Single-Photon Double-Slit Interference Experiment

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Light exhibits properties of both waves and particles, and this experiment provides insight into the conditions in which each of these sets of properties hold true. When light passes through a set of two adjacent slits, it passes through both simultaneously, interferes, and produces an interference pattern on the detector. These properties are evidence for the wave nature of light, and measuring the interference pattern allows us to calculate the wavelength of light. We find in this experiment that even when only one photon is in the channel at a time, it still passes through both slits, interferes with itself, and produces the pattern. We finally test the single-slit diffraction when one of the slits is blocked, which produces the expected single-slit interference pattern with very small fringes. Thus light can exhibit particle-like qualities such as grouping into discrete quanta as photons, and wave-like qualities such as diffraction and interference, agreeing with previous experiments.

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 deBroglie 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 when measuring photon counts as when measuring wave intensity. 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 block one of the slits, the experiment is reduced to a single-photon single-slit apparatus, and we see the single central curve of a much wider interference pattern caused by single-slit diffraction. 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 wave-like 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 proportional 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 between adjacent maxima on the interference pattern.

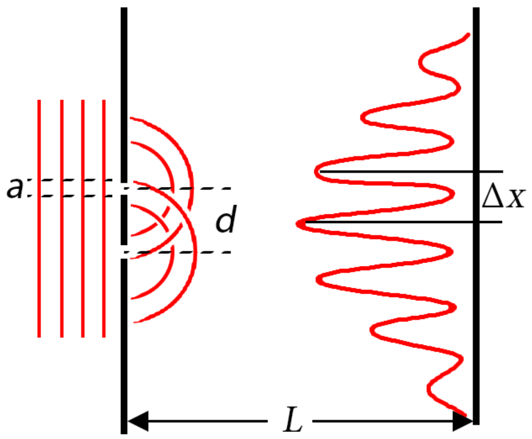

FIG. 1. Two-slit interference pattern. This figure shows wave-fronts of light coming in from the left (such as from our laser), hitting the double slit, and diffracting in accordance with Huygen's principle (each slit acting as a point source of new light waves). The light waves interfere after passing through the slit to produce the pattern shown on the right, where the size of the nodes represents the intensity at that point on the 1-D detector. L represents the distance between the double slit and the detector, d is the distance between the centers of the two slits, and a is the width of the slit itself. Both slits are the same width. Δx is the distance between adjacent maxima in 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. These calculations give a good approximation that we can use as an initial guess for our fitting function to then optimize. We will 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 a better way of checking λ.

We will assume the distance between the slit and the detector is great enough that the light wave sources from the slit will be approximately flat and parallel to the detector upon reaching it. Further, we expect our data to fit to the Fraunhofer model, which does not depend on light being a particle or a wave, but rather allows us to gather intensity data and make calculations based on only that and measured values of the apparatus. Fitting to this model would also allow us to find λ, but using the approximation in Eq. (1) gives us a rudimentary value of λ to use as an initial guess for the fit. 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 (both slits have the same width), and letting the center-to-center slit separation be d as before, we will define the useful intermediate variables

$$\alpha = \frac{\pi a}{\lambda} \sin\theta \text{ and } \beta = \frac{\pi d}{\lambda} \sin\theta \ . \tag{2}$$

We can then calculate the intensity of a double slit interference pattern using

$$I_2(\theta) = I_0 \left(\frac{\sin\alpha}{\alpha}\right)^2 \cos^2\beta \ . \tag{3}$$

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 roughly $\frac{1}{4}I_0$, and the expression simplifies to

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

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) is 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 gauge for the high-voltage amplifying input for the photo-multiplier tube (PMT) that we will use as our main detector. We calibrated the equipment and set this to 900 V 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 visual representation of each photon hitting the detector, and the PCIT records counts 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 used this as a point of comparison when taking data. Our device is not sensitive enough to detect a photon or its photoelectron itself, so the PMT is a tube that amplifies photoelectrons to a point where they can be measured as a pulse at the end of the tube. Due to this process, we

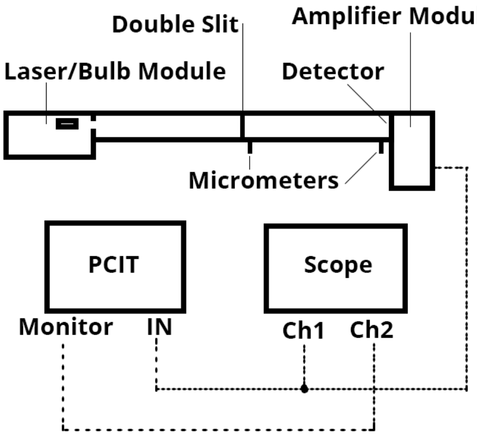

FIG. 2. The experimental apparatus. Dashed lines represent wired connections, while solid lines are used for labels. The laser or bulb light is emitted from the leftmost section of the channel and detected at the rightmost side. The micrometer next to the double slit controls a slit blocker which can be moved to block one of the slits when performing a single-slit trial. The rightmost micrometer controls the movement of the detector slit from side to side. The detector sends a pulse through the wire to the scope and PCIT every time a photon strikes it, and the scope displays this while the PCIT keeps a count of pulses for a specified time period. This pulse/time serves as our intensity measurement. Pulses are only counted by the PCIT if their voltage is above a certain threshold set by the PCIT; this threshold is displayed on the scope by using the Monitor output on the PCIT.

don't know if a measured pulse resulted from a photon hitting the PMT or from an electron generated thermally inside the detector. In order to help avoid these false positives, the PCIT has a discriminator threshold that causes the PCIT to only count pulses above a certain energy level, since a thermal electron generated in the middle of the detector would not cause as much of a photoelectron cascade as a photon hitting the beginning of the PMT. Dark counts result mainly from thermal electrons that appear near the beginning of the tube, when they still have time to cascade electrons up to a passable intensity. We set our pulse threshold to 0.7 V. 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 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 data-sets were taken with the micrometer position as the independent variable, and intensity as the dependent variable, whether it be voltage or counts/sec. Our apparatus has a shutter which can be lowered to cover the PMT, revealing a photodiode in its place; we use the photodiode for taking measurements with the laser, and the PMT for the much lower intensity bulb.

Figure 2 shows the setup for taking data with the bulb; when using the laser, the assembly is simpler. Instead of the scope and PCIT, we use a digital multimeter (DMM) connected directly to the amplifier module. The intensity is taken as the voltage reading on the DMM, and this reading does not change significantly over time. When taking data with the bulb, we take multiple measurements for each position and average them to get our intensity. This is done because the PMT is much less consistent than the photodiode, and data points from the fluctuating intensity fall into a Poisson distribution. An important source of background with the PMT is the dark counts mentioned previously. We account for these by adding a constant to our fitting function, with the initial guess of our measured average $\simeq 70$ counts/sec, and allowing the fitting function to optimize this value and shift vertically in accordance with the true dark counts reflected in our data. We also do not know where exactly on the detector the central maximum, x_0, is, so our fitting function will optimize this as well, performing the appropriate horizontal shift.

When using the bulb, rather than ensuring single photons pass through the slit at a time, we ensure there will only be one photon in the entire U-channel at a time. We can do this using our knowledge of the speed of light, the length of the channel, and the order of magnitude of the photon emission rate of the bulb with the green filter. We know the length of the channel is $d \approx 1$ m, and the speed of light is $c = 3 \times 10^8$ m/s. The manual gives a quantum efficiency of 0.1, meaning that only about 10 percent of photon events register on the detector. We are measuring photon events through a detector slit, so only some photons pass through the slit and hit the detector; we will say that the slit is roughly 1 percent of the detector width. If we use a high bulb setting such that the rate of photons observed by the detector is on the order of 10^3 counts/sec, then we expect the actual photons reaching the end of the tube to be $10^3 \times 10 \times 100 = 10^6$, so we can approximate the photons arriving every 10^{-6} sec, or 1 μs. Each photon is in the channel for about $d/c = 3$ ns. Thus the probably of there being at least one photon in the channel at any given time is 1×10^{-3}, and the probability of there being more than one photon at a time is $1 \times 10^{-6} \approx 0$.

IV. ANALYSIS AND DISCUSSION

Our apparatus has these standard values which will be used throughout our analyses: $L = 500.00 \pm 0.05$ mm, $d = 0.457 \pm 0.001$ mm, $a = 0.10 \pm 0.05$ mm. For our rudimentary approximation of λ for the red laser light, we use our data-set for the laser's interference pattern to measure Δx, then refer to Eq. (1) to find $\lambda_{laser} = 0.658 \pm 0.005$ μm, where Δx is the micrometer position measured with respect to the position of the central max, which we determined to be roughly $x_0 = 5.350 \pm 0.001$ mm. This uncertainty in x_0 is due to the micrometer's finest markings being 0.01 mm. The manual gives $\lambda_{laser} = 0.670 \pm 0.005$ μm, fairly close to our approximation. Regardless of the light source, if the apparatus is aligned correctly the pattern should have the same central max position, since the double slit and other apparatus parameters do not change. We assume this to be the case for our approximation and initial guess for the fitting function for the bulb's interference pattern, and the fitting function will verify this or find the true value.

We modify the Fraunhofer model in Eq. (3) and substitute in the parameters in Eq. (2) to create our double-slit fitting function,

$$I_2(\theta) = I_0 \left(\frac{\sin \frac{\pi a}{\lambda} \sin \theta}{\frac{\pi a}{\lambda} \sin \theta} \right)^2 \cos^2 \frac{\pi d}{\lambda} \sin \theta + D \ , \qquad (5)$$

where D is the vertical shift to account for dark counts, x_0 serves as a horizontal shift to find the central max position, and

$$\theta = \pi - \frac{x - x_0}{L} \ . \qquad (6)$$

Similarly, the single-slit fitting function is

$$I_2(\theta) = \frac{I_0}{4} \left(\frac{\sin \frac{\pi a}{\lambda} \sin \theta}{\frac{\pi a}{\lambda} \sin \theta} \right)^2 + D \ . \qquad (7)$$

Fitting Eq. (5) to the data should give a more accurate value of λ_{laser}. The intensity in this case is measured as voltage, and we found the intensity at the central max to be $I_0 = 2.070 \pm 0.005$ V. This value goes into the fitting function as an initial guess. Figure 3 shows a data-set gathered from the laser's double-slit interference pattern, overlaid with the Fraunhofer fit. The fit of this data has a correlation coefficient of 0.641, so we are fairly confident in our results.

We can also calculate λ for the bulb. Δx for the double-slit pattern is measured as 0.65 ± 0.05 mm. This is less certain than the bulb measurement because we have far less distinction on the 0.01 mm level, and would need to take many measurements at several different points for comparison. This is meant to be a rough approximation to give us an initial guess for the fit, so we are not going to strive for more accuracy than $\pm$ 0.05 mm. Equation (1) gives us $\lambda_{bulb} = 0.594 \pm 0.005$ μm. We measured the intensity at the central max to be $I_0 = 252 \pm 5$ counts/sec. Figure 4 shows this data-set with the Fraunhofer approximation in Eq. (5) fitted to it.

We now move from the double-slit to single-slit interference patterns by adjusting the slit blocker to cover either the near or far slit. For these single-slit trials, we increase the output intensity of the bulb itself to ensure the counts we record will not be too close to the dark counts. This affects only our I_0 required for the fitting function in Eq. (7), so we re-measured I_0 for the double-slit with this new bulb intensity setting to find $I_0 = 2430 \pm 20$ counts/sec. With only the near slit open, our central max position is now 5.920 ± 0.001 mm, with an intensity of 980 ± 10 counts/sec. With only the far

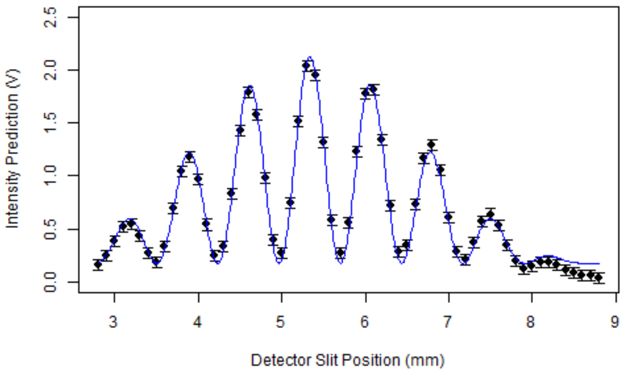

FIG. 3. Data-set for laser interference through a double-slit. Eq. (5) is fitted to it. The fitting parameters are $\lambda = 0.656 \pm 0.005$ μm, $I_0 = 2.15 \pm 0.05$ V, $a = 0.085 \pm 0.002$ mm, $d = 0.447 \pm 0.002$ mm, $x_0 = 5.335 \pm 0.004$ mm, and $D = 0.18 \pm 0.01$ V. Error in x translates to error in y, so only vertical error bars are shown.

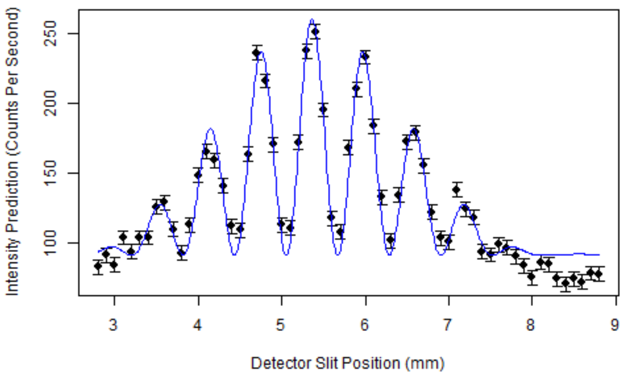

FIG. 4. Data-set for single-photon (bulb) interference through a double-slit. Eq. (5) is fitted to it. The fitting parameters are $\lambda = 0.583 \pm 0.005$ μm, $I_0 = 260 \pm 5$ counts/sec, $a = 0.102 \pm 0.003$ mm, $d = 0.020 \pm 0.002$ mm, $x_0 = 5.361 \pm 0.004$ mm, and $D = 91 \pm 2$ counts/sec. Error in x translates to error in y, so only vertical error bars are shown.

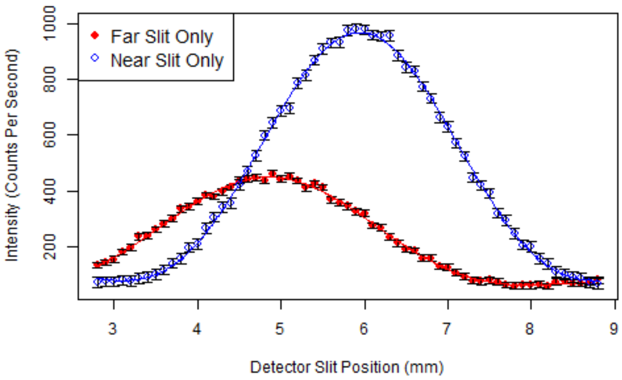

FIG. 5. Data-sets for single-photon (bulb) interference through two different single-slits. Eq. (7) is fitted to each. The fitting parameters for the far slit are $\lambda = 0.587 \pm 0.005$ μm, $I_0 = 1540 \pm 10$ counts/sec, $a = 0.0957 \pm 0.0007$ mm, $x_0 = 4.853 \pm 0.007$ mm, and $D = 64 \pm 2$ counts/sec. The fitting parameters for the near slit are $\lambda = 0.579 \pm 0.005$ μm, $I_0 = 3550 \pm 20$ counts/sec, $a = 0.1044 \pm 0.0006$ mm, $x_0 = 5.943 \pm 0.005$ mm, and $D = 80 \pm 4$ counts/sec. I_0 in both of these is the central intensity that the double slit would produce, not the central intensity of the single slit pattern. The single slit max intensity is about $\frac{1}{4}I_0$. Error in x translates to error in y, so only vertical error bars are shown.

slit open, the central max position is at 4.910 ± 0.001 mm, with $I_0 = 460 \pm 20$ counts/sec. These data-sets and their fits are shown in Fig. 5. We would expect these two data-sets to have similar max intensities, but they were taken using a different bulb, since the bulb burned out in between data collections. The new bulb had a central intensity about 9 times as much as the old bulb, and this shows in the plot. The purpose of this plot is to show the offset in x_0 between the two sets, and how this offset is nearly equal to the slit separation, a.

These figures and calculated fitting parameters make sense in all four cases. When the photons are free to go through both slits in the double-slit cases, they interfere with each other and themselves to form an interference pattern, with a measurable wavelength. If we block one of the slits, the apparatus reduces to a single-slit device, and we see a single-slit diffraction pattern on the detector. This is still an interference pattern, but with Δx much bigger than in the double-slit cases. This makes only one curve appear in our case, but on a wider detector we would see oscillation. These results fall in line with Young's experiments [2] and make physical sense.

V. CONCLUSIONS

This experiment successfully demonstrated that light will travel as a wave, even when only one photon is present. As Young did in his time, we demonstrated that a beam of many photons creates an interference pattern on a detector after passing through a double-slit, and we also showed that sending one photon at a time through the double-slit produces the same pattern, which disappears if one of the two slits is blocked. When one slit is covered, the apparatus reduces to a single-slit diffraction, showing an interference pattern with fringes so much smaller than the double-slit's as to be nearly indistinguishable.

Our experimental results were limited by the amount of data we were able to take. The PMT would give better data if we could take many more measurements and calculate the average for every position of the detector slit. This research can, in the future, help to identify other quantum-mechanical phenomena related to optics and the nature of light.

[1] R. A. Serway, *Physics for Scientists & Engineers (3rd ed.)* p. 1150, (Cengage Learning, 1990).

[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).