Single Photon Diffraction and the Battle of Quantum and Classical Physics

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(Dated: September 19, 2024)

Quantum theory and classical theory cannot agree on how light behaves. Light has been shown to act as a wave, but the quantum description of a light wave function is simply not permitted by classical physics theory. Our experiment passes one photon at a time to light detectors in order to analyze the quantum physics of the photon. By using a single photon diffraction apparatus, we show that classical Fraunhofer diffraction calculations have the same form as the quantum wave function calculations, illustrating how the photon can interfere with itself, contrary to classical definitions. This experiment concludes that quantum theory is dominant over classical theory.

I. INTRODUCTION

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.

in 1905, Einstein published a paper discussing the photoelectric effect and how the energy of light is quantized in singular packets, or photons[4]. These results heavily disagree with the modern understanding of optics. The application of the photoelectric effect gives us the photomultiplier tube (PMT), which will allow us to detect when a single photon is incident on our detector. By convincing ourselves that a single photon is hitting the detector at a time, we may analyze the quantum physics of a single photon.

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. Instead, we would expect a uniform distribution of photons if classical theory is correct.

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 by analyzing the single-photon behavior of light.

II. METHOD

A photon detector was used to test the nature of light, shown in Figure 1. The apparatus was a covered channel that contains light sensors, three slits, and a light source. The sensors were then connected to a voltmeter 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 traveled from the light source to the focusing slit to block excess light and polarize the remaining light vertically. Downstream of the focusing slit was the diffracting slit(s), with either a single or double slit in place.

Downstream of the second slit was the receiving slit, which allowed only a small portion of a light fringe to be incident on the photodiode. 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 consisted of a photodiode and a PMT. The photodiode converted the light energy from the photons to electric current, and the potential difference generated can be measured by a connected voltmeter to measure the light intensity. The PMT generated one electric pulse for each incident photon, and the PMT was connected to a pulse counter to record the number of photons incident per time interval.

There were two different modes of use for the apparatus. The first mode was with the laser and the photodiode – the receiving slit was moved across the light fringes

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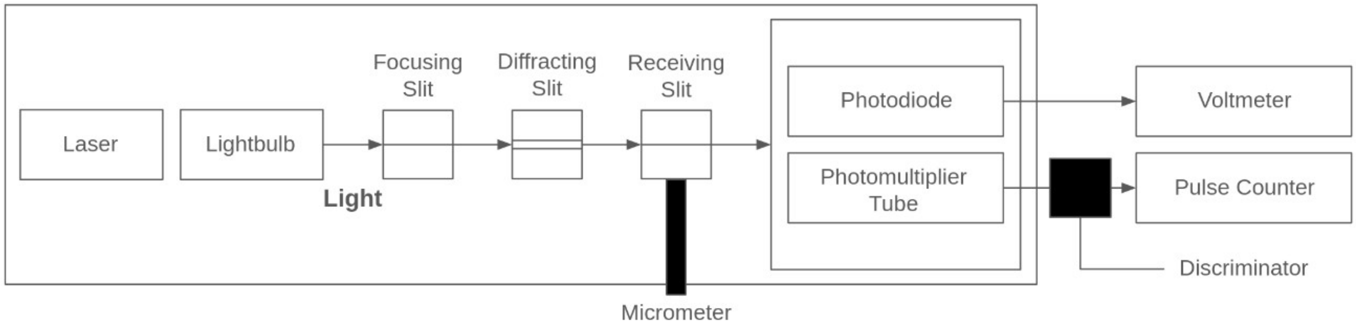

FIG. 1. A top-down view of the apparatus used for the experiment. A cover was placed over the channel in order to reduce noise. The bulb may be removed so that the laser may be used instead. The beam traveled through a polarizing single slit, then a diffracting slit, and finally past an adjustable receiving slit. At the end of the channel lay both a photodiode and a PMT, which received the light through the receiving slit. The voltmeter increased in voltage when the intensity of incident light increased. The PMT emitted one electric pulse for every photon detected, and a discriminator "discriminated" between these electric pulses from the PMT to only transmit pulses that are considered to be above the noise value. After the discriminator, a pulse counter measured how many pulses occured within a given time interval. The focusing slit polarized the initial light and blocked scattered light. The diffracting slit can be either one or two slits. The receiving slit may be adjusted so that different light fringes may be measured for intensity.

and the resulting potential difference was recorded. The second mode was with the light bulb and the PMT – the receiving slit was again moved across the light fringes and the resulting photon count per second was recorded. The bulb mode was considered the single photon mode, which was acquired through multiple means.

To ensure that only one photon was hitting the detector at a time, a narrow green light filter was placed over the bulb to reduce the overall intensity of the light and the number of incident photons on the PMT. Additionally, the discriminator was adjusted to ensure that only the electric pulses above the noise are registered to the pulse counter. This was achieved by using an oscilloscope to visually ensure that each time a pulse was counted, the pulse was above the voltage noise level.

In order to ensure that there was only one photon in the channel at a time, the bulb power and discriminator were adjusted until the interval of time between photon detections was greater than 3 nanoseconds, which is the time interval expected for photons to be separated by 1 meter on average. The greatest number of incident photons/second on the detector during this experiment correlated to about a 10 millisecond difference in time between photons, which was sufficient to claim that there was only one photon in the channel at a time.

In order to reduce noise during the experiment, several methods were utilized. Firstly, the darkness of the channel with the cover on was measured before each sequence of measurements and subtracted from the final measurements to ensure accurate results. The channel was covered with a tight lid to reduce the noise of light from outside, and the discriminator was utilized during single photon measurements to ensure that measurements made by the pulse counter were free from low-voltage noise. The measurement of photons/second with the single photon experiments was averaged over 10 seconds to increase accuracy.

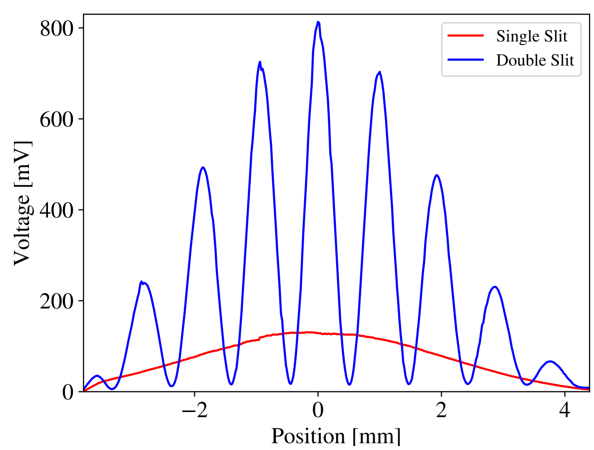

FIG. 2. The data collected using the laser and both slits. Error bars are not shown due to the density of measurements, but the uncertainty on each measurement x_i is claimed to be $\sqrt{x_i}$. The x-axis measures displacement from the x-value of peak intensity, and the y-axis measures the resulting voltage from the photodiode. The peak voltage for the single slit experiment is 130.5 $\pm$ 11.4 mV, and the peak voltage for the double slit experiment is 813.4 $\pm$ 29.5 mV.

III. RESULTS AND DISCUSSION

Four experiments were completed to determine the nature of light. First, classical diffraction and interference patterns were tested in Figure 2 with the red laser. Then, quantum diffraction and interference were tested in Figure 3 with the single photon.

The intensity observed along an interference or diffraction pattern is described by the Fraunhofer diffraction

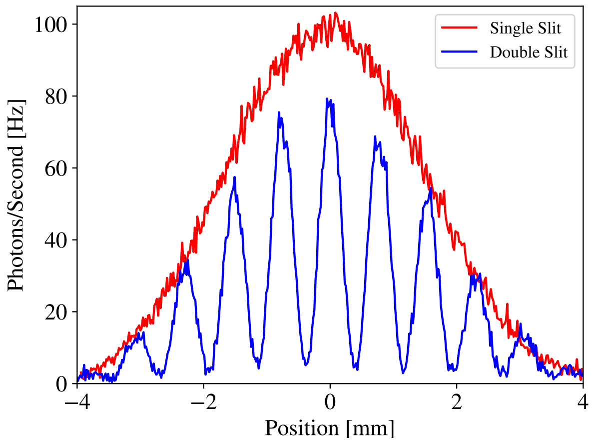

FIG. 3. The data collected using the single photon mode and both slits. Error bars are not shown due to the density of measurements, but the uncertainty on each measurement x_i is claimed to be $\sqrt{x_i}$. The x-axis measures displacement from the x-value of peak intensity, and the y-axis measures the resulting photon count rate from the pulse counter. The peak rate for the single slit experiment is 103.2 ± 10.2 Hz, and the peak voltage for the double slit experiment is 79.3 ± 8.9 Hz.

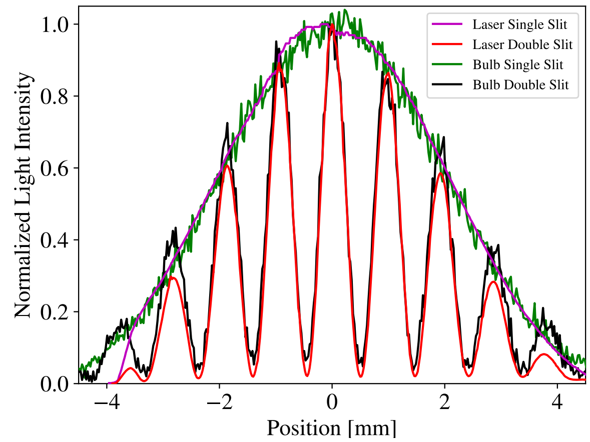

FIG. 4. This plot normalizes the data from Figures 2 and 3 and plots them on one area. The single photon data is horizontally normalized by the ratio of the laser wavelength to the bulb wavelength.

equation,

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

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 $b = 0$. For these experiments, we claim a voltage instrumental uncertainty of ±0.1 mV and a micrometer uncertainty of ±0.01 mm.

In Figure 2, we see two curves that have maximums at 0 mm and generally decrease as the distance to 0 increases. The magnitude of the single slit data is much lower than the data of the double slit, which is due to recalibration since the data were taken on different days and had to be setup each time. However, we still see the same scale of gradual decrease in general amplitude in both the single and double slit data. These features in the figure follow what is expected from Equation 4, and so we claim that the apparatus is sufficient to observe Fraunhofer diffraction and is ready for the single photon experiment.

In Figure 3, we see two curves with much more noise than in Figure 2. The maximum magnitudes are closer than is seen in Figure 2, but still off by a significant degree, which is again due to recalibration after multiple days. The shape of the bell curve that sits over each set of data is thinner on the x-axis than in Figure 2, which is due to the shorter wavelength components in Equation 5. Although all the measurements of this data are much noisier than in Figure 2, a smooth path along the curve can still be traced, which will become clearer as we overlay the normalized data.

In Figure 4, we see the vertically and horizontally normalized data combining the laser and single photon measurements. In this figure, we no longer see the effect of recalibration for different days, nor do we see the effect of the wavelength parameter λ in the difference of these different data sets. The single slit data for both data sets is closely mirrored except for the drop off in the laser data at about -4 mm, which is likely do to the blocking of light in the measurements of the laser single slit data, which was rectified in all following measurements. Additionally, we see that each set of data appears to fit within the same packet or bell curve, which is expected for Fraunhofer diffraction.

The double slit data for both the single photon and laser experiments closely follow each other as well – the peaks and troughs appear at the same position for each data set, and both sets gradually decrease away from the center maxima. However, the single photon data does not go as close to zero as the laser data, and the peaks of the single photon data are much higher in the data points farthest from the central peak. This may be caused by the increased sensitivity of the PMT compared to the photodiode and the predicted random behavior of the photon as a wave function; since the detecting area of the detector is not infinitesimal, intensity from light just outside of the measured position may bleed into the resulting intensity of the measurement, and it could also be the result of an unlikely photon density from the wave function.

The data clearly shows that the single photon data displays the same Fraunhofer diffraction as is seen in the laser data, which implies that the wave function from quantum mechanics and the classical wave definition of light exhibit the same behavior.

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 near-identical classical interference patterns from the laser data and the quantum interference patterns from the bulb data. Since the diffraction curves are so similar and the single photon distribution is not uniform, we can say that we have observed Fraunhofer diffraction occurring in the single photon experiment. This shows that single photon interference is indeed possible, and furthermore that the wave function calculations have the same form as classical Fraunhofer diffraction calculations. Because of this, we must conclude that quantum theory is the dominant theory to describe physics.

V. LOG

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

VI. IMPROVEMENTS

1. Included a plot comparing normalized laser data to single photon data.
2. Mentioned the photoelectric effect in the introduction.
3. Trimmed the introduction.
4. Removed figures with fitting and included figures with normalized comparison.
5. Mentioned that quantum calculations have the same form as Fraunhofer diffraction in the conclusion and abstract.

[1] I. Newton, *Opticks: or, a treatise of the reflexions, refractions, inflexions and colours of light* (England, 1704).

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[4] A. Einstein, Annalen Phys. **322**, 132 (1905).