Particle-Wave Duality and “Which-Way” Information

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Abstract – Samantha To

This experiment aimed to support particle-wave duality with the Young’s double slit experiment and the “which-way” information through Mach-Zehnder Interferometer. This was done with a collimated laser beam of 0.62 μW aimed at a double slit with a slit width of 10 μm and slit separation of 90 μm. An interference pattern was seen with an EM-CCD camera at the Fraunhofer zone. The visibility of the interference pattern supports the particle-wave duality of photons. Similarly for the Mach-Zehnder Interferometer, a collimated laser beam of 87 μW was split to form two beam of perpendicular polarization and then recombined with a polarizer to show the “which-way” information of the photon. Both parts of the experiment has enlightened the theory of light with the particle-wave duality and “which-way” information.

I. Introduction – Graham Jensen

We present the results of a recreation of Young’s double slit experiment using single photons as well as an experiment demonstrating the effect of “which-way” information measurement. Young’s double slit experiment with single photons is performed to determine if individual photons self-interfere and produce wave-like interference fringes after sufficient counts. In Young’s setup, light propagates through a pair of parallel rectangular slits resulting in an interference pattern observed on a screen a distance away. By attenuating the light to the level where only one photon on average is traveling through the apparatus at a time, the interference property of individual photons is determined. If two intensity maxima are recorded in the paths of the slits, photons demonstrate particle-like behavior. Conversely, if an interference pattern emerges, individual photons are self-interfering and a wave-particle duality of light is revealed. This experiment is investigated and the results are compared with previous observations.

The effect of “which-way” information measurement is the cornerstone of the Copenhagen interpretation of quantum mechanics. According to this philosophy, the state of a system is described by its probability wavefunction and lacks definite position or momentum until a measurement is performed. Measurement of a system causes a collapse of its wavefunction forcing the system to take a stance. An experiment to examine the effect of “which-way” information measurement is performed utilizing a Mach-Zehnder interferometer. The setup consists of a laser beam incident on a polarizing beam splitter. As the light interacts with the beam splitter, two beams with orthogonal polarizations are created. When the beams are recombined at a non-polarizing beam splitter they are directed toward a variable polarizer. This polarizer is adjusted to go through 200 degrees of relative polarization and the resulting beam is recorded by an EM-CCD camera. If the variable polarizer is at a polarization of forty-five degrees between the two beams, the light propagating through the polarizer maintains an uncertain origin. If the variable polarizer is closer in angle to one of the beams, the majority of the light recorded
by the EM-CCD camera is known to be from one beam. If the interference pattern depends on the angle of polarization, then, in agreement with the Copenhagen interpretation, knowledge of “which-way” information collapses the wave function. This experiment is performed and the results are compared with expected observations.

II. Theory – Samantha To

The identification of light has always fascinated scientists. This debate can be rooted to Aristotle who believed that light was a wave-like disturbance of air and Democritus who argued that light was in the form of a solar atom. In 1678, Christiaan Huygens proposed a wave theory of light that explained interference patterns and wavefronts that propagated in straight lines. However, this wave theory had many shortcomings and was later undermined by Isaac Newton’s corpuscular theory of light in his 1704 book called “Opticks”. While Newton’s particle theory solved many of Huygen’s weaknesses such as reflection, it also failed to produce a complete model of light.3

In the 20th century, several experiments showed conflicting conclusions on the identification of light through the use of an interferometer. An interferometry is an experimental technique that relies on the superposition of waves to provide a meaningful result. In the case of single photon behavior in the Young’s Interferometer and Mach-Zehnder Interferometer, the “which-way” measurement of a photon collapses the wave function and destroys the interference patterns on the optical screen. According to the Heisenberg Principle, there is no way we can determine with certainty both the momentum and position of a particle without destroying the interference patterns. The wave function of a particle supports the Heisenberg Principle with the use a probability function that is calculated by the integral of the square of the wave function. With the introduction of two different paths, the wave function will describe a superposition of both paths and create an interference pattern at the film. If, instead, “which-way” information is introduced and a method of determining which path the photon takes is available, then the wave functions collapse and the interference patterns disappear.

The Young’s experiment consists of a collimated laser beam and a barrier with two parallel slits. With the use of the particle theory of light, the collimated laser beam is attenuated with spatial filters to achieve approximately one photon per meter passing through the apparatus. If the particle theory provides a complete model of light, we would expect to see two parallel intensity maxima in the direct path of the laser beam as shown in Figure 1.2

![Fig1. This diagram shows the theoretical patterns on the optical screen if light behaved as a particle such as bullets.](image)
Fig 2. This diagram shows the theoretical patterns on the optical screen if light behaved as waves such as water.

If the light propagated like a wave instead, we would expect to see interference patterns on the optical screen as shown in Figure 2. With the use of geometry, we can calculate the distance on the optical screen between the central maxima and the nth local maxima in Figure 2 with the following equation:

$$z = \frac{n \lambda D}{d}$$

where $z$ is the distance between the central maxima and the nth local maxima, $D$ is the distance from the double slit barrier to the optical screen, $\lambda$ is the wavelength of the incoming laser beam and $d$ is the distance between the two slits.  

The Mach-Zehnder Interferometer Experiment relies on the light’s “which-way” information. A collimated beam is again attenuated with spatial filters to obtain single-photon intensity and then split with a polarizing beam splitter where one beam has a respective 90degree polarization and direction offset from the other. Both beams are redirected to and combined at a non-polarizing beam splitter and interference patterns are seen at both the Fresnel and Fraunhofer Diffraction. To show the “which-way” information, a polarizer is placed at the end of the apparatus immediately in front of the EM-CCD camera. When the polarizer is set to 45degrees, both wave functions are equally represented and infringement patterns are seen on the EM-CCD camera. When the polarizer is adjusted towards 0 or 90 degrees, we predict that the patterns would diminish in intensity as the wave function term of one beam has a higher value than the other.
III. Experimental Setup and Procedure – Graham Jensen

Setup

Fig 3. This diagram shows the basic set-up of the Mach-Zehnder Experiment. The Polarizer B and C were used only to confirm the vertical and horizontal polarization of each respective beam. One EM-CCD camera was used to record the intensity of the recombined laser beam.

Figure 3 illustrates the experimental setup utilized for data collection. 633nm light from a He-Ne laser is attenuated by a series of neutral density filters before reaching a spatial filter where the beam’s radius is increased. From here, the beam is split into two paths for use in two separate measurements. For the Young’s double slit experiment, the beam is again attenuated by a series of neutral density filters. The beam passes through the double slit and one more neutral density filter before reaching the EM-CCD camera (the final filter protects the sensitive camera from overexposure).

For the Mach-Zehnder setup, the beam first passes through an adjustable aperture used for controlling beam diameter. The beam then propagates through a series of neutral density filters before being polarized to 45 degrees by polarizer A. The now polarized beam is split by a polarizing beam splitter into a horizontally polarized and vertically polarized beam. The polarizers in the paths of each arm (polarizers B and C) ensure a correct polarization is achieved. After reflecting off mirrors the beams
are recombined at a non-polarizing beam splitter and the resulting beam passes through a variable polarizer (labeled above as polarizer D). This light is recorded by the EM-CCD camera.

**Experimental Procedure**

**Young’s Double Slit**

After assembling the setup shown in the section above, the power of the incident beam must be determined using a power meter. A beam power of $0.62 \mu W$ is measured at a wavelength of 633nm. From these values, the appropriate amount of attenuation needed to allow only one photon per meter can be determined using the following equation.

$$N = \frac{P\lambda}{hc^2}$$

Where $N$ is the number of photons per meter, $P$ is the power of the beam, $\lambda$ is the wavelength, $h$ is Planck’s constant, and $c$ is the speed of light. Applying this to our setup, we find a needed attenuation value of $\sim 10^{-4}$.

With the laser properly aligned and the appropriate attenuation applied, the EM-CCD camera may be safely operated. By attenuating the laser to only one photon per meter, the EM-CCD camera measures the results of single photons propagating through the double slit at once. The camera records the light incident on its detector with respect to position. By examining the data for an interference pattern, we may determine whether single photons self-interfere or not.

**Mach-Zehnder Interferometer**

As with Young’s double slit experiment, the needed attenuation of the beam must be determined. The power of the beam is found to be $87 \mu W$. By applying this result to the equation previously used, we find a necessary attenuation of $\sim 10^{-6}$.

The alignment of the Mach-Zehnder interferometer is a more laborious process than the alignment of Young’s double slit. For proper use of a Mach-Zehnder interferometer, the two orthogonally polarized arms need to be recombined at the non-polarizing beam splitter. The beams must overlap perfectly at the output of the beam splitter as well as a distance far away. To increase the precision of this process, a variable aperture is confined shrinking the beam size to a narrower diameter. Overlapping smaller beam spots result in a more precise alignment. When the beam spots overlap at these two points, a collinear beam is achieved and experimental procedures may begin.

Once properly aligned, a variable polarizer (labeled polarizer D in the setup schematic) is positioned at the output of the non-polarizing beam splitter and the EM-CCD camera is placed in the beam path. As with the Young’s double slit experiment, the EM-CCD camera records the light incident on the detector with respect to position. The variable polarizer is rotated 200 degrees in increments of 10 degrees with data collected at each increment. If “which-way” information knowledge affects light, we will see an interference pattern when the variable polarizer is 45 degrees between the polarization of each arm of the split beam, due to the uncertain origin of the detected light.

This data is analyzed by considering the visibility of the interference fringes with the following equation.

$$Fringe\ Visibility = \frac{l_{\text{max}} - l_{\text{min}}}{l_{\text{max}} + l_{\text{min}}}$$

Where $l_{\text{max}}$ is the maximum measured intensity and $l_{\text{min}}$ is the minimum. This provides a quantitative analysis of the interference pattern.
IV. Result – Samantha To

The Young’s double slit experiment sought to support the particle-wave duality with the presence of interference patterns as obtained by the EM-CCD camera. As calculated above, the necessary attenuation value of the filters needed to be of the order of 4. Thus, a larger attenuation value such as 5 would yield a photon per 10 meters. Figure 4 shows clear infringement patterns which support the particle-wave duality property of photons.

**Fig4.** Interference patterns of a single acquisition image as obtained with 4 orders attenuation, 0.5 sec acquisition time and 150 camera gain.

**Fig5.** Interference patterns as obtained with 4 orders attenuation captured with the EM-CCD camera for the acquisition time of 0.005 sec and 1 camera gain. The image on the right shows a single acquisition images while the image on the left is the accumulation of 10 acquisition images.

**Fig6.** Intensity graphs corresponding to the interference patterns in Figure 5.
Fig 7. Interference patterns as obtained with 6 orders attenuation captured with the EM-CCD camera with 255 camera gain. The image on the left shows a single acquisition image with an acquisition time of 0.005 sec while the image on the right is a single acquisition image with an acquisition time of 0.05 sec.

Fig 8. Intensity graphs corresponding to the interference patterns in Figure 7.

Figure 5 shows a comparison of a single acquisition image and an accumulation of 10 acquisition images of shorter run time and lower gain. We can see that the accumulation image shows the interference pattern more clearly than the single acquisition image as expected. As shown in Figure 7 above, a longer acquisition time yields a larger visibility value. Figures 6 and 8 reinforces the presence of the interference patterns in Figures 5 and 7.

Mach-Zehnder Interferometer supported the “which-way” information by producing a varying intensity dependent on the polarization immediately before the EM-CCD camera. The maximum fringe visibility is seen when the polarizer is at 45 degrees.
Fig 9. This set of images shows the interference patterns of the Mach-Zehnder Experiment with each respective corrected polarization.
As the polarizer changes towards 90 and 0 degrees, the infringement patterns become obscured and decrease in intensity. The above infringement patterns were obtained with 6 orders attenuation captured with the EM-CCD camera with 255 camera gain and an acquisition time of 0.1 sec.

V. Conclusion – Graham Jensen

The data collected in these experiments is in agreement with previous observations. The Young’s double slit experiment with single photons revealed the wave-particle duality of light by producing interference fringes even when only one photon propagated through the apparatus at a time. This is remarkable because single photons must be self-interfering as they pass through a double slit: a non-intuitive notion. The Mach-Zehnder interferometer experiment confirmed that knowledge of “which-way” information collapses light’s wavefunction and destroys its wave-like interference pattern.

A property of the data previously unmentioned is the dots on the Mach-Zehnder interferometer images. These imperfections are most likely caused by water droplets forming on the inside of the lens. This occurs because the -60 degree Celsius operating temperature of the CCD camera induces condensation. Another imperfection is observed on the Young’s double slit data. An intensity minima is observed at the center of the image where there theoretically should be a maxima. This is due to the use of a glass double slit rather than an air double slit setup. The reflected beams from the glass slits caused destructive interference at the center maxima. However, this imperfection did not prevent the confirmation of the wave-particle duality of light.

VI. Reference