Single Photon Quantum Information Experiments Any Physics Department Can Build!

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https://www.physlab.org/optics-lab/
Salient Features of a Quantum Understanding of the World

- Quantization
- Superposition
- Entanglement
- Interference
- Uncertainty
- Measurement
Overview of the single photon lab

a) Optical setup
b) Photon detection and counting
c) Photon statistics
Figure 1.4: 405 nm pump beam hitting the BBO crystal stack. BBO crystals down-convert 405nm photons into two 810nm photons.

Figure 1.6: An SPCM on the left and its power supply on the right.
Producing single photons

- Type I spontaneous parametric downconversion with β-barium borate (BBO)\(^1\)
- Pump beam 405 nm, 50 mW
- Generation of polarization-entangled photon beams
- Gating of one beam at detector A projects the other beam into single photon state.
Detecting single photons

- Each detector comprises an avalanche photodiode that outputs a 20 ns 5V pulse on each detection of a photon.
- Pulses coincident at two or more detectors are counted by a coincidence counting unit (CCU).
- Pulses from individual detectors are also counted by the CCU.
- The counts are transmitted to a computer for visualization and analysis of results.
What do photon statistics tell us?

- Classically, sub-Poissonian ($\Delta n < \sqrt{n}$) light is impossible.
- A coherent source shows Poissonian ($\Delta n = \sqrt{n}$) whereas a fluctuating source shows super-Poissonian ($\Delta n > \sqrt{n}$) statistics.
- Our single-detector counts show super-Poissonian while the gated (coincidence) counts show sub-Poissonian statistics.
Particle nature of light

- Hypothesis: a single particle can only be detected at one place\(^4\).

- 2\(^{nd}\) order correlation function

\[ g^{(2)}(0) = \frac{P_{ABB'}}{P_{AB}P_{AB'}} \]

- In an experimental run of 10 minutes, we obtained

\[ g^{(2)}(0) = 0.080 \pm 0.005 \]

- Hanbury Brown-Twiss experiment
Measuring the quantum state - I

- A general pure state can be expressed as
  \[ |\Psi\rangle = a |H]\rangle + b e^{i\phi} |V]\rangle \]
- Measurement destroys the single photon. So we perform measurements on identically prepared photons.
- Three parameters require us to make measurements in three different bases.

<table>
<thead>
<tr>
<th>Input</th>
<th>Prediction</th>
<th>Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>H\rangle$</td>
<td>$a = 1.000, b = 0.000$</td>
</tr>
<tr>
<td>$</td>
<td>45^\circ\rangle$</td>
<td>$a = 0.707, b = 0.707$, $\theta = 0.000$</td>
</tr>
<tr>
<td>$</td>
<td>L\rangle$</td>
<td>$a = 0.707, b = 0.707$, $\theta = -1.571$</td>
</tr>
</tbody>
</table>
Measuring the quantum state - II

• The peanut method

• Used in antenna polarimetry, optical polarimetry, quantum state measurement

• Applies both to classical and quantum light (single qubit)

• Can be used to determine the Stokes parameters or the ellipse parameters
Hippopedal intensity plots: drawing comparisons between antenna and optical polarimetry

Muhammad Hamza Waseem, Faizan-e-Ilahi, and Muhammad Sabieh Anwar*
Classical Erasure Experiment

(a) 

(b) 

Screen
Interferometry and Quantum Erasure

[Diagram of interferometer with labels: Laser, P, HWP, PBS, A, B, BDP, HWP, BDP, HWP, BDP, P]

[Graphs showing normalized intensity vs. polarizer orientation and HWP orientation]
Testing entanglement – Nonlocality I

• Entanglement gives rise to ‘spooky action at a distance’. There could be a hidden variable involved.

• Bell inequalities – experimental tests for local realistic theories:

• CHSH test of local realism\(^7\)

\[ |S| \leq 2 \]
\[ S = E(a, b) - E(a, b') + E(a', b) + E(a', b') \]
\[ E(\alpha, \beta) = P_{HH} + P_{VV} - P_{HV} - P_{VH} \]

• We prepared the state

\[ |\psi\rangle = \frac{1}{\sqrt{2}} (|H\rangle_A |H\rangle_B + |V\rangle_A |V\rangle_B) \]

and for the angles

\[ a = -45^\circ, \ a' = 0^\circ, \ b = -22.5^\circ, \ b' = 22.5^\circ \]

we obtained

\[ S = 2.331 \pm 0.004 \]
Testing entanglement – Nonlocality II

- Hardy’s test of local realism
- Another test – another inequality

\[ H \leq 0 \]

\[ H = P(\beta, -\beta) - P(\beta, \alpha^\perp) - P(-\alpha^\perp, -\beta) - P(-\alpha, \alpha) \]

- We created the state

\[ |\psi\rangle = \sqrt{0.8} |H\rangle_A |H\rangle_B + \sqrt{0.2} |V\rangle_A |V\rangle_B \]

and obtained

\[ H = 0.107 \pm 0.002 \] which violates local realism.
Testing entanglement – Nonlocality III

- Freedman’s test of local realism
- Yet another inequality!

\[ \delta = \left| \frac{N(22.5^\circ) - (67.5^\circ)}{N_0} \right| - \frac{1}{4} \leq 0 \]

- We created the state

\[ |\psi\rangle = \frac{1}{\sqrt{2}}(|H\rangle_A |H\rangle_B + |V\rangle_A |V\rangle_B) \]

and obtained

\[ \delta = 0.095 \pm 0.003 \]

which violates local realism.

How do we check if the state is perfectly entangled?
Gauging entanglement? Tomography!

- A set of measurements with different bases to determine the two-qubit density matrix\(^9\):
  \[
  \hat{\rho} = \frac{1}{4} \sum_{i,j=0}^{3} S_{ij} \hat{\sigma}_i \otimes \hat{\sigma}_j
  \]

- For the Bell state
  \[
  |\psi\rangle = \frac{1}{\sqrt{2}} (|H\rangle_A |H\rangle_B + |V\rangle_A |V\rangle_B)
  \]

we obtained the density matrix with fidelity 0.75 using maximum likelihood estimation\(^9\).
<table>
<thead>
<tr>
<th>State</th>
<th>Predicted density matrix</th>
<th>Measured density matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>H\rangle$</td>
<td>$\begin{pmatrix} 1 &amp; 0 \ 0 &amp; 0 \end{pmatrix}$</td>
</tr>
<tr>
<td>$</td>
<td>V\rangle$</td>
<td>$\begin{pmatrix} 0 &amp; 0 \ 0 &amp; 1 \end{pmatrix}$</td>
</tr>
<tr>
<td>$</td>
<td>D\rangle$</td>
<td>$\begin{pmatrix} 0.5 &amp; 0.5 \ 0.5 &amp; 0.5 \end{pmatrix}$</td>
</tr>
<tr>
<td>$</td>
<td>A\rangle$</td>
<td>$\begin{pmatrix} 0.5 &amp; -0.5 \ -0.5 &amp; 0.5 \end{pmatrix}$</td>
</tr>
<tr>
<td>$</td>
<td>L\rangle$</td>
<td>$\begin{pmatrix} 0.5 &amp; 0.5i \ -0.5i &amp; 0.5 \end{pmatrix}$</td>
</tr>
<tr>
<td>$</td>
<td>R\rangle$</td>
<td>$\begin{pmatrix} 0.5 &amp; -0.5i \ 0.5i &amp; 0.5 \end{pmatrix}$</td>
</tr>
</tbody>
</table>

Table 6.1: Results of single qubit tomography.
<table>
<thead>
<tr>
<th>State</th>
<th>Predicted density matrix</th>
<th>Measured density matrix</th>
<th>Fidelity</th>
</tr>
</thead>
</table>
| $|HH\rangle$ | \[
\begin{pmatrix}
1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
\end{pmatrix}
\] | \[
\begin{pmatrix}
0.93 & -0.11 & 0.03 & -0.03 \\
-0.11 & 0.06 & 0.00 & 0.01 \\
0.03 & 0.00 & 0.00 & 0.00 \\
-0.03 & 0.01 & 0.00 & 0.01 \\
\end{pmatrix}
\] | 0.93 |
| $|VV\rangle$ | \[
\begin{pmatrix}
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 \\
\end{pmatrix}
\] | \[
\begin{pmatrix}
0.02 & -0.01 & -0.01 & 0.07 \\
-0.01 & 0.02 & 0.01 & -0.10 \\
-0.01 & 0.01 & 0.05 & 0.05 \\
0.07 & -0.10 & 0.05 & 0.91 \\
\end{pmatrix}
\] | 0.91 |
| $\frac{|HH\rangle+|VV\rangle}{2}$ | \[
\begin{pmatrix}
0.5 & 0 & 0 & 0.5 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0.5 & 0 & 0 & 0.5 \\
\end{pmatrix}
\] | \[
\begin{pmatrix}
0.49 & 0.05 & 0.01 & 0.30 \\
0.05 & 0.05 & 0.02 & 0.01 \\
0.01 & 0.02 & 0.05 & -0.01 \\
0.30 & 0.01 & -0.01 & 0.41 \\
\end{pmatrix}
\] | 0.75 |
Quantum process tomography of a magneto-optic transformation

Ali Akbar, Faizan-e-Illahi, Muhammad Sabieh Anwar*
\[ \chi^F = \begin{pmatrix} 0.71 & -0.024i & 0.45i & 0.051i \\ 0.024i & 0.00 & -0.015 & 0.00 \\ -0.45i & -0.015 & 0.29 & 0.032 \\ -0.051i & 0.00 & 0.032 & 0.00 \end{pmatrix} \]
References


