Abstract

The purpose of this experiment was to observe both the wave and particle nature of light. This was accomplished by demonstrating that single photons interfere with themselves. We were able to do this through the use of two different setups. The first was a Mach-Zehnder interferometer, which was responsible for making an ambiguous path. This results in the single photons accumulating in an interference pattern. The second setup was the Young double slit. By attenuating a laser beam to individual photons, we will still observe an interference pattern that corresponds to the interference patterns seen through waves. Based on our observations, we were able to show that single photons do in fact interfere with themselves.

Theory and Background

When we think about interference, we normally think about the superposition of waves and how peaks and valleys cancel each other to create patterns of varying intensity. When we think of classical objects interfering with each other, it does not make sense, as an object needs to have something to interfere with. If we sent a stream of objects, through a double slit apparatus, we expect something like figure 1, where there are only two bright lines, one corresponding to each slit.

However, we do not get this outcome with a stream of photons given that one does not know which slit the single photons go through. This is known as “which-path” information, which is necessary to observe single photon interference. If there is any way to know what path the photon will take, there will not be an interference pattern at the screen. This is because when we observe the path of the photon, we are collapsing the wavefunction, which causes the photon to act like a particle, which does not interfere with itself.

Figure 1: This shows what we would expect by shooting classical objects through double slits over time. We expect the objects to go through a single slit and continue in a straight path until it hits the camera. However, individual photons do not follow this pattern.
This is an example of the wave-particle duality of light. We have individual photons interfering with themselves. We are able to utilize filters to separate photons in time, and then using the “which-way” information, we observe interference patterns that are what we expect from waves.

**Experiment**

The first experiment that we performed was carried out through the use of a Mach-Zehnder interferometer and the EM-CCD camera, which was used to image the interference patterns. Figure 2 shows the setup of the interferometer.

![Mach-Zehnder Interferometer Setup](image)

Figure 2: The setup for the Mach-Zehnder Interferometer

In this setup, the beam splitter breaks up the beam into vertical and horizontal polarized light. Both polarizer A and B should be at 45 degrees. This allows for the “which-way” information, which produces the wave-like interference pattern at the detector. The neutral density filters are used to attenuate the beam to a single photon level. The laser was a 633 nm with an output power of roughly 5 uW.

For this experiment, we can rotate polarizer B and see how the visibility changes. According to Malus’s Law, our visibility should vary as cosine squared of the polarizer angle. It is important to note that we are defining fringe visibility as the contrast, which is the ratio of the difference between max and min to the sum of the min and max intensities. The fringe visibility changes because when we change the angle, we can figure out where the photon is going, thus observing it as a particle instead of a wave.

The second experiment involves the use of the Young double slit experiment. The setup is shown in figure 3. The slits that we used have a width of 10 microns with a separation of 90 microns. Using this setup, we can look at different images after a certain number of accumulations. According to our theory, we should get a pattern that resembles the wave property of light.
The procedure for this experiment is as follows:

1. Align the Mach-Zehnder interferometer. This is very tedious and it is important that the bright spots overlap both in the near field and in the far field. Place the EM-CCD so that the beam is in the camera.
2. Rotate polarizer B between 0 and 360. Record the interference pattern. Using ImageJ software, measure the intensity and thus the visibility for each angle.
3. Attenuate the laser to a single photon level using the neutral density filters. Adjust the parameters (exposure time, gain, accumulations) of the camera to determine the best image.
4. Setup the Double slit apparatus. Once again place the EM-CCD such that the beam is on the camera.
5. Arrange the camera parameters to get the best image of the interference pattern.

Results and Analysis

Using the Mach-Zehnder interferometer, we were able to get our fringe visibility to resemble a cosine squared function based on angle. Figure 3 shows a plot of the visibility for all the angles.
Based on this data, we can see that there is a dependence on the polarizer angle for the interference pattern of the light. The interference pattern for waves has a high visibility, as you can see the individual fringes, whereas the interference pattern for particles has a low visibility. This is because particles just go through the aperture onto the screen in any place, so what we see is a constant row of photons, no bright or dark spots.

As expected, when the polarizer is oriented at 45 degrees (or any 90 degree increment), we have a visibility peak. This is equivalent to the detector noticing fringes, which means the light is acting as a wave. This means that at 45 degrees, the photon is unsure of which path to take, so there is no collapse of the wavefunction. The following images represent different interference patterns.

Figure 5: This shows two different interference patterns. The left image is when the polarizer is at 180 degrees. This has a low visibility because the photons know which path to take, so they act as a particle. The image on the right is at 40 degrees. This has a much higher visibility because the photons do not know which path to take and they exhibit a wave interference pattern.
Then we were able to attenuate the laser beam to a single photon level with the polarizers set at 45 degrees. The power of the laser is 6 uW. The following images show different settings on the camera.

Figure 6: This shows the interference pattern with 3 orders of magnitude neutral density filters, 0 gain and a 0.1 exposure time. Here we clearly have a wave interference pattern.

Figure 7: This shows the interference when we changed the filters to 5 orders of magnitude. This increased the distance between photons. Same camera settings were used.
Figure 8: This shows the interference patterns for 7 orders of magnitude of filters. The left image is after 20 accumulations, while the right is after 50 accumulations. The exposure time is .005 seconds, while the gain is set to max (255).

From all of this data, we see that we have interference patterns that we expect from waves. However, we are detecting only single photons. This shows that through the use of the Mach-Zehnder interferometer, we were able to show that photons can interfere with themselves.

The next experiment we performed to determine that single photons interfere with themselves was the Young double slit. As explained earlier, we can attenuate the laser to a single photon level. If photons interfere with themselves, we will get a wave-like interference pattern.

In order for our laser to emit single photons, we need to use 4.5 order of magnitude neutral density filters. When we do this we get the following interference pattern.

Figure 9: This shows the double slit interference pattern with 4.5 order of magnitude filters. This is what we expect, as it shows a wave interference pattern.

Figure 10: This shows the double slit with 7 orders of filters. The left image is after 20 accumulations, and the right image is after 100 accumulations. This was taken using a .1 second acquisition time. We once again can see the wave interference patterns.

Based on our observations from the Young double slit, we see that we have an interference pattern that resembles the wave nature of light. Seeing that we have the laser attenuated to a
single photon level, we once again have shown that photons can and do interfere with themselves.

**Summary**

Based on our experiments, we were able to observe the wave-particle duality of light. Through the use of a Mach-Zehnder interferometer, we were able to show that when light is unsure of its path; there is no collapse of its wavefunction, which means it exhibits properties of a wave. This was done through a polarizer set at 45 degrees. When the polarizer was moved away from 45 degrees, the light knew what path to take, and its wavefunction collapsed, and we observed the particle nature of light. Through the use of the Young double slit apparatus, we were able to show that photons can interfere with themselves. This is due to the fact that we were able to attenuate a laser beam to a single photon level through the use of neutral density filters, and send them through the double slits. However, we observed an interference pattern that was in the form of a wave interference pattern. This means that single photons can interfere with themselves.