Design for Undergraduate Experiment using Photon Entanglement

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Abstract

We report on the attempts made to set up a high-intensity source of entangled photons produced by spontaneous parametric down conversion in a birefringent nonlinear crystal. The entangled photons can then be used in undergraduate quantum experiments designed to demonstrate violations of the Bell inequalities and experiments designed to demonstrate the quantum behavior of light. The production of the entangled photons occurs by noncollinear type-II phase matching where an ultraviolet light source from an argon ion laser is shined on a beta barium borate crystal producing entangled photons in the near-infrared spectrum. The near-infrared entangled photons are then detected using photomultipliers tubes encased in custom housings. The data from the photomultiplier tubes is then feed through a series of an amplifier, discriminator, and a coincidence counter which is interfaced with a computer via Labview. In this report, we have detailed our numerous attempts to observe the entangled photons using various photographic mediums and although, in the ten week period, we did not succeed in detecting the entangled photons, we discuss possible problems and our plans for future attempts.

Introduction

A. Background

In 1935, Albert Einstein, Boris Podolsky and Nathan Rosen, published an article which came to be known as the "EPR Paradox" [7]. In this paper they proceeded to argue that quantum mechanics was an incomplete theory because it involved a violation of locality [7]. Locality is a fairly intuitive idea, because it is the idea that A affects B by direct interaction with B. In other words, in order for A to affect B, A must be physically touching B [7]. For example in order to move a pencil, you must go to the pencil and physically move it. You might think of examples that may appear to be nonlocal, but in truth all of our macroscopic interactions are local. For example you could affect the pencil by telling a friend to move the pencil instead of you. Therefore you affected the pencil without ever physically touching the pencil. But the truth behind this example is that your vocal cords sent a vibration through the air to the ear of your friends who then in turn moved the pencil [7]. So your vocal cords were physically touching air molecules which in turn were touching air molecules and transmitted the vibrations all the way to your friend's ear, whose ear and brain interprets the vibrations and then they move the pencil. Another example is that you push a button that launches a rocket 500 yards away. This may appear to be nonlocal, but the truth is that your pushing the button initiates either a signal in the air if it is a radiowave signal or a signal through wires. In the first case the air molecules are bumping into each other and transmitting the signal, and in the second case the electrons in the wire are transmitting the signal.

Now that we have defined locality and its opposite nonlocality, let us turn to the idea of entanglement. The idea behind entanglement is that there is some link between two particles such that once you know the entangled attribute of one particle you know the entangled attribute of the other particle [7]. Particles can be entangled in a number of ways such as location, spin, excitation state and so on [7]. However, the tricky part is that nothing is predetermined in quantum mechanics. Quantum mechanics dictates that you can never know the precise location of a particle, however you can know that two entangled photons are precisely a certain distance apart from one another, despite the fact that neither one has a definite position [7]. Notice from this example that entangled objects can be separated by distance [7]. As a better and more relevant example, a photon has a 50 percent chance of being polarized vertically and a 50 percent change of being polarized horizontally. Therefore when looking at a single photon, there is a 50/50 chance it could be polarized vertically or horizontally and you will not know until you measure the polarization. However, you can have two photons entangled in such a way that one must have a vertical polarization and the other must have a horizontal polarization, yet quantum mechanics dictates that you do not know which one is vertically polarized and which one is horizontally polarized because they each have an equal probability of being either polarization.

This is where the paradox arises. For our next example we will have Jill measure photon A and Jack measure photon B. We will say that photon A and photon B are created in some "machine" and sent towards Jill and Jack respectively. The photons are entangled so that one will have a horizontal polarization and one will have a vertical polarization. Before any measurements are made, according to Jill, photon A has a 50/50 chance of being either horizontally polarized or vertically polarized and the same goes for Jack with photon B. Now say that Jill measures the polarization of photon A before Jack measures the polarization of photon B. If Jill measures photon A to have a vertical polarization, then we know for certain that photon B has a horizontal polarization. But before Jill measured photon A, photon B had a 50/50 chance of being polarized vertically or horizontally, but after Jill measures photon A, now photon B has a 100 percent probability of being horizontal.

There are two ways to interpret the above example. The first way is fairly intuitive and states that the polarizations of A and B are determined at the moment of creation. Meaning that the instant that photon A and B are created in the "machine," they have their respective polarizations, but these polarizations are unknown to Jill and Jack. Therefore, from the perspective of Jack and Jill, their respective photons still have a 50/50 chance of being polarized vertically or horizontally. The EPR paper sided with this interpretation [7].

The second interpretation, which is given by quantum mechanics, states that the polarizations of A and B are not determined at creation but are instead determined at the moment of measurement. The first interpretation stated that as photon A travels towards Jill, it already has a vertical polarization but that this polarization is unknown to Jill, therefore from her point of view there is still a 50/50 chance of either polarization. The second interpretation states that as photon A travels towards Jill, it has neither a vertical nor a horizontal polarization, but instead exists as a superposition of these two states. However, the instant that Jill measures photon A, it no longer exists in a superposition state, but instead will have a vertical polarization. This idea is not intuitive at all, because it states that a photon has a definite polarization only when you measure it. Meaning that measuring the photon has some affect on the photon itself. Now we turn our focus back to photon B. Since the polarization of photon A is a superposition of vertical and horizontal polarizations, likewise, the polarization of photon B is a superposition as well. Also, since photon A and photon B are entangled, when a definite horizontal polarization is measured on one of them, then we know that the other one has a definite vertical polarization. So when Jill measures photon A to have a definite vertical polarization, this means that, in that very same instant, photon B must have a definite horizontal polarization, where previously photon B existed as a superposition of vertical and horizontal polarizations. The paradox arises from the questions of how does photon B, which has an equal likelihood of being horizontal or vertical, "know" when photon A was measured and at what polarization it was measured at? Photon B must "know" when photon A was measured and at what polarization it was measured in order to preserve the entangled property of the two photons. And since photon A and photon B can be separated by any length of distance, this gives rise to the idea that somehow photon A has instantaneously affected (or communicated) with photon B. However, this idea violates locality because it happens instantaneously and it happens over any amount of distance. It is because of this violation of locality that the EPR paper argued that quantum mechanics was an incomplete theory [7].

The solution to this paradox was final discovered in 1964 by John S. Bell. Bell argued and showed that if the world is truly "local" or classical, then quantum experiments should obey certain mathematical relations known as "Bell inequalities" [7]. If the quantum mechanical theory is correct, the experiments would violate these inequalities. In 1981, it was shown by experimentation that these inequalities are violated and therefore quantum mechanics is correct in this aspect and correct in the assertion that the world is nonlocal [7].

B. Purpose

The main objective behind this summer research was to gather the necessary materials and information required to produce pairs of entangled photons and detect them so that they may be used in other modern physics experiments. Since many of the necessary materials required to generate entangled photons by our method, were not owned by the college, a major goal was to order and acquire all of the necessary optical instruments. Once all of the materials were acquired it was a matter of setting up the apparatus to generate the entangled photons and detect them. If successful, the apparatus could be used in experiments that verify the quantum nature of light [2] and experiments that demonstrate a violation of the bell inequalities [1]. Once the procedures and methods for performing these experiments were developed, the experiments would be integrated into the modern physics and quantum physics classes at Saint Mary's College, thus updating and improving the range of experiments that can be performed in those classes.

The entangled photons will be generated by spontaneous parametric down conversion (SPDC) in a nonlinear crystal. Ultraviolet light will be shined on the crystal and by SPDC, a single photon with a wavelength of 351.1nm (UV) will be converted into two photons with wavelengths of 702.2nm (Near-infrared) [1]. The entangled photons will travel through rotatable polarizer's that can be adjusted to model the different Bell inequalities [1]. Then the photons, if not stopped by the polarizer's, will travel to detection devices for data analysis and subsequent testing of the Bell inequalities.

Polarizer's are designed so that one orientation will block photons with vertical polarizations and if you rotate the polarizer 90 degrees, then the same polarizer will block photons with horizontal polarizations. In the experiment, two polarizer's are used, one in front of each detection device. By changing the rotation angles of the two polarizer's and observing the coincidences (i.e. when both detectors register detections), the Bell inequalities can be tested [1].

Materials

A. Optical Instruments

A portion of this summer research project went to researching and purchasing materials and optical instruments, since many instruments needed for the experiment were not previously owned by the college. Most importantly among them being the ultraviolet filter at 350 nm and the two near-infrared filters at 702 nm. In the process, we have expanded and updated the available tools for the optical table in the lab. A list of the new optical instruments and their applications in our experiment can be found in Appendix A.

B. Laser

In order to perform the experiment we needed a laser that emits UV light with a wavelength of 351.1 nm [1]. The college owns a Stabilite 2017 Argon Ion gas laser made by Spectra Physics. However this laser was set up to emit a monochromatic or single-line blue visible light with a wavelength of 488nm. In order to get the laser to emit a UV light we had to order a secondary package from Spectra Physics that allowed us to change the wavelength emitted by the laser. The package included a high reflector mirror that replaces its counterpart in the back of the laser unit and an output coupler mirror that replaces its counterpart in the front of the laser unit. With the UV package installed the laser emits a multi-line or broadband beam ranging from 333.6 nm to 363.8 nm (More on this in the Future Investigations and Conclusion Section).

The laser is water cooled and uses a system of two closed water circuits to transfer heat from the laser. The first circuit uses deionized water which flows through a filter, the laser unit, a heat sink, and then a pumping/cooling unit. The second circuit is tap water and is pumped through a hose assembly that runs through the other side of the heat sink. Therefore the majority of the heat is transferred in the heat sink, between the two systems without there ever being an exchange of water. About half of the heated tap water is drained away while the other half is recycled and combined with cool tap water from a faucet in order to maintain a high enough water level.

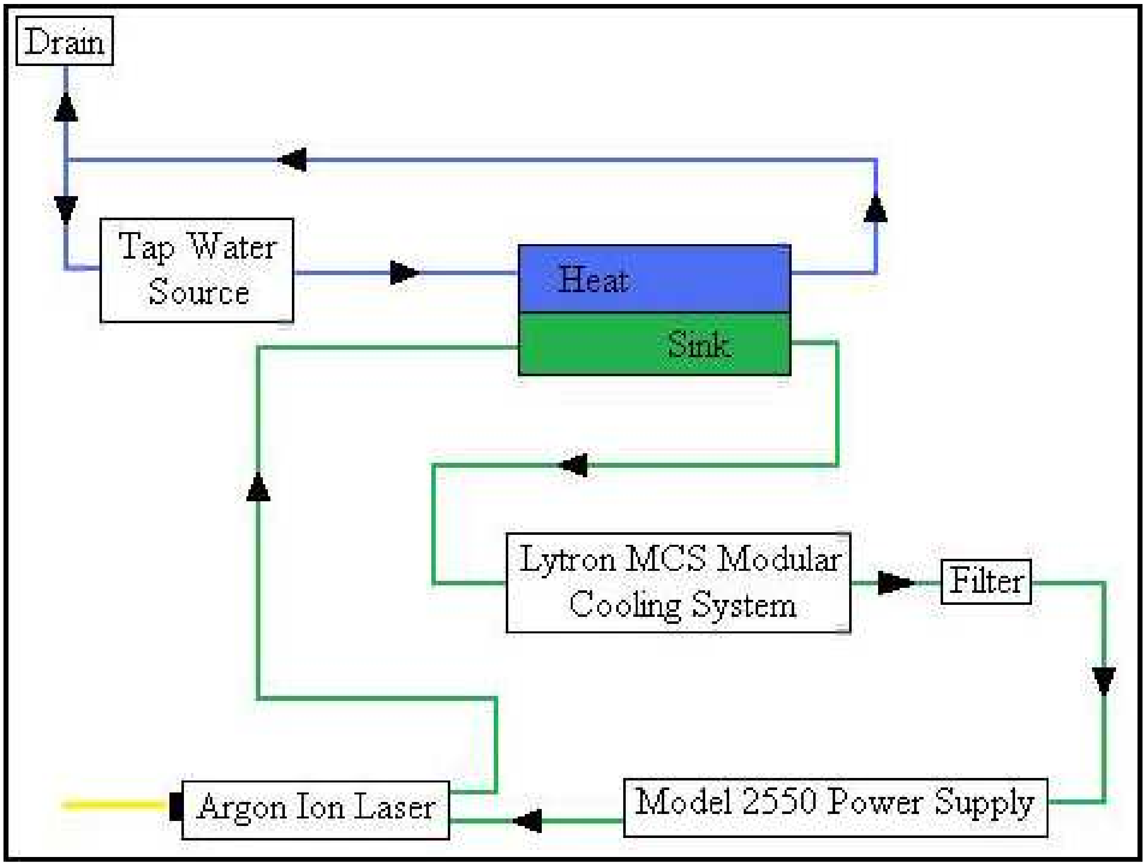

FIG. 1. A schematic of the cooling system used with the laser. The green and blue colors represent the two separate water circuits.

C. Crystals

In order to produce the entangled photons and observe the quantum nature of light, only 1 β-BaB_2O_4 (Beta-Barium Borate or BBO) crystal is necessary [2]. However, to test the Bell inequalities, an additional two more BBO crystals of shorter length are required [1]. In both experiments a 3mm crystal is used for the SPDC of the UV light. While in the second experiment, the two shorter crystals are used to compensate for the longitudinal and transverse walk-off between the ordinary and extraordinary polarized light cones emitted from the 3mm crystal [1]. We purchased four BBO crystals; two shorter 5x5x1.5mm crystals and two longer 5x5x3mm crystals with the second 3mm crystal as a backup for the first. The sides of the crystals have humidity-barriers and antireflective coatings because of the hygroscopic nature of the crystal [2]. Therefore when not in use, the crystals are kept in a desiccant jar.

BBO crystals can be designed for either type-I or type-II phase matching. In type-I phase matching; the down-converted correlated photons have the same polarization and are emitted in a single cone concentric with the pump [1,3]. In type-II phase matching, the correlated photons are emitted in two separate cones with perpendicular polarizations (i.e. one is ordinary polarized and the other extraordinary polarized) [1,3]. In order to test the Bell inequalities the entangled photons mush have perpendicular polarizations, therefore our crystals are cut for type-II phase matching with an optical angle of 49.3°. The optical angle of the crystals allows for collinear SPDC operation when the pump beam is orthogonal to the aperture surface of the crystal [1,3].

Meaning that the extraordinary and ordinary cones are tangent along one line, which is in the pump beam direction, and the entangled photons travel collinearly with the pump beam (Figure 2a) [1,3]. If the angle between the crystal optical axis and the pump beam is decreased then the two cones will separate from one another and no intersection occurs, but if the angle is increased the two cones move closer together and intersect along two lines (Figure 2b) [1]. The entangled photons are emitted along the intersections of the cones and are noncollinear with the pump beam. This is an important property; since the majority of the pump beam passes through the crystal unaffected, the noncollinear property separates the signal and idler beams from the unaffected pump beam. This makes it much easier to detect the signal and idler waves and distinguish between them.

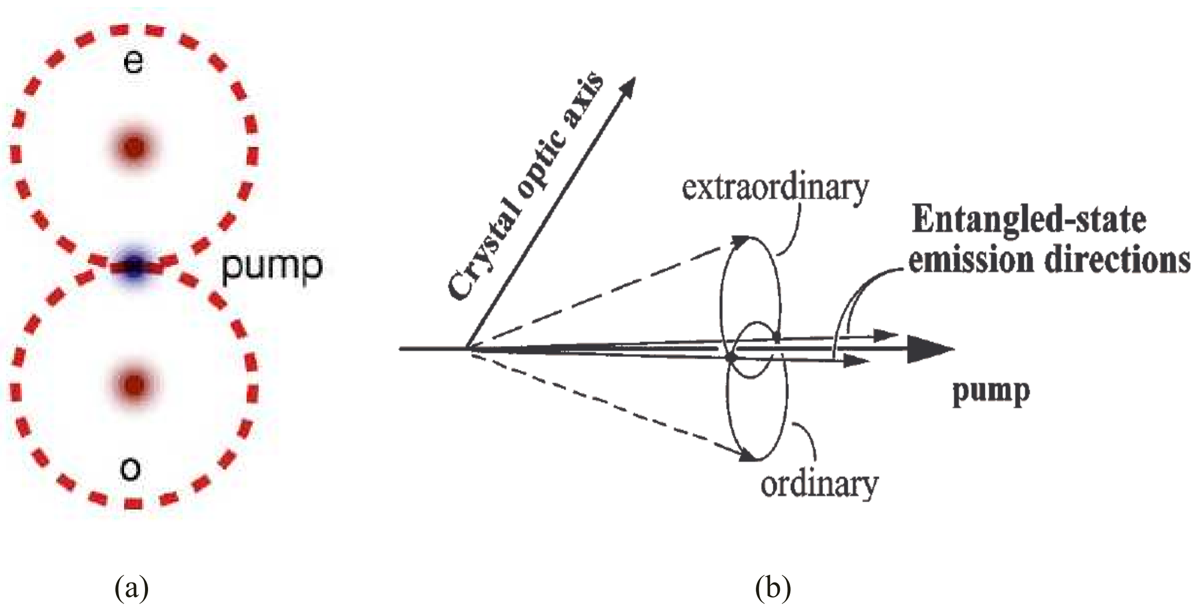

FIG. 2. (a) Representation of collinear SPDC in a BBO crystal [Image from Reference 3]. The ordinary (o) and extraordinary (e) cones are tangent along a single line, which is in the same direction as the pump beam. (b) Representation of noncollinear SPDC in a BBO crystal [Image from Reference 1]. The ordinary and extraordinary cones are tangent along two lines that lie in the same plane as the pump beam.

D. Electronics

Photons are detected with a photomultiplier tube (PMT) which then sends a signal through a series of electronics for data processing. The college owns 4 Bialkali 28mm side-on PMT's made by Hamamatsu Photonics (Product number: R4220P). The PMT has a detection range of 185nm to 710nm with peak sensitivity at 410 nm and high quantum efficiency for wavelengths in the nominal range 200nm-550nm (Figure 3) [4]. The PMT is connected to a high-voltage power supply socket assembly also made by Hamamatsu Photonics (Product number: C6270). The PMT power supply socket has an output range of 0V to 1250V. The power supply socket requires a constant 15V DC source to operate and for this we used a Hewlett Packard E3610A Power Supply. To reduce light intensity, the PMT's and power supply sockets were placed in metallic custom housings. The power supply sockets and the custom housing were designed so that a digital multi-meter (DMM) operating in DC mode could be used to check the voltage applied to the PMT by the high-voltage power supply. The DMM reads a range of 0V-5V corresponding to the 0V-1250V range of the power supply socket. Therefore to get the voltage applied to the PMT, multiply the reading from the DDM by 250. We found that a setting of 750V (3V by DMM) provided optimal detection and negligible dark current counts.

The signal from the PMT was then sent to a Lecroy Model 612A 12 Channel PM Amplifier where the signal was amplified by a factor of 10. In order to discern between dark current and actually photon detection, the amplifier sent the amplified signal to a Lecroy Model 821 Quad Discriminator. The discriminator sent out a pulse whenever it received a signal that had a voltage higher than the set threshold level. This pulse was then sent to a Hewlett Packard 53131A 225 MHz Universal Counter. The counter was interfaced with a computer using Labview. When performing the experiment to test the Bell inequalities, there are multiple PMT's sending signals at once and because we are interested in coincidences between certain PMT's, we add a Lecroy 4-Fold Logic Unit in between the discriminator and the counter. The logic unit can be setup so that it will only send out a pulse when it receives simultaneous pulses from two sources.

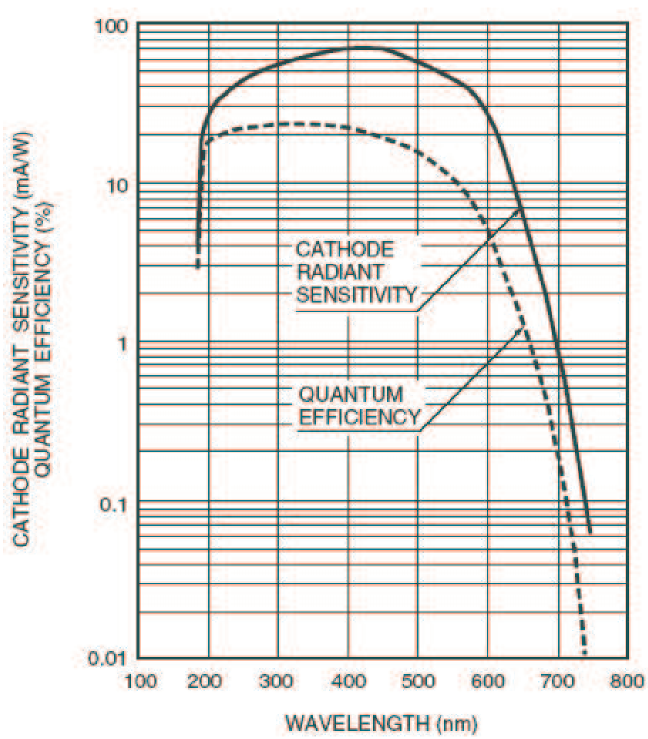

FIG. 3. The Cathode Radiant Sensitivity and Quantum Efficiency graph for the R4220P PMT. [Image from the Hamamatsu Photonics website. See Ref. 4].

Experiment

A. Setup

There were two setups that we created in order to generate and detect the photon rings. These setups were designed for the purpose of viewing an image of the two photon rings on our photographic materials.

In the first setup, the laser light shines through the 350nm UV filter which filters out unwanted wavelength created by the laser. The light that goes through the filter is reduced by an adjustable aperture so that only a very narrow beam is allowed through. Next in line is the crystal which is placed behind the aperture. After the crystal is the infrared filter, which is placed there so that the pump beam is blocked and only the SPDC photons are allowed past. In order to create an image of the two photon rings, we used various photographic materials which were placed behind the infrared filter. The idea was that the SPDC generated photons would travel from the crystal through the infrared filter and onto the photographic material. In order to cut down on the background light and light that got around the filters and apertures, we used a large sheet of black aluminum with a small opening in the aluminum placed directly behind the infrared filter.

The second setup built off of our first setup and included more instruments that we believed were necessary as we began to try and ascertain why we were not observing the photon rings on our photographic materials (More on this in the Future Investigations and Conclusion Section). This second setup has all of the components of the first setup but adds in a mirror, a prism, and a lens. The lens has a focal length of 8cm and the prism is a glass prism. The setup is shown in Figure 4 and consists of the UV filter, prism, aperture, mirror, lens, crystal, infrared filter, and lastly the photographic material. Once again a barrier with a small aperture opening was created out of black aluminum to block unwanted light from reaching the photographic material.

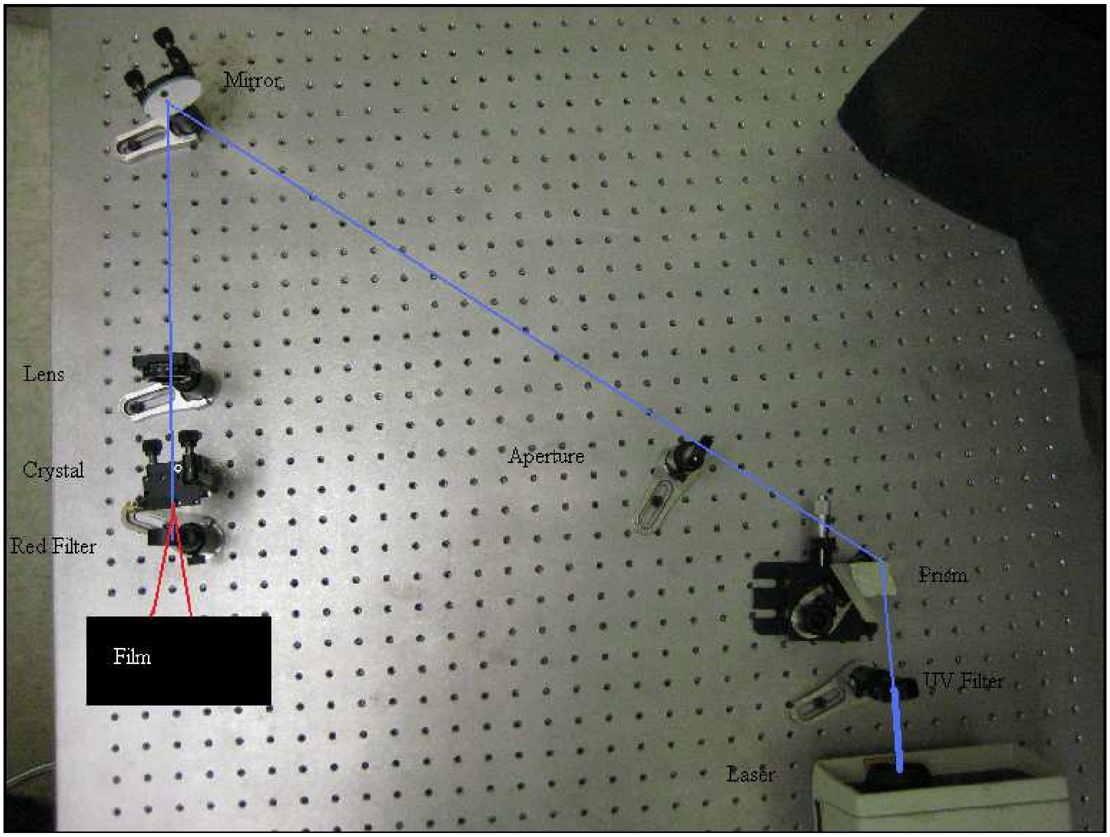

FIG 4. Image of the second setup. The blue lines represent the path of the UV light, while the red lines represent the path of the near-infrared light.

B. Photographic Materials

In order to determine if the laser and crystal apparatus was generating the desired entangled photons, we used various photographic mediums in order to obtain some form of an image that would indicate we were producing the two rings of entangled photons. We were looking for something akin to Figure 5, with some differences depending on how the optical axis of the crystal was angled to the pump beam. Remember that the way our crystal was cut, if the pump beam was orthogonal to the surface then we would expect the rings to intersect at one point only, if the crystal was tilted one way then the rings would separate completely, and if the crystal was tilted the other way then we could expect the rings to intersect in two places like the image in Figure 5. For the majority of our photographic attempts, we left the crystal surface orthogonal to the pump beam.

We used four different mediums to try and view the photon rings produced by SPDC in the crystal. In using all four mediums, a dark room was required to ensure that the images were contaminated a little as possible by background light. The four mediums are: standard paper film, high-speed panchromatic film, infrared film, and a standard digital camera.

The digital camera was different from the other three mediums, in that, for the other three mediums we were looking for an image of the two photon rings, whereas for the camera we were looking for small red point and black everywhere else. This is due to the fact that the digital camera, like most cameras, has a built in lens which, in this situation, focuses the two photons rings to a single point, since they originated from a single point. The digital camera had a maximum shutter length of 30 seconds therefore we were able to take numerous amounts of picture since it did not allow for a long exposure time. The camera images provided no evidence that the SPDC process was taking place in the crystal. The majority of the images were completely black with a few having color due to fluorescence contamination.

For the next three photographic materials, there was no mechanical limit to the exposure time. Therefore we performed exposures of the materials for times ranging from 30 minutes to 3 hours with the mode of our attempts being 1 hour. Black aluminum was used to create an aperture directly behind the infrared filter so that unwanted light could not strike the film. The next photographic medium that we tried after the digital camera was paper film. The paper film was Oriental Photo VC-RC II Glossy 5x7 paper film. The film was mounted on black paper and placed at various distances (nominal 6cm-15cm) behind the crystal. The film was then developed in Lauder Chemical Formula 721 Paper Developer and a standard fixer. Once again there was no evidence of the two photon rings. The next photographic medium we tried was Rollei Infrared 4x5 inch sheet film. Similarly to the paper film, the infrared film was mounted on black paper and placed at various distances from the infrared filter. The infrared film was then developed in Lauder Chemical Formula 76 Film Developer and a standard fixer. We expected the infrared film to give us the best results since the down converted light is in the near-infrared spectrum, but once again there was no evidence of the photon rings in the infrared film. The last photographic material we tried was high-speed panchromatic film. In total we performed 39 exposures with the three film mediums (14 paper film, 14 infrared film, 11 panchromatic film) and numerous camera exposures. The majority of the images indicated that no light had impacted the material which gives us confidence in our reduction of background light but shows that the laser and crystal apparatus was not producing the photon rings. The few images that did show that light had struck the material were inconclusive in showing the two photon rings.

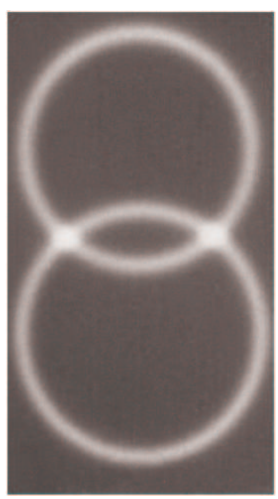

FIG 5. Image from Reference 1 (Photograph by M. Reck). The image is a photograph of the rings of photons generated by SPDC in the crystal. The picture was taken using infrared film. The entangled photons are emitted along the intersections of the cones.

Data

After performing many variations of the laser-crystal apparatus and attempting to use different photographic materials, we tested our instruments and the laser to ensure that they were operation in the ranges required to perform their particular function. The three instruments we tested were the laser, the infrared filter, and the UV filter.

For our experiment it is critical that the laser emits a wavelength of 351.1 nm, therefore we used a spectrometer to discern the wavelength(s) being emitted from the laser. The spectrometer we used was a Ocean Optics USB2000 Fiber Optic Spectrometer, and since the light from the laser emitted is UV light, we replaced the standard focusing lens on the Spectrometer with a UV Collimator which is designed so that the spectrometer can determine the wavelength of the UV light without the unwanted fluorescence created by the standard focusing lens. Figure 6 shows the spectrum emitted by the laser with the UV filter in between the laser and the collimator.

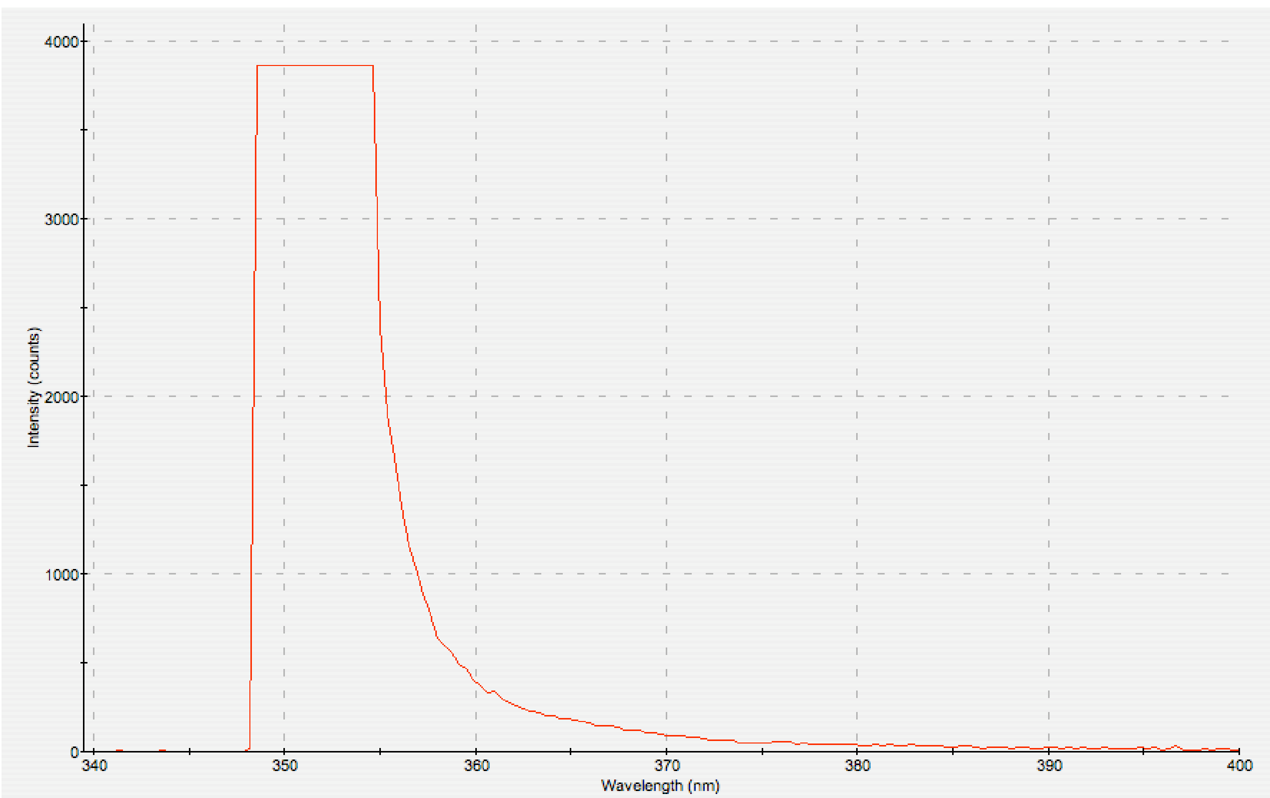

FIG 6. The spectrum of light emitted by the laser with the UV filter between the laser and the spectroscope collimator. The plateau at about 3800 is due to the limitations of the spectrometer.

For both the UV filter and the infrared filter we placed the collimator of the spectrometer directly behind the filter and then exposed the filters to sunlight. Since sunlight emits all wavelengths we were able to discern what wavelengths were being filtered out by the filter and which were being let through. We are testing the UV filter to make sure that it allows through light at a wavelength of 351.1 nm. For the infrared filter we are testing to make sure that it allows through light at a wavelength of 702.2 nm. Figure 7 shows the result from exposing the spectrometer itself to sunlight with no filter and it represents the control group. Figure 8 shows the spectrum that is allowed through the UV filter and Figure 9 shows the spectrum that is allowed through the infrared filter.

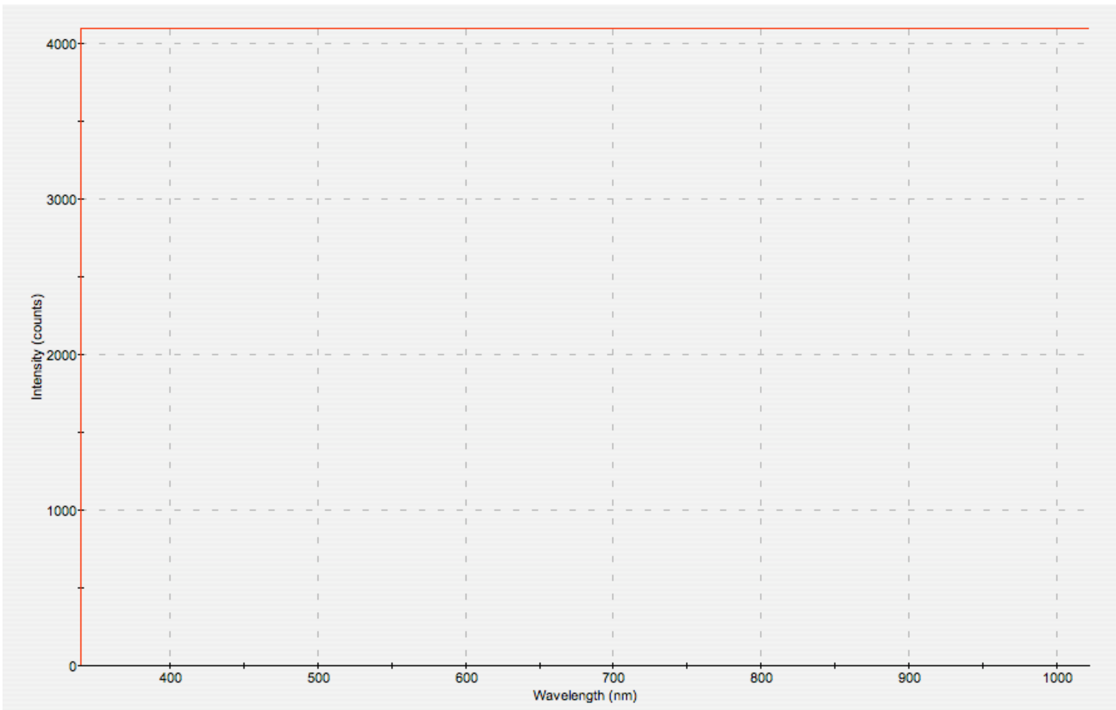

FIG 7. The graph shows the spectrum of light when the spectrometer is pointed directly at the sun. This graph is the control group for Figure 7 and Figure 8. The plateau at about 4100 counts is due to the limitation of the spectrometer.

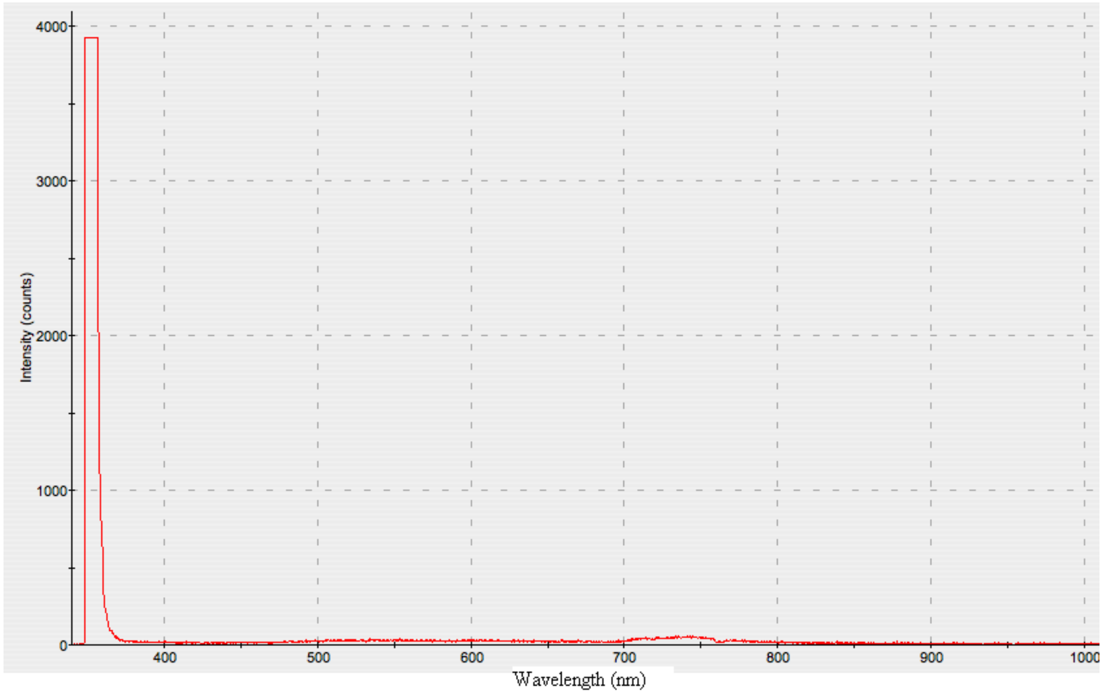

FIG 8. The graph shows the spectrum of light that passes through the UV filter. The column width ranges from about 348.9nm to about 359.5nm. The plateau at about 3800 counts is due to the limitations of the spectrometer

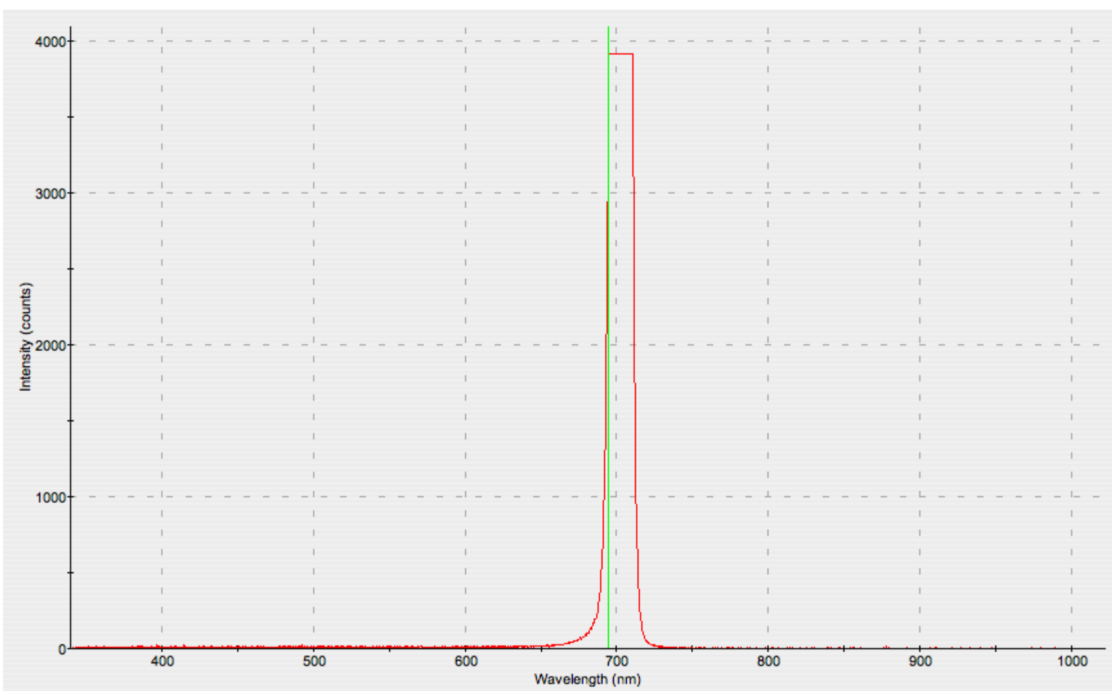

FIG 9. The graph shows the spectrum of light that passes through the infrared filter. The column width ranges from about 695.3nm to about 711.0nm. The plateau at about 3800 counts is due to the limitations of the spectrometer. The green line shows where 695.26nm is.

Future Investigations and Conclusion

In the ten weeks that we had to perform this experiment we have made considerable progress although we have not yet been able to create an image of the two photon rings. In this conclusion we will investigate reasons why we believe we have not gotten the images we are looking for despite our numerous trials. From Figure 8 and Figure 9, we can say with confidence that the filters are performing to the desire specifications, meaning that the filters allow through the wavelengths that we want. The graph of the UV filter shows that the filter lets through the range of wavelengths 348.9nm to 359.5nm. This works well with our experiment since we want a wavelength of 351.1nm to shine on the crystal and this wavelength is within the range that passes through the filter. The infrared filter works well with our experiment because, we want the filter to allow through the wavelength 702.2 and the filter lets through the range of wavelengths 695.3nm to 711.0nm.

When looking at the laser we begin to see some problems that may be preventing us from generating the two photon rings. In other experiments using the same process to create entangled photons, the lasers that were used were single-mode laser operating at 351.1nm or 351nm [1,5]. However as was stated in the Laser subsection of the Materials Section, when the Stabilite 2017 Argon ion laser is shining UV light, it is emitting in multi-mode, not single-mode. A single-mode laser is designed to emit only one wavelength at high intensity with a very small bandwidth. A multi-mode laser emits a range of wavelengths with high intensity. The laser that we used in our experiment emits a multi-mode wavelength range of 333.6 nm to 363.8 nm. Although the wavelength that we want, 351.1nm, is contained within this range, there is a large intensity of unwanted excess light that is emitted by the laser. Figure 6 shows the spectrum of light that is emitted from the laser and that passes through the UV filter. Therefore we can see that some of the light from the laser is being cut off by the UV filter because Figure 6 shows that the wavelengths 333.6nm to about 346nm do not get past the filter. However there is still a large range of wavelengths getting through the UV filter and at high intensity. All of this light is striking the crystal and the excess light may be preventing the SPDC process of the 351.1nm from taking place. It is for this reason that we designed and implemented the second setup of our experiment. The idea was that the prism would separate the different wavelengths of light from each other and we would be able to isolate the 351.1nm wavelength and redirect only that wavelength at the crystal. However the prism that we used was a low quality standard prism and it did not perform the function that we required. Therefore for our future attempts we will need to order a prism that is UV specific, meaning that it will separate the UV wavelengths. With this prism we will be able to separate the desired wavelengths from the excess wavelengths and redirect only those desire wavelengths at the crystal.

In addition to obtaining a new prism, it is likely that we will need new PMT's as well. We built the housing units for the R4220P PMT's because these PMT's were needed in another experiment and because they were readily available at the college. However, when we examined Figure 3, the quantum efficiency graph, we noticed that these particular PMT's have very low quantum efficiency for the near-infrared spectrum. In other words these PMT's will not effectively detect the 702.2 nm wavelength that is required in our experiment. It is possible that these PMT may be adequate but because of the low-intensity of the entangled photons, it probable that they will not be sensitive enough. Therefore, new PMT's will most like have to be ordered as well. We searched around for PMT's with high quantum efficiencies in the near-infrared range and we found Multi-Alkali 28mm side-on PMT's made by Hamamatsu Photonics (Product Number: R3896). The nice thing about these PMT's is that they are the same size as the R4420P PMT's and can use the same high-voltage power supply socket assembly. This means that they are interchangeable with the R4220P PMT's and we can use the same custom housing for the R3896 PMT's. The R3896 PMT has a detection range of 185nm to 900nm with peak sensitivity at 450 nm and high quantum efficiency for wavelengths in the nominal range 200nm-700nm [Figure 10] [6].

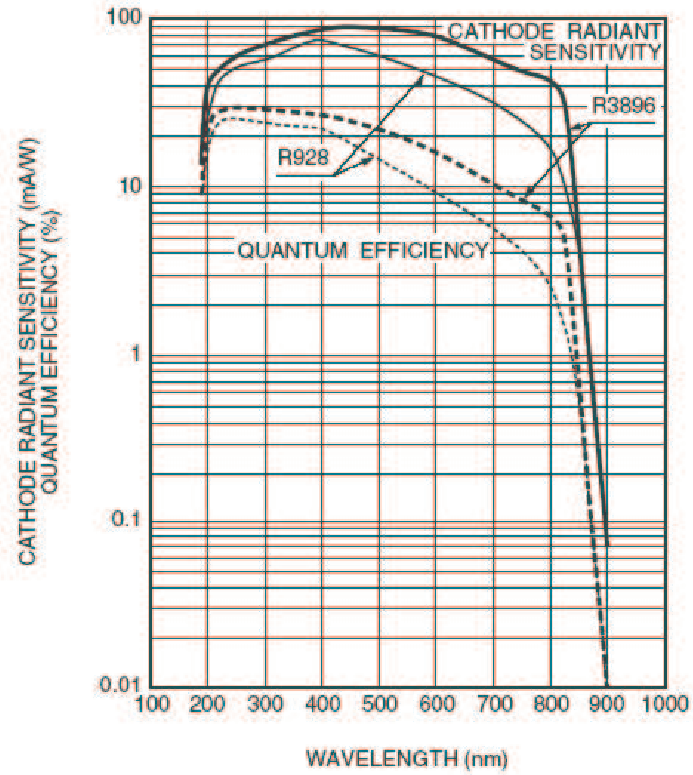

FIG. 10. The Cathode Radiant Sensitivity and Quantum Efficiency graph for the R3896 PMT. [Image from the Hamamatsu Photonics website. See Ref. 6].

Appendix A

Optical Instruments

The following is a table of the optical instruments purchased for this summer research and their usages in the experiment:

Optical Instrument	**Usage**
4 Adjustable Apertures	Removing excess light and controlling beam size
1 Dual-Axis Goniometer	Change the angle the crystal face makes with laser.
4 Small Clamping Arms	Used with Kinematic prism mounts to hold crystals
4 Kinematic Mirror Mounts	Mount Mirrors and Polarizers
4 Kinematic Prism Mounts	Mount Crystals
2 Cage Rotation Mounts	Mount Polarizers and Crystals
2 Precision Cage Rotation Mounts	Mount Polarizers and Crystals
1 Precision Rotation Mount	Mount Polarizers and Crystals
3 Flip Lens Mounts	Hold the laser line filters.
1 Translation Plate	Move the crystal closer to or farther away from laser.
2 Half Wave Plates	Used to rotate the polarizations of the entangled photons
3 Polarizers	For use in the Bell inequality experiments.
1 20μm aperture	Fixed aperture for reducing light intensity on PMT
1 10μm aperture	Fixed aperture for reducing light intensity on PMT
1 Laser Line Filter- 350nm-10 FWHM*	Filter light
2 Laser Line Filter- 702nm-10 FWHM*	Filter light
1 Detector Card- 250-540nm	Used to locate and align the UV laser beam
1 Spanner Wrench	Used to adjust retaining rings on rotation and lens mounts
4 Mini-Mounting Posts	Used to mount the crystal unit onto the goniometer
2 Mini-Post Holder	Used to mount the crystal unit onto the goniometer
1 Black Hole Beam Terminator	For stopping and containing the excess UV laser beam.

*FWHM- Full Width at Half Maximum

References

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