Down-Conversion and Photon Counting

Tristan Perry, Jaden Miller[1]

[1]*Physics Department, Appalachian State University, John E. Thomas Hall, 287 Rivers St, Boone, NC 28608*

Abstract. A setup and alignment of, and trials done with a system using an argon laser, BBO crystal, single photon counting detectors, and pulse counters provided the ability to detect and count down-converted photons. Count data was analyzed and graphed to present a notably higher photon count at the expected projection position, when compared to the same trial done without the birefringent BBO crystal in place. Setup and alignment procedure is detailed, and potential modifications and future uses are outlined.

I. Introduction

Photons incident on a non-linear crystal, such as a β-Barium-Borate (BBO) crystal, split into two photons of energy summing to that of the original photon. This process was first studied in 1970 by David C. Burnham and Donald L. Weinberg of NASA[1]. Studies involving quantum behavior such as entanglement often rely on successful down-conversion and counting of photons, and the 2022 Nobel Prize was won by scientists researching entanglement[2].

Down-conversion, in simplified terms, adheres to conservation of energy and momentum (see **Figure 1**) so that

$$E = hf = \frac{hc}{\lambda} \qquad \text{(Eq 1)}$$

$$E_1 = E_2 = \frac{E}{2} = \frac{hf}{2} = \frac{hc}{2\lambda} \qquad \text{(Eq 2)}$$

where E is the energy associated with an original photon before down-conversion, which splits into the photon pair, E_1 & E_2. Note that since each of the new photons share equally half the energy of the original, wavelength λ doubles. This process is referred to as degenerate spontaneous parametric down-conversion. The use of a birefringent crystal, such as the BBO, takes advantage of the physical property of the crystal, specifically that of having two distinct indices of refraction. These photon pairs can be detected individually through the use of Single Photon Detectors.

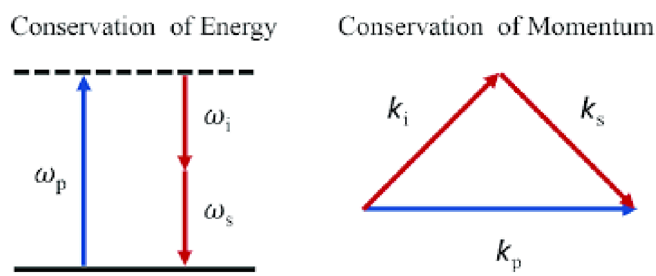

FIG 1. Simple diagram conveying conservation of energy and momentum [Phase matching conditions arising from energy and momentum conservation... | Download Scientific Diagram (researchgate.net)]

Setting up the alignment of a system to detect these photons requires an understanding of the behavior of photon down-conversion and relative geometry. Detectors have specifications depending on the manufacturer that determine an ideal wavelength range for maximum probability of detection, meaning that the wavelength of photons from the source laser and detector specs should match up somewhat to produce an effective counting experiment.

FIG 2. EKSMA BBO crystals for use in optical experiments

A proper setup for both achieving down-conversion and detecting those photons is a challenge in itself. Ideally, the same setup used to detect down-conversion can be run without the BBO crystal in place, and if the detectors are aligned properly, the count of photons at a down-converted wavelength should be somewhat higher with the crystal. An oscilloscope can be used to measure pulses sent as an output from the detectors, and pulse counters can be used to get a number count of photons detected. This alone does not assure that detection of down-conversion is occurring, but is a valid method to test the possibility of it.

The dispersal of down-converted photons exiting the BBO crystal forms a cone with a central axis along the path of the original beam (**Figure 3**). Two points on equal opposite sides of the cone are the most likely position at which to detect the photons. The beam incident on the BBO crystal is rotated and attenuated to horizontal alignment with the use of a wave plate and polarizer. This ensures, due to the necessary vertical alignment of the BBO crystal, that conditions are met for proper down-conversion and dispersal.

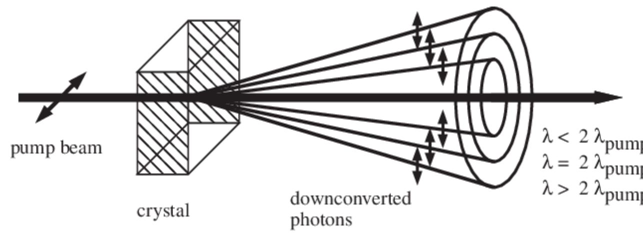

FIG 3: Type 1 downconversion dispersal pattern [Type I spontaneous parametric downconversion. Photons from a pump beam... | Download Scientific Diagram (researchgate.net)]().

Once the proper setup is achieved, experimentation can begin on counting trials both with and without the BBO crystal in place. As previously mentioned, a higher photon count with the crystal indicated that some of the original beam is indeed being refracted at the angle which the detectors are set to receive. This also allows for the identification of noise in the signal from the detectors, as background readings will be present without the crystal, and can be dealt with accordingly in analysis.

Uncertainties relevant to data collection, when performing a counting experiment, are calculated using weighted averages. The uncertainties of the equipment must also be taken into account when considering wavelength- the specifications of the laser used (Stellar Pro ML/150 Argon Laser, or SP for brevity) give an uncertainty of $\pm 1\%$ in wavelength output.

II.Methods

Setup and alignment procedure for this experiment was modeled after one provided by Dr. Kiko Galvez[3] in his document *Alpha immersion – hands-on Activities.* The diagram shown in **Figure 4** outlines the basic layout used.

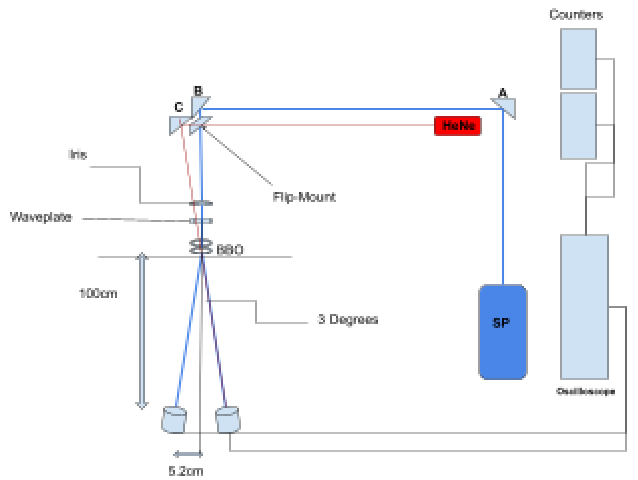

FIG 4: Setup diagram for alignment and counting

Two lasers are needed for the setup, referred to as the HeNe (UniPhase Helium Neon Gas Laser 1508P-0) in red and the SP shown in blue. The position of the mirrors in the diagram are relative to the workspace used, in this setup a 45° mirror (**A**) reflects the SP laser at 90°, and repeated with a second mirror at another 45° (**B**). This directs the SP beam along an optical rail on which the BBO crystal will eventually be mounted. The second HeNe laser is used to reflect at 45° from a flip-mounted laser to match the trajectory of the SP. The flip mount allows the lasers to be interchangeably used- the HeNe with the mirror flipped into place, and the SP with the mirror flipped out of the way. Once both lasers are aligned to travel along the same path, two irises can be used to calibrate the path of the beams so that they travel straight. This is done through the careful manipulation of the X and Y adjustment screws on the mounts of the mirrors until both beams can pass through the center of both narrowed irises. The first iris can be placed as marked in the above diagram, and the position of the second iris should be marked as this will be the location of the BBO crystal after alignment. Note that both lasers must be aligned to proper height and leveled so that the beams they produce are equivalent in X and Y projection.

Now that both lasers are properly aligned, the use of pythagorean geometry can be utilized for proper detector placement. The BBO crystal should be placed where the second alignment iris was marked, and 100cm from this location, a simple index card can be mounted and marked in the center where either beam will hit at the end of the rail. With the SP laser powered off, the flip mount flipped out of the path of the HeNe laser, a third mirror (**C**) is placed to the side of the flip mounted laser such that it catches and reflects the beam of the HeNe. Position and alignment of this mirror will need adjusting until the HeNe both passes through the center of the BBO crystal, and makes a 3° angle from the central laser path. A mark should be made where the laser is incident on the index card 100cm from the crystal. The distance from the central mark to the new mark from the HeNe should measure as follows:

$$tan(\theta) = \frac{O}{A} \qquad \text{(Eq 3)}$$

$$O = (100cm)tan(3^{o}) \qquad \text{(Eg 4)}$$

Where O = 5.2cm, and A = 100cm. The laser alignment method allows for a more accurate "check" of these measurements which would otherwise deal with visual uncertainty of a meter stick and protractor, where $\boldsymbol{\delta}A$ and $\boldsymbol{\delta}O$ would be $\pm\ 0.1cm$ and $\boldsymbol{\delta}\theta\ \pm\ 0.5°$. Each detector should be positioned to read photons at this distance on either side of the central mark.

FIG 5: Setup for photon counting

FIG 6: Oscilloscope and TeachSpin Pulse Counters

Once detector position is found, Single Photon detectors should be mounted at the same height as the HeNe and SP beam outputs. IDQ ID-100 detectors were used for the original setup. These detectors use an output cable and module that sends a 3.3V pulse signal out upon the detection of a photon. The output can be linked to an oscilloscope, such as the Tektronix TDS 2024C model shown in the setup image (**Figure 6**). Before running the setup, note that as with many photodetectors, the models used are very sensitive to overload, and thus ND filters should be used to prevent overload, and accurate photon sensing when using the SP or any laser should be performed in a dark room. Between the iris and BBO crystal, a half-wave plate is placed, oriented horizontally, to match the horizontal orientation of the BBO crystal. This rotates incoming light to pass through the crystal optimally. The crystal used for this setup was a EKSMA Optics BBO 6x6x1 th29.2 ph0, designed to accept this particular orientation of light, and designed to project downconverted photons at the previously mentioned 3° in a cone orthogonal to the crystal.

If allowed to run with input from the SP laser only, the setup at this point should read pulses, which can be displayed on the oscilloscope, and counted by TeachSpin pulse counters. Note the purpose of the HeNe laser is simply for alignment procedures, and is not required for photon counting. It is imperative to always practice safe laser use[4].

Different methods can be used to verify the wavelength of the photons being detected- this helps to identify if the detectors are receiving down-converted photons, or otherwise. Type-1 down-conversion, which this setup is intended to produce, should disperse pairs of photons that have half the energy, and twice the wavelength of the original beam from the SP laser. For this equipment:

$$\lambda_{DC} = 2(514.5 \text{ +/- } 1\%)\text{nm} = (1029 \text{ +/- } 2\%)\text{nm} \qquad \text{(Eq 5)}$$

where λ_{DC} is the expected wavelength of down-converted photons, given the output wavelength of the SP laser at (514.5 +/- 1%) nm. Attempts were made to utilize a SPCM (Single Photon Counting Module) program and hardware card for a PC designed to interface with the detectors, specifically to record coincidences- which occur when both photons of a down-converted pair are detected at the same time in each detector. The PC could not properly interface with the hardware unfortunately, and upon moving the hardware to a new unit, ultimately its use was abandoned. With the aid of Dr. Brooke Hester and Dr. Patricia Allen of the Appalachian State Physics department, along with guidance from Dr. Kiko Galvez of Colgate University, further attempts at troubleshooting the program and hardware, and considering alternative options were undergone. A Red Dog board along with a written code for counting single photons as well as coincidences was sent to be used as an alternative and although eventually is likely to be useful, could not operate properly at the time of this report. Thorough realignment attempts were made and ultimately it was determined that for the time being, a more simple method could prove useful in determining the possibility of detecting down-converted photons.

A simple counting trial was conducted, both with and without the BBO crystal in the mount. This served two purposes- firstly to identify the signal to noise ratio, and secondly to determine if a higher photon count with the crystal in the mount could indicate that the detectors were detecting down-converted photons which were being projected at the location expected. In theory, without the crystal, less photons are projected away from the original beam of the SP laser.

III.Results & Discussion

Two counting trials were conducted, with data collected from the TeachSpin pulse counters with and without the BBO crystal in the mount.

Table 1: First trial of N = 30, analyzed with simple counting uncertainty

Avg. Photon count with BBO	(Photons)
Left	49.9
Right	41.8
δN_{AVG}=√N + 0.01N	$\pm$ 5.8 Photons
Avg. Photon count No BBO	
Left	46.3
Right	39.2
δN_{AVG}=√N + 0.01N	$\pm$ 5.8 Photons

As seen in Table 1, preliminary data collection and analysis was inconclusive for testing the effectiveness in the BBO-detector system, but did present useful information on the background noise present. Realignment of the setup to achieve more even and steady counts eventually led to far higher photon counts, and when analyzed with weighted averages, appeared more useful (Table 2).

Table 2: Data collected (N = 30) after realignment and analyzed using the equations below (Eq 6-Eq9).

Detector	W_{AVG} Photon count with BBO	**δ**W_{AVG}
Left	2318.7	$\pm$8.7
Right	2059.3	$\pm$8.2
Both (Possible pairs)	2138.3	$\pm$6.0
	W_{AVG} Photon count No BBO	
Left	48.7	$\pm$1.3
Right	37.7	$\pm$1.1

$$\sigma_N = \sqrt{N} \qquad \text{(Eq 6)}$$

$$W = \frac{\sum_{i-1}^{n} \omega i N i}{\sum_{i-1}^{n} \omega i} \qquad \text{(Eq 7)}$$

$$\omega i = \frac{1}{\sigma_i^2} \qquad \text{(Eq 8)}$$

$$\sigma_{Wavg} = \frac{1}{\sqrt{\Sigma i W_i}} \qquad \text{(Eq 9)}$$

This trial presents similar numbers in the setup without the BBO crystal as the first, which would be expected, and higher numbers of photons detected with the BBO in place, suggesting that indeed the geometry of the setup was detecting photons at the expected down-conversion angle. This also further decreased the signal-to-noise ratio significantly, as background photons are still detected at rates shown without the BBO crystal when the crystal is in place.

Graphed below (**Figure 7**) are the results from the second trial, showing a significantly higher amount of photons counted for counts collected with the BBO crystal in place.

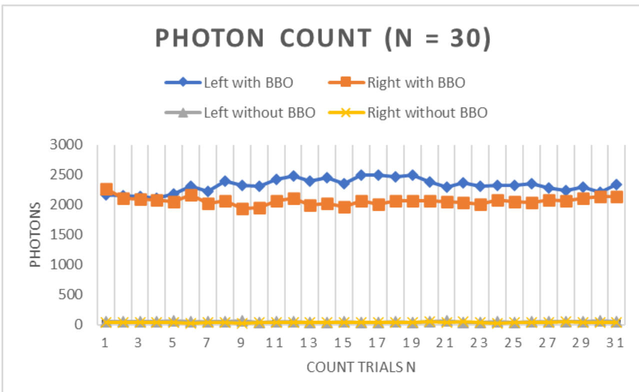

FIG 7: Trial of data graphed, summarized previously in Table 2.

At this time, only the position of projected photons, and not wavelength, has been confirmed. Upon further review of the specifications of the equipment, mainly the detectors and SP laser used, the setup may have a relatively low probability of detecting down-converted photons. This is in part due to the process of down-conversion, in that most of the main laser beam from the SP passes through the BBO crystal without refraction, but photons do have some small probability of splitting into down-converted pairs[1]. As far as the specifications of the equipment, as stated previously the SP laser is set to produce a beam of photons at **λ** = (514.5 +/- 1%) nm, so that down-converted photons are expected to have a wavelength of **λ** = (1029 +/- 2%) nm. The detectors, however, have a specified wavelength detection range (**Figure 8**) in which photons are most likely to be detected.

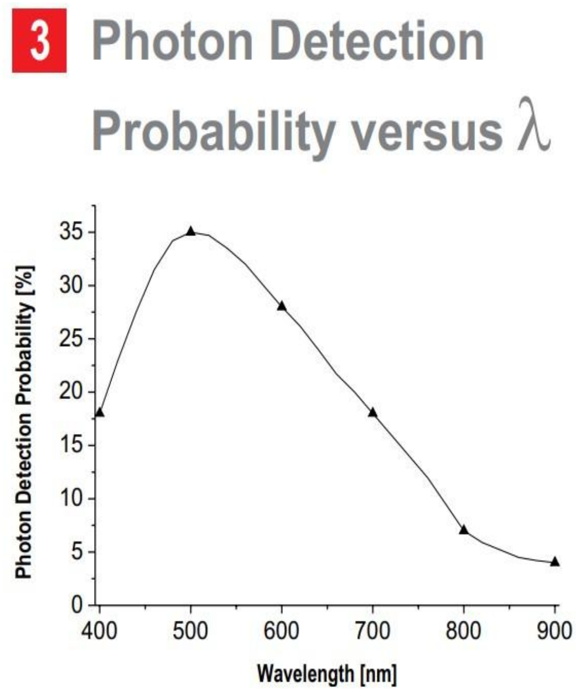

FIG 8: Specified photon detection probability by wavelength of IDQ ID-100 Single Photon Detectors. [ID100 visible photon counting module from ID Quantique]

It can be justifiably assumed that although not zero, the probability of detecting photons of the desired down-converted wavelength is very low[5].

IV. Conclusions and Future Work

The detection of the photons at the location expected after down-conversion from the SP laser passed through a BBO crystal is possible with the setup and equipment used, however improvements can and should be made for future experiments. The probability of detecting pairs of photons at the expected down-converted wavelength is low, and to improve this, it may be useful to use a different set of detectors, such as the IDQ ID230 Infrared Single Photon Detector[6]. This model is designed to detect photons at a range of 900-1700nm (**Figure 9**). This both provides optimized detection based on down-converted photons from the SP laser, and is less likely to detect photons from the original beam.

Specifications

ID230 Infrared Single-Photon Detector		
Wavelength range	900 nm to 1700 nm	
Deadtime	2 µs to 100 µs, in 1 µs steps	
Output pulses	LVTTL, 100 ns width	
Optical coupling	Optical fibre (SMF or MMF62.5)	
Efficiency range (1) calibrated at λ = 1550 nm	10%, 15%, 20%, 25%	
Timing jitter at 25% efficiency level	Maximum 200 ps (150 ps typical)	
Noise performance @ efficiency level (2)	10%	20%
Max. dark count rate	< 80 Hz (as low as < 50 Hz)	< 200 Hz (as low as < 100 Hz)
Dimensions	60 cm x 27 cm x 25 cm	
Weight	30 kg	
Control interface	USB 2.0	
Operating temperature	+10°C to +25°C, max. 60% humidity	
Power supply	90-264 VAC, 127-327 VDC (50-60 Hz) Max current @ 115 VAC: 5.6 A Max. current @ 2.75 VAC: 2.75 A	

FIG 9: IDQ ID230 specifications via product brochure.

Implementing such a new detector unit, as opposed to changing the laser, is ideal. This is due to the safety concerns associated with using a UV laser to produce photons the IDQ ID100 detectors are optimized to detect. Modification or replacement of the SP laser was considered, but would likely be more costly in addition to posing hazards that would need to be addressed with safety equipment and enclosure.

If such modifications were made to the setup, it is possible that further use could enable experiments involving quantum entanglement, as Type-1 down-conversion is known to produce not only pairs of down-converted photons, but those pairs display quantum entanglement[1].

V. APPENDICES

Relative equations:

$$E = hf = \frac{hc}{\lambda} \qquad \text{(Eq 1)}$$

$$E_1 = E_2 = \frac{E}{2} = \frac{hf}{2} = \frac{hc}{2\lambda} \qquad \text{(Eq 2)}$$

$$tan(\theta) = \frac{O}{A} \qquad \text{(Eq 3)}$$

$$O = (100cm)tan(3^o) \qquad \text{(Eg 4)}$$

λ_{DC} = 2(514.5 +/- 1%)nm = (1029 +/- 2%)nm (Eq 5)

$$\sigma_N = \sqrt{N} \qquad \text{(Eq 6)}$$

$$W = \frac{\sum_{i-1}^{n} \omega i N i}{\sum_{i-1}^{n} \omega i} \qquad \text{(Eq 7)}$$

$$\omega i = \frac{1}{\sigma_i^2} \qquad \text{(Eq 8)}$$

$$\sigma_{Wavg} = \frac{1}{\sqrt{\sum i W_i}} \qquad \text{(Eq 9)}$$

REFERENCES

1. Couteau, C. (2018, September 1). *Spontaneous parametric down-conversion*. arXiv.org. Retrieved November 7, 2022, from https://arxiv.org/abs/1809.00127
2. Press release. NobelPrize.org. Nobel Prize Outreach AB 2022. Wed. 7 Dec 2022. <https://www.nobelprize.org/prizes/physics/2022/press-release/>
3. Galvez, K. (2022). *Alpha immersion – hands-on Activities*. Colgate University. Retrieved December 2, 2022, from http://egalvez.colgate.domains/pql/wp-content/uploads/2019/08/Activities19.pdf
4. Mittleman. (n.d.). Laser Lab: Safety and Procedures. Retrieved December 9, 2022, from https://www.brown.edu/research/labs/mittleman/sites/brown.edu.research.labs.mittleman/files/uploads/pre-lab%20lecture.pdf
5. *ID100 visible single-photon detector*. ID Quantique. (2022, November 29). Retrieved December 11, 2022, from https://www.idquantique.com/quantum-sensing/products/id100/
6. *ID230 infrared single-photon detector*. ID Quantique. (2022, November 29). Retrieved December 11, 2022, from https://www.idquantique.com/quantum-sensing/products/id230/

7. Pedrotti, F. L., Pedrotti, L. M., & Pedrotti, L. S. (2007). *Introduction to optics: Frank L. Pedrotti, Leno S. Pedrotti, Leno M. Pedrotti.* Pearson Prentice Hall.
8. ModuLaser. (2013, September 18). *Argon Laser: Stellar Pro ML/150 Argon Laser*. Modu-Laser. Retrieved December 11, 2022, from https://modu-laser.com/argon-laser-products/all-in-one-argon-laser-systems/stellar-pro-ml150
9. Hossieni, H., Fatah, J. M. A., Mohammad, S., & Naby, M. (2018). From Hyperion to photon, a brief survey in the timeline of photon. *Physics Essays*, *31*(3), 246–253. https://doi.org/10.4006/0836-1398-31.3.246
10. Pearson, B. J., & Jackson, D. P. (2010, February 10). *A hands-on introduction to single photons and quantum mechanics for undergraduates*. https://www.aapt.org/. Retrieved November 20, 2022.
11. Dehlinger, D., & Mitchell, M. W. (1970, January 1). *Entangled photon apparatus for the Undergraduate Laboratory*. American Association of Physics Teachers. Retrieved December 2, 2022, from https://aapt.scitation.org/doi/10.1119/1.1498859