Experiments with Individual Photons in an Undergraduate Lab

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Support: NSF, Whitman College

Quantum Mechanics

Quantum information is changing how we think about quantum systems.

- Convey this to students

Many experiments involve photons

- Doable by undergraduates

Project Goals

1) Develop a series of advanced undergraduate laboratories exploring modern aspects of quantum mechanics
   - Study the properties of individual photons
2) Develop course materials that take advantage of these labs
   - Use photon polarization as an example 2-dimensional quantum system

New Course

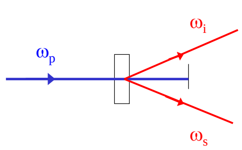
Will be taught this fall

Four experiments

- Spontaneous parametric downconversion
- Proving light is made of photons
- Single photon interference
- Test of local-realism

#1 Spontaneous Parametric Downconversion

One photon converted into two



Energy Conservation

$\omega_p = \omega_s + \omega_i$

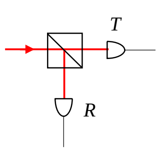
$\omega_s \sim \omega_i \sim \omega_p/2$

Momentum Conservation

$\vec{k}_p = \vec{k}_s + \vec{k}_i$

Photons produced at the same time

#2 Light is Made of Photons

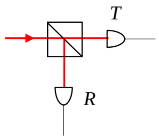


If a single photon is incident on a beamsplitter, it can only go one way

- Only one detector will fire
- No coincident detections

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

Single Photon on a Beamsplitter



- Quantify:

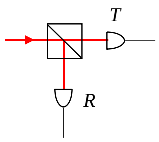
$$g^{(2)}(0) = \frac{\langle : \hat{I}_T \hat{I}_R : \rangle}{\langle \hat{I}_T \rangle \langle \hat{I}_R \rangle} = \frac{P_{TR}}{P_T P_R}$$

$$P_{TR} = 0$$

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

The degree of second-order coherence

Classical Wave on a Beamsplitter



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

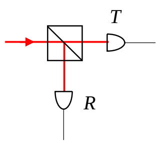
$$I_T = \mathcal{T} I_I \quad I_R = \mathcal{R} I_I \qquad \mathcal{T} + \mathcal{R} = 1$$

$$g^{(2)}(0) = \frac{\langle I_I^2 \rangle}{\langle I_I \rangle^2}$$

$$\langle I_I^2 \rangle \geq \langle I_I \rangle^2 \quad \text{(Cauchy-Schwartz inequality)}$$

$$\therefore g^{(2)}(0) \geq 1 \quad \text{(for a classical wave)}$$

Distinguishing Classical and Quantum Fields



Classical waves: $g^{(2)}(0) \geq 1$

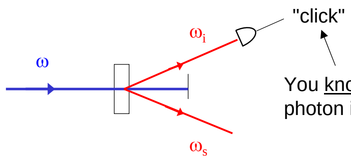
Therefore, any field with $g^{(2)}(0) < 1$ cannot be described classically, and is inherently quantum mechanical.

Single photon state: $g^{(2)}(0) = 0$

Making a Single Photon State

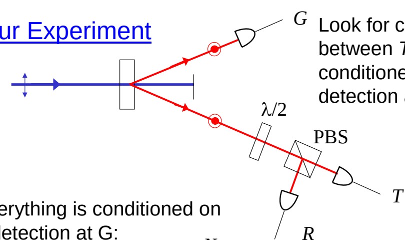
Spontaneous parametric downconversion

- Photons always come in pairs



You know you have a photon in the other beam

Our Experiment



Look for coincidences between *T* and *R*, conditioned on a detection at *G*.

Everything is conditioned on a detection at G:

$$P_{GTR} = \frac{N_{GTR}}{N_G}$$

$$g^{(2)}(0) = \frac{P_{GTR}}{P_{GT}P_{GR}} \qquad P_{GT} = \frac{N_{GT}}{N_G} \qquad g^{(2)}(0) = \frac{N_{GTR}N_G}{N_{GT}N_{GR}}$$

$$P_{GR} = \frac{N_{GR}}{N_G}$$

Results

Integration time per pt.	Number of pts.	Total acq. time	$g^{(2)}(0)$	St. dev. of $g^{(2)}(0)$
2.7 s	110	~ 5 min.	0.0188	0.0067
5.4 s	108	~ 10 min.	0.0180	0.0041
11.7 s	103	~ 20 min.	0.0191	0.0035
23.4 s	100	~ 40 min.	0.0177	0.0026

In 5 minutes of counting we violate the classical inequality $g^{(2)}(0) \geq 1$ by 146 standard deviations.

Why not 0?

Perfect single photons have $g^{(2)}(0) = 0$.

- i.e., we expect no coincidences between *T* and *R*

Why do we measure $g^{(2)}(0) = 0.0177 \pm 0.0026$?

Accidental coincidences

- Due to finite coincidence window (2.5 ns)

Expected accidental coincidence rate explains difference from 0.

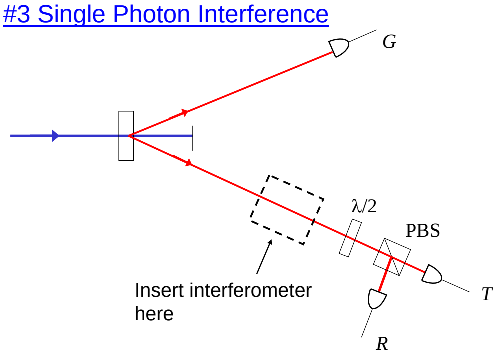
Other Field States

Have recently measured other field states

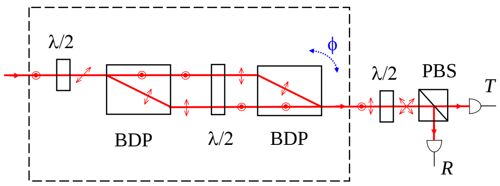
Classical fields: $g^{(2)}(0) \geq 1$

- Downconversion *without* conditioning
- Laser below threshold
- Pulsed laser
- White light source (R.C. Haskell, Harvey Mudd College)

#3 Single Photon Interference



Polarization Interferometer



Easy to align
- equal pathlengths

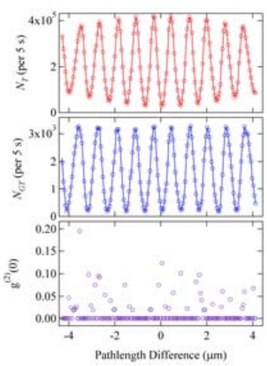
EXTREMELY stable

Results

Raw Counts (*V*=88%)

Coincidence Counts, Single Photons (*V*=89%)

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

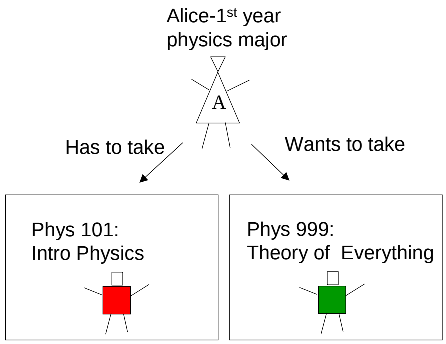


#4 Test of Local-Realism

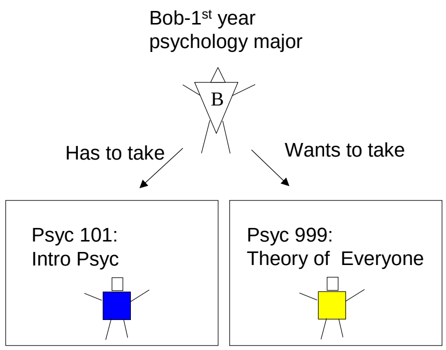
Could do a Bell inequality test
- Dehlinger and Mitchell

We use Hardy's test
- Essentially the same as a test of a Bell inequality
  - More intuitive
- Easy to switch back and forth between Hardy and Bell

Alice



Bob



The Situation

Alice

- Randomly chooses Phys 101 or 999
  - 101
    - Prof wears red or blue
  - 999
    - Prof wears green or yellow

Bob

- Randomly chooses Psyc 101 or 999
  - 101
    - Prof wears red or blue
  - 999
    - Prof wears green or yellow

Analyzing the data

On days when they both to to 101:

- They SOMETIMES see RR (9% of 101-101 visits)

1) Alice R, Bob R OK [P(R,R)=0.09]

Analyzing the data

On days when they go to opposite classes:

- If one measures R, the other ALWAYS measures G

1) Alice R, Bob R OK [P(R,R)=0.09]
2) Alice R ➔ Bob G [P(R,Y)=0]
3) Bob R ➔ Alice G [P(Y,R)=0]

Clearly, the wardrobe choices of the faculty are NOT random.

Inference

On days where Alice and Bob both go to 101 and measure RR:

- We know that such days are possible
  - 1) Alice R, Bob R OK [P(R,R)=0.09]

If Bob changes his mind and goes to 999:

- He MUST measure G
  - 2) Alice R ➔ Bob G [P(R,Y)=0]

If Alice changes her mind and goes to 999:

- She MUST measure G
  - 3) Bob R ➔ Alice G [P(Y,R)=0]

If BOTH change their minds, they must measure GG

- P(G,G)≥P(R,R)=0.09

Inference

Must be possible for Alice and Bob to measure GG

- P(G,G)≥P(R,R)=0.09

The Data

Alice and Bob NEVER measure GG

- P(G,G)=0

Explanation?

Inference involves classical assumptions:

- Locality - Faculty don't communicate
- Reality - Makes sense to talk about measurements that weren't explicitly performed

Imperfect Correlations

Our inference assumed perfect data:

P(G,G) ≥ P(R,R)   P(R,Y)=0 , P(Y,R)=0

Imperfect correlations, need to modify the inequality:

P(G,G) ≥ P(R,R) - P(R,Y) - P(Y,R)   [CH inequal.]

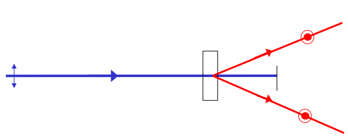
Must be satisfied by any local-realistic system

Define

H = P(R,R) - P(R,Y) - P(Y,R) - P(G,G)

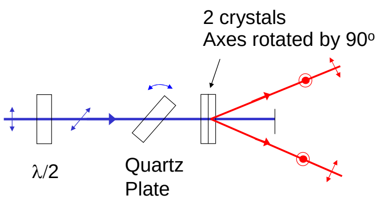
H ≤ 0	Local-Realism
H > 0	Quantum Mechanics

One Crystal Source



$$|\psi_{pol}\rangle = |VV\rangle$$

Polarization Entangled Source



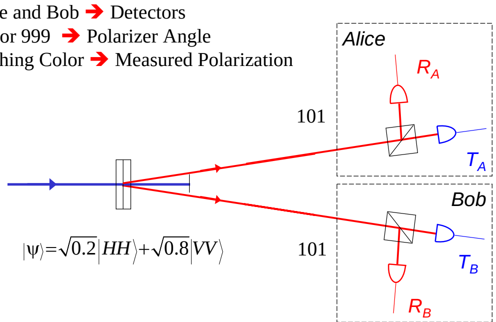
$$\left|\psi_{pol}\right\rangle = a\left|HH\right\rangle + be^{i\phi}\left|VV\right\rangle$$

$$\frac{a}{b} \rightarrow \lambda/2$$

$$\phi \rightarrow \text{Quartz Plate}$$

The Experiment

Faculty ➔ Photons
Alice and Bob ➔ Detectors
101 or 999 ➔ Polarizer Angle
Clothing Color ➔ Measured Polarization



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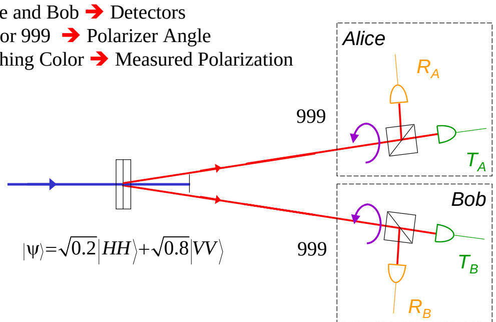

Results

H $\leq$ 0 Local Realism
H > 0 Quantum Mechanics

Best Results: H = 0.1178 $\pm$ 0.0016

- Violates H $\leq$ 0 by over 70 standard deviations

In a Teaching Lab

4 groups of students

- All saw over a 10 st. dev. violation

Hardy

State

- $|\psi\rangle = \sqrt{0.2}|HH\rangle + \sqrt{0.8}|VV\rangle$

Measurements

- Joint probabilities at 4 sets of angles

Classical inequality

- H$\leq$0

Bell

State

- $|\psi\rangle = \frac{1}{\sqrt{2}}(|HH\rangle + |VV\rangle)$

Measurements

- Joint probabilities at 4 sets of angles

Classical inequality

- S$\leq$2

Summary

New QM course:

- Photon polarization -- 2-state system
- Integrated laboratory component
  - Spontaneous parametric downconversion
  - Proving light is made of photons
  - Single photon interference
  - Test of local-realism