Classical and Quantum Physics at Odds:
Double Slit Interference Observations for a Single Photon

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New theories of quantum mechanics challenges the assumptions accepted by classical physics, especially in its description of light. In a double slit experiment, a beam of photons is directed through two narrow openings. Light passes through both slits, causing points of constructive and destructive interference. Classical and quantum physics disagree on the behavior of a single photon passing through the same double slit. Classical physics predicts that the photon will behave as it it simply passing through a single slit. Quantum mechanics, however, predicts that the photon's wave function accounts for both slits and interferes with itself. In this research, we design an experiment to observe the behavior of a single photon passing through a double slit. We find that the frequency of photons that strike the detector build an interference pattern of oscillating maxima and minima contained in a diminishing sinusoidal curve envelope centered on the middle-point of the double slit. The interference pattern strongly aligns with the intensity pattern generated by shining a laser beam through the same slit. The results of this experiment strongly support the predictions made by quantum physics.

I. INTRODUCTION

Classical physics and quantum mechanics disagree on the fundamental nature of the photon. Under quantum mechanics, a photon is a realization of a wave function, which describes the probability of when and where the photon may be observed. The photon exists everywhere in space. Given this logic, the wave function of a single photon must interfere with itself. In classical physics, it is impossible for a photon to interfere with itself, regardless if it is modeled as a particle or wave.

The definition of light is often evolving with the discovery and improvement of physics. In Issac Newtons book, *Optiks*, Newton studies the fundamental nature of light. Light can be reflected by mirrors, refracted when passing from one medium to another, dispersed into its colors, and diffracted by obstacles [1]. Newton also theorized that light was made of "corpuscles", or little particles, with velocity and momentum. Christiaan Huygens disagreed with Newton's particles. Instead, he proposed that light was a sum of spherical wave fronts propagating through space [2]. The Huygens–Fresnel principle accurately describes the diffraction of light passing an obstacle, such as a single or double slit.

In 1865, James Maxwell derives the equation of an electromagnetic wave [3]. The velocity of the wave matched the experimentally measured speed of light. Next, Max Planck deduced that the energy of light is quantized and proportional to its frequency [4]. And then begins the field of quantum mechanics.

According to quantum mechanics, a photon is described by its wave function. The probability $P(x,t)$ of a wave function $\psi(x,t)$ is given by the following:

$$P(x,t) = \psi(x,t)^* \psi(x,y) \tag{1}$$

The wave function of a double slit $\psi_{ds}(x)$ is the superposition of two single slits, $\psi_1(x)$ and $\psi_2(x)$:

$$\psi_{ds}(x) = \psi_1(x) + \psi_2(x) \tag{2}$$

The computing the probability for the double slit wave function $P_{ds}(x)$ yields:

$$P_{ds}(x) = \psi_1^*\psi_1 + \psi_2^*\psi_2 + \psi_1^*\psi_2 + \psi_2^*\psi_1 \tag{3}$$

The $\psi_1^*\psi_1 + \psi_2^*\psi_2$ component is always positive. But, $\psi_1^*\psi_2 + \psi_2^*\psi_1$ may be negative. The combination of these two components cause constructive and destructive interference. This causes oscillations in intensity observed as bright peaks and dark troughs within a diminishing sinusoidal envelope.

However, classical mechanics predicts that the single photon will behave as if it were passing through a single slit, which has a smoother intensity distribution with one central peak. A single photon cannot interfere with itself.

Classical and quantum mechanics fundamentally disagree on the behavior of light. To test this, we use an apparatus observe the effects of a single photon passing though a double slit. The results to prove or disprove classical physics.

II. METHOD

To test the wave-like or particle-like nature of the photon, we use a photon detector apparatus (see Figure 1). The apparatus consists of a light-sealed box contains a light source, three slits, and a light sensor. The sensors are then connected to an external voltmeter or pulse counter.

There are two options for the light source: a red 670 ± 5 nm laser with a 5 mW power output, or a #47 light bulb with a $541 - 551$ nm green filter. A single slit, the focuser, is fixed in front of the light source. This polarizes the light into a single beam. The beam travels down the

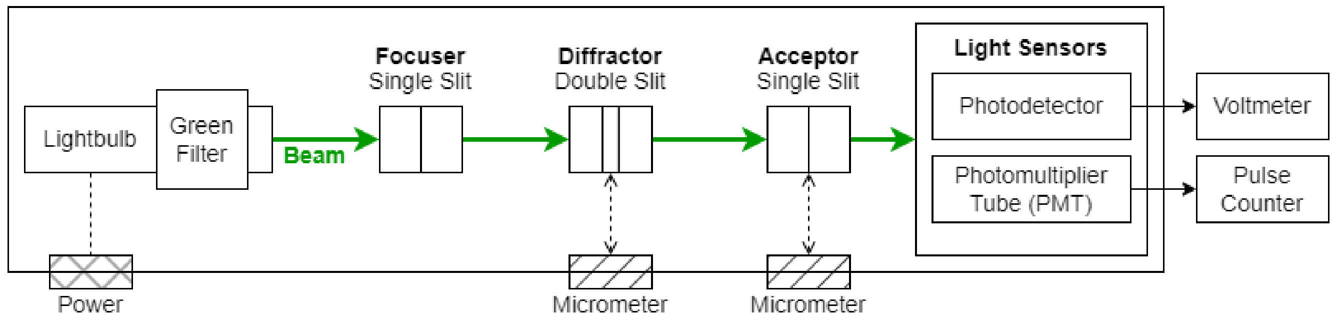

FIG. 1. Diagram of the photon detector. When the light source is powered on, it produces a beam of photons directed through three sets of single or double slits. The first slit is a single slit, which collimates the beam and blocks scattered light. The second slit, either single or double slit, can be adjusted by a micrometer. This slit is used to test the wave-particle nature of the photons. The rightmost single slit is placed just before the beam reaches the photo-sensors; its position can be adjusted using the micrometer to take measurements across the sensor width. The light source may be either a laser or light bulb: the red laser is used for calibrating the instrument, and the green filtered light bulb is used to generate single observable photons. The sensors include a photodetector and photomultiplier tube (PMT). The photodetector generates an increasing voltage with increasing intensity of incident light. The PMT emits an electrical pulse for each incident photon.

box and strikes a second slit, the diffractor. This slit can be exchanged to be a single or double slit, which create different diffraction patterns. The position of the diffractor slit can be adjusted using a micrometer. The light beam is diffracted by the slit and travels further down the box. At the far end of the box, there are some light sensors. The sensors integrate across their entire surface, so a single slit is placed directly in front of the sensor. Using a micrometer, the acceptor slit can be swept across the face of the sensor allowing the experimenter to measure the light intensity at difference angles with respect to the diffractor slit's center.

The apparatus contains a photodiode and photomultiplier tube (PMT) to detect incident light. The 1 cm^2 solid-state photodiode converts energy from the incident photons into electric current. Its output power varies $< 0.1\%$ in time, which is satisfactory for this research. The photodiode can be connected to a voltmeter to record the light intensity. The second sensor, the PMT, is much more sensitive than the photodiode. It generates a single electrical pulse for each incident photon. The PMT can be connected to a pulse counter–which counts the number of electrical pulses in a given time interval–and an optional oscilloscope–which can be used to observe the individual pulses. Lastly, the PMT should only be used with the green-filtered bulb, as the power from the red laser would damage the sensor.

The apparatus has two modes of operation: quantitative and single-photon modes. The quantitative mode utilizes the red laser light source with the photodiode light sensor. The voltage of the photodiode is recorded as the acceptor slit micrometer is moved across its full length. This mode demonstrates the classical, wave-like behaviors of a light beam. Conversely, the single-photon mode can test the classical and quantum nature of the photon. This mode requires the green-filtered bulb and PMT. The number of incident photons is recorded by the pulse counter as the acceptor slit is moved across its length.

III. RESULTS AND DISCUSSION

In this research, we performed four distinct experiments. The first used the quantitative apparatus mode with a single slit. the second also used the quantitative mode but with a double slit. The results of this experiment are used as a baseline that demonstrates the wave-like properties of light. The third and fourth experiments use the single-photon mode of the apparatus for the single and double slits, respectively. We declare the following instrumental uncertainties: the voltmeter is ± 1 mV, the photon counter is ± 1 Hz, and the micrometer is ± 0.01 mm.

Fraunhofer diffraction can be modeled by Equations 4 and 5 where a is the width of the slit and b is the distance between the slits. In the case where $b \to 0$, Equation 4 describes a single slit.

$$I(\theta) = I_0 \cos^2(\beta) \frac{\sin^2(\alpha)}{\alpha^2} \tag{4}$$

$$\alpha = \frac{\pi a \sin\theta}{\lambda}, \beta = \frac{\pi b \sin\theta}{\lambda} \tag{5}$$

We use Equation 4 to fit a curve to the data. The values of α and β for each experiment are shown in Table I.

Figure 2 shows the voltage of the photodiode with respect to the position across the sensor of the first two experiments (quantitative mode). The single and double

Source	Slit	α [rad]	β [rad]
Laser	Single	0.95	0.0
(FIG. 2)	Double	0.68	4.3
Bulb	Single	0.98	0.0
(FIG. 3)	Double	0.95	5.3

TABLE I. Fraunhofer diffraction (Equation 4) α and β for all experiments in this work. These are all best fit values selected by visual classification.

slit intensity patters are distinct: the single slit generates a smooth diminishing sinusoidal curve while the double slit oscillates within an envelope. The single slit is dominated by the particle-like qualities of the photon, as there are no observable interference effects. The intensity is brightest at the center of the slit and dims with increasing angles away from the slit. The double slit, however, demonstrates the wave-like behavior of light. The intensity functions shows maxima and minima points that align with constructive and destructive wave interference, respectively.

The laser data shows some small concerns. Equation 4 predicts that, for a double slit, the minima should go to zero, but we do not observe this in the data. This suggests that there is a bright reflection within the enclosed box of the apparatus. There also appears to be some shadow over the photodiode past 10 mm. Despite these challenges, the overall data demonstrates the expected Fraunhofer diffraction. Thus, the apparatus is acceptable for single photon observations.

Both the single and double slit effects for a laser (high density of photons) can be predicted with classical physics. But, classical and quantum physics disagree on the behavior of single photon passing through a double slit. In classical physics, a single photon cannot interfere with itself. So, the intensity pattern should be a smooth diminishing sinusoidal curve for both one and two slits. According to quantum mechanics, the wave function of the photon can indeed interfere with itself. Thus, the intensity pattern for a double slit must contain maxima and minima.

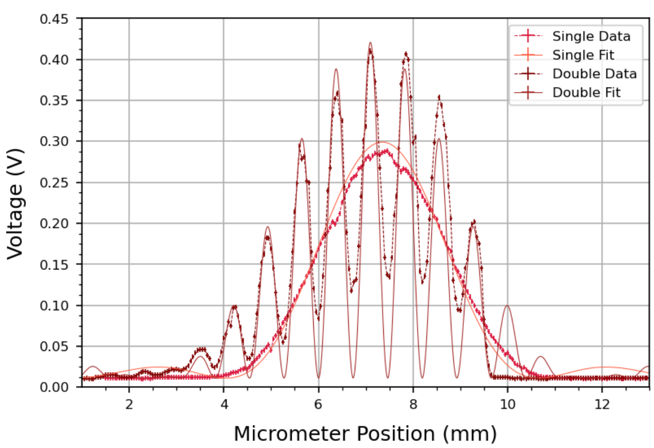

FIG. 2. Red laser voltage interference patterns for single and double slit diffractor. The micrometer position describes the length across the photodiode. The voltage is measured for the photodiode. The single slit voltage is a smooth bell curve with a maximum of 288 ± 1 mV; this curve is shifted right to align with the double slit data. The double slit voltage oscillates with increasing and decreasing voltages with the minima and maxima forming a bell curve. The peak maxima voltage is 410 ± 1 mV and the peak minima voltage is 134 ± 1 mV.

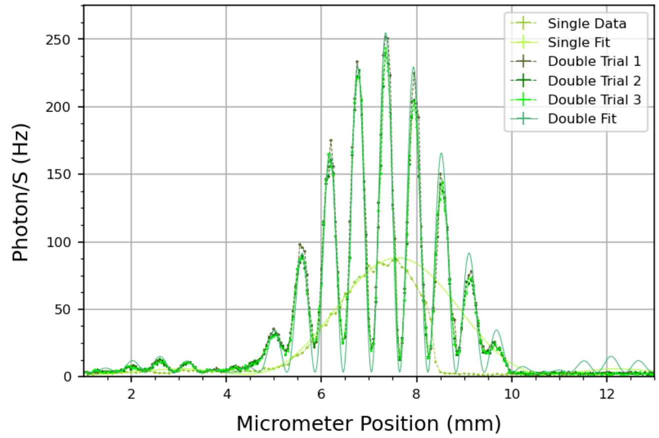

FIG. 3. Green single-photon frequency patterns for a single and double slit diffractor. The micrometer position describes the length across the PMT. The photon frequency is measured using a photon counter. The three double slit trials are in agreement with the minima and maxima location. The frequency oscillates with distance, similar to a double-slit interference pattern. The maximum photon frequency for the double slit 251.6 ± 1 Hz. The single slit photon frequency is a smooth bell curve with a peak frequency of 86.3 ± 1 Hz.

Figure 3 shows the result of the third and fourth experiments: the photon frequency of the PMT a for a single and double slit. We performed three trials with the double slit; for each trial, we integrate the number pulses over a 10 second interval to calculate the photon frequency. For the double slit, the frequency of single photons integrated over time appears to generate an interference pattern while the single slit does not. The micrometer position at the maxima and minima of each double slit trial have a high level of agreement, which shows clear points of interference.

To verify if the oscillations shown in Figure 3 are caused by wave-like interference, we over-plot the voltage function of the double and single slit, laser and bulb experiment (Figure 2). To better compare the two light sources, we multiply the micrometer position of the laser by the ratio of the red laser's wavelength over the green bulb's wavelength; this converts the longer red wavelengths to be compared to the shorter green wavelengths. The final plot is shown in Figure 4. The laser and bulb double slit intensity functions show very strong agreement for the locations of the minima and maxima, which is evidence that the oscillations in the single-photon intensity are due to the wave function of a single-photon

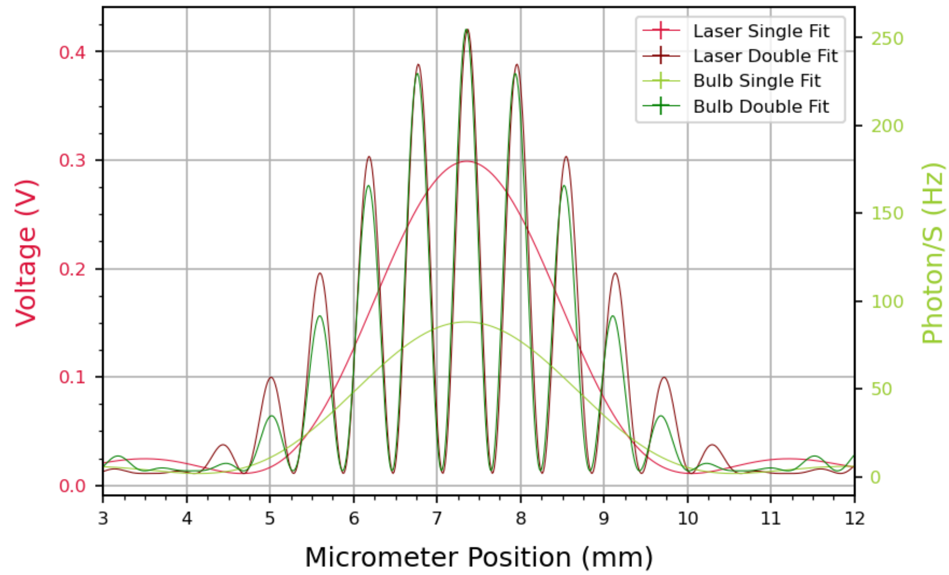

FIG. 4. Models of the red laser (red lines) and green single-photon (green lines) intensity interference for a single and double slit. The micrometer position describes the position over the light sensor. We adjust the red laser data by the wavelength ratio of red and green to compare to the single-photon frequency function. The micrometer position of the red laser and green photon maxima and minima show close agreement.

interfering with itself.

IV. CONCLUSION

The goal of this research was to challenge the classical and quantum physics description of photons. According to quantum mechanics, the wave function of a single function can interfere with itself. However, in classical physics, this effect is paradoxical and thus impossible. To investigate this dilemma, we designed an experiment to beam single photons through a double slit. If the photon does, in fact, interfere with itself, we expect to see an interference pattern on a screen across from the slit. If classical physics rules, then we should see a smooth distribution of photons on the screen.

We observe that the photon frequency oscillates within a diminishing sinusoidal envelope across the full length of the photon detector. The locations of the maxima and minima are consistent with a laser beam (containing a large number of photons) passing through the same single slit. Therefore, the frequency oscillations are due to the wave function of the single photon interfering with itself. This provides strong evidence in favor of quantum mechanics.

V. IMPROVEMENTS

Here is a list of the improvements from the previous draft of this research paper: (1) performed an additional experiment with a single slit for the single photons, (2) all data plots now show the discrete data points with error bars, (3) we added models to the single and double slit data for the laser and bulb experiments using the Fraunhofer diffraction equation, (4) improved the vertical axis in Figure 4, (5) Moved the quantum mechanical equations from the Results section into the Introduction, (6) removed redundant text, and (7) fixed grammatical errors.

[1] I. Newton, S. Smith, and B. Walford, *Opticks, or, a treatise of the reflections, Refractions, Inflexions and colours of light: Also two treatises of the species and magnitude of curvilinear figures* (Printed for Sam. Smith, and Benj. Walford, printers to the Royal Society, at the Prince's Arms in St. Paul's Church-yard, 1704).

[2] C. Huygens, *Treatise on light: In which are explained the causes of that which occurs in reflexion, &; in refraction and particularly in the strange refraction of Iceland crystal* (Van der Aa, 1690).

[3] J. C. Maxwell and T. F. Torrance, *A dynamical theory of the electromagnetic field* (The Society, 1865).

[4] M. Planck, *Ueber das gesetz der energieverteilung im normalspectrum (On the law of distribution of energy in the normal spectrum* (Annalen der Physik., 1901).