Abstract
The goals for this experiment were to reproduce and demonstrate the wave-particle duality of light, and to observe the effect of obtaining “which path” information on the interference of two light beams in a Mach-Zehnder interferometer. Wave-particle duality was demonstrated by sending a HeNe laser beam (\(\lambda = 632.8\) nm) through Young’s double slit interferometer at different attenuation settings to test for wave-behavior dependence on beam intensity, wherein we found that the interference pattern remains apparent for attenuation of the beam to single-photons. In order to observe the relationship between gathering path information and the intensity of the interference, we redirected and split the same HeNe beam into two arms of orthogonally polarized light, recombined them, then tested for how collecting which path information affects interference. We found that the interference pattern diminishes as which path information is obtained.

I. Background & Theory

Before quantum theoretical descriptions of the behavior of light were developed, the nature of light was heavily debated by proponents of the corpuscular theory of light and by supporters of wave theory. The two most important contenders in this fight were Sir Isaac Newton, who supported the idea that light is corpuscular, and Christiaan Huygens, who produced significant evidence in favor of the wave theory of light (Mehra). Despite the fact that Huygens presented a sound argument via the Huygens-Fresnel principle, most physicists of the day supported corpuscular theory simply because Newton supported it.

In the early 19th century, Thomas Young published a series of lectures wherein he described his famous double-slit experiment, demonstrating that light shows interference patterns comparable to sound waves and water waves: “Supposing the light of any given colour to consist of undulations of a given breadth, or of a given frequency, it follows that these undulations must be liable to those effects which we have already examined in the case of the waves of water and the pulses of sound” (Young). Young’s evidence had a substantial impact on the debate, and is considered one of the most important experiments in the history of physics. This is the experiment that we wish to reproduce herein.

Figure 1: Thomas Young’s sketch of the diffraction of water waves as they propagate through a double slit. Letters C, D, E, and F denote positions on the back wall where deconstructive interference causes minimums to form.
After Young’s experiment, more evidence supporting the wave theory of light was brought forth by other scientists. Fresnel showed that polarization could occur only if light propagates as a wave, and Maxwell later demonstrated that light is an electromagnetic wave. Despite the fact that the wave theory of light seemingly had to be true, more evidence in favor of a particle theory of light arose. In 1905, Einstein published *On a Heuristic Viewpoint Concerning the Production and Transformation of Light*. In the paper, Einstein successfully applied Max Planck’s theory that energy can be ‘quantized’ to the ominous photoelectric effect earlier observed by Heinrich Hertz.

Einstein’s paper laid the foundation for the confirmation that light can behave like particles. This created a paradox; physicists had substantial experimental evidence that showed that light behaves like a wave, but they also had a substantial amount of experimental evidence showing that light behaves like a particle. This conceptual difficulty still has not been resolved. It has been made clear that light behaves both as a wave in some situations and as a particle in other situations, which is the basis for the modern description of light as having wave-particle duality.

The fact that the character of light changes as conditions of the environment change is in itself a property of light that we wish to explore using the Mach-Zehnder interferometer (MZI). The MZI is used to try to determine ‘which path’ information about a system of interfering beams of light with orthogonal polarizations. According to quantum theory, attempting to determine the path of light waves collapses the associated wave function that describes the wave-behavior of the beam, which causes the light to start behaving like a beam of particles. We show in this experiment that as we attempt to investigate which path light is taking, the wave-nature of the system diminishes.

An effective method for determining this is to find the fringe visibility of the interference patterns we produced over the course of the experiment. Fringe visibility is described mathematically by the relation

$$\text{Visibility} = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}} \quad \text{(Equation 1)}$$

where $I_{\text{max}}$ and $I_{\text{min}}$ denote the maximum and minimum intensities of the fringe pattern, and visibility is a dimensionless number that indicates how much contrast there is between the maxima and minima of the interference pattern. This report does not make use of equation 1, though, because the concept of fringe visibility is intuitive enough that we can infer the relative fringe visibilities of given patterns simply by observing the contrast between fringes.

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1 This is not the most general definition of fringe visibility, but it is sufficient enough to carry us through this experiment.

2 Checked for by placing a piece of paper (or some other material) in the path of the recombined beam at
II. Experimental Setup

![Experimental Setup Diagram]

**Figure 2**: Diagram of the experimental setup. Both interferometers (Young’s and Mach-Zehnder) are represented in this diagram. The first three components of the diagram (Laser, first set of ND Filters, and Spatial filter) are components of both interferometer setups. At the first non-polarizing beam splitter (NPBS 1), the beam is split into two paths. The beam that continues through the NPBS 1 (horizontal beam) is attenuated and directed to the double-slit interferometer, and the beam that gets redirected (vertical beam) is routed into the Mach-Zehnder interferometry setup. The EM-CCD cameras shown at the end of each path are two representations of the same camera that we move as we conduct each experiment. The laser is a 5mW, Helium-Neon laser with wavelength 632.8 nanometers. The PBS component is a polarizing beam splitter that separates the beam into two arms with orthogonal polarizations. The arms are then recombined at NPBS 2 and are tested for interference.
III. Procedure & Results

1. Alignment
   a. Place the power meter in the path of the laser following the spatial filter and adjust the spatial filter until max power is found.
   b. Mach-Zehnder interferometer – Alignment is accomplished by adjusting the mirrors (Figure 2) until the arms are collinear. First, adjust the spatial filter so that the beam width is minimalized. If the setup is correctly calibrated, the output, recombined beam should only show one dot of light near to and far from the position where the EM-CCD camera will be placed. If two dots are apparent at some position, the beams are intersecting somewhere, but are not collinear. After the beams are found to be collinear, reset the spatial filter to the appropriate beam width.
   c. Double-slit interferometer – The most convenient way to check for alignment is to put the double-slit in the path of the laser in order to check for fringe visibility. Adjust the position of the double-slit until a maximum fringe visibility is found.

2. Testing for Particle Behavior – The light must be attenuated to single-photon levels so that the camera may obtain granular images. This is achieved by placing Neutral Density Filters (Figure 2, ND Filters) in the path of the beam at positions to be determined based on the conditions the experimenter wants to test. In order to attenuate the beam to a near single-photon level, the order of magnitude of filtration must be calculated using the relation

\[ \frac{N}{d} = \frac{P\lambda}{hc^2} \]

Where \( \frac{N}{d} \) represents the number of photons \( N \) per some distance \( d \); \( P \) is the power of the laser, \( \lambda \) is the wavelength, \( h \) is Planck’s constant, and \( c \) is the speed of light. In order to get approximately one photon per meter, the power needs to be adjusted so that \( N/d = 1 \) if \( d = 1 \) meter.

3. Spatial Filter – The spatial filter’s purpose is to ‘clean’ and collimate the beam. It consists of a microscope objective, aperture, and lens.

4. After the beam goes through the spatial filter, it is split into two beams by the first NPBS. The transmitted beam is used for the double-slit experiment and the reflected beam is used for the Mach-Zehnder experiment.

Mach-Zehnder Procedure and Results

1. Polarizer rotation and ‘Which Path’ Information – This part of the experiment doesn’t actually require step 2, as single photons are not necessary for observing the affect of which path information on interference intensity. Assuming that the setup is

\[^2\] Checked for by placing a piece of paper (or some other material) in the path of the recombined beam at different distances from Polarizer B
\[^3\] It is also important to make sure that Polarizer B is not permitting one of the beams to transmit. This would make the system seem properly aligned
aligned and the camera is placed correctly, we set Polarizer B to 45° and made sure that an interference pattern is produced with high fringe visibility. We then took images of the resulting recombined beam at different angles for Polarizer B in increments of 10° from 0° to 360°, obtaining the images shown in figure 3. The results confirm that obtaining which path information destroys our ability to detect wave behavior. When Polarizer B is set to 45 degrees, both arms are transmitted, which causes the interference pattern, and does not allow us to extrapolate ‘which path’ information about the system. As we rotate the polarizer in order to make the path known, the wave behavior diminishes. At 0° and 90°, the interference pattern completely vanishes, but we know exactly which path the light took.

2. **Single Photon Interference** – This part of the experiment requires different attenuations of the beam all the way to the single photon level in order to observe the affect of beam attenuation on fringe visibility and interference. We took images of the recombined beam with combinations of different attenuation, polarizer, and camera settings, and we found that increasing the number of accumulations increases fringe visibility, implying that the detector is accumulating single photons. We also found that the production of fringes is not affected by attenuation to the single photon level, which is proof of wave particle duality.

![Figure 3: Dependence of interference intensity on polarizer rotation. The top left image is the result of Polarizer B being set to 0°. Each image after that, from left to right, is the result of increasing the polarizer angle by 10°. It is clear that the fringe visibility increases as the polarizer angle approaches 40°, falls after 50°, then begins to increase again after 90°.](image-url)
Figure 4: Images of the interference pattern that is produced by the two orthogonally oriented beams in the Mach-Zehnder interferometer. Both images were acquired with 5.35 order of magnitude filtration, 10µs exposure time, and gain set to 255. Image (a) is an accumulation of 20 images (20 superimposed images) and (b) is an accumulation of 240 images. Figures 4.c and 4.d profile the fringe intensity, as a function of pixel distance, of images (a) and (b) respectively.
Young’s Double-Slit Procedure and Results

The goal behind reproducing Young’s famous experiment was to demonstrate the wave-particle duality of light. We accomplished this by producing the interference pattern caused by the diffraction of collimated light waves as they propagate through the two slits, indicating the wave nature component of light, and by attenuating the test beam to a single photon level in order to observe particulate detection by the EM-CCD camera in the form of granular images.

The wave nature of light is very obviously demonstrated in figure 5. The corpuscular theory of light offers no explanation of these results, allowing us to be confident that light is a wave-like phenomenon. Figure 6, however, undoubtedly shows proof of the existence of particles. Figures 6c and 6a both show significant amounts of granularity, with Figure 6c being the more granular image. The granularity shows that individual particles are hitting the EM-CCD in spatially confined regions, which is enough evidence to provide confidence to the theory that light behaves like a particle.

**Figure 5**: Results from imaging the interference pattern caused by double-slit diffraction of the He-Ne laser. Figure 5a is a raw image of the interference pattern generated after 3 orders of magnitude attenuation with .1 second exposure time and no gain. Figure 5b is a surface plot of figure 5a, which shows clearly distinguishable maxima and minima resembling the pattern described by Young.

Both images (Figures 6a and 6c) were taken with 4.66 orders of magnitude filtration, but with different accumulation times. The plot profile of Figure 6a (which is figure 6b) shows a more sharply contrasting interference pattern than the plot profile of figure 6c, indicating that fringe visibility increases with accumulation.
Figure 6: Figures 6a and 6c were taken with 4.66 orders of magnitude filtration, 50ms exposure time, and a 255-gain setting, but with different accumulation settings. Figures 6b and 6d are plot profiles of 6a and 6c, respectively.
IV. Conclusion

Because it was demonstrated that photons propagating through the double slit one at a time still produce an interference pattern, it must be true that the photons interfere with themselves! Since this is exactly what we have demonstrated over the duration of laboratory two, we can be confident that we have successfully demonstrated single photon interference and the wave-particle duality of light.

Bibliography
