Lab 3/4: Confocal Microscopy Imaging of Single Emitter Fluorescence and Hanbury-Brown and Twiss Interferometer Setup, Photon Antibunching

Lab 1: Entanglement and Bell’s Inequalities

Lab 2: Single Photon Interference

Conclusion

Acknowledgments
LAB 3&4
CONFOCAL MICROSCOPY
OF SINGLE EMITTER
FLUORESCENCE AND
HANBURY, BROWN AND
TWISS SETUP, PHOTON ANTIBUNCHING
Imaging through a “pinhole”. In this experiment it was a small detector in APD.

This creates small depth of focus and it removes light from sources that are irrelevant to experiment.

High Numerical Aperture achieved with oil immersion.
Examples include quantum dots, nano-diamonds, dye molecules and carbon nanotubes.

- Single emitter emits single photon separated by time. After photon is absorbed, it takes a certain amount of time to release it (fluorescence lifetime). After this, the emitter can absorb another photon.
Spectrum of Gold Nanoparticles (532 nm calibration)
Antibunching

- Attenuated laser beams have photons that come in pairs or triplets. This is not true antibunching.
- Single emitters exhibit antibunching, since they are only capable of emitting one photon separated by time.
Applications

- Can be used for secure communication
- Possible as qubits in a quantum computer
- Single emitters can be used in combination with classical systems for transfer of encrypted data.
Hanbury, Brown and Twiss Setup

Diagram showing a setup with:
- Single Photon Source
- Beam Splitter
- APD Module
- Computer Card
- APD Module
When APD 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.
The beam splitter gives a photon a 50/50 chance of going one way or the other.

• One time that we will 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.
Zero Time (66 ns aprox.)
Raster Scan of Nanodiamonds with .35 Transmission Filter
Unsuccessful Antibunching
Quantum Dots

- A laser source with a wavelength of 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.
Quantum Dot Blinking
Quantum Dot Scan (532 nm excitation)
Fluorescence Lifetime of a Quantum Dot (532 nm excitation) 68 ns
Antibunching! Hurrah!
Results

- Antibunching was observed in quantum dots but unfortunately not in our other kinds of samples.
- Blinking was observed in quantum dots
LAB 1
ENTANGLEMENT AND
BELL’S INEQUALITIES
Entanglement

- Wave-Functions are not separable
- Measurement of one particle alters the state of another particle.
- Entanglement proposed in EPR paper (1935)
  - Called “Spooky Action at Distance”
- Bell’s Inequalities show entanglement (proposed by J.S Bell, 1964)
Bell’s Inequality

- Allows for experimental testing of interpretation of quantum mechanics
- The inequality is satisfied for classical situations, but can be violated in quantum situations, for certain parameters
- The classical argument is that \(|a| + |b| + |c| \geq |a+b+c|\)
- Bell’s theorem: No theory of local hidden variables can fully reproduce the predictions of quantum mechanics
| $S| = |E(\alpha,\beta)-E(\alpha,\beta')| + |E(\alpha',\beta)+E(\alpha',\beta')|$

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

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
Experimental Setup

Laser
Quartz Plate
Filter
BBO Crystals
Polarizer
Filter
Lens
APD
Beam Stop
Computer Counter Card (with time window of 26 ns)
Experimental Entanglement

- Created by a process called Spontaneous Parametric Down Conversion
- Second order non-linear optical process
- One photon is converted into two photons of longer wavelength.
- Process carried out using two type of BBO crystals
- One crystal converts one polarization component while the other does the orthogonal component
|\psi_{entangled}\rangle = \frac{1}{\sqrt{2}} (V_s V_i \rangle + e^{i\phi} |H_s H_i\rangle)

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

The result is that the phase goes to zero.

|\psi_{entangled}\rangle = \frac{1}{\sqrt{2}} (V_\alpha V_\beta \rangle + e^{i\phi} |H_\alpha H_\beta\rangle)
Entanglement

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

- \[ |\psi_{\text{entangled}}\rangle = \frac{1}{\sqrt{2}} ( (\cos^2 \alpha + \sin^2 \alpha) |V\alpha\rangle_s |V\alpha\rangle_i + (\cos^2 \alpha + \sin^2 \alpha) |H\alpha\rangle_s |H\alpha\rangle_i ) \]

- \[ |\psi_{\text{entangled}}\rangle = \frac{1}{\sqrt{2}} ( |V\alpha\rangle_s |V\alpha\rangle_i + |H\alpha\rangle_s |H\alpha\rangle_i ) \]
Overlapping Light Cones
Quartz Plate Rotation

Coincidence Counts

Counts

Vertical Angle

0-0
90-90
45-45
135-135
Quartz Plate Rotation

Horizontal Axis

Coincidence Counts

Angle

-5 -4 -3 -2 -1 0 1 2 3 4 5

135-135
45-45
0-0
90-90
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<tr>
<th>$E(\alpha, \beta)$</th>
<th>0.775745</th>
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<td>$E(\alpha', \beta')$</td>
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<tr>
<td>$E(\alpha', \beta)$</td>
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<tr>
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<tr>
<td>$</td>
<td>S</td>
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$|S|$ value was greater than 2, therefore the inequality was violated (For 45 and 90 degree rotations)
<table>
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<tr>
<td>$E(\alpha',\beta)$</td>
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<tr>
<td>$E(\alpha',\beta)$</td>
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$|S|$ value was smaller than 2, therefore the inequality was NOT violated (For random degree rotations)
$(\cos(A-B))^2$ Dependence
Results

- Inequality was violated for certain angles.
- For random angles is not violated.
- Cosine squared dependence in angle rotations that violate inequalities.
LAB 2
SINGLE PHOTON
INTERFERENCE
Objective of this experiment is that light exhibits both particle and wave properties in certain situations.

Single Photons are expected to display interference effects:
- Wave: Diffraction Interference
- Particle: Photoelectric effect
“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. In other words, the photon will interfere with itself.

- If we remove one of the possibilities, we know “which way” information go. The wave function will go down unto that path and will not interfere with itself.
The wave particle duality of light allows photons to interfere with themselves.

If enough single photons are accumulated over time, a fringe pattern will be visible.

This experiment used attenuated laser light to emulate a single photon source. On average there was less than 1 photon per meter.
Young’s Double Slit Apparatus
Experimental Setup

- EM-CCD captures images of single photons and accumulates them to reveal a double slit pattern.
- This demonstrates the particle (single photons captured as pixels) and the wave nature of light (Double Slit interference).
Single Accumulation
20 Accumulations
100 Accumulations

![Graph showing a trend in gray value over distance](image)
Results

- Wave Particle duality demonstrated.
- Fringe Visibility increased as single photons accumulate on picture over time.
- Signal becomes increasingly sinusoidal with increased number of accumulations.
Mach-Zehnder Interferometer
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 attenuated with neutral density filters. Spatial filter cleans up the beam.
0 Degree Rotation
50 Degree Rotation
90 Degree Rotation
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.
Each of these experiments demonstrated both theory and applications of quantum and nano optics.

All the labs combined presented a thorough demonstration on how to incorporate quantum and nano theory into experimental applications.
Acknowledgments

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