Single Photon Interference: Wave-Particle Duality and the Quantum Eraser

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Abstract:

Using a Young's double slit interferometer and a Mach-Zehnder interferometer, we generated single-photon interference fringes and demonstrated the wave-particle duality of light. With both interferometers, we observed the behavior of single photons by attenuating laser light with neutral density filters down to the single-photon per meter level. The first experiment with the double slit shows that, even at single-photon levels, an interference pattern is formed when viewing a sufficient number of photon impacts suggesting that each photon travels through both slits and interferes with itself. A "quantum eraser" is used in the second experiment, where we used a Mach-Zehnder interferometer to show how the visibility of the interference fringes is related to the amount of which-path information. To make a quantum eraser, the following alterations to a traditional Mach-Zehnder interferometer are made: the first beam splitter in the interferometer is polarizing and the the second is non-polarizing, a polarizer oriented with its fast axis at 45° is introduced before the first beam splitter, and the quantum eraser itself, a polarizer located after the second beam splitter, is inserted. With these alterations, the angle (θ) of the quantum eraser can be used to control the visibility (V) of the interference fringes by $V = |sin(2\theta)|$. Maximum intensity is thus seen when the polarizer is set to $\pm 45 * m°$ ($m = 1, 3, 5, \ldots$). We performed these experiments with both an EMCCD camera and a CMOS camera to compare their performance at single-photon levels.

Introduction and Theoretical Background:

Brief History of the Physics of Light

The scientific consensus on the nature of light has oscillated between particle-like and a wave-like for hundreds of years. In 1637, Descartes used an analogy to how sound waves speed up in different mediums to explain how light refracts when it enters new mediums. In the late 17th century, Newton rejected this conception in favor of Gassendi's particle theory of light in order to explain reflection and refraction. At the same time, men like Huygens and Hooke theorized that light was an oscillation in some undetectable medium which encompasses our world. Just as sound waves can interfere, in 1801 Young used a simple double slit experiment to show that light interfered with other light as well. By the middle of the 19th century, the wave theory was generally accepted.

New findings by Faraday then hinted at some relation between light and electromagnetism. Inspired by this, Maxwell examined the relationship between electromagnetic radiation and light. In 1873, he theorized that light was an electromagnetic wave and came up with a complete mathematical description of its behavior. Unfortunately for Maxwell's theory, the description was not complete for long. The equations he had come up with failed to explain the spectrum of blackbody radiation. Planck, in 1900, theorized that light only comes in discrete packets, or quanta, in order to account for this problem. Einstein then took this idea of quanta and used it to explain the photoelectric effect in 1905. Einstein took it a step further and added that these "light quanta had a 'real' existence".

Twenty years later, these light quanta had a name, photons, and it was clear that no theory of light was complete without accounting for these particle-like photons. However, (disputed as to who was first to show this) it was soon shown that even single photons appear to interfere with themselves. That leads us to today's conception of the wave-particle duality of light. [1]

Wave-Particle Duality

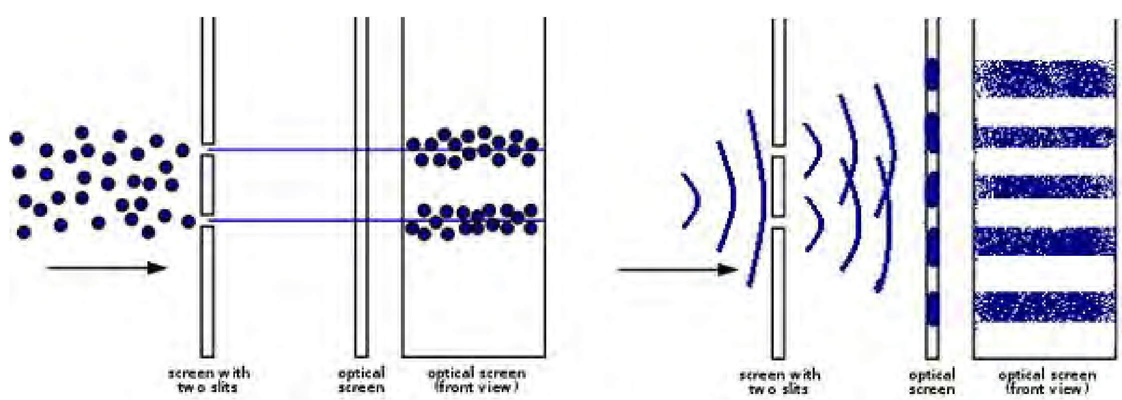


Figure 1: Pictured (Left) is what one would expect a particle's impact pattern on a screen to be after passing through two slits compared to (Right) what one observes when photons pass through two slits. [2]

Today, it is accepted that photons, although they are typically conceived of as particles, exhibit properties of both particles and waves. This is the so-called wave-particle duality. A typical particle incident on two slits either travels straight through one slit or the other and then travels straight onwards. A photon incident on two slits does not behave this way. It will generate an interference pattern on the other side if many photon impacts are accumulated, just like a wave. Interestingly, this behavior can only be seen when there is no way to know which slit the photon traveled through. In other words, when there is no "which-path" information.

In the second part of our experiment, we set out to test this effect of "which-path" information on the visibility of an interference pattern formed by a mach-zehnder interferometer at single-photon levels. First of all, to reduce the light to approximately single photons levels, we measure the incidence power on a detector at the location of the camera and determine the number of photons per meter with the following equation:

$$\frac{photons}{meter} = \frac{P_{measured} * \lambda}{hc^2} \qquad \textbf{(Eq. 1)}$$

We can say that we are at approximately single-photon levels when the count is less than 1 photon/m. Once this is achieved, our experiment uses a polarizing beam splitter and a polarizer after the second, non-polarized beam splitter of a mach-zehnder interferometer – this polarizer is dubbed the "quantum eraser" for reasons that will become apparent. 45° light incident on the polarizing beam splitter is sent in equal parts down both paths, so each photon has an equal chance of traveling down either. We can then control, by altering the angle of the quantum eraser, which path's light passes through the polarizer. When considering single photons, this means that, if light from one path is blocked out completely and a photon passes through the polarizer, we know the photon travelled down the unblocked path. If the polarizer blocks light from both paths equally, there's no way to know which path a transmitted photon travelled down. In other words, we can use the polarizer angle to control how much which-path information we have. What we aimed to show in this lab is that the visibility of the interference pattern is directly related to the angle of the quantum eraser according to:

$$V_{fringes} = | sin(2 * \theta_{eraser}) | \qquad \textbf{(Eq. 2)}$$

In our use, visibility is a measure of the contrast of our interference fringes. Effectively, it's a measure of the difference between the brightest, high intensity, and dimmest, low intensity, regions of the fringes. We will use the equation:

$$V = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} \qquad \textbf{(Eq. 3)}$$

To calculate visibility from the images taken in our experiments. We can see that a visibility of 1, the maximum, can only be seen when the minimum intensity is 0, and the minimum intensity, 0, can be seen when the maximum intensity and minimum intensity are equal. In the visibility = 0 case, there are no fringes – all points being viewed are of uniform intensity. [3] [4]

EM CCD and CMOS Cameras

In selecting a camera for single-photon experiments, there are a few main factors to consider: signal/noise, cost, and necessary speed of data capture. In this lab, we use two types of cameras with different advantages and disadvantages in these areas: an EMCCD camera and a CMOS camera.

The essential difference between the two cameras in operation is the detector chip. An EMCCD camera has an EMCCD chip, as the name indicates. On any CCD, a charge is generated when a photon impacts the chip, and the charge is shifted down the chip to where it can be converted to a digital signal and sent to a computer. On an EMCCD, there is an additional section, the electron multiplying section, that amplifies the strength of all signals passed down the CCD chip towards the reading and converting section. On a CMOS chip, the way signals are read is different. Charges are still created when a photon impacts the detector, but, on this type of chip, each charge bin has the capability of reading the signal. This means that there's no need to pass the charge down the detector. Unlike CCD chips, CMOS chips are designed in such a way that they can be fabricated with the same equipment as many common semiconductor chips and this leads to a dramatically lower price to manufacture and thus purchase CMOS chips. However, there is no electron multiplying section and thus the signal to noise is much worse on the CMOS chip. Because of this difference in sensitivity, the CMOS must use much longer exposure times to capture enough light to generate an image equivalent to what an EMCCD could generate.

Overall, an EMCCD chip has better signal/noise ratio and can capture images at single-photon levels much faster given the needed exposure time for image capture with a CMOS. In terms of cost however, an EMCCD cameras cost tens of thousands of dollars while a CMOS camera costs hundreds to thousands of dollars. [5]

Experimental Setup and Procedure:

This lab has two main components: Young's Double Slit Interferometer and the Mach-Zehnder Interferometer. The schematic for these two setups is shown in figure 2, and figure 3 show the lab setup. We repeated each of the experiments on these two interferometers with two different detectors, the EMCCD camera and the CMOS camera. Figure 4 shows the EMCCD camera used.

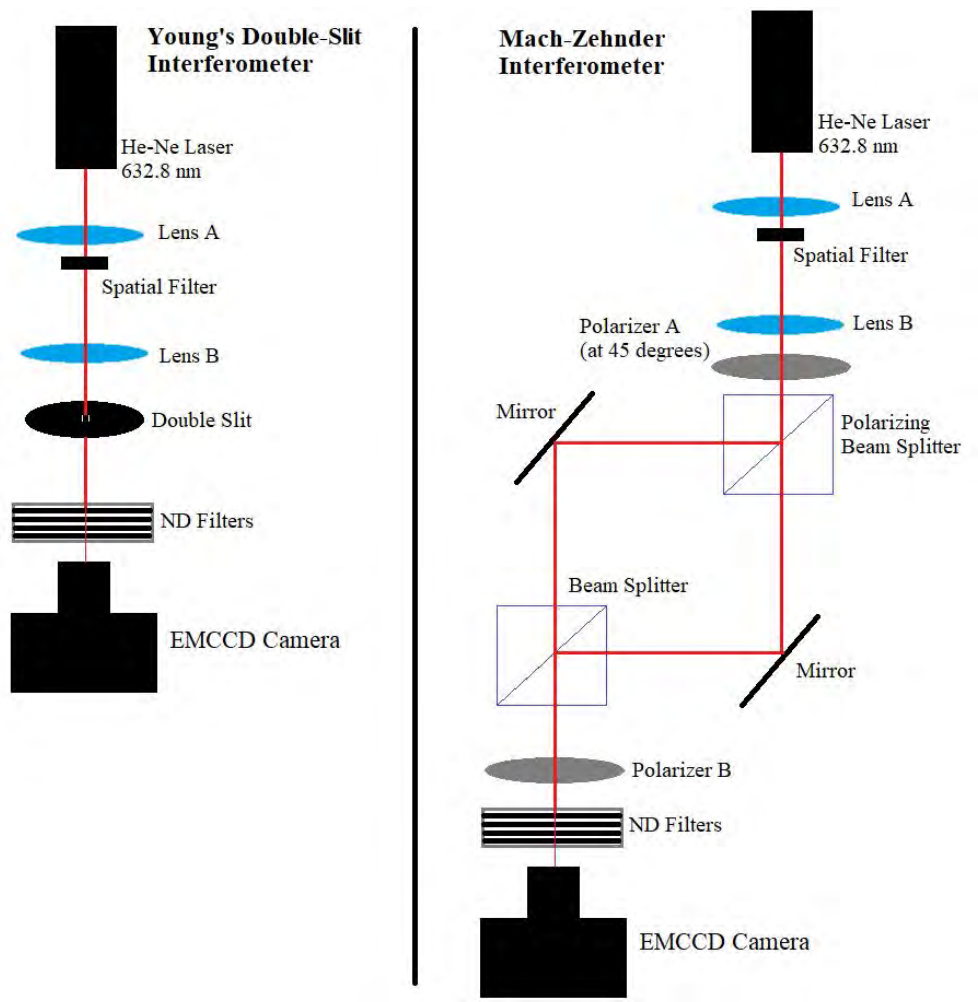


Figure 2: The experimental setup for the two types of interferometers. For the Mach-Zehnder interferometer Polarizer A is set to 45° in order to have an equal amounts of horizontally and vertically polarized photons that go through the polarizing beam splitter. After taking measurements on the EMCCD camera, we repeated the measurements with a CMOS camera.

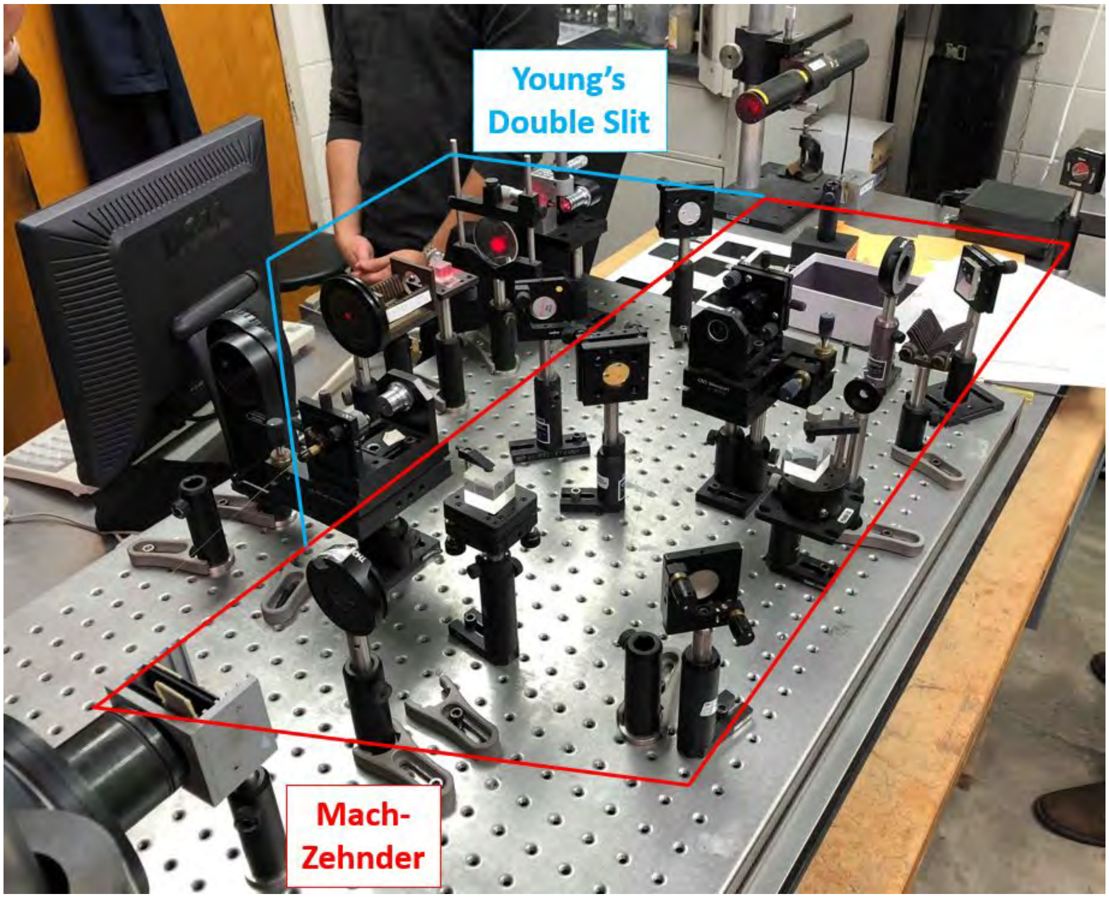


Figure 3: The lab setup of the two interferometers used.

Young's Double Slit Interferometer

In order to test the wave-particle duality of single photons, we must first be able to produce single photons. The first step of the experiment is to test the power of the laser at the detector and calculate how many neutral density (ND) filters are needed to create one photon per meter. Lens A works to focus the laser through the spatial filter. This filter creates a gaussian profile for the laser. Lens be then recollimates the laser light. The light then passes through the double slit, creating an interference pattern. After we have our single photon source, we are able to align the proper detector with the rest of the system. For this part of the experiment we are only testing limits of the camera and its respective software. After taking images of different acquisition times for the CMOS and different gains, accumulations, and acquisition times for the EMCCD camera, we could move on to the Mach-Zehnder Interferometer.

Mach-Zehnder Interferometer

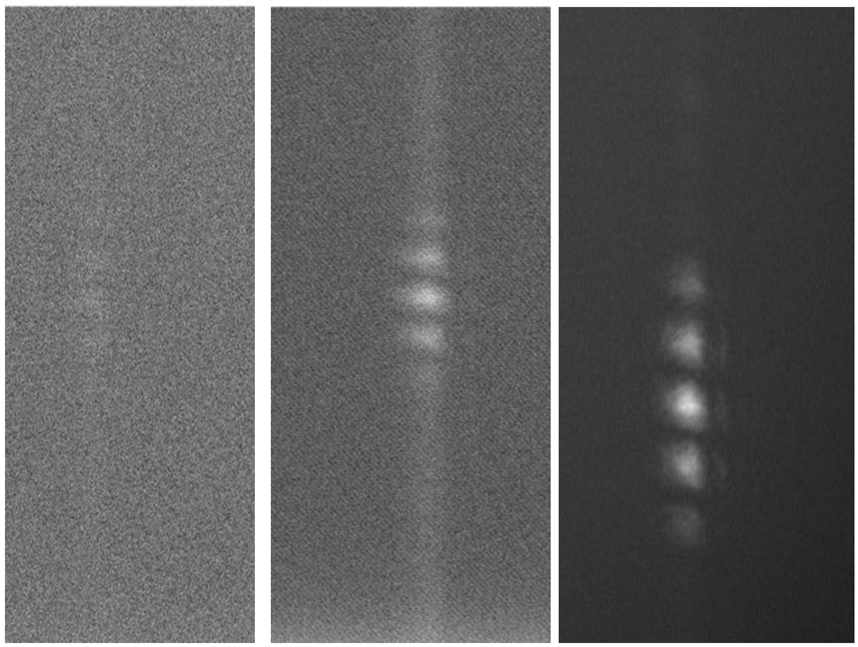
The first step for this interferometer is the same as for Young's double slit, measuring the power and calculate the corresponding ND filters needed. Lens A, the spatial filter, and Lens B all work the same as the Young's double slit setup. Polarizer A is used to make sure the amount of light is the same on both sides of the polarizing beam splitter. The polarizing beam splitter is how we know which path the photon took. The two mirrors then reflect the beam into the last beam splitter. After the two paths recombine the final beam goes through Polarizer B. After attenuating the beam to one photon per meter, we could begin to take images. We rotated Polarizer B in increments of 10° from 0° to 350°, taking images at every increment. By rotating this polarizer, we can get rid of the which path information and eliminate the particle-likeness in the interferogram. This polarizer is appropriately named the quantum eraser.

Figure 4: The EMCCD camera used in this lab.

Results and Analysis:

Electron Multiplying CCD

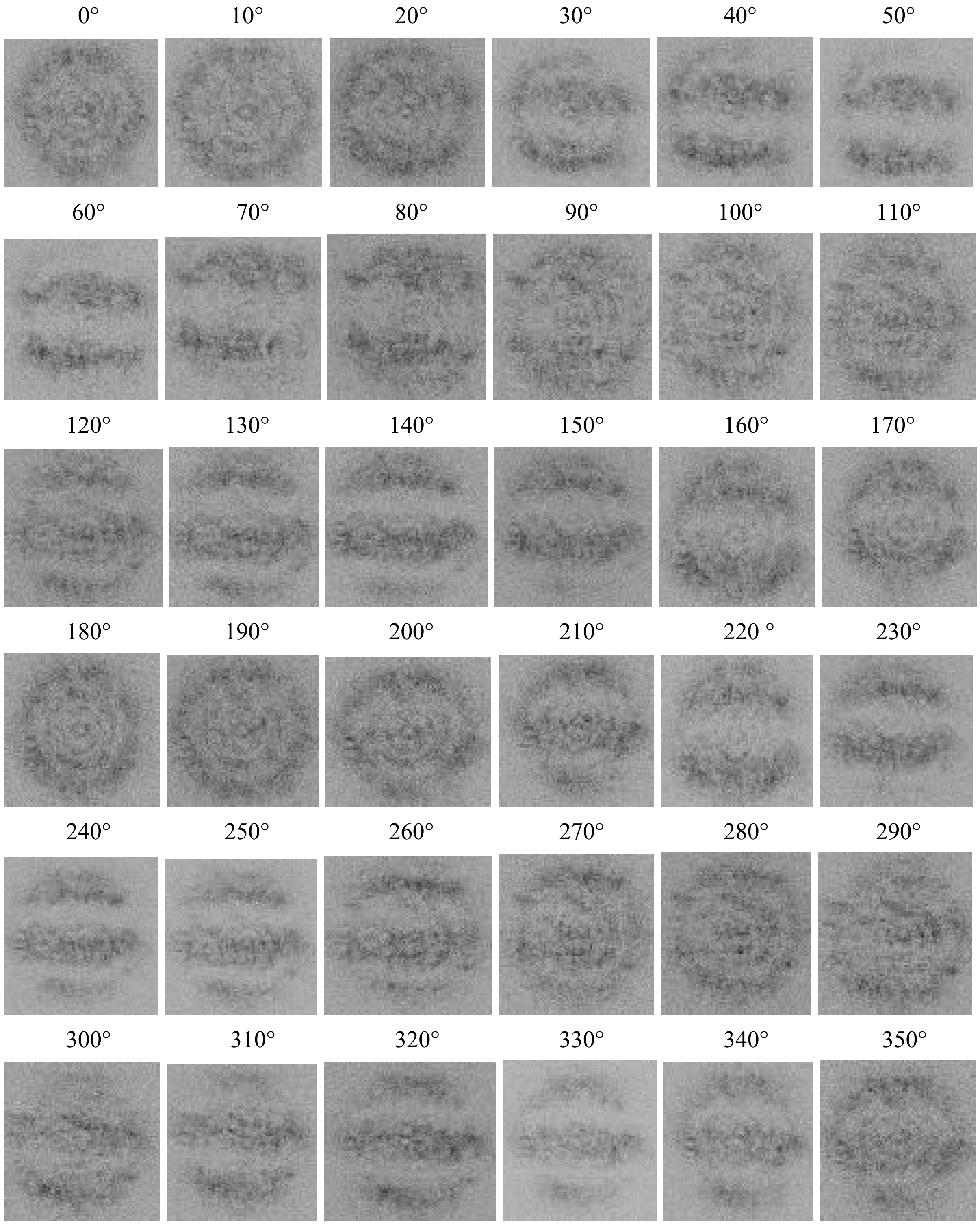
Young's Interferometer was used in this experiment to test the difference between the settings on the EMCCD camera. The results are shown in figure 5. The settings that were used were the acquisition time, gain, and accumulations. Accumulations are overlaid images of the detector used to detect noise. We calculated that we needed four ND filters shown below. The order of magnitude (10^m) is the required number of ND filters needed to attenuate the beam to the single photon per meter range.



(a) **(b)** **(c)**

Figure 5: **(a)** 1ms acquisition time with no EM gain. You can barely start to see the fringes. **(b)** 1ms acquisition time with no EM gain and 20 accumulations. The fringes are very visible and there is less noise. **(c)** 20ms acquisition time, EM gain of 500, and 20 acquisitions. The fringes are extremely visible and you can start to see the second order fringes. The EM gain also gets rid of a lot of noise.

Using the EMCCD camera, we then used the Mach-Zehnder interferometer with the quantum eraser to test the wave particle duality. We calculated that we needed 4 neutral density filters in order to get one photon per meter. Figure 6 shows that when the polarizer is rotated from 0° to 350°, you can clearly see that interference pattern is dependent on the polarizer angle, with a maximum visibility around multiples of m*45° where ($m = 1,3,5\ldots$). One thing to note in figure 4 is the amount of noise. For the EMCCD camera there are five different types of noise: shot noise, readout noise, dark current, spurious noise, and the noise factor or amplification noise. Figure 7 shows the histogram of the 240° interferogram. The amount of noise has a very large impact on the visibility of the fringes, which we will demonstrate later.



<u>Figure 6:</u> The interference pattern based on the polarizer angle with the images were inverted for clarity. We used no EM gain or accumulations and a 50ms acquisition time for each image.

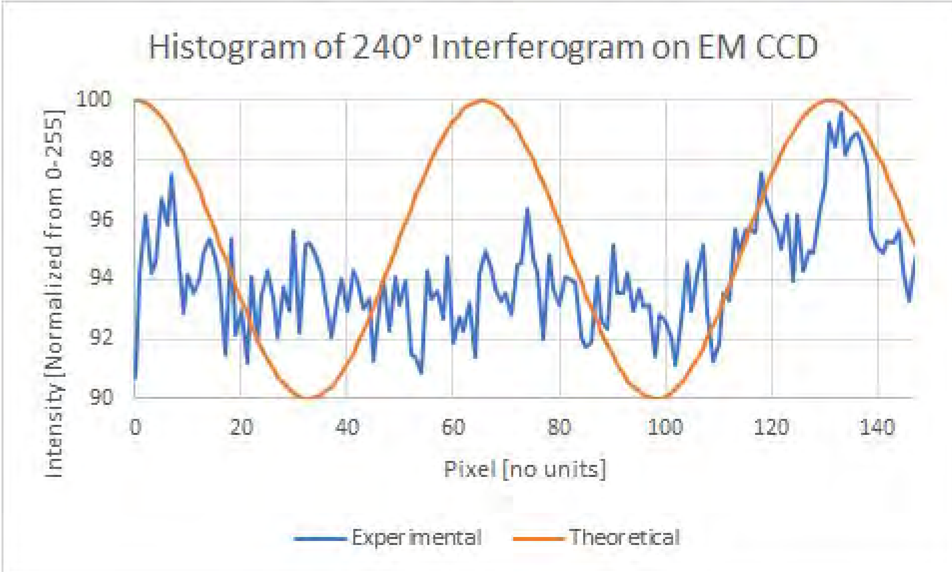


Figure 7: The histogram for one of the interferograms that has the highest fringe visibility. The noise distorts the results making it difficult to accurately calculate the visibility.

Using each of the histograms such as the one in figure 7 for all of the angles shown in figure 6, we were able to calculate the visibility as a function of polarizer angle. Theoretically, this should show the wave-particle duality as the result should be similar to *sin(2Θ)*. Since this function is dependant of the histograms similar to that in figure 7, noise is still a large factor of error. Figure 8 shows the visibility for the EMCCD camera.

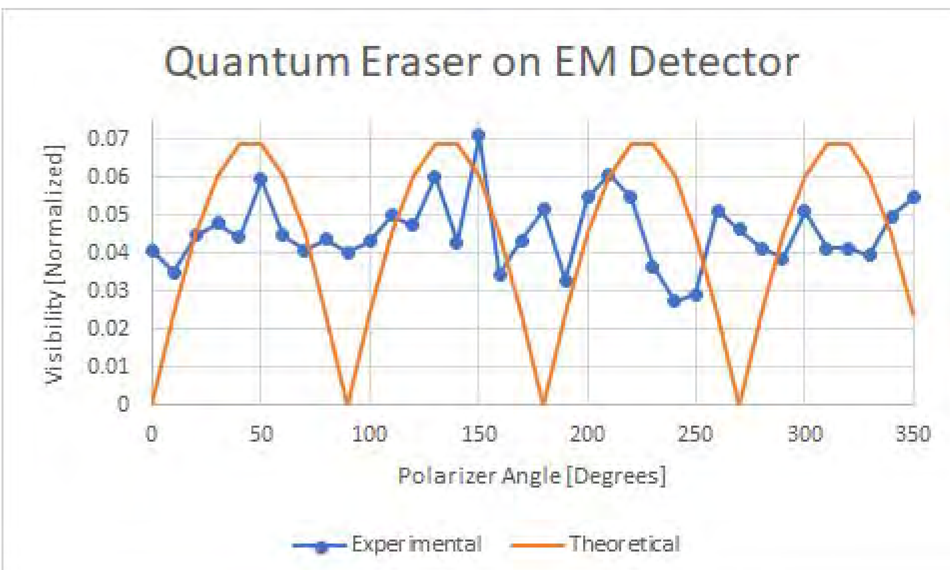
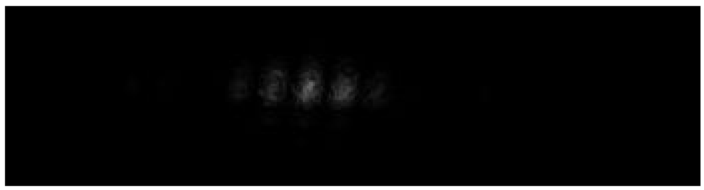


Figure 8: The visibility of the fringes for the EMCCD camera. The noise not only makes it difficult to see any pattern, but also lowers the amplitude to a fraction of the maximum visibility of one.

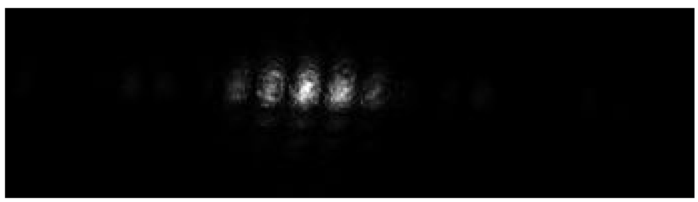
CMOS

Similarly to the EMCCD we used Young's interferometer to test the settings on the software. The only setting in this case was the acquisition time. The results are shown in figure 9. We calculated that we needed 3.5 ND filters this time.

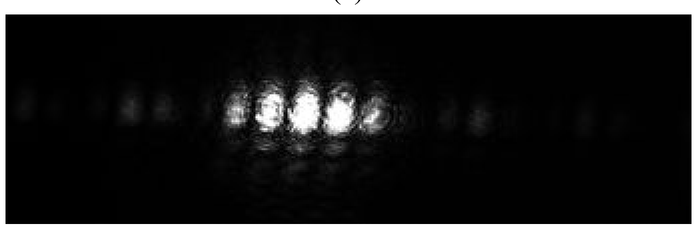
(a)



(b)



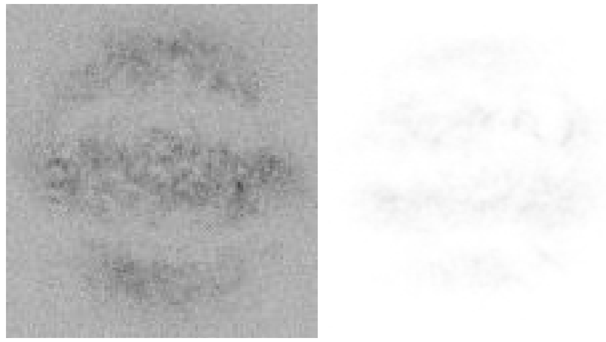
(c)



(d)

Figure 9: **(a)** 0.1s acquisition time. Fringes are not visible. **(b)** 1s acquisition time. Fringes are slightly visible. **(c)** 3s acquisition time. Fringes are clearly visible. **(d)** 10s acquisition time. Fringes are clearly visible and second order fringes are also visible.

In comparison to the EMCCD camera, the intensity measured was very low, but this also means that the noise was reduced substantially. Figure 10 demonstrates this comparison between the 240° interferograms. For the CMOS we calculated that we needed 3.5 neutral density filters. The same pattern was observed in the CMOS camera as figure 6, where the visibility is a function of the polarizer angle. Since there was much less noise in this image, the brightness had much less error as shown in figure 7. Using similar histograms to that used in figure 11 we were able to plot the function of visibility versus polarizer angle, where the experimental and theoretical match quite nicely as shown in figure 12.



EM CCD CMOS CCD

Figure 10: The intensity of the EMCCD image is much larger than the CMOS, but there is much less noise in the CMOS image, yielding better results. The inverse was taken of each image for clarity.

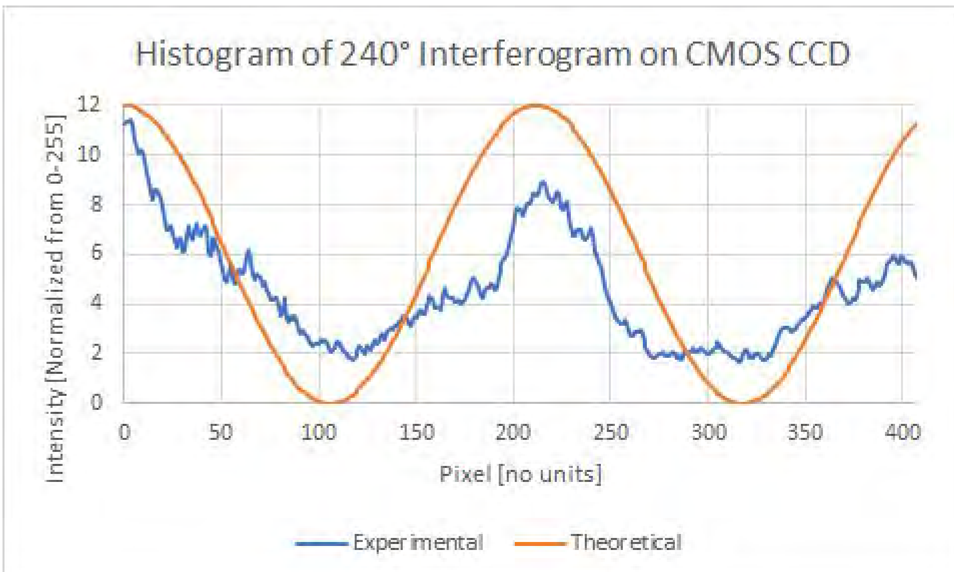


Figure 11: The histogram for the CMOS detector shows the interference pattern much better than that in figure 7. We used a 10s acquisition time for all of the images on the CMOS.

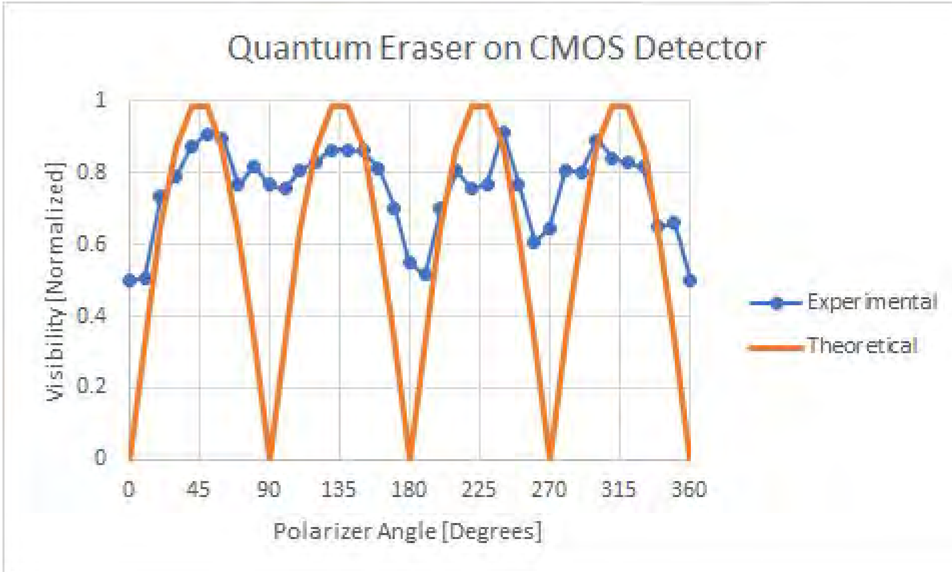


Figure 12: Visibility as a function of polarizer angle for the CMOS Detector.

The visibility as shown in Figure 12 matches nicely with our *sin(2Θ)* dependance that we were looking for. The discrepancy in the minima are most likely due to noise, as this excess energy will not allow for a lower minimum value in intensity. This is also most likely why the maxima cannot reach the theoretical visibility of one as defined by equation 3, where the lowest possible value for minimum intensity is zero.

In comparison to the EMCCD camera, the CMOS camera has much less noise, but we had to use a 10 second acquisition time for each measurement and the intensity was still extremely low for use with single photons. The EMCCD camera had a lot of noise, which most likely contributed to the high intensity measured and an extremely high amount of error. If we had taken every image similar to figure 5.c where we used the EM gain and multiple accumulations, we most likely would have gotten better results.

Conclusion:

In this lab, we set out to show the wave-particle duality of photons with two experiments: single photon interference using a Young's double-slit interferometer for our first experiment and using a Mach-Zehnder interferometer for the second. With the first experiment, we successfully showed that single photons generate interference patterns when they pass through two slits. We saw how single photon impacts on the detector form an interference pattern when many impacts are accumulated. With the second experiment, we set out to show that the visibility of these interference fringes depends on your knowledge of which path of the interferometer the photon travelled. This, in theory, manifests itself as *a* $|sin(2\theta)|$ *dep*endence of visibility on the angle of a quantum eraser, but we did not successfully show this dependence with the EMCCD camera. We did, however, show that dependence with the CMOS camera, albeit weakly. The noise in the EMCCD images proved too intense for any meaningful visibility calculation, and the noise in the CMOS camera images weakened the strength of this dependence significantly but not completely. In order to fix this noisy data, we would have to use a higher gain value or longer exposure time.

Contributions:

Kyle: Experimental Setup and Procedure, Results and Analysis
Liam: Abstract, Introduction and Theoretical Background, Conclusion

A very special thanks to **Matthew Orenstein** and **Yuhui Du** for their assistance in collecting data on the first day in the lab.

References:

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