Verifying the Wave-Particle Duality of Light

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Abstract

By performing Young's double slit experiment with a high intensity laser and analyzing the resultant interference pattern we were able to verify the classical wave theory of light. Performing the same experiment with a low intensity source so as to isolate single photon events using a photomoultiplier tube and pulse counter we were able to recover a qualitatively identical interference pattern. We conclude that light exhibits particulate characteristics as well as wave-like characteristics. This phenomenon is referred to as wave-particle duality.

1 Introduction

1.1 Physical Motivation

What is light? Serious consideration of this question began in ancient Greece. Plato believed light consisted of rays emitted from our eyes that allowed us to "feel" things far away [1]. This is the so-called "extramission" theory of light which Euclid formalized in his famous work *Elements*. Ptolemy carried the extramission theory even further and experimentally verified the small-angle approximation of the law of refraction between two media in his treatise on the subject *Optics* [1].

The extramission theory of light was disproven in the early 9th century by the "Father of Modern Optics" Alhazen [1]. He did so by placing two lanterns outside of a dark room each with its own circular aperture placed in front of it. The lanterns projected light through their apertures and into the room forming circular patterns on the opposite walls. He discovered that covering one of the lanterns caused its corresponding circle of light to disappear from the wall. He thus concluded that light does not emanate from the eyes of humans but rather form light *sources*.

It took until Newton to formulate a formal corpuscular theory of light beyond that of ancient Greek speculation. He presented his theory of light and color in his aptly named work on the subject, *Optiks*. Newton's contemporary Huygens subsequently demonstrated the wave nature of light through experiments where he observed that light passing through a circular hole formed a conical path rather than a rectilinear one.

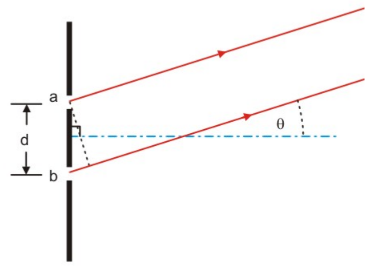
In the early 19th century Young's double slit experiment [1] unhinged Newton's corpuscular theory of light as the mainstream theory. The subsequent works of Fresnel on diffraction and Maxwell on electromagnetism further solidified the idea that light is a wave.

Following the work of Planck on blackbody radiation, in 1905 Einstein published *On a Heuristic Viewpoint Concerning the Production and Transformation of Light* in which he presented his theory explaining the photoelectric effect. He argued that light travelled as discrete "quanta" of energy thus reintroducing the particle theory of light.

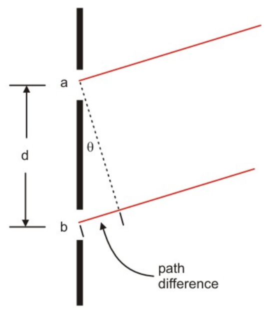
At this point in our story, we've somehow learned tremendous amounts about the nature of light and yet seemingly come no closer to an answer to our original question. What is light? Our experiment aims to show that the answer is both. Light behaves as *both* a particle and a wave.

1.2 Theory

Consider a double slit filter with slits separated a distance d



Take d to be small enough such that the two light rays may be well approximated as parallel.



The path difference is given by

$$\text{path difference} = d \sin \theta \tag{1}$$

The condition for constructive interference of outgoing spherical waves is that the path difference be integer multiples of the wavelength. This gives the following relationship

$$n\lambda = d \sin \theta \tag{2}$$

Assuming that the screen on which the interference pattern is visible is far away we may apply the small angle approximation. Let Δx be the spacing between bright fringes and L be the distance to the screen. The relation becomes

$$\lambda = \frac{d\Delta x}{L} \tag{3}$$

$$\frac{\lambda}{d} = \frac{\Delta x}{L} \tag{4}$$

2 Experimental Setup

Our experiment consisted of two smaller experiments each with their own set of measurements. The end goal is to compare the two sets of measurements and make a conclusion about the properties of light.

The first is Young's double slit experiment [2] with a laser serving as the high-intensity (here we take high-intensity to mean that the individual constituents of the light beam may not be distinguished by the observations of the experiment) light source.

The second is a modification of Young's double slit experiment where a low-intensity bulb is used in place of a laser to isolate singular photon events in the detection scheme. Both employ the use of the same apparatus with only some modifications in configuration which will be detailed in their respective sections.

The apparatus operates as follows. Light leaves a source located at one end of the tube and travels through a single slit in order to form a coherent source signal. The now focused signal then enters a double-slit before continuing on to the detector at the other end of the tube. The detector can be configured as either a photodiode or a photomultiplier. Add the figure once you're ready to move everything into two-column format

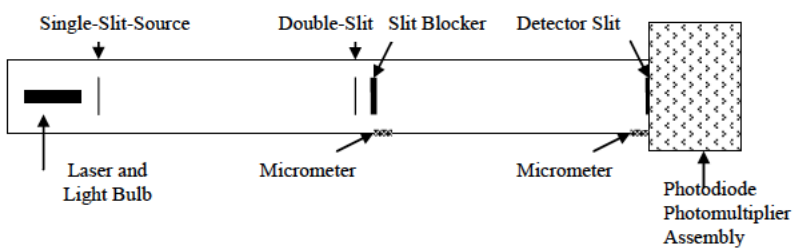


Figure 1: Experimental apparatus
Adapted from Teach Spin Manual

2.1 Laser Setup

For the first experiment a red laser was used as a a light source and the photodiode was configured as the detector. The photodiode converts incoming light into current which is subsequently converted to a voltage via a circuit internal to the device. We recorded this voltage by connecting a multimeter to the DC output on the face of the detector.

Varying the position of the slit using the built in micrometer adjustment varies the measured output voltage and serves as evidence of fringe patterns on the detector. We collected voltage data in .25mm increments in the range 0-10mm.

2.2 Low Intensity Bulb Setup

Following the data collection with the laser source we switched to a low-intensity bulb behind a green light filter. the bulb is supplied with low current and thus emits light on the red end of the spectrum [3], this makes the production of green photons very unlikely and allows for detection of one photon events. This allows The intensity of the bulb is too low to provide accurate measurements from the photodiode in order to measure data the detector configuration is set to the photomultiplier which was is connected to an oscilloscope and a pulse counter in parallel.

The photomultiplier amplifies the signal of incoming photons to create a detectable voltage. The pulse counter then detects the output voltage of the photomultiplier and records a count if the voltage exceeded the configured discriminator threshold.

A cross-calibration was performed between the voltage threshold on the pulse counter and the voltage source on the photomultiplier to optimize the signal to noise ratio. The noise being the "dark" counts seen when the photomultiplier was closed.

After the calibration was performed we took a series of three counts at each slit position in the range 0-9mm with intervals of .25mm so as to be able to perform a comparison to the laser data.

3 Analysis and Results

3.1 Verifying One-Particle Events

The validity of the conclusion of our experiment is contingent upon us actually observing one-photon events with the bulb/photomultiplier configuration. With the green filter in place on the bulb TeachSpin quotes a photon event rate of 10^6 photons per second. this gives an average of 1 photon every 10^{-6} seconds. Considering that the length of the apparatus from source to detector is about a meter [3] and the speed of light is 3×10^8 m/s the time of flight of a single photon would be 3×10^{-8} seconds. So if there were just one photon at a time in the tube we would see a count rate of 3×10^8 photons per second. The photomultiplier tube outputs a voltage when an incident photon enters the tube. This voltage signal was captured on an oscilloscope.

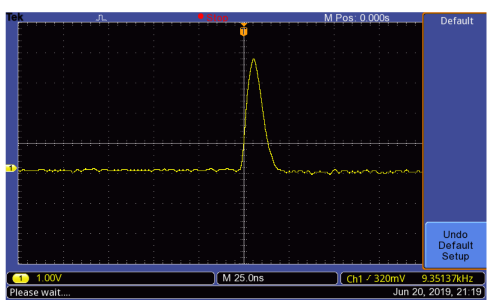


Figure 2: Sample Oscilloscope Reading From Photomultiplier

Given the scale of the oscilloscope reading in Figure 1 we see that the extent of the pulse is less than 2.5×10^{-9} seconds. This is an order of magnitude less than the travel time of a single photon. Thus we conclude that the statistical likelihood of observing more than one photon at a time is very low.

3.2 Comparing Both Experiments

Classically, we would expect a double-slit interference pattern for the laser light source. As far as the single-photon source, classical particle theory would predict no interference. The low intensity nature of the bulb experiments makes it prone to noisiness in the data collection. A background noise test was conducted and the average of the noise (272.9 counts) was subtracted from the data. The results are below

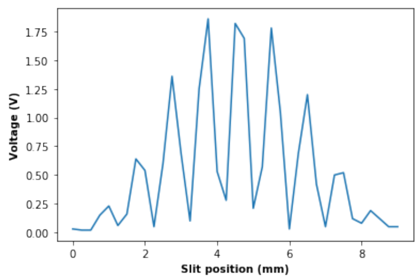


Figure 3: Laser Data

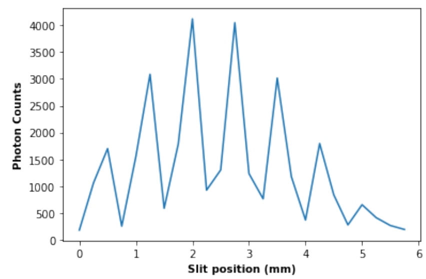


Figure 4: Bulb Data

We see the same distinct interference pattern (six significant peaks). The closer slit spacing for the bulb data is consistent with the lower wavelength of the green light according to (4). Source code used for this analysis can be found at **https://github.com/Salazar-99/Modern-Laboratory**.

4 Conclusion

We were able to confirm through oscilloscope measurements that with the bulb source we were measuring single photon events. We observed qualitatively identical interference patterns for both high-intensity and low-intensity (one photon at a time) sources. We conclude that light behaves as a wave even when being measured as a particle.

References

[1] M. Al-Amri, M. El-Gomati, M. Suhail Zubairy, *Optics In Our Time*, Springer, 2016

[2] R. Fitzpatrick, *Waves and Oscillations*, Taylor and Francis Group, Boca Raton, 2013

[3] Teachspin, *Two-Slit Interference, One Photon at a Time. A Conceptual Introduction to the Experiment*