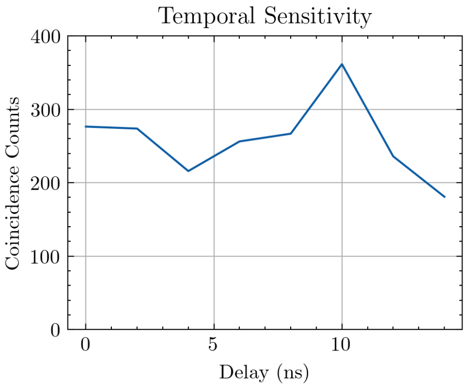
In this section, we want to delay CH2 by a set amount to investigate the correlation of the photon emission. This is done by attaching a longer cable, delaying the photon through CH2 by 25 ns



Using this configuration, we get:

Channel 1 Singles Count	1313767
Channel 2 Singles Count	952503
Coincidence Count	8105

The coincidence counts are not affected by the delay. This shows the photon emission is uncorrelated. We can actually use the coincidence counter to set a delay without needing to change the length of the cable. Removing the extra cable, we can increment the delay and produce the following graph:

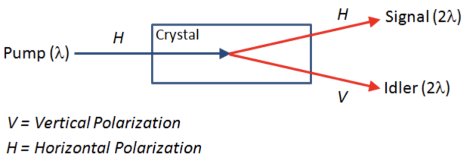


We see that the graph is relatively flat, meaning that. This means there is no temporal sensitivity in the coincidences, i.e., they are completely accidental as assumed previously.

2 Generating Bi-Photons

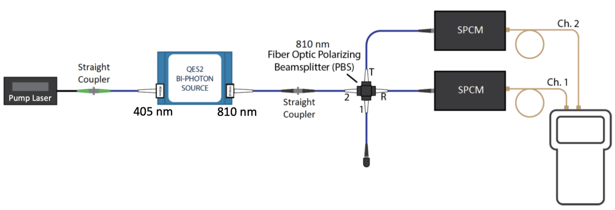
In this experiment, we want to produce a small amount of photons from a well-defined location and with a very specific wavelength and polarization.

When a photon (405 nm) is focused on a PPKTP crystal, two photons of higher wavelength (810 nm) is emitted. The two photons are called the signal (horizontal polarization), and idler (vertical polarization) photons.



This process is called spontaneous parametric down-conversion (SPDC). In this experiment, we separate the two photons using a polarizing beam splitter.

Here is how we configure our equipment:



The QES2 (bi-photon source), is a type-II SPDC, meaning that it emits bi-photons with perpendicular polarizations. In contrast, a type-I SPDC will emit bi-photons with the same polarization.

2.1 Measuring Temporal Sensitivity

Once again, we want to measure the dark counts. We have a window size of 3 ns, dwell time of 0.1 s, and no delay.

Channel 1 Dark Count	2960
Channel 2 Dark Count	210
Coincidence Count	0

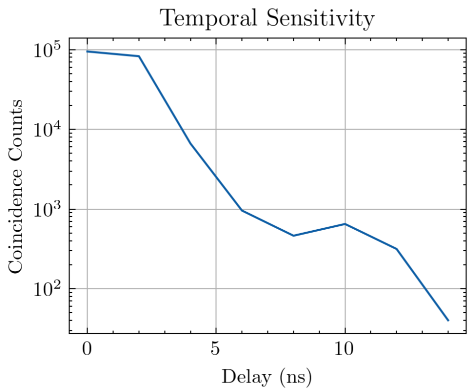
Next we measure the counts with the pump laser on to get:

Channel 1 Count	218770
Channel 2 Count	240210
Coincidence Count	948

The beam splitter allow us to separate the photons into the horizontally and vertically polarized photons:

	Single Counts	Dark Counts	Photons
H-polarised	240210	210	240000
V-polarised	218770	2960	215810

Now similar to the previous experiment, we adjust the delay and plot the relationship between the coincidence and the delay:



Unlike the first experiment, we have a strong peak at no delay, suggesting that the two photons are correlated which makes sense since they originate from just 1 photon.

2.2 Calculating the Coincidence Ratio

By detecting just one photon in a bi-photon pair, it can indicate the presence of another photon along a different path. This is known as *heralding*. The reliability of this is known as the *heralding efficiency*. Fiber losses and poor detector efficiency could reduce this efficiency.

This statistic is actually very difficult to measure using our equipment so we use a related statistic called the *coincidence ratio*, this tells us what fraction of our produced bi-photon pairs actually survives and is measured as a pair by our two detectors.

$$\text{Coincidence Ratio} = \frac{\text{Coincidence} - \text{Accidentals}}{\frac{\text{CH1}+\text{CH2}}{2}} \tag{2}$$

CH1 Counts	201070
CH2 Counts	239250
Coincidence Counts	8900
CH1 Detector Efficiency	0.5
CH2 Detector Efficiency	0.5
Calculated Accidental Rate	2886
Coincidence Ratio	0.0273
Coincidence Ratio (ideal)	0.0546

Using the equation, we can build the following table:

The coincidence ratio of 0.0273 indicates that the detection of a single bi-photon in one path indicates the presence of the other bi-photon in another path with only 2.73% certainty.

2.3 Source Flux

The total number of bi-photon pairs for every milliwatt of pump laser power is called the *flux*.

Pump Laser Power (mW)	9.087
Coincidence Counts	8900
Bi-Photon Flux (pairs/sec.mW)	979.42
CH1 Detector Efficiency	0.5
CH2 Detector Efficiency	0.5
Actual Bi-Photon Flux (pairs/sec.mW)	3917.68

The actual bi-photon flux is found by dividing the bi-photon flux by the efficiency of detector 1 and 2 multiplied together. The reason for this is because the coincidence count is not going to register if either detector 1 or 2 fails.

2.4 Source Degeneracy

The QES2 has a small heater changes the temperature of the crystal. Doing so changes the wavelengths of the emitted signal and idler photon. For a given pump wavelength, there is a unique crystal temperature that will produce signal and idler photons with exactly the same wavelength. We want the bi-photons to be degenerate, i.e., have the same wavelength. But sometimes there is a small difference in wavelength which average to 810 nm due to the conservation of energy. In this experiment we will control the bi-photons to be either degenerate or non-degenerate.

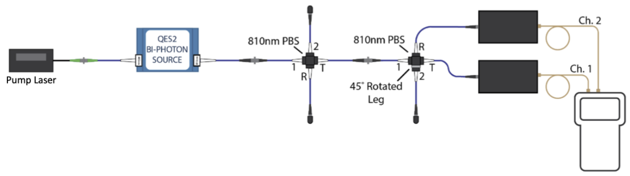
Temperature	68.6	57.51	47.6	38.8	30	21.2
CH1 singles	117230	120800	141930	141310	132350	137540
CH2 singles	100140	103040	111140	111690	108210	111890
Coincidence	3980	4470	4830	5080	5370	4840

Temperature changes in the crystal caused slight wavelength shifts in QES2 bi-photons, with minimal impact on results and only a weak increase in the coincidence counts as a function of temperature.

3 Measuring Quantum States

3.1 The Rectilinear Basis

Polarization is conveniently defined to be relative to the horizon. Doing this gives us the horizontal polarization state $|H\rangle$ and the vertical polarization state $|V\rangle$. This set of these two states gives us the rectilinear basis. We assemble the apparatus as shown here:



This setup will allow us to investigate how photons of different polarizations behave when they encounter a PBS. Only the photons in the $|H\rangle$ state should transmit through the PBS. To confirm that we are indeed seeing only the $|H\rangle$ state of light, we use the second PBS and expect no reflected photons from it.

	No Rotation	90° Rotation
CH1 Counts (T)	18540	1615
CH2 Counts (R)	2474	13554
Coincidence	2	1

No rotation leads to the $|H\rangle$ photons transmitted to the second PBS. This leads to low reflected counts from the second PBS as discussed previously. The reason we see non-zero reflected photon is due to the polarizers not being 100% efficient. Similar logic can be used for the 90° rotation, which transmits $|V\rangle$ photons instead. The photons in this setup behaves deterministically, which means if we know the polarization when entering the PBS, we can predict what they'll do after exiting the PBS.

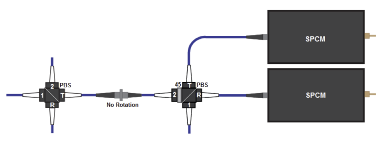
3.2 The Diagonal Basis

The rectilinear basis isn't the only reference frame that we can use to describe polarization states. We could have also chosen a 45° angle with the horizon as our reference. This is called the diagonal basis and is given in terms of the rectilinear basis as

$$|D\rangle = \frac{1}{\sqrt{2}}(|H\rangle + |V\rangle) \tag{3}$$

$$|A\rangle = \frac{1}{\sqrt{2}}(|H\rangle - |V\rangle) \tag{4}$$

We rotate the second PBS by 45° in order to perform a measure in the diagonal basis as shown below:



This setup gives us the following results:

	No Rotation	90° Rotation
Channel 1 Counts	10680	8568
Channel 2 Counts	7109	8125
Coincidence Channel Counts	6	6

We see a roughly even number of counts for both CH1 and CH2. This because the output of the first PBS is

$$|H\rangle = \frac{1}{\sqrt{2}}(|D\rangle + |A\rangle) \tag{5}$$

and so the probability of measured in either the diagonal states will be equal. The counts of CH2 is less perhaps due to some equipment or human error. In rotating the second PBS 90°, we can interpret this in two ways:

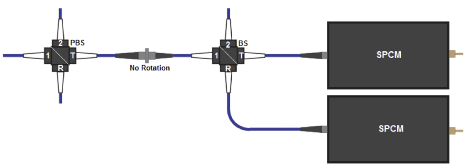
- We are measuring $|H\rangle$ along the diagonal basis but we have swapped the diagonal basis states.

- We are measuring $|V\rangle$ along the original diagonal basis states.

Both interpretations are equivalent still give us equal probability of each measurement. In contrast to the previous section, this experiment is nondeterministic because we don't know what each individual photon will do at the second PBS.

4 Non-Polarizing Beamsplitter

In this experiment, we want to perform measurements with the non-polarizing beamsplitter (BS) by swapping it for the second PBS:

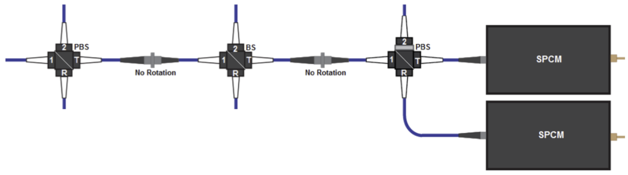


	No Rotation	90° Rotation
Channel 1 Counts	11840	10648
Channel 2 Counts	11963	13594
Coincidence Channel Counts	12	10

The BS splits the beam regardless of polarization, so this experiment is still non-deterministic. However, the difference to before was is the $|H\rangle$ states are both transmitted and reflected by the BS instead of only being transmitted by the second PBS.

4.1 The Output of the BS

We predicted in the last section that the output of the T and R output of the BS should contain 100% of $|H\rangle$ state photons. We will test this using a third PBS:



Our equipment in the lab was faulty and stopped working around this time. Our data was incorrect so I have used data from another student (Sanjana Mahesh):

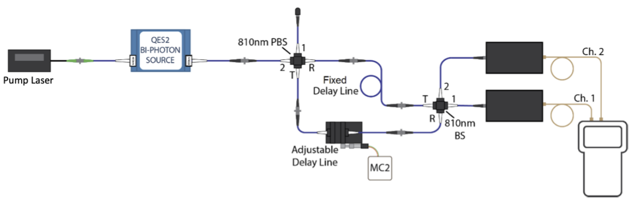
	T Output	R Output
Channel 1 Counts	184331	253980
Channel 2 Counts	2660	7028
Coincidence Channel Counts	39	119

We see that the CH1 counts is significantly higher than the CH2 counts for both the T and R ports of the BS. This means that we have $|H\rangle$ state photons coming out from both ports of the BS, which confirm that it does not split based on polarization like the PBS.

5 Photon Indistinguishability

5.1 Two Photons Interacting with a BS

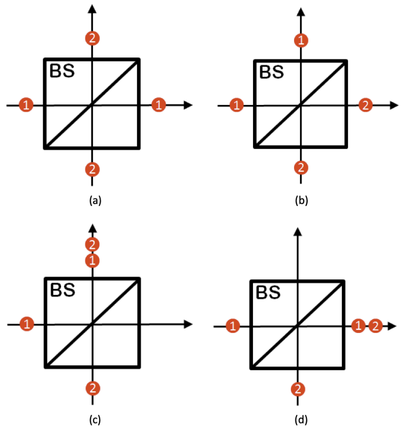
In the previous experiment, we have investigated a single photon interacting with a BS. In this part, we will use two photons instead. Our apparatus setup is shown below:

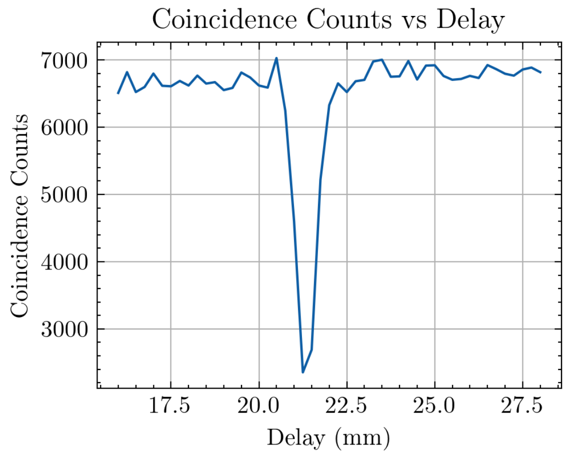


The PBS separates the two bi-photons into a fixed delay line and an adjustable delay line before encountering a common BS. When the photons are incident on the BS at the same time, we can have 4 possible occurrences:

For situations (c) and (d), we will not get coincidence counts because only one detector registers a signal. For measuring this interaction, the photons need to be indistinguishable for reasons discussed later. This means the bi-photons need to have the same polarization, wavelength and arrival times. We can set the first two parameters equal using the equipment. Using the variable delay line, we will sweep over delays in order to find the point at which the two photons are indistinguishable.

The dip in the graph shows when we get both detectors registering a photon within the coincidence





window. This point corresponds to the point where the two photons are indistinguishable. When this occurs, the photons have correlated behavior. In this case, the bunch together and leave out the same port as shown situations (c) and (d). However, when one photon is delayed, it is possible to distinguish them based on their respective paths by inferring from the arrival times.

The reason why indistinguishable photons bunch is due to the destructive interference of the non-bunching probabilities. Consider the superposition of all possibilities:

$$|\psi\rangle = |1\rangle_T |1\rangle_R + |2\rangle_T |0\rangle_R + e^{i\pi} |0\rangle_T |2\rangle_R + e^{i\pi} |1\rangle_T |1\rangle_R \tag{6}$$

where the phase shift has been added to conserve energy. Using $e^{i\pi} = -1$, we have

$$|\psi\rangle = |1\rangle_T |1\rangle_R + |2\rangle_T |0\rangle_R - |0\rangle_T |2\rangle_R - |1\rangle_T |1\rangle_R . \tag{7}$$

Now if the bi-photons are indistinguishable, then $|1\rangle_T |1\rangle_R = |1\rangle_T |1\rangle_R$ and so they cancel:

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|2\rangle_T |0\rangle_R - |0\rangle_T |2\rangle_R) \tag{8}$$

If the photons are distinguishable, then the canceling of the first and last terms cannot be done. This is in full agreement with our observations.

5.2 The Effect of Source Degeneracies

Recall that the temperature affects the wavelength of the emitted photon and the idler photon. There is a critical temperature at which the bi-photons will be degenerate and if the crystal temperature is either too hot or cold, the bi-photons will have differing wavelengths and be distinguishable.

Now since the dip observed in the previous section is due to the destructive interference of two indistinguishable photons, the dip should reduce intensity as the output is made non-degenerate. We first move the variable delay to the point in which the lowest dip occurred in the coincidence data. Next we alter the temperature to find its effects on the dip:

Temp	71.7	60.1	50.3	41.3	32.7	23.4
CH1	309631	306683	320713	328601	330456	347552
CH2	245307	258236	249341	246363	252882	251631
Coin	4582	6947	6858	6561	6483	6183

We see that the temperature of 71.7° is very close to the critical temperature for indistinguishable bi-photons; and hence we see a coincidence counts at their lowest. Changing the temperature from this value increases the coincidence counts since the photons are now distinguishable. The singles counts are not affected as we expect since it doesn't depend on the disguishability of bi-photons.