On the Quantum Nature of Light

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Various experiments have conclusively proved that light is made up of particles called photons. One such experiment is reproduced here. A single photon source is created using spontaneous parametric downconversion. The resultant beam is passed through a beam splitter and incident on three detectors. The degree of second-order decoherence $g^{(2)}(0)$ is calculated after measuring coincidence counts for the detectors. The classical prediction of $g^{(2)}(0) \geq 1$ is seen to be violated.

I. QUANTIZED LIGHT: AN INTRODUCTION

Classically, light can be seen as a transverse wave with mutually perpendicular electric and magnetic fields obeying Maxwell's equations. This notion was challenged in the early 1900s when the photoelectric effect was discovered [1]. Since then, light has been understood to be grainy, consisting of packets of energy called photons.

One experiment to demonstrate that light is quantized involves counting coincident detections of photons from a single-photon source at equally distanced detectors. This experiment was reproduced at the single-photon lab at PhysLab, LUMS.

We first created a single photon source using spontaneous parametric downconversion (SPDC).

II. CREATING A SINGLE PHOTON SOURCE

Before delving into the actual process, we need to understand polarization.

A. What is Polarization?

Classically, the polarization of the light source specifies the direction of the electric field $\mathbf{E}$ in relation to the wavevector $\mathbf{k}$. An electric field can then be written as

$$\mathbf{E} = A\mathbf{e}_H + Be^{i\phi}\mathbf{e}_V, \tag{1}$$

where $\mathbf{e}_H$ and $\mathbf{e}_V$ are unit vectors corresponding to horizontal and vertical polarization respectively. A and B represent the relative amplitudes and ϕ represents the relative phase of the two polarization states.

In quantum mechanics, the polarization state of photons can be explained in the form of state vectors in braket notation. Using the orthonormal basis of vertical and horizontal polarization states $\{|H\rangle, |V\rangle\}$, we can write

$$|\psi\rangle = A|H\rangle + Be^{i\phi}|V\rangle, \tag{2}$$

where unlike the classical picture, the numbers multiplying the polarization kets correspond to probabilities and not actual amplitudes.

Unitary operators are used to represent polarization manipulating elements. In the $\{|H\rangle, |V\rangle\}$ basis, these are just the Jones matrices.

The polarization of the incident photons is affected by the SPDC process and we can use the aforementioned notation to understand it.

B. The SPDC Process

In SPDC, a pump beam of frequency ω_p strikes a nonlinear crystal and divides into a signal beam of frequency ω_s and an idler beam of frequency ω_i. The pump photon is absorbed by an electron in the crystal, thereby exciting it. As the electron returns to its ground state, it releases two photons each of which has half the frequency as the original photon[2]:

$$\omega_s = \omega_i = \frac{\omega_p}{2}. \tag{3}$$

Throughout our experiment, we used linearly polarized light at angle θ to the vertical. Two beta barium borate (BBO) crystals, rotated 90° relative to each other, were used. Their combined action on the polarization state of the input photon can be summarized as follows[2]:

$$\cos\theta\,|V\rangle + \sin\theta|H\rangle \xrightarrow{BBO} \cos^2\theta\,|HH\rangle + \sin^2\theta\,|VV\rangle\,. \tag{4}$$

C. The Schematic for the Experimental Setup

As FIG. 1 shows, the crystals were cut to ensure that the signal (going towards B) and idler (going towards A) beams make an angle of 3° from the pump beam. The perpendicular distance between the BBO and the line joining the detectors was measured to be 114.0 ± 0.5 cm. The distance x between the two detectors was then calculated as

$$x = \frac{2\tan 3^\circ}{45} = 12.0 \pm 0.2\,\text{cm}. \tag{5}$$

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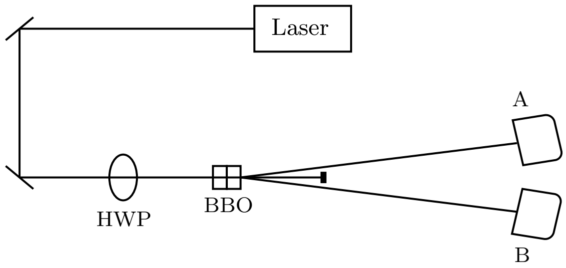
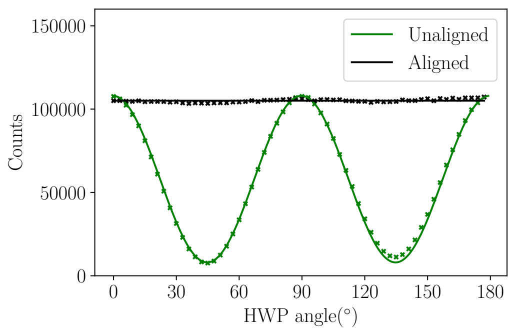
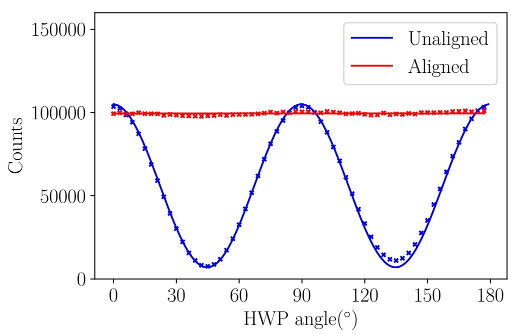


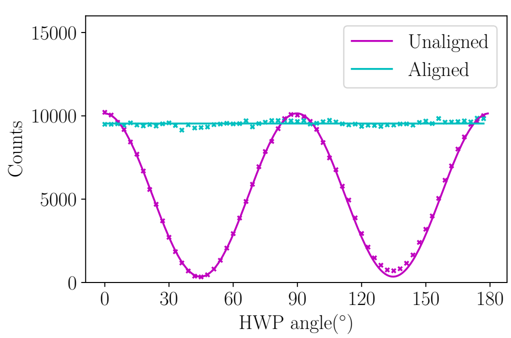
FIG. 1: Schematic of the SPDC Experiment



(a) Single counts for detector A in counts per second.



(b) Single counts for detector B in counts per second.



(c) Coincidence counts for detectors A and B in counts per second.

FIG. 2: Counts for each detector before and after aligning the second BBO crystal.

The height of the beam above the table was maintained at 13.80 ± 0.05 cm. After the detectors were set up, the half-wave plate (HWP) was inserted in its position. The role of the HWP is to change the input polarization to a combination of horizontal and vertical polarization. Its role can be specified using the unitary operator[2]

$$\hat{O}_{HWP}(\theta) = \begin{pmatrix} \cos 2\theta & \sin 2\theta \\ \sin 2\theta & -\cos 2\theta \end{pmatrix}. \tag{6}$$

The software Vivado was used to change the fast axis of the HWP. At first, only one BBO crystal was aligned with the detectors by using a back-propagated, collimated laser. The detectors were turned on and the photons incident on them per second (henceforth referred to as counts) collected and graphed via a pre-written Spyder code. The HWP was rotated through a cycle of 180° and the second crystal was aligned to ensure maximized single and coincidence counts on the detectors. The results are summarized in in FIG. 2.

As can be seen, with one crystal unaligned, the counts follow a sinusoidal curve as expected since one BBO only downconverts electrons with one type of polarization. After alignment, the counts fluctuate very little around a high mean value since both vertically and horizontally polarized photons are being downconverted.

For the AB coincidence counts in FIG. 2(c), the accidental counts N_{AB}^{acc} were removed before plotting the data points. N_{AB}^{acc} can be approximated by[3]

$$N_{AB}^{acc} \approx 2 N_A N_B \tau, \tag{7}$$

where τ is the width of one pulse corresponding to detection by the FPGA. In our case, $\tau = 20$ ns.

III. DEMONSTRATION OF THE QUANTUM NATURE OF LIGHT

After alignment of the detectors, a single-photon state is created for the signal beam incident at B. This is because its photodetection is now conditioned on the simultaneous detection of the idler beam photons[2]. Proceeding further, we added a third detector (B′) to the setup.

A. The Schematic of the Experimental Setup

As FIG. 3 shows, we added a polarizing beam splitter (PBS) in the direction of the signal beam. The PBS ensures that only horizonatally polarized light is incident on B by re-directing the vertically polarized component to B′. Once again, alignment of the optical equipment was performed by rotating the HWP to maximize the coincidence counts AB and AB′. The results are summarized in FIG. 4 and 5.

As FIG. 4(a) shows, the counts at detector A fluctuated a little around a mean value. This fluctuation was

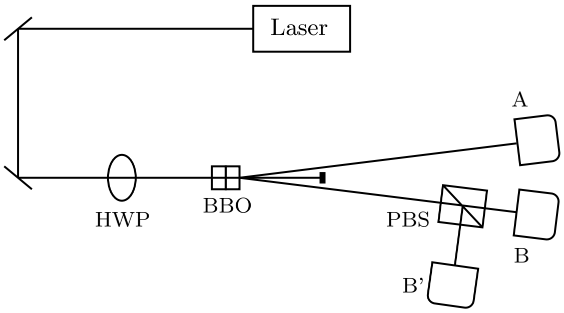
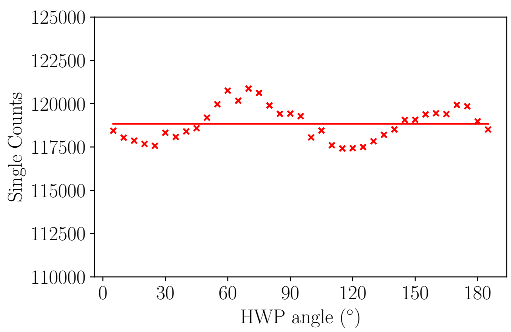
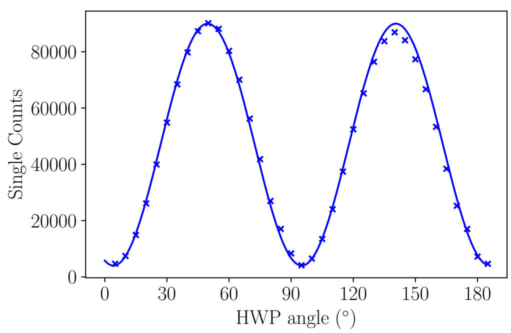


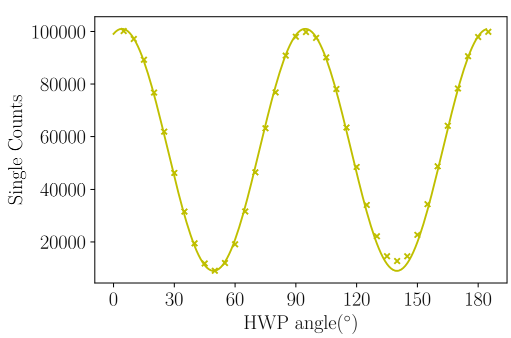
FIG. 3: Schematic of the three-detector experiment.



(a) Single counts for detector A in counts per second.

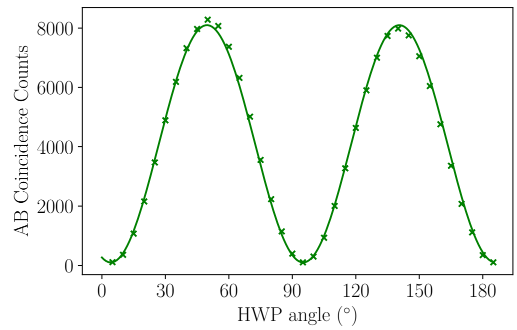


(b) Single counts for detector B in counts per second.

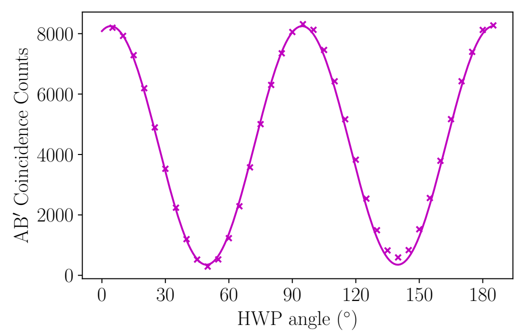


(c) Single counts for detector B′ in counts per second.

FIG. 4: Single counts for each detector after alignment.



(a) Coincidence counts for detectors A and B in counts per second.



(b) Coincidence counts for detectors A and B′ in counts per second.

FIG. 5: Coincidence counts for AB and AB′ after alignment.

due to slightly imperfect alignment. For detectors B and B′, however, we got a sinusoidal variation of counts on changing the HWP angle as expected since the PBS only allows one component of polarization to pass on to one detector.

Similarly, in FIG. 5, it can be clearly seen that the conicidence counts AB and AB′ followed a sinusoidal pattern. Furthermore, they were completely out of phase with each other as expected.

To proceed further, we need to define the degree of second-order coherence $g^{(2)}(0)$.

B. The Degree of Second-Order Coherence

The degree of second-order coherence $g^{(2)}(0)$ is a measure of how well are the intensities of two electromagnetic waves correlated. Classically, the expression for the detectors B and B′ can be written as[4]

$$g^{(2)}(0) = \frac{\langle I_B(t) I_{B'}(t) \rangle}{\langle I_B(t) \rangle \langle I_{B'}(t) \rangle} = \frac{\langle [I_I(t)]^2 \rangle}{\langle I_I(t) \rangle^2}, \tag{8}$$

where $I_I(t)$ is the intensity of the incident light at time t. Since the mean of squares is always greater than or equal

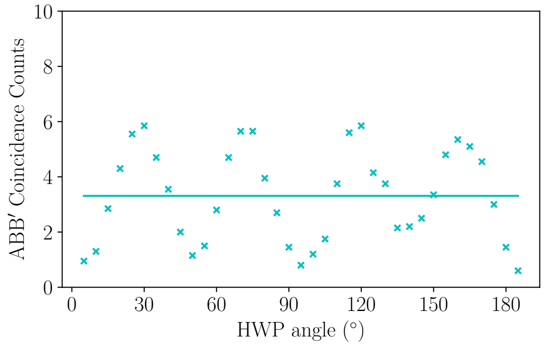


FIG. 6: Three-fold coincidence counts at detectors A, B and B′.

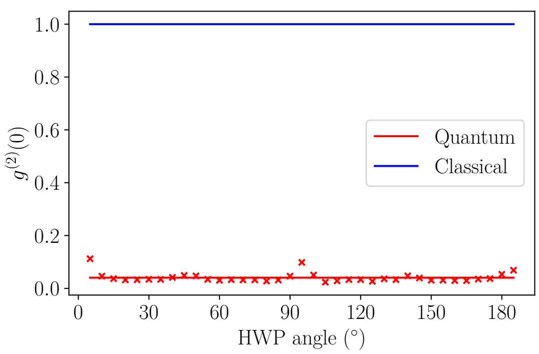


FIG. 7: The degree of second-order coherence calculated for the experiment. The lowest classical prediction is plotted as a guide.

to the square of the mean, we get $\langle [I_I(t)]^2 \rangle \geq \langle I_I(t) \rangle^2$. Therefore,

$$g^{(2)}(0) \geq 1. \tag{9}$$

This inequality is violated for a quantum light source. In quantum mechanics, since we deal with probabilities instead of intensities, we get the following expression for $g^{(2)}(0)$:

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

where P_{AB} is the probability of simultaneous detection at A and B while N_{AB} is the coincident counts at A and B. The others are similarly defined. Notice that for a purely quantum source, single photons cannot be incident simultaneously at B and B′. Therefore, $N_{ABB'} = 0$ and

$$g^2(0) = 0. \tag{11}$$

In the lab, however, we found accidental three-fold coincidence at the detectors due to purely random detections. These are plotted in FIG. 6. Note that compared to the two-fold coincident detections, these are negligible. Therefore, they will not affect the correlation function much.

We calculated the error in $g^{(2)}(0)$ due to two-fold accidental detections. This can be written as[2]

$$g^{(2)}(0)' = 2N_A\tau \left(\frac{N_{B'}}{N_{AB'}} + \frac{N_B}{N_{AB}} \right).$$

This error was subtracted from the degree of second-order coherence previously calculated. The results are plotted in FIG. 7. As can be clearly, seen the degree of second-order coherence is very close to 0. Since the classical inequality in Equation (9) is violated, we conclude that light indeed consists of single photons i.e. it is quantized.

IV. CONCLUDING REMARKS

The quantum nature of light is introduced to students mainly via the photoelectric effect. This relatively simple experiment demonstrates that light is quantized in a different way via more easily understood concepts. With such equipment readily available at the single-photon laboratory and further experiments on quantum concepts already designed, students can vastly improve their understanding of quantum mechanics.

[1] A. Einstein, On a Heuristic Point of View Concerning the Production and Transformation of Light, Annalen der Physik **17**, 132 (1905).
[2] M. H. Waseem, F. Ilahi, and M. S. Anwar, *Quantum Mechanics in the Single Photon Laboratory* (IOP Publishing Ltd, 2020).
[3] B. J. Pearson and D. P. Jackson, A hands-on introduction to single photons and quantum mechanics for undergraduates, Am. J. Phys. **78**, 471 (2010).
[4] M. Beck, *Quantum Mechanics: Theory and Experiment* (Oxford University Press, 2012).