Quantum Optics & Quantum Information

by Omar Santiago Magana-Loaiza
Outline

- Motivation
- Single Photon Interference
- Single Photon Source
- Entanglement and Bell’s Inequalities
- Future Work

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Motivation

Why was this laboratory class so much fun and interesting?

http://www.nature.com/nature/journal/v456/n7223/full/456706a.html

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We illustrate the wave particle duality of light:

Mach-Zehnder interferometer.

Single Photon level

Which-way information.

http://stochastix.wordpress.com/tag/wave-particle-duality/
For our case we attenuated the power from 1 uW to 100 pW with an average photon separation of 0.93 meters. This corresponds to an attenuation coefficient of 4 orders of magnitude.
Mach-Zehnder Interferometer

He-Ne Laser 633 nm

Spatial filter and collimator

Polarizer A

Polarizer B

Polarizer C

Polarized Beam Splitter

Mirror

Non Polarized Beam Splitter

EM CCD

Polarizer D

Filter

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Which –way information

We collapse the wave-function!

A destruction of the wave-function using one of the polarizers

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Young experiment

\[ I = \left| \psi_I \right|^2 = (E_1 e^{ikr_1} + E_2 e^{ikr_2})(E_1 e^{-ikr_1} + E_2 e^{-ikr_2}) \]
\[ = I_1 + I_2 + E_1 E_2 e^{ikr_1-ikr_2} + E_1 E_2 e^{ikr_2-ikr_1} \]
\[ = I_1 + I_2 + 2\sqrt{I_1 I_2} \cos[k(r_1 - r_2)] \]
Wave-particle duality of light becomes clear!

a) 0.1 sec 4 orders of magnitude
b) 5 sec. 7 orders of magnitude
c) 5 sec. 8 orders of magnitude
d) 10 sec. 8 orders of magnitude
e) 10 sec. 8 orders of magnitude
f) 5 sec. 8 orders of magnitude
g) 5 sec. 8 orders of magnitude
h) 1 sec. 8 orders of magnitude
One of the most amazing experiments I ever seen!

Quoting J. Kimble “tickle one of the two systems, causes the second laugh”.

\[
|\psi\rangle = \frac{1}{\sqrt{2}} \left( |V\rangle_{q_1} |V\rangle_{q_2} + |H\rangle_{q_1} |H\rangle_{q_2} \right)
\]

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

http://www.optics.rochester.edu/workgroups/lukishova/QuantumOpticsLab/homepage/opt253_08_lab1_entangl_manual.pdf

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Polarizers play an important role.

We have a behavior similar to Malus Law!

\[ P_{VV}(\alpha, \beta) = \left| \langle V_\alpha | V_\beta | \psi_{Bell} \rangle \right|^2 \]
\[ P_{VH}(\alpha, \beta) = \left| \langle V_\alpha | H_\beta | \psi_{Bell} \rangle \right|^2 \]
\[ P_{HH}(\alpha, \beta) = \left| \langle H_\alpha | H_\beta | \psi_{Bell} \rangle \right|^2 \]
\[ P_{HV}(\alpha, \beta) = \left| \langle H_\alpha | V_\beta | \psi_{Bell} \rangle \right|^2 \]

\[ P_{VV}(\alpha, \beta) = \frac{1}{2} \cos^2(\beta - \alpha) \]
\[ P_{VH}(\alpha, \beta) = \frac{1}{2} \sin^2(\beta - \alpha) \]

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

\[ E(\alpha, \beta) = \frac{N(\alpha, \beta) + N(\alpha, \beta_\bot) - N(\alpha, \beta_\bot) - N(\alpha_\bot, \beta)}{N(\alpha, \beta) + N(\alpha, \beta_\bot) - N(\alpha, \beta_\bot) - N(\alpha_\bot, \beta)} \]
Experimental setup
Down-Converted cones

Following the Clauser, Horne, Shimony and Holt ideas:

\[ s = -\frac{1}{\sqrt{2}} - \frac{1}{\sqrt{2}} + \frac{1}{\sqrt{2}} + \frac{1}{\sqrt{2}} = 2\sqrt{2} \]
Experimental results
Experimental results

Values to calculate the parameters E and S

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<td>$\alpha'=135^0$</td>
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We violated Bell's inequalities!

We proved non-locality!
Experimental Quantum dots as single emitters

Resonance in optical frequencies.

Size of the structure

Particle in a box

$$g^{(2)}(\tau) = \frac{\langle n_1(t)n_2(t+\tau) \rangle}{\langle n_1(t) \rangle \langle n_2(t+\tau) \rangle}$$
Experimental setup

Electrical calibration

Confocal microscopy

http://www.optics.rochester.edu/workgroups/lukishova/QuantumOpticsLab/homepage/opt253_labs_3_4_manual_08.pdf

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Photonic Bandgap Materials

http://www.optics.rochester.edu/workgroups/lukishova/QuantumOpticsLab/homepage/opt253_labs_3_4_manual_08.pdf
CdSe Quantum dots blinking
Antibunching of CdSe QDs

\[ g^{(2)}(\tau) = \frac{\langle n_1(t) n_2(t+\tau) \rangle}{\langle n_1(t) \rangle \langle n_2(t+\tau) \rangle} g^{(2)}(0) \]

\begin{align*}
\geq 1 & \quad \text{Classic light source} \\
< 1 & \quad \text{Quantum light source} \\
\circ & \quad \text{Single photon emitter}
\end{align*}

Hanbury and Twiss setup

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Colloidal Quantum dots blinking
Fluorescence Lifetime

\[ Counting = A \exp\left(-\frac{\Delta t}{\tau}\right) \]

The average lifetime determined by averaging the 4 curves shown above and fitting was 67.2 ns with an error percentage of 4.72%.
I think that in the future will be interesting to use a Mach-Zehnder and Young interferometer to calculate coherence parameters.

The measurement of second order correlation function in the Mach-Zehnder interferometer will allow to experimentally compare the difference between antibunching and coherent light.
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