Single Photon Two Slit Interference

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In this paper, we investigate the double-slit interference patterns produced by single photons. Results were attained using a Teachspin apparatus equipped with a low-intensity light source to ensure that individual photons passed through the slits, thus, ruling out classical wave interference. The resultant interference pattern serves to illustrate theoretical predictions of wave-particle duality and emphasizes the probabilistic interpretations of quantum mechanics.

I. INTRODUCTION

Interference patterns are phenomena produced by the superposition of wave-like systems with themselves or other wave-like systems. So characteristic is superposition and the interference patterns it produces to wave-like phenomena that a system's exhibition of interference patterns is often taken as proof of its wave-like qualities. This investigation is oriented towards the observation of two-slit interference patterns for two key scenarios. First, in a classical context, we observe interference patterns produced by the electromagnetic waves emitted by a laser within the TeachSpin apparatus. Second, we investigate the quantum regime by recording interference patterns formed by single photons through the double slit apparatus, a scenario that would not be expected to yield any type of interference pattern according to classical principles.

As aforementioned, a system's exhibition of superposition and interference patterns is customarily taken as sufficient evidence for a system's wave-like characteristics. Because of this, photons' and electrons' exhibition of probabilistic interference patterns served as a validation of quantum mechanics and its description of particles with probabilistic wavefunctions.

A. Double Slit Interference

One of the fundamental properties of waves is their ability to superimpose with one another. The existence of two or more waveforms at any given point results not in the observation of two separate waveforms but rather the observation of a single waveform produced by the combination/superposition of the two or more waveforms. Because waves have the ability to superimpose with one another, the presence of two or more waves within the same region can lead to interesting patterns as they interact/interfere. Through slight modifications, a system can be made to produce various interference patterns. The double-slit interference pattern is a commonly utilized interference pattern produced by the direction of a wave-emitting source, taken to be infinitely far from the slits in order to ensure the parallel propagation of the waves through the slits, upon a lens composed of two slits (Figure [1]).

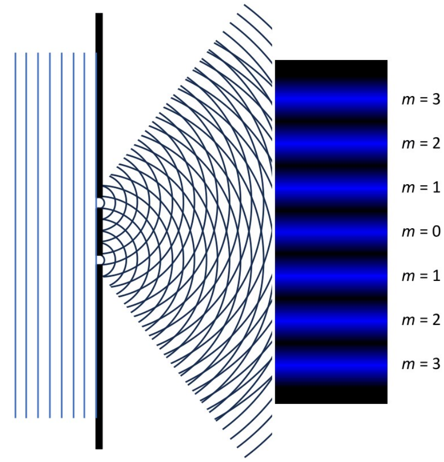

FIG. 1. Illustration of the double slit experiment, displaying the diffraction of parallel propagating waves through a double slit aperture and the resultant intensity pattern. Included in the figure are labels of the central and the first three maxima. Figure from ref[1].

The parallel propagating waves from the source that encounter the slits and are not reflected back towards infinity, diffract as they pass through the slit, giving rise to the conical wave patterns seen in Figure [1]. Because the waves are no longer parallel propagating, they interfere and superimpose. Regions in which the waveforms from the two conical sections interfere constructively give rise to a higher observed intensity, and regions in which the waveforms interfere destructively are observed as regions with low intensity or even no intensity. It is the contrast between these low and high-intensity regions that gives rise to the characteristic double-slit interference pattern.

II. EXPERIMENT

In order to examine both the classical example of double-slit interference utilizing a continuous flow of photons and the probabilistic interference pattern created by photons traveling through the slits individually the TeachSpin apparatus is equipped with both a red laser of an intensity sufficient to ensure a fairly continuous flow of photons through both slits and a low intensity green filtered light bulb. Because the light bulb emits a relatively low number of photons per second and these photons traverse the distance to the detector so quickly it is a great approximation to assume they transmit through the slits one at a time. Interference patterns produced by the case where numerous photons are allowed to pass through the slits at any given time, allowing for the interference and interaction of individual photons with others, correspond fairly well to other physical instances of wave phenomena – the interaction of water molecules within a body of water for example – and thus classical intuitions. However, with phenomena like Compton scattering supporting the characterization of photons as particles, classical mechanics predict no sort of interference pattern for the instance of single photon transmission through the slits, with nothing to interact with it would seem no interference pattern should arise. And following the observation of a small amount of individual photons through the slits it appears no pattern arises, rather a scattered collection of single photon detections. However, following numerous repetitions of single photon transmission, an interference pattern composed of photon detections develops, Figure [2].

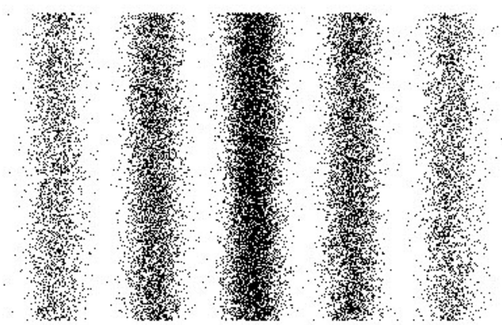

FIG. 2. Single photon interference pattern following numerous photon transmissions. The interference pattern is given by photons' tendency towards certain regions of the detector, the maxima. Figure from ref[2]

In the absence of any other particles, the only explanation for single photon interference patterns is that photons must interact with themselves in some way. Quantum theory's description of particles with probabilistic wavefunctions aligns perfectly with the observed phenomena and quickly adopted it as supportive evidence.

III. EXPERIMENTAL OVERVIEW

As mentioned in section II, our investigation will be divided into two observations. Out first experiment is directed towards the observation of classical double slit interference, utilizing the continuous flow of photons generated by the TeachSpin apparatus, shown below, and our second is the observation of single photon interference patterns, using the apparatus' low intensity light bulb. Procedures of light-source alignment are identical in both investigations, consisting of slight adjustments to the positions of the light sources and slits. Data will also be collected by taking readings of the effective intensity of light at various detector positions, reached through adjustments to the detector slit micrometer (as seen in Figure 3), in both investigations. However, the method used to obtain these effective intensities in each investigation is slightly different. In the classical observation, the effective intensity of light is obtained by observing the voltage generated by a photo-diode composed of an operational amplifier and a resistive element. When light is directed upon the photo-diode, the circuit generates a given voltage; as the intensity of the light grows, so does the voltage generated. The voltage generated by the photo-diode's interaction with the laser's photons acts as the effective intensity of light at a given location, as displayed in Figure [4]. Because the individual photons emitted from the light bulb generate significantly less effective power to the detectors than the continuous flow of photons generated by the laser, the second investigation utilizes a photomultiplier tube (PMT) instead of a photo-diode as a detector. When photons interact with the photomultiplier tube, their signal is amplified and input to a pulse counter. By varying the discrimination amplitude of the pulse counter, investigators can dictate the minimum signal amplitude required for the pulse counter to register a photon. Data collected for any discrimination amplitude will be fairly accurate provided the discrimination amplitude is well over the amplitude of electronic noise generated within the circuit. It is the number of photon counts within a given time (1 second in our observation) that serves as the effective intensity of light in the second investigation, as displayed in Figure [5].

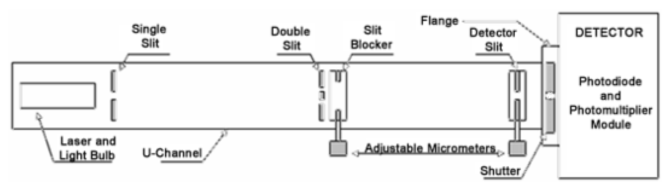

FIG. 3. TeachSPin interference apparatus. Light travels is emitted by either the laser or bulb source before traveling through the U-channel, first through a double slit aperture before reaching the movable detector slit on the far end of the apparatus. By adjusting the apparatus's micrometers, we can move the detector slit along the width of the channel; allowing for us to measure the intensity/photon counts as a function of position and construct a spacial interference pattern. Figure from ref[3].

IV. RESULTS AND ANALYSIS

We obtained interference patterns for both classical and quantum regimes using the TeachSpin two-slit interference apparatus. The classical interference data were acquired using a coherent red laser source, while the single photon regime was explored using a low-intensity green-filtered light bulb. The results for each regime are summarized in Figures 4 and 5.

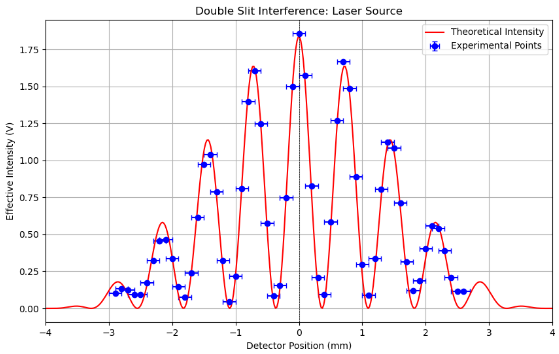

FIG. 4. Double-slit interference pattern using a continuous flow of photons/laser source. Experimental data (blue) represents photodiode voltage as a function of detector position. The red line shows the theoretical prediction according to equation 2 and the known slit width ($a = 0.0855mm$), slit separation ($d = 0.457mm$), slit and detector separation ($L = 497 \pm 1mm$), and laser wavelength ($\lambda = 670 \pm 5nm$). Error bars correspond to instrumental precision ($\pm 0.01mm$ and $\pm 0.001V$).

Figure 4 shows the classical interference pattern obtained from the continuous light source (laser). The intensity profile reveals well-defined peaks and troughs, characteristic of constructive and destructive interference. The theoretical prediction is based on the interference-diffraction model for two slits of finite width given by ref [4] to be:

$$I(\theta) = I_0 \left(\frac{\sin \Phi}{\Phi} \right)^2 \cos^2 \left(\frac{\Delta\Phi}{2} \right), \quad (1)$$

$\Phi = \frac{\pi a \sin \theta}{\lambda}$ accounts for single-slit diffraction and $\Delta\Phi = \frac{2\pi d \sin \theta}{\lambda}$ accounts for two-slit interference, where: θ represents the angle of diffraction of light through the double-slit, a is slit width given to be 0.0855 mm, d is slit separation given to be 0.457 mm, and λ is wavelength given to be $\lambda = 670 \pm 5nm$ (laser) and $\lambda \approx 545nm$ (bulb) with λ dependent on the source used.

Assuming small angles of diffraction ($\theta \approx 0$), we apply the approximation $\sin \theta \approx x/L$, where x is the detector's position relative to the central maximum and L is the distance from the slits to the detector, measured to be 497 ± 1 mm. Substituting this into Equation 1, the intensity as a function of detector position becomes:

$$I(x) = I_0 \left(\frac{\sin \beta}{\beta} \right)^2 \cos^2 \left(\frac{\pi d x}{\lambda L} \right), \quad (2)$$

With the substitution:

$$\beta = \frac{\pi a x}{\lambda L}$$

This equation models the observed intensity pattern across the detector as a product of single-slit diffraction (the envelope) and two-slit interference (the oscillatory term). Overall, as visualized in figures 4 and 5, the theoretical curve provided by equation 2 fits the observed pattern well, with slight deviations in fringe intensity possibly arising from detector alignment errors or imperfections in the slit fabrication.

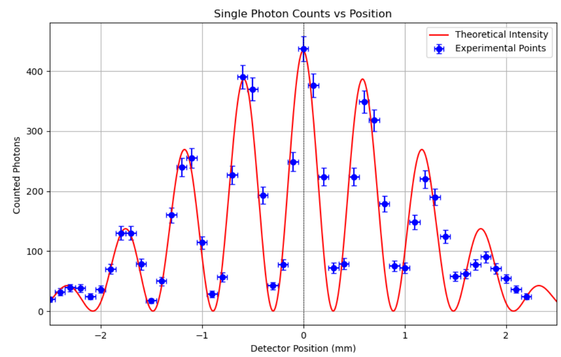

FIG. 5. Single photon interference pattern using a low-intensity bulb source. Photon count per second is plotted against detector position. Vertical error bars represent the square root of counts at a given location and horizontal error bars represent uncertainty according to measurement precision ($\pm 0.01mm$). The red curve represents the theoretical prediction according to equation 2 and the known slit width $a = 0.0855mm$), slit separation ($d = 0.457mm$), slit and detector separation ($L = 497 \pm 1mm$), and bulb wavelength ($\lambda \approx 545nm$).

In contrast, Figure 5 presents the interference pattern obtained from the single photon regime. At low intensities, photons passed through the slits individually, yet over time, a statistically significant interference pattern emerged. This result aligns remarkably well with the theoretical prediction, reinforcing the quantum mechanical interpretation of photons as entities with probabilistic wavefunctions that can interfere with themselves.

The photon count at each position refers to the number of observed photons over 1-second intervals. The vertical error bars represent Poisson uncertainties, given by $\sqrt{N}$, where N is the photon count per second. The central fringes matched the predicted maxima well, while some asymmetries at the outer edges likely stem from fluctuations in the bulb's output or slight shifts in alignment during measurement.

These results vividly demonstrate the wave-particle duality of light. Even when photons arrive one at a time, their cumulative behavior produces an interference pattern consistent with classical wave interference, revealing the quantum nature of light.

V. ERROR ANALYSIS

In this investigation, uncertainties within the measurements of voltage, photon counts, and measurements of distance serve as the primary sources of error. Because no regressions were used to display data and no equations were used to process measurements, no error propagation is necessary. Rather, all data points possess uncertainty according to the precision of the instruments. All measurements of distance were taken using a micrometer screw drive included in the TeachSpin apparatus and with divisions up to $0.01mm$ giving an uncertainty of $\pm0.01mm$ to all measurements of distance. Measurements of voltage used to determine the effective intensity of light in the first observation were taken using a digital multimeter with precision up to single millivolts, providing an uncertainty of $\pm1.0mV$ to all measurements of voltage. As outlined in Section III, the relative light intensity used to construct Figure 5 was attained using a pulse counter. However, there is a slight variance in the number of pulses recorded by the counter at any given location. To account for the variance in registered counts, an uncertainty of $\sigma_N = \sqrt{N}$, where N is the number of photon counts observed at a position, is attached to all measurements of photon counts. The use of Poisson's uncertainty for our second investigation accounts for the reduced vertical uncertainty for lower count data points.

VI. CONCLUSIONS

This study provides a clear comparison of double-slit interference in two cases: a classical scenario with a continuous flow of photons and a seemingly contradictory case using individual photons. In both cases, excellent agreement with theoretical predictions was observed. The observation of interference patterns generated by single particles is a powerful testament to the validity of quantum mechanics's description of particles using probabilistic wavefunctions. Were this description ineffective and particles were to behave entirely as dictated by classical mechanics, photons would have no way to interact with the experimental configuration and a random distribution of photon counts should arise. However, described by wavefunctions that are defined at all points in space, photons gain the ability to interact with both slits and produce interference patterns.

Future investigations would benefit from higher precision instruments, thus reducing uncertainty within measurements of voltage and distance, and from ensuring a light bulb source of constant luminosity. Whereas the laser seemed to maintain a fairly constant luminosity, leading to almost no variance in measurements of voltage at a given location, photon counts at a given location varied noticeably. This variance is certainly linked to the probabilistic nature of photons, however, any improvements made to the consistency of the bulb's luminosity would reduce variance in measurements.

[1] Oregon State University, Double-slit experiment diagram (n.d.), accessed: March 17, 2025.

[2] Brilliant Light Power, Double slit experiment image (n.d.), accessed: 2025-03-23.

[3] D. V. Baak and S. Penn, Two-slit interference, one photon at a time.

[4] OpenStax, Mathematics of interference (2025), accessed: 2025-04-10.