A RESEARCH ON THE DETECTION OF THE ENTANGLED RED PHOTONS IN THE SPONTANEOUS PARAMETRIC DOWN-CONVERSION EXPERIMENT

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Abstract

The spontaneous parametric down-conversion experiment is a quantum optics experiment which demonstrates the very phenomenon of quantum entanglement. The idea of this research project is to conduct this experiment on a self-designed optics system and record observed entangled photon pairs as well as red light cones produced by a non-linear BBO crystal. The BBO crystal is the key component of this experiment and a 405nm laser beam will shine through the crystal to produce down converted 810nm photon pairs. The measuring and data collection tools are a photon counting module and a optics camera. The ultimate goal of this project is to create an optics system and a guide for the spontaneous parametric down-conversion experiment, which will become one of the optics experiments performed in the senior optics lab course. The entire optics system was very successfully built, with the following components aligned in a line: a 405nm laser, a 100mm focus lens, a BBO crystal, a fixed aperture, a red light filter and a camera. The results from the experiment show some indication of the two red light cones produced by the crystal. Further experiments will be carried out to confirm the down-converted light cones and to test the coincidence rate of SPDC.
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Chapter 1

Introduction

In the field of quantum optics, the spontaneous parametric down-conversion (SPDC) phenomenon is a common way to produce photon pairs in entangled quantum states. In this paper, a detailed experimental design and method will be presented. The SPDC experiment is based on the theory of quantum mechanics and quantum optics. The basic idea is to use a laser as the pump beam source to stimulate a nonlinear crystal, which will produce light of twice the wavelength of the pump beam. There are two types of SPDC, type-I and type-II. In type-I SPDC, a single light cone will be produced with photon pairs of the same polarization whereas in type-II SPDC, photon pairs with perpendicular polarization are created. This paper will focus on the research on the type-II SPDC experiment. The main goal of the research is to establish an optics system for the type-II SPDC experiment that can be performed in a senior optics lab courses by undergraduate students.

The experiment involves different optics and electronics instruments and apparatuses. The source beam is a 405nm 200 mW laser that acts as the pump beam. The beam will be directed to travel through a Barium borate crystal (BBO), which is a nonlinear crystal. The BBO crystal produces the entangled photons that will eventually be detected. This will be explained in detail in the theory section. The last component is the detector and the proper receiver, and in this experiment there will be two sets of detecting devices: a CMOS camera with a computer, and a photon counting module with an oscilloscope. The observation involves the direct imaging of the down-converted photons and the detection of entangled photon pairs.

1.1 Theory of Spontaneous Parametric Down-conversion

The SPDC phenomenon is well described by quantum mechanics and quantum optics. In this section, the mechanism, the properties of the photons will be discussed. Spontaneous parametric
down-conversion refers to the phenomenon where the part of the pump beam going through the BBO or other nonlinear crystal gets converted to a higher wavelength beam due to the conservation of momentum and energy. The crystal splits the beam into pairs of photons that are phased matched in the domain of frequency with correlated polarization. In type-II SPDC, the photon pairs will have perpendicular polarization where one of the photons are extraordinarily polarized. SPDC is a $2^{nd}$ order quantum optical effect where the dependence of the polarization of dipole on the electric field is quadratic. The incident single photons are called pump beam and as it goes through the BBO crystal the two newly produced photons are called the signal and idler. The term spontaneous refers to the fact that there is no input signal or idler field for stimulation. The signal and idler are generated spontaneously inside the crystal by quantum vacuum fields. The process is parametric because it depends on the electric field and the intensities of the incident photons, which results in the phase relationship between the input and output fields. Down-conversion comes from the fact that the signal and idler photons always have a lower frequency than the pump photons[1].

The conservation laws make sure that the signal and idler have the same combined energy and momentum of the pump photon. This is given by the following:

$$\omega_{\text{pump}} = \omega_{\text{signal}} + \omega_{\text{idler}} \quad (1.1)$$

$$\mathbf{k}_{\text{pump}} = \mathbf{k}_{\text{signal}} + \mathbf{k}_{\text{idler}} \quad (1.2)$$
Figure 1.1: The graphic depiction of generating type-II SPDC[2]. In the experiment a 405nm laser is used as the pump beam. The two green cones represent the light cones of two perpendicular polarization. The intersecting points are where the entangled photons are created.

SPDC requires the pump photons to interact with a nonlinear crystal and among the three photons (pump, signal and idler) the interactions are within a uniaxial crystal. There the pump photon is polarized in an extraordinary direction relative to the optical direction of the crystal. The direction of propagation of signal and idler beam depends on a lot of factors, like their frequencies with respect with each other, the properties of the crystal, etc. Moreover, the strength of the down-converted beams are determined by the phase matching conditions. In this experiment a type-II BBO crystal is used to produce entangled photons. The result of the interactions is: there will be two light cones coming out of the crystal, slightly overlapping, along with the pump beam. See figure 1.1 for details. The two, in our case red, light cones represent the ordinarily and extraordinarily polarized photons. The two intersecting points are the interesting part: the two photons at these two points have a superposition of polarization. The polarization is uncertain at the two points, yet due to the conservation laws the polarization is following either the one from the top cone or the one from the bottom. This gives us a quantum entanglement of two polarization states of the two photons.

The formulation of this quantum phenomenon follows basic optics and quantum mechanics. The vertical polarization of the upper light cone in figure 1.1 refers to one quantum state, while the lower light cone represents the other. The orthogonality of the two polarization sets two orthogonal quantum states of photons. The BBO crystal produces the the light cone at twice the wavelength as
the pump beam[3]. Therefore, when we shoot 405nm laser light through the crystal, the expected down-converted light would be at 810 nm. The quantum state of a random photon is:

$$|\psi\rangle = \alpha|V\rangle + \beta|H\rangle$$  \hspace{1cm} (1.3)

This is what we get when we make a measurement of the photon. Here $\alpha$ and $\beta$ are some complex parameters to be determined by the probabilities, and they are normalized, meaning $|\alpha|^2 + |\beta|^2 = 1$. $|V\rangle$ is the vertically polarized state and $|H\rangle$ is the horizontally polarized state. This is a general form of $|\psi\rangle$, the quantum state of a photon produced by the crystal. It is a superposition of the two. Since we only get either vertically polarized photons or horizontally polarized photons, in most cases either $\alpha$ or $\beta$ is zero. The most interesting part is the intersection points where the pair of photons are the superposition of the two quantum states. They are entangled, implying that if we know the state of one photon, we immediately know the state of the other. The state of the system is given by:

$$|\psi_{\text{system}}\rangle = \alpha|V\rangle_1|H\rangle_2 + \beta|H\rangle_1|V\rangle_2$$  \hspace{1cm} (1.4)

Due to the quantum entanglement in this pair of photons SPDC has always been a good source of quantum entangled states [4]. We can now take a closer look at the geometry of the nonlinear crystal. As it is of the shape of a cube, with three sides $L_1, L_2$ and $L_3$ parallel to the x, y and z directions. The laser provides a bump beam whose cross section is completely within the cubic body of the crystal. The light propagate in the z-direction. We take the first-order perturbation, and then by using expressions from [5], we have the state generated by SPDC [6]:

$$|\psi\rangle = |\text{vac}\rangle + \text{const} \times \int dk_s \int dk_i \sin \frac{1}{2}(\omega_s + \omega_i - \omega_p)t \times \Phi(k_s, k_i)|1; k_s\rangle|1; k_i\rangle$$  \hspace{1cm} (1.5)

where

$$\Phi(k_s, k_i) = \int dq_p v(q_p) \sqrt{\frac{\omega_s \omega_i \omega_p}{n^2(k_s)n^2(k_i)n^2(k_p)}} \times \prod_{j=1}^{3} \sin \frac{1}{2}(k_s + k_i - k_p)_j L_j$$  \hspace{1cm} (1.6)

$q_p$ is the transverse component of the incident light wave vector $k_p$, $v(q_p)$ is the angular spectrum of the pump beam, and $n(k_j)$ are the indices of refraction of the BBO for signal, idler and pump ($s, i, p$ respectively).
1.2 Motivation

The motivation behind this research is to develop a way for undergraduate students to do the SPDC experiment in the senior optics lab course. This is a very typical quantum entanglement phenomenon. It has been performed by many physics people, mostly for the creation of entangled quantum states. The knowledge required for students to understand SPDC is not that much. The knowledge from quantum mechanics and the lectures on optics make it very feasible for students to truly understand this phenomenon. It would be very beneficial for the students, by using the optics system, to observe and record this phenomenon.

The famous EPR paradox argued about quantum entanglement. After that the theory of quantum mechanics and quantum optics have become more developed and more accepted. It has rooted in the very fundamentals of quantum mechanics. The direct observation and the detection of the coincidence rate of the entangled photons would be a very fascinating physics experiment on quantum entanglement. This would be a really great opportunity for students and us to go through the actual experimental proof of a famous physics theory.

In one word, this research on the development of an optics system for the SPDC experiment has lots of benefits and potential applications. It could be adopted into the senior optics lab course, it could function as a source of quantum entangled states, and it can also be an exploration of different optics system designs.
Chapter 2

Experiment

2.1 The Optics System

The bump beam source of the experiment is a 200mW 405nm laser. In this research three different experimental methods were tested for the detection of red light cone, as well as the entangled photon pairs. Initially, a photon counting module would be used to see the coincidence rate in SPDC. Later during the research, the emphasis shifted to the direct detection, or imagining of the two light cones produced by the BBO crystal. This was done by using a CMOS camera manufactured by THORLABS.

![Optical Schematic](image_url)

Figure 2.1: An optical schematic of the simplest setup. In this setup the camera looks at the circles on the red light filter directly without an imaging lens

Figure 2.1 shows the simplest optics set up during our research. The laser goes though a focus lens in order to maximize the intensity of the pump beam at the center of the crystal. A well focused bump beam leads to asymmetric broadening of both the ordinary and extraordinary light distribution[7]. Therefore, focusing the laser beam is crucial to the experiment. All of our experiments use a 1-mm-thick type-II SPDC BBO crystal that is pumped by 405nm light. The half opening angle of the crystal, one of its many characteristics, is $5^\circ$. This would affect the size of the circles we will be looking at through the camera. Before the camera, a red light filter is used
to stop the pump beam, as well as another disturbing light, from entering the camera. During our research on the experiment, two types of red light filters were used because the first filter could not satisfy us on its filtering. This will be mentioned in the data section, where comparison will be made between the filters.

Figure 2.2: A photon of the optical setup. We have the laser on the left, the focus lens in the middle, the camera on the right, just behind the crystal. Note that in this setup the imaging lens is attached to the camera. In most cases, another focal lens is needed to see the red cones.

Figure 2.2 shows one of the optical setups that were tested in the experiment. The laser is 20cm away from the focus lens, which has a focal length of 10cm. In this configuration the camera tries to capture the light cones right before they expand to much. Sitting in a rifle gun box, the entire system is isolated from the outside world while the crystal is stimulated by the laser.

2.2 Procedure of the Experiment

2.2.1 Imaging with an Imaging Lens

Capturing the image of the light cones with the imaging lens on the camera seems natural. However, since the light cone spreads out at a $5^\circ$ angle, it would be hard to capture the ring from far away. The lens of the camera is 6mm long, while the back sensor of the camera is 6.66mm(H) x 5.32mm(V). It would be much harder to capture the double red rings from just a few centimeters away. Moreover, the intensity of the red light decreases by $1/r^2$, which makes it even harder for long distance capture. What we came up with was to use a fresnel lens. The advantage of a fresnel
lens is it has a relatively small package with a large focal length compared to a regular lens with the same focal lens. So with the Fresnel lens the camera can be placed 10cm-30cm away from the crystal. The Fresnel lens we used had a focal length of 14cm. Different approaches to eliminating all the disturbance and the bump beam after the crystal have been tried. In figure 2.2, we can see that there's a lot of space. We have tried to use a small aperture right before the pump beam goes into the crystal. That way the light beam gets as small as possible, intensifying its intensity.

### 2.2.2 Imaging without an Imaging Lens

Without the imaging lens, the camera functions as a film. The sensor of the camera directly stares at the filter, where the light cones are projected as two light rings. Without the imaging lens, the camera must get extremely close to the crystal because no lens will focus the light. That means the light cones will directly land on the back sensor of the camera. There have been lots of experiments on the imaging of type-II SPDC, a lot of them were done without an imaging lens [4][7]. The problem we encountered was that the back sensor of the camera lies inside the case so there was a limit on how close the sensor can get to the crystal. Initially we used two filters that we had. The filter only lets 0.002% light at 405nm go through, while it’s transmission rate for 810nm is 84.82%. It turns out under the power of the laser beam, these filters did not do a good job on prohibiting 405nm light going through. In fact, we had to us other opaque materials to block the center of the filter so that the pimp beam does not go through. Later we ordered a much better filter: THORLABS bandpass filter FBH810-10. This filter does a very good job at transmitting 810nm light and its passband is extremely narrow. Its transmission rate of 405nm light is just $7.22 \times 10^{-6}\%$. In the analysis section there will be a comparison of the two filters.
Chapter 3

Images and Results

3.1 Experimental Images

During the process of research, we tried a lot of different configurations of apparatuses. The results are that we have seen indications of down-converted red light.

Figure 3.1: The ring structure seen on an old filter. This was taken by the camera with an imaging lens. The camera was 28cm from the crystal (lens to crystal) and the fresnel lens was in the middle of the two, with a focal length 14cm. Note the black spot at the center of the square. The square is the old filter and the black spot is what we use to stop the pump beam from going through.
Figure 3.2: This is a picture of the laser beam going through the crystal and a diffraction grating. The purpose of the diffraction grating is to separate the red light from the blue light due to the difference in wavelength. The spectrum of the diffraction pattern gives us the estimation of red light produced. Also, this test was performed for the conformation of down-conversion. The brightest spot in the middle is the pump beam. The two dots on the left are the first and second diffraction peak. Particularly in the second peak, red light shifts a lot more toward the outer circle.
Figure 3.3: This is taken by the camera without the imaging lens. The camera was 4cm away from the lens, while attached to it was the better narrow band filter. With the old filter, way too much light pass through and all the camera cannot differentiate the light. With this filter we can see two suspicious rings that intersect. Remember the filter only pass IR light so the white rings are actually 810nm. One method to determine the authenticity of the rings is to see if they have perpendicular polarization. The following two pictures show exactly what we need.

Figure 3.4: In this picture a polarizing disk was placed between the crystal and the camera. As the disc rotated, one ring disappeared completely while the other remains.
Figure 3.5: Keeping everything still but the polarizing disc gives this picture from fig. 3.4. The disc rotated by 90°. It’s very clear that the brightness of the rings swapped.

### 3.2 Interpretation

Figure 3.1 and figure 3.2 shows hints of down-converted light from the crystal. In figure 3.1, the two ring structure seems to be clear yet the brightness is off. From figure 3.2 we learned that red light in that region was intense. Though it was out-shined by the pump beam, the diffraction pattern gave us a better idea of the presence of red light generated by the crystal.

The results from figure 3.3 to 3.5 were really exciting. Yet there was one big question about this pair of rings. The size does not match the predicted number, which would make the ring take over the entire camera back (the entire screen). The polarization phenomenon indeed takes a big leap toward the red light cones. Nonetheless further experiment showed the line rings are created by the internal reflection of the beam inside the crystal. The real imagines of the red light cones still remain undiscovered.
Chapter 4

Conclusion

4.1 Conclusion

The research on developing and optics system to conduct experiments on SPDC is quite successful. Multiple experiments have been carried out on the BBO crystal to explore this phenomenon. During the search for down-converted red light cones and the image of the light rings, lots of discoveries were made. Some hints and implications of the rings in the images taken during the experiments show some evidence of the red light produced by the crystal. Further experiments still need to be carried out on the direct imaging of the light rings. This has been a very beneficial research in the sense that lots of experimental methods have been tested, lots of configurations have been built and practiced. It has given us a clearer path as of what the next step is going to be.

4.2 Future Work and Improvement

It is possible that the laser beam is not the best quality beam in terms of scientific research. Perhaps a replacement can be test in the same system. Also, the utilization if the photon counting module is the next big task. The detecting of the coincidence rate would be a very meaningful quantum optics experiment. In this research this activity was not carried out often. The focus of future exploration should be on the recording of type-II SPDC coincidence rate.
## Appendix

This table contains information about the main optics apparatuses and components used in this research project.

<table>
<thead>
<tr>
<th>Component</th>
<th>Model and Manufacturer</th>
</tr>
</thead>
<tbody>
<tr>
<td>BBO Crystal</td>
<td>NEWLIGHT; NCBBO5100-405(II)-HA5-AR</td>
</tr>
<tr>
<td>Bandpass Filter</td>
<td>THORLABS; FBH810-10—</td>
</tr>
<tr>
<td>CMOS Camera</td>
<td>THORLABS; DCC1545M</td>
</tr>
<tr>
<td>Photon Counting Module</td>
<td>EXCELITAS; SPCM-AQ4C</td>
</tr>
</tbody>
</table>

Almost all other equipment and apparatuses are Thorlabs products.
Bibliography


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