# Double Slit Interference, One photon at a Time: the Wave-Particle Duality

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Bachelor of Science with a concentration in Physics from
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## Abstract

Single Photon interference through a double slit apparatus is one of the defining experiments of quantum mechanics. There is no other simple experiment that shows the wave-particle duality so well. These experiments are not new, but their value for instruction purposes is substantial. It is possible to purchase an apparatus, but expensive. Here we attempt, inexpensively, to recreate this experiment for its use in future instruction.

## I. Introduction

Richard Feynman described the double-slit phenomenon as one "which is impossible, absolutely impossible, to explain any classical way, and which has in it the heart of quantum mechanics [1]." The experiment succeeds in completely confusing anyone capable of understanding its meaning. Are photons (or anything else) particles or waves? How can they possibly be both? It is a scary thing to realize that the mind can not grasp the true nature of the very phenomenon we are used to seeing. The behavior of photons and other small particles can be characterized and predicted, but it can not be explained in the classical sense. The double slit experiment illustrates this better than any other.

Performing this experiment, voted one of the most beautiful in physics [2], first-hand makes the phenomenon it reveals much more impressive. Light's switch from wave behavior to particle behavior upon observation is possibly the clearest illustration of the "collapsing" of a wave function. Currently there are experimental apparatuses available for purchase, but they cost as much as $5500 [3]. We attempt to create our own apparatus in order to show the wave-particle duality and make it more concrete and accessible to students.

## II. Theory

The original double-slit interference experiment was preformed by Thomas Young [4] in the early 19$^{th}$ century, to show that light was a wave. A typical experiment consists of a light source, a screen with two slits small enough to cause the light to diffract, and a second screen on which the image is projected, as shown in Fig. 1. The parameter $\Delta$ is the difference in the distance the light travels to get to a particular location on the screen. When $\Delta = n\lambda$, where $\lambda$ is the wavelength and $n$ is an integer, constructive interference is at a maximum. When $\Delta = (n + 1/2)\lambda$, destructive interference occurs. If $Y >> d$ then $\angle CEB \cong \angle CBE \approx 90$. As a result, $\angle EBA \approx \theta$ and

$$d \sin(\theta) = n\lambda\ . \tag{1}$$

So, because sin($\theta$) = X/$l$ a point of maximum constructive interference will occur on the screen whenever

$$X = \frac{l\lambda n}{d} \tag{2}$$

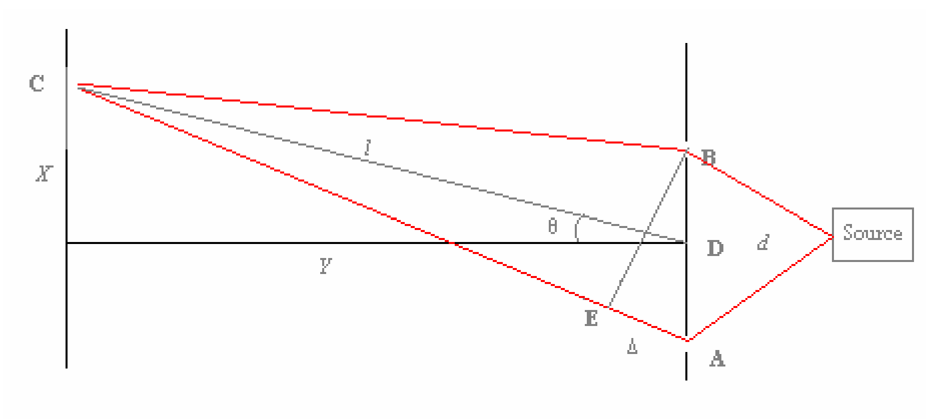


Figure 1. Schematic of a Double-Slit Experiment. Maxima occur when *X=nλ*l/d.*

When one slit is blocked the interference pattern disappears, although there may be diffraction of the light from a single slit. The maximum is in front of the open slit, and would be a distance *d*/2 away from the central two-slit maximum.

Young used his result to prove that light traveled as a wave. However, experiments near the turn of the century proved that light traveled in distinct amounts, or quanta, of energy called photons. The energy of a photon is determined by *E=hf,* where *f* is the frequency of the light. Eventually Geoffrey Taylor determined that interference patterns built up over time even in the smallest amounts of light [5]. It was not long before it became apparent that even if only one photon is in the apparatus at a time the build up of individual photons over time results in an interference pattern. The photons appeared to be traveling through both holes. Even more bizarre, when an attempt is made to detect which hole the photons are going through, it is found that they do indeed only go through one hole, but the interference pattern disappears.

The Photon Multiplier Tube (PMT) is used to make direct counts of photons [6], and suggests the individual, particle nature of photons. It consists of a photocathode, a series of dynodes with a high applied voltage used to amplify the signal, and a collection anode that transfers current to some form of detector. A PMT works by emitting an electron from the photocathode when a photon is encountered. At the first dynode the primary electron produces the emission of an integral value (k) of electrons. At each successive dynode each electron also emits k electrons, and the number of electrons connected by the anode is $k^n$ , where n is the number of dynodes. This allows the number of electrons released by the photocathode to be precisely counted. We see that by counting the individual photons at different locations in front of two slits, we see an interference pattern.

## III. Experimental Methods

The experimental apparatus is based on one used in lecture demonstrations at Harvard University [7]. The apparatus consists of a diode Laser, two adjustable polarizers to reduce the light intensity, a screen with two parallel slits, 100 µm wide, about 300 μm apart, a final screen with an adjustable detector slit, a lens and a PMT photon counting apparatus (Fig. 2). The counting apparatus is a manufactured EMI Gencom STARLIGHT-1 Photon Counting Photometer, which uses an end-window EMI 9924A photomultiplier tube. The entire apparatus was encased by a box of light-tight black acrylic, which we constructed with epoxy.

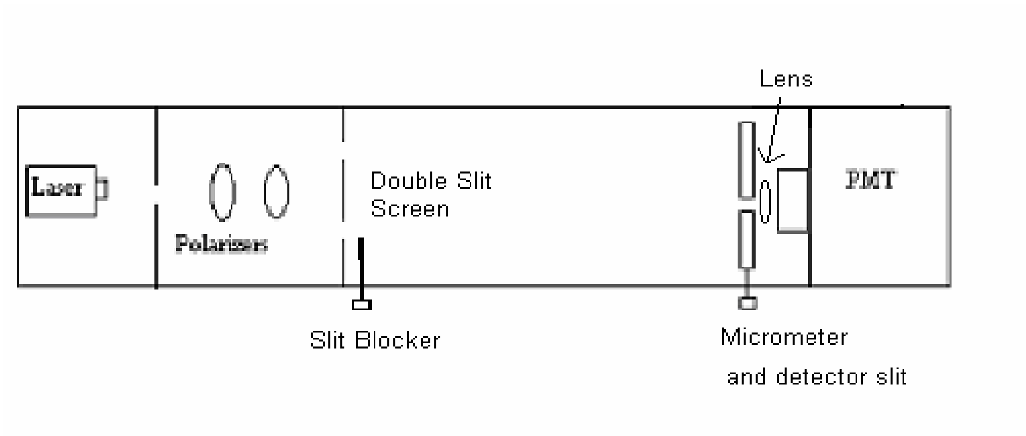


Figure 2. General set-up of the experiment

The polarizing filters are used to cut the light down to an intensity low enough that only one photon is in the apparatus at a time. The polarizers work according to Malus' law: $I = I_0\cos^2\theta$, where $\theta$ is the angle between the polarizers' transmission axes.

Using the detector slit, the PMT measures photon counts at different positions of the screen. Counts can be plotted with respect to $X$ and the interference pattern constructed. We measured the interference pattern by moving our 50 μm detector slit in 50 μm intervals across the interference pattern. A lens with a focus length of 5 cm was used to focus the light into the PMT. A razorblade on a moveable mount has been used as a slit blocker in order to observe the pattern that is formed without any interference.

In addition to facilitating the collection of data, the PMT is necessary in order to determine whether or not there is only one photon in the apparatus at a time. First a one-to-one correspondence between the mean number of photon counts and light intensity must be established. Initially we attempted to detect this relationship by increasing the current delivered to a lamp and relating the counts recorded to the power delivered.

We also measured the correspondence by relating the counts to the skew angle between the two polarizers. A 90 degree measure of relative rotation for the polarizers (the state in which unpolarized light should be completely blocked by the two filters) was estimated by determining which whole degree on the rotating mount yielded the lowest count. Counts were then taken in five degree increments for 180 degrees.

We also used a photodiode to make sure that the polarizers were working properly. In the photodiode, photons are absorbed by a semiconductor, which elevates electrons to the conduction band. With a small applied voltage the electrons generate a current proportional to the light intensity. Photodiodes do not, however, allow the number of photons collected to be counted.

**IV. Results**

First, we wanted to show that the PMT was measuring single photons by varying light intensity into the PMT. We first used an ordinary incandescent lamp. Background counts from the PMT when it was not exposed to light were about 9 counts/sec (Table. 1). The count rate was not bound to be directly related to the power supplied.

| Current | Voltage | Power | Gate | Counts |
|---|---|---|---|---|
| closed pinhole | | | 1 | 9 |
| 0 | 0 | 0 | 1 | 47 |
| 0.250 | 1.24 | 0.31 | 1 | 122 |
| 0.300 | 1.80 | 0.54 | 1 | 129 |
| 0.350 | 2.45 | 0.86 | 1 | 173 |
| 0.375 | 2.82 | 1.05 | 1 | 232 |
| 0.400 | 3.16 | 1.26 | 1 | 439 |
| 0.425 | 3.56 | 1.51 | 1 | 715 |
| 0.450 | 3.93 | 1.77 | 1 | 1170 |

Table 1. Photon counts recorded for variable power input, the closed count number was different from the 0 count number because of minimal background light in the room.

After about one watt of power had been supplied the count rate started to climb irregularly (Fig. 3). The relationship between power and number of photons counted was obviously not linear, and appeared exponential.

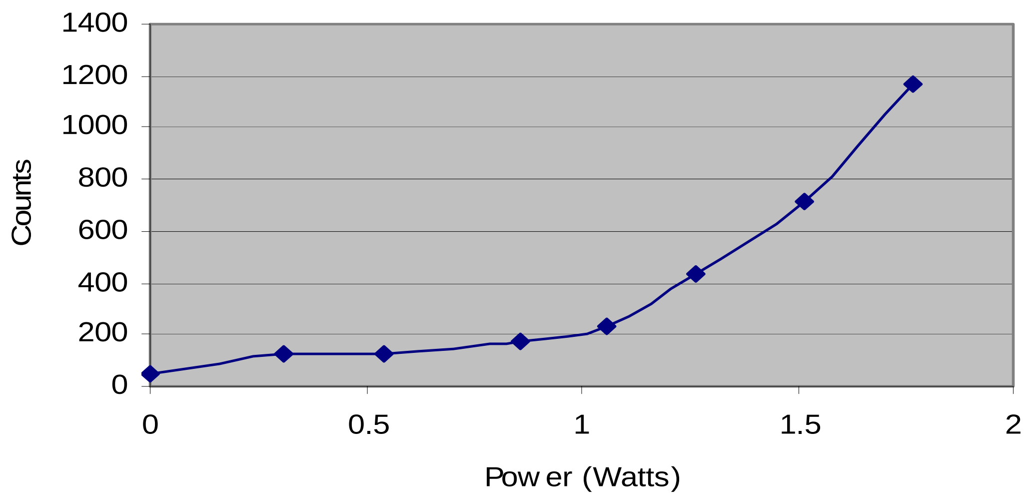


Figure 3. Graph of results in Table 1.

We hypothesized that this might be due to the fact that the increase in intensity over the entire spectrum might not be uniform for the lamp we were using. Using a laser and a pair of polarizers would remove this as a potential problem.

For the next experiment we used both the PMT and photodiode for measurement to determine the relationship between photon counts and light intensity (Fig. 4).

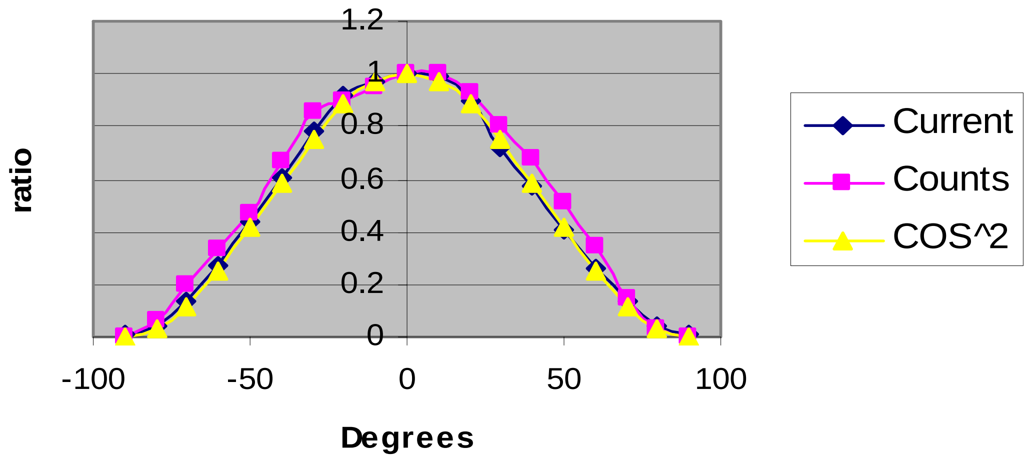


Figure 4. Shows curve of current generated by the photodiode, photon counts from the PMT, and $\cos^2\theta$. The position of θ=90 was chosen where the photon count was at a minimum.

The shape of each curve is quite similar. However, while the photodiode's curve is almost perfectly in line with the $\cos^2\theta$ curve, the PMT's count curve is a bit off in places. These differences however are mostly within the margin for error. This suggests a 1-to-1 correspondence. The lowest number of counts/sec (used for the measurements) is about $2x10^6$ photons/sec. The apparatus is about .5m in length, and the average distance between the photons can be estimated by c/(Photons/sec)=150m, where c is the velocity of light.

Once a 1-to-1 correspondence had been established, we measured the interference pattern generated by the apparatus when photon counts were at a minimum, i.e. when θ=40°. Figure 5 shows the interference pattern generated. Also shown is the pattern generated with one slit blocked. Unfortunately, due to

| Degrees | | Values | | As Ratio | | |
|---|---|---|---|---|---|---|
| Labled | Relative | Current (A) | Counts*10^6 | Current | Counts | $Cos^2$ |
| 40 | -90 | 0.07 | 1.78 | 0.014 | 0.000539 | 3.75E-33 |
| 50 | -80 | 0.23 | 200 | 0.046 | 0.060606 | 0.030154 |
| 60 | -70 | 0.68 | 640 | 0.136 | 0.193939 | 0.116978 |
| 70 | -60 | 1.34 | 1086 | 0.268 | 0.329091 | 0.25 |
| 80 | -50 | 2.21 | 1559 | 0.442 | 0.472424 | 0.413176 |
| 90 | -40 | 3.04 | 2212 | 0.608 | 0.670303 | 0.586824 |
| 100 | -30 | 3.9 | 2808 | 0.78 | 0.850909 | 0.75 |
| 110 | -20 | 4.61 | 2961 | 0.922 | 0.897273 | 0.883022 |
| 120 | -10 | 4.85 | 3122 | 0.97 | 0.946061 | 0.969846 |
| 130 | 0 | 5 | 3300 | 1 | 1 | 1 |
| 140 | 10 | 4.98 | 3290 | 0.996 | 0.99697 | 0.969846 |
| 150 | 20 | 4.47 | 3050 | 0.894 | 0.924242 | 0.883022 |
| 160 | 30 | 3.6 | 2656 | 0.72 | 0.804848 | 0.75 |
| 170 | 40 | 2.85 | 2244 | 0.57 | 0.68 | 0.586824 |
| 180 | 50 | 2.05 | 1685 | 0.41 | 0.510606 | 0.413176 |
| 190 | 60 | 1.28 | 1153 | 0.256 | 0.349394 | 0.25 |
| 200 | 70 | 0.67 | 470 | 0.134 | 0.142424 | 0.116978 |
| 210 | 80 | 0.21 | 120 | 0.042 | 0.036364 | 0.030154 |
| 220 | 90 | 0.07 | 3 | 0.014 | 0.000909 | 3.75E-33 |

Table 2. Data for Figure 4.

the finite nature of our detector slit the resolution of the interference pattern does not show complete destructive interference (0 counts at some x value). However, the size of the pattern is the same as what would be predicted by Equation 2. For

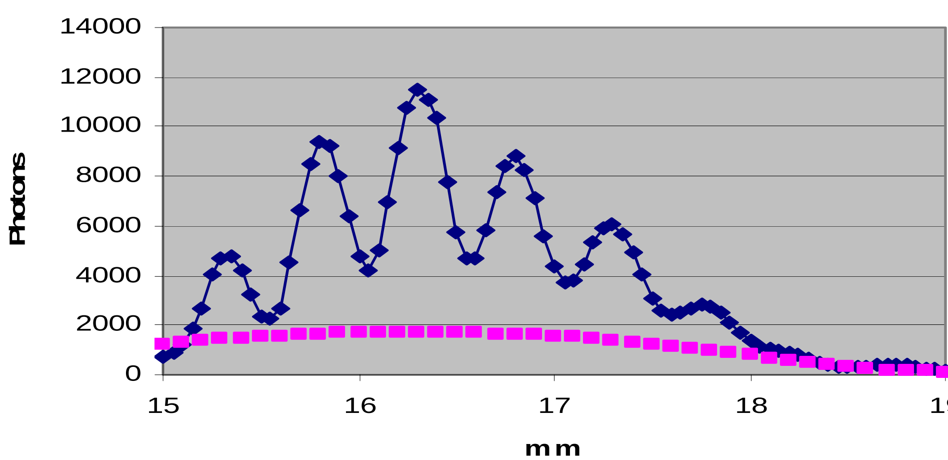


Figure 5. Interference pattern generated by two slit apparatus, and the pattern generated with a blocked slit. Distances shown are the distances labeled on the micrometer for our apparatus.

the apparatus used $\lambda$=633nm, $l$=17cm, and $d$=300μm approximately. From this we would predict a spacing of about .42mm. A spacing of about .45 is observed. The peak value of the interference pattern is at a point 100 μm higher than the peak value for no interference. This is close the 150 μm one would expect ($d$/2).

**V. Discussion**

The results from the first two experiments suggest that using a PMT can not be used to generate a true photon count of a multi-chromatic light source. It is possible that the power supplied to the light source is not an accurate measure of the intensity, but a radiation sensor was used to produce the same result (data not shown). Most likely the exponentially shaped curve was because as the intensity of the light increased the percentage of the light in the PMT's optimal range also increased.

If the change of dominant wavelength related to power output is the cause of the non-linear increase in photon count than a Laser should be able to produce a consistent pattern. Our data shows this, and a direct 1-to-1 ratio of photon counts to light intensity was shown using a photodiode and Malus' law.

Our attempt to make the apparatus as inexpensive as possible imposed a number of limitations. The nature of our double-slit slide does not allow us to either know its dimensions accurately, or to cover one of the slits directly (there is a .5 cm protective glass covering on each side). As a result we were required to overshoot a little with the slit blocker, or some of the light from the blocked slit would escape around the edges, generating a pattern that exhibited interference on one half, and did not on the other. In addition, the interference pattern could be recreated with better resolution with a smaller detection slit. The wavelength of the HeNe laser used is also uncomfortably close to the upper edge of the PMT's maximum performance capabilities. A laser with increased frequency would be an improvement.

The interference pattern generated by the photons shows the wave-particle duality, as it occurred while there was an average of only one photon in the apparatus at a time. The pattern generated is close to that predicated, and the discrepancy is likely due to a lack of precision in measuring $d$ and $l$, especially the former. When the slit is blocked the interference pattern disappears. The experiment successfully shows that photons interfere with themselves, though they are measured as distinct, local phenomena.

## VI. References


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[5] Taylor, G. I, Interference fringes with feeble light, *Proceedings of the Cambridge Philosophical Society,* **15,** 114 (1909).

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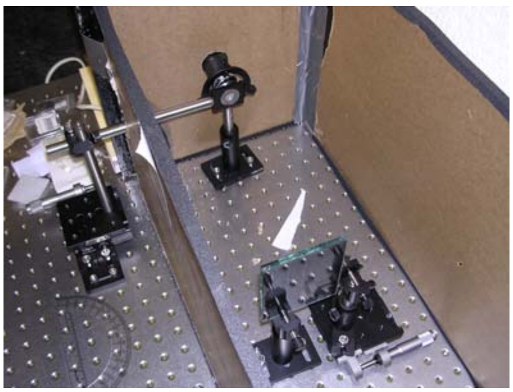
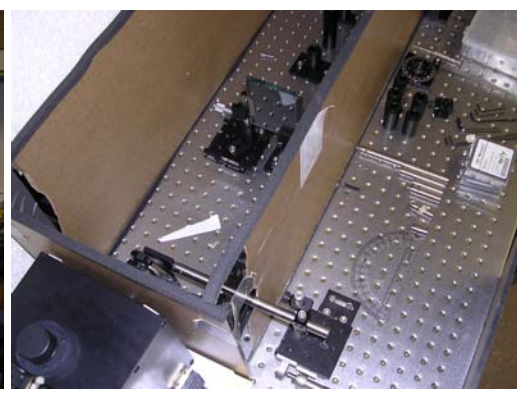
Appendix A: The Apparatus





Appendix B: Program used for Data Analysis

The program gives the average value and the standard deviation of any set of numbers.

```
#include <iostream.h>
#include <cstdlib.h>
#include <string.h>
#include <math.h>

struct Node {
  float data;
  Node* next;
  Node* prev;
};

int main() {
  int a,i;
  float b = 0.0;
  float avg;
  float s=0.0;
  Node* A;
  Node* curr;
  Node* temp_next;

  A = new Node;
  curr = A;
  cout << "Input number of Variables > " << endl;
  cin >> a;
  cout << "Input variable " << i+1 << " > ";
  cin >> curr->data;
  cout << "Variable " << i+1 << " = " << curr->data << "\n";

  for(i=1;i<a;i++) {
    temp_next = new Node;
    cout << "Input variable " << i+1 << " > ";
    cin >> temp_next->data;
    cout << "Variable" << i+1 << "=" << temp_next->data << "\n";
    curr->next = temp_next;
    temp_next->prev = curr;
    curr = curr->next;
  }
  curr->next=NULL;

  curr = A;
  while(curr !=NULL) {
    b += curr->data;
    curr = curr->next;
    avg = b/a;
    }
  curr = A;
  while(curr !=NULL) {
    s += (curr->data - avg) * (curr->data - avg);
    curr = curr->next;
    }

  cout << "AVERAGE: " << avg << endl;
  cout << "Standard Deviation is: " << sqrt(s/a) << endl;
  return 0;
}
```