Photon Detection

Reproducing the evidence of the quantum nature of Light.

Author: Daniel Shafi Batla (24100003)

1 Abstract

The mysterious nature of light, its ability to travel without a medium, has always been a scientist's dream to fully understand. The quantum nature of light has been a paradigm shifting notion.Although it can be intuitively understood, this phenomena has been particularly difficult to produce in the laboratory. The single photon laboratory allows us to measure the coincidences based on the compositions of polarization of the light and through the second order coherence term, the evidence of particle nature can be reproduced.

2 Introduction

This two tier experiment involved down conversion of photons from a 405 nm violet blue light by aligning the birefrengent crystal to 810 nm. The light was further split into two directions based on their polarization to achieve distinct readings at the detectors. .

The second part of the experiment produced the evidence of the quantum nature of light through the experimental set up laid out in the first part and measuring the coincidental signal at detectors after a 20 ns clock was triggered (20 ns is the smallest achievable window through the circuit that is processing the signal) once the signal was intercepted by one of the detectors.

3 Theoretical Background

3.1 Overview

The aim of the experiment was to bifurcate a continuous beam of photons, and then pass one of them through a polarizing beam splitter, the split beam was then intercepted by the two detectors.The down converted beam that did not pass through the beam splitter, was intercepted by a third detector which triggered the clock for coincidental counts. The corresponding signal was intercepted by either of the detectors that received the signal from the polarizing beam splitter.

It was required to find the count of photons shared amongst the 2 detectors and then compare the number of photons at both of the detectors during the 20 ns time window,once they were detected by the detector that received the unsplit beam. There was a narrow acceptable range of less than 2 photons being detected in the 15 seconds for accidental photon incidence at detectors placed behind the beam splitters.

The individual detection of differently polarized photons in a narrow time window, allowed us to argue against the preconceived notion of the continuous nature of light and produced evidence for light travelling in small packets.

3.2 Polarization

Light being an Electromagnetic wave has a set direction for its Propagation,Magnetic field and the Electric Field. The vector along the direction of the Electric field is known as the Polarization vector and due to the orthogonality of the two fields and the propagation, knowing the direction of one of them suffices.

A polarizer essentially only allows light with polarization in a certain direction, these can be linear, circular or elliptical depending on the phase they introduce in the light;however, this experiment made use of linear polarization using a Half Wave Plate (HWP).
Linear polarization has a set direction along its axis, and allows light with polarization parallel to that axis only.If the polarization is along an arbitrary direction $\vec{e_\theta}$, and we have a field in an arbitrary direction :

$$\vec{E} = E_0 e^{ik \cdot r - \omega t} \vec{\epsilon} \tag{1}$$

then the field transmitted through the Polarizer will be :

$$\vec{E_T} = E_0 e^{ik \cdot r - \omega t} (\vec{\epsilon} \cdot \vec{e_\theta}) \vec{e_\theta} \tag{2}$$

There is a phase shift introduced between the 2 lights of different polarization, and any beam of light can be written in the following form

$$|\phi\rangle = \begin{pmatrix} A \\ Be^{i\phi} \end{pmatrix} \tag{3}$$

Where the first element represents the weights associated with the vertically polarized light and the one below represents the weights associated with the horizontally polarized light, and just like always, $|A|^2 + |B|^2 = 1$ holds [1].

These states can be written in terms of the angle of the polarization at which the polarizer is aligned:

$$|\phi\rangle = \begin{pmatrix} cos(\alpha) \\ sin(\alpha) \end{pmatrix} \tag{4}$$

The signal of the Electromagnetic field looks like:

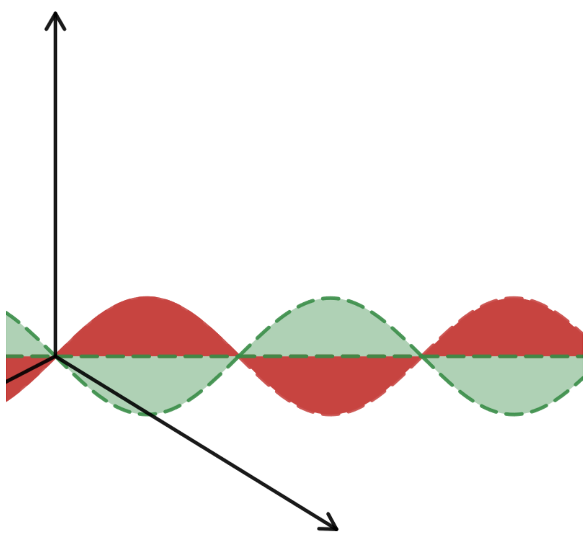

Figure 1: A half vertically and horizontally polarized signal

The amount of light that we want polarized in any particular direction is controlled by a half wave plate as it allows us to align and alter amount of light in a particular direction of polarization. Passing through the half wave, the state transforms such that the weights of the horizontally and vertically aligned lights depend on the angle at which the HWP is aligned. Furthermore, passing through the Half wave plate a phase factor is introduced between the waves such that one polarization hits the detector before the other.

$$|\phi'\rangle = J_{HWP}\,|\phi\rangle \tag{5}$$

$$|\phi'\rangle = \begin{pmatrix} cos(2\theta) & sin(2\theta) \\ sin(2\theta) & -cos(2\theta) \end{pmatrix} \begin{pmatrix} cos(\alpha) \\ sin(\alpha) \end{pmatrix} \tag{6}$$

$$|\phi'\rangle = \begin{pmatrix} cos(2\theta - \alpha) \\ sin(2\theta - \alpha) \end{pmatrix} \tag{7}$$

If the light is polarized with and angle of $\pi/4$ and the HWP is also aligned at the same angle, we will have half of the light vertically polarized and the other half horizontally polarized.

In essence, the Half wave plate aligned at $\pi/4$ will reverse the polarization of the horizontally polarized light to vertical polarization and vice versa;furthermore , it will introduce a phase difference between the two lights of polarization so there is a window equal to the period of the light as a phase shift of $\pi/2$ such that there is a window of half a period between the detection of the two differently polarized light.

After passing through the HWP, there is a phase shift introduced in the signal and it looks like the following when set at $\pi/4$ radians:

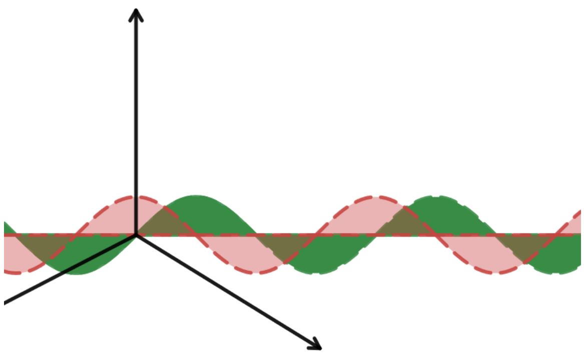

Figure 2: A HWP processed signal

3.3 Spontaneous Parametric Down conversion (SPDC)

As the name suggests, the experiment requires us to down convert a part of the 405 nm light, i.e it requires us to lower its frequency, and bifurcate it into 2 photons of a wavelength of 810 nm.

It is a non linear process as it changes the frequency, i.e the energy of the emitted light and we detect twice the number of photons emitted by the light source.

The process is called spontaneous as it happens readily without any idler beams or additional signal to trigger the process by an external stimulus.[1] It is parameterized by the input polarization of the light supplied and down converts the light in the following manner :

$$|H\rangle \rightarrow |VV\rangle$$
$$|V\rangle \rightarrow |HH\rangle$$

so if the signal provided to the converter is :

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

then after down conversion, the signal becomes :

$$|\phi'\rangle = \frac{1}{\sqrt{2}}(|VV\rangle - |HH\rangle)$$

The birefringent crystal down converts the light by exciting its electrons in one step as it absorbs the 405 nm photons; however, while coming back to the original state, it must come down via an intermediary energy state which is equidistant from the ground state and subsequently emit two photons in response to the incidence of one photon of twice the wavelength.

3.4 Photon Detection

As per the classical theory, light is a continuous Electromagnetic wave. It is not thought of as particles.The down converted photons travel in 2 separate beams, so an originally vertically polarized photon corresponds to a 2 Horizontally polarized photons, travelling at an angle of 6 ° between them:

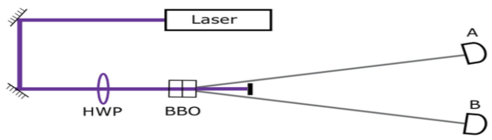

Figure 3: Down converted signal [1]

Since we have introduced a phase shift between the vertically polarized light and the horizontally polarized light, once a signal is detected at unsplit end, we shall only receive either a vertically polarized beam or a horizontally polarized beam in the coincidence time window.

In order to show the quantum nature of light,we must show that if we split one of the down converted beams using a polarizing beam splitter, and take the signal onto two different detectors, then in that 20 nanosecond window, the beam splitter will receive photons of a particular polarization, and hence will be received by only one of the detectors.

Classically, through the beam splitter, we would have detected light at all times even during that narrow window as we would have argued that there is a signal that appears in all directions at all times, justifying the continuity of light;however,it would be an evidence of the particle nature of light, if there are photon coincidence counts detected on one of the photons in that time window.

To give an overview, there are 2 photon detectors A and B used for alignment of the birefringent crystals,and for Photon detection there is another detector B' placed. In order to differentiate between the two types of photons, there is a beam splitter introduced in the path of the beam originally hitting the detector B, and the signal will be received by two detectors B and B'. As soon as the photon is detected by detector A, the clock will be triggered and in that interval, there shall be detection only in one of the detectors, (see figure 4).

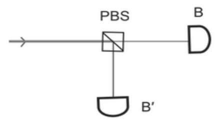

Figure 4: split Beam onto two detectors [1]

This is described by the second order term of coherence, $g^{(2)}(\tau)$, since this is not a purely single photon experiment, but a heralded one, as we are not working with a truly single photon source, we will have a time interval of 20 nanoseconds, in which we will detect photons at either detectors. The following is the expression for second order coherence term:

$$g^{(2)}(0) = \frac{N_A N_{ABB'}}{N_{AB} N_{AB'}} \tag{8}$$

where N_A is the number of photons detected by detector A, $N_{ABB'}$ corresponds to the coincidental photon count at B and B' after detection at A , N_{AB} corresponds to the number of photons detected at A and B and not at B', whereas $N_{AB'}$ corresponds to the number of photons detected in that window at A, B' , and not at B.

Classically,There should be an equal count of photons at A, B and B' at any instance of time, which will give : $g^{(2)}(0) \geq 1$ on the other hand it should be close to zero as per the quantum nature of light so : $g^{(2)}(0) < 1$ should hold.

The expression that is used in showing the wave nature (classical) is as follows:

$$g^{(2)}(0) = \frac{\langle I_B(0)\rangle \langle I_{B'}(0)\rangle}{\langle I_B I_B'(0)\rangle} \tag{9}$$

The $\langle I_B(0)\rangle$term represents the coincidence counts at detector A and B, whereas, $\langle I_{B'}(0)\rangle$ represents the coincidence counts at detectors A and B'. The $\langle I_B I_B'(0)\rangle$ term represents the average of the product of the counts at AB and AB'. The value should at all times hence be close to the denominator as the numerator is the product of averages and the denominator of the term is the average of the products. This is an entirely classical quantity as we are not measuring the count of photons in a particular time window that was at all three of the detectors hence ignoring the negligible count of the coincidence at the 3 detectors.

The readings were taken while rotating the half wave plate as that changed the respective compositions of polarization of the light and will also change the readings on the photon detectors consequently;however, the accidental coincident count on all three of the detectors must stay to their minimum, regardless of the supplied polarization.

4 Experimental Procedure

4.1 Optical Alignment for SPDC

The first and foremost task was to ensure that the light reflected from the mirrors, right after being emitted by the source were travelling parallel to our optical table, this was necessary, to ensure everything could be placed at the same height. These measures had a greater significance as the down converted light was invisible, and re aligning during the experiment would have be particularly more difficult.

The height of the light above the optical bread board was set at $13.5 \pm 0.05cm$. This was ensured by placing two irises, 40 inches apart, as measured by the distance between the mounting holes as they are an inch apart. The mirrors were then adjusted to ensure that the light passed through both of the irises mounted at the height stated above.

The next step required placing the BBO (Beta Barium Borate) Crystal that worked as our down converter, in the path of the light. The light beams from the crystal made an angle of 6 °, each of them making an angle of 3 ° from the vertical.

The distance along the optical table between the BBO crystal was multiplied by $tan(3)$ which gave us the horizontal distance from the mounting hole of the BBO. In our case it was set to be $6.0 \pm 0.05cm$.

Since the optical bread board only have holes at a distance of 1 inch,a railing was placed that allowed us to place the detectors 45 inches vertically and 6 cm horizontally from the crystal.

The detectors were placed, at their respective positions and their further alignment was required to ensure the down converted beam passed through them, Since it does not lie in the visible spectrum, as additional alignment LASER is used for both of the detectors. The alignment LASER is plugged into the back of the collimator to which the detectors would be connected, and from there the collimator is aligned so that the LASER passes through the BBO, and takes the perfect reverse trajectory. The process is illustrated through in (see Figure 5)

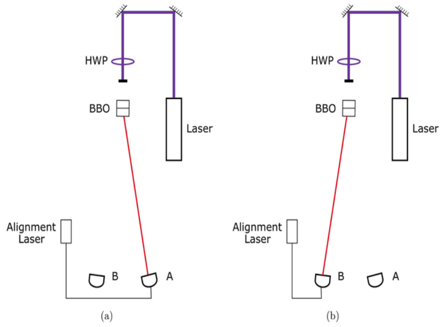

Figure 5: Aligning the Collimators[1]

The detectors were turned on and then coincidence counts were read.

To ensure we were receiving the light of horizontal and vertical polarization, The Half wave plate was rotated to 45 °, and then the photon count was read. The photon count was lower than it should have been (see fig about to come), and the BBO crystal was aligned so that it down converted the photons of both polarization.

4.2 Optical Alignment for Photon Detection

Once BBO, and the two collimators were aligned, the third collimator was aligned for the B' detector. Additionally a Polarized Beam splitter was placed in the path of the light that was originally in the trajectory of the detector B. To align the light through the beam splitter and the detector B' 2 different colored LASERs are used for alignment. First the collimator to which detector B' will be connected, is aligned so that the spot from the collimator B and and the collimator B' are incident at the same position on the Polarizing Beam splitter. Once the spots align with each other on the beam splitter, the beam splitter is aligned so that the laser from that splitter also passes through the BBO crystal.

The alignment process can also be seen in the image below:

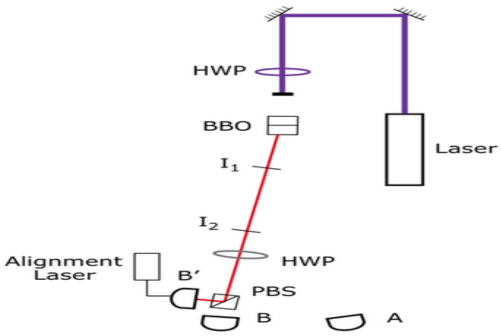

Figure 6: Alignment for Photon Detection [1]

4.3 Data acquisition for Photon Detection

Once the apparatus is aligned, the detectors are turned on.The coincidence counts of AB, AB', ABB', and individual counts at A, B and B' are measured. The count is taken initially at the half wave plate aligned at zero °, and perfect mixing of the polarisation of light. We start rotating the Half wave plates by increments of five ° and alter the polarization of the incident light on the beam splitter and take the readings. We take the readings to ensure that the coincidence counts vary between AB and AB'; however they consistently remain close to zero for ABB' as these will be accidental coincidences.

5 Results and Further Discussion

5.1 Alignment of the Birefringent Crystals

The light initially was of polarization of 45 ° and the HWP was aligned at 0°. As discussed in (7), the compositions of vertical and horizontal polarization for was noted to be:

$$|\phi'\rangle = \begin{pmatrix} cos(\pi/4) \\ \\ sin(-\pi/4) \end{pmatrix} = \begin{pmatrix} \frac{1}{\sqrt{2}} \\ \\ -\frac{1}{\sqrt{2}} \end{pmatrix}$$

Which shows that initially there would be around the same amount of photons detected at the both detectors; however, when the half wave plate is aligned at 67.5 ° one of the polarization will completely vanish as it can be seen below :

$$|\phi'\rangle = \begin{pmatrix} cos(2(3\frac{\pi}{8}) - \frac{\pi}{4}) \\ \\ sin(2(3\frac{\pi}{8}) - \frac{\pi}{4}) \end{pmatrix} = \begin{pmatrix} cos(\pi/2) \\ \\ sin(\pi/2) \end{pmatrix} = \begin{pmatrix} 0 \\ \\ 1 \end{pmatrix}$$

With the unaligned crystal, the HWP is rotated 180° in 60 seconds at the speed of 3°/sec. At 22.5 seconds as can be seen in figures 7, 8 and 9 the photon count dramatically drops as we reach the angle of 67.5° or $\frac{3\pi}{8}$ radians. This meant that one of the crystals of the birefringent crystal - BBO was unaligned and it only down converted either Horizontally polarized light or vertically polarized light. The birefringent crystal was then aligned so that both of the polarization were down converted.

It can also be seen in the images below, that after alignment the overall photon count stabilized for individual detectors and the coincidence count between detectors A. The HWP was again rotated 180° and the total counts for individual detectors either stayed the same or increased throughout the rotation.

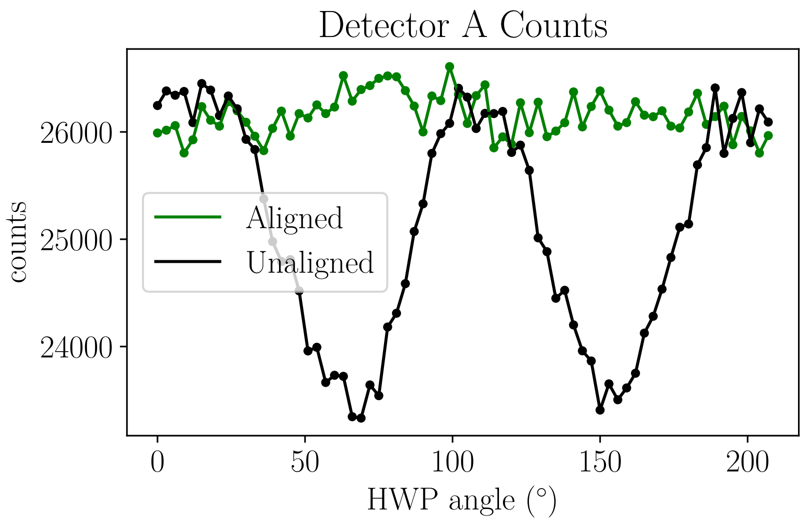

Figure 7: Photon Count for alignment at Detector A

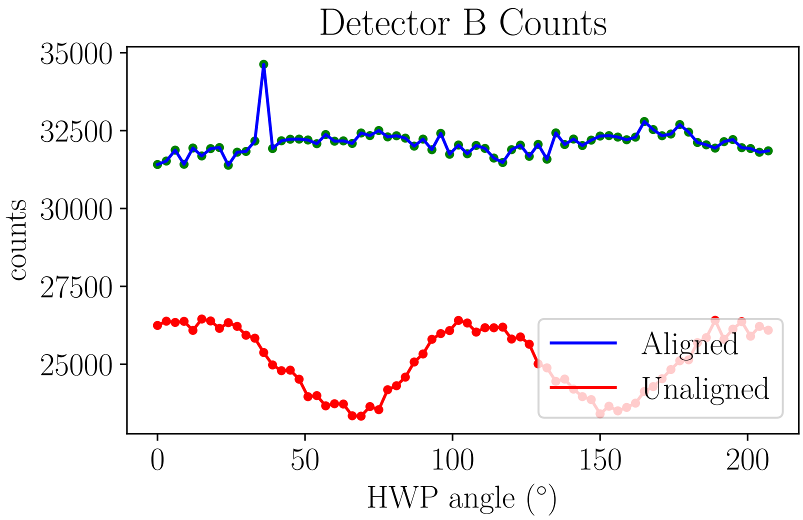

Figure 8: Photon count for alignment at Detector B

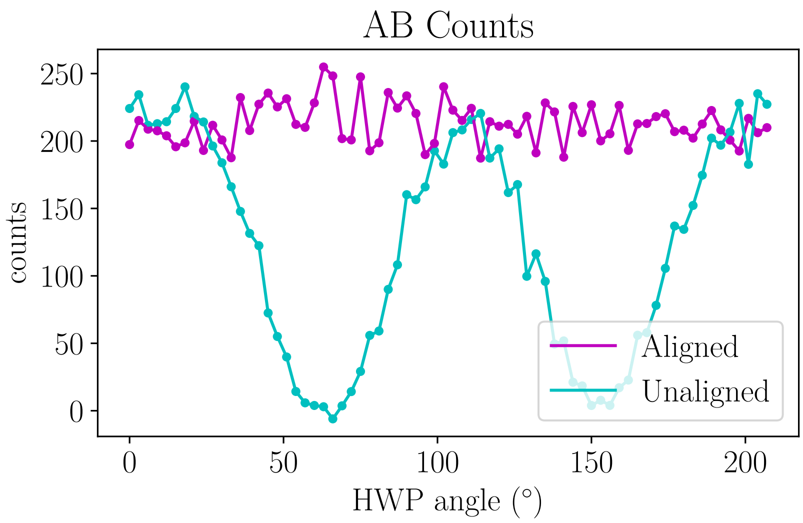

Figure 9: Coincidence counts for alignment at Detectors A and B

5.2 Splitting of the Beam and Photon Detection

Once the Birefringent crystal was aligned, the polarizing beam splitter was placed between detectors B and B'. This ensured that detectors B and B prime received opposite polarization of the light.

To reiterate what was discussed in subsection 4.2, the beam splitter allows us to exhibit the particle nature of light, as it can be argued that in the narrow 20 nanosecond window, there will only be photons emitted of a particular polarization.Photons striking Detector A trigger the clock and in that interval the counts received by any detector will be taken as coincidental counts between detector A and the detector that picked up the signal. Thankfully we see that only one of the Detectors pick up counts as can be seen in figure 15.

The half wave plate is rotated from 0° to 180° in increments of 5°. The data at each angle was collected for 15 seconds and averaged. It can be seen in figure 10, as the half wave plate was moved, the photon count did not change considerably as both of the polarization are received at Detector A;however, for Detectors B and B', it can be seen from figures 11 and 12, that as the angle is increased from 0° to 180° the count changes as the compositions of polarization in the beams is changed.This happens because of the polarizing beam splitter that splits the down converted beam depending based on its polarization;consequently, detectors B and B' receive lights of opposite polarization.

The figures 13 and 14 show the coincidence counts of AB and AB' respectively, and as it can be seen that the coincidence counts have an opposite trend. In the window of 20ns after a signal is picked by detector A, either detector B picks a signal or detector B' picks a signal. As the Half Wave Plate is rotated, the compositions of polarization are changed. These 2 graphs do hint towards the particle nature;however, they are not enough as apart form a few angles, there are several points where we see both detectors B, and B' reading a signal;however,the complete idea of capturing photons at either B or B' once detected at A in the 20 ns window is not enveloped by these graphs.
Figure 15 shows the coincidence counts at the three detectors at all angle. If in the 20 ns window after a signal was detected by detector A, a signal was detected by B and B' both, if that count was high, that would have shown statistical evidence of the classical nature of light as we would have detected light at both of the signals in one time window, showing that we had a continuous flow of both of the polarization of the light. The low coincidence count throughout the rotations is the evidence of quantum nature of light. This idea is further strengthened by the red plots shown in figure 16 as they have been calculated using eq (8).

The blue plots in the same figure were calculated using eq (9), and shows that if coincidence counts at A,B and B prime are discounted we recover our classical limit that shows that around the same photons are intercepted by detectors B and B' given any window of time.

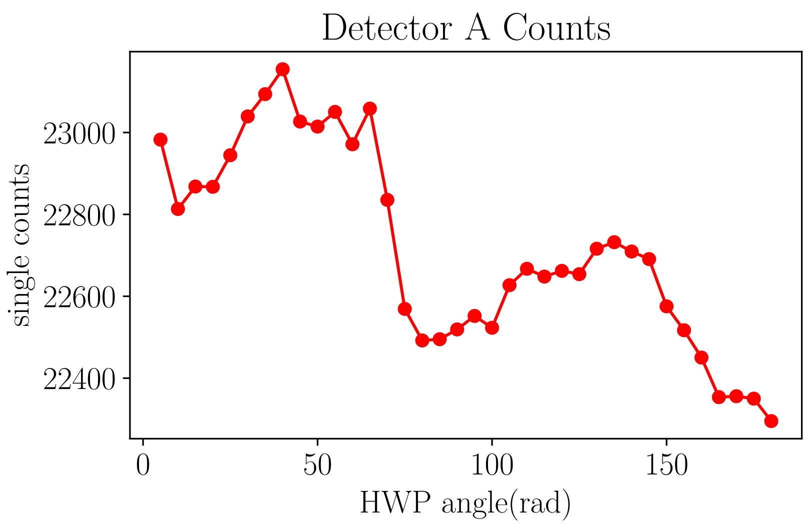

Figure 10: Photon Detection at Detector A

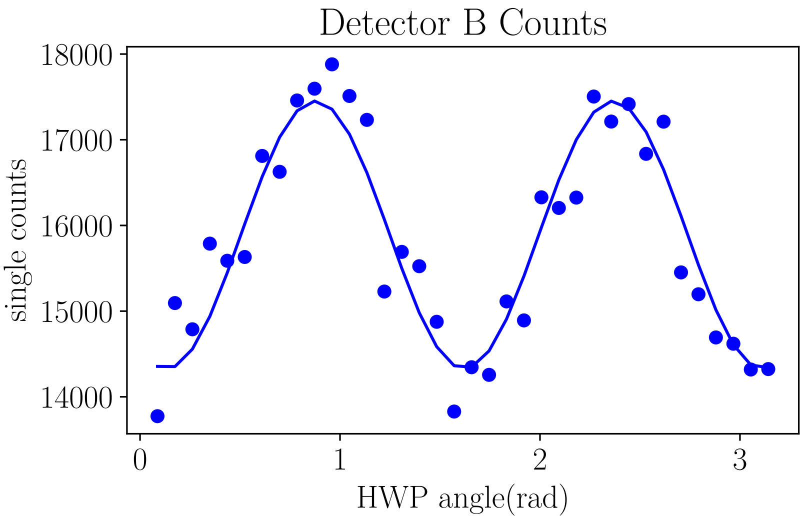

Figure 11: Photon Detection at Detector B

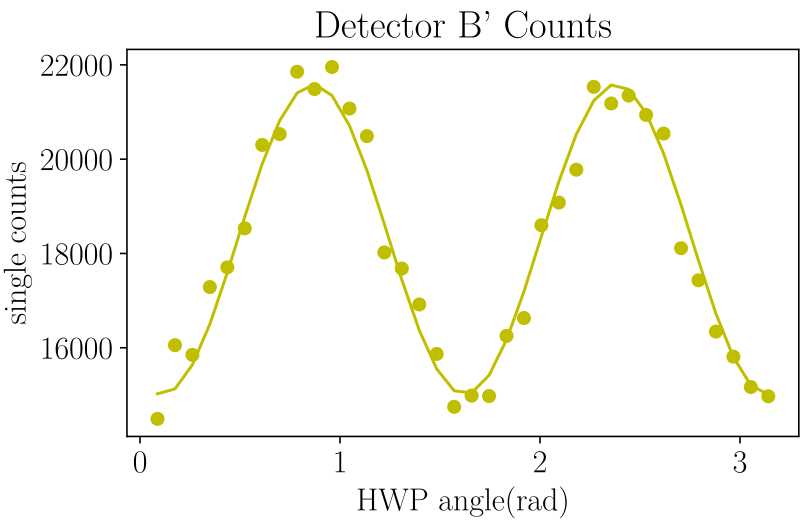

Figure 12: Photon Detection at B'

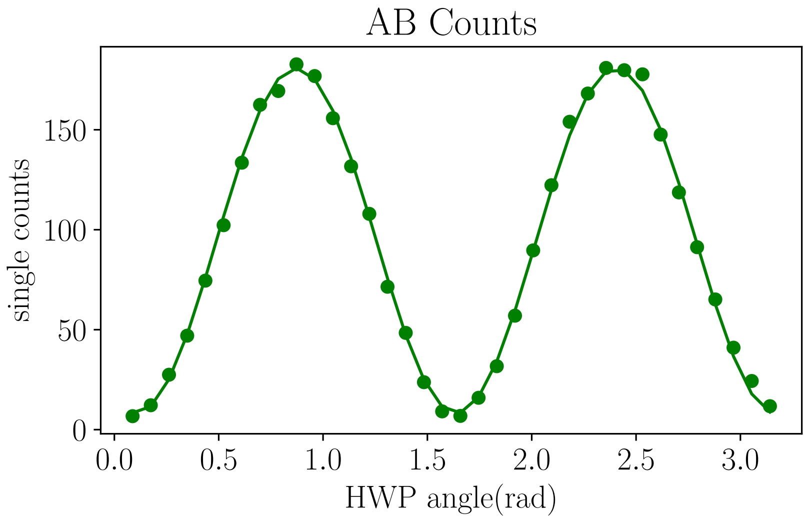

Figure 13: Coincidence Photons detection at Detectors A and Detectors B

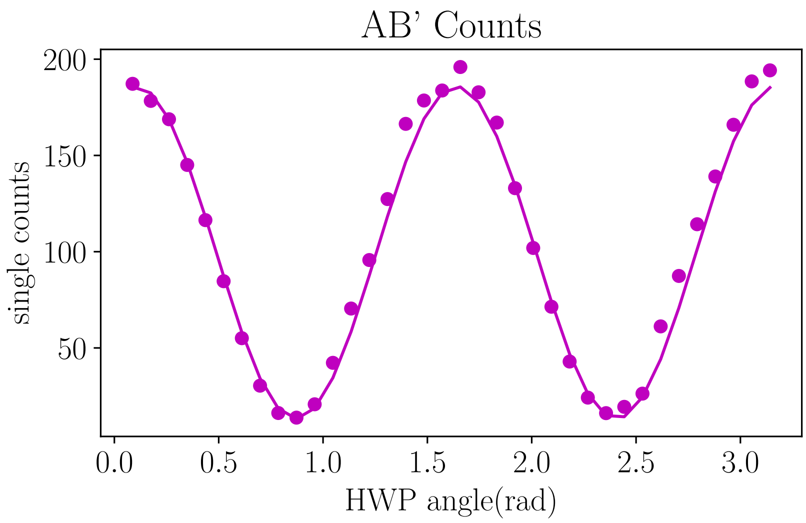

Figure 14: Coincidence Photons detection at Detectors A and Detectors B

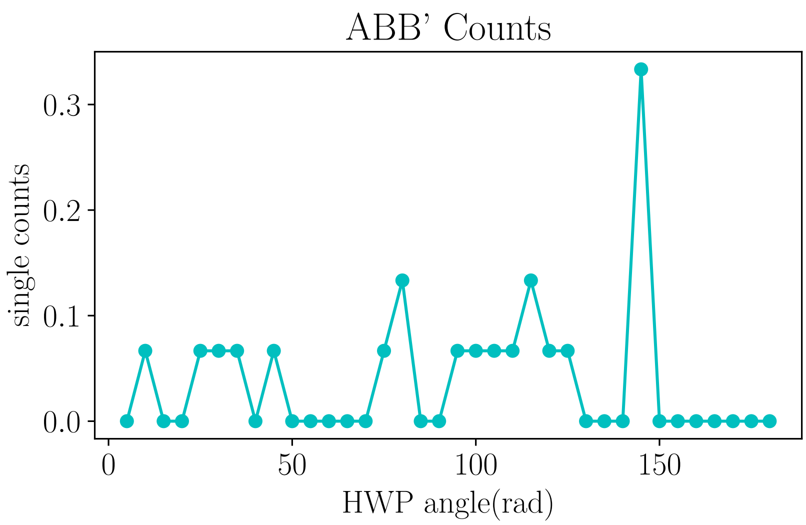

Figure 15: Coincidence counts for alignment at Detectors A,B and B'

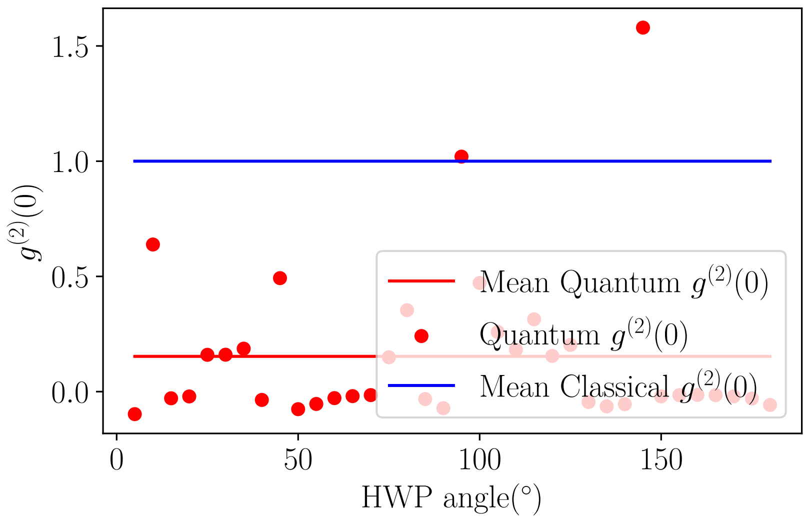

Figure 16: The Second Order Coherence Terms

6 Conclusion

The sophistication of the single photon lab allowed the detection of photons produced in the lab, using a heralded photon apparatus.Although, we did not have a single photon source, we were able to produce evidence of single photons using statistical tools and data of coincidence counts from the three detectors that intercept the down converted photon beam.

References

[1] S. A. Muhammad Hamza Waseem and F. e Ellahi, *Quantum Mechanics in the Single Photon Laboratory*. IOP Publshing, Bristol, 2020.