Two-Slit Interference, One Photon at a Time

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Abstract

An incandescent light source ($\lambda = 546 \pm 5$ nm) and a laser light source ($\lambda = 670 \pm 10$ nm) both underwent single and double slit interference. The incandescent light had a low enough intensity to ensure single photons were going down the chamber. Both light sources showed interference patterns consistent with that predicted by Fraunhofer diffraction, showed through the fit values of slit separation and slit width being close to the measured values. These results show that even single quanta of light have wave-like qualities.

1 Introduction

From Einstein to Newton, great physicists have contemplated the nature of light: is it a particle, or is it a wave? This so-called *particle-wave duality* has been debated for some time and finally accepted with Einstein's 1921 Nobel Prize in physics that explained the photoelectric effect through the quanitization of light [1].

This experiment primarily explores the wave-like properties of light through classic single- and double-slit interference. Both a laser light source ($\lambda = 670 \pm 10$ nm) and a filtered incandescent light source ($\lambda = 546 \pm 5$ nm) underwent single and double-slit interference show show light's wave-like properties. Interference is predicted to follow Fraunhofer diffraction [2]:

$$I(\theta) = I_0 \left[\frac{\sin(\Phi/2)}{\Phi/2} \right]^2 \cos^2(\Delta\phi/2) \qquad (1)$$

Where: $\Phi = kD\sin(\theta)$ and $\Delta\phi = kd\sin(\theta)$, with D being the slit width, d the slit separation, and $k = \frac{2\pi}{\lambda}$. It should be noted that for single slit interference, d = 0, and so the cosine term goes to 1.

These interference patterns are often explained as light traveling as a wave and interacting with itself to create constructive and destructive interference. This theory of interference of multiple photons can be investigated by performing double and single slit interference with a laser, which provides enough intensity to ensure multiple photons are emitted at a time that could interfere with one another.

The question then arises: are these interference patterns still observed when only one photon is sent down the chamber? Single photon emission guarantees at least some particle-like properties due to quantization, so will the interference patterns still be observed? If they are, then these patterns must not be explained by photons interfering with other photons, but by the photon interfering with itself. This can only be possible if the individual photon is acting as a wave that propagates through the chamber. If it was acting entirely as a particle, it could never interact with itself in the same way.

2 Experimental Set-up

A diagram of the experimental set-up is shown in figure 1. The source was aligned such that the coherent beam of light would go through an initial slit to spread out the light, then through a 1 cm^2 hole, and then through the double slits. The double slit had the following characteristics: $d_{right} = 0.096 \pm 0.005mm, d_{left} = 0.112 \pm 0.005mm, D = 0.393 \pm 0.005mm$.

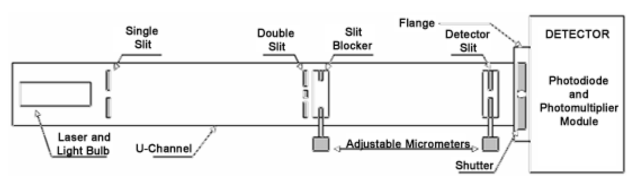

Figure 1: A diagram of the set-up used to achieve double and single slit diffraction with both light sources. Figure taken from the Advanced Lab Manual [2].

Just after the double slit is a slit blocker. This is adjustable via a micrometer, allowing for the left slit, the right slit, both slits, or no slits to pass light through to the detector. Once a light source is aligned, the positions of all of these configurations are recorded for repeatability.

After the double slits and slit blocker, the beam traveled an additional 50. cm before reaching a detector slit ($D = 0.183mm \pm 0.005mm$). The detector slit position is adjustable, attached to a micrometer, and can scan across the wall that the diffracted beam displays onto.

The experiment started by looking at the interference pattern of laser light. For the laser, the intensity was measured by a photo-diode, which produces a current that is proportional to the intensity of light detected, that is then converted to a voltage. This voltage is output to terminals on the back of the detector module, and thus this voltage is used as a proxy for intensity of light. The photodiode and subsequent amplification circuitry ensures $8.8 * 10^6$ V/W of incoming optical power [2]. The detector slit is then scanned across the wall to record the distribution of intensities across the detector. The measured voltage is stable due to the high intensity, so only one measurement per position is needed.

The incandescent light source is then investigated. The alignment procedure is the same as before, and a green filter is placed over the bulb to attenuate the light and ensure the previously mentioned range of wavelengths. The detector is now a photo-multiplier tube (PMT), allowing a count of individual photons. Rate of arrival is measured, sampling the amount of photons arriving in 10 seconds. The count is not stable and is subject to Poisson statistics, so three measurements per position of the detector slit are taken. Although the photomultiplier is not 100% quantum efficient (close to 4 % for green light [2]), the count still acts as a good proxy for intensity, as the count measured is proportional to the actual count at the detector.

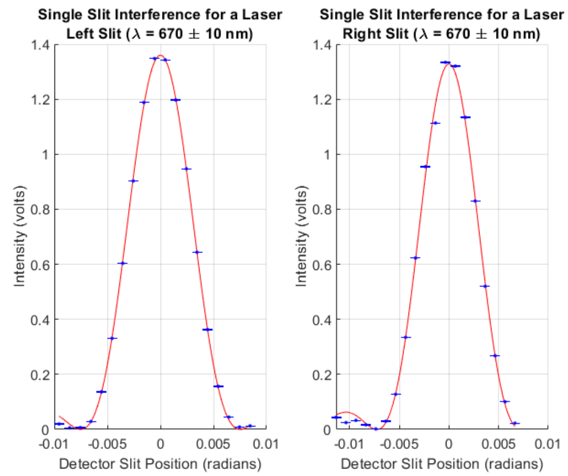

Figure 2: Data taken for double slit interference (blue) and its (red) for a laser light source. It should be noted that troughs do not reach zero due to the detector slit having a finite width.

3 Data Acquisition and Analysis

The laser source had data recorded with two single-slit diffraction patterns (left slit or right slit showing) in which the detector slit was moved from 0.00 to 9.00 $\pm$0.005mm in steps of 0.5 ± 0.005 mm. Data was also recorded when both slits were unblocked in steps of 0.5 ± 0.005 mm, from 0.00 to 9.00 $\pm$0.005 mm. Results are shown below in figures 2 and 3.

Similarly, the incandescent source had data recorded with two single-slit diffraction patterns (left slit or right slit showing) in which the detector slit was moved from 0.00 to 8.75 $\pm$0.005mm in steps of 0.25 ± 0.005 mm. Data was also recorded when both slits were unblocked in steps of 0.5 ± 0.005 mm, from 0.00 to 8.75 $\pm$0.005 mm. Results are shown below in figures 4 and 5.

Throughout data acquisition for both light sources, the background intensity was measured by noting the proxy for intensity when both slits were blocked. This was background noise was subtracted from measurements made.

Data was fitted according to interference predicted from

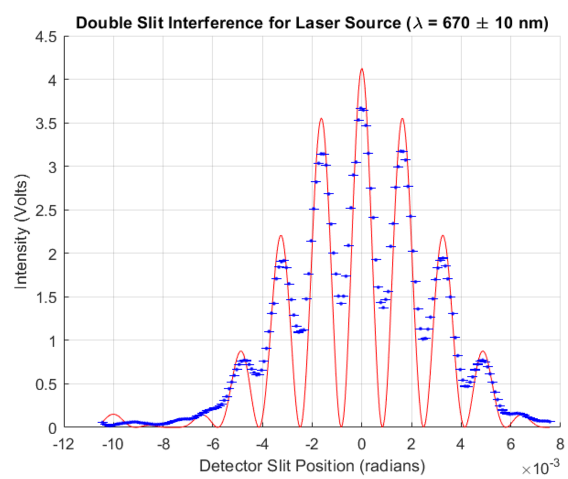

Figure 3: Data taken for double slit interference (blue) and its (red) for a laser light source.

Paramter	**Expected value**	Single Right Slit **Fit Value**	Single Left Slit **Fit Value**	Double Slit **Fit Value**
D (left, mm)	0.096 ± 0.0005	–	0.08915 ± 0.0002	–
D (right, mm)	0.112 ± 0.0005	0.09244 ± 0.0002	–	–
Avg. D (mm)	0.104 ± 0.0005	–	–	$0.08618 \pm 3 * 10^{-9}$
d (mm)	0.393 ± 0.0005	–	–	$0.4045 \pm 2.5 * 10^{-9}$

Table 1: Expected measured values of $k, d_{left}, d_{right}, avg.d, D$ and the values that the non-linear fit function gave for the laser light source. It should be noted the match of the double slit parameters due to the finite detector slit width causing the data to fit poorly.

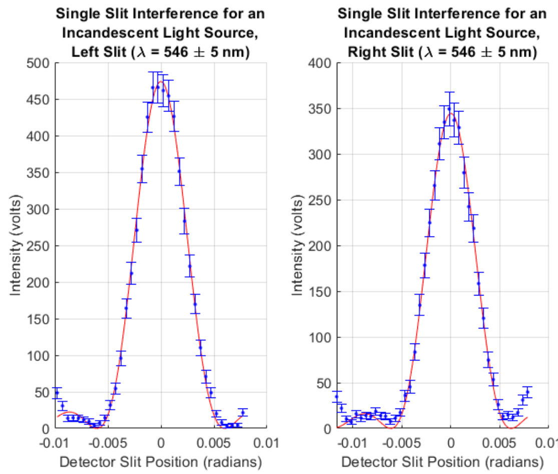

Figure 4: Data taken for double slit interference (blue) and its fit (red) for a incandescent light source. It should be noted that troughs do not reach zero due partially to the detector slit having a finite width.

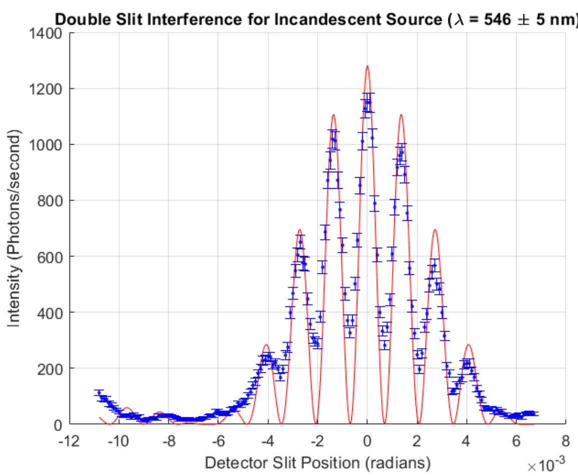

Figure 5: Data taken for double slit interference (blue) and its fit (red) for a incandescent light source.

equation 1. Even though there are no free parameters, the following parameters were fit for: width of slits, distance between slits, and maximum intensity. Results comparing the fit values to the expected parameters are shown in tables 2 and 1. If Fraunhofer diffraction is a good theory, then the fit parameters should return the same expected parameters, as well as fitting the data as expected.

4 Conclusions

Single photon emission of the incandescent source can be verified now that experimental data has been collected. The fit function for all incandescent light sources were integrated and then scaled with the slit width to obtain the rate of photons. The maximum rate of emission was for the double slits, with $1,064$ photons going through chamber every 10 seconds, which means a photon goes through to 50cm chamber every $9.398 * 10^{-3}$ seconds. If this is only 4 % of the actual count due to the PMT's quantum efficiency, then a photon goes down the chamber every $376 * 10^{-6}$ seconds. A photon going at the speed of light takes $1.66 * 10^{-9}$ seconds to traverse 50cm, which is roughly five orders of magnitude less time than the rate of photon emission. It can therefore be confirmed that individual photons are traveling down the chamber.

Looking at tables 2 and 1, as well as all above figures showing the fitted diffraction patterns, most expected diffraction patterns fit extremely well with the data. The exception is the double slit experiments, specifically matching the troughs of the experiment to that of the predicted pattern.

The single slit diffraction patterns across light sources match extremely well both graphically and in confirming the parameters of the experiment; all values are within agreement. The double slits graphs agree qualitatively with the fitted equations, although the fitted parameters aren't always in agreement. This is likely due to the uncertainty in slit widths being attributed to the precision of the instrumentation, when multiple measurements should have been taken so a standard deviation could be used as the uncertainty.

It should be noted that the double slit results have

Parameter	**Expected value**	Single Right Slit **Fit Value**	Single Left Slit **Fit Value**	Double Slit **Fit Value**
D (left, mm)	0.096 ± 0.0005	–	0.08821 ± 0.00069	–
D (right, mm)	0.112 ± 0.0005	0.08862 ± 0.00082	–	–
Avg. D (mm)	0.104 ± 0.0005	–	–	0.08279 ± 0.00025
d (mm)	0.393 ± 0.0005	–	–	0.3943 ± 0.0003

Table 2: Expected measured values of $k, d_{left}, d_{right}, avg.d, D$ and the values that the non-linear fit function gave for the incandescent light source. It should be noted the match of the double slit parameters due to the finite detector slit width causing the data to fit poorly.

troughs that do not go to zero intensity, as predicted by interference, and the fit parameters are poor. This is a result of the detector having finite width; it samples not just a the exact, infinitesimal position of interest, but also the surrounding positions, meaning each point sampled has contributions from surrounding points in the measured intensity value. This results in a poor fit graphically and poor agreement to the measured parameters. A thinner detector slit could have been used to get results that fit Fraunhofer diffraction better.

Overall, these results give merit to Fraunhofer diffraction being a good model for interference, and shows that light is behaving as wave when propagating through these slits. The fact that the theory held for the incandescent source emitting individual photons is strong evidence that even quanta of light have wave-like behavior.

But, within this experiment is evidence that light has particle-like behavior. The PMT counter relies on the assumption that light arrives in quantized packets, and are therefore able to the individually counted like a particle. The PMT also relies on the photoelectric effect to produce a cascade of electrons for each photon, another particle-like behavior of light. This experiment therefore gives credit that light is neither a particle nor a wave, but has properties of both, as captured in the concept of particle-wave duality.

This concept of duality is needed in order to explain many phenomena.The photoelectric effect is only explainable if light is acting as a particle, just like interference, diffraction, and polarization are phenomena that are only explainable if light is a wave.

References

[1] The nobel prize in physics 1921. *NobelPrize.org*, 2019.

[2] HWS Physics. *Advanced Laboratory Manual*. Hobart and William Smith Colleges, 2019.