Double Slit Lab Report

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Abstract

We conduct measurements highlighting the behavior of light as it passes through various diffraction gratings. As such, we qualitatively confirm the wave nature of light, in accordance with geometrically derived theoretical predictions. We conducted a traditional double slit experiment where we observe both the particle and wave properties of light. We further extend this experiment to the limit where we are firing one photon at a time at the slits - in which case we see the same results. By detecting discrete photons, we are able to conclude that individual photons exhibit a wavelike behavior. Thus, we show that wave-particle duality is an intrinsic property of photons.

1 Introduction

Light is pervasive in our everyday life, yet most have a poor understanding of what it actually is. One of the great fathers of classical physics attempted to understand light. In 1704, Isaac Newton published his book "Opticks: or, A Treatise of the Reflexions, Refractions, Inflexions and Colours of Light." In his book Isaac Newton made the bold claim that light behaves in a corpuscular nature, or as a particle, thus setting the precedent for years to come [4]. Only a few scientists thought that light was travelling as a wave vibrating through some sort of medium, labelled the ether. There was evidence for both pictures but few would challenge the great Isaac Newton.

In 1790, at age 17, Thomas Young first read Newton's "Opticks." He admired Newton's work but felt it was insufficient in explaining how light both reflects and refracts at some surfaces, and how different colors of light refract at different degrees. Young was skeptical of the particle nature of light. In 1801, he created his famous double slit experiment. He covered a window with a piece of paper with a tiny hole in it. A thin beam of light passed through the hole, in which he held a thin card, effectively creating two slits and splitting the beam in two. light from each slit then interfered with the light from the other slit to produce a series of light and dark fringes on the opposing wall. Young was also able to use his data to calculate the wavelengths of different colors of light with great success. While Young's work would appear to confirm that light is a wave, it was not received well - scientists did not want to believe Newton was wrong [1].

Over 100 years later, as modern physics began to emerge, it was understood that light could demonstrate properties of both particles and waves. In 1927, Davisson and Germer demonstrated the electrons exhibit the same behavior. The concept of wave-particle duality emerged, in contradiction with both Newton and Young.

This brings us to our modern day understanding of superposition. It is now known that if we restrict Young's double slit to an experiment where we fire 1 photon at a time, that photon will pass through the slits in the probabilistic fashion of quantum mechanics and produce an interference pattern on an opposing screen. The photon can be thought of as interfering with itself- it goes through one slit, the other slit, both slits, and no slit all at the same time. Yet, when we try to observe this phenomenon we will only measure the photon being in one location.

These experiments provide insight into all matter, not just photons. In 1965, in one of Richard Feynman's now-famous lecture series he discussed how single electrons fired at a double slit would produce a similar interference pattern and thus demonstrate wave-particle duality in ordinary matter [3]. At the time, completing such an experiment was not feasible, but his prediction has now been confirmed. Today we can even produce such interference patterns with molecules of up to 2000 atoms [2].

In this lab we will reproduce Young's double slit experiment with modern day technology. We will restrict ourselves to the single-photon limit, thus showing the essence of wave-particle duality. Further we, will experiment with several other diffraction patterns beyond the double slit. These additional experiments will be restricted to a qualitative analysis.

2 Theoretical Considerations

2.1 Device Configuration

For our first experiment we are using the "Two-Slit Interference, One Photon at a Time" device from TeachSpin [5], shown in figure 1.

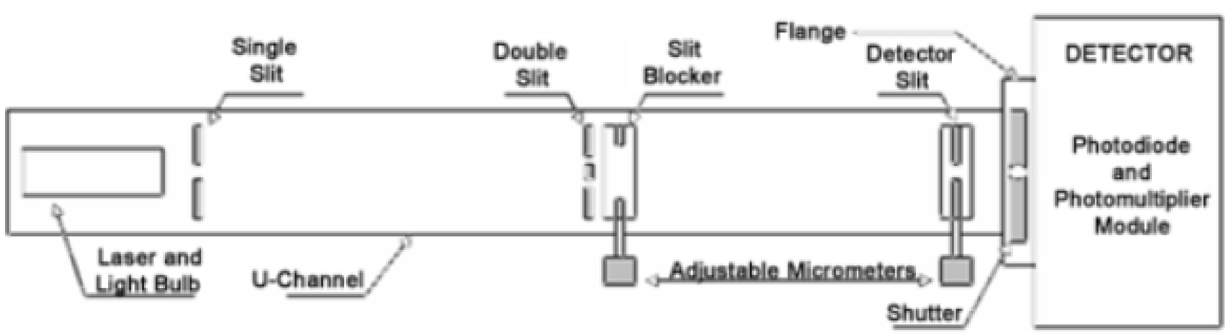


Figure 1: Depiction of the TeachSpin "Two-Slit Interference, One Photon at a Time" device.

The instrument consists of a black anodized aluminum U-Channel, a little over a meter in length, with a removable cover. At one end, we can place either a 670 nm, 1mW laser or a small flashlight bulb. The detection system at the opposite end can be either a photodiode or a complete photon counting module.

The flashlight bulb is connected to a variable voltage-regulated power supply. Incandescent light bulbs produce light through blackbody radiation, with their filament being the blackbody. The spectral radiance (power per unit solid angle per unit area normal to propagation) of the emitted light is governed by Planck's law of blackbody radiation:

$$B(\nu, T) = \frac{8\pi\nu^2}{c^3} \cdot \frac{h\nu}{e^{h\nu/kT} - 1} \tag{1}$$

where h is Planck's constant, c is the speed of light, k is Boltzmann's constant, ν is the frequency of light emitted from the blackbody, and T is the temperature of the blackbody. Plotting this equation as a function of frequency, we can see several Temperature curves (figure 2). As we decrease the supplied voltage to our light bulb, we are decreasing the current passing through the filament and thus decreasing the temperature of the filament. As such, we are both decreasing the total output light intensity across all frequency ranges and shifting the peak frequency range to high wavelengths. In layman terms, this means that our light is dimming and transitioning to more red light.

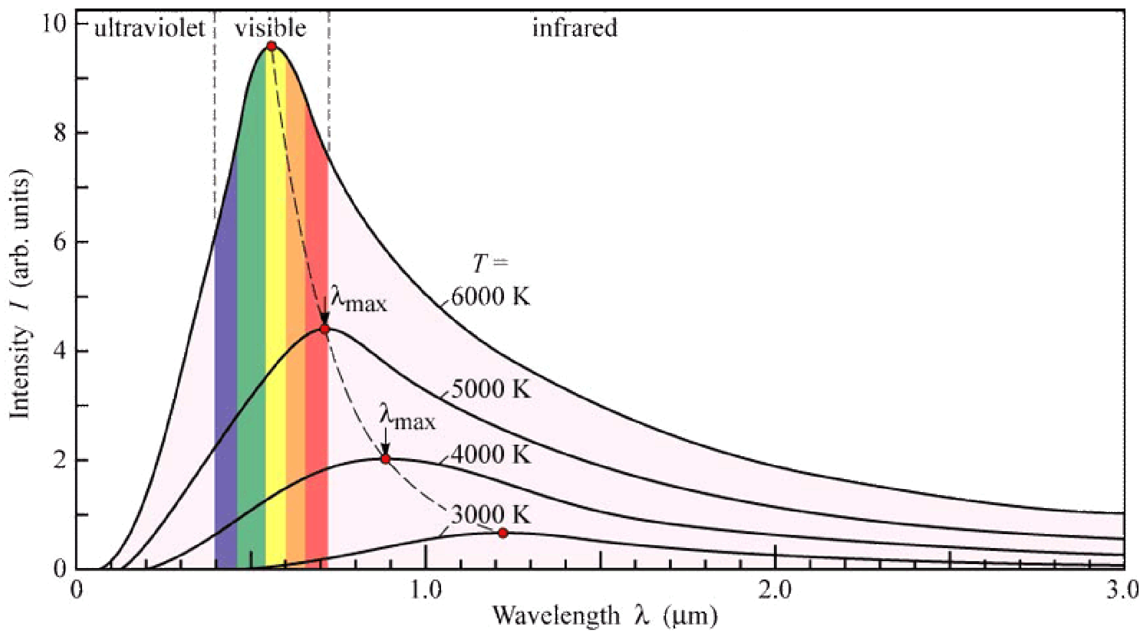


Figure 2: Frequency spectrum for blackbody radiation at various temperatures. These regressions are governed by Planck's law of blackbody radiation. Note that as the temperature decreases, the total power radiated (area under curve) decreases and the peak wavelength shifts to longer wavelengths.

Additionally, our lightbulb is enclosed within a container such that light can only escape through a narrow band pass green filter. By decreasing the voltage of our lightbulb, we have greatly decreased the number of produced "green" photons. At the detector, these photons are received at a rate of 10^1 to 10^5 per second. The total travel time is on the order of $1m/c = 1m/(3 \cdot 10^9 m/s) = 1/3 \cdot 10^{-9}s$. If we have our maximally observed number of photons per second 10^5, we see that on average, our photons are spaced by $1s/10^5 = 10^{-5}$. Comparing the travel time of $1/3 \cdot 10^{-9}s$ per photon to the average spacing between photons 10^{-5}, we see a 4 order of magnitude difference. Thus it can safely be concluded that these photons are isolated from one another.

Just in front of the light source is a single entrance slit. With either the laser or bulb illuminating this slit, the central maximum of the slit's diffraction pattern is aligned to cover a double slit assembly about 40 cm down the U-channel. Just past the double slit, a movable "slit blocker" can be manipulated manually using a micrometer mounted on the outside of the U-channel. Using the slit blocker, we can compare the patterns created by the double slit to those created by either of the single slits.

At the far end of the U-channel is a movable single slit, the detector slit. It is also attached to a translational stage actuated by a micrometer. We can move the detector slit across the interference pattern in front of either the photodiode or cathode of a photo-multiplier to make quantitative measurements of either the light intensity or photon arrival rate as a function of position. Rather than manually moving the detector slit, we have an electric motor attached to our micrometer. When powered, the motor moves the slit at a speed of a few microns per second. The motor can turn the micrometer in either direction. With the use of this motor we can continuously take measurements as we scan the detector slit across the produced diffraction pattern.

2.2 Geometric Optics

We will now discuss the geometric properties of Young's double slit experiment, casting our photons as rays rather than individual particles. Our initial light ray passes through two slits, effectively becoming to distinct light rays, before being incident upon a screen for observation. These two rays have slightly different starting location. As such, for any point on the screen (except $\theta = 0$) they will have a different path length. This is summarized in figure 3a. Using simple trigonometry we can derive their path difference to be:

$$\Delta l = dsin\theta \tag{2}$$

Treating our rays as waves, it is straightforward to postulate that if the path difference at a point on the screen happens to be an integer multiple of the wavelength of the light, then constructive interference will occur.

$$dsin\theta = m\lambda : m = 0, 1, -1, 2, -2, ...(constructive) \tag{3}$$

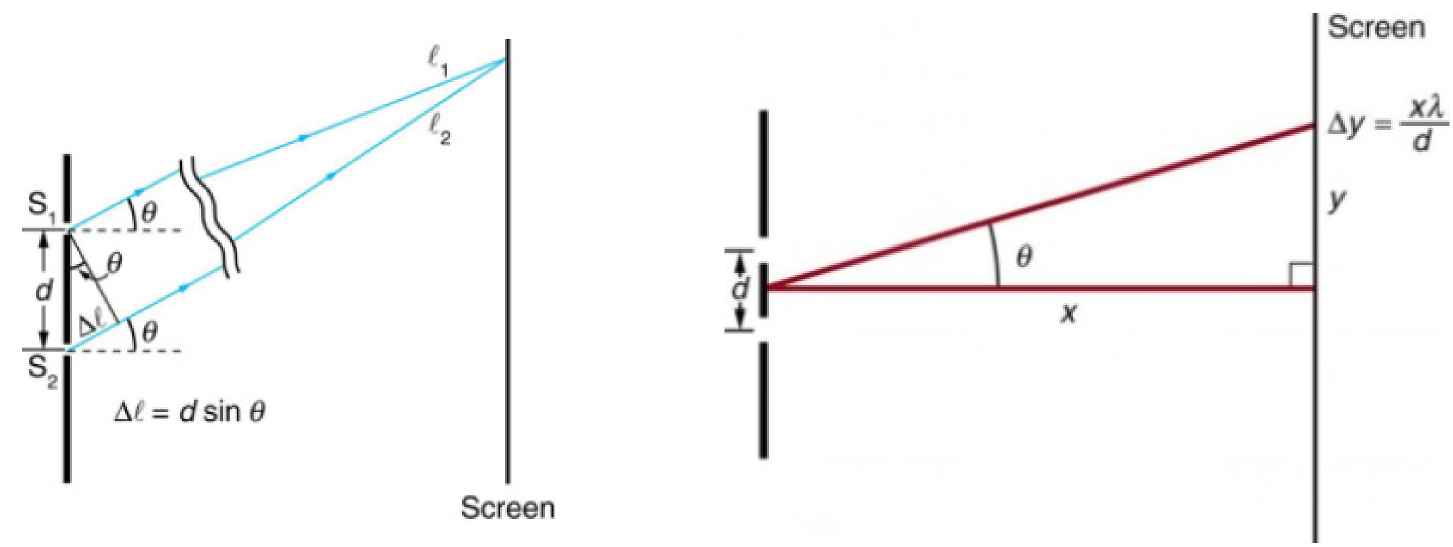
We can write this equation for two adjacent peaks (m, m+1), apply the small angle approximation $sin\theta \approx tan\theta$, and note that $tan\theta = y/x$ (from figure 3b to solve for the distance between them.

$$(m+1)\lambda - m\lambda = dsin\theta_2 - dsin\theta_1 \tag{4}$$

$$\lambda = d(tan\theta_2 - tan\theta_1) \tag{5}$$

$$\therefore \lambda = \frac{d}{x} \cdot \Delta y \tag{6}$$

With this simple approach we can calculate the wavelength of light used in our experiment.



(a) 0.75A

(b) 1A

Figure 3: Depiction of double slit interference geometries. Figure 3a shows how slightly different starting positions leads to a difference in path length denoted Δl. Figure 3b shows the relation between the angle, θ, and the position on the screen, y.

2.3 Wave-Particle Duality

We have just discussed our experimental expectations if our light rays are indeed waves. However, they may behave as particles. In the case of particles we do not expect to see any interference pattern on the screen. Rather, we expect to see two peaks in line with each slit. The differences in these two outcomes are summarized in figure 4.

We can try to reconcile these two outcomes with a quantum mechanical approach to the double slit experiment, where we know work with photons as opposed to light rays (following [3]). Let the wave functions Φ_1 and Φ_2 represent the probability that our photons pass through one slit or the other. The total wavefunction at the detector is therefore $\Phi_{det} = \Phi_1 + \Phi_2$, and the probability of detecting a particle is:

$$\Phi_{det}^2 = \Phi_1^2 + \Phi_2^2 + 2|\Phi_1||\Phi_2|cos(\Delta\xi) \tag{7}$$

where ξ is the phase difference of the two wavefunctions measured at the detector (analogous to the difference in path lengths). Solving equation 7, we see both wave and particle behaviors.

If the two wavefunctions are entirely in phase, $cos(\Delta\xi) = 1$, we get constructive interference:

$$\Phi_{det}^2 = \Phi_1^2 + \Phi_2^2 + 2|\Phi_1||\Phi_2| \tag{8}$$

If the two wavefunctions are entirely out of phase, $cos(\Delta\xi) = 1$, we get destructive interference:

$$\Phi_{det}^2 = \Phi_1^2 + \Phi_2^2 - 2|\Phi_1||\Phi_2| \tag{9}$$

Lastly, if we close one slit, the corresponding wave function for the photon passing through that slit goes to 0. Let $\Phi_2 = 0$, we now see that there is not interference term:

$$\Phi_{det}^2 = \Phi_1^2 \tag{10}$$

Thus we have expressed an equation for the probability of detecting a photon which states that the photon will individually behave as a wave in the presence of two slits, through an interference term. Yet, in the presence of only one slit it will behave entirely like a particle. We hope to confirm this expectation through direct experimentation.

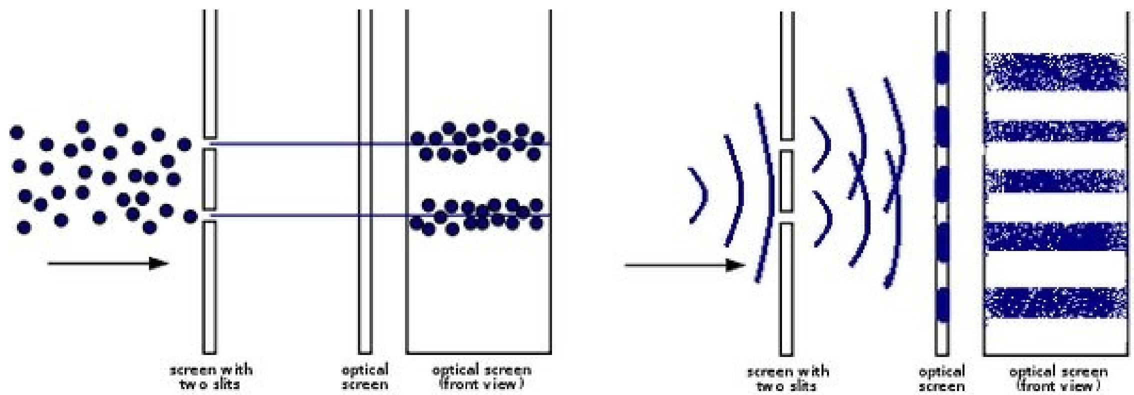


Figure 4: On the left we see the expected particle distribution on our screen if we shoot particles through the double slits. On the right we see our expectations if we shoot waves through the double slits, allowing for an interference pattern.

3 Experimental Methods

3.1 Double Slit Experiment

Using the our double slit apparatus discussed in section 2.1, we carefully make measurements with both a laser and a light bulb as a light source.

For making measurements with the laser, we use a photodiode detector; with the light bulb, we use a photomulitiplier module. For both devices, our measurements are made electronically. As such our data is recorded in data files on a computer, making future analysis easier.

For both the laser and the lightbulb, we record data while moving our slit through the entire range of the diffraction pattern. We are not actively recording the position of the detector slit. However, the motor driving the detector slit turns at a constant rate. As such, the time of our data measurements are directly proportional to the position of our detector. This will be taken into account in our analysis.

3.2 Alternative Interference Patterns

While we first conduct our experiment by shooting photons through a double slit, we can also imagine numerous other configurations through which we could shoot the photons. Additionally we could alter the dimensions of the two slits - their separation and their thickness. For the second part of our experiment we will qualitatively explore these effects.

We will pass a simple laser through various patterns enumerated in figure 7 on page 8 and observe the diffraction patterns they produce. We measure light intensity using a Pasco Light Sensor mounted on a translational stage. We continuously record data as we use the translational stage to move our light sensor through the diffraction patterns. With Pasco visualization software we can then make our observations.

From equation 6 we see that as we increase the spacing between our slits, we expect the spacing between our diffraction peaks, Δy to be smaller. We have not discussed the implications of changing the size of the slits themselves, this, along with the effects of our various diffraction gratings, will be experimentally observed.

4 Data Analysis and Results

4.1 Double Slit Experiment

For our first double slit experiment, our data processing is completed using python. We import, organize, and plot our data. These can be seen in figures 8a, 8b, and 5 below. Our python scripts are attached at the end of the appendix of this report.

With the data gathered, we can not make many precise calculations. However, using equation 6 we can calculate our approximate expected distance between peaks. The slits are separated by 0.4mm, the light travels a distance of approximately 0.5m before detection, and the laser produces 670nm light, therefore:

$$670 \cdot 10^{-9}[m] = \frac{0.40 \cdot 10^{-3}[m]}{0.5[m]} \cdot \Delta y \tag{11}$$

$$\Delta y \approx 800\mu m \tag{12}$$

Unfortunately, we do now know the exact translational speed of the detector slit. From figure 5 we see that our peaks are approximately 8 seconds apart. Therefore, if our calculations are correct this would imply that the micrometer is being turned such that the detector slit moves approximately $100\mu m/s$. with regards to the order of magnitude, this seems entirely reasonable.

More notable is the confirmation of the prediction modeled by section 2.3. As seen in figure 5, when both slits are open, an interference pattern is observed, the photons behave as waves. When one slit is closed, no interference pattern is present and the photons behave like particles.

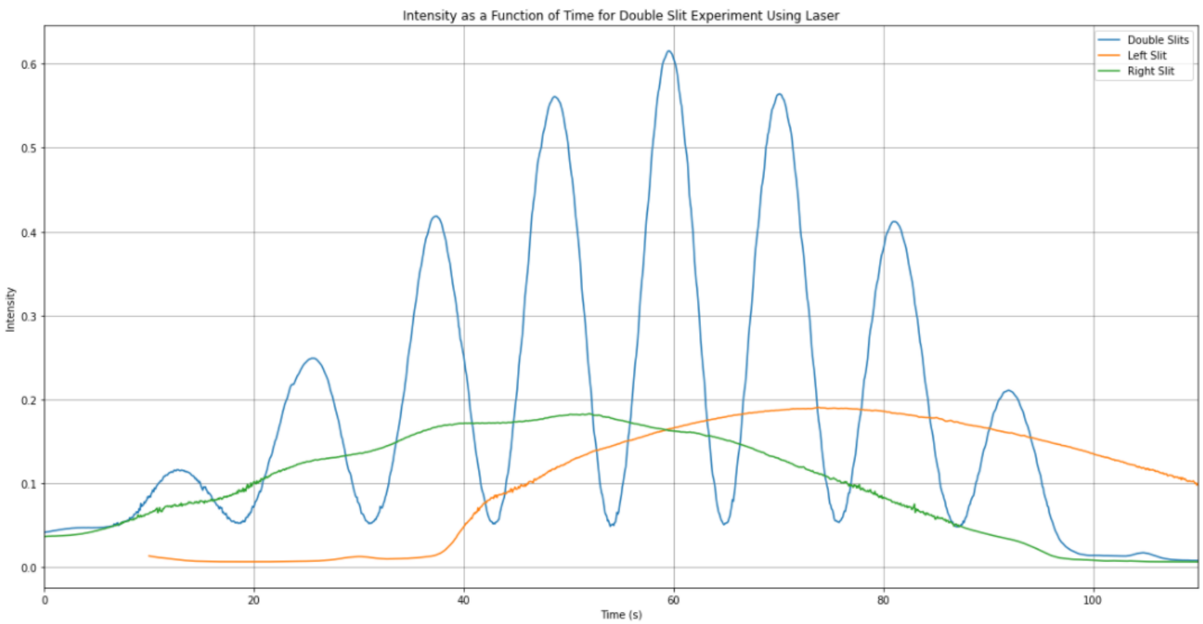


Figure 5: Plot of the measured photon intensities for our double slit experiment when using a laser light source. We display results when either the left or right slits are covered, and when they are both exposed.

Furthermore, we see the same results when using the light bulb to restrict ourselves to the single photon limit. These results can be seen in figure 9. While the data collected using the photo multiplier and a single slit seems to be very noisy (there is a signal to noise ratio of about 2 to 1), the result when using both slits is remarkable. In order to better visualize the behavior of the individual photons in the single slit experiment, we digitally applied an averaging filter. With this filter we can see that our two data sets peak in a similar fashion to the single slit cases in figure 5.

Looking at the double slit case in the single-photon limit, we undoubtedly see a strong interference pattern. It is so clear that it is not necessary to apply a similar averaging filter. We have therefore demonstrated that even in the extreme case when a single photon is being fired at a time, there is still and interference pattern. This result supports the derivations of section 2.3.

4.2 Alternative Interference Patterns

As with analyzing our data in the above section, the majority of our work comes with digitally processing the data. In contradiction with the previous section, there is no need to apply averaging for visualization purposes. There is no discernible noise in measuring the light intensities. However, a major problem for the data gathered in our second experiment is that we measured position using a sensor which does not have a definite reference point. The 0 point of our positional data for each recording is where the respective recordings start, as such they do not line up. Knowing that the central maxima of each diffraction pattern contains the peak value, we could digitally shift our figures so that they are centered about these maxima.

With the variety of diffraction gratings we used, we have a large number of figures associated with this experiment. The most notable of these results is shown in figure 6. We see the diffraction patterns produced by four double slit configurations. This figure highlights a problem with the accuracy of our position sensor. While the sensor works well when moving in one direction, it tends to lose accuracy when changing direction. In figure 6 we passed our light sensor through the diffraction pattern multiple times. As such, in our data, with each change in direction, our diffraction pattern is slightly shifted. This issue is not addressed digitally because it does not obscure the results of the experiment. We can clearly see that when the width of the diffraction slits increases in size, the diffraction pattern decreases greatly in intensity and disperses horizontally. This change in intensity was not predicted by our calculations. Additionally, it is evident the as the distance between the two slits increases, the spacing between adjacent peaks decreases. This is exactly what we predicted with equation 6.

Figure 6: Diffraction patterns produced by four different double slit configurations. 'a' corresponds to the width of each slit, and 'd' corresponds to the distance between slits. These data were measured by repeatedly passing a sensor through the diffraction patterns. With this, each pass resulted in a slight positional offset. Despite this, all relevant results can be observed.

Our other figures from this experiment can be seen in the appendix. They include figures 9a, 9b, and 10. Figure 9a plots the diffraction patterns for various numbers of slits whose width and spacing are the same. It confirms our earlier claim that diffraction patterns produced with more than two slits produce the same spacing between the peaks of their diffraction patterns (baring they share the same width and spacing of their slits). Additionally, it shows that as the number of slits increases, the overall intensity of these peaks also increases. We predict that this is simply due to a greater amount of light passing through the slits.

Figure 9b shows the "diffraction patterns" produced when using single slits of varying widths. The most obvious observation is that as the width of the slit increases, the intensity of the light peak greatly increases, which may seem obvious. However, in conjunction with this the width of the peak also narrows. Smaller slits seam to promote our light beam to diverge more quickly. Since figure 9b is produced used only single slits, we would not expect any diffraction patterns to appear. Surprisingly, however, we can see multiples small bumps characteristics of diffraction with the larger diameter slits. We suspect that as the size of the slit increases, the path difference between the left and right sides of the slit becomes more noticeable, eventually leading to interference as if there were two slits. Lastly, in figure 10 we plot the diffraction patterns produced by a circular aperture. The results of this final experiment are analogous to the results in of varying width single slit experiment (figure 9b).

5 Conclusion

Throughout this lab we have conducted measurements highlighting the behavior of light as it passes through various diffraction gratings. Through these experiments we can qualitatively confirm the wave nature of light. As shown in the latter half of our experiment, if we vary several parameters of our diffraction gratings, the behaviour of the diffraction patterns agrees with our theoretical predictions. These predictions are derived entirely geometrically.

In addition, we conducted a more traditional double slit experiment. In this experiment we showed that with both slits open, an interference pattern is produced by the light which passes through. However, if one of the slits is closed, we observe a peak intensity value at only one location, there is no diffraction - our light behaves as a particle. We further extend this experiment to the limit where we are firing one photon at a time at the slits. It is not very surprising that in this limit, when passing through a single slit, our photons behave quite well as particles. Amazingly, when both slits are open we still see an interference pattern. Thus, the wavelike property of photons is not a consequence of them interfering with each other, it is an intrinsic property of the individual photons. This experiment epitomizes the wave-particle duality of photons. We are detecting discrete photons, yet uncover the intrinsic wave properties we have discussed.

Our understanding of the nature of light has come a long way since Newton first claimed that it was composed entirely of particles. Historically, the experiments conducted in this lab, and the discovery of wave-particle duality led to many new questions regarding the superposition of states, the Heisenberg uncertainty principle, and the behavior of matter in similar situations. Regarding the results of these experiments, as Feynman put it: "we therefore have to accept that each electron (and indeed all matter) has both a wave-like nature (to create the interference pattern) and must also be considered as an individual particle (since this is what was detected)" [3].

References

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[2] Yaakov Fein; et al. Quantum superposition of molecules beyond 25kda. *Nature Physics, 15(12): 1242-1245*, 2019.

[3] Andrew Murray. Double slits with single atoms. `https://physicsworld.com/a/double-slits-with-single-atoms`, 2020.

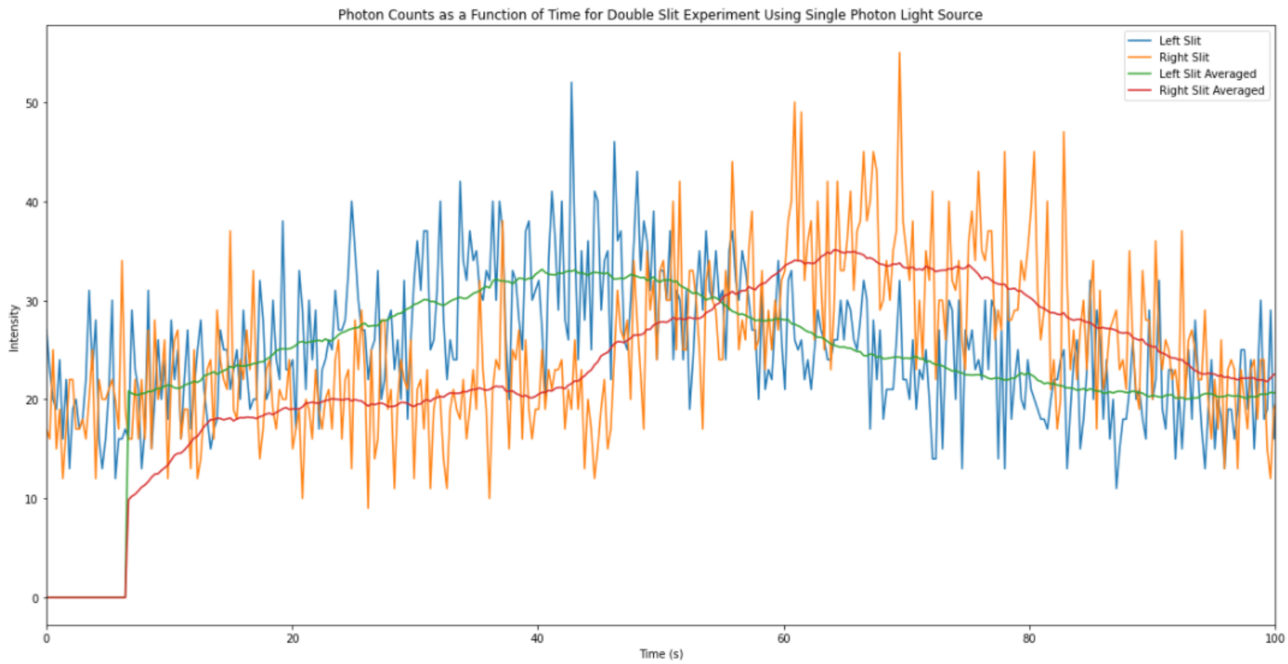
[4] Isaac Newton. Opticks: or, a treatise of the reflexions, refractions, inflexions and colours of light. also two treatises of the species and magnitude of curvilinear figures. 1998.

[5] TeachSpin. Two-slit interference, one photon at a time. `https://www.teachspin.com/two-slit`, 2021.

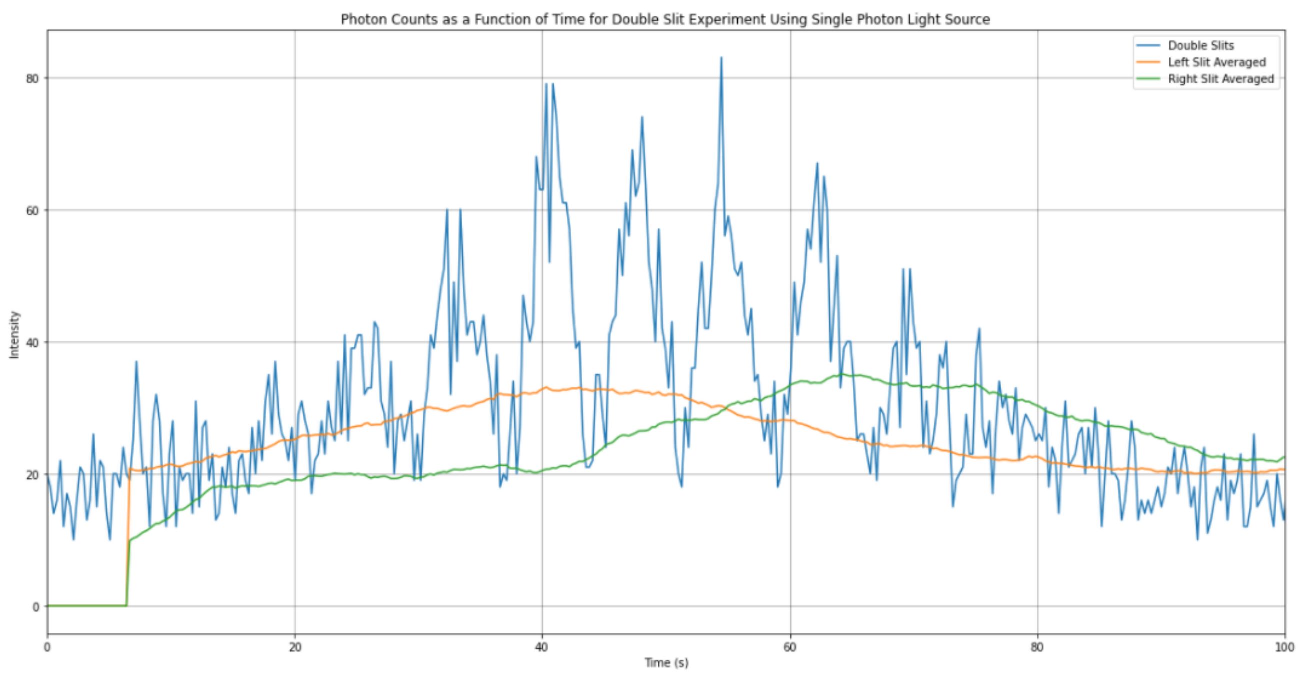
Appendix

Single Slit: a = 0.02mm	●
Single Slit: a = 0.04mm	◆
Single Slit: a = 0.08mm	⧓
Single Slit: a = 0.16mm	▼
Circular: 0.2mm dia	⧗
Circular: 0.4mm dia	▶
Square Pattern	◀
Hex Pattern	▲
Double: a=0.04mm d=0.25mm	●
Double: a=0.04mm d=0.5mm	◆
Double: a=0.08mm d=0.25mm	▼
Double: a=0.08mm d=0.5mm	⧗
Mult: N=2 a=0.04mm d=0.125mm	◀
Mult: N=3 a=0.04mm d=0.125mm	●
Mult: N=4 a=0.04mm d=0.125mm	◆
Mult: N=5 a=0.04mm d=0.125mm	⧓

Figure 7: List of the various slit configurations used in the second part of our experiment. Qualitative observations are made regarding the diffraction patterns they produce

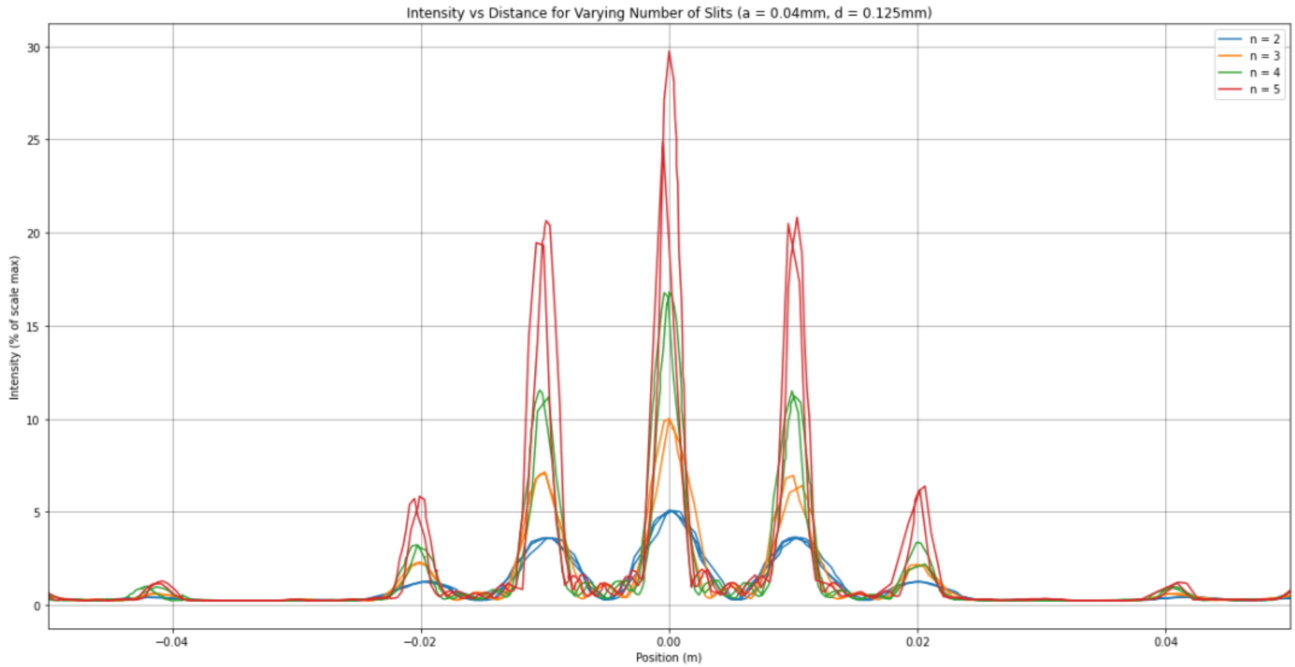


(a) Plot of our photon counts when using a single-photon light source as a function of time for both our left and right slits. In order to better visualize our data, we have applied an averaging filter which averages the nearest 50 points at each time. While the peaks are not very large, it is evident that there are two discrete peaks.

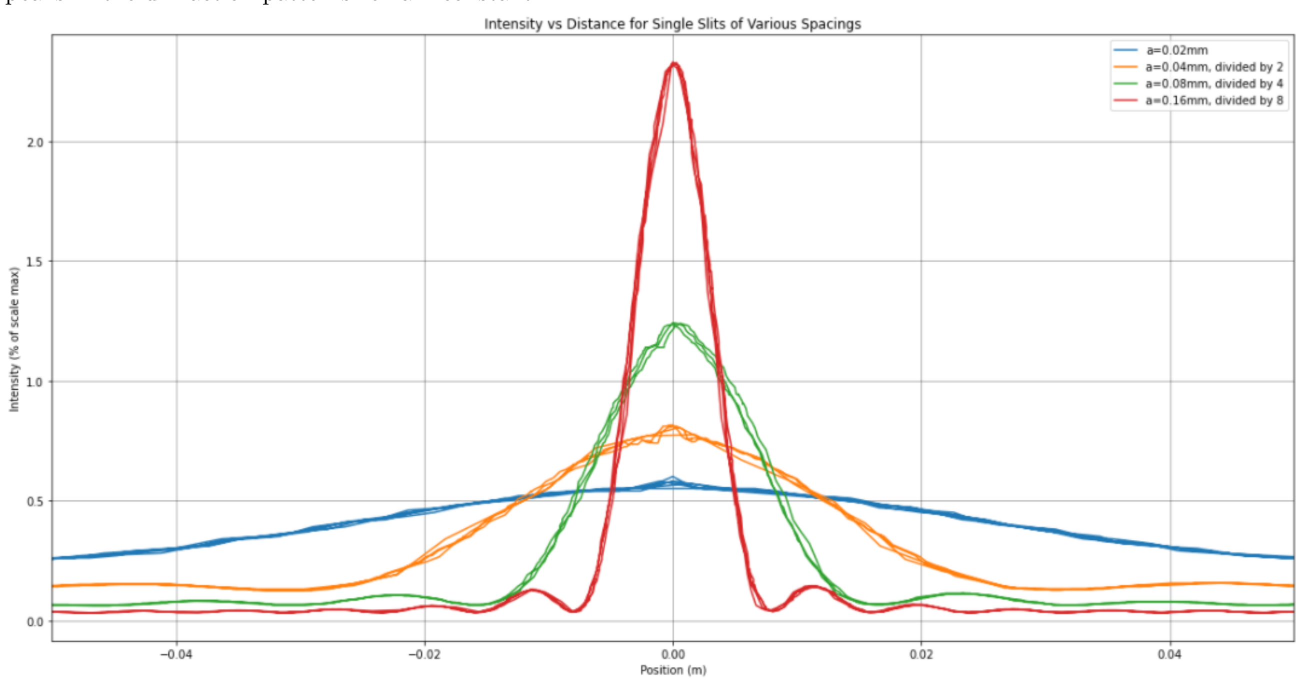


(b) Plot of our photon counts as a function of time when using a single-photon light source. For visualization purposes, the averaged value form figure 8a are plotted alongside our data. We plot the averaged data rather than actual data for clarity.

Figure 8



(a) Plot of four different diffraction grating with varying numbers of slits. The slit width in each configuration remained constant at 0.04mm, and the spacing between slits remained at d=0.125mm. Note that the distance between adjacent peaks in the diffraction patterns remain constant.



(b) "Diffraction patterns" produced by firing photons through various single slits, each of a different width. Note that the light intensities for the larger slits must be scaled down for visualization. Despite being produced by a single slit, we see nuances of interference produced in the larger slits. This may be because as the slit increases, the path difference between the left and right sides of the slit becomes more noticeable, eventually leading to interference as if there were two slits.

Figure 9

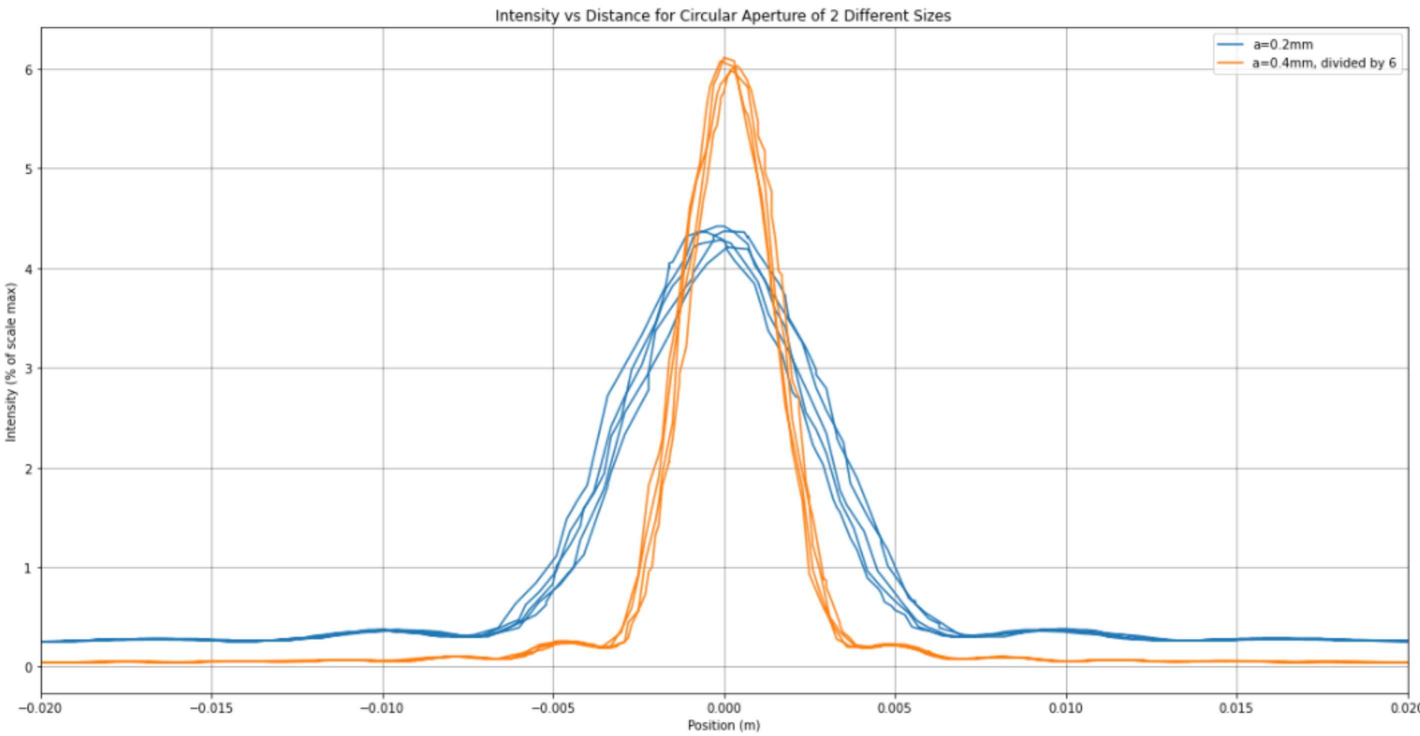


Figure 10: "Interference patterns" produced by passing light through circular apertures of different diameters. Very little interference is seen. Note that a smaller aperture allows less light to pass through, and causes greater divergence in the beam that does pass through.