- Presentation -
Quantum and Nano-Optics Laboratory

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University of Rochester
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Laboratory 1: Entanglement and Bell’s Inequalities

Goal: To demonstrate the existence and nonlocal behavior of entangled systems by violating an altered version of Bell’s inequalities created by Clauser, Horne, Shimony, and Holt (CHSH)
Background
EPR Paradox

• 1935: Einstein, Podolsky, and Rosen (EPR) publish *Can Quantum-Mechanical Description of Reality Be Considered Complete?*
  – Propose a *Gedankenexperiment* to disprove quantum theory
  – “Spooky action at a distance”
Background
Bell’s Inequalities

• 1964: John Stewart Bell publishes *On the Einstein Podolsky Rosen Paradox*
  – Bell’s Inequalities (utilizing electron spin)
    \[ |A| + |B| + |C| \geq |A + B + C| \]
  – Hidden Variables require local reality
Background

CHSH Inequality

- 1969: Clauser, Horne, Shimony and Holt (CHSH) publish *Proposed Experiment to test local hidden-variable theories*
  
  - Proposed modification of Bell’s Inequality using photons

\[
E(\alpha, \beta) = P_{VV}(\alpha, \beta) + P_{HH}(\alpha, \beta) - P_{VH}(\alpha, \beta) - P_{HV}(\alpha, \beta), \quad \text{and}
\]

\[
S = |E(a, b) - E(a, b')| + |E(a', b) + E(a', b')|, \quad \text{where}
\]

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

If \(|S| > 2\), the inequality is violated and entanglement is confirmed.
Background
Entanglement Theory

• Quantum Entanglement: Inseparable State

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

• We create entangled states via Spontaneous Parametric Down-Conversion (SPDC)

• A change in one feature of the system instantly changes the state of other features of the system
Experimental Setup & Procedure

Image taken from the lab manual, and edited by me

<http://www.optics.rochester.edu/workgroups/lukishova/QuantumOpticsLab/homepage/opt253_08_lab1_entangl_manual.pdf>
Spontaneous Parametric Down Conversion

Spontaneous Parametric Downconversion

Pump

Nonlinear $\chi^{(2)}$ crystal

$s$ (signal)

$i$ (idler)

Momentum Conservation

$k_s$ $k_i$

$k_{PUMP}$

Energy Conservation

$\omega_{PUMP}$ $\omega_s$ $\omega_i$

$\phi_{PUMP} = \phi_s + \phi_i$
BBO Crystals

• β Barium Borate Crystals – Nonlinear Process
• Orthogonal Polarization of cones created by Orthogonal Optical Axes of BBO crystals

\[ \lambda_s + \lambda_i = \lambda_{\text{pump}} \]
Imaging the Cone

Intensity of the cone does not change as analyzer polarization changes. This is because there are equal components of vertically and horizontally polarized light.
Waveplate (Quartz)

- Half-Wave Plate
- Introduces Phase Shift between two polarization components of the pump beam
Cos² Dependence
Results:

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<th>Polarizer B</th>
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Conclusion

This data yields an $|S|$ value of 2.14, thereby confirming the non-local reality of entangled particles.
Laboratory 2: Single Photon Interference

Goal: To reproduce and demonstrate the wave-particle duality of light, and to observe the effect of obtaining “which way” information on the interference of two light beams in a Mach-Zehnder interferometer.
17th and 18th Century: Newton vs. Huygens

- Newton advocated a corpuscular theory of light
- Huygens had already demonstrated how wave-theory could better explain diffraction
- Newton’s theory dominated the 17th and 18th century simply because Newton advocated it
Background
Thomas Young

- 1801: The Double-Slit Experiment
  - Determines that light must behave as a wave in order to explain the interference pattern
Background
Einstein - The Photoelectric Effect

• In 1905, Albert Einstein applied Planck’s theory of discrete energy to the Photoelectric effect
• The idea of the photon is developed and it becomes clear that light can not only be wavelike
Background
Wave-Particle Duality

- The idea that light behaves like a wave under certain conditions and like a particle under other conditions
- No underlying mechanism as far as we can tell
- Fundamental concept of quantum mechanics
Beam is collimated by the spatial filter before entering the double slit

Background
Mach-Zehnder Interferometer
Experimental Setup & Procedure
Attenuating Beam to Single Photons

- In order to observe single photon interference/particle behavior, the beam must be attenuated so that single photons are hitting the detector.
- This is done by calculating the number of photons $N$ there are per some arbitrary chosen distance $d$ given the power $P$ and wavelength $\lambda$ of the beam.

\[
\frac{N}{d} = \frac{P\lambda}{hc^2}
\]
Results:
Double-Slit Experiment

interference pattern observed after 3 orders of magnitude attenuation with .1 second exposure time and 0 gain
Results:
Double-Slit Experiment (Cont.)

Particle Behavior
The features of the image are very granular, indicating that there are spatially confined packets of light (photons) being detected one at a time by the camera.

Wave Behavior
Despite the obvious existence of particles, an interference pattern is still formed, indicating that single photons are interfering with themselves.

5 orders of magnitude, .0005s Exposure, 255 gain, and 20 Accumulations
Results:
Double-Slit Experiment (Cont.)
Fringe Visibility and Accumulation

- Fringe visibility is a dimensionless quantity used to define the contrast between the maxima and minima of fringes

\[ \text{Visibility} = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}} \]

- We found that there is a definite relationship between fringe visibility and accumulation/exposure time

Two images of the fringe pattern caused by interference taken under similar conditions, with the only exception being the accumulation number.

20 Accumulations

120 Accumulations
Results:
Mach-Zehnder Experiment
Which Way?

Images of fringes taken at every 10° increment from 0° to 360°

Trying to figure out with path the light came from with the analyzer polarizer destroys the interference pattern.
Results:
Mach-Zehnder Experiment
Granularity and Fringe Visibility

Both images were acquired with 5.35 order of magnitude filtration, 10μs exposure time, and gain set to 255. Image (a) is an accumulation of 20 images (20 superimposed images) and (b) is an accumulation of 240 images. Figures 4.c and 4.d profile the fringe intensity, as a function of pixel distance, of images (a) and (b) respectively.
Conclusion

Being that photons propagating through the slit one at a time still produce an interference pattern, it must be true that the photons interfere with themselves!
Laboratory 3-4: Confocal Microscope Imaging of Single-Emitter Fluorescence and Photon Antibunching Detection Using a Hanbury Brown & Twiss Setup

Goal: To image a variety of fluorescing single photon sources using a confocal microscope, and to detect antibunched photons using a Hanbury, Brown, and Twiss interferometer.
Background
Antibunching

• Photons that are separated in time
• Show a negative relationship (anticorrelation).
• produced by single emitters
• They are separated in time because of the fluoresce lifetime of the single emitter that is being investigated
Background
Antibunching (Cont.)

More specifically, antibunched photons are photons for which the second-order correlation function produces a value less than 1 when the time delay $\tau = 0$. The second-order correlation function is defined as follows:

$$g_{T,R}^{(2)}(\tau) = \frac{< I_T(t + \tau)I_R(t) >}{< I_T(t + \tau) >< I_R(t) >}$$

- Classically behaving light produces $g^2(0) \geq 1$
- Coherent light fields produce a $g^2(0)$ value of 1.
- The classical theory of light cannot explain values of $g^2(0) \geq 1$
We use oil immersion to increase the numerical aperture of our objective.
Experimental Setup
Results:

We were successfully able to detect antibunched photons from a single Colloidal Quantum Dot emitter
Results: Blinking
Results: Fluorescence Lifetime

\[ N(t) = a_0 e^{-t/\tau} \]

\[ \tau \approx 60 - 100 \text{ns} \]
The successful acquisition of data showing antibunched light confirms that light can take the form of quanta, again confirming quantum theory.
What I Learned?

Everything we Covered!
Thank You!