Proof of the Particle Nature of Light Through Coincidence Experiments

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Single photon experiments aim to verify and test the pre-existing proof of single photon existence. By replicating these experiments, we measured coincidences between multiple detectors to disprove the optical theories of classical mechanics, as well as prove the existence of photons. Our experiments were not able to measure the expected coincidence rates for random, multichromatic light, although we were able to fully verify the quantum mechanical nature of light that is photons through down conversion and manipulation of the Mach Zehnder interferometer.

INTRO

Classical mechanics initially described light in the form of electromagnetic waves. The notion that light is quantized was first proposed by Einstein, through the implications of the photoelectric effect. The photoelectric effect describes light hitting a sheet of metal that in turn ejects an electron with energy proportional to the frequency of the light, a relation later established mathematically by Planck [3]. Einstein was the first to propose the particle wave duality of light in 1905, without explicit proof [2]. Despite Einstein's proposal, semi-classical theories could still be used to explain the photoelectric effect by proposing that only the atoms in the optical detector(s) are quantized, not the light itself. By this logic, light only exists in the form of electromagnetic waves.

To sufficiently prove the existence of light in quantized packets, light must be split by some means and measured by multiple detectors non-simultaneously. The technology of modern detectors makes it impossible for us to measure perfect simultaneity, although it is possible to measure a pulse induced by light over an extremely short time frame (coincidence window). Detecting accidental coincidences, even when using the shortest coincidence window possible, is close to inevitable also because light travels too fast for the particles to be sufficiently spaced. In 1956, Hanbury Brown and Twiss used an arclamp source to observe far more coincidences than previous expectations of quantum mechanics which could only be explained quantum mechanically as photons arriving in bunches to the detectors [1]. It was the nature of the arclamp that made simultaneous detection common. The existence of light as quantized packets can be fully proven through experiments that manipulate the paths and state of the light. Detection of less, as well as significantly more, coincidences than expected can be demonstrated and explained through quantum mechanics.

The definition of a photon is still a topic of debate in the scientific world today. It can be simply conceptualized as a small, massless particle that travels in wave form at the speed of light, when in actuality, quantized states of the radiation field involve excitations of spatial modes [1]. The best description explains how a particle can be absolutely massless, but does not allow sufficient visualization of the concept of light in the form quantized packets (photons). In 1986, the existence of light in quantized packets we call photons was proven through the single photon experiments we aim to replicate.

THEORY/EXPERIMENTAL PROCEDURE

General

The counts of a single detector, or both simultaneously (N_A, N_{AB}, respectively), along with the time interval for which the detector(s) are measuring (t, in seconds), can be used to determine the counts or coincidence rates ($R_{A,}$ R_{AB}, in counts/second) with the following formula:

$$R_x = \frac{N_x}{t} \qquad (1)$$

Units: N_A: counts; t: seconds; R_A: counts/second

Uncertainties in both counts and count rates are found using (with the same units as corresponding values):

$$\delta N_x = \sqrt{N_x} \ \ , \delta R_x = \frac{\delta N_x}{t} \, , \qquad (2)$$

Early experiments of radiation coincidences provided an absolutely random source of radiation which was used as a model to describe the expected anticoincidence parameter for random detection, valued at one. The anticoincidence parameter (α) can be descried as a relation of probabilities, which are derived from counts on each detector and both. The relation can be simplified using count rates and the coincidence window used in the following equation:

$$\alpha = \frac{\mathrm{R}_{AB}}{\tau_C R_A R_B} \qquad (3)$$

The coincidence window (τ_C) is in units of seconds, which shows us that α is in terms of $(\text{counts})^{-1}$

Uncertainties for products of values and their uncertainties for independent quantities can be applied to the uncertainty in our anticoincidence parameter with the equation

$$\frac{\delta\alpha}{\alpha} = \sqrt{(\frac{\delta \mathrm{R}_{AB}}{\mathrm{R}_{AB}})^2 + (\frac{\delta R_A}{R_A})^2 + (\frac{\delta R_B}{R_B})^2 + (\frac{\delta \tau_C}{\tau_C})^2} \qquad (4)$$

The equipment used for all experiments is listed below

1. 155SL 00449 Helium Neon Laser
2. Iris
3. Crystal Beam Splitter
4. Granger Detectors
5. Mirrors
6. Fiber optic Cables
7. Lab Pro
8. Computer

9. Altera Circuit Board
10. Neutral Density Filters – 3, 4, 5 orders of magnitude
11. GED Flashlight
12. Diode Laser LDCU 89386
13. Backstop
14. Barium Boron Crystal
15. Polarizer
16. LabView
17. 1 nanometer Filter
18. Half wave plate
19. Granger interferometer (Beam splitter)
20. Mach Zehnder Interferometer

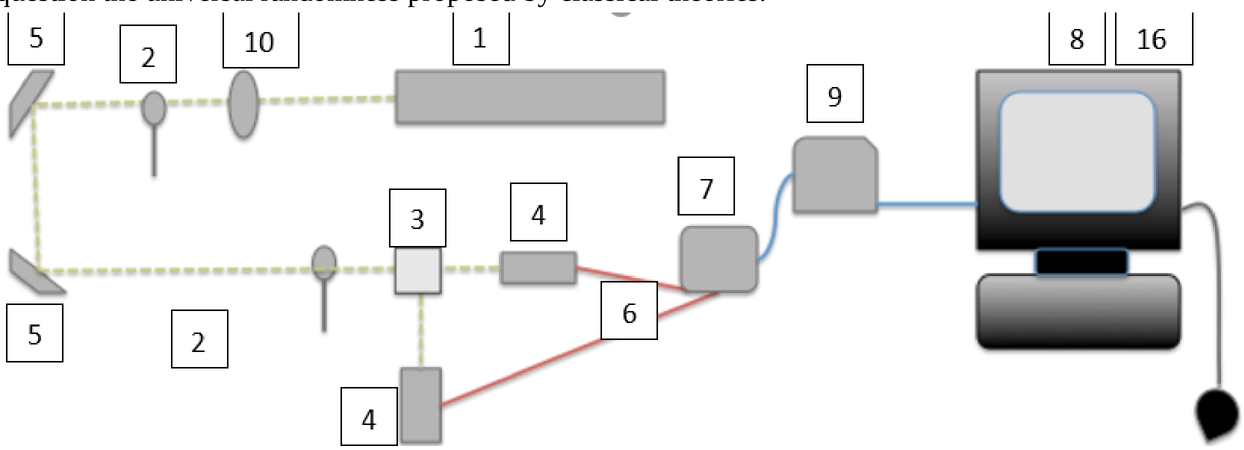
White light/ HeNe Laser

White light can be used to produce light at all frequencies, ensuring randomness in detection. We can use an assumed value of one for alpha, as long as our setup is as exact and efficient as possible. In general, classical mechanics predicts an anticoincidence parameter greater than or equal to one, implying that when light is as random as possible, it can only have the anticoincidence parameter as low as one. Showing these coincidences is not an indication of quantum packets of light due to the fact that semiclassical mechanics predict the electromagnetic wave to continuously hit the detectors, which themselves randomly eject energized electrons which get recorded by the counters.

Our white light setup aimed to replicate what has been established as a completely random light source. We used neutral density filters (x5, x3) to significantly dim our white light by 8 orders of magnitude so that the detectors could read the light without harm. Before the white light was put into the experiment, we used our Helium Neon laser (wavelength 632.8nm) to visually align the beams. To do this we first directed the beam along the path without filtering, and visually observed the light as it hit the backstop behind and between both detectors. By ensuring the detectors are at the same height as the beam appears on the backstop, and arranging their positions so that the beam is as centered between them as possible, we hope that we will see even counts on both detectors when we replace the HeNe laser with our flashlight.

We now input the flashlight, allowing the light to follow the same path as the aligning HeNe, although now instead of just letting the beam through, irises must be used to keep the light that passes through as laser like as possible (visually linear). When the light reaches the final iris before the detectors, it should assume the conic shape we expect, and we should observe near equal counts on each detector, if our alignment from the HeNe was sufficient. We observed that the white light did get counts near even on each filter, but we were not able to extract nearly enough coincidences to yield the expected coincidence parameter that we expect to see from a random light or radiation source (1), as proposed and proven in classical mechanics. This data was too inconclusive to report, although it can be found in the appendix section. [1]

A HeNe laser should give us less random coincidences than white light, in theory. Semiclassical mechanics still holds their theory of electromagnetic waves while using laser light. The expected anticoincidence parameter for laser light is also expected to be around one. To explain this apparent randomness in quantum mechanical terms, photons that are emitted extremely close together and happen to take different paths can be detected as coincidences if the coincidence window used is too long to differentiate between when the two photons arrive. According to classical mechanics, the waves divide, and when they hit the detectors, cause random pulse signals that can either show coincidences by chance, or be independent [1]. The Helium Neon laser experiment cannot be used as complete evidence of photon particles. We must examine a scenario in which we do not only see randomness in our coincidences, to question the universal randomness proposed by classical theories.



Setup for HeNe/White light Experiment. HeNe Laser (1), or GED Flashlight (11), is light source. Neutral density filters (10) lower intensity, irises focus light in beam. Beam splitter divides light evenly to into two granger detectors (4). Fiber optic cable transmits light signal to Lab Pro, which converts light signal to pulse. Altera circuit board takes pulse and determines coincidences based off preset coincidence window. Counts and coincidences recorded in computer/LabView program.

Using a very similar setup as we did for the white light, we remove the flashlight and allow the HeNe laser to take the same path. Using a polarizing beam splitter we can direct the light in multiple directions. In order to get an even and symmetrical split, we use a wave plate to polarize the light at forty-five degrees. Couplers are used to direct the beam to the desired location of the detectors.

We initially aligned the crystal by replacing our detectors with bare fiber optic cable without neutral density filters, and adjusted the alignment of the setup until we could observe illumination of the fiber optic cables. We saw the light bounce from side to side within the cable, in a zig zag pattern, indicating that the light had to come into the cable at some small angle, or the cable itself was at an angle, which we expected. The light we observed was significantly and near equally bright, so we deduced that the laser setup with the crystal was now well aligned.

Now inserting all three neutral density filters, we replaced the fiber optic cables from their ports and replaced them with the Granger detectors. The detectors took in all light that hit it, and for each particle of light, sent an electric pulse to our circuit board. The circuit board determines the coincidence window, from four preset settings (Up/Up, Up/Down, Down/Up, Down/Down) that give us different coincidence window values, although we are not told what they are. If a pulse from each detector both overlap within the same coincidence window, a coincidence is recorded.

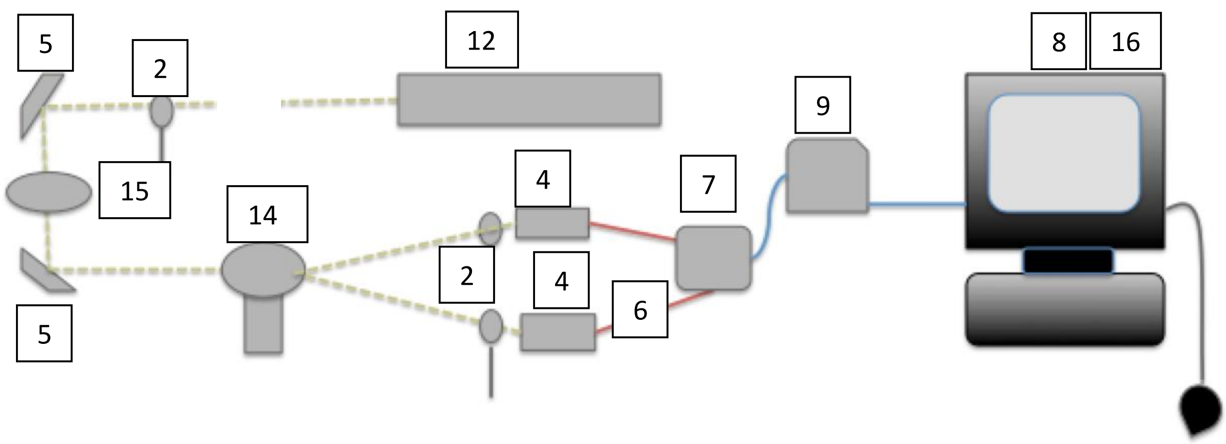
Directions	$R_A \pm \delta R_A$	$R_B \pm \delta R_B$	$R_{AB} \pm \delta R_{AB}$
Up, Up	3900±10	5660±10	.2±.1

Down, Down	3920±10	5690±10	.8±.1
Down, Up	6640±10	5770±10	.4±.1
Up, Down	4020±10	5780±10	.4±.2

Rates for HeNe Two fold Experiment. Individual count rates and coincidence rates between detectors A and B found from counts in equation (1). Uncertainties found through equation

Two Fold Diode Laser/BBO Crystal

Through the process of down conversion, coincidence rates should be significantly higher than our helium neon laser experimental results. Spontaneous parametric down conversion cannot be explained by classical mechanics, and is essential to supporting quantum mechanics. Down conversion is the process by which a single photon can be transmitted into the crystal, and converted into two output photons with significantly lower, but equal frequencies. This in turn increases the wavelengths of the emitted photons equally, therefore decreasing each photon's energy. Down conversion requires a light source that emits a much shorter wavelength, so that when the photons emerge from the crystal, they are within the range that the detectors can read. For this process we used a diode laser. The process of down conversion is essential because the photons are emitted exactly simultaneously, which eliminates the randomness that we have seen previously.



Setup for Two-fold Diode/BBO Experiment. Diode Laser (12) emits light through iris (2), mirrors (5) direct through polarizer (15), into BBO crystal (14). BBO crystal down converts photons through irises and into Granger detectors (4). Light signal transmitted through fiber optic cables (6) and into Lab pro (7), where signal converted to pulse. Pulse travels through Altera circuit board (9), where coincidences determined and then recorded on computer (8) in LabView program (16).

The reasoning behind getting a much higher anticoincidence parameter can only be explained quantum mechanically, and after the previous experiments, it has already been established that the light waves should induce electrons to be counted randomly. These photons must be simultaneously emitted to show high coincidence rates and therefore high anticoincidence parameters, which should be impossible, according to classical mechanics. Classical mechanics would expect these waves of light to behave exactly like the divided HeNe laser light. This is used to disprove their theory, although it does not fully conclude light to be composed of particles. To reveal the quantum mechanical nature of light, we must demonstrate photons behaving unequivocally without expected randomness through the exploitation of the correlated properties of light.

For this experiment we are using a diode laser as our source, but unlike the HeNe setup we did need to use neutral density filters on the detectors. The light from the diode is emitted with a wavelength of 401.7 nanometers. We must substitute our polarizing beam splitter with a nonlinear Barium Boron (BBO) crystal. This light travels from the laser along the mirrors and into our BBO crystal. Before it reaches the crystal, however, we have inserted a polarizer to polarize the photons at fourty degrees. This allows the crystal to down convert each incoming photon into two identical photons and direct them symmetrically at three degrees from their original path on either side, with equal frequencies, energies, and wavelengths of 803.5 ± .2 nanometers. With this new wavelength we can safely direct the photons into the detectors without harming the equipment. The process of alignment is significantly more difficult than in the previous experiments, as our light at 803.5 nanometers is in the ultraviolet range and not visible. To properly align our setup, we executed the following steps:

1. Set back reflection
2. Maximize Counts on detector A
3. Maximize Counts on detector B
4. Tune detector B to maximize coincidence counts
5. Tune BBO crystal to maximize coincidences further
6. Repeat steps 4 and 5 to increase completely
7. Tune detector A to maximize counts

Back reflection is a method in which we disconnected the end of the fiberoptic cable not connected to our detector, and shone a hand held red laser pointer through that end. The beam travelled through the cable and out of our (switched off) detector. From this we align the detector so that the beam coming out of it is hitting the BBO crystal, the source of our light in the main part of the experiment. Once our setup was properly aligned, the down converted photons were recorded by the detector and eventually into LabView the same way our HeNe light was recorded. The light is emitted from the BBO crystal, which is nonlinear and cut at twenty-nine degrees, will exit the crystal at three-degree angle from its original path in a conic manner. This cone is what we are trying to hit the edges of, since that is where the most photons will be detected.

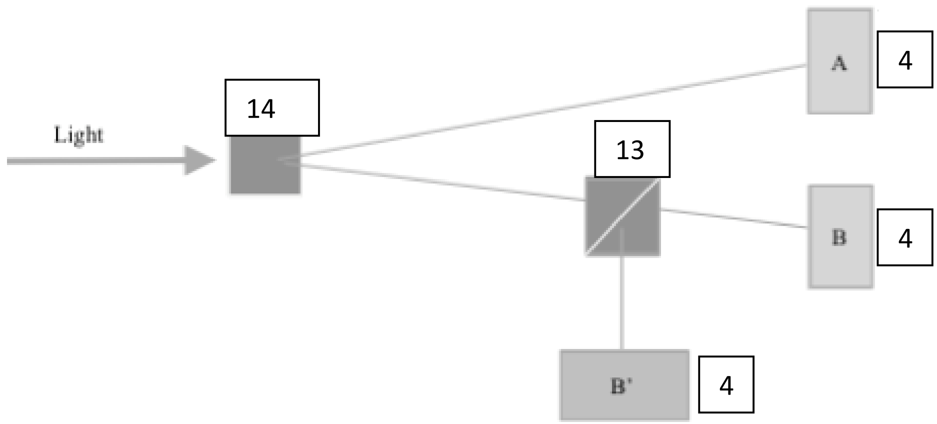
Configuration	$R_A \pm \delta R_A$(c/s)	$R_B \pm \delta R_B$(c/s)	$R_{AB} \pm \delta R_{AB}$(c/s)
Up, Up(A)	27900±200	204100±100	49950±70
Up, Up(B)	27900±200	204200±100	50080±70

Rates for Diode/BBO Two-fold Experiment. Individual count rates and coincidence rates between detectors A and B found from counts in equation (1). Uncertainties found through equation (2).

We only took data using our Up/Up configuration because Up/Up gave us the shortest coincidence window and therefore the least accidentals.

Three Fold Diode Laser/BBO Crystal

Light is expected to produce an anticoincidence parameter of at least one, according to classical mechanics. We have seen how perfectly correlated light sources (photons), produced simultaneously from down conversion, can produce far greater results for our coincidence rate and anticoincidence parameter than was said to be possible through classical mechanics. We use this knowledge to expand our experiment to measuring three fold coincidences.



Setup for Three fold Diode/BBO Experiment. Light enters BBO (14) from same path Two fold BBO. Light Travels to detector A (4), and to Granger interferometer (beam splitter) (13) which divides and directs beams and into detectors B, and B'. Signals transmitted and recorded same way as in previous experiments.

The setup we used for the three-fold diode experiment was nearly identical to the last, with the only adjustment being the addition of a Granger interferometer, or beam splitter. There is another Granger detector, B', positioned perpendicular to the path from the beam splitter to detector B, to catch and record the reflected beam from the beam splitter.

If our light source consists of photons, we should observe no coincidences between all three detectors, because of the nature of the down conversions. Each photon in the split "arm" of the experiment is paired with a photon from the other arm, and because the beam splitter in the second arm cannot send a photon in both directions, the photon must choose one direction or the other, cause one of the detectors on the second arm to not get a count. Incidentally however, we can still observe coincidences if two photons that enter the crystal are close enough together to fit in the same coincidence window, and the two photons that are sent through the second arm choose different paths at the beam splitter, triggering a (random three fold) coincidence. These random coincidences, however, will produce far lesser coincidence rates and therefor far lesser anticoincidence parameters, which indicates that what we have described is valid. But, the proof of single photons will only be complete if we see the anticoincidence parameter and coincidence counts/rates go to absolutely zero.

To align the new detector and beam splitter, we input the HeNe laser with an iris in front of it and direct its beam to bypass the BBO and hit our beam splitter similarly to how the arm from the BBO would. The angle of entry doesn't need to be exact; it just needs to enter the beam splitter on the correct face of the cube. We do this to align the detectors B, B', because B' is new, and the angle of entry is now slightly different for B than it was before with the direct signal from the BBO. The same wavelengths apply to the to the beam in this setup as they did for the two-fold diode experiment.

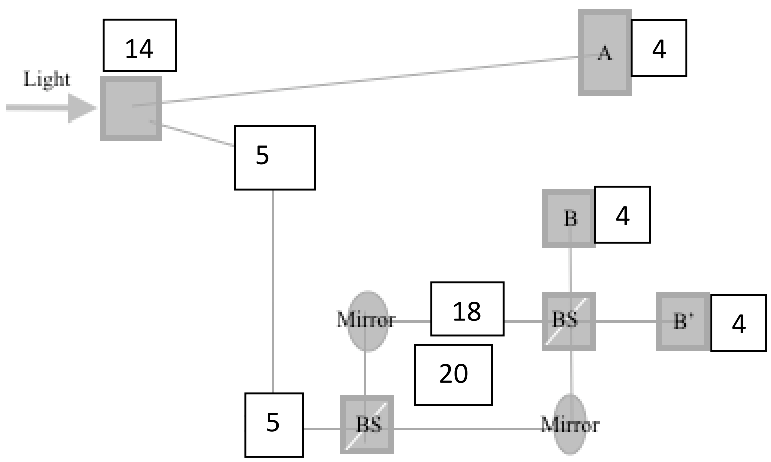
After we aligned the setup, we recorded trials at a time interval of one hundred seconds, and using equation (1), we were able to get our rates for all three detectors as well as our coincidence rates in all combinations for two fold, and the three-fold rate.

Configuration	$R_A \pm \delta R_A$	$R_B \pm \delta R_B$	$R_{B'} \pm \delta R_{B'}$	$R_{AB} \pm \delta R_{AB}$	$R_{AB'} \pm \delta R_{AB'}$	$R_{ABB'} \pm \delta R_{ABB'}$
UU	14490±10	7442±9	3312±6	1927±4	6302±8	0±0
UD	14470±10	7450±9	3307±6	1973±4	6447±8	0±0
DU	14460±10	7430±9	3303±6	2016±4	6540±8	0±0
DD	14460±10	7430±9	3298±6	2114±5	6853±8	0±0

Rates for Diode/BBO Three fold Experiment. Individual count rates and coincidence rates between detectors A and B found from counts in equation (1). Uncertainties found through equation (2). All coincidence rates in units of counts per second.

Three Fold Mach-Zehnder

The final progression in verifying the existence of single photons uses three fold coincidences again, but in order to fully eliminate all coincidences, we must differentiate between the paths of our second arm.



Setup for Mach Zehnder Interferometer experiment. Light enters BBO as shown previously. Mirrors (5) direct beam from arm 2 of BBO into Mach Zehnder interferometer (20) which consists of two mirrors and two Granger interferometers (BS). Half wave plate (18) insterted within MZ interferometer to make paths distinguishable through polarization. Light signal recorded by detectors same way it has previously.

The setup is nearly identical to the setup we used for our last experiment with the Mach Zehnder interferometer in place of our beam splitter. First, we used white light in order to confirm no difference in path lengths. We do this by sending a white light source through the beam splitter in a close to direct manner, and use LabView to see the interference pattern displayed photons from detectors A and B as we vary the path length within the interferometer. We observed the consistency of the interference pattern displayed using LabView in order to determine our when our path length difference lined up to give us maximum coincidences. The adjustments were made by turning a micrometer attached to one of our mirrors, which is a device that allows us to adjust the position of the mirror extremely gradually. We adjusted the micrometer until we observed a very gradual interference pattern, much wider than the one we initially observed before adjusting. The main point of this was to get the path lengths aligned enough to observe the expected interference pattern in LabView, making the paths functionally indistinguishable.

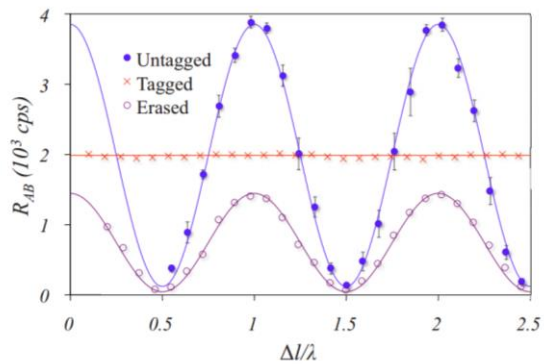
We have a half wave plate placed within the interferometer on the top path around the rectangle, which adds a polarization of one-hundred thirty degrees to each photon, orienting them horizontally, considering they had been polarized vertically initially to effectively split before our BBO crystal. This can be thought of as the half wave plate “tagging” the photon.

We then return to using the full setup, sending the diode laser through the BBO and then the paths of the first arm and the Mach Zehnder interferometer on the second arm. The down converted photons from the second arm of the BBO split will enter the Mach Zhender interferometer, in which it can choose one of the two paths around the rectangle. We inserted our one nanometer filters in front of each detector.

Originally, our light emerging from the HeNe laser has a wavelength of about four hundred with an uncertainty of twenty. To reduce this, we put one nanometer filters in front of each detector to maximize our coherence length and therefore our coincidences. Coherence length describes the length of a given spectrum observed by that light, which must overlap with the spectrum of the other photon in order to interfere or coincide with. The smaller the uncertainty, the longer the coincidence length, and the greater chance there is that photons will produce coincidences. Interference patterns are maximized due to the fact that only photons with identical wavelengths can be shown to interfere with each other. The one nanometer filters used give us an uncertainty of one nanometer, reducing our overall variance from forty nanometers to two.

The Mach-Zehnder interferometer can be used to create two paths along which the photons can be either altered through polarization or not, using a half wave plate. By gradually adjusting the path lengths within the Mach Zehnder interferometer (not using our half wave plate), we can create an interference pattern by causing the coincidences between A and B to behave sinusoidally with respect to the change in path length. The interference pattern is observed at full magnitude without the half wave plate, meaning that a photon could have traveled through either path, or without disproof, both paths at the same time. When we insert our half wave plate, light is vertically polarized, or tagged, in the arm of the interferometer containing the plate. The Mach Zehnder interferometer should now display no interference pattern between our coincidence rates and path length difference. After tagging the photons with polarization, we can tell that our photons must be choosing one of the paths through the interferometer due to the fact that our interference pattern will disappear to a constant rate of coincidences. The reasoning being that orthogonally polarized particles cannot interfere with each other as a function of path length difference.

Further examination of photons, and the justification of what is proposed by quantum mechanics here can be accomplishes by observing the effects of a quantum eraser. By a polarizer directly before our detector B, oriented at forty-five degrees, our light is given a probability of one half to be transmitted through the polarizer with a vertical incoming polarization. All photons that are transmitted through the “eraser” (forty-five-degree polarizer) will now be re polarized in parallel with those transmitted through arm A, creating an interference pattern reduced in magnitude from our original. The quantum eraser further justifies the theories of quantum mechanics by giving us proof that the way we manipulate photons with our half wave plate is in fact the reason we see no interference pattern. [1]



[1]

Expected interference patterns of coincidences when we use no polarization methods (indistinguishable paths) (blue), only the half wave plate (distinguishable paths) (red), and the quantum eraser (purple) are shown below

Configuration	$R_A \pm \delta R_A$	$R_B \pm \delta R_B$	$R_{B'} \pm \delta R_{B'}$	$R_{AB} \pm \delta R_{AB}$	$R_{AB'} \pm \delta R_{AB'}$	$R_{ABB'} \pm \delta R_{ABB'}$
Up, Up	23060±15	5859±8	2699±5	4682±7	2250±5	0±0
Up, Down	23050±15	5898±8	2705±5	4747±7	2310±5	0±0
Down, Up	23060±15	5911±8	2719±5	4855±7	2348±5	0±0
Down, Down	23040±15	5922±8	2721±5	5030±7	2443±5	0±0

Rates for Three fold Diode/BBO Experiment. Individual count rates and coincidence rates between detectors A and B found from counts in equation (1). Uncertainties found through equation (2). All rates in units of counts per second.

ANALYSIS

White Light/Helium Neon Laser

Coincidence windows from white light were unrealistically long. Due to this, we used our HeNe laser source to determine the coincidence window.

Configuration	$\tau_C \pm \delta\tau_C$(ns)
Up, Up	9 ± 4
Up, Down	16 ± 3
Down, Up	16 ± 4
Down, Down	40 ± 10

Coincidence window values from HeNe laser. Found using equation (3). Anticoincidence parameter assumed to be 1.

These coincidence window values and their uncertainties used for all experiments. We expected the coincidence window to be in the range of nanoseconds, which we were able to observe.

Diode/BBO

With our measured counts and count rates we calculated the following alpha values using equation (3).

Trial 1: $\alpha \pm \delta\alpha = 97 \pm 5$ (seconds/counts)

Trial 2: $\alpha \pm \delta\alpha = 97 \pm 5$ (seconds/counts)

These values confirm our expectation that the BBO crystal emits identical photons simultaneously to create coincidences at a far higher rate than the expectation of classical mechanics for our anticoincidence parameter. There have been many experiments that find the anticoincidence parameter to be much higher, even in the thousands, but we can deem our results significant enough to verify quantum mechanics due to the fact that our results capture values two orders of magnitude higher than the anticoincidence parameter assumed to measure random coincidences.

We observe extremely high error values for our count rates, which we can attribute not only to high counts and therefore uncertainties in counts, but also by our short time interval of ten seconds, which we divide our uncertainty of counts by (equation 3).

Three Fold Diode/BBO

Configuration	$\alpha_{AB} \pm \delta\, \alpha_{AB}$(c/s)	$\alpha_{AB'} \pm \delta\, \alpha_{AB'}$(c/s)	$\alpha_{BB'} \pm \delta\, \alpha_{BB'}$(c/s)	$\alpha_{ABB'} \pm \delta\, \alpha_{ABB'}$(c/s)
Up, Up	6500 ± 600	4400 ± 400	0±0	0±0
Up, Down	3700 ± 400	2600 ± 300	0±0	0±0
Down, Up	3800 ± 400	2600 ± 300	0±0	0±0
Down, Down	1800 ± 200	1200 ± 100	0±0	0±0

Anticoincidence parameters from three-fold Diode/BBO experiment. Values calculated using equation (3). Uncertainties calculated using equation (4). Error found using a method of 10 percent, due to calculation inconsistencies.

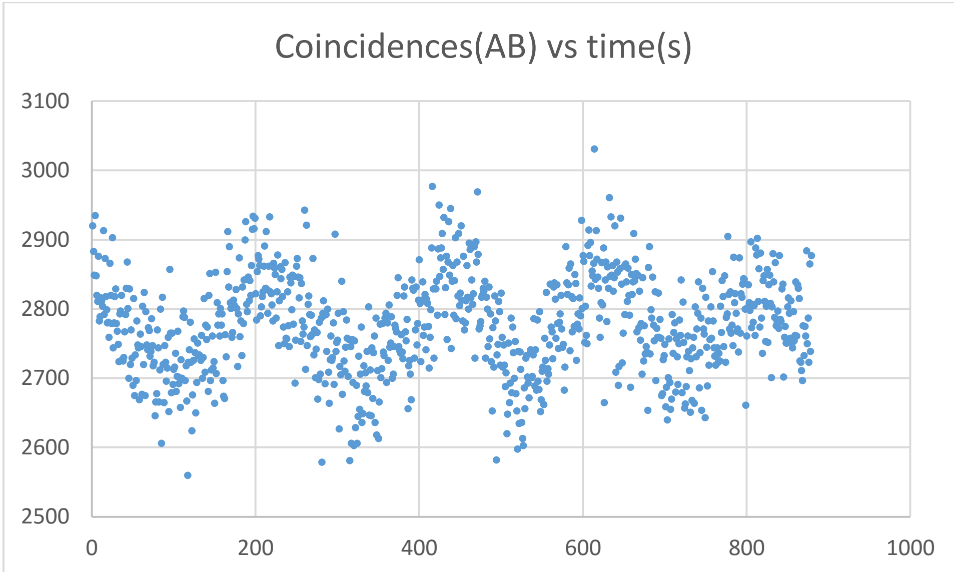
We did not record any coincidences between B and B' (and therefore no triple coincidences), as predicted by quantum mechanics. It is confirmed to be highly unlikely after we observed no coincidences for all circuit board configurations (coincidence windows). As expected, the shorter the coincidence window, the higher the anticoincidence parameter between A and B, and A and B'. This indicates that the amount of photons that had piled up on each other before the BBO down conversion and caused accidental coincidences was not significant compared to the individual coincidences.

Three Fold Mach Zehnder Interferometer

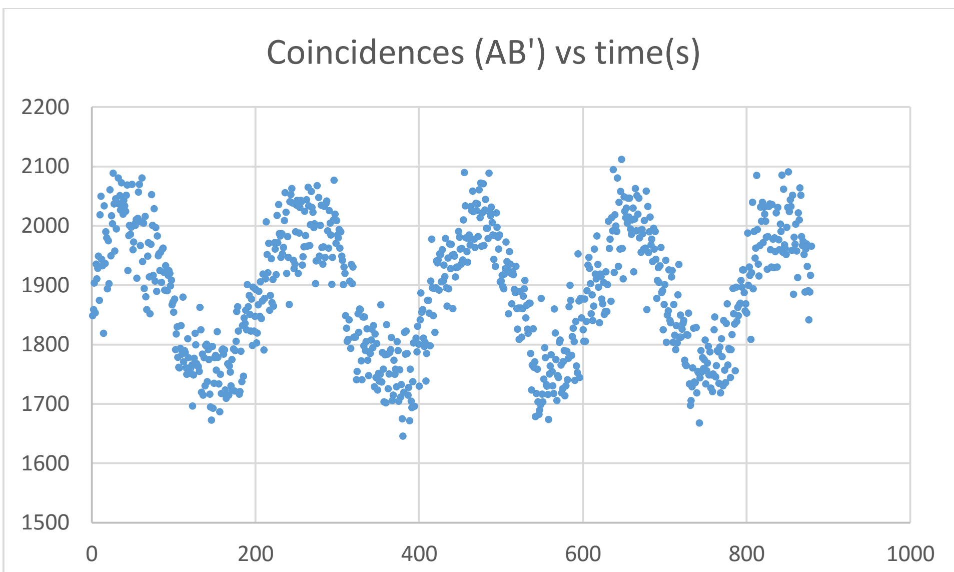
Configuration	$\alpha_{AB} \pm \delta\, \alpha_{AB}$(c/s)	$\alpha_{AB'} \pm \delta\, \alpha_{AB'}$(c/s)	$\alpha_{BB'} \pm \delta\, \alpha_{BB'}$(c/s)	$\alpha_{ABB'} \pm \delta\, \alpha_{ABB'}$(c/s)
Up, Up	4000±1000	4000±1000	0±0	0±0
Up, Down	2200±800	2300±800	0±0	0±0
Down, Up	2200±800	2300±800	0±0	0±0
Down, Down	1000±300	1100±400	0±0	0±0

Anticoincidence parameters from three fold Mach Zehnder experiment. Values calculated using equation (3). Uncertainties calculated using equation (4).

Coincidence rates correspond to very high anticoincidence parameters between A and B and A and B'. We did not expect to record triple coincidences, nor coincidences between B and B'. Like the previous three-fold experiment, we saw, as expected, the value for our anticoincidence parameters decrease as the coincidence windows increased. This confirms that the coincidence window does not affect the simultaneous nature of the down converted photons.



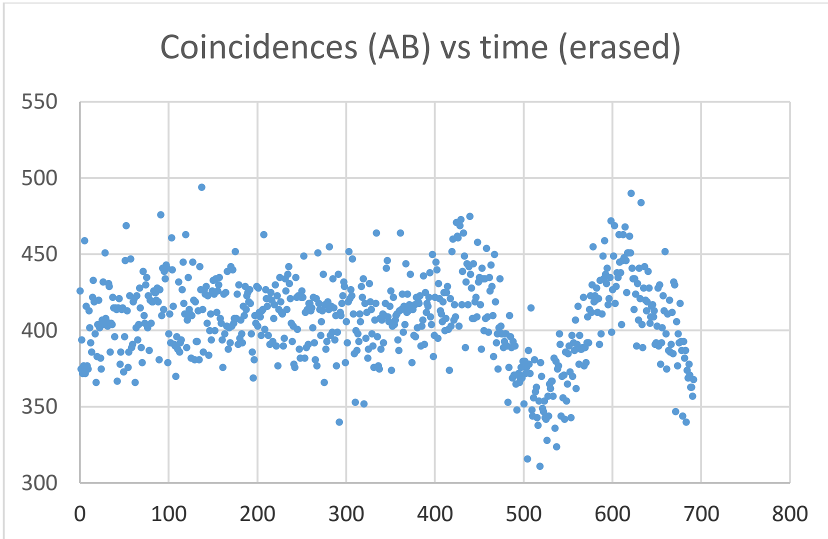
Graph interference pattern between detectors A and B'. No half wave plate or polarizing eraser inserted.



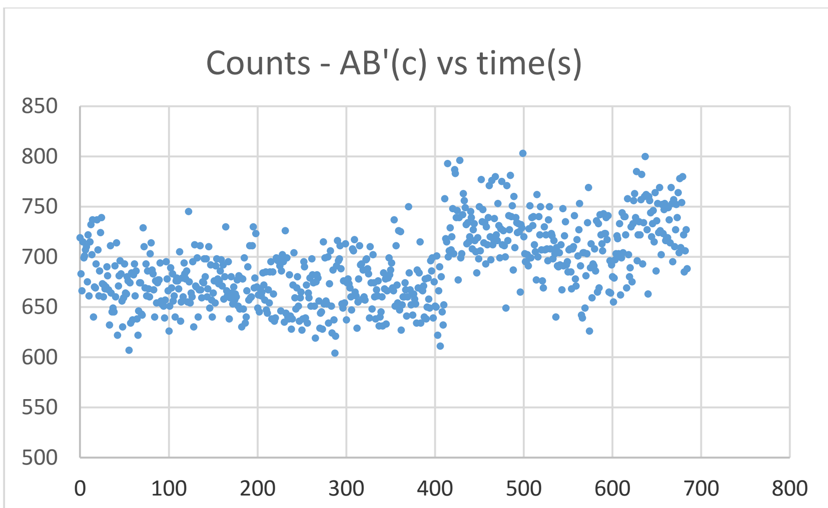
Graph interference pattern between detectors A and B'. No half wave plate or polarizing eraser inserted.

With no half wave plate in the Mach Zehnder interferometer, we observed the expected interference patterns for coincidences between both combinations of detectors.

We inserted our half wave plate, and then another polarizer between our interferometer output and detector B. Ther photons are polarized at an angle of eighty-five degrees by the last polarizer, which acts to “un-tag” the majority of photons, as opposed to our theoretical eraser, which polarized forty-five degrees.



Graph of coincidences between detectors A and B as a function of time.



Graph of coincidences between detectors A and B as a function of time.

An interference pattern was successfully restored, but with less overall coincidences than what we observed without this eraser. These graphs reflect exactly what we have expected for our eraser method. We can ignore the initial flat line and focus on the period where we see the height of the coincidences. The quantum eraser was put in front of B, so we are able to see the interference more vividly than that of AB, meaning the photons are repolarized to create the pattern.

CONCLUSION

In these single photon experiments we were able to successfully disprove the theory of classical mechanics of light, as well as prove the particle nature of light as proposed through quantum mechanics. All anticoincidence parameter values reflected our expectations for each experiment, supporting quantum theory. Interference patterns (or lack thereof) displayed by our graphs further supported quantum mechanics. Error values tended to fluctuate due to the fact that our time intervals were inconsistent from trial to trial. All error, however, did capture all values we had predicted as well.

Works Cited

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2. Fowler, Michael. "Modern Physics." *Galileo*. N.p., n.d. Web. 22 Apr. 2016.
3. The Editors of Encyclopædia Britannica. "Photoelectric Effect." *Encyclopedia Britannica Online*. Encyclopedia Britannica, n.d. Web. 22 Apr. 2016.

APPENDIX

Raw data of HeNe counts

Directions	N_A	N_B	N_{AB}	$R_A \pm \delta R_A$	$R_B \pm \delta R_B$	$R_{AB} \pm \delta R_{AB}$
Up, Up	117114	169714	6	3903.80±11.4	5657.13±13.7	.20±.081
Down, Down	117694	170719	24	3923.13±11.6	5690.63±13.7	.80±.11
Down, Up	199144	173178	11	6638.13±11.4	5772.60±13.8	.37±.11
Up, Down	120687	173386	11	4022.9±11.5	5779.53±13.8	.37±.16

Raw data of Diode BBO 2 fold experiments

Configuration	$R_A \pm \delta R_A$	$R_B \pm \delta R_B$	$R_{AB} \pm \delta R_{AB}$	$\alpha \pm \delta \alpha$
Up, Up(A)	278590.1±166.91	204129.0±142.87	49945.2±70.67	96.94±4.85
Up, Up(B)	278679.0±166.94	204228.0±142.91	50080.2±70.77	97.12±4.86

Raw data for Coincidence window from the HeNe experiment (used throughout)

Configuration	τ_C(ns)	$\delta\tau_C$(ns)
Up, Up	9	4
Up, Down	16	3
Down, Up	16	4
Down, Down	36	10

Raw data for 3 fold diode experiment

Configuration	RA	RB	RB'	RAB'	RAB	RBB'	RABB'
UU	14491.46	7442.08	3312.3	1927.17	6301.97	0	0
UD	14473.56	7449.56	3307.33	1972.71	6446.5	0	0
DU	14454.99	7435.99	3302.65	2015.56	6540.29	0	0
DD	14463.54	7429.6	3298.2	2113.54	6852.77	0	0

Eraser Error

	δR_A	δR_B	$\delta R_{B'}$	$\delta RA_{B'}$	δR_{AB}	$\delta R_{BB'}$	$\delta R_{ABB'}$
UU	12.038048	8.6267491	5.7552585	4.38995444	7.9384948	0	0
UD	12.030611	8.6310834	5.7509391	4.44152001	8.0290099	0	0
DU	12.022891	8.6232187	5.7468687	4.48949886	8.0872060	0	0
DD	12.026446	8.6195128	5.7429957	4.59732531	8.2781459	0	0

Raw data 3 fold BBO MZ interferometer

Configuration	R_A	R_B	$R_{B'}$	R_{AB}	$R_{AB'}$	$R_{ABB'}$
Up, Up	23057	5859	2699	4682	2250	0
Up, Down	23049	5898	2705	4747	2310	0
Down, Up	23059	5911	2719	4855	2348	0
Down, Down	23036	5922	2721	5030	2443	0

Error for configurations found through equation (3)

Configuration	δR_A	δR_B	$\delta R_{B'}$	δR_{AB}	$\delta R_{AB'}$	$\delta R_{ABB'}$
Up, Up	15.18453	7.65441	5.19519	6.8425142	4.74341649	0
Up, Down	15.1819	7.679844	5.200961	6.8898476	4.80624594	0
Down, Up	15.18519	7.688303	5.214403	6.967783	4.84561658	0
Down, Down	15.17762	7.695453	5.216321	7.0922493	4.94267134	0

Anticoincidence parameter MZ:

Configuration	α_{AB}	$\alpha_{AB'}$	$\alpha_{ABB'}$
Up, Up	3.81E+03	3.97E+03	0
Up, Down	2.18E+03	2.32E+03	0
Down, Up	2.23E+03	2.34E+03	0
Down, Down	1.02E+03	1.08E+03	0

Error:

Configuration	$\delta\ \alpha_{AB}$	$\delta\ \alpha_{AB'}$	$\delta\ \alpha_{ABB'}$
Up, Up	1.20E+03	1.25E+03	0
Up, Down	7.72E+02	8.19E+02	0
Down, Up	7.87E+02	8.28E+02	0
Down, Down	3.41E+02	3.61E+02	0