Demonstrating Quantum Nature of Light using Single Photons

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Supervision

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1 Abstract

This paper aims to present an experimental approach that utilizes single photons to demonstrate the quantum nature of light. We performed two closely related experiments: spontaneous parametric down-conversion (SPDC) and an empirical demonstration of the existence of photons. The SPDC experiment entailed the creation of entangled photon pairs, while the second experiment involved modifying the SPDC setup to provide evidence for the existence of photons. Our results demonstrate the quantum nature of light and highlight the importance of single-photon experiments in understanding the fundamental properties of quantum systems.

2 Introduction

The quantum nature of light is a fundamental concept in physics that has been difficult to demonstrate directly due to the inherent uncertainty and randomness of quantum phenomena. For most of history, scientists believed that light waves behaved as continuous classical waves generated through orthogonal electric and magnetic fields. This notion was challenged in the early 1900s by Einstein's discovery of the photoelectric effect. Following the discovery, light has been understood to be a quantized wave consisting of trillions of packets of energy called photons. Since then, researchers have been vigorously trying to develop new experiments to verify and research the quantum nature of light. One such experiment involves using single photons, first done in isolation in 1974.

3 Theoretical Background

0.1 Polarization

Polarization is a characteristic of transverse waves whose oscillations are perpendicular to the direction of the wave's motion. There are two dimensions perpendicular to any given line of propagation, so for a transverse wave moving along the z-axis, there are two independent polarization states: vertical and horizontal. Polarization can also be along an arbitrary direction in the x-y plane. Light is a transversely electromagnetic wave, and the direction of oscillation of the electric field vectors defines its polarization. The experiments described below focus on linearly polarized light, where all the electric field vectors propagate in the same plane and parallel to a fixed direction. The polarization of any arbitrary direction in the x-y plane can be denoted by:

$$f_n = Ae^{i(kz-wt)}\hat{n}, \tag{1}$$

where $\hat{n}$ denotes any arbitrary direction.

0.2 Half Wave Plate

Have-wave plates are optical devices that rotate the polarization of linearly polarized light by twice the angle between its optic axis and the initial direction of polarization. The half-wave plate also introduces a phase difference between the two components of the electric field vectors. The projection operator can be used to understand the effect of the half-wave plate on a photon, as shown in the diagram below[1].

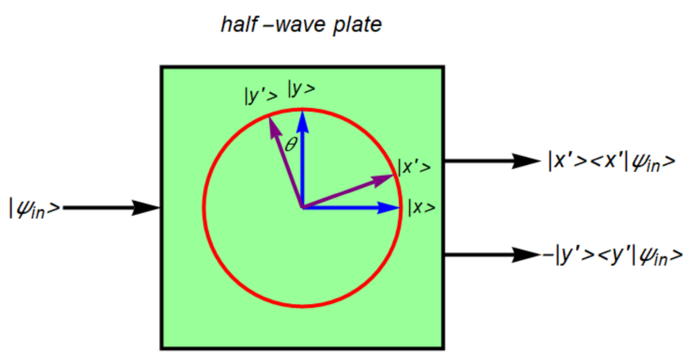

Figure 1: Projection Operator for Half Wave Plate

The wave function's x and y components can be addressed separately. The probability amplitudes for the x and y decomposition should align with the angular dependencies of coincidence counts we measure in the experiment. The probability amplitudes are:

$$P_{|x\rangle} = cos^2(2\theta_H - \alpha), \tag{2}$$

$$P_{|y\rangle} = sin^2(2\theta_H - \alpha), \tag{3}$$

where θ_H and α represent the angle of the half-wave plate and filter, respectively.

0.3 Spontaneous Parametric Down-Conversion

Spontaneous Parametric Down-Conversion is the method through which a pump photon of a specific frequency is used to produce two photons (a signal and an idler) with half the frequency of the pump photon (explicitly called "down-conversion"). It is parametric because the output photons depend on the polarization of the pump photons rather than their intensities. A material with birefringence, such as a β-Barium Borate (BBO) crystal, is used to achieve this effect. A BBO crystal has two indices of refraction: one for light polarized perpendicular to the optic axis (ordinary polarization) and one for light polarized parallel to the optic axis (extraordinary polarization). Hence, they can achieve this down-conversion because they have a non-linear optical response, meaning that they can change the frequency of the light beam in a non-linear manner. This is in contrast to linear optical processes, which do not change the frequency of the light beam but can alter other properties such as intensity, phase, or polarization.

4 Experimental Setup for SPDC and Results

Before we proceed with the experiment to empirically prove the existence of photons, we must ensure that SPDC is taking place successfully. We set up our experiment to achieve this, as shown in figure 2.

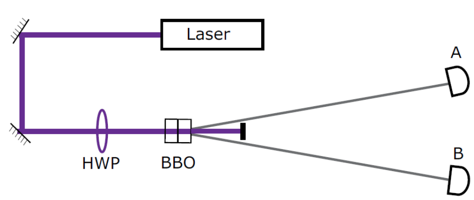

Figure 2: Experimental Set up for SPDC

The pump laser generates light with a wavelength of approximately 405 nm. Subsequently, the down-converted beams have a wavelength of 810 nm. The input light is vertically polarized, reflected off two mirrors, and passed through a half-wave plate, which introduces a phase shift that rotates the linearly polarized light to form a 45-degree polarized light. The photons then hit two adjacent BBO crystals with a 90° relative rotation, producing a 3° deflection angle in our experiment. Due to their relative rotations, the BBO unit will down-convert both horizontally and vertically polarized light to produce the signal and idle photons that have the opposite polarization to the pump photon. The conversion output looks like this:

$$|H\rangle \rightarrow |VV\rangle\,, \tag{4}$$

$$|V\rangle \rightarrow |HH\rangle\,. \tag{5}$$

Finally, the down-converted photons reach detectors A and B, which output electric pulses for each detected photon. These single-photon pulses and coincident counts on the two detectors are transmitted to a computer and monitored in real time.

After properly aligning the optical setup, we begin rotating the angle of the half-wave plate. The half-wave plate would polarize at particular angles only to allow the state vertical component to pass through and stop the horizontal component. This causes a decrease in the number of counts on detector A at certain angles, around 45 and 135 degrees, as shown in the figure below.

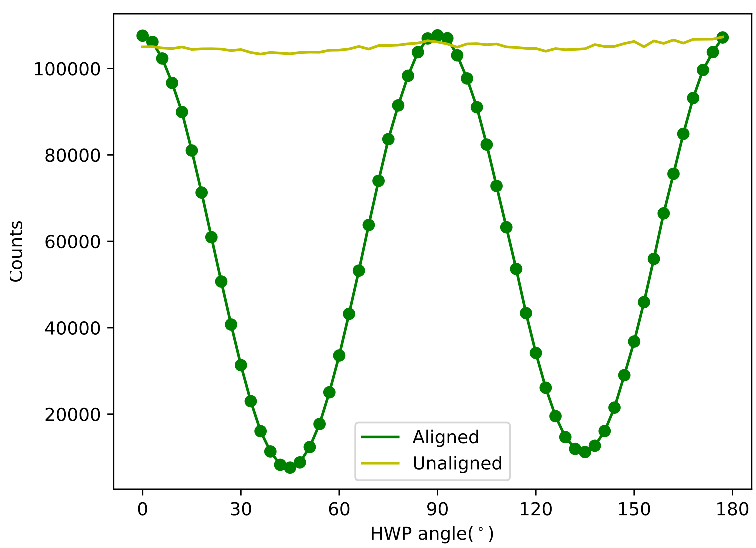

Figure 3: Detector A Counts

We repeat the same process and record the counts measured on detector B, which should depict a similar graph to the count in detector A.

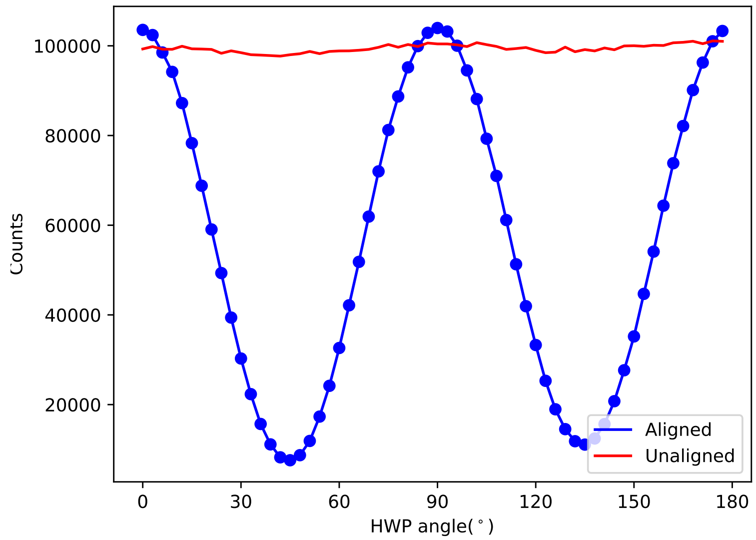

Figure 4: Detector B Counts

Suppose the half-wave plate has not been introduced in the setup, then the pump light remains vertically polarized. The BBO crystals would only produce a single pair of photons, with one reaching detector A and the other reaching detector B.

After we have maximized the photon counts on detectors A and B by fine-tuning the detector face angles and the BBO crystal, we begin measuring the coincidence counts of the detectors. A reading is recorded as a coincidence count if both detectors register an electrical pulse within 20 nanoseconds of each other. The coincidence count for the detectors can be seen below.

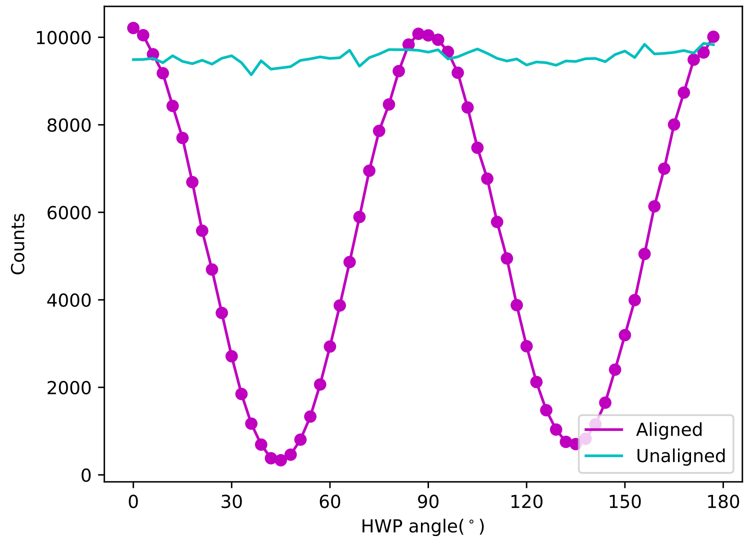

Figure 5: Detector AB Coincidence Counts

The increase or decrease in coincidence counts varies at the same angles as the counts on A and B, implying that the coincidence counts are indeed the paired photons measured after down-conversion.

5 Experimental Setup to Verify Quantization

After confirming the SPDC phenomenon, we move on to a three-fold coincidence count frame shown in figure 6.

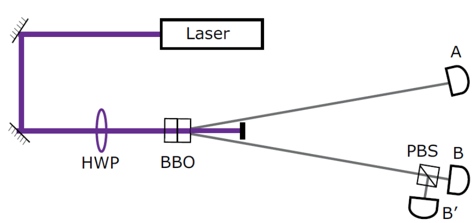

Figure 6: Setup to detect quantization of light

Compared to the initial setup, we can see the addition of Detector B' and a Polarizing Beam Splitter (PBS). A PBS is a device used to split an incoming light beam into two separate beams based on the polarization of the light. It uses a particular crystal that allows light waves with certain polarizations to pass through while reflecting light waves with other polarizations. These two beams are then directed to separate detectors or optical elements for analysis or further processing. In our case, the output of the PBS goes into detector B, placed on the transmission side, and detector B' on the reflection side. The PBS reflects vertically polarized photons and allows horizontally polarized photons to pass through. Vertically polarized photons are detected at detector B' whereas horizontally polarized photons are detected at detector B. When we observe coincidences between detectors A and B', we count photon pairs that are vertically polarized $|VV\rangle$. When we observe coincidences between detectors A and B, we count photon pairs that are horizontally polarized $|HH\rangle$. Detection of a vertically polarized photon $|H\rangle$ at detector A does not count towards coincidences with detector B' because there is no simultaneous detection at detector B', and vice versa[2].

We first look at the three detectors' count rates individually to ensure everything is in order and we are getting a substantial photon count.

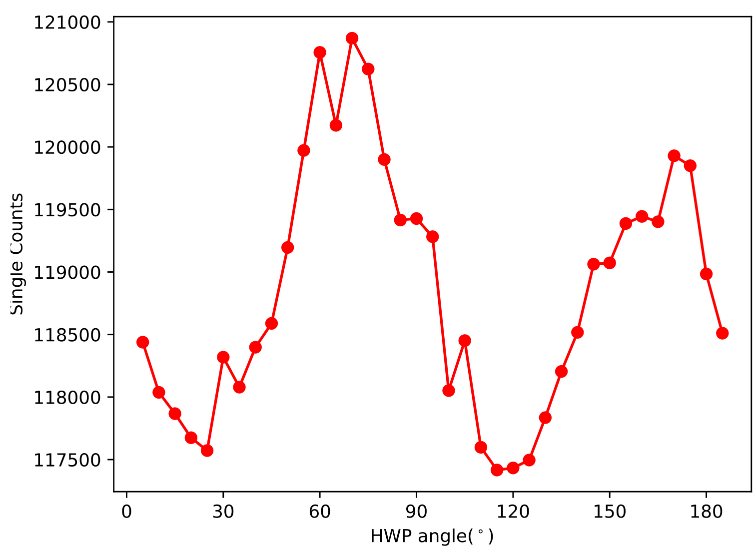

Figure 7: Detector A Count Rate

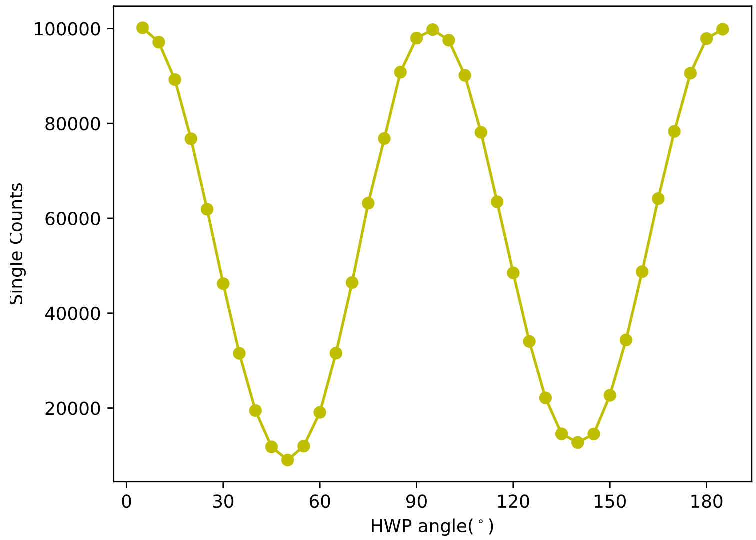

Figure 8: Detector B count Rate

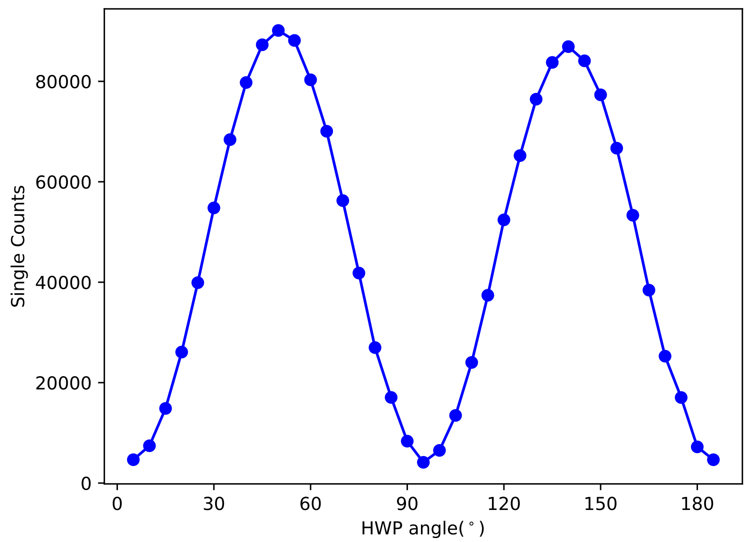

Figure 9: Detector B' Count Rate

The above figures confirm that our regular count rates are substantial. It is also interesting to note that the count rate of detector B and B' are inverted, where the count rates for B reach the maximum when the count rate for B' reach their minimum and vice versa. This is expected as the PBS sends vertically polarized light to B' and horizontally polarized light to B. Hence when the HWP is set at approximately 45°, all the photons are vertically polarized and give a high count at B' and a low count at B.

6 Results and Discussion

To demonstrate the quantum nature of light, we measure the coincidence counts for ABB', AB, and AB'. This was done by rotating the HWP by 5° and noting the coincidence counts for all three detectors obtaining 36 values for each. The data points are plotted in the figures below.

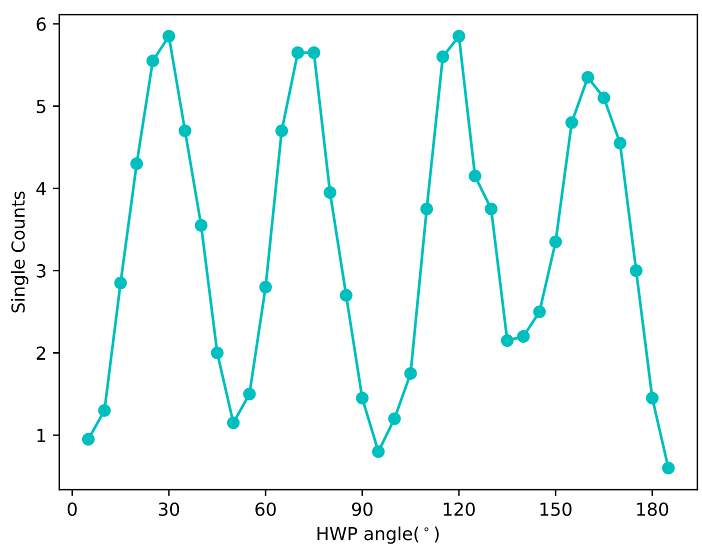

Figure 10: Detector ABB' Coincidence Counts

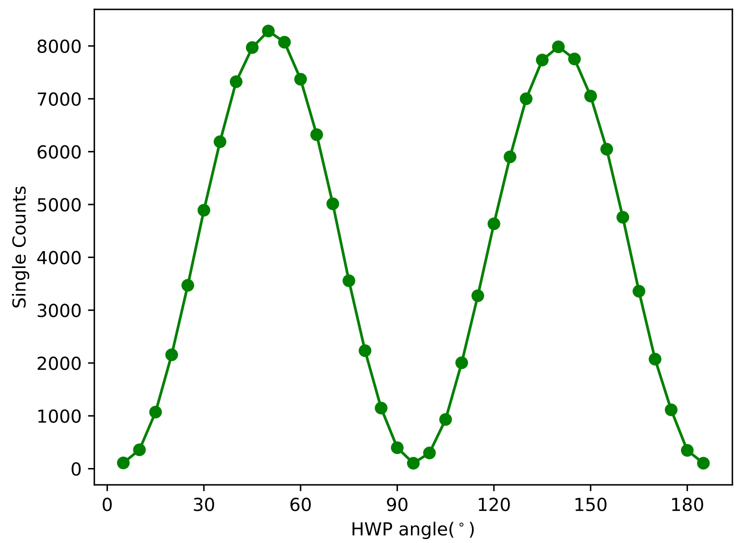

Figure 11: Detector AB Coincidence Counts

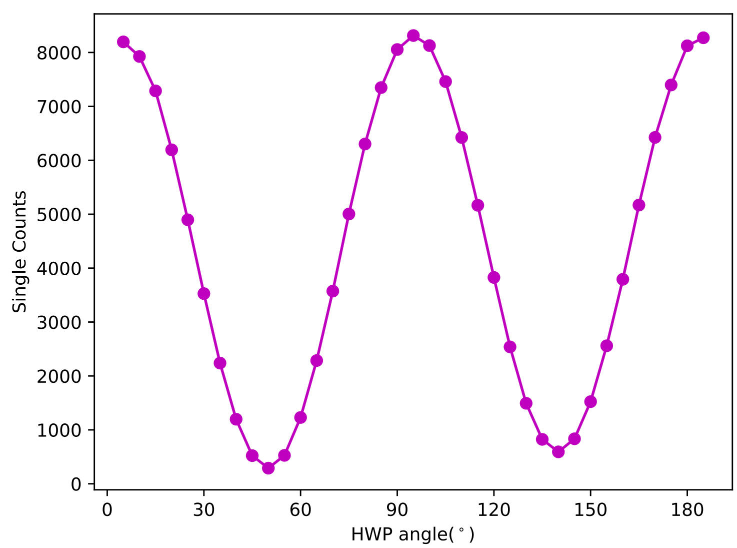

Figure 12: Detector AB' Coincidence Counts

In figure 10, notice that the coincidence counts for ABB' are almost close to zero, with the highest coincidence count being 6, compared to the coincidence counts for detector AB and AB'. This is a rudimentary way of appreciating that light is quantized because one of the two down-converted photons will go to detector A, and the other one can either go to detector B or detector B' but not both, unlike the classical model. The minimal count rates seen in detector ABB' are due to random errors caused by accidental coincidence. Furthermore, the coincidence counts for detectors AB and AB' are sinusoidal. The AB detector counts are the horizontally polarized photons and hence have a $cos^2(2\theta_H)$ dependence as predicted by equation (2). Conversely, The AB' detector counts are the vertically polarized photons and hence have a $sin^2(2\theta_H)$ dependence as predicted by equation (3). By overlapping the two plots for AB and AB' the phase shift between the two becomes apparent.

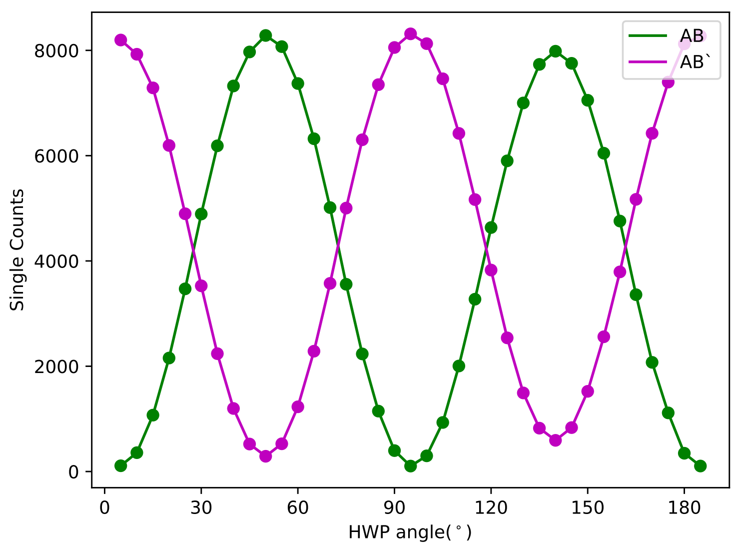

Figure 13: Detector AB' Coincidence Counts

We employ the second-order correlation function to showcase the quantum nature of light mathematically. The second-order correlation function measures the correlation between the arrivals of photons at two detectors. It is a measure of the probability that a photon will arrive at one detector at a given time, given that it has already arrived at the other detector. The second-order correlation function is often used in the study of quantum systems, as it allows researchers to understand the statistical properties of photons and other particles. It is typically denoted as $g^{(2)}(\tau)$, where tau is the time delay between the arrival of photons at the two detectors. A value of $g^{(2)}(\tau)$ greater than 1 indicates that the photons are correlated and bunched. In comparison, a value of $g^{(2)}(\tau)$ less than 1 indicates that the photons are not correlated and display anti-bunching. Anti-bunching means that the photon detections are relatively equally spaced apart with significant time intervals in between. A completely quantized system would have perfect anti-bunching, meaning the second-order correlation function would be zero. In our experiment, we viewed the coincidence counts with a time delay of zero seconds because the detectors were almost the same distance from the incoming source. Subsequently, the formula for the function becomes:

$$g^{(2)}(0) = \frac{P_{ABB'}(0)}{P_{AB}(0)P_{AB'}(0)}, \tag{6}$$

where $P_{ABB'}(0)$ is the probability of a coincidence count for three-fold detection, $P_{AB}(0)$ is the probability of a coincidence count at AB, and $P_{AB'}(0)$ is the probability of a coincidence count at AB'. These probabilities can be expressed using the number of coincidence counts as follows:

$$P_{ABB'}(0) = \frac{N_{ABB'}}{N_A}, \tag{7}$$

$$P_{AB}(0) = \frac{N_{AB}}{N_A}, \tag{8}$$

$$P_{AB'}(0) = \frac{N_{AB'}}{N_A}. \tag{9}$$

Substituting these expressions into our second-order correlation function, we get:

$$g^{(2)}(0) = \frac{N_A N_{ABB'}}{N_{AB} N_{AB'}}. \tag{10}$$

We then plug in the coincidence count values from all 36 data points and plot them against the half-wave plate angles as shown in figure 14.

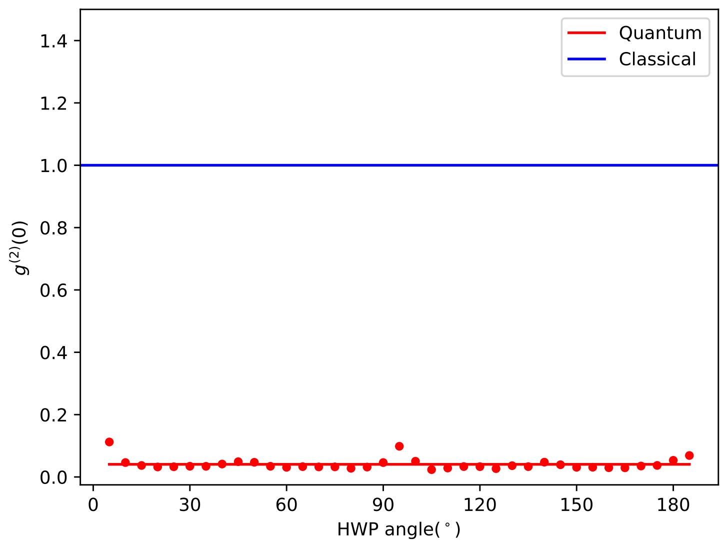

Figure 14: second order coherence for various angles of the HWP

It is clear from figure 14 that barring random experimental errors like accidental counts, our optical system is perfectly quantized as the $g^{(2)}(0)$ factors are all below 1 and very close to 0, alluding to the anti-bunching of the photons.

7 Conclusion

In short, the aforementioned results provide strong evidence for the validity of the quantum theory and highlight the importance of using single photons as a tool for studying the quantum world. During the advent of quantum theory, the humble single-photon experiments served as the benchmark for deepening our understanding of the fundamental nature of the universe and opened up new avenues for research in fields related to entanglement and spectroscopy.

References

[1] M. S. Suzuki, "Quarter-wave plate and half-wave plate," *Department of Physics, SUNY at Binghamton*, 2020.

[2] M. H. Waseem and M. S. Anwar, "Quantum mechanics in the single photon laboratory," *IOP Publishing*, 2020.