Wave Particle Duality with Single Photon Interference

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In the experiments of the Mach-Zehnder Interferometer and Young’s Double slit we observe the wave particle duality in single photon interference. In the Mach-Zehnder interferometer we separate and distinguish the path of the laser beam by measuring the polarization. However the only time we observe interference is when we destroy this information with an additional polarizer right before the EM-CCD camera. Additionally in Young’s Double Slit experiment going down to the single photon levels we see the wave-like interference. These two observations prove the wave-particle duality and further open our curiosity to the properties of light.

BACKGROUND

The study of the properties of light has been an interesting one due to elaborate experimental setup to observe the phenomenon known as the wave particle duality. The study of light and its duality in nature can be traced back to the 1600s. There were two schools of thought one by Christian Huygens who believe that light was a wave and Issac Newton who believe light was made up of particles. Later because of Dr-Broglie this duality issue was categorized to the complementarity by the de-Broglie wave length. Though through the work done by many scientists such as Max Plank, Albert Einstein, Arthur Compton, spear headed the discovery that all particles such as matter exhibit wave like properties [1]. This is difficult to understand because for macroscopic objects such as ourselves our wave properties cannot be detected. Like these scientists there are many more that proved the wave-particle nature. From work when observation first became mathematics in Newton’s deterministic laws to the unpredictability of the quantum experiments leads us to the phenomenon of the wave-particle duality found today [2].

In the Young’s Double slit experiment we studied the wave particle duality. In the experiment we used multi photons to levels to traverse the slit and recorded the interference pattern in our EM-CCD camera. After that we used filters to bring down the level of photons to a single photon level and varying the exposure time we had the photons hit the EM-CCD camera as particles. Still in which we observed the same interference patterns. Lastly we used the Mach-Zehnder interferometer to study the “which path” information and it proved the wave-particle duality of light as well.

THEORY

We being with the Mach-Zehnder experiment where the “which path” information is tested. When we split the beam into the horizontal and vertical polarization we gain information of which photon is which. When we have them interfere through the last NBPS, non-polarizing beam splitter, and take away Polarizer B, (Fig1), we should not see interference. However if we do destroy the information we should see the fringes of the wave like interference [3]. We can define an equation for Visibility of the fringes as follows.

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

Where $I_{\text{max}}$ is largest peak of intensity and $I_{\text{min}}$ is the smallest intensity captures by the EM-CCD camera. Further when we turn on the laser the laser outputs a wavelength of $\lambda = 632.8\text{nm}$ and our recording will start in the multi-photon level. To adjust to a single-photon level we need to attenuate. Knowing the wavelength, $\lambda$, and the power of the laser, $P$, the number of photons per meter is as follows.

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

Where $h$ is Plank’s constant. Measuring the path of the laser beam to be $d$ we can calculate the order of atten-
In Young’s Double slit we will use the same equations but now we calculate the fringe distance given the distance from the slit to the camera, $L$, and knowing the slit separation, $a \approx 90 \mu m$.

$$\Delta y \approx \frac{L \lambda}{a}$$

**EXPERIMENTAL SETUP**

For the two experimental setups we use Dr. Svetlana G. Lukishova’s laboratory at the University of Rochester. For the Mach-Zehnder Interferometer (Fig.1) and the Young’s Double Slit (Fig.2) the materials we use are listed as follows:

**Mach-Zehnder**

- 5 Mirrors
- 2 NPBS
- PBS (Polarizing Beam Splitter)
- HeNe Laser
- EM-CCD
- 2 Polarizers
- Spatial Filter
- 2 Apertures

1. We used the laser beam provided by the HeNe Laser to go through the spatial filter first so that the laser beam would have an improved quality and a larger diameter. This will allow the fringes in the interference to be more visible in our EM-CCD camera.

2. We used a NPBS, non-polarizing beam splitter, to share the work space with the Young’s double slit experiment.

3. Adjusting the height and rotations of mirrors 1 – 3 we align the laser beam. This is the step that requires the two apertures. We use the apertures at two points one close to the mirror and the other as far as we can have it go. By measuring the height of the beam we align the laser beam. The key thing is to make sure the laser beam was parallel to the table.

4. Put the PBS, polarizing beam splitter to split the laser beam in a 45 degree. This laser beam will split into a horizontal and vertical polarization. We put a polarizer in front of the PBS so we make sure that the intensities out of the PBS are as equal as can be. We use a power meter to equate both the horizontally and the vertically polarized intensities by varying the Polarizer A.

5. Using the mirrors 4 and 5 bring the laser beam to the NPBS to have them recombine. The laser beam passes through the NPBS and separates into perpendicular polarizations. After that we use the Polarizer B to have the option to destroy the information of where the beam comes from, setting the angle to about 45°. This will allow the interference to happen as the beams recombine in the NPBS.

6. Lastly we have the laser beam go to the EM-CCD camera, for the recording of the interference. We note that the EM-CCD camera need to be turned on when its internally cooled to -60 degrees centigrade. All this as in Figure 1.

7. Lastly the attenuation holders are for the attenuation slits that we use to bring down to single photon levels.

**Young’s Double Slit**

- NPBS
- HeNe Laser
- EM-CCD
FIG. 3: Using Image J software we analyzed the data of (A) Polarizer B turned to 91° (B) Polarizer B turned to 230°.

FIG. 4: Intensity graph using Matlab of Fig. 3 B.

• Spatial Filter

1. We use the same table with the same EM-CCD camera, the same spatial filter to enlarge the diameter, and improve the laser beam. Using the laser beam that goes through the NPBS we direct to go through the Slit with the pinholes like in Figure 2.

2. Put the EM-CCD camera in line with the laser beam right after the attenuation holder to record the observations. Lastly the attenuation holders hold the attenuation slides to bring the laser beam to single photon levels.

FIG. 5: All with Gain 255 and increasing exposure time. (A and B) Exposure time 0.00001s (C and D) Exposure time 0.0001s (E) Exposure time 0.001s and (F) Exposure time of 0.01s. The Visibility starts from (B-F) (7,12,22,25,78)%.

Attenuation, $\gamma$, is about $3 \times 10^{-5}$ for(B,C,E, and F), $3 \times 10^{-6}$ for A and $3 \times 10^{-4}$ for D.

RESULTS

Mach-Zehnder

The first of our observation was in the multi-photon level. From the “which-path” theory we expect that as long as we know where the photons are coming from, either with $|H\rangle$, Horizontal Polarization, or $|V\rangle$, Vertical Polarization, after the last NPBS we will not see any interference. If we destroy the information by mixing the states with a polarizer in the end we should see the fringes. By adjusting Polarizer B we get maximum fringes when set to 45° to the vertical polarization. However we loose the fringes when we deviate from the complete mixing of the states as shown in Figure 3. From the intensity graph in Figure 4 and Equation 1 we calculate visibility, $V = 0.5088$.

In order to reach the single-photon level we attenuate using both Eq 2-3 and measuring the distance the laser beam travels to be $d \approx 0.66m$, the power was read to be $P \approx 0.78 \mu W$ and since $h = 6.63 \times 10^{-34} Js$ we calculate $\gamma \approx 2 \times 10^{-4}$.

Young’s Double Slit

We begin Young’s Double Slit experiment by first observing the the fringes in the multi-photon level. We notice that the fringes are like waves where the two pinholes (Fig. 2) add the waves in a sense. Going to the single-
FIG. 6: Intensity graph using Matlab of Fig. 5 D. $V \approx 0.22$.

FIG. 7: Single-Photon interference in Young’s Double Slit. Varying exposure time: (A-H) 0.0001, 0.001, 0.0015, 0.002, 0.005, 0.01, 0.1, 0.1 seconds.

photon level we might expect to see a different pattern, like the lab manual suggests in the analogy of a bullet going through a double slit. However in the single photon level we see exactly as before in the multi-photon level. The photons interfere as they go through the double slit. This is totally different than the bullet example in the lab manual that proves the photons are both waves and particles [4]. Eq 2-3 and $d = 0.23m$ and the laser power, $P = 60nW$, attenuation will be $\gamma = 4.6 \times 10^{-3}$. Using Eq 4 $\Delta y = 1.6 \times 10^{-13}m$. We notice as we increase exposure time the fringes become more visible, and from Fig 8 and

FIG. 8: Intensity graph using Matlab of Fig. 7 H.

DISCUSSION AND CONCLUSION

The multi-photon and the single-photon levels were studied in both Mach-Zehnder and Young’s Double Slit. The results of both prove the wave particle duality, by observing the wave like fringes recorded on the EM-CCD camera.

In the Mach-Zehnder experiment the “which path” information was even more proof that photons are both waves and particles. The photons travel through the interferometer, splits into two beams (|V⟩, |H⟩), recombines in the NPBS and only interfere when Polarizer $B$ combines both polarizations in a $45^\circ$ to the vertical polarization.

In the Young’s Double Slit we see some finer fringes and this is do to the material of the double slit prepared by other graduate students. The material used to make the double slit there is some reflection which is credited toward the finer fringes in the observations. In Figure 7 we see the center of the fringes the most visible finer of the fringes. Lastly as the exposure time is decreased such as in Figure 7 its harder to see because of the lack of photons gathered in the single-photon level. From this we see that if we increase the exposer time we will observe the same interference pattern as two adding waves would do over time. Over all the fact that in the single-photon level, the photons seems to go through slit and then EM-CCD camera records the interference pattern as multi-photons as exposure time increases show that the photon interferes with itself! From this we conclude that the photon is defiantly both a wave
and a particle.

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