Contents

• Lab 1: Entanglement and Bell’s Inequalities
• Lab 2: Single Photon Interference
• Lab 3-4: Confocal Microscopy Imaging of Single Emitter Fluorescence and Hanbury, Brown, and Twiss Setup, Photon Antibunching
• Conclusions
• Acknowledgements
• References
Lab 1
Entanglement and Bell’s Inequalities
Entanglement

\[ |\Psi_{12}\rangle \neq |\Psi_1\rangle \otimes |\Psi_2\rangle \]

- Particles cannot be separated into separate wave functions.
- Measurement of one entangled particle’s state gives reliable information about the other(s).
- Entanglement (spooky action at distance) was first introduced as an example of quantum theory’s incompleteness in EPR paper (1935).
Bell’s Inequality

• John Bell introduced a way to test quantum mechanics with an inequality (1964).
• The inequality is satisfied for classical situations, but can be violated in situations that involve quantum effects, for certain values of parameters.
• There is another version of this inequality that is more suitable for experimental testing (CHSH).
CHSH Inequality

\[ |S| = |E(\alpha, \beta) - E(\alpha, \beta')| + |E(\alpha', \beta) + E(\alpha', \beta')| \]

\[ E(\alpha, \beta) = \frac{N(\alpha, \beta) + N(\alpha_\perp, \beta_\perp) - N(\alpha, \beta_\perp) - N(\alpha_\perp, \beta)}{N(\alpha, \beta) + N(\alpha_\perp, \beta_\perp) + N(\alpha, \beta_\perp) + N(\alpha_\perp, \beta)} \]

- Developed by Clauser, Horne, Shimony, and Holt.
- The classical argument is that
  \[ |a| + |b| + |c| \geq |a+b+c| \]
- Whenever \(|S|>2\), the inequality is violated.
Entanglement in the Experiment

• Entanglement is created in this setup using a process called Spontaneous Parametric Down Conversion.
• This is a second order non-linear optical process.
• One photon is converted into two photons of longer wavelength.
Entanglement in the Experiment

• This process is carried out using two type one BBO crystals.

• The optical axes of the crystals are perpendicular to each other. Incident light is linearly polarized 45 degrees with both crystals’ optical axes.

• One crystal converts one polarization component, while the other does the other, orthogonal component.

\[ |V\rangle \rightarrow |H_s H_i\rangle \quad |H\rangle \rightarrow |V_s V_i\rangle \]
Entanglement in the Experiment

\[ |\psi_{\text{entangled}}\rangle = \frac{1}{\sqrt{2}} (|V_sV_i\rangle + e^{i\phi} |H_sH_i\rangle) \]

- There is a phase difference between the two components that is compensated for by the quartz plate.

- The result is that the phase goes to zero.

\[ |\psi\rangle = \frac{1}{\sqrt{2}} (|V_\alpha V_\beta\rangle + |H_\alpha H_\beta\rangle) \]
Overlapping Cones
Entanglement in Any Coordinate System

\[
|H\rangle = \cos \alpha |H_\alpha\rangle - \sin \alpha |V_\alpha\rangle \\
|V\rangle = \cos \alpha |V_\alpha\rangle + \sin \alpha |H_\alpha\rangle
\]

\[
|\psi_{\text{entangled}}\rangle = \frac{1}{\sqrt{2}} \left( [\cos \alpha |V_\alpha\rangle_s + \sin \alpha |H_\alpha\rangle_s][\cos \alpha |V_\alpha\rangle_i + \sin \alpha |H_\alpha\rangle_i] \\
[\cos \alpha |H_\alpha\rangle_s - \sin \alpha |V_\alpha\rangle_s][\cos \alpha |H_\alpha\rangle_i - \sin \alpha |V_\alpha\rangle_i] \right)
\]

\[
|\psi_{\text{entangled}}\rangle = \frac{1}{\sqrt{2}} \left( (\cos^2 \alpha + \sin^2 \alpha)|V_\alpha\rangle_s |V_\alpha\rangle_i + (\cos^2 \alpha + \sin^2 \alpha)|H_\alpha\rangle_s |H_\alpha\rangle_i \right)
\]

\[
|\psi_{\text{entangled}}\rangle = \frac{1}{\sqrt{2}} \left( |V_\alpha\rangle_s |V_\alpha\rangle_i + |H_\alpha\rangle_s |H_\alpha\rangle_i \right)
\]
CSHS Inequality in the Experiment

- Coincidences of photons arriving at the same time are counted for specific combinations of the polarizer angles.
- These angles were selected for maximum violation. Classical and quantum situations can get the same result at certain angles.

<table>
<thead>
<tr>
<th>Polarizer A</th>
<th>Polarizer B</th>
<th>Net coincidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>45</td>
<td>-22.5</td>
<td>241.6004625</td>
</tr>
<tr>
<td>45</td>
<td>22.5</td>
<td>49.70820696</td>
</tr>
<tr>
<td>45</td>
<td>67.5</td>
<td>27.81832161</td>
</tr>
<tr>
<td>45</td>
<td>112.5</td>
<td>240.8037829</td>
</tr>
<tr>
<td>0</td>
<td>-22.5</td>
<td>200.9381061</td>
</tr>
<tr>
<td>0</td>
<td>22.5</td>
<td>235.7104968</td>
</tr>
<tr>
<td>0</td>
<td>67.5</td>
<td>128.2238311</td>
</tr>
<tr>
<td>0</td>
<td>112.5</td>
<td>84.34675305</td>
</tr>
<tr>
<td>45</td>
<td>-22.5</td>
<td>34.29263416</td>
</tr>
<tr>
<td>45</td>
<td>22.5</td>
<td>287.6417333</td>
</tr>
<tr>
<td>45</td>
<td>67.5</td>
<td>314.515383</td>
</tr>
<tr>
<td>45</td>
<td>112.5</td>
<td>74.17161817</td>
</tr>
<tr>
<td>90</td>
<td>-22.5</td>
<td>91.70037671</td>
</tr>
<tr>
<td>90</td>
<td>22.5</td>
<td>96.9416073</td>
</tr>
<tr>
<td>90</td>
<td>67.5</td>
<td>214.7333936</td>
</tr>
<tr>
<td>90</td>
<td>112.5</td>
<td>209.8243169</td>
</tr>
</tbody>
</table>
Cos²(A-B) Dependence

Coincidence Counts

A=45 degree
A=135 degree

Polarizer B (degrees)
## Results

<table>
<thead>
<tr>
<th>Expression</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E(\alpha, \beta)$</td>
<td>0.924385</td>
</tr>
<tr>
<td>$E(\alpha', \beta')$</td>
<td>0.448381</td>
</tr>
<tr>
<td>$E(\alpha', \beta)$</td>
<td>0.256745</td>
</tr>
<tr>
<td>$E(\alpha, \beta')$</td>
<td>-0.62411</td>
</tr>
<tr>
<td>$</td>
<td>S</td>
</tr>
</tbody>
</table>
Lab 2
Single Photon Interference
Wave Particle Duality

• The debate over the nature of light is centuries old. Is light a particle or a wave?
• The objective of this experiment was to prove that light exhibits both particle and wave properties in certain situations.
Representing a Photon

\[ \Delta x \Delta p \geq \frac{\hbar}{2} \]

• The probability of where a photon is can be represented by a wave function.
• Observing the photon, which gives certainty of its location, collapses the wave function.
• The probability of where the photon is the property of the particle that is “waving”.
Which-Way Information

• If a photon has even probability of taking two paths that recombine later, the wave function will take both paths and interfere!

• If we remove one of the possibilities, we know “which-way” information. The wave function will only go down the one path and will not interfere with itself.
Single Photon Interference

• Due to wave particle duality, it is possible to interfere a single photon with itself.
• If enough single photons are accumulated in an image over time, a fringe pattern will be visible, just as if there were billions of photons.
• This experiment used an attenuated laser to emulate a single photon source. On average there was less than 1 photon per meter, which was approximately the length of the interferometer.
Mach-Zehnder Experimental Setup
Experimental Setup

• The polarizing beam splitter sends one polarization component one way and the other polarization component the other way.

• Rotating polarizer B changes which polarization component gets through, “which way information”.

• Laser beam is 633nm He-Ne that is attenuated with neutral density filters. Spatial filter cleans up the beam.
320 degrees, V=0.3679
340 degrees, V=0.2668
0 degrees, $V=0.0370$
Results

• Fringe pattern visibility was destroyed when which-way information was known, which was whenever one polarization was completely blocked (multiples of 90°).

• Only one photon was in the interferometer on average, but interference fringes were still accumulated! Single photon interference was realized.
Double Slit Experimental Setup
Experimental Setup

• Classic Young’s double slit experiment, at the single photon level.
• The EM-CCD captures images single photons and accumulates them to reveal a double slit pattern.
• A demonstration of the particle nature (capturing single pixels locating photon) and wave nature (double slit pattern).
1 Accumulation
10 Accumulations
50 Accumulations
100 Accumulations
Lineout Average of Different Accumulations

Lineout Average of Various Accumulations

Intensity Ranging from 0 to 255

Vertical Line Across Fringes (pixels)
Visibility Ranging from 0 to 1
Results

• Wave particle duality was demonstrated.
• Fringe visibility increased with accumulations of single photons.
Lab 3-4
Confocal Microscopy Imaging of Single Emitter Fluorescence and Hanbury, Brown, and Twiss Setup, Photon Antibunching
Confocal Microscope

• Imaging through a “pinhole”, in our case the small detector size in APD.

• This creates a very small depth of focus and cuts out light from objects we are not interested in.

• High numerical aperture, only possible with oil immersion.
Other Emitters
Emitter
Effective Pinhole
Other Emitters
Effective Pinhole
Single Photon Sources

• Examples include single atoms, certain single molecules (quantum dots, nano-diamonds, and dyes).

• Single emitter in a field will emit single photons separated in time. After a photon is absorbed, it takes a certain amount of time to emit the light, the fluorescence lifetime. Only after this time can an emitter absorb another photon.
Antibunching

- Attenuated laser beams will have photons that can come in pairs or triplets. This is not antibunching.
- Single emitters will exhibit antibunching, since they are only capable of emitting one photon at a time.
- Antibunching can be demonstrated experimentally.
Applications of Single Emitters

• Can be used for completely secure communication.
• Possibly as qubits in a quantum computer.
• A single emitter that can be easily controlled and well understood is necessary for these applications.
Hanbury, Brown, and Twiss
Experimental Setup

Single Photon Source  Beam Splitter  APD Module  Computer Card
Experimental Setup

- When one detector receives a photon, a TTL pulse is sent to the computer card that starts the charging of a capacitor.
- When the other detector receives a photon, another pulse is sent to the computer card that signals to stop charging the capacitor.
- The time between these pulses can be determined from the charge on the capacitor.
Experimental Setup

- The beam splitter gives a photon a 50/50 chance of going one way or the other.
- One time that will we expect to have no counts is the zero time.
- Creating a histogram of all the times recorded should show that the histogram goes to zero around the zero time.
Quantum Dots

- The quantum dots used in our experiments were CdSeTe that emit at 790nm.
- A He-Ne laser source with a wavelength of 633 nm was used to excite the quantum dots.
- Quantum dots “blink” with time. This can be seen as stripes on a raster scan.
- Quantum dots can also be “bleached”, due to damage from long exposure to a field.
Photonic Band Gap Materials

• Structure with periodic optical properties that exhibit wavelength specific reflection as a result of interference effects, similar to thin film interference.
• Can use liquid crystals as a distributed feedback structure, creates a micro-cavity that enhances quantum dot emission.
• In our experiments, cholesteric liquid crystals were used.
Successful Antibunching
Results

- Antibunching was observed in quantum dots
- Blinking was observed in quantum dots.
Conclusion

• Each of these experiments has demonstrated the quantum effects that can be observed in light.

• This lab has taught us how to conduct such experiments and how to use the necessary equipment to collect the data.

• We have also learned the underlying theory in these experiments.
Acknowledgements

• Dr. Lukishova for teaching this challenging and fascinating lab.
• Eric Brost for his help throughout the course.
• Scott Barker for being a courteous lab partner.