Diffraction of a Single Quantum Photon

E. K. Dunn[*]

Department of Physics, University of Kansas, Lawrence, Kansas, USA

(Submitted 15 September 2011)

Double slit diffraction forms the basics of the wave behavior of light. Interference of a single photon with itself is predicted by quantum mechanics. Both experiments are highly reproducible. HeNe laser light and green filtered light were used to produce interference patters detected by photodiode and photomultiplier tube. Both single and double slit patterns shown in this experiment were modeled by Fraunhofer diffraction. A photon has the ability to be in two places at once and interfere with itself.

I. INTRODUCTION

Young's double-slit diffraction experiment is a classic example of the wave light. His experiment showed that light had a definable wavelength determined from constructive and destructive interference. At that time light was thought to be made of corpuscles. Young's experiment shifted the view of light to waves. And yet many years later the photoelectric effect and blackbody radiation showed light to be in discrete quantities. Light seemed to show properties of both waves and particles. The answer came in the form of quantum mechanics. This experiment is a reproduction of Young's original double slit diffraction experiment but goes a step further by observing the interference of a single photon with itself.

II. DEVICE AND METHODOLOGY

The device used in our experiment is the TWS1-A manufactured by TeachSpin.[1] It consists of a 5 mW HeNe laser (650 ±5 nm) assembly and alternately a standard filament light bulb with green filter (541 nm- 551 nm).[1] They project light down a U-channel to a photodiode/ photomultiplier tube (PMT) combo. The photodiode is used in conjunction with the laser and the PMT is used for the fainter green light. The light is obstructed by several slits: a 'source slit' to control the beam, a 'blocking slit' to switch between single and double slit diffraction, the double slit, and a detector slit for filtering out only a narrow band of light for detection. The 'blocking slit' and detector slit are attached to micrometers for easy manipulation while the device is in operation. This allows for undisturbed measurement of light intensity and reduced light leak. The photodiode's output is measured with a Fluke model 175 voltmeter. The PMT has a built in discriminator[1] which is then fed to a Computer Measurements Company model 7270 counter. The total distance from source to detector was 1.0 m.

Double and single slit diffraction intensity patterns can be modeled by the equation

$$I(\theta) = I_0 (cos\beta)^2 \frac{sin\alpha^2}{\alpha} \quad (1)$$
$$\alpha = \frac{\pi a}{\lambda} sin\theta \quad (2)$$
$$\beta = \frac{\pi d}{\lambda} sin\theta \quad (3)[1]$$

Here Θ is the angle offset from maximum intensity, d is the slit spacing center-to-center, a is the slit diameter, and λ is the wavelength of light.

A. Laser Light Diffraction

The first part of the experiment is single and double diffraction of red laser light. The apparatus was aligned to produce a beam of red laser light down the channel. This was verified with white cards provided by TeachSpin. The 'blocking slit' micrometer measurement given by X_c was used to change between no slits, one slit, and two slit operation by blocking the incoming light to the double slit. The detector slit micrometer measurements were given by X_p. A background voltage was determined with both slits blocked. With the beam aligned a single slit chosen, the detector slit was cycled from 3.00 mm to 8.00 mm in increments of .25 mm. A second set of data was taken over a wider range to determine the edge limits of the detector slit. The blocking slit could then be moved to allow light over both slits. Data was then taken over a wide range of 0.50 mm to 10.00 mm in increments of 0.25 mm.

B. Single Photon Diffraction

The second part of the experiment is single and double diffraction of single photons of filtered green light. A PMT must be used because of the low intensity light. This part was conducted similarly to the first part of the experiment. The apparatus was aligned to produce a beam of green light down the center of the apparatus. The discriminator, high voltage and trigger levels were set to produce between 10^3 and 10^4 counts per second. A simple pushbutton timer was used. A background count was taken with both slits blocked. Counts in a 100 second time period were taken at 0.25 mm intervals from 3.00 mm to 8.00 mm for single slit diffraction. The time interval was
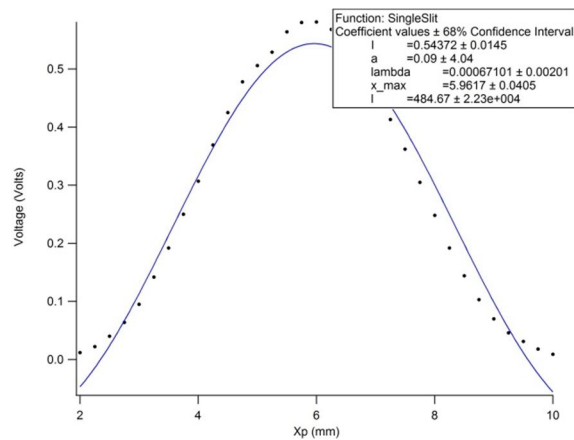
Figure 1 Single-Slit Diffraction of HeNe Laser Light
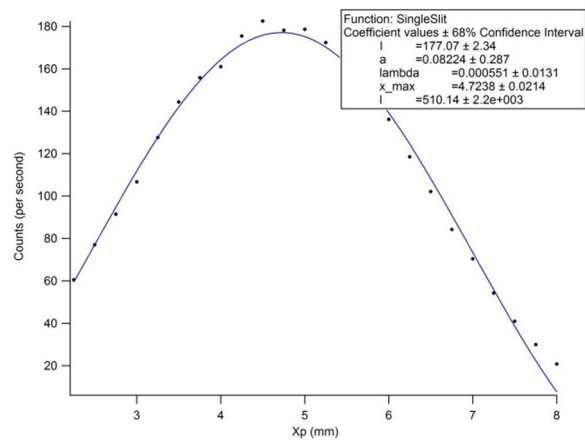

Figure 2 Single-Slit Diffraction of Filtered Green Light
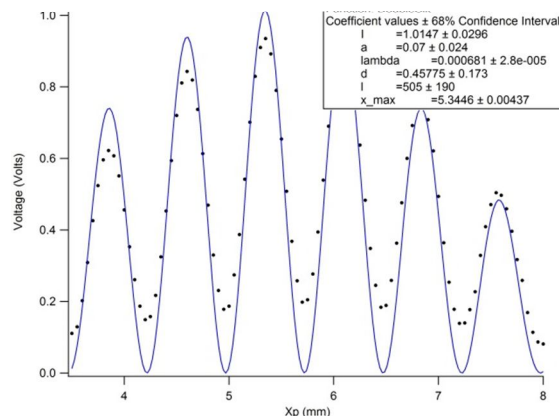

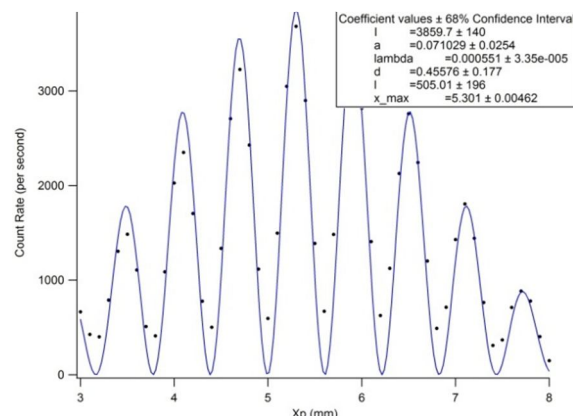Figure 3 Double-Slit Diffraction of HeNe Laser Light

Figure 4 Double-Slit Diffraction of Filtered Green Light

reduced to 50 seconds with the double slit to compensate for the need of finer intervals of 0.10 mm.

III. RESULTS & DISCUSSION

Both the single and double diffraction patterns observed were similar to the original experiment conducted by Young. We observed Fraunhofer diffraction in all cases. The data had some discrepancies that may have been avoided.

The largest source of uncertainty in single photon diffraction came from the measurement of time. We used a simple push button timer accurate to 0.1 seconds. Simple human reaction time is the source. This contributed more uncertainty to maxima where the count rate was higher. This could have been solved by using the clock signal feature. A waveform generator could have been used to turn the counter on for a very precise time interval. We were stuck flipping switches and pressing buttons which resulted in a high uncertainty.

We noticed that moving the blocking slit micrometer a few hundredths of a millimeter caused a jump in intensity. We originally thought this was due to the second slit opening up. This was not the case however. The double slit and blocking slit were not entirely parallel causing part of the slits to be blocked.

We decided that measurements should be taken again over a wider range. It was helpful to determine the position of the blocking slit with white paper prior to beginning the experiment.

The discrepancies between the fit and data are the product of assumptions. Equation 1 assumes a point detector, infinite distance between source and detector, plane wave entering the slits, infinite slit lengths, as well as monochromatic light. None of these are completely satisfied. A large discrepancy can be seen in the destructive interference sections in double slit diffraction. In theory, they should be exactly zero. The graph also shows that this discrepancy increases closer to the central maxima.

A maximum rate of 3.6×10^3 photons per second was recorded. With the PMT only registering about 4% of total photons results in 9.0×10^4 photons in the device per second. Travel time of one meter is 3.33 ns for light. So we can say that 99.97% of the time a single photon is in the device by itself. A single photon interferes with itself.

IV. CONCLUSIONS

We observed single and double slit diffraction of light indicating light has a wave-like nature. We also observed that light can be detected in discrete

numbers indicating particle-like nature. It can be said that light can behave as waves or particles. We observed that a single photon of light can interfere with itself giving rise to the idea that the photon is in two places at once: "The Essential Quantum Paradox."[1]

ACKNOWLEDGMENTS

---

[*]Present address: Department of Physics, University of Kansas, Lawrence, KS 66045
[1]"Two Slit Interference, One Photon at a Time 'The Essential Quantum Paradox.'" D. V. Baak. TeachSpin, Inc. Buffalo. 2004.