Single-Photon Double-Slit Interference Experiment

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Keywords: first keyword, second keyword, third keyword

I. INTRODUCTION

The most essential, fundamental evidence and motivation for quantum physics is that of the wave-particle duality of light. Light demonstrates clear wavelike properties such as refraction and interference, but light was also shown to have a particle nature with Albert Einstein's photoelectric effect, where discrete quanta of light, "photons," were measured [1]. Louis de Broglie later showed that all objects have this same wave-particle nature on a small enough scale.

The discovery of the wave-particle duality of light opened the door to the exploration of quantum mechanics. The original double-slit experiment performed by Thomas Young in 1801 was intended to prove that light was a wave. Because we now know light has wavelike qualities, we would expect to see an interference pattern when shining a beam of light through a double-slit onto a detecting surface, and this is exactly what Young saw in his experiment [2]. This was intended to prove that light is solely a wave, and not a particle, but it can be repeated with one slight change: ensuring that only a single photon is in the channel at a time. When the experiment is done in this way, by using a low-power bulb and filtering it such that only one photon is emitted in each discrete time interval, it is evident that the double-slit interference pattern appears just the same. Each photon passes through both slits simultaneously, interfering with itself and producing an interference pattern on the detector just as if there was a beam of many photons.

We will firstly be reproducing Young's experiment to demonstrate the interference pattern from a beam of light, and then restricting the beam of light to single photons going down the channel at a time, demonstrating that an interference pattern is still produced. If we attempt to "tag" each photon to discover which slit it went through, the interference pattern disappears. This we establish via a slit blocker, which prevents photons that passes through either the near or far slit from reaching the detector. We will record data for each of these scenarios and show consistency with previous discoveries which indicate that although a wave-particle duality exists, light can exhibit only one set of qualities at a time.

II. THEORY AND BACKGROUND

When light acts as a wave, it has the same characteristics of any wave, namely a wavelength, amplitude, and frequency. As such, we expect Huygen's principle to apply, causing the light to go through the double slit, exiting in two bands that interfere as they travel. Figure 1 shows this interference as well as the pattern this produces on the detector.

In addition to this wavelike property of interference, we need to take into account the rate at which light particles (photons) are exiting the bulb and passing the double slit. This rate is akin to the intensity of the light waves. For the laser, this rate is rather high, making it unclear if photons are interfering with themselves or with others. When we switch to the incandescent bulb with a green filter, this rate goes down so drastically that there is either 0 or 1 photon in the entirety of the channel [3]. At this point, we can safely assume we are measuring the interference patterns of single photons with themselves, thus demonstrating the wave-particle duality of light.

We will be using an approximation given in the manual because L, the distance between the double slit and the detector, is much larger than δx, the distance

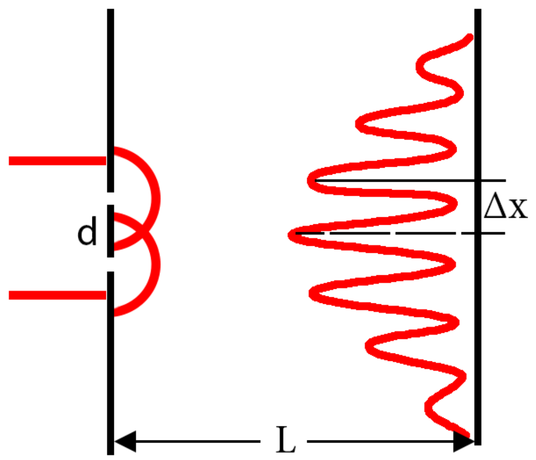

Figure 1. Two-slit interference pattern. This figure shows diffraction due to Huygen's principle and the resulting interference pattern from an incoming beam of photons, such as our laser.

between adjacent maxima on the interference pattern. This approximation, given by

$$\frac{\delta x}{L} = \frac{\lambda}{d} \tag{1}$$

allows us to calculate λ, the wavelength of the laser light, given the slit separation, d. We will compare our result to the laser's expected wavelength enumerated in the manual for consistency. We will also use our data to reproduce the interference pattern and compare it to those found in similar experiments and in the manual, and we can fit our data to this pattern as another way of checking λ

The method of analysis we will use follows the Fraunhofer/Fresner method, which does not depend on what light actually is (a particle or a wave), but rather allows us to gather data and make calculations based on it. The Fraunhofer approximation will be satisfactory for our needs, requiring some parameters of the apparatus that we can get from the manual and verify, and some other parameters which we can get from our measurements. For this approximation, we will use θ to track the angle between the slit and the point we are measuring on the detector. Letting a be the width of the slit itself (whether it be a single slit or one of a double slit), and letting the center-to-center slit separation be d as before, we will define the useful intermediate variables $\alpha = \frac{\pi a}{\lambda} sin\theta$ and $\beta = \frac{\pi d}{\lambda} sin\theta$. We can then calculate the intensity of a double slit interference pattern using

$$I_2(\theta) = I_0(\frac{sin\alpha}{\alpha})^2(cos\beta)^2. \tag{2}$$

In this equation, I_0 is the measured intensity at the central maximum of our double slit interference pattern. The intensity on the single slit interference pattern can also be predicted using this method, with some modifications. The central intensity should be $\frac{I_0}{4}$, and the expression simplifies to

$$I_1(\theta) = \frac{I_0}{4}(\frac{sin\alpha}{\alpha})^2. \tag{3}$$

These equations will be our main way of analyzing and comparing data between the single- and double-slit patterns.

III. APPARATUS AND EXPERIMENT

The experimental apparatus (Fig. 2) consists of mainly a U-channel, one end of which produces photons and the other of which detects them. The detector end of the U-channel has a guage for the high-voltage amplifying input for the photomultiplier tube (PMT) that we will use as our main detector. We calibrated the equipment and set this to 900 Volts for all of our measurements with the bulb. The detector end is connected to a pulse counter/interval timer (PCIT) and an oscilloscope. The scope gives us a pictoral representation of each photon hitting the detector, and the PCIT actually records a count in a set time interval. Due to base-level fluctuations in the equipment and the inherent sensitivity in the PMT, we have a "dark count," the number of detected photons in an interval when the shutter is closed and no light is actually hitting the PMT. We measured this dark count to be around 70 counts/second, and had to use this as our zero when analyzing other measurements. In order to help avoid false positives, the PCIT has a discriminator threshold which can be set via a dial, and which causes the PCIT to only count photon strikes above a certain energy pulse level. We set ours to 0.7 Volts. The oscilloscope should also show the discriminator threshold alongside the pulses coming through, giving a visual representation of the PCIT neglecting low-energy pulses.

The source of light and the detector can both be switched out. The laser module can be slid to the side after removing the lid to the U-channel, revealing a path for the bulb behind it. We had to replace the bulb after a burnout, and that was done following the manual [3]. The laser should be used with the photodiode detector (shutter down), since it is meant for much higher energy. The PMT can be revealed by raising the photodiode out of the way (shutter up), and should only be used when measuring single-photon events from the bulb. Using the laser or removing the lid with the PMT revealed can cause serious damage to it.

We took the first set of data using the laser, which was fairly simple and created the double-slit interference

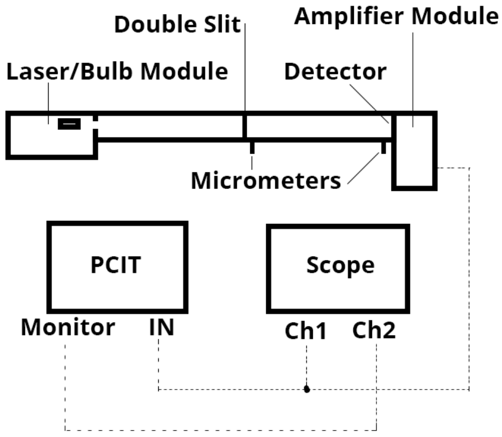

Figure 2. The experimental apparatus. Dashed lines represent wired connections, while solid lines are used for labels.

pattern just as expected. With the laser, the assembly is simpler than in figure 2: instead of the scope and PCIT, we only have a digital multimeter (DMM) connected directly to the amplifier module. All other data was taken with the bulb, moving the slit blocker with the central micrometer to reveal the near slit only, far slit only, or both slits. The detector is simply a bucket for photons and cannot measure where they struck, so the apparatus has a micrometer-controlled detector slit that we manually move along the interference pattern. Each of our datasets were taken with the micrometer position as the independent variable, and either voltage (laser) or photon count (bulb) as the dependent.

IV. ANALYSIS AND DISCUSSION

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ACKNOWLEDGEMENTS

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[2] Andrew Robinson, *The Last Man Who Knew Everything* pp. 123-124, (Pi Press, New York, NY, 2006)
[3] TeachSpin Instruction Manuals, *Two-Slit Interference, One Photon at a Time (TWS2-A) Rev 2.0* (6/2013)

Appendix: Appendix

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