Single Photon Interference

December 19, 2006

D. Lancia • P. McCarthy
Overview

• Classical Interference
  – Intensity Distribution

• Quantum Mechanical Interference
  – Probability Distribution

• “Which Path?”
  – The Effects of Making a Measurement

• Wave-Particle Duality
  – Simultaneous Wave and Particle Behavior

• Single Photon Interference
  – Laser Attenuation
  – Mach-Zehnder Interferometer
  – Young’s Double Slit Setup
Classical Interference with Young’s Double Slit

\[ I_{1,2} = I_1 + I_2 + 2\sqrt{I_1 I_2} \cos \delta \]

Position of intensity maxima:

\[ x = m\lambda \frac{z}{d} \]

- \( \delta \) = phase difference between \( E_i \)
- \( z \) = distance from slits to observation plane
- \( d \) = distance between slits
- \( \lambda \) = source wavelength
- \( x \) = displacement from the z-axis
- \( m \) = any integer
A Quantum Mechanical View of Interference

Probability of a particle passing through a slit

\[ P_i = |\phi_i|^2 \]

Intensity of a wave passing through a slit

\[ I_i = |E_i|^2 \]

Single Photon Interference
A Quantum Mechanical View of Interference

Probability of a particle passing through 2 slits

\[ P_{1,2} = \left| \phi_1 + \phi_2 \right|^2 \]

Intensity of a wave passing through 2 slits

\[ I_{1,2} = \left| E_1 + E_2 \right|^2 \]

Single Photon Interference
The “Which Path?” Puzzle

- Knowing which path or slit a photon travels through is a form of measurement.
- One way to determine “which path” is by maintaining different polarization states in each path of an amplitude-splitting interferometer (Mach-Zehnder).
- Measuring the photon collapses its wave function.
- Particle behavior is observed and the interference pattern fails to form.
- If no information exists to link a photon to a specific path, the wave behavior resumes and an interference pattern is observed.
The “Which Path?” Puzzle

Probability of an observable particle passing through 2 slits

\[ P_{1,2} = P_1 + P_2 \]

An interference pattern fails to form
Wave-Particle Duality

- Individual photons arrive at the observation screen.
- Over a period of time, photon detection accumulates in an interference pattern.
- Single photon probability distribution is identical to an interference pattern that is formed by classical EM waves.
Amplitude Splitting vs Wavefront Splitting
Interferometers

Mach-Zehnder Interferometer
- Dielectric interfaces transmit part of the wave and reflect the other
- Both reflected and transmitted waves have lower intensity than incident wave – it is said to be “split”

Young’s Double Slit
- Pinholes or slits used to split a wave into multiple wavefronts
- Compensates for lack of spatial coherence

Single Photon Interference
Combined Interferometer Setup

Single Photon Interference
Approximating a Single Photon Level

In order to approximate one photon in the interferometer at any given time, measure each path of the Mach-Zehnder setup and calculate as shown

\[ \text{power} = 2.06 \text{mW} \]

\[ \frac{\text{photons}}{s} = \frac{\text{power}}{h \nu} = 6.53 \times 10^{15} \]

\[ \frac{\text{photons}}{\text{meter}} = \frac{\text{photons}}{s} \frac{1}{c} = 2.18 \times 10^{7} \]
Laser Attenuation

- Use all available neutral density filters to attenuate the laser to a level of approximately one photon per meter
- Path length of interferometer is less than 0.5 m
- 7.7 photons per meter is a good approximation of an average of one photon in the system at a time

<table>
<thead>
<tr>
<th>Neutral Density Filter</th>
<th>Transmission</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.316</td>
</tr>
<tr>
<td>3</td>
<td>0.344</td>
</tr>
<tr>
<td>4</td>
<td>0.349</td>
</tr>
<tr>
<td>OMA 1</td>
<td>0.080</td>
</tr>
<tr>
<td>OMA 3</td>
<td>1.17 x 10^{-4}</td>
</tr>
</tbody>
</table>

\[
\left( \frac{\text{photons}}{\text{meter}} \right)^{(\text{attenuation})} = 7.7 \text{ photons/m}
\]
Mach-Zehnder Interferometer Setup

- Laser—633 nm He-Ne, \( \approx 2.06 \text{ mW} \)
- Neutral Density Filters
  - Attenuate laser beam
- Spatial Filter
  - Expands and cleans beam
- Polarizing Beam Splitter
  - Divides single photon wave function (\( \varphi \)) into two paths
  - Polarizes outgoing photon
- Polarizers B and C
  - Polarizes outgoing photon horizontally and vertically
- Non-Polarizing Beam Splitter
  - Recombines photon wave functions from each arm
- Polarizer D
  - Adjusted to transmit H and V polarized photon interference
- EM-Cooled CCD Camera

Single Photon Interference
Mach-Zehnder Interferometer Procedure

• Test each “arm” of the interferometer to confirm polarization state of the photon
  – Polarizer B at 90°, a bright spot is observed
  – Polarizer B to 0°, a dark spot is observed
• The photon in path 1 is horizontally polarized
  – Polarizer C at 90°, a dark spot is observed
  – Polarizer C at 0°, a bright spot is observed
• The photon in path 2 is vertically polarized
Mach-Zehnder Interferometer Procedure

• Test the interferometer with and without polarizer D
  – No fringes appear when polarizer D is removed
  – Replace polarizer D test at 0° and 90°
  – Angles which match the horizontal and vertical polarizations of each arm prevent interference from occurring
Mach-Zehnder Interferometer Results

1. Acquisition Time = 0.5 s, Polarizer D Removed
2. Acquisition Time = 0.5 s, Polarizer D 180°
3. Acquisition Time = 0.5 s, Polarizer D 270°

Single Photon Interference
Mach-Zehnder Interferometer Procedure

- The fringes appear when polarizer D is replaced and set at 220°
  - Evidence that the presence of polarizer D obscures the ability to determine the state of the photon in the system
  - Angle near the equivalent of 45° allows the photon wave function to enter from both arms of the interferometer
  - Single photon interference is observed
Mach-Zehnder Interferometer Procedure

• Using EM-cooled CCD camera with highly attenuated laser source
  – ND Filters 1-OMA, 2-OMA, 2, 3, 4
  – Capture single photon interference at various exposure times
  – Evidence of particle accumulation in the interference pattern is observed
Mach-Zehnder Interferometer Results

4. Acquisition Time = 0.005 sec  
5. Acquisition Time = 0.05 sec  
6. Acquisition Time = 0.5 sec  
7. Acquisition Time = 1.0 sec  

Gain = 280  
all exposures

Single Photon Interference
Mach-Zehnder Interferometer Summary

• Confirmed that presence of “which path” information causes particle behavior and no interference pattern
• Fringes reappear when “which path” information is removed
• Short CCD camera exposures show evidence of particle accumulation with attenuated laser source
• Fringe pattern formed by single photons is identical to that formed by an unattenuated laser
• Interference occurs because the wave function of the photon travels both paths of the amplitude-splitting interferometer
Young’s Double Slit Setup

- Laser source, neutral density filters, spatial filter—same as Mach-Zehnder setup
- Non-polarizing beam splitter—directs photons to double slit plate
- Double-slit plate
  - Glass plate containing closely spaced small slits
  - Produced lithographically
- EM-cooled CCD Camera
Young’s Double Slit Procedure

- Using EM-cooled CCD camera with highly attenuated laser source
  - ND Filters 1-OMA, 2-OMA, 2, 3, 4
  - Capture single photon interference at various exposure times
  - Evidence of particle accumulation in the interference pattern is observed
Young’s Double Slit Results

8. Acquisition Time = 0.05 sec

9. Acquisition Time = 0.5 sec

10. Acquisition Time = 1.0 sec

11. Acquisition Time = 2.0 sec

Gain = 300 all exposures

Single Photon Interference
Young’s Double Slit Results

12. Acquisition Time = 1.0 sec
   Gain = 300
   Neutral Density Filters: 2, 3, 4
Young’s Double Slit Summary

• “Which path” behavior previously determined, not possible to test in this setup due to small slit spacing
• Fringe pattern formed by single photons is identical to that formed by an unattenuated laser
• Short CCD camera exposures show evidence of particle accumulation with attenuated laser source
• Interference occurs because the wave function of the photon travels both paths of the wavefront-splitting interferometer
• Interference from glass plate reflection visible within each double slit interference fringe
Sources of Error

- Accuracy of laser power measurement
- Results more indicative with greater laser attenuation
- Background noise in images – stray room light and alignment
- Thermal noise on CCD
- Interference from reflection off of glass plate in Young’s setup
Possible Improvements

- More laser attenuation
- Use APD along with CCD camera for alternative data collection
- Use different lasers with varying wavelengths
- Use slit spacing (90 μm), size (10 μm), and distance to camera (20 cm) to compare to theoretical classical interference pattern
- Use parametrically down-converted photons in each arm of interferometer
Conclusions

- Amplitude splitting and wavefront splitting interferometers both showed single photon interference patterns.
- The existence of information that can determine which path a photon has taken will eliminate the interference pattern whether that property of the photon is measured or not.
  - Observed when polarizer D was altered in the Mach-Zehnder setup.
- Photons act as particles – they arrive one at a time at the detector and accumulate over time.
  - Exposures of varying duration showed this particulate nature and accumulation.
- Photons also behave like waves – the probability of their detection position follows exactly the interference pattern of classical waves.
  - A relatively high-intensity interference pattern which is visible by the human eye is the result of many single photons interfering.
References


• The Feynman Lectures on Physics, Vol 3, Richard P. Feynman, Robert B. Leighton, Matthew Sands, Addison-Wesley, 1965

• Optics, 4th ed., Eugene Hecht, Addison-Wesley, 2002

• OPT 263K Laboratory Manual
Acknowledgements

• Dr. Svetlana Lukishova
• Lab Partners:
  – Vikram Jagannathan
  – Jie Zheng
• University of Rochester Kauffman Foundation
• Nickolaos Savidis