The Duality of Light

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Using a single and double slit apparatus, the Young and Feynman interference experiments were conducted and compared to one another. This was done using a red laser with both the single and double slits. Using a photomultiplier tube and a micrometer, we were able to record the intensity of the light at various positions of the light pattern. Also, a light bulb with a green filter was used to send singular photons down the apparatus, like Pier Giorgio Merli did in 1974 with singular electrons.[1] The intensity of the light then comes in the form of photon counts, and was also measured at various positions by adjusting the value of the micrometer. The data collected was plotted as the intensity of the light versus the value of the micrometer which adjusts the position of the photodiode. The data were fit with the double and single slit equations by plugging in our known values. This prediction fit matches the experimental data well in all four plots. This results supports the idea of light as a wave and light as a particle.

INTRODUCTION

Wave-particle duality is the concept that all particles or quantum entities can be described as either a particle or a wave.[2] This concept of duality also extends to light and singular photons of light. Up until the 1800's, it was an ongoing theory postulated by Isaac Newton that light was a particle. This was accepted in the scientific community until Thomas Young did his experiment with light using a double slit in 1803. Young passed light through two slits much smaller than the space between them. According to Newtons theory, two well defined bright spots would have been seen down the line from the light source, but this was not the case. Instead Young observed an interference pattern with his experiment. With his work, Young changed the idea that light acts not only as a particle but also as a wave.

Then in 1905, Albert Einstein explained the photoelectric effect and concluded that light must be divided into individual packets. This ongoing paradox between light as a particle or a wave led to Pier Goirgio Merli obtaining the famous interference pattern in 1974.[1] This interference pattern applied when one electron at a time passed though a double slit implying that each photon then interferes only with itself.

For this experiment, I recreated Young's experiment using a diode laser and Feynman's experiment using a dim bulb with a filter to produce green light and send single photons down the tube.

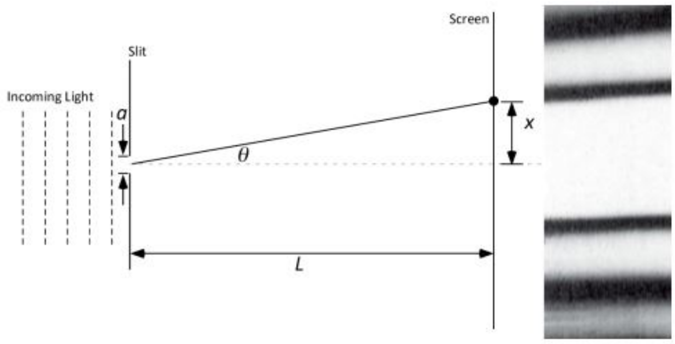

FIG. 1: Geometric representation of light passing through a single slit and onto a screen. Figure taken from Ref.1

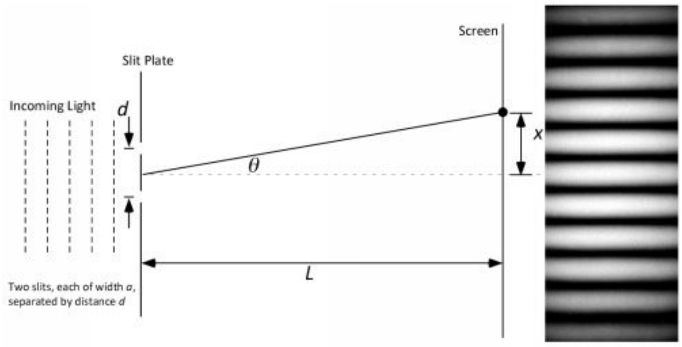

FIG. 2: Geometric representation of light passing through a double slit and onto a screen. Figure taken from Ref.1

THEORY

Single Slit Diffraction

Classical physics teaches us that a wave going through a single slit will spread and create a diffraction pattern. Using Huygens' principle we can think about the light at the slit to be made up of many singular waves. These waves will travel outward from the slit of width a to a place down line from the source called x. From the slit the light will travel down the tube forming an angle θ from the normal. The geometry of this process can be seen in Fig.1. After exiting from the slit, the light will be phase shifted causing the diffraction pattern. From this we get constructive and destructive interference. The destructive interference occurs when two of the waves are out of phase by half of their given wavelength.

Double Slit Interference

Double slits produce two coherent sources of waves that will interfere once leaving the two slits of separation d. These waves will overlap and interfere again constructively and destructively. The constructive interference creates the bright spots and the destructive interference creates the dark spots. This translates to the highs and lows in intensity seen later in the report. Similarly to a single slit, constructive interference occurs when two waves differ by a whole integer of their wavelength and destructive occurs when the two waves differ by any half integer of their wavelength. The separation of the two slits is represented by d and the angle of travel from the norm is θ, as seen in Fig.2.

Intensity of the Light

We know that the intensity of light is proportional to the square of the amplitude of a given wave. In these experiments, the intensity will be the square of the sum of the light hitting the observation screen at the end of the tube. We also expect the maximum intensity to be at the central maximum of the pattern. We are given [1] that the intensity pattern for a single slit of length L to the observation screen is

$$I = I_{max}\left(\frac{\sin\alpha}{\alpha}\right)^2, \tag{1}$$

for

$$\alpha = \frac{\pi a}{\lambda}\sin\theta. \tag{2}$$

With Eqn.1, we can geometrically rewrite the portion in parenthesis as

$$\left(\frac{\sin\alpha}{\alpha}\right)^2 = \text{sinc}\left(\frac{\pi a}{\lambda}\frac{x}{L}\right)^2, \tag{3}$$

where we substitute in our values from α and $sin\theta$ goes to x/L because of the small angle approximation theorem. This gives us a final equation for intensity of

$$I = I_{max}\ \text{sinc}\left(\frac{\pi a}{\lambda}\frac{x}{L}\right)^2. \tag{4}$$

The double slit intensity equation is very similar to the single slit equation. The double slit turns out to be the same function multiplied by a cosine function squared, so

$$I = I_{max}\ \text{sinc}\left(\frac{\pi a}{\lambda}\frac{x}{L}\right)^2 cos^2\beta, \tag{5}$$

for

$$\beta = \frac{\pi d}{\lambda}sin\theta. \tag{6}$$

The small angle approximation theorem also applies to the double slit, making $sin\theta$ go to x/L.

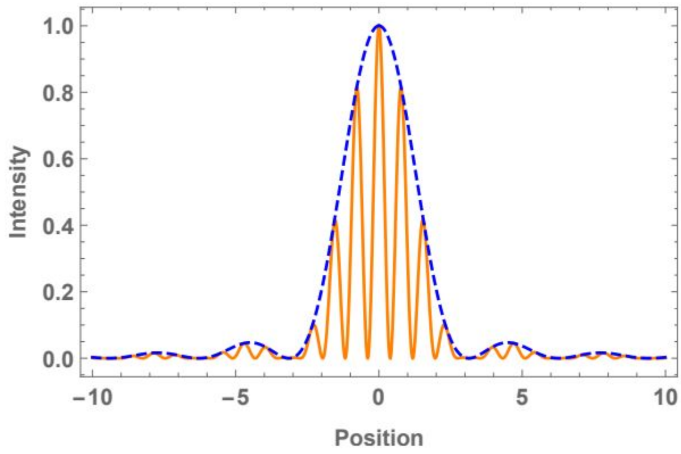

FIG. 3: Graphed intensity patterns for double slit interference (solid) and single slit diffraction(dashed). Figure taken from Ref.2

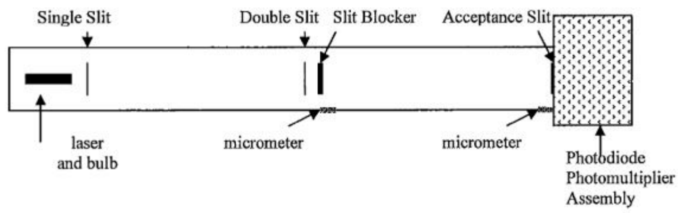

FIG. 4: Visual schematic of the apparatus from a top down view. Figure taken from Ref.1

Qualitative Analysis of Intensity

The single slit intensity pattern is given by a sinc(x) function. We can plot this and see a large central maximum followed by a drop off into a zero region. This pattern is exactly what we will observe when measuring intensity for a single slit diffraction pattern. The double slit intensity pattern is similar. Its amplitude follows the same general shape, but it is changed by the cosine squared giving it many peaks and valleys unlike the single slit plot. The single slit and double slit functions can be seen in FIG.3.

PROCEDURE

Apparatus

The apparatus used in these experiments, schematically shown in FIG.4, was specifically designed for them, and made by TeachSpin. The slits were first aligned so that swapping back and forth from either experiment could be done quickly and easily. The channel of which light traveled down was covered by a thick top piece and held down by four braces to keep it secure. This is important because if the photomultiplier tube (PMT) is exposed to normal room light, it can be seriously damaged and will need replaced. The shutter for the PMT was kept closed at all times unless data was being collected.

Young's Experiment

Once the apparatus slits are aligned and set up, it was connected to a multmeter. The apparatus was connected to a multimeter to output the intensity of the light in terms of voltage. Using a micrometer to control the position of the acceptance slit, intensity could be measured at specific locations on the observation screen behind the slit. Before taking data, a dark measurement of intensity was taken as a base level. For me, the base measurement of voltage was 0.0085 V. I took measurements for the single slit first, making measurements every 0.1 mm on a range of 0 to 6.0 mm. Then data was recorded for the double slit, making measurements roughly every 0.1 mm, but the spacing was adjusted as needed to ensure measurements were taken at the minimum and maximum intensity points. This range also extended from 0 mm to 6.0 mm.

Feynman's Experiment

In the Feynman experiment, intensity was a measurement of counts of photons at a certain position over a time interval of 10 seconds. This was done using a photomultiplier tube. The PMT, when struck by a photon, releases electrons that follow the potential to another plate behind it. When those electrons hit the second plate, that plate then releases electrons and the cycle continues. This process repeats itself until a measurable change in current can be recorded. The PMT receives the photon and multiplies the signal, giving it the name of photomultiplier. For this experiment, a discriminator was used to differentiate between photons hitting the plate and noise. I used a discriminator value of 50 mV on the Pulse Counter/Interval Timer. It was this device that gave us a digital output for how many photons hit the PMT in the set time interval of 10 seconds. For the PMT a potential of 5.5 (550V) was applied to it. Before collecting data, a dark run had to be conducted. I ran a dark run for a covered PMT with the bulb on, and an uncovered PMT with the dim bulb turned off. For both, a photon count of about 25 was recorded over the set time interval of 10 seconds. With the same setup as the dark run for a covered PMT, the PMT was uncovered and intensity was measured at position intervals of 0.1 mm for a single slit. For the double slit, intensity was measured at position intervals of roughly 0.1 mm, and again dialing in maximum and minimum intensities to the nearest 0.01 mm. For all position, both with the single and double slit, measurements for intensity were taken three times and averaged.

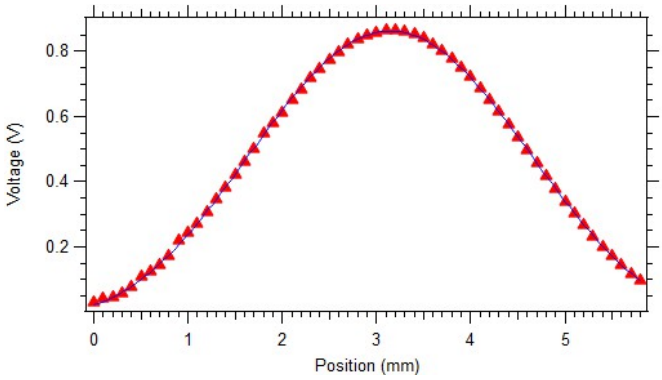

FIG. 5: Plot of voltage versus position for a single slit diffraction pattern using a red laser. Fit with a theoretical curve using known values.$I_{max} = 0.865$V

RESULTS

Analysis and Results

The data from both experiments, intensity and position, were entered into IgorPro for analysis. A plot of the single-slit diffraction data versus a theoretical curve is shown in FIG.5 and the data versus theory of the double slit is shown in Fig. 6. Each data set was made into an intensity versus position plot, with a theoretical curve appended to the plot. The dark rates were subtracted from the final intensities before plotting.

The theory curve for the double and single slit experiments were generated using known values and plugging them into their respective equations stated in the theory section. The known values used to calculate the fit are: $\alpha = 0.085$mm, $d = 0.353$mm, $L = 0.5$m, $\lambda_{laser} = 635$nm, and $\lambda_{bulb} = 545$nm.

There were many forms of error in these two experiments. The most significant forms being voltage read by the multimeter and recorded number of photons hitting the PMT. The multimeter was rated to be within ± 0.0003V of the true value. For the number of photons hitting the PMT, the error was calculated to be $(\pm I)^{1/2}$. This calculation comes from implementing Poisson statistics.

The results from the Young experiment turned out as good as one could hope. As seen in FIG.5 and FIG.6, the collected data points follow the theoretical curve well, confirming our figures from earlier in the report. This was expected from the results, as wave nature should easily seen when firing many photons from a laser through two slits.

The Feynman experiment turned out just was well as the Young experiment. Both FIG.7 and FIG.8, plots

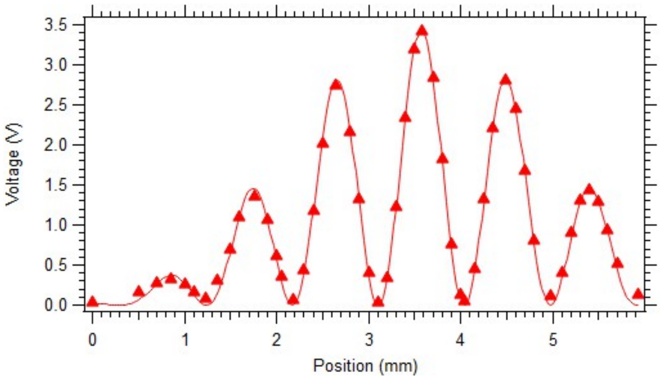

FIG. 6: Plot of voltage versus position for a double slit interference pattern using a red laser. Fit with a theoretical curve using known values. $I_{max} = 3.42$V

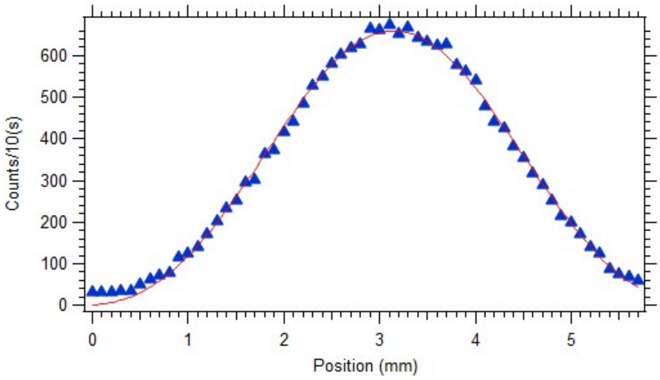

FIG. 7: Plot of counts versus position for a single slit diffraction pattern using a filtered bulb. Fit with a theoretical curve using known values. $I_{max} = 674$ photons

of intensity versus the position of the detector, followed their theoretical curves using known values quite well.

CONCLUSION

Young's experiment was recreated using a red laser for double and single slit interference. The data recorded and plotted using IgorPro fits the theoretical lines quite well, confirming that photons do exhibit wave behavior, as stated by Young in his experiment in 1803.

Feynman's experiment was also recreated using a dim bulb with a green filter over it to send one photon at a time at through the double and single slit. This data set, averaged out over three measurements per position, also fit the theoretical line very well. Again, confirming that light does exhibit wave behavior.

With all these results and our four figures, its clear that light behaves like a wave. However, the Feynman experiment is harder to interpret because its results mean that individual photons interfere with themselves. Even in the absence of other photons. This is the case because

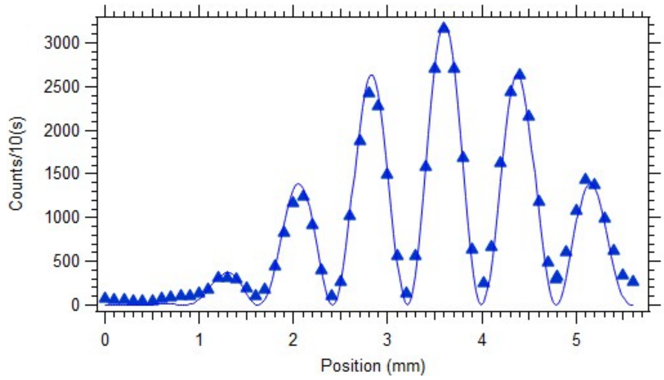

FIG. 8: Plot of counts versus position for a double slit interference pattern using a filtered bulb. Fit with a theoretical curve using known values. $I_{max} = 3164$ photons

photons are quantum mechanical objects that have quantum wave functions. This quantum wave function is what causes the photon to interfere with itself as it travels from its source to the detector. Once the photon reaches the detector, that wave function is negligible as its position is brought to a single point on the detector. Once the photon comes into contact with the detector it is then recorded and turned into a clicking noise from the pulse counter.

References

1. The College of Wooster, Physics Junior Independent Study Lab Manual, (2018): 54-57.

2. Fuller, Chase. The Young and Feynman Experiments: Is Light a Wave or a Particle? Wooster Physics, Junior Independent Study, 2018, pp. 3.

3. “Wave–Particle Duality.” Wikipedia, Wikimedia Foundation, 10 Feb. 2020, en.wikipedia.org/wiki/Wave–particle duality.