Observing the Quantum Nature of Light Through a β-Barium Borate Crystal

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In this lab we attempted to create and observe pairs of correlated photons in order to investigate the particle-like nature of light. A β-Barium borate (BBO) crystal was pumped with ultraviolet light in order to create pairs of correlated down converted photons. We then observed these pairs of photons using a photon counting module. By collecting data over several time intervals and utilizing counting statistics we were able to determine whether or not the BBO crystal was truly producing correlated down converted photons. However, the experiment yielded inconclusive results. We were not able to detect a statistically significant quantity of coincidences, and therefore we were unable to determine if our BBO crystal was down converting photons. However we were successful in setting up our photon counting module, and detecting coincidences.

I. INTRODUCTION

β-Barium borate (BBO) is a versatile nonlinear crystal, suitable for use in harmonic generation operations, optical parametric oscillators, and in electro-optical applications from the near infrared to the deep ultraviolet. It is a part of the family of χ^2 nonlinear crystals, featuring large nonlinear coefficients, high thresholds for laser damage, and low thermo-optic coefficients. For our purposes, it will serve as a down-conversion crystal that converts a photon of ultraviolet light into two photons of lower frequency while conserving energy and momentum.

In this experiment, we are using UV light and a BBO down-conversion crystal to measure two correlated photons of visible light in order to demonstrate the particle-like nature of light. Observing correlated photons hitting our detectors would demonstrate the particle nature of light, as it would show that energy is delivered to the detectors in small, discrete packets that hit the detector at a definite time. We use the BBO crystal cut at 29° so that the twin photons emerge with approximately equal energies at 3° from the initial direction. When light particles pass through our χ^2 crystal, the photons will sometimes convert into the two down-converted crystals. These pairs of down converted photons are emitted at an angle of 3 degrees from the central beam, creating a cone of down converted photons as can be seen in Figure 1. The two down-converted photons should hit our two sensors (which are placed at 3° from the center), simultaneously. Using a photon counting module and coincidence detector, we can gather data about the frequency with which coincidences occur. More coincidences should occur when using the crystal than when shining randomly produced light from an incandescent light bulb onto our sensors, since the two down-converted photons should hit the sensors at the same time.

Our experiment is modeled after a paper by Brett J. Pearson and David P. Jackson at Dickinson College: *A Hands-on Introduction to Single Photons and Quantum Mechanics for Undergraduates*. In their experiment, they determined that the two light sources are heavily correlated. Our experiment yielded interesting results which were not consistent with this conclusion.

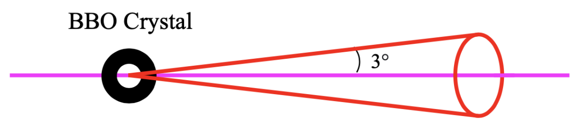

FIG. 1. Path of photons through BBO crystal cut at 29°. Pink line is representative of the initial photon path, and the red lines are representative of the path of down-converted photons. The red circle outlines the possible final locations of our photons.

II. THEORY

Occasionally, when a photon hits a BBO crystal, the crystal will absorb the incident photon and re-emit two photons simultaneously. This process is called spontaneous parametric down conversion. In spontaneous down conversion, both energy and momentum are conserved. Our BBO crystal produces two photons of equal energy, and therefore of equal wavelength which will be half of the incident light. This is because:

$$E_{photon} = \frac{hc}{\lambda} \tag{1}$$

So in order for energy to be conserved:

$$E_{2photons} = 2(\frac{hc}{2\lambda}) \tag{2}$$

Since momentum must be concerned, and each photon in a pair has equal energy, the two photons will be emitted exactly opposite each other, making the same angle from the central beam. Our BBO crystal cut at 29° emits these pairs of photons at an angle of 3° from the direction of the initial photon. Since the down converted photons are emitted simultaneously, if we position photon detectors at 3° from the central beam, at the same distance from the BBO crystal, down converted photons will hit our detectors simultaneously. Utilizing a photon counting module, we can determine when a pair of photons hits our detectors at the same time, i.e. are coincident.

Single photon and coincidence detection between photons ultimately relies on counting statistics. In order to be sure that we have created pairs of down converted photons, we must see more photon coincidences than we would see from a source of random, non-correlated light.

First, we must determine the width of our time frame for determining how close together photons have to hit the sensors to be considered a coincidence. Our sensors convert an incoming "particle" to an electronic pulse with a pulse width, τ_c. For the counting circuit to register a coincidence, some portion of the pulse from the first detector must overlap with some portion of the pulse from the second detector. For two sensors hit with random non-correlated light, all coincidence counts are purely accidental. Let us call those coincidences R_{acc}. If the average count rates for the two detectors are given as R_1 and R_2, the expected rate, in nanoseconds, of accidental coincidences is given by:

$$R_{caccidental} = \tau_c R_1 R_2 \tag{3}$$

Since for a coincidence to register we must have photons incident with both detectors within τ_c seconds of each other. Rearranging, we find:

$$\tau_c = \frac{R_c}{R_1 R_2} \tag{4}$$

The Dickinson College paper demonstrated a metric to calculate how often coincidences are occurring relative to the amount of photons emitted. This metric is α, the "anti correlation parameter, where:

$$\alpha = \frac{P_c}{P_1 P_2} \tag{5}$$

and provides a helpful way to quantify how correlated the light hitting the two detectors is. In equation (5) P_c gives the probability of measuring a given coincidence count, P_1 is the probability of measuring a given count in detector 1, and P_2 is the probability of measuring a given count in detector 2. The probability of measuring a given number of event in a time interval T is: $\frac{N}{N_p}$ where N is the number of events observed, and N_p is the number of possible events. In our case $N_p = T/\tau_c$ since the largest possible number of coincidences observed is seeing a coincidence every τ_c seconds. So, since $N_c = R_c$, $N_1 = R_1$, and $N_2 = R_2$: we have:

$$\alpha = \frac{\frac{N_c}{N_p}}{\frac{N_1}{N_p}\frac{N_2}{N_p}} = \frac{N_c}{N_1 N_2} N_p = \frac{T R_c}{\tau_c R_1 R_2} \tag{6}$$

Where R_c is the number of coincidences and R_1 and R_2 is the count rate for each detector. If α is found to be greater than 1, then we are seeing more coincidences than we would expect from random light, and therefore we know the BBO crystal is creating down converted crystals which hit our detectors simultaneously. If α is found to be equal to 1 then we are seeing exactly as many coincidences as would be expected from a source of random light, and we are not seeing down converted photons. Thus, α is known as our anticorrelation parameter; a value of $\alpha > 1$ is an indicator of the quantum nature of light, while a value of $\alpha = 1$ demonstrates that correlated photons are not being produced, and supports the wave model of light.

III. EXPERIMENTAL METHODS

Our goal was to recreate the process used by Dickinson College to determine if photons are being down-converted through the crystal. Their setup utilized the same materials which we used.

Our setup utilizes a 405 nm 150 mW laser. The light from this laser is reflected first by a mirror and then by a polarizing beam splitter which polarizes the light to be in the plane of the table. The light then passes through a half-wave plate. The polarizer is necessary as the BBO crystal creates the most down converted photons at a specific polarization angle. After passing through the polarizer, the 405 nm light then passes through the BBO crystal. Two irises were used to help align the setup, as can be seen in Figure 2 Only about .00000001% of our 405 nm photons will be down converted into two 810 nm photons. However, this low percentage is inconsequential to the $3.066 * 10^{17}$ photons being emitted per second by our 150 mW laser. The beam which passes straight through the BBO crystal is stopped by a beam block to prevent extraneous light from bouncing around.

The two 805 nm beams of light (which are part of the cone of photons in Figure 1) created by the spontaneous down conversion will be 3 degrees to either side of the central 405 nm beam (See Figure 2.)

The two beams are aligned to hit detectors which first filter the incoming light, and then transfer it through fiber optic cables into our photon counting module (PCM). Our PCM was produced by Perkin-Elmer and is the SPCM-AQ4C model. It takes fiber optic inputs from four channels, and converts these to electrical signals which have four output channels. The line filters are designed to only let through light with a wavelength of approximately 800 nm which helps greatly to remove extraneous light. Our PCM then sends electrical signals to a coincidence counter which can detect if the photons hit the our detectors at the same time.Our coincidence counter is a programmable gate array version of a time-to-amplitude-converter. The coincidence detector then outputs data which we use the labview program Coincidence.vi to analyze. This program can be found here: http://people.whitman.edu/ beckmk/QM/labview/labview.html. The program showed us the number of photons in a particular interval along with the coincidences based on the electrical signals inputted to the computer.

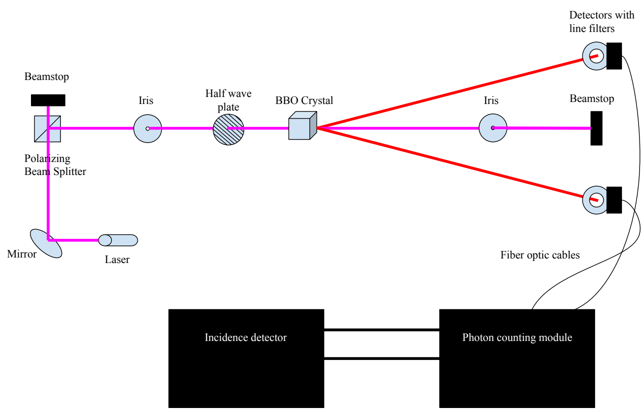

FIG. 2. Diagram of experimental setup for measuring correlated photons. Laser light, after being reflected and polarized, is split into two photons of lower frequency, which then hit the detectors and get recorded by the counting module.

	Trial 1	Trial 2	Trial 3	
R_1	710000	32500	60500	
R_2	670000	23000	51200	
R_c	21000	32	140	avg:
τ_c	44.14	42.81	45.20	44.05 $\pm$1.20

TABLE I. Counts from shining an incandescent light bulb onto our sensors. R_1 = Counts from detector 1. R_2 = Counts from detector 2. R_C = Number of Coincidences. τ_c values are calculated using data above.

	Our τ_c Value	τ_c Value from Paper
DD	44.05 ± 1.20	45.51
DU	25.38 ± 2.19	18.10
UD	18.98 ± 1.46	12.31
UU	12.33 ± 0.68	8.12

TABLE II. τ_c values calculated from the four settings on the coincidence calculator, contrasted with those listed in the aforementioned Dickinson paper.

In order to determine if we are detecting coincidences from the BBO crystal, the room where the set up resides must be as dark as possible. This must be the case for two reasons. First, too much light will destroy the photon counting module, and second, extraneous light will make it difficult to determine whether or not we are seeing pairs of photons generated through spontaneous down conversion because because we may be seeing coincidences between photons of ambient room light.

IV. RESULTS AND DISCUSSION

A. Measuring τ_c

As can be seen in equation (6), in order to know how correlated our two sources of light are, we must know the coincidence interval τ_c. To calculate our τ_c, we replaced our laser with an incandescent light bulb which emits photons randomly. In a dark room, we turned on our incandescent light bulb (keeping our laser off) in the location of our BBO Crystal. We placed attenuators in front of our sensors as to ensure that a smaller amount of photons hit our sensors since our sensors are quite sensitive to light. Then, we took counts on both of our sensors and also counted the coincidences. There were two switches on our electronic coincidence detector which altered the coincidence interval τ_c, each of these switches could either be up (U) or down (D). For each permutation, (UU UD DU and DD), we used equation (4) to calculate τ_c, and found that DD resulted in the longest coincidence interval. For our further experimentation we utilized the longest coincidence interval as it perfectly matched the coincidence interval used in the Dickinson experiment. Although we could have utilized any of the coincidence intervals, we decided to use one similar to what was used in the Dickinson experiment as this allowed us to more easily compare results. As can be seen in TABLE I, we obtained that τ_c had a value of approximately 44 ns for the configuration DD.

B. Measuring Correlated Photons

After determining τ_c we collected coincidence data in 2 trials. In our first trial we aligned the detectors at 3° from the central beam and maximized our counts in each of the detectors by adjusting each detector and the BBO crystal. We then collected coincidence data over 125 seconds to calculate alpha. In our second trial moved our detectors to 2.4°, readjusted the sensors and BBO crystal to maximize photon counts hitting each detector, and then recorded photon coincidence data for 180 seconds in order to determine alpha.

In our first trial, with our detectors positioned 3° from our central beam, we found α to be equal to 1.19 after recording coincidence data for 125 seconds in 5 second intervals, as can be seen in TABLE II. We got this result by first calculating α for each second of coincidence data, and then averaging our results.

In our first trial we saw a relatively high number of photons hitting each detector, with around 25,000 photons hitting detector 1, and around 17,000 hitting detector 2. The fact that we did not see roughly equal counts hitting each detector suggests that our setup was not properly aligned, however, after an enormous amount of fidgeting with each aspect of the setup we were unable to get equal counts on each detector. These counts were the maximal number of photons we were able to get to hit each detector. Tiny adjustments in each detector would result in extreme decreases in the number of photons hitting that

Interval	R1	R2	RC	α	
1	26497	14998	2	.57	
2	27357	15664	3	.79	
3	27089	15758	7	1.86	
...	...	...	...	...	
24	26897	15354	3	.82	
25	26600	15330	0	0	Avg: 1.23 $\pm$.58

TABLE III. Counts from shining ultraviolet light through the BBO crystal. R1 = Counts from detector 1. R2 = Counts from detector 2. RC = Number of Coincidences. α = calculated values from the table. Full data below in TABLE III.

detector, suggesting that we were seeing light that was in some way influenced by the BBO crystal. However our value for α was 1.19, as can be seen in TABLE II. This α value is extremely close to 1; for reference, in the experiment conducted at Dickinson College, the lowest α value observed was 18. The α value we obtained of 1.19 suggests that we did not observe a statistically significant number of down converted photons.

In order to determine if we were seeing randomly scattered light from our BBO crystal, we did a seconds trial where we positioned our detectors at 2.4° from the central beam. We hypothesized that the light scattered from the BBO crystal would be more likely to scatter at smaller angles from the central beam, and so we expected that our counts in each detector should increase from the previous trial, while our α should remain near 1, because we are observing random light.

In our second trial we found α to be 1.48, after averaging data from 180 seconds. Our total counts in this trial were much lower than in our first, so we averaged data over a longer time period. We recorded data in 3 60 second intervals, and then averaged our results.

After positioning our detectors at 2.4° from the central beam, and realigning them to maximize the counts hitting each detector, the counts we found for each detector were far lower than in our first trial. However for our second trial, α was still quite close to 1, with a value of 1.48 as can be sen in TABLE IV . This data suggests that the BBO crystal is not randomly scattering light from laser, and is scattering light at the quite specific angle of 3°. However, our data also suggests that the light hitting the detectors at 3° is not down converted, since we obtained an α approximately equal to 1 in our first trial. Our results suggest that the BBO crystal we are using is not down-converting our photons, and rather, we are observing 405 nm light that is being scattered at 3° and is passing through our line filters.

This could possibly be due to water vapor turning the beta-barium-borate crystal into its hydrated form, gamma-barium-borate, which does not have the same non-linear properties as BBO, and therefore would not produce down converted photons. This may be the case since the crystal has been likely exposed to water vapor over multiple years. It is quite peculiar that the light being scattered by the crystal is scattered at such a specific angle of 3°. However, we are not well versed enough in the phenomenon of refraction, or the molecular structure of BBO to make a plausible hypothesis on why this could be.

In the future, we could test this by placing our BBO crystal in a setup which is known to produce desirable results. If our crystal produces results we are looking for, then we should keep running tests, perhaps inserting quartz into the pathway since other experiments (specifically the down conversion setup at Harvey Mudd College) contained quartz. If the crystal is still non-functional, then the next step would be to obtain a new crystal.

V. CONCLUSION

In this experiment we were successful in setting up labview, configuring and aligning our setup, as well as determining τ_c. We were not successful in determining the quantum mechanical nature of light by observing down converted photons. Although our anticorrelation parameter α was found to be greater than 1, as predicted by the photon model, it was orders of magnitude smaller than what was produced by Pearson Jackson at Dickinson College. Our α of 1.19 is likely greater than 1 only because of random chance, and does not demonstrate that down converted photons were produced by the BBO crystal. However, we observed a strange phenomenon of photons being refracted by the BBO crystal without being down-converted, as shown by our low coincidence count. This yielded inconclusive results on the particle nature of light. Possible extensions of our work could include investigating the sources of error in our experiment, such as deficiencies in the BBO crystal, in order to maximize α. If that can be accomplished, this experiment would prove to be a useful educational tool in demonstrating the quantum nature of light.

VI. ACKNOWLEDGEMENTS

Thanks to Gabriel Konar-Steenberg, Janice Hudgings, and Dwight Whitaker for providing assistance working in the lab. Big thanks to B.J. Haddad for letting us take a look at a down conversion setup constructed at Harvey-Mudd College.

VII. EXTRA TABLES

Interval	R1	R2	RC	α	
1	26497	14998	2	.57	
2	27357	15664	3	.79	
3	27089	15758	7	1.86	
4	27253	15475	7	1.88	
5	27033	15707	6	1.60	
6	27032	15711	3	.80	
7	27142	15511	4	.57	
8	26819	15289	6	1.66	
9	26856	15457	5	1.37	
10	26943	15554	6	1.63	
11	26957	15302	7	1.93	
12	27297	15699	8	2.12	
13	27042	15219	6	1.65	
14	27020	15371	2	.55	
15	27139	15386	5	1.36	
16	26661	15191	5	1.40	
17	26614	15162	3	.84	
18	27025	15197	7	1.93	
19	26780	15345	5	1.38	
20	26751	15203	4	1.12	
21	26750	15507	5	1.37	
22	26784	15056	2	1.56	
23	26954	15276	0	0	
24	26897	15354	3	.82	
25	26600	15330	0	0	Avg: 1.23 ±.58

TABLE IV. Counts from shining 405 nm light through the BBO crystal with detectors positioned at 3° from the central beam. Coincidence data for each trial was recorded over a 5 second interval. R_1 = Number of photons which hit detector 1 during each interval, R_2 = Number of photons which hit detector 2 during each interval, and R_C = Number of coincidences during each interval. α was calculated for each trial using equation (6) and then the 25 values for α were averaged.

Trial	1	2	3	α
R1	161561	161693	161984	1.633548319
R2	206676	206032	205963	1.227987459
RC	40	30	39	1.594049681
				Avg: 1.485195153

TABLE V. Counts from shining 405 nm light through the BBO crystal with detectors positioned at 2.4° from the central beam. Coincidence data for each trial was recorded over a 60 second interval. R_1 = Number of photons which hit detector 1 during each interval, R_2 = Number of photons which hit detector 2 during each interval, and R_C = Number of coincidences during each interval. α was calculated for each trial using equation (6) and then the three values for α were averaged.

[1] Pearson, Brett J., and David P. Jackson. "A Hands-on Introduction to Single Photons and Quantum Mechanics for[...] Undergraduates." *American Journal of Physics*, vol. 78, no. 5, 2010, pp. 471–484., https://doi.org/10.1119/1.3354986.