Single Photon Diffraction and the Battle of Quantum and Classical Physics

Michael Wieber, Nicholas Georgiu*
Department of Physics and Astronomy,
University of Kansas, Lawrence, KS, 66045, USA

(Dated: September 11, 2024)

Quantum theory and classical theory cannot agree on how light behaves. Light has been shown to behave as a wave, but the quantum description of a light wave function is simply not permitted by classical physics theory. By using a single photon diffraction apparatus, we show that diffraction patterns are present in single photon diffraction, illustrating how the wave function can interfere with itself, contrary to classical definitions. This experiment concludes that quantum theory is dominant over classical theory.

I. INTRODUCTION

The theories of quantum physics and classical physics disagree with each other. In classical mechanics, particles behave according to Newtonian physics – that is, it travels as a singular object through space. However, according to quantum mechanics, small particles behave like a wave function, or a probability distribution that gives the probability that a particle will be at any position at some given time. Recently, the photon has been under contention – quantumly, it is described to be able to interfere with itself and create the same interference phenomenon as is seen classically. By the theory of classical mechanics, such an interference is impossible since the photon is a single particle.

Until relatively recently (early 1800s), light was largely accepted to be a particle – so-called "corpuscles" of light[1]. This theory was mostly propagated by Newton, though some, like Christiaan Huygens[2], disputed this idea, instead claiming that light was a wave. Despite the few dissenting voices, the corpuscular theory of light widely accepted until Thomas Young performed his double slit experiment[3], suggesting that light did, in fact, behave like a wave, exhibiting interference patterns. The evidence presented by Young would later become the basis for the argument that light behaved like a wave until the 1900s.

In 1901, Planck published a paper discussing how the energy of light is quantized[4]. Planck's findings could be revolutionary, however it is yet doubtful whether classical or quantum mechanics will rule the study of physics.

According to the wave function theory of quantum mechanics, a photon is completely described by its wave function. That is, the probability that a photon is at a certain position at a certain time is given by

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

For the wave function of a double slit, we add the two wave functions to see

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

which gives the probability equation for the double slit as

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

This equation may have both positive and negative components simultaneously, which leads to constructive and destructive interference. This phenomenon would result in a single photon exhibiting the same array of bright peaks and dark troughs as the classical situation. However, the classical description of light does not allow for the single photon to interfere with itself as the wave function describes.

To come to a conclusion regarding quantum versus classical physics, this experiment was designed. We aim to prove or disprove the theories of quantum mechanics.

II. METHOD

A photon detector is used to test the nature of light (see Figure 1).

The apparatus is a covered channel that contains a light sensor, three slits, and a light source. The sensors are then connected to a voltometer or pulse counter.

The light source may either be a 670 ± 5 nm laser with a 5 mW power output or a light bulb with a 541-551 nm narrow band filter. The light travels from the light source to the focusing slit to block excess light and polarize the remaining light vertically. Downstream of the focusing slit is the diffracting slit(s), with either a single or double slit in place.

Directly downstream of the second slit is the slit-blocker, which is used to calibrate the apparatus. The slit-blocker may be adjusted by the micrometer to zero, one, or two slits of light from the diffracting slits(s). Downstream of the slit-blocker is the receiving slit, which allows only a small portion of a light fringe to be incident on the photodetector. The receiving slit may be adjusted by a micrometer so that different areas of the light fringes may be measured for intensity.

The light sensors consist of a photodiode and a photomultiplier tube (PMT). The photodiode converts the light energy from the photons to electric current, and

* Email: michaelwieber@ku.edu

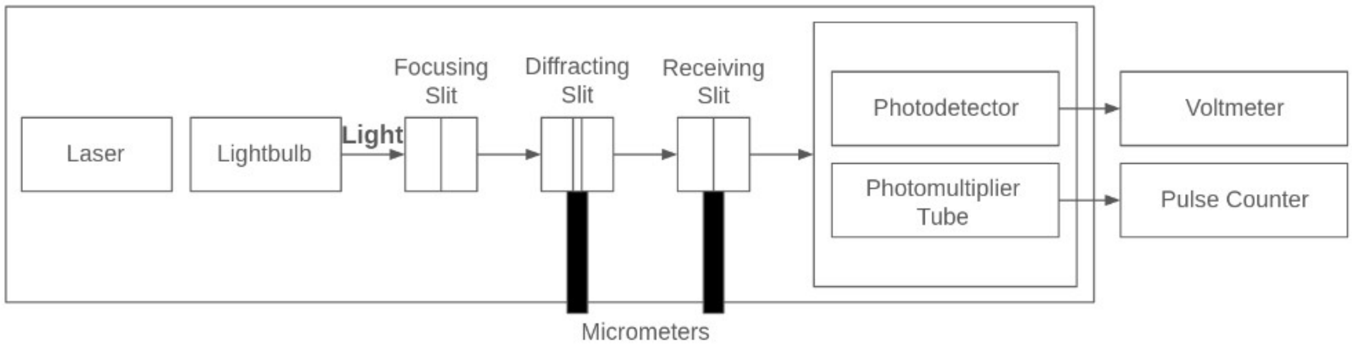

FIG. 1. The apparatus used for the experiment. The light source may be either the laser or the filtered light bulb. The beam travels through a polarizing single slit, then a diffracting slit, and finally past an adjustable receiving slit. At the end of the channel lies a photodetector which receives the light through the receiving slit. and a photomultiplier tube (PMT). The PMT has a shutter that may or may not allow light to pass. The PMT emits one pulse for every photon detected. The voltmeter increases in voltage when the intensity of light increases. The focusing slit polarizes the initial light and blocks scattered light. Directly in front of the diffracting slit is a light blocker, which can be adjusted by the micrometer to allow zero, one or both of the slits of light to the receiving slit when the diffracting slit is a double slit. The diffracting slit can be either one or two slits. The bulb may be removed so that the laser may be used instead. The receiving slit may be adjusted so that different light fringes may be measured for intensity.

the potential difference generated can be measured by a connected voltometer to measure the light intensity. The PMT generates one electric pules for each incident photon, and the PMT is connected to a pulse counter to record the number of photons incident per time interval.

There are two different modes of use for the apparatus. The first mode is with the laser and the photodiode – the receiving slit is moved across the light fringes and the resulting potential difference is recorded. The second mode is with the light bulb with the PMT – the receiving slit is again moved across the light fringes and the resulting photon count per time interval is recorded. The second mode

III. RESULTS AND DISCUSSION

Three experiments were completed to determine the nature of light. First, classical diffraction and interference patterns were tested in Figure 2 and Figure 3 with the red laser. The models seen in Figures 2, 3 and 4 are based off of the equation for Fraunhofer diffraction,

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

where

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

In Equation 5, we say a is the width of the light slit(s), b is the distance between slits, λ is the wavelength of the incoming light, θ is the angular displacement from the central fringe, and in Equation 4, we say I_0 is the light intensity at the central fringe. Note that for a single diffracting slit, we see $b = 0$. Equation 4 is used to model the phenomena observed. For these experiments, we claim a voltage uncertainty of ± 0.1 mV, a micrometer uncertainty of ± 0.01 mm, and a photon rate uncertainty of ± 1 Hz.

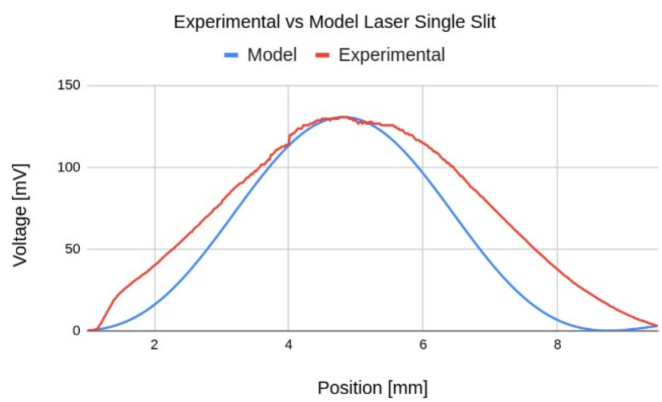

FIG. 2. Comparing the experimental data versus the model for single slit diffraction with a laser. The model used is based off of Equation 4, with $\lambda = 670$ nm. The x-axis is the position of the micrometer as it moves the receiving slit across the end of the instrument channel, and the y-axis reports the voltage from the photodiode, proportionally to the light intensity. The peak voltage of the model is 130.5 ± 1 mV.

In Figure 2, we see a smooth bell curve fit compared to the raw data from the single slit diffraction of the laser. We can see that the fit moderately aligns with the data, suggesting that diffraction is, in fact, occurring. One concern with the data is that the width of the fit is less that the width of the data.

In Figure 3, we see several oscillating smooth curves and the raw data from the double slit diffraction of the laser. The fit agrees with the data, suggesting that interference is, in fact, occurring. Once concern with the data is that the heights of the fit peaks are lower than

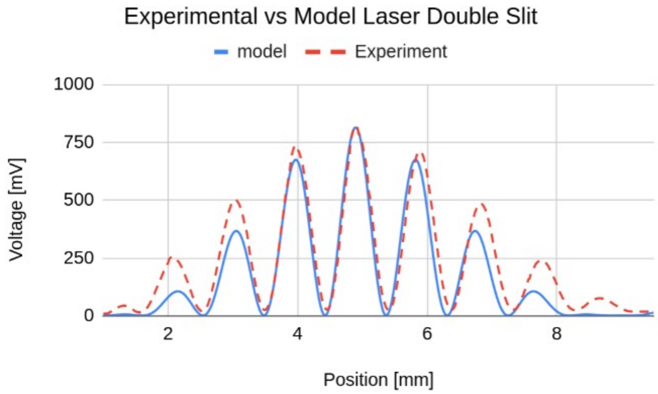

FIG. 3. Comparing the experimental data versus the model for double slit diffraction with a laser. The model used is based off of Equation 4, with $\lambda = 670$ nm and $b = 0$ from 5. The x-axis is the position of the micrometer as it moves the receiving slit across the end of the instrument channel, and the y-axis reports the voltage from the photodiode, proportionally to the light intensity. The peak voltage of the model is 813.4 ± 1 mV.

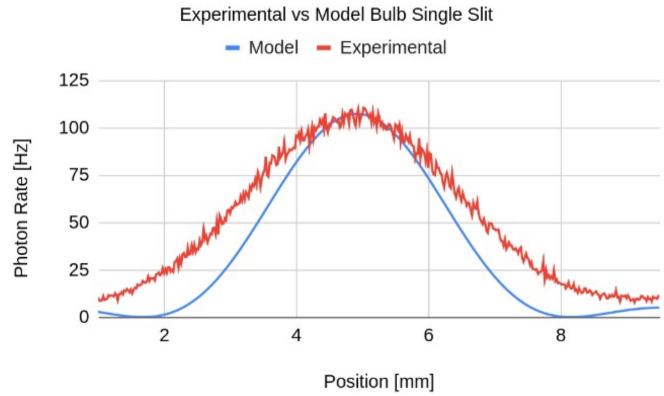

FIG. 4. Comparing the experimental data versus the model for single slit diffraction with the green bulb. The model used is based off of Equation 4, with $\lambda = 551$ nm and $b = 0$ from 5. The x-axis is the position of the micrometer as it moves the receiving slit across the end of the instrument channel, and the y-axis reports the voltage from the photodiode, proportionally to the light intensity. The peak voltage of the model is 107.2 ± 1 Hz.

the data.

The same results can be seen in Figure 4, where the light bulb with the green filter diffracts from the single slit into a rounded peak, and the fit agrees with the data. Similarly to the data from the laser through the single slit, we see that the width of the fit is smaller than the width of the data. For the data seen here, we counted the number of incident photons on the PMT over a ten second range.

We expect these data discrepancies to be reduced during further analysis, as this analysis is not complete. Refinement of the *alpha* and β values should increase the fit of the data.

IV. CONCLUSION

The purpose of this experiment was to consider whether light behaves according to quantum theory or classical theory. Quantum theory allows for a single photon to interfere with itself, but this is impossible in classical physics.We have seen the comparison of the classical interference and diffraction from the laser data and the quantum diffraction from the bulb data. We have observed diffraction occurring in the single photon, single slit experiment with the green bulb, showing that single photon interference is indeed possible. Because of this, we must conclude that quantum theory is the dominant theory to describe physics.

The data and logbook can be found here: `https://docs.google.com/document/d/13ihcBKSYwaZntzHw_T2aJuDXUgiArpcMS5Cef4GVF2A/edit?usp=sharing`

V. IMPROVEMENTS

[1] I. Newton, *Opticks ... Second edition, with additions* (W. & J. Innys, 1718) pp. 321–323,336–349.

[2] C. Huygens, *Traité De La Lumière* (A Leide: Chez Pierre vander Aa, marchand libraire, 1690).

[3] T. Young, Philosophical Transactions of the Royal Society of London **92**, 12 (1802).

[4] M. Planck, annalen der physik **309**, 553 (1901).