Exploring Fundamentals of Quantum Mechanics with Optics

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REED COLLEGE
Photon Laboratories

Experiments

- Spontaneous parametric down conversion
- “Proving” light is made of photons
- Single photon interference
  - Quantum eraser
- Quantum state measurement
- Tests of local realism
  - Entanglement
- Hong-Ou-Mandel interference
- Entanglement witness
- …
“Proving” Photons Exist

If a single photon is incident on a beamsplitter, it can only go one way

- Only one detector will fire
- No coincident detections

"…a single photon can only be detected once!"
- P. Grangier et al.
Quantify:

\[ g^{(2)}(0) = \frac{\langle \hat{I}_T \hat{I}_R \rangle}{\langle \hat{I}_T \rangle \langle \hat{I}_R \rangle} = \frac{P_{TR}}{P_T P_R} \]

\[ P_{TR} = 0 \]

\[ \therefore g^{(2)}(0) = 0 \quad \text{(for a single photon input)} \]

The degree of second-order coherence

**Single Photon on a Beamsplitter**
Classical Wave on a Beamsplitter

\[ g^{(2)}(0) = \frac{\langle I_T I_R \rangle}{\langle I_T \rangle \langle I_R \rangle} = \frac{P_{TR}}{P_T P_R} \]

\[ I_T = \mathcal{T} I_i \quad I_R = \mathcal{R} I_i \quad \mathcal{T} + \mathcal{R} = 1 \]

\[ g^{(2)}(0) = \frac{\langle I_i^2 \rangle}{\langle I_i \rangle^2} \]

\[ \langle I_i^2 \rangle \geq \langle I_i \rangle^2 \quad \text{(Cauchy-Schwartz inequality)} \]

\[ \therefore g^{(2)}(0) \geq 1 \quad \text{(for a classical wave)} \]
Spontaneous Parametric Downconversion

One photon converted into two

Energy Conservation

\[ \omega_p = \omega_s + \omega_i \]

\[ \omega_s \sim \omega_i \sim \omega_p / 2 \]

Momentum Conservation

\[ \mathbf{k}_p = \mathbf{k}_s + \mathbf{k}_i \]

Photons produced at the same time
Making a Single Photon State

- Spontaneous parametric downconversion
  - One photon converted into two
  - Photons always come in pairs

You know you have a photon in the other beam
“Proving” Photons Exist

[Diagram showing light paths through a beam splitter, mirrors, and detectors labeled G, BS, T, and R]
**Typical Student Results**

\[ g^{(2)}(0) \geq 1 \quad \text{(for a classical wave)} \]
\[ g^{(2)}(0) = 0 \quad \text{(for a single photon input)} \]

<table>
<thead>
<tr>
<th>( g^{(2)}(0) )</th>
<th>St. dev. of ( g^{(2)}(0) )</th>
<th>St. devs. Violation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.064</td>
<td>0.008</td>
<td>117</td>
</tr>
<tr>
<td>0.109</td>
<td>0.049</td>
<td>18</td>
</tr>
<tr>
<td>0.103</td>
<td>0.037</td>
<td>24</td>
</tr>
<tr>
<td>0.107</td>
<td>0.006</td>
<td>149</td>
</tr>
</tbody>
</table>
“Proving” Photons Exist
Single-Photon Interference
Results

Coincidence Counts, Single Photons ($V=89\%$)
Results

Coincidence Counts, Single Photons ($V=89\%$)

Simultaneously displays wave-like (interference) and particle like ($g^{(2)}(0)<1$) behavior.
Quantum Teleportation

Transmit the quantum state of a particle from one place to another

- Don’t send the actual particle
- Send information necessary to recreate the state
- No cloning theorem
  - State of original particle must be destroyed
Two-Particle States

\[
|0\rangle_A |0\rangle_B \quad |0\rangle_A |1\rangle_B \quad |1\rangle_A |0\rangle_B \quad |1\rangle_A |1\rangle_B
\]

Bell States

- A basis for 2-particle systems

\[
|\phi^+\rangle_{AB} = \frac{1}{\sqrt{2}} (|0\rangle_A |0\rangle_B + |1\rangle_A |1\rangle_B )
\]

\[
|\phi^-\rangle_{AB} = \frac{1}{\sqrt{2}} (|0\rangle_A |0\rangle_B - |1\rangle_A |1\rangle_B )
\]

\[
|\psi^+\rangle_{AB} = \frac{1}{\sqrt{2}} (|0\rangle_A |1\rangle_B + |1\rangle_A |0\rangle_B )
\]

\[
|\psi^-\rangle_{AB} = \frac{1}{\sqrt{2}} (|0\rangle_A |1\rangle_B - |1\rangle_A |0\rangle_B )
\]
Quantum Teleportation

$\left| \phi^+ \right\rangle_{AB}$
Quantum Teleportation

\[ |\psi\rangle_a = (\alpha |0\rangle_a + \beta |1\rangle_a) \]

\[ |\Psi\rangle = |\psi\rangle_a \otimes |\phi^+\rangle_{AB} \]
Quantum Teleportation

\[ |\psi\rangle_a = (\alpha |0\rangle_a + \beta |1\rangle_a) \]

\[ |\Psi\rangle = |\psi\rangle_a \otimes |\phi^+\rangle_{AB} \]

\[ = \frac{1}{2} |\phi^+\rangle_{aA} \otimes (\alpha |0\rangle_B + \beta |1\rangle_B) \]

\[ + \frac{1}{2} |\phi^-\rangle_{aA} \otimes (\alpha |0\rangle_B - \beta |1\rangle_B) \]

\[ + \frac{1}{2} |\psi^+\rangle_{aA} \otimes (\beta |0\rangle_B + \alpha |1\rangle_B) \]

\[ + \frac{1}{2} |\psi^-\rangle_{aA} \otimes (-\beta |0\rangle_B + \alpha |1\rangle_B) \]

\[ |\psi'\rangle_B = (\beta |0\rangle_B + \alpha |1\rangle_B) \]
Quantum Teleportation

\[ |\psi\rangle_a = (\alpha |0\rangle_a + \beta |1\rangle_a) \]
\[ |\Psi\rangle = |\psi\rangle_a \otimes |\phi^+\rangle_{AB} \]
\[ = \frac{1}{2} |\phi^+\rangle_{aA} \otimes (\alpha |0\rangle_B + \beta |1\rangle_B) \]
\[ + \frac{1}{2} |\phi^-\rangle_{aA} \otimes (\alpha |0\rangle_B - \beta |1\rangle_B) \]
\[ + \frac{1}{2} |\psi^+\rangle_{aA} \otimes (\beta |0\rangle_B + \alpha |1\rangle_B) \]
\[ + \frac{1}{2} |\psi^-\rangle_{aA} \otimes (-\beta |0\rangle_B + \alpha |1\rangle_B) \]
\[ |\psi\rangle_B = \hat{U} |\psi\rangle_B = (\alpha |0\rangle_B + \beta |1\rangle_B) \]
\[ |\psi\rangle_B = \hat{U} |\psi\rangle_B = (\alpha |0\rangle_B + \beta |1\rangle_B) \]
Four-Photon Source
Four-Photon Source

one photon into two photons
**Four-Photon Source**

One photon into two photons

PBS

Input pulses: 50fs, 80 MHz
Photon pairs: ~10 kHz
Four simultaneous photons: ~1Hz
Four-Photon Source

One photon into two photons

PBS

Input pulses: 50fs, 80 MHz
Photon pairs: ~10 kHz
Four simultaneous photons: ~1Hz
Interference of Independent Sources

one photon into two photons

PBS
Hong-Ou-Mandel Interference

One photon into each arm
Each can either reflect or transmit
Four possibilities
Hong-Ou-Mandel Interference

Two possibilities to go to opposite detectors
Hong-Ou-Mandel Interference

Two possibilities to go to opposite detectors: add them
Hong-Ou-Mandel Interference

Two possibilities to go to opposite detectors: add them $\pi$ phase shift on one term
Hong-Ou-Mandel Interference

Two possibilities to go to opposite detectors: add them $\pi$ phase shift on one term
Terms where photons go opposite ways cancel
Hong-Ou-Mandel Interference

Photons ALWAYS go to the same detector

- No coincidence detections between the two detectors

Mosley et al., PRL 100, 133601 (2008)
Research Interests

Quantum tomography
  • State preparation and measurement (SPAM) tomography
Error detection
  • Quantum Key Distribution (Cryptography)
Weak and protected measurements
Summary

Photon Labs
  • Explore fundamental quantum mechanics
  • Many different experiments
  • They work!

The future
  • More than two photons
  • Quantum teleportation
  • Telecom band (1550 nm)
With lots of help from:

Faculty:  R. Davies (Utah St.)
          D. Branning (Trinity College)
          E. Galvez (Colgate)


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