The Young and Feynman Experiments: Is Light a Wave or a Particle?

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To investigate the wave-particle duality of light, the Young and Feynman interference experiments were conducted and compared. A laser diode producing light of wavelength 640 ± 10 nm was used with single and double slits. Using a photodiode and a micrometer, measurements of the intensity at different positions were taken. Then, a green light filter was placed on a dim incandescent bulb to both restrict the number of photons released, and control their wavelengths to a range of 541 nm to 550 nm. In similar fashion to the Young experiment, the intensity of the light, in the form of photon counts, was measured at different positions using an adjustable screen and a photo-multiplier tube. The data sets were plotted against position alongside theoretical prediction lines of the intensity as a function of position. The data match the intensity prediction lines with no adjustable parameters well, even in the single photon regime. This result supports the idea of wave-particle duality.

I. INTRODUCTION

Is light a wave or a particle? This question has plagued scientists for centuries. Until the early 1800s, most were satisfied with the idea that light is a particle, as postulated by Isaac Newton. Geometric optics, built on the foundation of the particle interpretation of light, accurately accounted for a variety of systems. It seemed the question was answered. That is, until Thomas Young published the results of his double slit experiment in 1803.

Young allowed light to pass through two slits. The adjacent slits had widths that were about ten times smaller than the distance between them. If light were a (classical) particle, he would have found two, well-defined bright spots corresponding to the two slits. That was not the case. Instead, Young observed what could only be described as an interference pattern– interference arising from light as a wave. His experiment convinced physicists that light was indeed a wave and the particle interpretation was discarded.

However, the particle interpretation resurfaced when Albert Einstein published *Concerning an Heuristic Point of View Toward the Emission and Transformation of Light* in 1905. He accurately described the photoelectric effect using quantization of light with definite energies [1]. In other words, the photoelectric effect is best described using an interpretation of light as discrete packets of energy. These would later be called photons, coined by Gilbert Lewis in a letter to the editors of *Nature* in 1926 [2].

The question arose again: Is light a particle or a wave? As quantum mechanics developed in the 20th century, so too did a nuanced understanding of light. Richard Feynman proposed his own style of double slit experiment, this time using an apparatus designed to pass one photon at a time through the double slits. By counting the photons as they arrive at different spots along an observation screen, he hypothesized that the individual quanta of light would build an analogous double slit interference pattern as observed over 200 years prior by Young.

In this paper, I perform Young's experiment using a laser diode and Feynman's experiment using a dim, filtered, incandescent light bulb to probe the true nature of light.

II. THEORY

The geometric interpretation of light is enough to analyze optical systems with lenses and mirrors, but is inadequate to describe single slit diffraction and double slit interference. For these systems, we will require the wave interpretation of light. Treating light as a wave allows us to take advantage of waves' ability to superpose and constructively or destructively interfere.

The second common assumption we make is that the slit width a is appreciably smaller than the separation between them, d. The slit width should be on the order of 10 times as small or smaller. We also assume the distance L between the observation screen and the slit is far greater than the wavelength λ of the light passing through the slits. This changes the domain of the interference from the Fresnel regime to the Fraunhofer regime.

Third, we are going to assume the incident light is monochromatic. This is physical because lasers produce effectively monochromatic light, and certain light filters can select a narrow range of wavelengths to transmit, allowing white light to become effectively monochromatic. We eliminate unnecessary complications by assuming λ is a constant.

Lastly, we will assume the incident light is a plane wave that travels perpendicular to the plane of the slits and observation screen. This is a safe assumption to make, as the source or screen can be oriented such that the incoming light will be perpendicular to the plane of the screen.

A. Single Slit Diffraction

To understand single slit diffraction, we consider the incident light at the slit. We can use Huygens' princi-

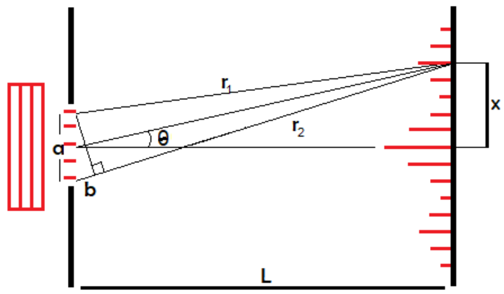

FIG. 1: A plane wave incident on single slit with width a. The observation screen is a distance L from slit, while points of interest on it are a distance $\pm x$ from the central maximum.

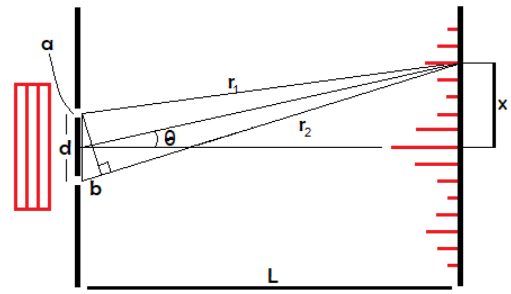

FIG. 2: A plane wave incident on a double slit with separation distance d and slit width a. The observation screen is a distance L from the double slit, while points of interest on it are a distance $\pm x$ from the central maximum

ple to think about the light taking up the space of the slit of width a to be comprised of many singular waves, all traveling to some specific place x on the observation screen. The light will have to travel out from the slit at some angle θ from the normal, as shown in Fig. 1.

Because each wave travels a different distance, signified by b, at the same speed, there will be a phase shift between them. This phase shift is what causes the diffraction pattern. At predictable spots on the observation screen, we see constructive and destructive interference. Destructive interference will occur when two waves are out of phase by one half their wavelength. To investigate where this condition applies, we can relate θ, λ, and a by breaking the slit into two equal parts of size $a/2$. Doing this and applying the geometry, we find

$$\frac{a}{2}\sin\theta = \frac{\lambda}{2}. \quad (1)$$

From this, if we divide the light at the slit into $2m$ parts, we find the destructive interference condition to be

$$\sin\theta = m\frac{\lambda}{a}. \quad (2)$$

B. Double Slit Interference

The double slit interference derivation is similar to the single slit diffraction case. Instead of $2m$ waves, there are two waves separated by an appreciable distance. It is this separation distance that causes the additional fringes that are not present in the single slit case.

Carefully accounting for the geometry in Fig. 2, the maximum condition is

$$b = a\sin\theta = n\lambda \quad (3)$$

where n is an integer. Making a similar geometric argument, a minimum will be when the phase difference is one half of a wavelength. Mathematically,

$$b = a\sin\theta = \left(\frac{1}{2} + n\right)\lambda. \quad (4)$$

C. Intensity Functions

A careful derivation of the respective intensity patterns of both configurations is beyond the scope of this paper. Instead, I can attempt to motivate them.

Intensity is proportional to the square of the amplitude of a wave. In our experiments, it would be the square of the sum of the light reaching the observation screen. This makes sense because we should have only positive intensities. Furthermore, we should expect the maximum possible intensity of the pattern to be at the central maximum. The intensity pattern for the single slit is

$$I = I_{max}\left(\frac{\sin\alpha}{\alpha}\right)^2, \quad (5)$$

for

$$\alpha = \frac{\pi a}{\lambda}\sin\theta. \quad (6)$$

The double slit intensity pattern is intimately related with the single slit pattern. It turns out that it is the same function multiplied by a cosine squared factor:

$$I = I_{max}\left(\frac{\sin\alpha}{\alpha}\right)^2\cos^2\beta, \quad (7)$$

for

$$\beta = \frac{\pi d}{\lambda}\sin\theta. \quad (8)$$

Let's consider these two equations qualitatively. The single slit intensity pattern is a $\sin(x)/x$ function. If we plotted this and moved away from zero along the x axis, we would see a clear central maximum, a zero region, a small positive amplitude, another zero region, another smaller positive amplitude, etc. This is what we observe in a single slit diffraction pattern!

The double slit intensity pattern is close to the diffraction pattern. Its amplitude follows the same overall shape, while being modulated by the cosine squared term. Both equations are plotted together in Fig. 3.

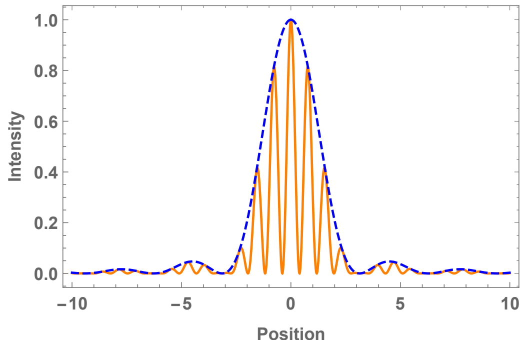

FIG. 3: Predicted intensity patterns for single slit diffraction (dashed) and double slit interference (solid).

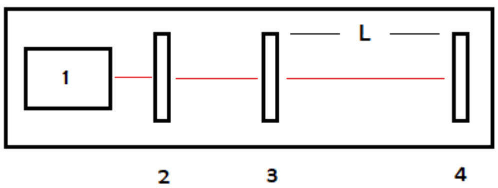

FIG. 4: A schematic of the optical channel. Object 1 is the light source. A broad single slit, component 2, makes a focused beam to pass to 3. Component 3 is a double slit with slit width $a = 0.085$ mm and separation distance $d = 0.343$ mm. A screen was used to block one slit when needed. Lastly, 4 is the intensity measurement device at $L = 0.5$ m from 3.

The double slit intensity pattern, just like the diffraction intensity pattern, is a very good mathematical description of what we see in the lab. If one were to observe a double slit intensity pattern, they would see a clear central maximum flanked by two dark spots. Then there would be two more bright spots– but not as bright as the central maximum.

III. PROCEDURE

A. Apparatus

The apparatus I used was a manufactured model by a company called TeachSpin. It allows for both the Young and Feynman experiments to be conducted in the same optical channel. Once all slits have been carefully aligned, one can simply switch the light source and sensor to change from one experiment to the other. A schematic of the relevant components of the optical channel is shown in Fig. 4.

A key feature of this apparatus is that the channel can be covered so the only light acting on the sensors is light from the chosen light source. This reduces systematic error in the Young experiment, and it is critical for Feynman's experiment. Needless to say, a detector capable of counting individual photons should only be exposed to very low intensity light– even moonlight is too intense.

B. Young's Experiment Procedure

After aligning the slits carefully, Young's experiment was conducted using the laser diode for the light source. The apparatus was connected to a multimeter precise to ± 0.0001 V to read the measurements of intensity by the photodiode. An opaque plate attached to a micrometer was placed just in front of the sensor and moved to allow for measurements of intensity at specific locations on the observation screen.

With the channel covered and laser off, a dark measurement of the intensity was taken. The base voltage of the photodiode was found to be 0.0085 V. The experiment was first conducted in the single slit regime, with measurements being taken every 0.02 cm. Both slits were uncovered to enter the double slit regime and, due to the more complex intensity pattern, a measurement was taken every 0.01 cm.

C. Feynman's Experiment Procedure

Measurements of intensity in the Feynman experiment are counts of photons at some position over set intervals of time. To accomplish this, a photo-multiplier tube was employed. The PMT is an instrument that is, at the most basic level, a capacitor. When a photon hits one of the plates, it knocks loose many electrons. The electrons then, due to the high operating potentials of the PMT, follow the potential to the other plate. These electrons knock loose more electrons, which fall across the PMT into another pair of plates. The process repeats until it creates a measurable change in current. The PMT takes one incident photon and multiplies the signal, hence the name photo-multiplier tube. A discriminator must be used to differentiate between an actual incident photon and noise. For my experiments, a potential of 550 V was applied to the PMT. The discriminator threshold was set as low as possible, to just above zero.

Furthermore, with these settings, the behavior of the PMT had to be investigated before the experiment could be conducted. The channel was covered and the PMT uncovered. I recorded several dark rates. It appears that the average dark rate lies somewhere in the mid 40 counts. This holds for whether the PMT is closed, open with no incident light, or blocked with the source powered.

With the same settings used to calculate the dark rate with the bulb powered and PMT blocked, I measured the intensities at position intervals identical to the Young experiment. Because the single photon, double slit experiment is statistical in nature, measurements were taken at each position three times and averaged.

IV. DATA AND RESULTS

A. Analysis and Error

To analyze the data, the intensity measurements were plotted against their respective positions and a theoretical prediction of intensity as a function of position was plotted alongside them. The dark rates for the respective experiments were accounted for.

The prediction lines in the single photon case are theory lines with no adjustable parameters. They were calculated using known and measured values. The knowns used to calculate the lines are: $a = 0.085$ mm, $d = 0.343$ mm, $L = 0.5$ m, and the photon wavelength $\lambda_p = 545$ nm. The wavelength filter selects a range of wavelengths between 541 nm and 550nm. A middle value of 545 nm was chosen as a representative.

In the laser case, there was a discrepancy between the reported wavelength and the data. The documentation of the laser diode suggests that the wavelength of the emitted light is 670 ± 5 nm. When calculating using this value, the theory does not match the data. If we accept that the data is a better indication of the wavelength of the laser light, we find that a wavelength of $\lambda_l = 640 \pm 10$ fits the data much more closely. Physically, the laser is a small diode (perhaps a few centimeters in length) so it is reasonable to assume the emitted wavelengths are not precise.

As far as error is concerned, there are two separate errors for the intensity measurements and one for position measurements. The position measurements are based on the limits of the micrometer, making the error simply ± 0.0002 cm.

The measurements of intensity in the Young experiment were updated in real time by the multimeter. As anyone who has tried to read a voltage off a precise multimeter knows, it tends to fluctuate rapidly between values. I can say with confidence that measured values of intensity are within ± 0.0003 V of the true value.

In the Feynman experiment, intensity measurements are discrete values. I assume Poisson statistics, which makes the error of individual intensity measurements, I_m, to be $\pm(I_m)^{1/2}$. The error of the average intensity is the average of the component errors.

B. Results

The results of the Young experiment are exactly what one would expect. Fraunhofer diffraction and interference are solid optical theories supported by numerous experiments. A plot of the single-slit diffraction data versus theory is shown in Fig. 5 and the data versus theory of the double slit regime is shown in Fig. 6. It is clear the data matches nicely with the fit line which was calculated using the inferred value for the laser diode wavelength instead of the documented value. This behavior was expected as, intuitively, the wave nature of light should be readily apparent when sending billions of photons through the double slits at a time. Things start to get interesting regarding the results of the Feynman experiment.

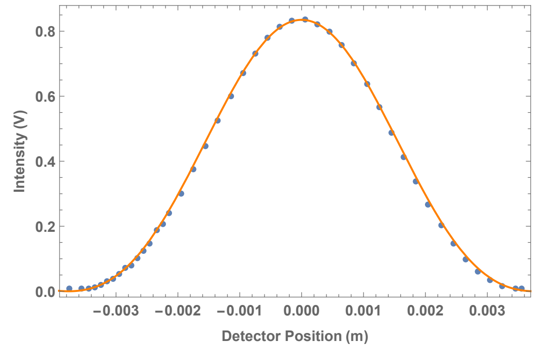

FIG. 5: The single slit data for the laser diode plotted with the theoretical single slit diffraction prediction, using $\lambda_l = 640$ nm and $I_{max} = 0.835$ V.

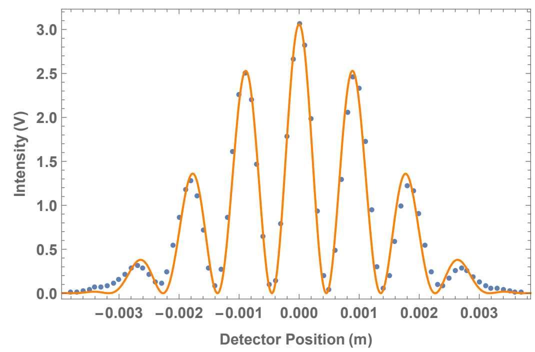

FIG. 6: The double slit data for the laser diode plotted with the theoretical double slit interference prediction, using $\lambda_l = 640$ nm and $I_{max} = 3.06$ V.

A plot of the data taken in the single slit regime versus a prediction line is shown in Fig. 7 and likewise for the double slit experiment in Fig. 8. The prediction lines were calculated using the classical mathematics for continuous light. The theory matches the data rather beautifully. There are implications from this wonderful, quizzical match.

Since the PMT is only about 4% efficient, we can estimate how many photons per second are reaching the end of the channel. If the maximum intensity of the photons from the single slit (we can ignore constructive interference effects by considering the single slit regime) is about 500 counts per 10 s, then there are 50 counts/s. Taking into account the efficiency gives us 1250 photons per second reaching the PMT.

If we assume that the photons are evenly spaced, then one photon hits the PMT every 1/1250 s, or 8×10^{-4} s. The entire channel (not just the distance L) is about 1 m in length. Dividing this by the speed of light gives the time spent in the channel by each photon: approximately 3.3×10^-9 s. Apparently, the time between counts is

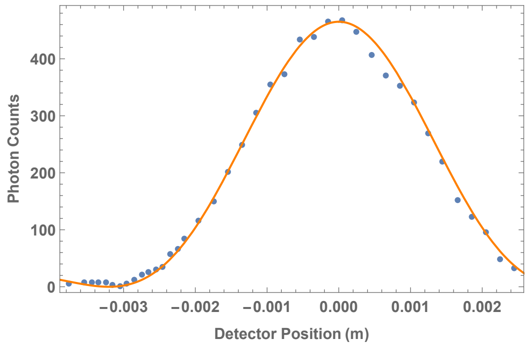

FIG. 7: The single photon single slit data plotted alongside the theoretical single slit diffraction pattern using $\lambda_p =$ 545 nm, and $I_{max} = 468$ counts.

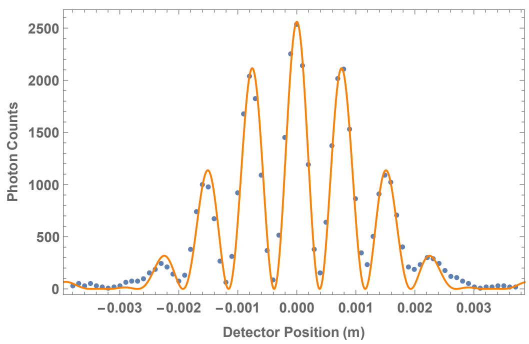

FIG. 8: The single photon double slit data plotted alongside the theoretical double slit interference, using $\lambda_p = 545$ nm, and $I_{max} = 2560$ counts.

several orders of magnitude larger than the time each photon spends in the channel.

If there is only one photon at a time going through the slits, then how are we seeing interference patterns at all in the Feynman experiments?

V. CONCLUSIONS

The Young experiment was conducted using a laser diode for both the single and double slit interference regimes. The data collected match theoretical lines with no adjustable parameters well, proving once more that many photons exhibit wave behavior. The Feynman experiment was also conducted. I used a dim, incandescent bulb with a green light filter to send one photon at a time through the single and double slits. I observed interference patterns identical to what I found in the Young experiment. The data for the Feynman experiment also matched the theoretical lines very well. The question remains: how should we interpret these results?

The Young experiment lends some rather strong evidence to the idea that light is a wave. From figures 5 and 6, it is clear that laser light interferes just like a wave should. The evidence gathered from the Feynman experiment is harder to interpret. Clearly, from figures 7 and 8 individual photons somehow interfere, even with nothing around to interfere with. Not only do they interfere, but the interference pattern is the same as the interference pattern that billions of photons make.

The answer lies in the strange world of quantum mechanics. Photons are inherently quantum mechanical objects with quantum wave functions. The double slit condition imposes itself on the wave function of the photon. Much like water waves through a double slit, the wave function of the photon *interferes with itself* as the photon travels from the source to the detector. It is the act of taking a measurement that collapses the position-space wave function to a single point x. This manifests as a 'click' on a pulse counter.

This can be further rationalized using the Heisenberg Uncertainty Principle, which all quantum objects obey. Compared to when it is traveling down the channel, a photon's x position is relatively well defined as it passes through the slits. This increases the uncertainty in its x momentum to compensate. This means the direction the photon travels after exiting the slit is relatively unknown. We "lose track" of it until another measurement is taken at the PMT, again collapsing the wave function to a point.

With the empirical evidence brought to bear, the answer to the question "Is light a particle or a wave?" appears to be "yes." Light has both particle and wave properties. Which property is more relevant to the situation at hand, however, is what makes these experiments interesting. The Feynman experiment forces *both* properties to be relevant. It is impossible to describe the results otherwise.

[1] A. Einstein, *Concerning an Heuristic Point of View Toward the Emission and Transformation of Light*, Annalen der Physik **17** (1905): 132-148.

[2] G. N. Lewis, *Letter to the Editor*, Nature **118** (1926): 874-875

[3] The College of Wooster, *Physics Junior Independent Study Lab Manual*, (2018): 54-57.