Background and References


Students are required to read ref. [1] carefully, and to skim ref. [2] before coming to lab.

The single photon experiment is part of our junior/senior level optics lab, in which four experiments are performed in round-robin fashion. Each lab group of 2 has only 3 hours (one lab session) to work in the quantum optics lab, plus one lab session for in-class data graphing (using IgorPro) and analysis.

What students should know before coming to lab:

- Know what linearly polarized light is (classically).
- Know how the polarization direction can be manipulated, in particular the effects of a $\lambda/2$-plate, of a polarizer, and of a polarizing beam splitter.
- Understand the process of spontaneous parametric down-conversion (SPDC) in an optically non-linear crystal (Beta Barium Borate, or BBO) and its significance for the anti-coincidence experiment.
- Understand the experimental set-up for the anti-coincidence experiment.

Questions students are to investigate in the quantum optics lab, with the experimental set-up as in ref. [1], which is already aligned for them:

1. How is the production of down-converted photons affected by rotating the $\lambda/2$-plate in front of the BBO crystal?
2. How can you use the $\lambda/2$-plate plate in front of the polarizing beam splitter to investigate the polarization of the down-converted photons?
3. What measurements do you need to take to determine whether light is a wave or a particle?
**Introduction/Theory**

Spontaneous Parametric Down-Conversion (SPDC):

Consider our specific single BBO crystal. When horizontally polarized light from a 405 nm Pump Laser is directed through this optically nonlinear crystal, there is a very low probability that within the crystal, an incident pump beam photon will “split” into a pair of “twin” photons of lower energy, in a process called Spontaneously Parametric Down-Conversion (SPDC). Due to the specific cut of the crystal, each of these down-converted beams are approximately three degrees off from the pump beam, and both will have the same linear polarization, namely vertical. Energy and momentum both are conserved in SPDC, so the pair of down-converted (DC) photons must have energies and momenta that combine to equal those of the pump photon. The DC photons will have approximately half of the energy, therefore around twice the wavelength, of the pump photon. This experimental set-up can serve as a single photon source: Since the DC photons are produced in pairs (called signal and idler photon), the detection of an idler photon announces the presence of a signal photon (“heralded” single photon source). Such a single photon source is fundamentally different from any other classical light source, or from a very much dimmed down laser. Although lasers or incandescent bulbs can be attenuated to the point where they emit on average very few photons per time interval, these photons tend to arrive in bunches, and not one at a time. In the anti-coincidence experiment that proves the existence of photons, the fact that a single photon at a time arrives at the beam splitter is crucial.

For this experiment, we will be looking at coincidences between multiple detectors. When a Single Photon Counting Module (SPCM) detects a photon, it emits a pulse to the Coincidence Counting Unit (CCU). A coincidence takes place when the CCU detects pulses from the SPCMs and determines that the pulses were separated by less than a given time interval (8ns in this case).

**Safety Preparation**

Before they are allowed to work with the blue diode laser (405nm, 50 mW, class IIIb), students have to take an online safety course offered by Laurence Livermore National Laboratory. Cal Poly Pomona’s safety officer pointed me to the link. The course is free, anyone can take it.

Students are given the following instructions: “Please click the link to the laser safety course and make up (and remember!) an ID number to log on. The ID number will allow you to log out and resume the training at your convenience.


*Work through the introduction and the first three modules of this laser safety training, and take the quiz after each module. It should take you about 45 minutes total. Once you have mastered the material of all three modules, please sign the safety training sheet before starting to work in the quantum optics lab.*

A copy of the safety training sheet can be found in Appendix 1.
In the lab instructions, the following warnings are repeated:

**WARNING:** Please DO NOT have the SPCMs on when the overhead lights are on. Please DO NOT touch any of the detectors, the laser, the crystal or the mirror. You must wear eye protection at all times when the laser is on. Be very careful not to reach across or otherwise place yourself in the path of the laser. You will also need to remove any jewelry; this includes rings, watches, bracelets and necklaces. The laser light is 405 nm. This is still in our visible range, but it is very close to UV. The laser can cause damage to your skin.

**Experimental Setup**

Fig. 1 shows a schematic of the experimental set-up, which is already assembled and aligned with the exception of the two λ/2-plates.

The light of the pump laser is linearly polarized, and the λ/2-plate (for 405nm) in front of the BBO crystal allows the students to rotate the plane of polarization of the pump photons. The λ/2-plate rotates the plane of polarization by twice the angle between its fast axis and the original polarization direction. By measuring the number of DC photons as a function of the angle of the λ/2-plate, the students can investigate how the DC rate depends on the polarization of the pump beam.

Both our BBO crystals are cut for type I SPDC, with the DC photons leaving the crystal at an angle of 3 degrees relative to the pump beam. In type I SPDC, both DC photons have the same polarization, which is perpendicular to the polarization of the pump photon. In our single BBO crystal (5mm x 5mm x 3mm, from Newlight Photonics), because of the way it is cut and mounted, horizontally polarized pump light produces DC photons that are vertically polarized. Vertically polarized pump light, on the other hand, does not produce any DC photons. Our double BBO crystal consists of two thinner individual crystals that are glued together with their axes perpendicular to each other (2 crystals, 5mm x 5mm x 0.5mm each, also from Newlight Photonics). One of the two parts of the double crystal therefore only produces vertically polarized DC photons, only from horizontally polarized pump photons, whereas the other part produces only horizontally polarized DC photons, only from vertically polarized pump photons.
Fig 1: Schematic of Anti-Coincidence setup (adapted from [1]).
Fig.2: The 405nm pump laser with λ/2-plate and BBO crystal (double crystal).

Fig.3: Single BBO crystal  
Fig.4: Double BBO crystal in glass jar with desiccant
Fig. 5: Polarizing beam splitter with collection optics: lenses focus the DC photons onto an optical fiber that guides them onto the detectors. The $\lambda/2$-plate in front of the polarizing beam splitter is not shown.
Data Acquisition

Data acquisition in this experiment is done via the Altera Board, an FPGA (Field Programmable Gate Array) that is used as the Coincidence Counting Unit (CCU). For every detected photon, the SPCM outputs a pulse with a height of 5V and a width of about 30ns. These pulses are the input to the CCU, via an adapter box that reduces the input voltage to 3.3V. The Altera board is programmed to count single detector counts for each of the four detectors, as well as coincidences between them. A coincidence is counted if two detectors record a signal within a time interval of 8ns. Fig. 6 shows an image of the CCU and the SPCMs.

Fig. 6: Left: FPGA Altera Board, used as the Coincidence Counting Unit (CCU). Right: Single Photon Counting Modules (SPCMs) from Perkin-Elmer/Excelitas, inside the support unit from qutools.

The Altera board is interfaced with a computer through a LabView program, the Labview vi (virtual instrument) **Coincidence_RS232(1_9)**, which communicates via a RS232 connector. Fig.7 shows a screenshot of the Labview vi for the anti-coincidence experiment. Fig.8 shows the Labview sub-vi for saving the data to file.
Fig. 7: Screenshot of the Labview vi for the anti-coincidence experiment.

Fig. 8: Screenshot of the Labview sub-vi for saving the data to file.
Student Data and Analysis

Students use the fitting program IgorPro to graph and fit their data. They are given the task to derive the appropriate fitting function using their knowledge of polarization and SPDC. By arguing that only one polarization of the pump laser will produce DC photons in the single BBO crystal, and that the number of DC photons depends linearly on the number of pump photons of the correct polarization, the fitting function becomes:

\[ N(\theta) = N_0 \cos^2 \left( 2 \cdot (\theta - \theta_0) \cdot \frac{\pi}{180} \right) + A, \]  

where \( N_0 \) is the maximum number of DC photon counts, \( \theta_0 \) is the offset angle, and \( A \) is the dark count rate. The factor 2 in the argument of the \( \cos^2 \) function is due to the fact that rotating the \( \lambda/2 \)-plate by an angle \( \alpha \) will rotate the plane of polarization by \( 2\alpha \). This fitting function is used in IgorPro, with \( N_0 \), \( \theta_0 \), and \( A \) as fitting parameters.

With some guidance, students are able to derive this fitting equation, and they usually make the connection to Malus’ law on their own. When using the double BBO crystal, the data is more difficult to understand.

Fig. 9 below shows graphs of the data students took for the double BBO crystal, together with their fits. The maximum counts for detectors A and B are somewhat different, mostly due to alignment issues.

![Fig.9: Left: Counts for the A, B, and B’ detectors are displayed vs the angle of the \( \lambda/2 \)-plate. Right: Coincidence counts of AB and AB’ are shown vs the angle of the second \( \lambda/2 \)-plate (first \( \lambda/2 \)-plate fixed).](image)

Students write a formal lab report in the format of a scientific journal article about this experiment. The first draft of the paper is peer-reviewed according to a detailed rubric, and critiqued by the instructor as well. Information on the formal lab report and the rubric are given in Appendix 2.
The new Erlangen Single Photon Detector

The electronics for this new detector has been developed and built at the University of Erlangen, Germany, by Andreas Strunz in the Physics Education Research group of Jan-Peter Meyn. As APD (Avalanche Photo Diode), two different models can be used (with slight modifications of the electronics):

- C30902STC (with single cooler, the same APD that is used in the SPCMs), or C30902SDTC (with double cooler) by Excelitas (formerly Perkin-Elmer)
- SAP500-T6 (or-T8) by Laser Components

Unlike the Excelitas detectors that are fiber coupled, the Erlangen detector is designed for free space use, with the plan to have the beam enclosed in light-tight tubes. The goal is to come up with a set-up for quantum optics experiments that is both less expensive and easier to handle than the currently available ones.

Since the pulse height of the Erlangen detector is only 1.5V, as compared to 5V of the SPCMs by Excelitas, it is necessary to change the adapter box connecting to the CCU. Instead of a voltage divider, a 50 Ohm resistor has to be connected to ground, and the signal measured across this resistor.

Fig.10: Left: The new Erlangen detector. Right: Pulse signal of the Erlangen detector. The pulse height is about 1.5V, and the pulse width 40ns. The dark count rate depends on the particular diode used and lies in the range between 500 cps (counts per second) and 5,000 cps. In this case, a value of around 2,000 cps was measured.

Acknowledgments

I would like to thank Mark Beck for generously sharing information on his experimental set-up for the single photon experiments. Many thanks also to Andreas Strunz and Jan-Peter Meyn for allowing me to benefit from their detector development.
This form is to be utilized by the department or Environmental Health & Safety to document the training of groups of employees.

Date ____________________

Name of Trainer ___Barbara Hoeling______________________________________________________

Subject(s) Covered : Laser Safety for the Quantum Optics Research Lab

- Turn on the outside warning sign when laser is on.
- Do not look into the laser beam, or at specular reflections (reflections from mirrors or shiny surfaces) of the beam.
- Use protective eye wear when laser is on.
- Take off all pieces of jewelry from your hands, as well as hanging necklaces or badges.
- Avoid skin contact with the laser beam.
- When using optical fibers, remember that a laser beam or bright light might be emitted from the fiber end.
- Do not attempt to align the 405nm beam yourself! Contact your instructor or the TA!

Phy417 students: Please print and sign your name legibly. Your signature below indicates that you have received and understood the training listed above, that you have completed the modules 0-3 of the online Laser Safety course at http://www.science.sjsu.edu/nucsci/laser/training/ and passed the quizzes for them, and that you will comply with the indicated procedures.

Print Name                                  Bronco ID Number                                                Signature

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Distribution:  Department
              Environmental Health & Safety
              Trainer

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Appendix 2: The Formal Lab Report and Peer Review

Phy417L, Instructor: Barbara Hoeling

For the “Quantum Optics” experiment in Phy417L, you are required to write a technical report (aka, “formal lab report”). Its format and structure are similar to scientific papers that are published in research journals. A physics paper, say in the American Journal of Physics, typically consists of the following sections: abstract, introduction, theory, procedure, analysis, conclusion, and references. Below are some details on what each of these sections should contain.

- **Abstract**: a very concise (3-6 sentences) summary of the paper. Usually appears in small print directly under the title. The most important part of the paper.
- **Introduction**: Answers the question: What is this experiment about, and why is it important? Gives a bit of historical background, what other people have done in this field, and how your own work fits in.
- **Theory**: Derivation of the theoretical equations you use for your experiment.
- **Procedure**: Explain how the experiment was performed, and how the measurements were taken, in such a way that a reader who has general knowledge of this field of physics could reproduce your experiment. **Do not put any tables of raw data!**
- **Analysis**: How did you reduce your data, i.e., how did you get from the tables of raw data to the numbers that are your final result? Graphs and error analysis belong here.
- **Conclusion**: What is the significance of your experiment? What have you shown? Some overlap with the abstract, but the conclusion can be a bit more elaborate, and can also contain an outlook to further plans or investigations.
- **References**

The whole formal lab report should be about 3 to 4 single-spaced pages long. Your score will be made up as follows: 30% first version, 20% peer review, 50% final version.

**Hints:**
- Graphs should be made in **IgorPro**, or any other graphing program that can do curve fitting with a chi-square analysis (i.e., that can give you the fitting parameters with uncertainties).
- In your graphs, do not connect the dots (chose “scatter graph”, or such).
- Equations must be put in using an equation editor (in a .doc: click on “insert -> object -> Microsoft equation editor), or by hand. Do NOT try to write equations in the regular text editing mode – they are too hard to read!
- The figures must be numbered and have a figure caption. Refer to them in the test (e.g., “Fig. 1 shows a schematic of the apparatus…”)
- Do not put any data tables in your lab report (Scientific papers never contain tables of raw data.).
- Do not write the procedure section like instructions in a lab manual. Describe what you and your partner actually did!
**First version (30%):**
Your first version of the formal lab report should be your best, most complete effort. It should be the version you would submit to the journal. Please provide two hardcopies of the first version, one for me and one for the (anonymous!) peer reviewer to whom I will forward your report. In addition, please email me the .doc (or .docx) file.

**Final version (50%):**
You will receive feedback from the peer reviewer and from me after one week. Revise your first version according to our corrections and suggestions, and submit your final version one week later, according to the schedule outlined in the syllabus.

*Note:* You **must** turn in your first version together with your final version, including my comments and my rubric, attached to it! You don’t have to attach the peer review you received.

**Peer review (20%):**
For the peer review you have to write, please use the rubric given below as a guideline. Print it out and assign the points as they seem appropriate to you. In addition, you have to write a one-half to one page essay critiquing your classmate’s formal report. In this review, you have to address the following questions: Is the physics correct, and explained well? Is the method of data taking appropriate? Are the data and results presented in a fashion that is easily understandable by the reader? Is the style of the report suitable for publication?

Please submit 2 (two!) hard copy and an e-file of your review to me one week after you received the lab report for review. I will forward one of the hard copies to the author. Do not contact the author yourself or mention to other classmates whose paper you are reviewing! The process should remain anonymous.
Peer Review of Quantum Optics Paper

Name of submitting author ________________

Total: 20 points

Short sections (3 pts)
- Summary of results in both Abstract and Conclusion sections
- Clear definition of the physical problem in Abstract
- Motivation for experiment(s) in the Introduction section
- Brief summary of the procedure/approach in the Introduction section

Theory (4 pts)
- Explanation of spontaneous parametric down-conversion, taking into account the polarization of the pump laser and of the down-converted photons
- Derivation of the expected dependences of the number of detected photons on the orientation of the two λ/2 - plates
- Explanation of expected results in the anti-coincidence measurements

Procedure (3 pts)
- Useful picture of the apparatus
- Clear discussion of data acquisition method and procedure

Graphs (3 pts)
- Appropriate graphs (2) for verifying the relationships derived in the theory section

Analysis (4 pts)
- Discussion of the information gained from the graphs
- Discussion of uncertainties
- Significance of the results

Presentation (3 pts)
- Grammar, spelling, and punctuation are correct
- Writing is clear, and technical terms are used correctly
- Equations are presented clearly and correctly
- Ideas progress logically within each individual section
- Entire report progresses logically: questions raised in one section are answered later
- References are appropriate and quoted properly
Appendix 3: Photon Statistics Experiment

In this experiment, you will have the opportunity to use state-of-the-art research equipment and software. You will detect photons using the Single Photon Counting Modules (SPCMs) manufactured by Perkin-Elmer, an array of four independent avalanche photon diodes (APDs). These APDs, which operate in Geiger mode, are standard equipment as it is used in quantum optics research laboratories. For data acquisition, you will use a LabView computer interface.

Your task in this experiment is to examine the dark count rate, i.e., the counts registered by one of the SPCMs when there is no light hitting it. **Note: You will be analyzing only one of the four independent detectors.** This is an important investigation of any detector that has to be conducted before it can be used for any “real” measurements. The question you have to answer is whether or not these dark counts are statistical in nature. In other words: Do the dark counts obey Poisson Statistics? For Poisson statistics, the standard deviation $\sigma$ is equal to the square root of the average total number of counts:

$$\sigma = \sqrt{N_{\text{ave}}}. $$

Fig. 6 shows a photo of the front panel of the SPCMs. The (lower) four fiber inputs are covered by black light-tight caps, which have to remain in place during the dark count measurements. The (upper) BNC connectors are the output signals of the four APDs which are going into the coincidence counting unit (CCU). The CCU output goes into the computer, and you can observe the number of counts in a given time interval on the LabView user interface. Labview allows you to set the counting interval and the number of counting intervals you want to measure, and then takes the data automatically for you. The data can be exported into an excel file.

Before coming to this lab, you have to discuss with your partner exactly what measurements you want to take. What counting intervals (between 1s and 10s) do you choose, and how many trial for each counting interval? The average number of total counts should be proportional to the length of the counting interval. You can determine this average and the standard deviation $\sigma$ by taking multiple trials for the same counting interval. The more trials per counting interval you take, the more accurately the standard deviation $\sigma$ can be determined. Remember that you only have one lab period to collect the data, so you need to manage your time! Check with the instructor before starting your measurements!

Caution: Do not turn on the SPCMs when the room lights are on!!!

Reading Assignments:
- Hecht, Ch 3.3.3 Photons.
- “Poisson Statistics” (MIT Department of Physics), 2. Theory of Poisson statistics and 3.3 Analysis. The pdf is posted on Bb.
- “Photon counting statistics – undergraduate experiment”, P. Koczyk, P. Wiewior, and C. Radzewicz, AJP 64 (3), March 1996. You may skip the experimental details about PMTs (photomultiplier tubes, which were used as detectors for our type of experiment before the advent of the APDs). The pdf is posted on Bb.
Student Data for the Photon Statistics Experiment:

Fig.11: Left: A histogram of 3000 trials for a 1-second counting interval. The theoretical Poisson probability distribution is also shown. Right: Graph of ln (σ) vs. ln (N_{ave}). The slope is close to ½, as expected for a Poisson distribution.