Two slit Interference: One photon at a time

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Abstract:

In this lab, the double slit experiment was performed. It was performed with the TeachSpin Two-Slit Interference Apparatus with two different sources of light. The first was a red laser and the second was a light bulb with green filter. The first one was supposed to show the expected patterns easily so that they can be identified when the experiment was recreated with the green light.

For the red laser, the Single Slit experiment showed a single broad peak with intensity of 2.1 V. The slit width that was calculated from the theoretical model was found to be $.0777 \pm .0006\ mm$. The true value of .09 mm was 20.5 standard deviations from the mean. The double slit experiment showed multiple peaks and troughs with the zeroth fringe having an intensity of 8.2 V and adjacent peaks at 6.8 V. The slit separation was found to be $.3300 \pm .0009$ mm. This was 24.86 standard deviations from the mean. Both experiments matched the theoretical models with the latter proving wave-particle duality was present.

The light with the green filter didn't produce single slit or double slit interference patterns that remotely resembled what they were supposed to be. Using the double slit interference data of another group member, the slit separation distance was found to be $.3580 \pm .0018\ mm$. The true value of .353 mm was found to be 2.45 standard deviations away from the mean. The theoretical model didn't match up with the experimental data except for the locations of the peaks. It could not be concluded that wave-particle duality was present from the analysis.

Introduction:

According to OpenStax University Physics Volume 3 Chapter 3.1, the history of the Double-Slit Interference begins in 1600's when physicists Christiaan Huygens and Isaac Newton investigated the nature of different phenomena like color and diffraction. Huygens believed that light had a wave like nature that could explain things like color and diffraction effects but newton did not believe that light had a wavelike nature. Newton's reputation made the wave nature of light an unexplored topic.

About two centuries later, a scientist by the name of Thomas Young demonstrated the interference behavior with the double slit experiment. In his original experiment, he used sunlight that was allowed to enter a pinhole on a board. The light then went through two pin holes on a second board. The light from these holes then fell on a screen where bright and dark spots were observed. The fringes could only be explained as a wave phenomenon and thus his name was placed in history [1].

Theory:

When light passes through the slits, the slits act as wave sources. This means that light can enter as a ray but then after leaving the slit becomes a semi-circular wave. Since there are two slits present, its reasonable to assume that there would be interference present. When the wave crests align, the intensity adds together. This is represented in equation 1.

$$d * \sin(\theta) = m * \lambda \; (1)$$

when the wave crest from source 1 aligns with a trough from source 2 and vice versa, the intensities of these waves cancel making dark spots. This is shown in equation 2.

$$d * \sin(\theta) = \left(m + \frac{1}{2}\right) * \lambda \ (2)$$

This yields the interference pattern shown below in figure 1. The peaks on the backdrop are where the waves add up and the troughs are where the waves cancel.

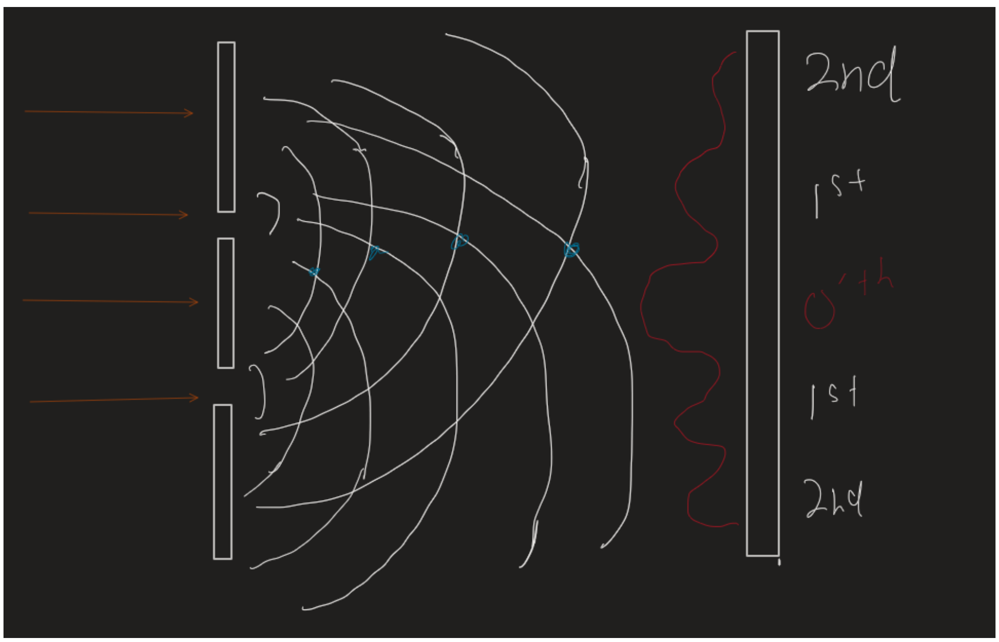

Figure 1: Double Slit interference diffraction behavior

Setup/procedure:

The apparatus used in this experiment is shown in figure 2.

Figure 2: TeachSpin Double Slit Interference apparatus

The apparatus is 1 m long and has the light sources at one end and the PMT/photodetector at the opposite end. In the middle is the slit holder as well as the barrier that can be modified with the micrometer screw. There is another micrometer screw near the PMT/photodetector that can be adjusted to prevent light from coming in. The oscilloscope and photon counter are used for mode 3 of the experiment where the light with green filter is used to count photons.

The OSF page for the Double Slit experiment was used to conduct the procedure. It was first necessary to bring the laser up so that when turned on, the light would hit the photodetector. A piece of paper was used to intercept the path of the laser light behind the two slits. There was a micrometer screw that determined the slit configurations. This micrometer reading was modified until a new light pattern emerged on the paper and the range that this light pattern was seen was noted. This was done for both slits closed, both slits open and for either slit being open. An example is shown below in figure 3 for the double slit.

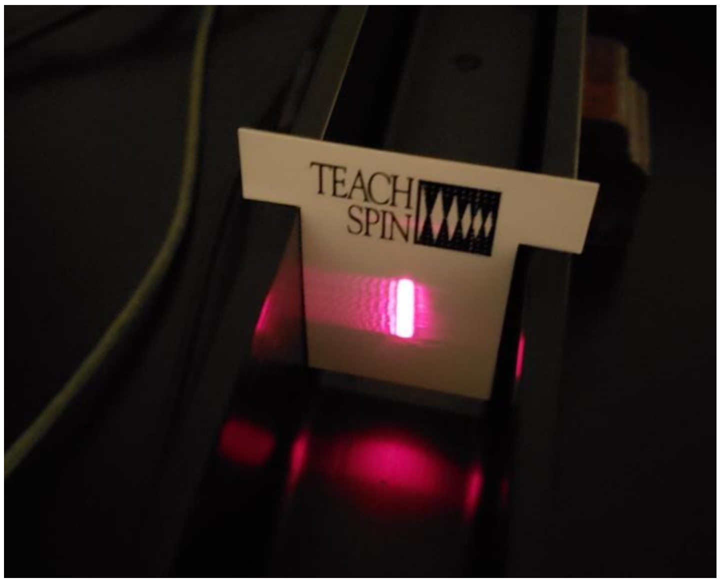

Figure 3: Double Slit Laser pattern

The slits were then placed to both slits open position at 5mm and the micrometer screw on the far end of the apparatus was modified in increments of .1 from 2 – 8 mm and increments of .5 from 0 – 2 and 8 – 10. When the photons from the laser got to the end of the apparatus, they hit a photodiode which generates a voltage. The more photons, the higher the voltage. These voltages were measured by a multimeter. This process was then repeated for the single slit configuration by modifying the middle screw position to 4.1 mm. These intensity values were then plotted in python.

Next, the green light bulb was used to perform the same experiment. There were some additional steps that needed to be taken beforehand. The multimeter was turned off and the oscilloscope is turned on. The oscilloscope is shown in Figure 4.

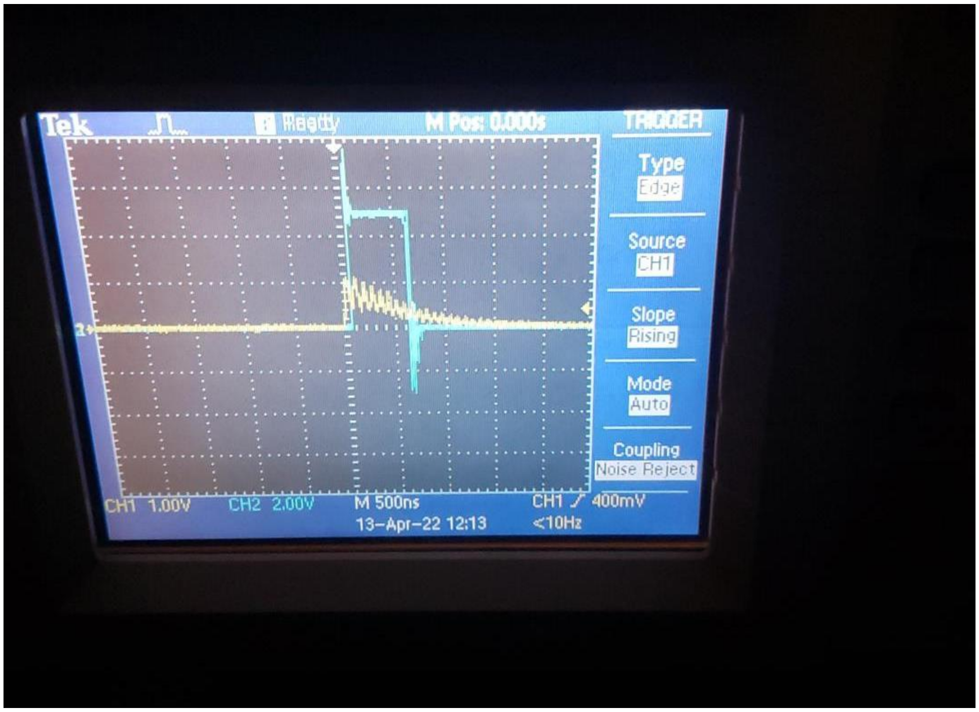

Figure 4: Oscilloscope traces – PMT signal (yellow) and Output TTL (blue)

The Oscilloscope has two traces, the yellow trace shows the raw output of the PMT device and the blue trace represents the Output TTL, which is a pulse signal that activates when the raw output exceeds a certain base voltage. It was desired to have the raw PMT signal imitate an exponential function without flattening at the top. This way one knows that the PMT is not experiencing any leaks or malfunctions. Then it is necessary to toggle the discriminator setting so that only one output pulse is seen on the screen and is sent out at 50 mV. These pulses are sent to the photon counter to show the physical count of the amount of photons. This is shown in Figure 5.

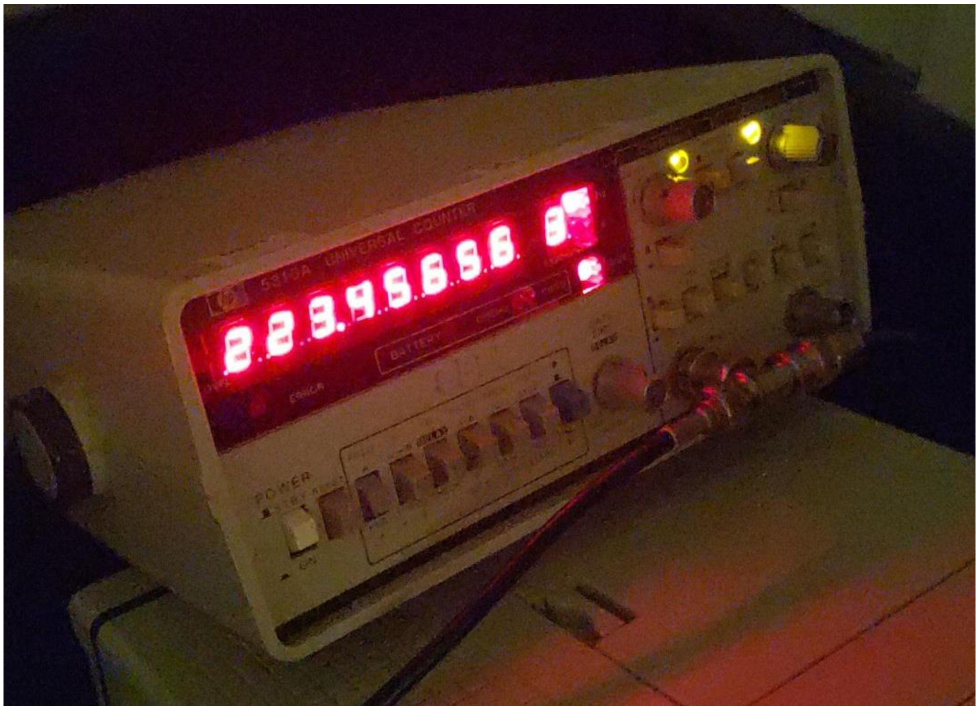

Figure 5: Photon Counter

The process was conducted in a similar fashion, both slits were open and the micrometer screw at the end of the apparatus was used to increment every .1 mm from 0 mm to10 mm to acquire intensity data. Then the single slit configuration was investigated in the same range and increment. These values were taken into python and plotted.

Afterwards, models were constructed according to different intensity equations for both single and double slit configurations [2]. The red laser is supposed to allow for a trivial collection of the desired interference patterns. The green light will be a more difficult version of the process that will attempt to recreate the patterns seen when conducting the experiment with the red laser.

Analysis:

In figure 6 ,the single slit data for the red laser is shown

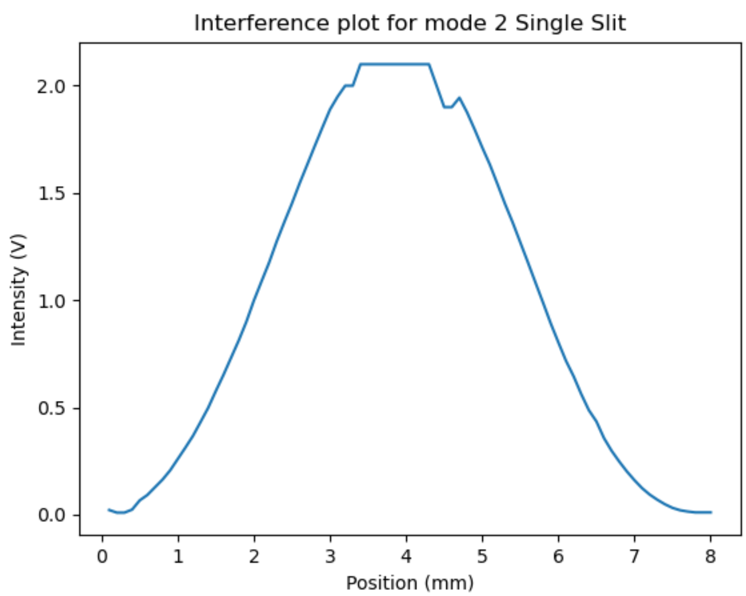

Figure 6: Single Slit Data for red laser

The peak voltage for the single slit configuration was found to be 2.1 V and then tapered off to 0 on both sides. This is behavior that is expected of particles. More particles would end up being in the middle then on the fringes.

The data from the double slit experiment from the red Laser source is shown in Figure 7.

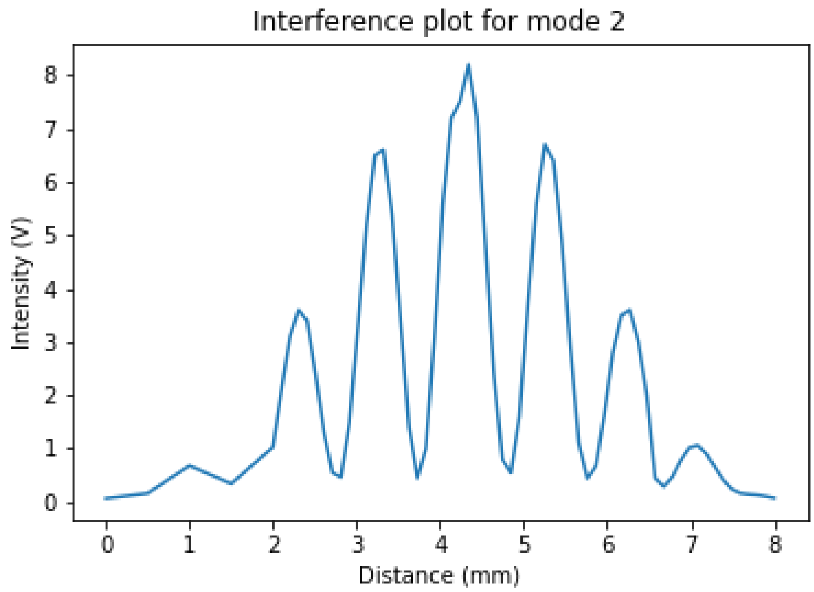

Figure 7: Double slit interference data for red laser

The graph shows an interference pattern commonly associated with wave phenomena. The photons which are particles are now acting as waves. There was a maximum of 8.2 V at around 4.5 mm. The graph is symmetric around the true maximum with the adjacent peaks having voltages of 6.8 V.

Figure 8 shows the results of the green light bulb single slit experiment. As can be seen, the data nowhere near resembles the single slit behavior that is expected. As such, no analysis can be performed on this data.

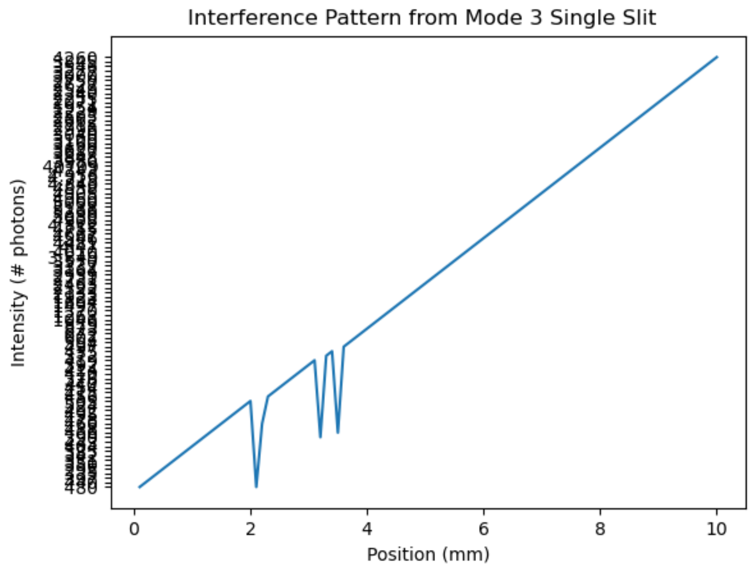

Figure 8: Single Slit Data for green light

The data for the double slit experiment is shown in figure 9.

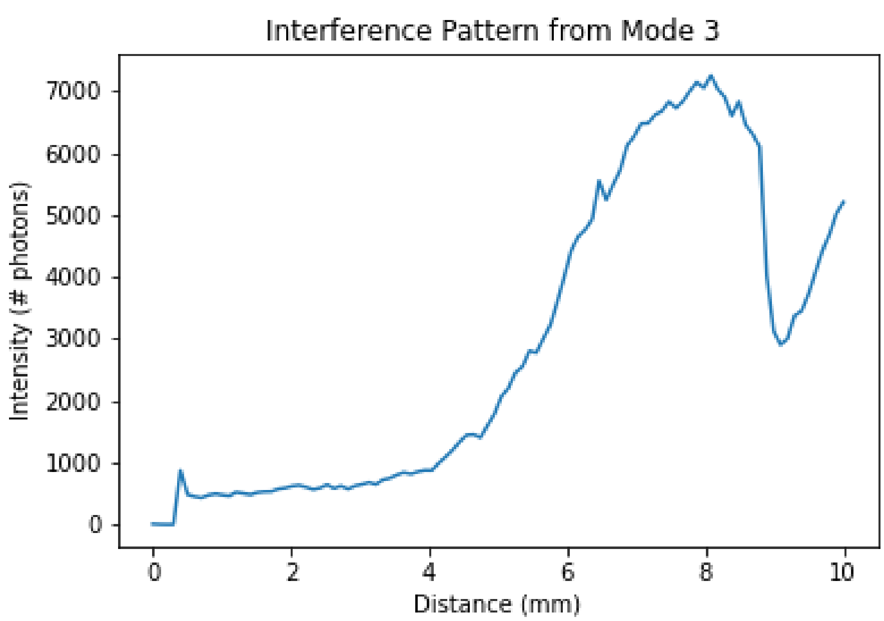

Figure 9: Double Slit Data for green light

This graph doesn't look like what was expected. It was believed that there was a grounding issue in the apparatus. Another group had some data that more closely resembled the desired behavior but not by much . This is shown in Figure 10.

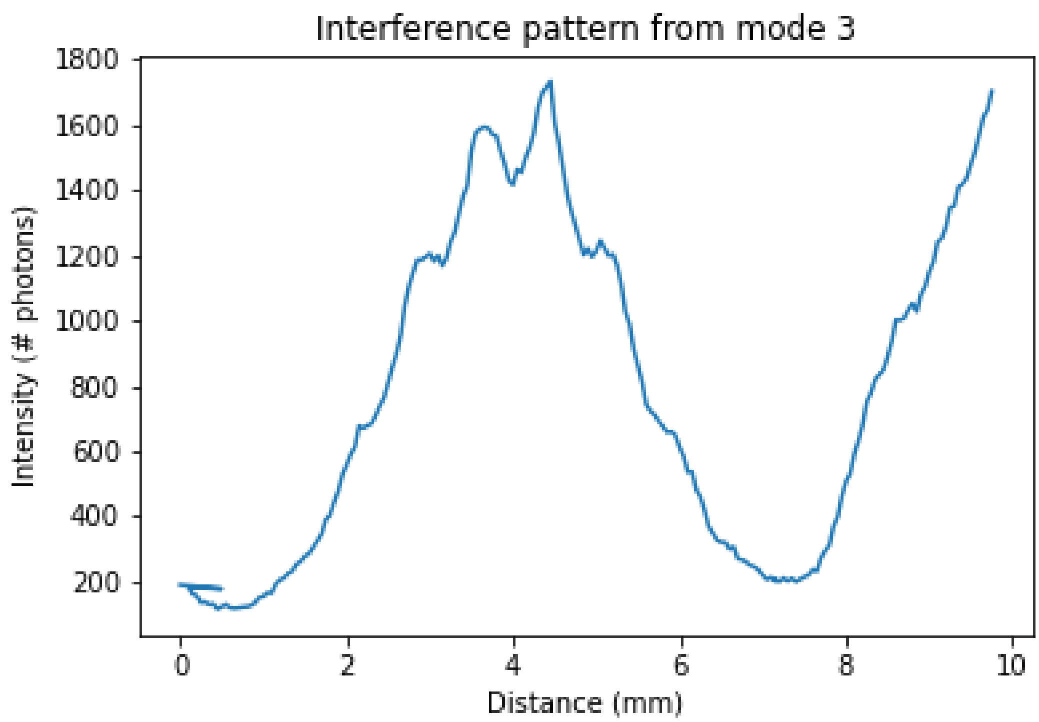

Figure 10: Green Double Slit Data for green light – other group

There are still issues present with this graph. The troughs should not be as high on the graph as they are. These points of destructive interference should have close to 0 photons intensity. There is an issue with the apparatus that needs to be addressed.

It was also necessary to find the errors in the single slit and double slit data. The single slit interference equation which explains the intensity is shown in equation 3.

$$I(\theta) = I_0 * \left(\frac{\sin(\mathrm{B})}{\mathrm{B}}\right)^2 \quad (3)$$

Where

$$\mathrm{B} = \frac{\pi * a * \sin(\theta)}{\lambda} \quad (4)$$

The resulting graph shown in figure 11 compares the theoretical data and experimental data for the single slit data for the red laser.

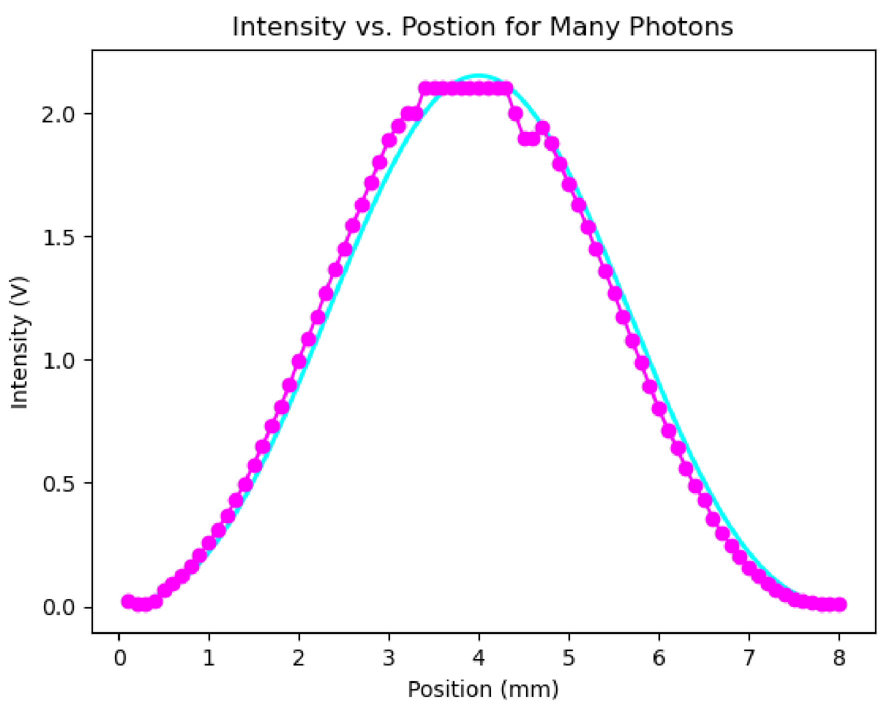

Figure 11: Experimental (Magenta) vs Theoretical (Blue) for single slit red laser

The experimental and the theoretical data line up nearly perfectly. The slit width that was calculated from the theoretical model was found to be $.0777 \pm .0006\ mm$. The true value was found to be .09 mm [3]. This was 20.5 standard deviations from the mean.

Below is shown a comparison of the Fraunhofer intensity theoretical plot vs the collected data. The Fraunhofer intensity shows the Intensity values as a function of theta. This is shown in equation 5.

$$\begin{aligned} I(\theta) &\propto \cos^2\left[\frac{\pi S \sin\theta}{\lambda}\right] \ \mathrm{sinc}^2\left[\frac{\pi W \sin\theta}{\lambda}\right] \\ &\propto \cos^2\left[\frac{kS \sin\theta}{2}\right] \mathrm{sinc}^2\left[\frac{kW \sin\theta}{2}\right] \end{aligned} \qquad (5)$$

Source: [4]

The equation above was used to construct a model to generate theoretical data for the double slit interference data in the red laser and green light experiments.

The double slit interference data comparison for the red laser is shown in figure 12 where the blue line is the theoretical data and the magenta line is the experimental data .

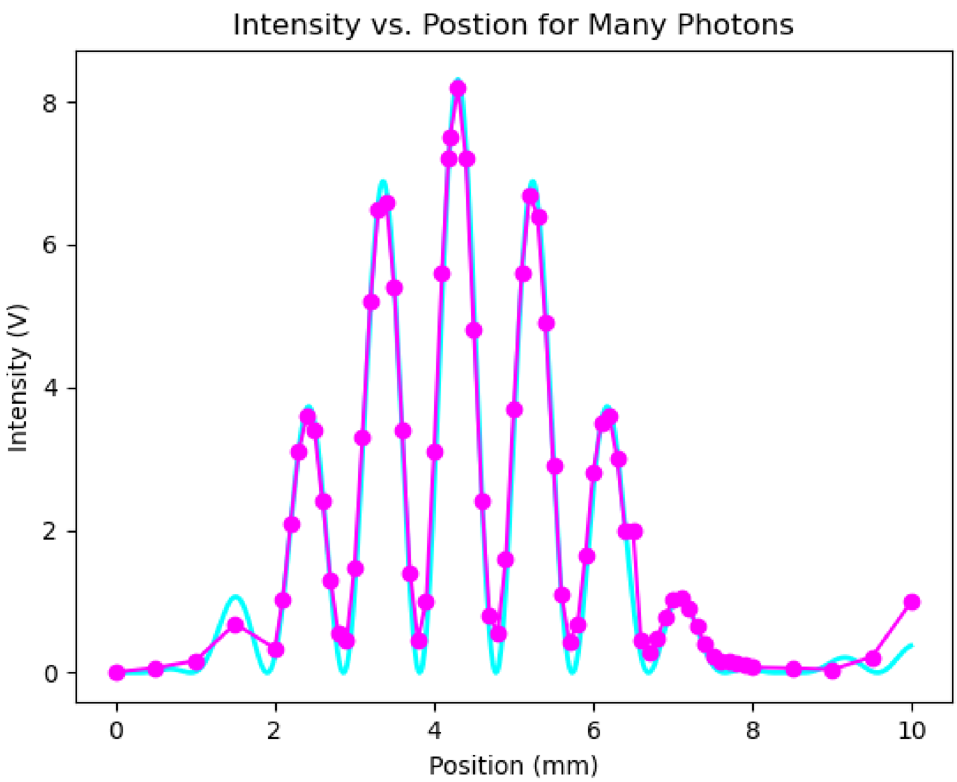

Figure 12: Experimental (Magenta) vs Theoretical (Blue) data for Double slit Red Laser

The theoretical and experimental data coincide nearly perfectly except for at inflection points in the peaks and the troughs. For the zeroth fringe, the theoretical intensity maximum was only .05 standard deviations from the mean. This value would be extremely common if this experiment were repeated many times. The theoretical separation was found to be $.3300 \pm .0009$ mm. The true value of .353 was 20.5 standard deviations away from the mean.

A close up inspection of the central fringe as well as certain parts of the adjacent fringes are shown below in Figure 13.

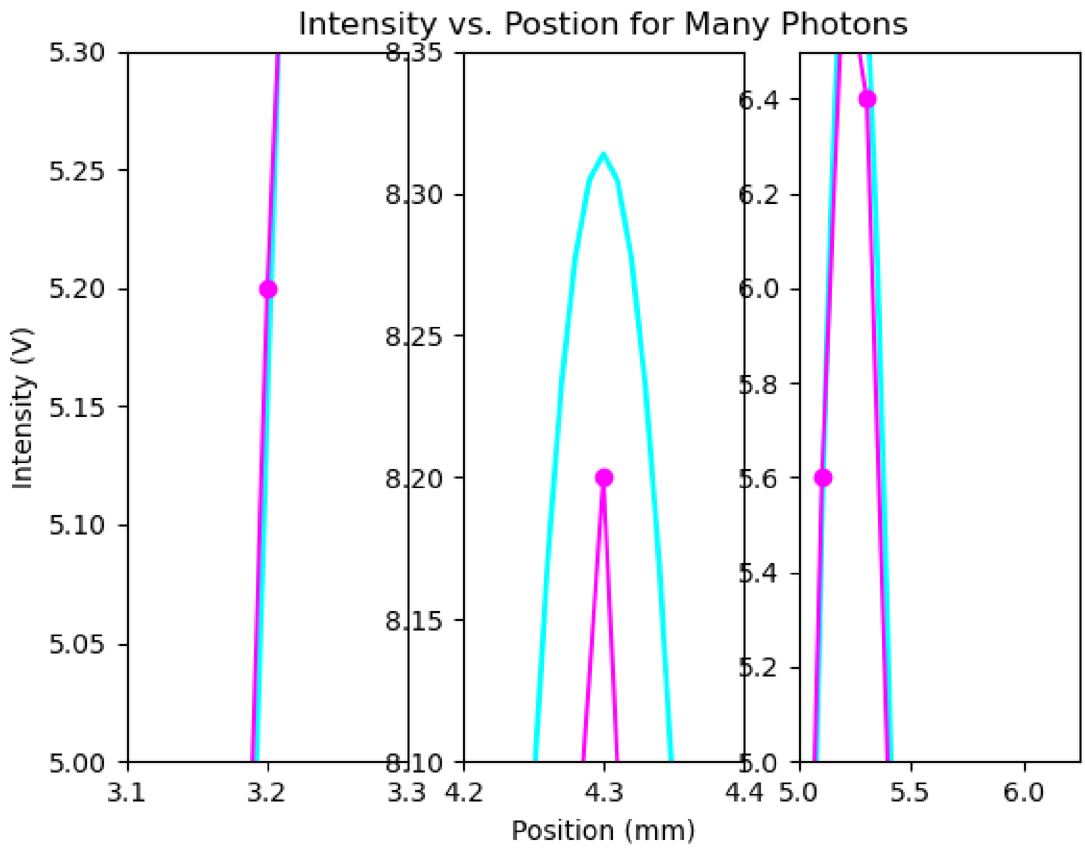

Figure 13: Close up inspection between Experimental(Magenta) and Theoretical (Blue) Data

The intensity comparison between the group's data and the theoretical model data for the double slit experiment with the green light is shown below in Figure 14.

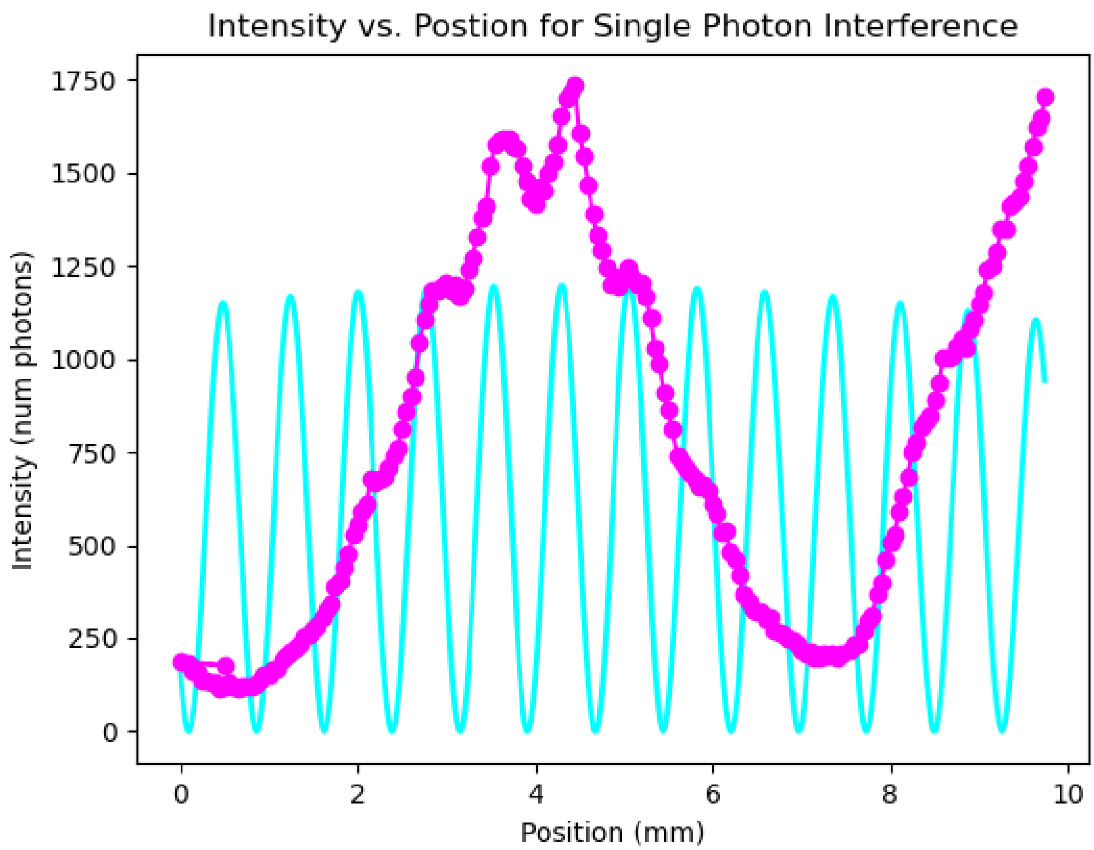

Figure 14: Experimental (Magenta) vs Theoretical (Blue) data for Double slit Green Laser

As can be seen, there are virtually no similarities. The only similarities are in the rough locations of the maximum and adjacent peaks. The zeroth fringe corresponds to a position of 4.3 mm and the adjacent peaks correspond to positions of 3.4 and 5.07 mm etc. The theoretical separation was found to be $.3580 \pm .0018\, mm$. The true value of .353 mm was found to be 2.45 standard deviations from the mean.

Looking at the results, the slit separation values between the red laser and the green light double slit interference experiments was close with the first being .330 and the second being .358. The discrepancy between the two results was .28 mm. The true value however was .353

mm [3]. So the value found in the latter experiment was closer to the true value in terms of number of standard deviations. Comparing the results to each other, the red separation value was 14.7 deviations from the mean for the green value. The green separation value was found to be 29.8 standard deviations from the mean for the red value. The separation values found by each of these models is completely different.

Conclusion:

The interference experiment was performed for both red laser and light bulb with a green filter. The single slit and double slit configurations were investigated for both. The ODR models were able to create theoretical data to compare to experimental data for both single slit and double slit experimental data for the red laser. An ODR model was attempted on the data given by the other group for the double slit experiment, but a model couldn't be made for the single slit because it was so erroneous.

For the red laser, the single slit configuration had a maximum value at 2.1 V and tapered off to 0 at the edges. The theoretical slit width was found to be $.0777 \pm .0006$ mm. The true value of .09 mm was 20.5 standard deviations from the mean. The double slit experiment for the red laser created the expected interference pattern indicating wave phenomena. Maximum intensity was found to be 8.2 V at 4.5 mm and adjacent peaks had 6.8 V at 3.3 mm and 5.2 mm. The theoretical separation was found to be $.3300 \pm .0009$ mm.

For the green light source, the single slit configuration did not yield results that resembled a single slit interference pattern and as a result couldn't be analyzed. The double slit configuration didn't yield any useful data either so another group lent us their data. Using that data, the maximum photon count was found to be 1700 photons/s at 4.6 mm. The theoretical separation was found to be $.3580 \pm .0018$ mm. The true value was 2.45 standard deviations from the mean. It was suspected that there might be a light leak or one of the slits isn't fully open. Either way, looking at the data alone suggests that wave-particle duality isn't proven.

The discrepancy between separation distances for the green light and red laser double slit experiment was found to be .28 mm. The values are also found to be completely different by seeing that green separation value is 29.8 standard deviations from the mean for red and that red separation value is 14.7 standard deviations for green. The values are not in agreement. The green separation value is closest to the true value of .353 mm being only 2.45 standard deviations from the mean while the red separation value is 24.86 standard deviations away from the mean.

From the analysis of the data, the green light double slit experiment did not yield evidence of wave-particle duality. As stated previously, there is most likely an issue with the apparatus pertaining to light leakage or a partially blocked slit. In fact, the data looks closer to that of a single slit interference pattern. The experiment must be conducted again after the apparatus is checked over and fixed.

References:

1. *3.1 Young's Double-Slit Interference - University Physics Volume 3 | OpenStax*. (n.d.). OpenStax. Retrieved April 29, 2022, from https://openstax.org/books/university-physics-volume-3/pages/3-1-youngs-double-slit-interference?query=double%20slit%20diffraction&target=%7B%22index%22%3A0%2C%22type%22%3A%22search%22%7D#fs-id1170903805603
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