

# Double Slit Experiment: One Photon at a time

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## Abstract

Particle wave duality is one of the most perplexing concepts in modern physics. This apparent paradox seems to defy intuition, which is built upon common experience. In this experiment the double and single slit experiments are performed one photon at a time. It is shown that a single photon experiences wave interference in both the single and double slit cases. In this sense the particle and wave natures of light are shown simultaneously, which motivates the paradox of duality in an undeniable way.

## Introduction

For centuries the nature of light has been considerably mysterious. Even the best understanding of light today, in terms of a particle wave duality, remains abhorrent to one's intuition. The question of whether light is a particle or a wave was posed first, perhaps, through the debate between Sir Isaac Newton and Christian Huygens. Newton advocated a corpuscular theory: he imagined that light was made of discreet particles which propagated in straight lines. Huygens argued an alternative explanation as a wave phenomena. The question was believed to be answered in 1801 when Thomas Young performed the first double slit experiment. He showed that an interference pattern would emerge when light was sent through two slits—clear evidence of wave phenomena.[1]

Given Young's powerful experimental evidence that light is a wave, this view dominated the 1800s. By the turn of the century Faraday and Maxwell had further expanded on the wave interpretation of light by showing that it is a propagating disturbance in an electromagnetic field. The nature of light as a wave phenomena seemed unquestionable. And yet it would be questioned again in 1905 by Albert Einstein. He showed that the photoelectric effect could be most naturally explained by interpreting light as discreet entities, i.e. the photon[2]. Hence it was also shown that light cannot be described simply as waves or as particles. Instead light must be viewed in terms of a particle-wave duality.

Hence we are stuck today with a concept that defies all logic. But as Feynman pointed out, “there is one simplification at least... [electrons and photons] are both screwy, but in exactly the same way”[3]. In other words we find in quantum mechanics that all matter is described by the particle-wave duality; hence, by understanding the quirky nature of light we understand some of the quirkiness of all matter.

In this paper we present the double slit and single slit diffraction experiments one photon at a time. We shall present strong evidence that the experiment is performed one photon at a time. Further it will be shown that the photons will nevertheless give interference fringes which closely match the predictions of a simple double and single slit interference model. These results superimpose the particle nature of light and the wave

nature of light, clearly motivating duality.

## Theory

We first introduce a simple model which describes classical wave interference for single and double slits, and can be found in any introductory physics textbook[4]. For single slit interference we have that

$$I(\theta) = I_m \left( \frac{\sin(\alpha)}{\alpha} \right)^2, \quad (1)$$

where

$$\alpha = \frac{\pi \cdot a}{\lambda} \sin(\theta). \quad (2)$$

Here  $I_m$  is the central maximum Intensity,  $a$  is the slit width, and  $\lambda$  is the wavelength of light.  $\theta$  is the angle which is measured relative to a line drawn at the the center of the single slit, perpendicular to that slit.

For the double slit case we have that

$$I(\theta) = I_m \left( \frac{\sin(\alpha)}{\alpha} \right)^2 \cos(\beta)^2, \quad (3)$$

where  $\alpha$  is defined as above, and

$$\beta = \frac{\pi \cdot d}{\lambda} \sin(\theta). \quad (4)$$

Here  $d$  is the distance between the centers of the two slits. It is assumed by this model that each slit has the same width,  $a$ .  $\theta$  is defined in a way that is similar to the  $\theta$  in equations (1) and (2). The only difference being that it is measured relative to a line drawn from the midpoint of both slits (see Figure 1).

We note that  $\theta$  is not a variable which was measured directly. The number of photons at a given location was found by allowing light to only pass through a detector slit which was mounted in front of the photomultiplier tube. This detector slit's location was varied, and measured, with a micrometer drive. Let the distance measured by the micrometer drive be called  $x$ .

In order to apply equations (1) through (4) to the data collected we shall relate  $x$

and  $\theta$ . Let  $q$  be the position of the central maximum of either a single slit or double slit plot. The difference  $x - q$  is shown in Figure 1. We see from the figure that

$$\theta = \arctan\left(\frac{x - q}{L}\right) \quad (5)$$

where  $L$  is the distance from the double slit to the detector slit. Using this expression we now have  $I$  has a function of  $x$ .

We now have a model for describing wave interference. Next we shall develop a method by which we can estimate the total number of photons which pass through a given slit.

Consider the plots given in Figures 3 through 5. We wish to find the total number of photons which pass through the double slit apparatus in one second, which we shall call  $P$ . We note the Photon Count in these plots are actually the number of photons which have passed through a detector slit, which happens to be of width  $a$ . In order to count the total number of photons, imagine that we break each plot into  $k$  rectangles, which are laid side by side; further imagine that the rectangles have width  $a$  and height  $I_k$ , where  $I_k$  is the average height of the curve across the  $k^{th}$  rectangle. The height of each rectangle then represents the photon count that would be measured if the detector slit were it placed in such a way that it overlapped the rectangle.

We then have that  $P = \sum_k I_k$ ; however, this calculation is inconvenient. But observe that  $I_k \cdot a$  is the area of the  $k^{th}$  rectangle. If  $a$  is small then  $\sum_k I_k \cdot a \approx \int_{data} I(x)dx$ , where  $I(x)$  is given by either equation (1) or (3). Hence,

$$P \approx \frac{1}{a} \int_{data} I(x)dx. \quad (6)$$

## Experimental Setup

The experiment was performed using Teach Spin's "Two-Slit Interference, One Photon at a Time" apparatus (see Figure 2). This apparatus consists of a long shaft, one meter long, which is sealed off from outside light sources. On the left side of apparatus is a light bulb whose intensity can be varied. On the end of the light bulb is a filter which only lets through light whose wavelengths are in the green spectrum. As the light bulb is brought

down to low intensities, a red shift in the bulb's output of wavelengths occurs. Hence the green filter blocks the majority of the light, allowing for very low light intensities. The beam of light passes through a single slit before moving on to the double slit. Just beyond the double slit is a wide slit which can be varied using a micrometer drive. This wide slit can be used to block one light from passing through one or both slits. At far right end of the tube is a detector slit, which can be varied with a second micrometer drive. The light then passes through the detector slit to the Hamamatsu R 212 Photomultiplier Tube.

When an incident photon strikes the photomultiplier tube an electron is released. The photomultiplier then multiplies the electron by  $10^5$ . Each time this electron pulse exceeds a certain threshold, which can be manually adjusted, the photomultiplier gives a clean ttl-level voltage pulse. These pulses signify a discrete photon event, and are sent to the TENMA test equipment 175 MHz universal counter (72-4095). This device counts the number of ttl pulses received per second. However, the device showed significant fluctuations in its measurement. This is believed to be a consequence of having so (relatively) few photons reaching the photomultiplier tube per second. In order to deal with these statistical fluctuations five data points per detector slit position were taken in the single slit case, and ten data points per detector slit position were taken in the double slit case. The average and standard deviations were then calculated, and plotted (see figures 3-5). The independent variable was the distance that the detector slit was moved, and the dependent variable was the rate of photon incidence.

The data was then fit using equations (1) through (5). The best fit parameters for the three plots are given in table 1. In table 2 are the slit widths and the slit separation, whose values were provided by Teach Spin.

## **Discussion**

We shall now show that there is, in fact, only one photon moving through the apparatus at a time. We shall calculate the total number of photons which pass through the two slits

using equation (6):

$$\frac{1}{0.085mm} \int_0^7 I(x) dx.$$

Here we are overestimating (but not by much) by integrating from 0 to 7.  $I(x)$  is given by equation (3), with the best fit parameters given in table 1. Numerically integrating with maple we find that  $P \approx 29,000 \frac{\text{photons}}{\text{second}}$ . However, according to the manufacturer of the apparatus the photomultiplier tube is only 4 percent efficient. Hence there are actually  $29,000 \frac{100}{4} \frac{\text{photons}}{\text{second}} = 725,000 \frac{\text{photons}}{\text{second}}$  passing through the two slits. Hence one photon passes through the two slits every  $1.379 \times 10^{-6} s$ . Since the distance from the bulb to the detector is approximately a meter in length the time it takes a photon to transverse that distance is  $\frac{1m}{3 \times 10^8 m/s} = 3.33 \times 10^{-9}$ . Observe that the time between photon events is three orders of magnitude greater than time of travel. Hence there is, on average, only one photon moving through the two slits at one time.

Even with only photon in the apparatus at a time, interference fringes are observed in the time averaged data – strong evidence of the wave nature of light. There are other curiosities in the data. Consider the central maximum of double slit data, which was found to be  $I_{mD}(1711) \frac{\text{photons}}{s}$ , and is found at the location  $x = 3.24$ . At this location the intensity for the left slit data is  $I_{mL} = 452 \frac{\text{photons}}{s}$ , and the intensity for the right slit data is 458. One might expect that with discreet events we would have that if we double the amount of slits through which light can pass then we would double the amount of light observed at a given point. Consider, instead, the square roots of these values. 41.36 for the double slit, 21.26 for a left slit, and 21.4. Observe that it is approximately true that  $\sqrt{I_{mL}} + \sqrt{I_{mR}} = \sqrt{I_{mD}}$ . Since the square root of the intensity of light is proportional to the electric field we may attribute this to the fact that when we have perfectly constructive interference, the magnitude of the resultant electric field vector will be the sum of the magnitudes of the individual vectors. But this strange additive property is consistent with Quantum Electrodynamics, and hence applies equally well to any other type of matter[5,3]. It is a fundamental property of nature.

Upon seeing the above result, one may be curious how all of the photons moving through the apparatus add together when we switch from single slit interference to double

slit interference. Fortunately this question is easily answered by equation (6). As before the integral was calculated for each plot from  $x = 0$  to  $7mm$ . For the left slit interference plot we have that  $P_L \approx 15,000 \frac{\text{photons}}{s}$ , and for the right slit  $P_R = 14,400 \frac{\text{photons}}{s}$ . Recall that for the double slit data  $P = 29,000$ . This approximately proves the following very satisfying result:  $P = P_L + P_R$ . Therefore we have that when one of the slits is blocked we also find that the portion of photons that would have passed through that slit are also blocked.

This experiment has shown the particle and wave aspects of light simultaneously. Particle-wave duality is hence both a natural and unavoidable consequence of this experiment.

## Acknowledgments

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- [2] P. Tipler, R. Llewellyn *Modern Physics* (W.H. Freeman Company 1999,2003), pp. 141-143.
- [3] R. Feynman, *The Character of Physical Law* (MIT Press 1967) pp. 128.
- [4] D. Halliday, R. Resnick, J. Walker, *Fundamental of Physics Volume 2* (John Wiley and Sons, Inc., 2005), pp 996-1003.
- [5] R. Feynman, *Quantum Electrodynamics* (Oxford University Press, 1988), pp. 78.

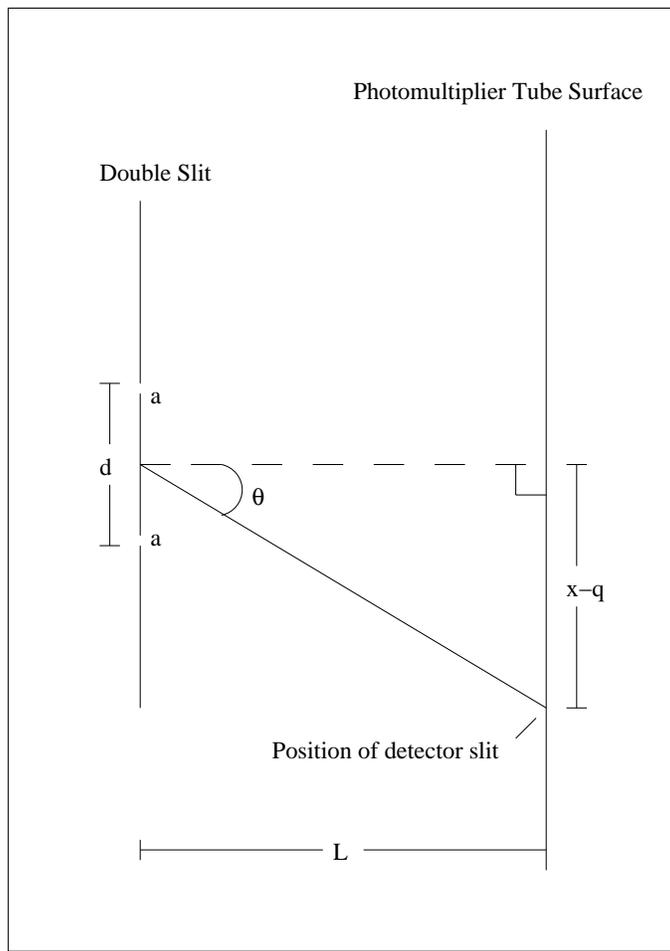


FIG. 1: This diagram shows the geometry of the parameters in equations (1) through (5).

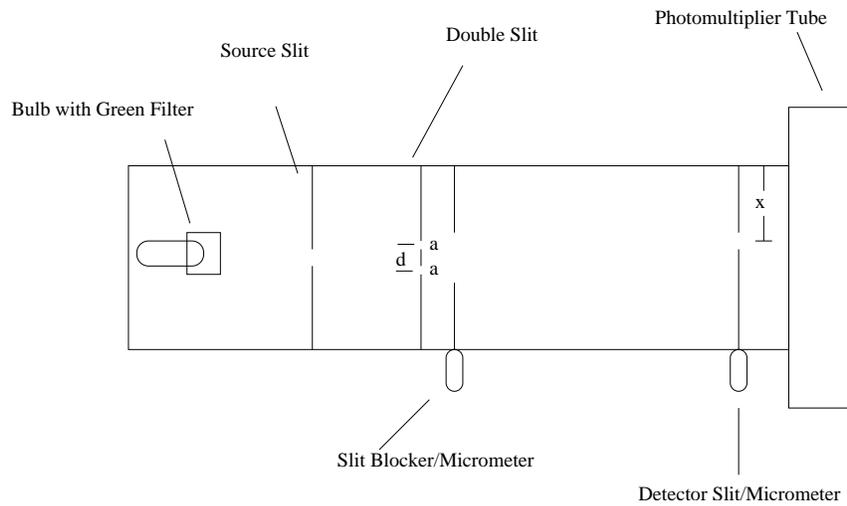


FIG. 2: This diagram shows the basic setup of the double slit apparatus.

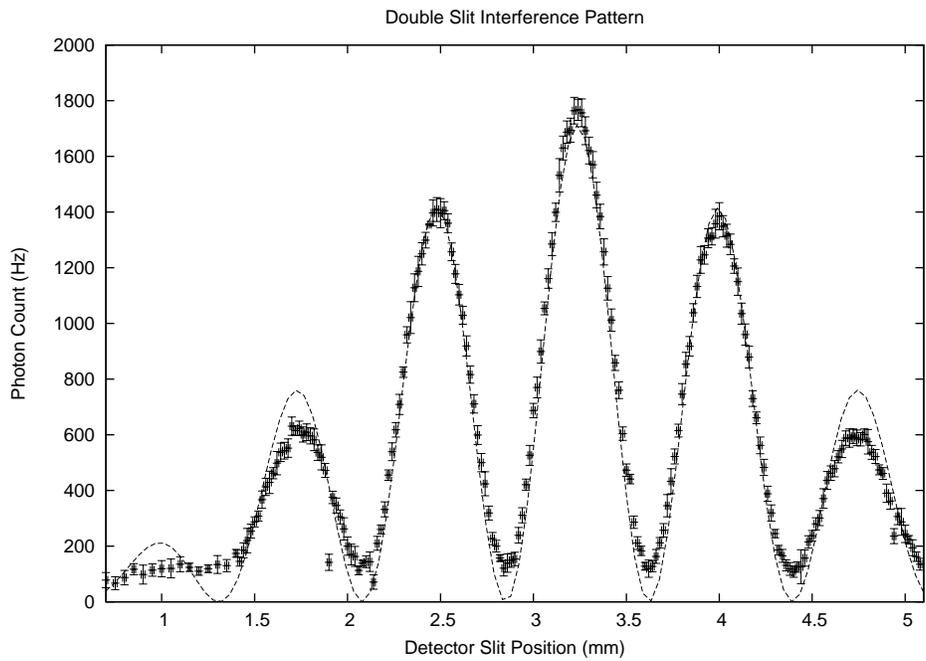


FIG. 3: Double slit interference pattern, one photon at a time.

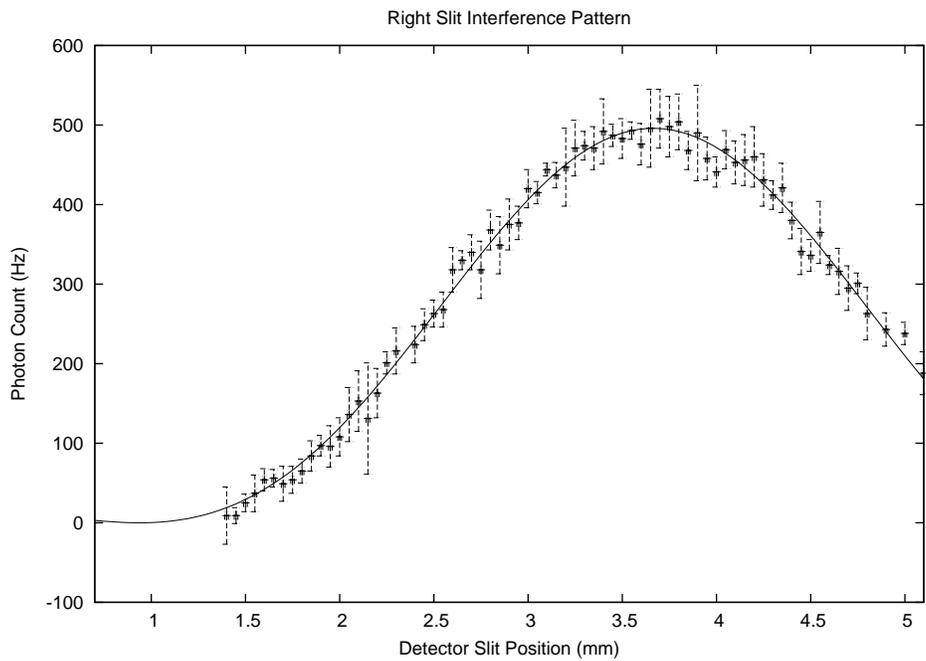


FIG. 4: Single slit interference pattern, one photon at a time.

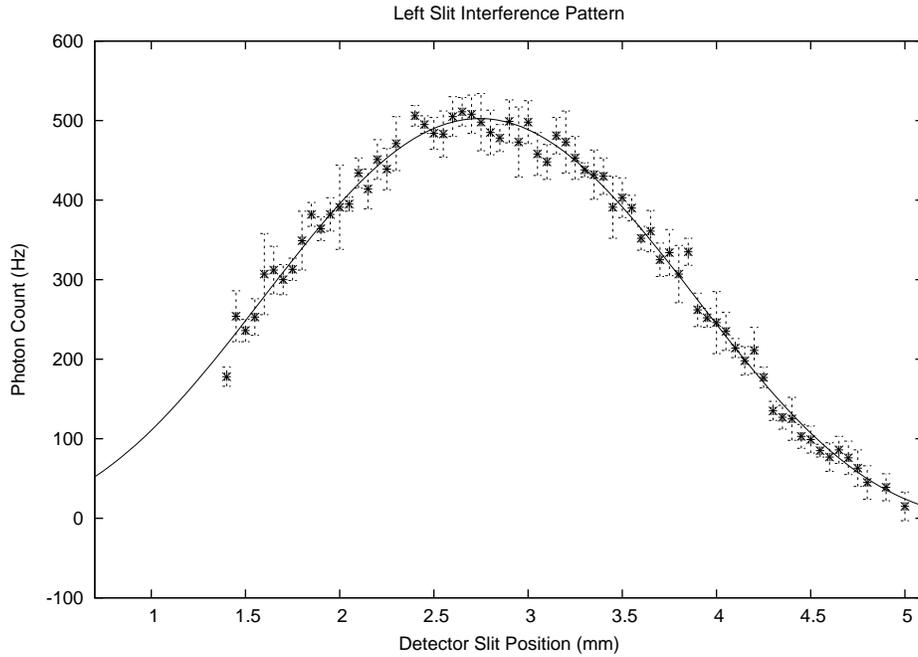


FIG. 5: Single slit interference pattern, one photon at a time.

TABLE I: Best fit parameters for above graphs.

	Central Maximum $\frac{\text{photons}}{\text{second}}$	Position of Central Max (mm)	Wavelength (nm)
Double Slit	$1711 \pm 14$	$3.24 \pm 0.002$	$545 \pm 1$
Left Slit	$503 \pm 3$	$2.74 \pm .008$	$470 \pm 4$
Right Slit	$496 \pm 2$	$3.67 \pm 0.008$	$460 \pm 4$

TABLE II: Geometric Parameters. The slit widths and separations were provided by teach spin.

Single Slit Width	0.085 (mm)
Double Slit Separation	0.353 (mm)
Detector Slit Width	0.085 (mm)
Distance from double slit to detector slit	500 (mm)