Single Photon Interference Demonstration for Undergraduate Courses

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Abstract

A difficult topic for students is comprehending that photons are both particles and waves. This demonstration deals with that topic by showing students the result from single photon interference.

It does this by using a CCD Camera, a laser, a 25 micrometer diameter pinhole, 140 cm of 10 cm diameter metal pipe painted matte black on the inside and outside, and a .25 mm separated double slit. Students are used to seeing in their lab courses fringe patterns, though with a continuous light source. This demonstration therefore shows this same pattern, though created with individual photons picked up by the CCD camera. From these individual photons, the maxima and minima fringes from the double slit can be seen quite well.

Therefore, due to the photons showing up as points on the screen, and seeing the famous interference pattern, students are able to come to the conclusion that light is both a particle and a wave. This document discusses both the design and different results that one can get out of this experiment.

Contents

1 Theory

The theory behind this demonstration is Wave-Particle Duality, which is based on the DeBroglie Hypothesis: all particles show evidence of having properties of both an object and a wave. This demonstration shows the wave-like nature of photons by sending one photon through a double slit at a time, with a fringe pattern still being created in the output. This demonstration is a newer approach to the one that is hosted on Harvard's website with the use of a CCD Camera, as they have a higher quantum efficiency than the low light level TV camera they used [1].

This is done by first sending the light source (monochromatic laser) through a pinhole, to reduce the intensity by spreading out the photons. Figure 1 shows pinhole diffraction that the laser undergoes in 3-dimensions. From this, it's shown that the light is spread out in all directions around the pinhole.

This is important because it shows that the photons do not stay coherent when traveling through the pinhole, and most of them diverge away from the center. Figure 2 shows not only how the light is dispersed over a distance, but also where the maxima is located and how dispersed it is. This would be what the double slit would ultimately be receiving.

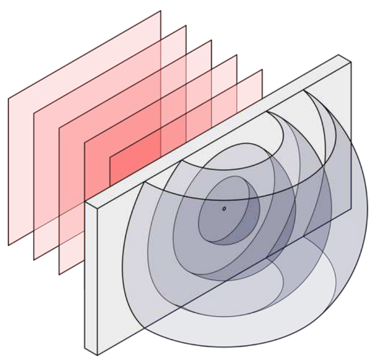

Figure 1: 3D depiction of how light propogates through a pinhole source [2].

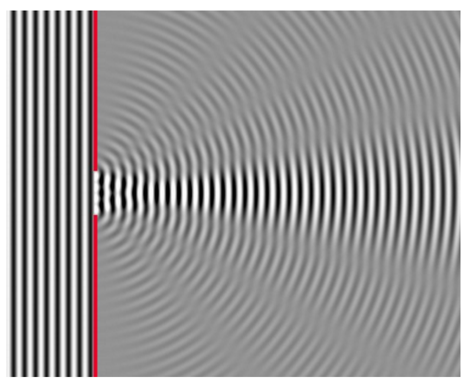

Figure 2: 2D depiction on how light propogates through a pinhole source [3].

The size of the double slit separation is 25 micrometers, and the size of the central maxima of the fringe pattern is 33 micrometers. The difference in the size between these can be found in the calculation below.

$$
\begin{aligned}
y &= \text{Displacement} \\
D &= \text{Distance to CCD Camera (0.80 m)} \\
m &= m\text{-value for maxima or minima (1.635 for central maxima)} \\
\lambda &= \text{Wavelength of source (633 nm} = 6.33\times10^{-7}\text{ m)} \\
d &= \text{Aperture diameter}
\end{aligned}
$$

$$y \approx D\left(\frac{m\lambda}{d}\right) \approx (0.80\text{m})\left(\frac{1.635 \times 6.33 \times 10^{-7}\text{m}}{2.5 \times 10^{-5}\text{m}}\right) \approx 33\ \mu\text{m}$$

This shows that the size of the central maxima is roughly 32% larger than the double slit, meaning that not all of the photons from the central maxima go through the double slit. The actual size of the slits themselves are much smaller than this, meaning that only a small fraction of the photons are actually going through the slits. This is reduced to essentially a single photon due to the low intensity of the light, since the photons from the laser are dispersed so much that only one goes through at a time. Then the photons leave the double slit and hit the CCD Camera that is 60 cm away from the double slit. The CCD Camera is connected to a PC running CCDOps which is the program for the camera.

A more rigorous, and mathematical calculation is performed below to solidify the idea that only one photon is hitting the CCD at any given time.

Source to Detector	=	1.4 m
Photon time in tube	=	$\frac{1.4\text{ m}}{3\times10^{8}\text{m/s}} = 4.67\times10^{-9}$ seconds
Sensor Quantum Efficiency	=	85% [4]
Images indicate approximately	70,000	photon “hits” per second

$$\left(\frac{70,000\text{ photons}}{.85\text{ efficiency}}\right) \approx 82,000\text{ photons striking any given second}$$

This leaves the average time between each photon hitting the CCD to be:

$$82,000\text{ photons} \times 4.67 \times 10^{-9}\text{ seconds in tube} \approx .5\text{ ms}$$

Therefore, the above calculation shows that there is no way for a photon to be interfering with another photon and thus must be interfering with itself since the spacing between each detected photon is .5 ms.

2 Experimental Setup

2.1 Housing and Double Slit

The housing for this demo is 140 cm of 10 cm diameter metal tube painted matte black on the outer and inner surfaces. It’s painted matte black so that it will absorb, and not reflect, stray photons into the surface, thus reducing the number of photons seen, since they won’t be reflecting off the tube into the CCD then and skew the results. A complete diagram of this setup can be seen in Appendix B. The metal tube is mounted on a custom made aluminum frame to prevent it from moving around from accidental knocking or when moving the demonstration. The frame also has a holder for the laser on one end of the tube as to keep the laser and pinhole aligned in transport or accidental knocks. On the opposite end of the tube is where the CCD camera is located and mounted in the metal tube.

The double slit is located about 80 cm away from the pinhole, with a slit separation of .25 mm. There is a 12 cm long cutout on top of the metal tube above the double slit. This cutout is used to gain access to the double slit, and to check the alignment. It is important to place the double slit directly in the middle of the setup so that it will be aligned with the CCD camera. To cover up the cutout, a lid was made to fit over the top and to be screwed down to hold it in place.

Figure 3: Picture of the laser housing. In this image, you can see the place holder for the laser, along with the mechanism to move the laser's position. The knobs allow fine tuning of the orientation of the laser by changing the pitch up or down and moving the laser left or right so it can be aligned with the pinhole.

2.2 CCD Camera and Color Wheel

The camera used is a Santa Barbara Instrument Group (SBIG) ST-7 CCD camera. The reason this camera was chosen was because of its high quantum efficiency. It is an astronomy camera meant to be used in conjunction with a telescope, so it has to be able to pick up individual photons, it has a quantum efficiency of 85% [4]. Therefore, not any camera will work with this setup, as this demonstration requires the use of a camera with a relatively high quantum efficiency.

The color wheel is a CFW-8 color wheel that was manufactured for use with the camera. The color wheel has 4 slides on it that are translucent with different colors which consist of: red, blue, green, and clear. It was realized that all of the noise in the system was a lower intensity than the data. The best results were seen with the use of the color wheel to gate on the intensities. Instead of just subtracting a normal dark frame from a single exposure, the program CCDOps takes a normal dark frame by closing the shutter, then takes an exposure with the blue filter, then takes an exposure through the clear filter. Then the program subtracts what it got in the dark frame and in the blue filter exposure from the clear filter exposure. The color wheel is not required, though the demonstration provides better results with the color wheel. However, the color wheel adds a substantial amount of time to the demonstration since without it, it only needs to take two exposures (dark frame and normal exposures) instead of three exposures with the color wheel (also the blue filter exposure).

Figure 4: Location for the Camera and Color Wheel. The hole is a bit larger than the CCD and the Color Wheel so they can be screwed in to prevent movement. Half way down the tube, there's a cutout lid which is directly above the double slit and is used for installing the double slit and making sure the laser without the pinhole is aligned.

2.3 Laser and Pinhole

The laser is a class 2 HeNe laser of 633 nm wavelength and a maximum output of less than 1 mW. The CCD is sensitive to 650 nm wavelength light, so having a laser relatively close to that wavelength is ideal so that the camera will pick up most of the light [4]. There is a housing for the laser to make it easier to align with the pinhole. The laser housing can be seen in Figure 5 below. The knobs on the bottom move the laser in the horizontal axis, while the bass knos at the top move the laser up and down. The alignment of the laser with the pinhole is crucial in the setup.

Figure 5: Housing for the laser. The bottom knobs are for shifting the laser horizontally while the brass knobs at the top are for changing the pitch of the laser vertically. This is for aligning the laser to the pinhole.

The pinhole is used to decrease the intensity of the light before it reaches the double slit which is just screwed into the end cap. The housing for the pinhole can be seen in Figure 6 below. This alignment is for aligning the pinhole to the double slit in the tube. The knob on the top of the pinhole change it in the vertical component, while the right knob changes the location of the pinhole in the horizontal component.

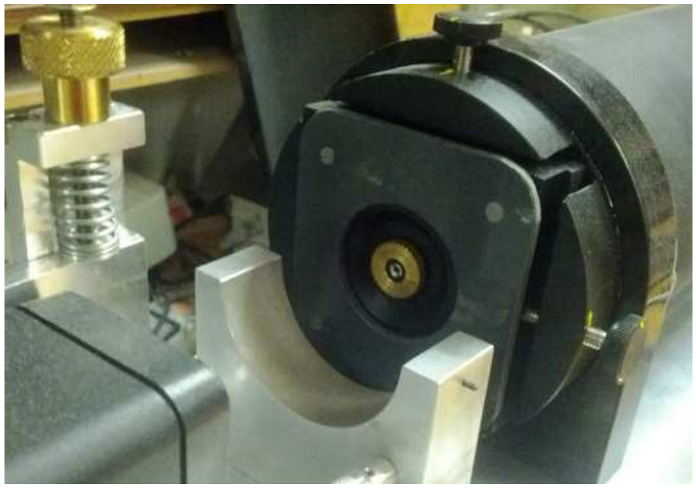

Figure 6: Housing for the pinhole. The knob on the top is for shifting the pinhole along the vertical axis, whil the knob on the right is for shifting along the horizontal axis. This is for aligning the pinhole with the double slit.

3 Collecting Data

The program used for the camera is the one provided by SBIG which is CCDOps. First, the camera's on-board cooling system needs to cool the camera to reduce the noise seen in the figures. If the temperature is too high, all that you get is noise and won't be able to distinguish the fringe patterns. However, since it's an on-board cooling system, the work load increases, and if the workload becomes too high, then there will be electrical noise to deal with as well. After various tests, -2°C was found to be te optimal temperature. To cool the camera, go to the "Camera" menu at the top, and then "Setup." Set cooling to active and the temperature to -2°C. In the bottom right of the program, you can see all of the camera data, for example: the temperature and load percentage. The camera will be at 100% load capacity until it is finished cooling when it will then fluctuate between 75%−85% capacity. Do not take any exposures until it is at the final load capacity.

If the color wheel is going to be used, it has to be setup to be used as a dark frame. To do this, go to the "Filter" menu and then "Filter Setup." From there, set the blue filter to the dark frame, and the clear filter to the normal capture filter. For the alignment procedure, go to section 5.1. When collecting the exposures, use the "Grab" option, fill in the desired exposure time, and for the dark frame option select "Also."

If the color wheel is being used, the fringe pattern should start to show up around 10 seconds exposure time. If no color wheel is being used, it should start to show at around a 20 second exposure.

Note: *In the figures below, they are not the same alignment because when the color wheel is taken off, the camera must be removed and the laser must be re-aligned after putting the camera back on.*

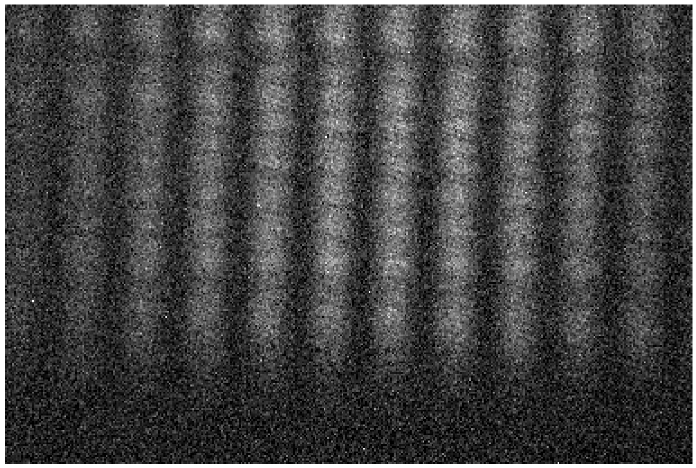

Figure 7: 60 second exposure without the color filter.

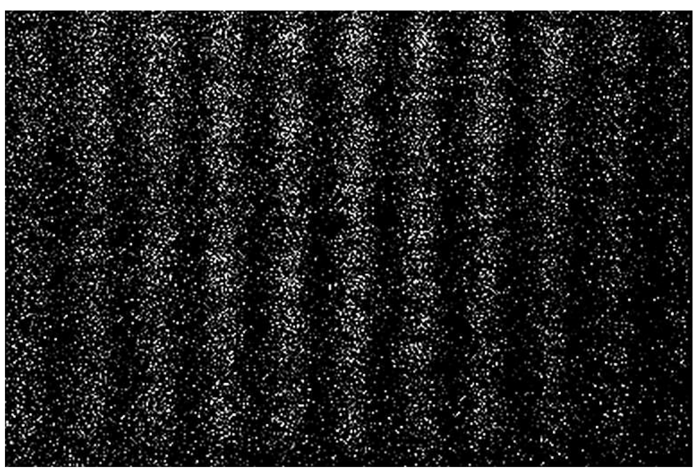

Figure 8: 60 second exposure with the color filter.

As can be seen in Figures 7 and 8 above, the color wheel produces much cleaner results. However, gating on the intensities also removes some of the acutal photons as well, so it is not an exact representation of each photon that struck the CCD camera.

4 Recommendations

4.1 Alignment

To make alignment easier, the following method is ideal. These recommendations come about by trying to find the best method to calibrate the demonstration for each setup.

First, take out the pinhole from the end cap. This is done to make sure the laser and the double slit are aligned. Check to make sure that the double slit and the laser match up, then in CCDOps do a focus instead of a grab frame for approximately 5 seconds. Make sure that a normal fringe pattern was captured, though it will be "blown out."If the capture is all white, there is too much light getting to the CCD which could be a result of a light leak, or too long of an exposure from the laser. What is being checked here is that the double slit and the CCD are aligned with each other. If not, adjust the double slit and laser accogrdingly. Try and get the fringe pattern to be centered to the capture area as that will give the best results.

Now, without moving the CCD, laser, or double slit, put the pinhole back onto the end between the laser and the double slit. With using the knobs for the pinhole, adjust the pinhole to be aligned to the path of the laser. Then, run a "focus" in CCDOps and try and get the individual photon fringe pattern. If there is none, try screwing the pinhole in 90° turns since the pinhole may have been poorly made and not be cented, try focus until you start seeing the pattern. If, after turning the pinhole 360°, there is still no fringe pattern, try adjusting the pinhole via the knobs to make sure it is aligned with the laser.

5 Conclusion

The overall setup performs quite well in producing the desired results for witnessing single photon interference. Various attempts were made in improving this setup, and the color wheel seems to make the optimum improvement.

As the calculations above indicated, this shows that the famous interference pattern still holds true for the case with a photon interfering with itself. However, there is no way to watch this *live* with this current setup, so this demonstration would have to be prepared before hand. Also, students would have to see the calculations above so that they would understand why it's being said that there is only one photon above instead of being able to watch it live. Since this cannot be shown live, the approach that was done at Florida State was to do one run to show the students the results for themselves, then show them a slideshow of runs at different intervals.

A
Double Slit Location

Figure 9: How the double slit is installed in the metal pipe.

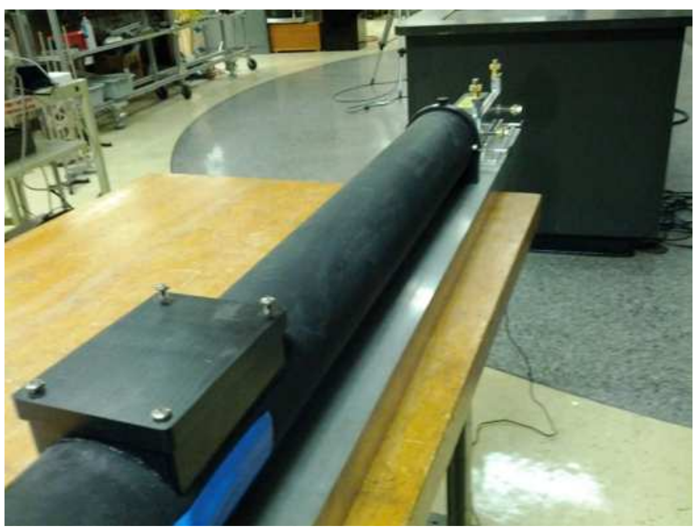

Figure 10: How the double slit "box" looks on the outside.

B Diagram of Setup

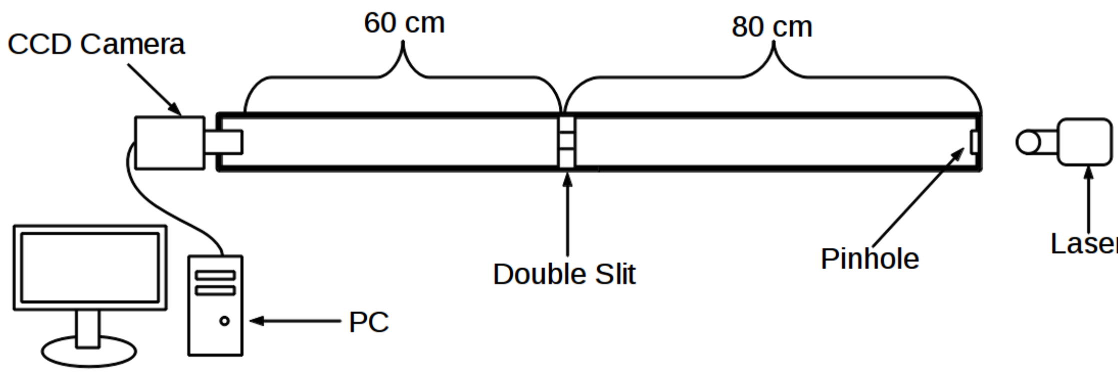

Figure 11: Diagram of setup

References

[1] Harvard University, *Quantum Mechanics: Single Photon Interference*, Accessed: February 2012; http://sciencedemonstrations.fas.harvard.edu

[2] Wikimedia, *Diffraction Through Pinhole*, Accessed: May 2012; http://commons.wikimedia.org/wiki/File:Diffraction_through_Pinhole.svg

[3] Dmitri Pogosyan, University of Alberta, *Wave Diffraction*, Accessed: May 2012; http://www.ualberta.ca/~pogosyan

[4] Santa Barbara Instrument Group (SBIG), *ST-7 Information*, Accessed: April 2012; http://ftp.sbig.com/sbwhtmls/st7.html