Understanding Single Photon Diffraction by a Double-Slit

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Double-slit diffraction is a well-understood phenomenon produced when waves encounter two thin slits that are very close together. Classically, particles do not act the same way; they only pass through a single path and do not interfere like waves. Despite proof from effects like the photo-electric effect, single photons also show this phenomenon. Understanding what situations single particles diffract is important as it is one of the simplest easily viewable results of quantum mechanics. In this report, I have set up a (pseudo) single-photon source in a light-tight box to test the different ways single photons react to double-slits. When I counted the single photons at different locations where I expected a diffraction pattern I found that they approximate a cosine squared function with peak separations of 0.54 mm which matches what the theory predicts to 0.25%. We did not see diffraction with polarized slits. The results show that single photons experience double-slit diffraction only when they are not tagged in a way that could reveal which slit they passed through. I also give additional recommendations for how to increase confidence and understanding from this experiment in the future.

I. INTRODUCTION

The question of whether to treat light as particles or waves has raged for centuries. The discovery of quantized packets of light (or photons) gave a lot of merit to the particle view of light. However, even individual photons still have wavelike attributes.

When a wave passes through two thin slits, it appears that there are two new wave sources. Waves coming out of the slits then interfere, creating lines of high and low intensity (figure 1). The m^{th} line of high intensity occurs at angle θ as given by

$$m = \frac{d \sin\theta}{\lambda} \tag{1}$$

where λ is the wavelength of the wave and d is the distance separating the slits. The full pattern produced is a cosine squared function of intensity.

When single photons are sent through a double-slit it diffracts. This is contrary to how we expect a particle to act. The pattern occurs in waves because of interference, but the single photon result then implies that the photon interferes with itself. Additionally, if we tag the photon see we can tell which slit it went through, it no longer produces the pattern. This result has huge implications that lead to the development of quantum mechanics. It was also discovered that any sufficiently small particle displays this phenomenon (e.g. electrons [1]).

This report shows that the double slit diffraction affects single photons unless the photons are somehow tagged while going through the slits. I do this by first attenuating a laser so I expect only a single photon in a light-tight box 99% of the time, then passing it through a double-slit. This still produces a diffraction pattern which shows that the single photons interfere. When I tested the double-slit experiment with polarizing slits, thereby tagging each photon that went through a slit, I saw that the photons went through a single slit at a time. The techniques used are described in the Methodology and Analysis/Results sections. Overall my findings show that single photons produce double-slit patterns as though they are waves, but only when the specific slit the photon went through is undeterminable. This followed that is predicted.

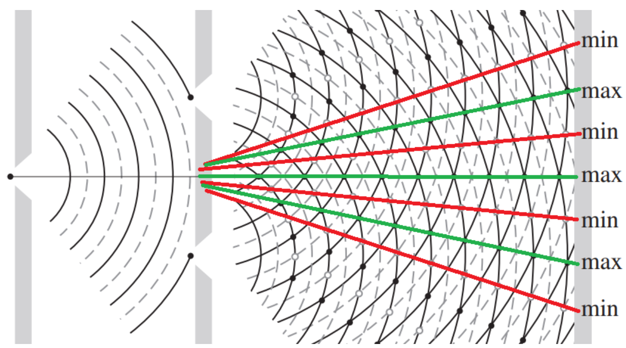

Figure 1. Two separated wave sources that produce waves that interfere. Red shows the destructive interference and green shows the constructive interference. (Reproduced from [2])

II. METHODS

The experiment is set up in a light-tight box that minimizes the confounding light that enters the box. This experiment is meant to test single photon diffraction, so first there must be only one photon in the experiment. Attenuate a laser to where it is predicted that there is a single photon in the box 99% of the time. This attenuator should always be in place when the experiment is proceeding. In my experiment, I used a 10^5 attenuator built into the box and an additional 10^3. To see the single photon diffraction we use a PMT that can detect single photons.

Send the attenuated beam into a double slit that has a large slit separation to slit width ratio. The diffraction

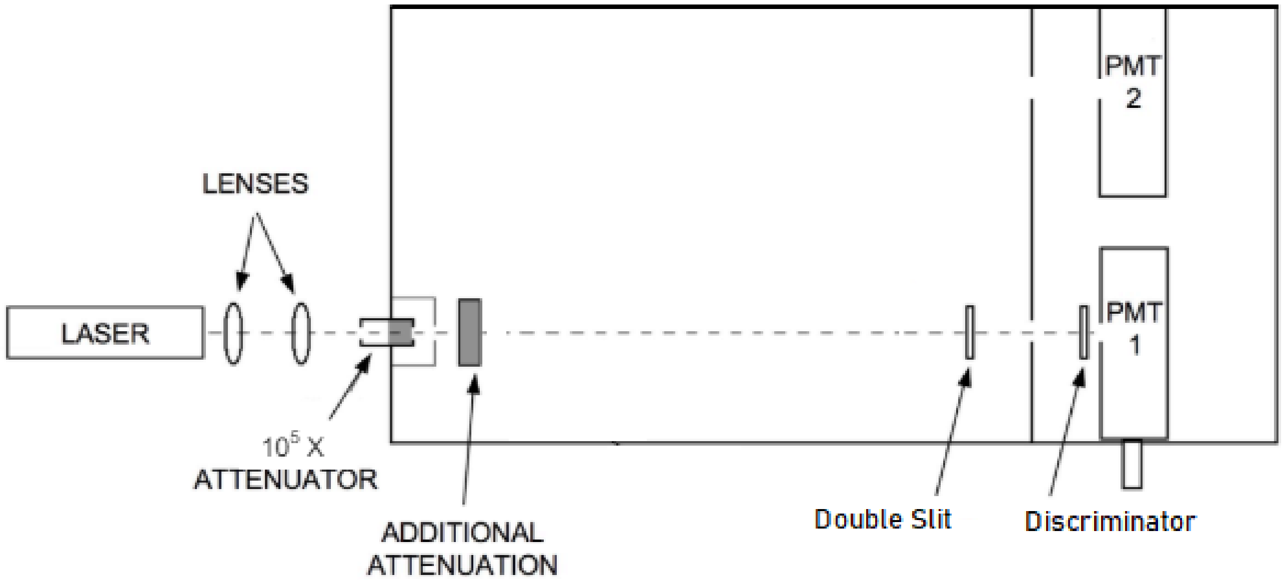

Figure 2. Setup for the single photon two slit diffraction. The beam is attenuated so there is only one photon in the box at a time (most of the time). (Produced based on [3])

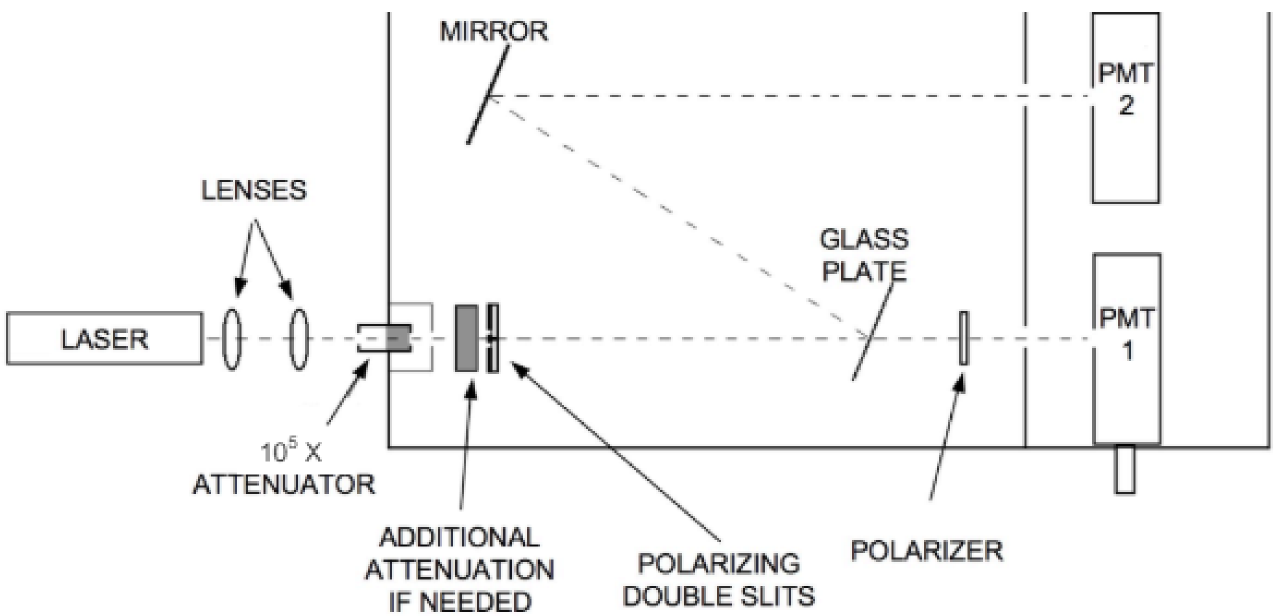

Figure 3. Setup for polarizing double slit experiment. The glass plate is oriented at Brewster's angle, so all single photons (dotted line) that are reflected are the same polarization. After the glass plate, a polarizer removes all the light polarized the same way as the reflected light. Each PMT sees only photons of a particular polarization now, and by extension, each PMT looks at the photons coming from a single slit. (Reproduced from [3])

pattern should appear on the PMT. Place a single slit right in front of the PMT that only lets in a small section of the diffraction pattern. This is called the discriminator and it should be able to be easily moved by very small amounts as it will be moved across the double-slit diffraction pattern to count how many photons get through at different positions. This setup is described in figure 2. The PMTs are connected to a photon counter. I used the photon counter and a stopwatch to count the number of photons at different discriminator positions 0.5 mm apart after 10 seconds at each position.

The second part of this experiment (figure 3) shows that the photons no longer diffract when we can distinguish them. I make the photons distinguishable by sending them through a double slit that polarizes one side one way and polarizes the other path 90° off. The

Incident photon spacing (ms)
22.5
24.5

Table I. While looking at the oscilloscope connected to the polarized experiment shown in figure 3 I looked for incident photons over two minutes. In two minutes, there were two cases of multiple photons that would fit on the screen. These are the time spacings between the photon measurements.

beam is then reflected off a glass plate that is positioned at Brewster's angle relative to the incoming light, which only reflects one polarization and lets some of both polarizations through [2]. Then a polarizer is placed behind the glass plate to ensure that only the light of the opposite polarization of the reflected light gets through. Both beams are separately aimed at different PMTs which are both connected to different channels of an oscilloscope. By watching the oscilloscope I can see when individual photons hit the PMT and how closely together the events are. Since we predict only one photon at a time we should only see one photon hit a PMT at a time.

III. DATA

The width of the double-slits is 5.8 µm and separated by 228 µm. The width of the discriminator is 50 μm. The laser has a wavelength λ of 543.3 nm and operates at 0.1 mW. The distance from the double-slit to the discriminator was measured as 22.1 ± 0.5 cm.

Photons were counted for 10.0 ± 0.1 seconds. The results are shown in red in figure 4. All the discriminatory positions measured have an associated uncertainty of 0.005 mm. We also established a noise of 10 ± 1 photons in ten seconds of counting when the laser was off with the discriminator in place.

For the polarized experiment, after 120 seconds there were only two coincident events seen, shown in table I.

IV. ANALYSIS & RESULTS

To get a single photon into the box at a time we attenuated the original laser to the point where we expect only one photon in the box 99% of the time. While this does not guarantee a single photon, we expect that it is good enough to show the single-photon double-slit phenomenon exists.

The probability of there being n photons at a time $P_{\langle n\rangle}(n)$ is given by

$$P_{\langle n\rangle}(n) = \frac{\langle n\rangle^n}{n!}e^{-\langle n\rangle} \tag{2}$$

$$P_{\text{0-or-1}} = P_{\langle n\rangle}(0) + P_{\langle n\rangle}(1) \tag{3}$$

where $\langle n\rangle$ is the expectation value of the number of photons. I wanted $P_{\text{0-or-1}} > 0.99$ or for there to be at most one photon in the box 99% of the time. If we have some initial laser power P then we know that there is E/t energy that is being measured:

$$\Rightarrow E \approx \langle n\rangle E_\gamma = \langle n\rangle h\nu = tP$$

and we know ν to some small uncertainty. We want to find a relationship between how much we need to $\langle n\rangle$ so we solve for a measured power $P = \frac{\langle n\rangle h\nu}{t}$. This gives us on average $\langle n\rangle$ photon per t. If we want to expect one photon in the box at a time we want to have $t = L/c$ where L is the length the photon travels to the detector. So with

$$P = \frac{\langle n\rangle h\nu c}{L}$$

Our He-Ne laser has a power of P_0 so to get to P we want to attenuate the laser by A.

$$P_0 A = P = \frac{\langle n\rangle h\nu c}{L} \Rightarrow A = \frac{\langle n\rangle h\nu c}{LP_0} \tag{4}$$

We need to solve equation 3 and equation 4.

$$\langle n\rangle = \frac{ALP_0}{h\nu c} \tag{5}$$

$$P_{0-or-1} = \frac{\langle n\rangle^1}{1!}e^{-\langle n\rangle} + \frac{\langle n\rangle^2}{2!}e^{-\langle n\rangle} > 0.99 \tag{6}$$

Solving this for $\langle n\rangle$ gives a value of around 0.1 and with that A gives us around 10^{-8}. This is the attenuation I used.

Figure 4 shows the cosine squared function that was fit to the data. I used the Python `scipy.optimize.curve_fit` function to produce the best fit. I did R^2 analysis on it separately and it has a 96.6% match to the data. The fit function has peaks separated by 0.54 mm. I was not able to figure out how the 0.1 second uncertainty in time or the 0.005 mm space uncertainty propagated properly into the resulting separation value of this type of best fit, but there is uncertainty present from measurement and fitting.

For the polarized slit experiment, I looked for 120 seconds and found two photons that were within 25 ms of each other. Since it takes the photons approximately 3.33 ns to pass through the box, these photons were not the same. Both PMTs were seeing individual photons, but far enough apart to say confidently that they were not diffracting.

V. DISCUSSION

From equation 1 we can find that our setup should produce diffraction patterns separated by 0.527 ± 0.001 mm. The error between this measurement and the best-fit curve measurement is 2.5%. This result shows excellent agreement with the predicted theory. The uncertainty does not appear to account for the error properly, but I suspect that if I were to figure out how to calculate

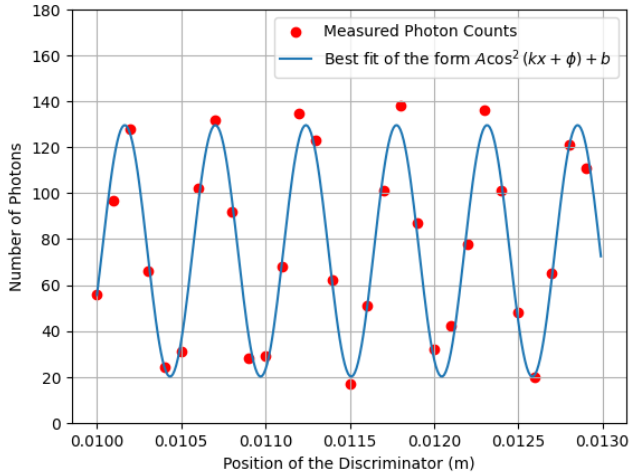

Figure 4. The measured photon counts are in red. These are the number of photons that are counted in 10.0 ± 0.1 seconds. A best-fit cosine function is plotted on top. This displayed function has a frequency of 0.00169, which corresponds to a 0.00054 m separation of peaks. The R^2 of this fit is 96.9%. Technically there should be a sinc function contribution, but the measurements are close enough to the line between the slits that it should not be a large effect.

the error associated with the best-fit method that error would match the discrepancy we see.

I was unable to get a complete picture of the polarized double-slit experiment. While the results do show that I see one signal at a time, and hence there is probably not any interference, I would like to have gotten a bit more data. Qualitatively I saw no interference pattern caused when the photons went through the polarized double slit.

VI. CONCLUSION

In conclusion, this report confidently shows that single photons produce a diffraction pattern from a double-slit experiment. Even though classical particles do not interfere, quantum mechanics results in interference from single photons. This has been shown to extend to other small particles like electrons and is predicted when using modern quantum mechanics.

This report also concludes that if photons are tagged based on which of the two slits it goes through, they no longer produce this effect, but would like to perform more experiments to confirm this. This is a very well-understood effect and this report concludes that the theory accurately predicts the effects of single photons passing through double slits.

There are a few ways others can improve on this experiment to get better results. Firstly the "light tight box" letting less light in would be helpful for the experiment, as the number of photons that gets in with no laser on is clearly non-negligible. The method used to obtain a single photon at a time is naive and there are better ways to produce single photons with less error and without decreasing the rate of photon production [4]. Finally, having an exact copy of the polarizing double slit, but with both slits polarized the same direction would allow me to see the way that polarizing changes the result directly.

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