Interference, Complementarity, Entanglement and all that Jazz

Mark Beck
Dept. of Physics, Whitman College

With lots of help from:

Faculty: Robert Davies (Seattle U)
Students: Ashifi Gogo, William Snyder, Jeremy Thorn (U of O), Matthew Neel (OSU), Vinsunt Donato (OSU)
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

Experiment Proving Photons Exist

1) Should be conceptually simple
2) Should display the "granular" nature of individual photons
3) Necessary to treat the field quantum mechanically
   - Not explainable using classical waves

Proving Photons Exist

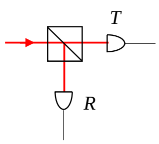
Photoelectric Effect?

- Satisfies criteria 1) & 2)
  - detector "clicks" are granular
- Does NOT satisfy criterion 3)
  - Does not require photons (i.e. a quantum field) for its explanation
  - Can be explained using a semiclassical theory (detector atoms quantized, field is a classical wave)

Grangier Experiment

- P. Grangier, G. Roger, and A. Aspect, Europhys. Lett. **1**, 173-179 (1986).

Single Photon on a Beamsplitter

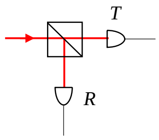


If a single photon is incident on a beamsplitter, what do we know about "clicks" at output detectors?

- Only one detector will fire
- No coincidence detections

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

Single Photon on a Beamsplitter



Quantify:

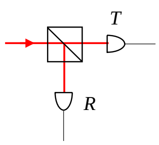
$$g^{(2)}(0) = \frac{\langle : \hat{I}_T \hat{I}_R : \rangle}{\langle \hat{I}_T \rangle \langle \hat{I}_R \rangle} = \frac{P_{TR}}{P_T P_R}$$

$$P_{TR} = 0$$

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

The degree of second-order coherence

Classical Wave on a Beamsplitter



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

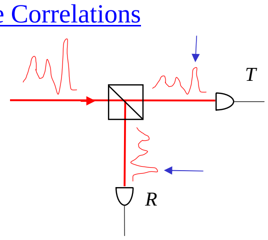
$$I_T = \mathcal{T} I_I \quad I_R = \mathcal{R} I_I \qquad \mathcal{T} + \mathcal{R} = 1$$

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

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

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

Positive Correlations



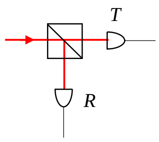
$P \propto I$

Fluctuating input wave simply splits equally at a beamsplitter

T and R are most likely to click at the same time

- Opposite behavior of a single photon

Distinguishing Classical and Quantum Fields



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

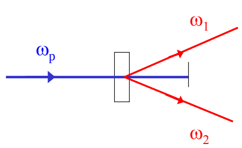
Therefore, any field with $g^{(2)}(0) < 1$ cannot be described classically, and is inherently quantum mechanical.

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

Making a Single Photon State

Spontaneous parametric downconversion

- One photon converted into two



$\omega_p = \omega_1 + \omega_2$

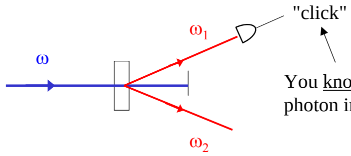
Nominally:

$\omega_1 \sim \omega_2 \sim \omega_p/2$

Making a Single Photon State

Spontaneous parametric downconversion

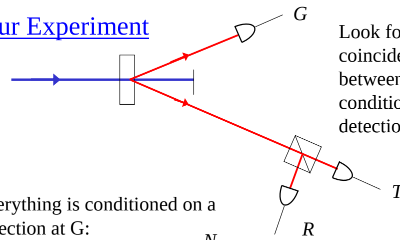
- One photon converted into two
- Photons always come in pairs



You <u>know</u> you have a photon in the other beam

In 1986 Grangier et al. used a cascade decay in Ca as a photon pair source.

Our Experiment



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

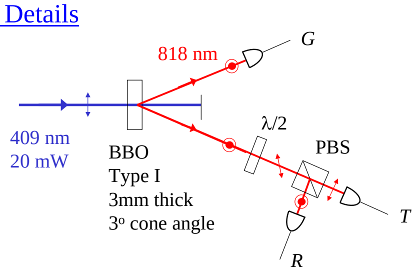
Everything is conditioned on a detection at G:

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

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

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

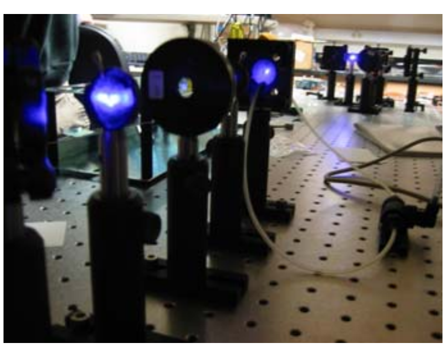
More Details



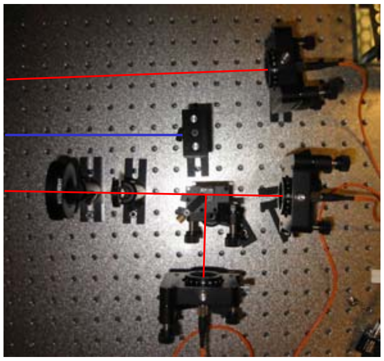
Detectors have RG780 filters

$N_G > 100,000$ cps $\qquad N_{GT} + N_{GR} > 8,000$ cps

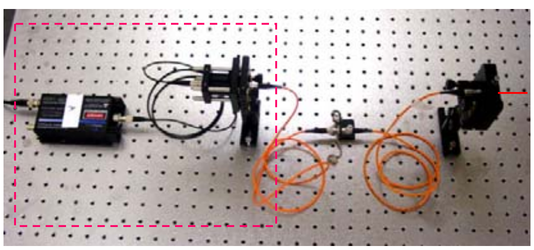
Experimental Setup



Experimental Setup



Collection Optics



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 $g^{(2)}(0) = 0$.

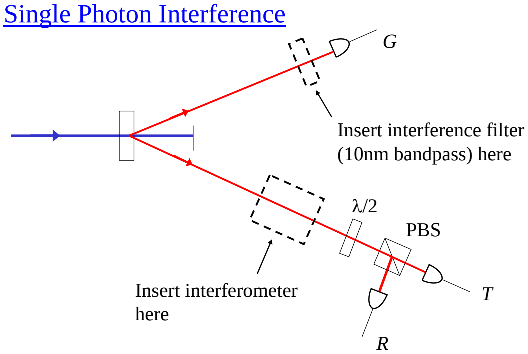
- i.e., we expect no coincidences between T and R

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

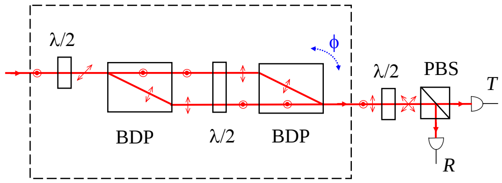
- Accidental coincidences
  - Due to finite coincidence window (2.5 ns)

Expected accidental coincidence rate explains difference from 0.

Single Photon Interference



Polarization Interferometer



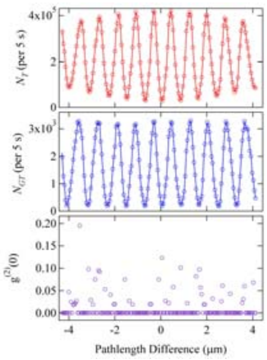
- Easy to align
  - equal pathlengths
- EXTREMELY stable

Results

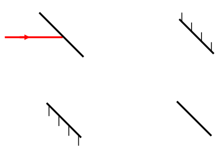
Raw Counts (V=88%)

Coincidence Counts, Single Photons (V=89%)

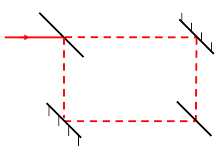
Simultaneously displays wave-like (interference) and particle like ($g^{(2)}(0)<1$) behavior.



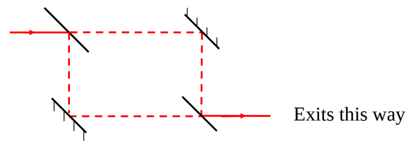
Wave-Particle Complementarity



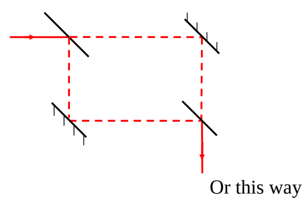
Wave-Particle Complementarity



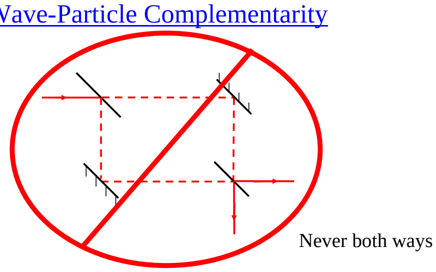
Wave-Particle Complementarity



Wave-Particle Complementarity

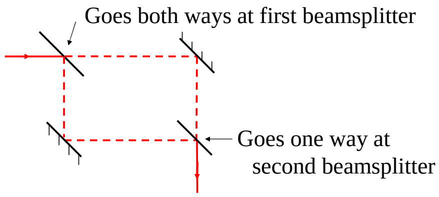


Wave-Particle Complementarity



Not even if phase of interferometer is adjusted so that on *average* the photon goes each way half the time.

Wave-Particle Complementarity



Wave-like behavior inside the interferometer

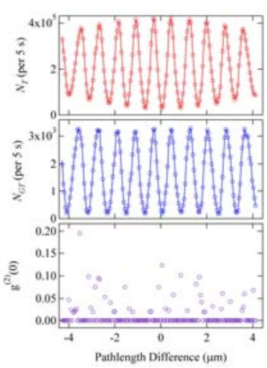
Particle-like behavior outside the interferometer

Results

Raw Counts (*V*=88%)

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

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



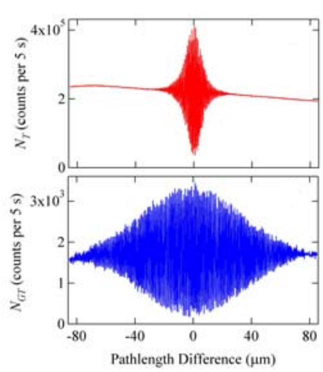
Results

Raw Counts
L_c=12μm (Δλ=57nm)

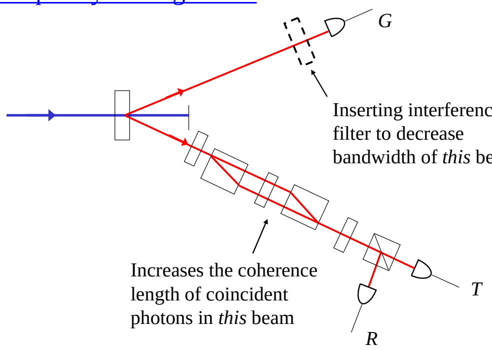
$$L_c = \frac{c}{\Delta \nu} = \frac{\lambda^2}{\Delta \lambda}$$

Coincidence Counts,
Single Photons
L_c=70μm (Δλ=10nm)

Interference filter in *gate* beam (Δλ=10nm)



Frequency Entanglement



Entanglement

Frequencies of the two beams are entangled

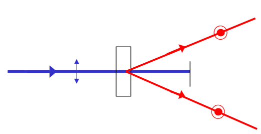
$\omega_p \Rightarrow$ frequency of pump (blue) beam

$$\omega_p = \omega_G + \omega_I$$

$\omega_G, \omega_I \Rightarrow$ frequencies of gate and interferometer beams

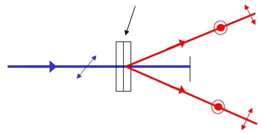
In coincidence, narrowing the distribution of ω_G narrows the distribution of ω_I.

Present Source



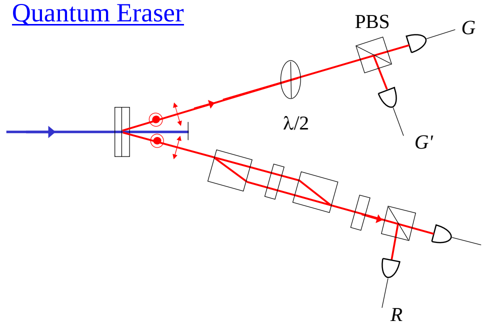
$$|\psi_{pol}\rangle = |\updownarrow, \updownarrow\rangle$$

Polarization Entangled Source

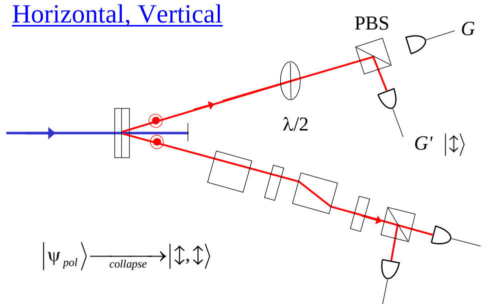


$$\left|\psi_{pol}\right\rangle = \frac{1}{\sqrt{2}}\left(\left|\updownarrow,\updownarrow\right\rangle + \left|\leftrightarrow,\leftrightarrow\right\rangle\right)$$

Quantum Eraser

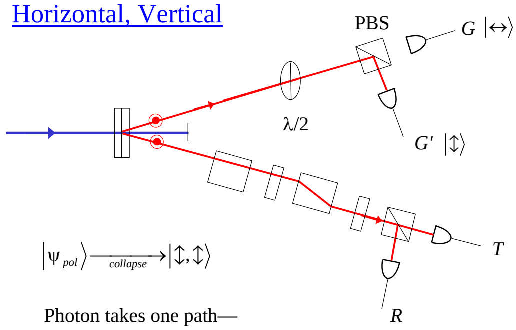


Horizontal, Vertical



$$\left|\psi_{pol}\right\rangle \xrightarrow[collapse]{} \left|\updownarrow,\updownarrow\right\rangle$$

Horizontal, Vertical



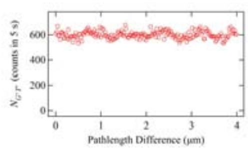
$|\psi_{pol}\rangle \xrightarrow{collapse} |\updownarrow, \updownarrow\rangle$

Photon takes one path—
No interference

Results

Takes one path

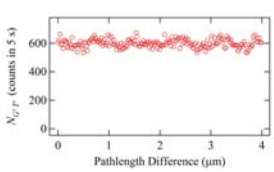
- Have which-path info
- No interference



Results

Takes one path

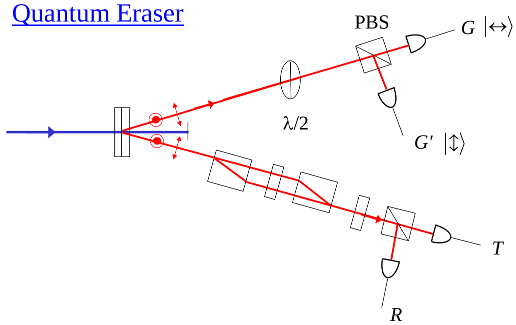
- Have which-path info
- No interference



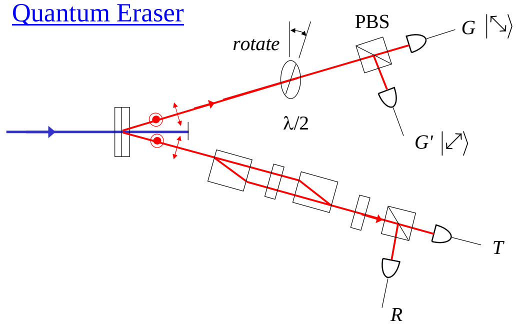
How do we see interference?

- Must take both paths
- Erase which-path info

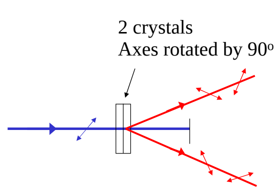
Quantum Eraser



Quantum Eraser



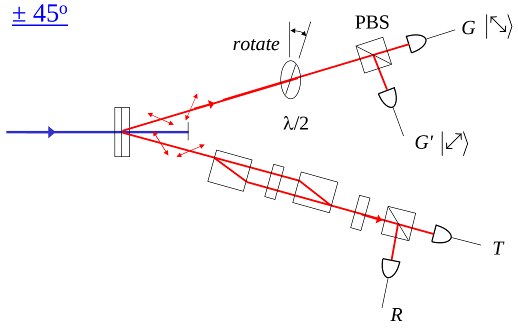
Entangled in *Any* Basis



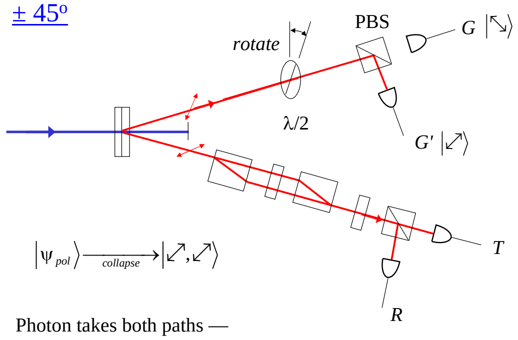
$$\left|\psi_{pol}\right\rangle = \frac{1}{\sqrt{2}}\left(\left|\updownarrow,\updownarrow\right\rangle + \left|\leftrightarrow,\leftrightarrow\right\rangle\right)$$

$$= \frac{1}{\sqrt{2}}\left(\left|\text{⤢},\text{⤢}\right\rangle + \left|\text{⤡},\text{⤡}\right\rangle\right)$$

± 45º



± 45º



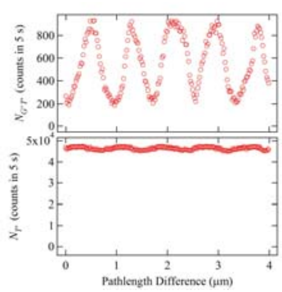
$|\psi_{pol}\rangle \xrightarrow{collapse} |\swarrow\!\!\nearrow, \swarrow\!\!\nearrow\rangle$

Photon takes both paths —
Interference

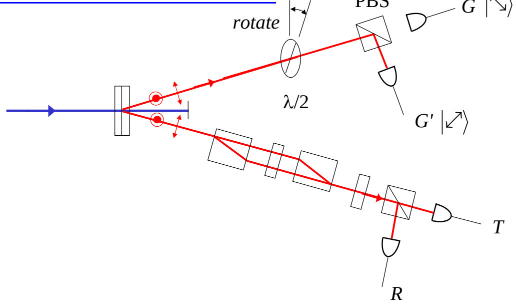
Results

Takes both paths
- Erased which-path info
- Interference

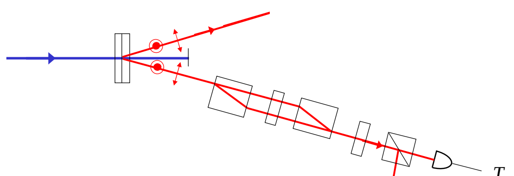
Raw counts (not coincidence)
- No interference
- Why?



No Coincidence Detection

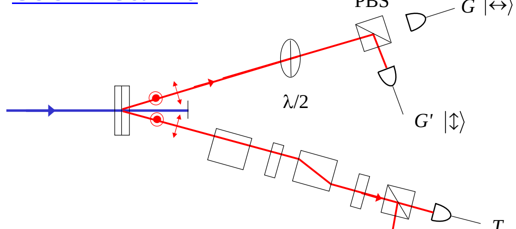


No Coincidence Detection



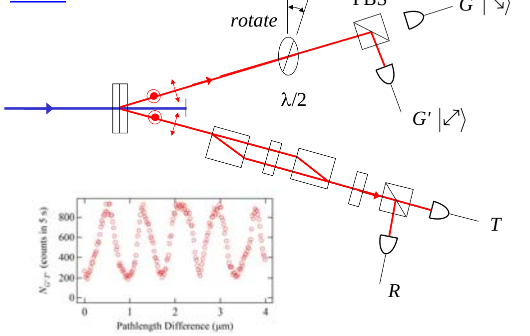
Detection at *T* does NOT yield which-path info.
Why no interference?

COULD Get Info



COULD IN PRINCIPLE know which way the photon went—
No interference

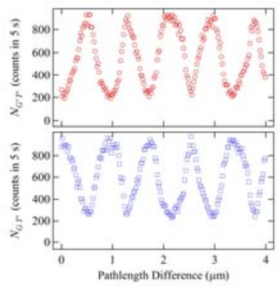
± 45º



Results

Each polarization makes its own interference pattern

- Out of phase



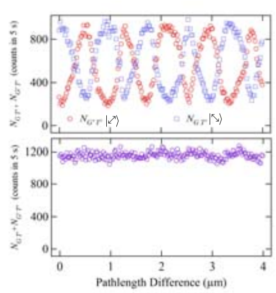
Results

Add *G* and *G'* coincidences

- No interference
- Why?

Again, we're not using gate polarization info

- Could do a different measurement that provides which-path information



Quantum Eraser

Interference

- Not having which-path information is not good enough
- The fact that which-path information is available *in principle* is enough to destroy interference

Only way to erase in principle information is to *explicitly* perform a measurement that erases it.

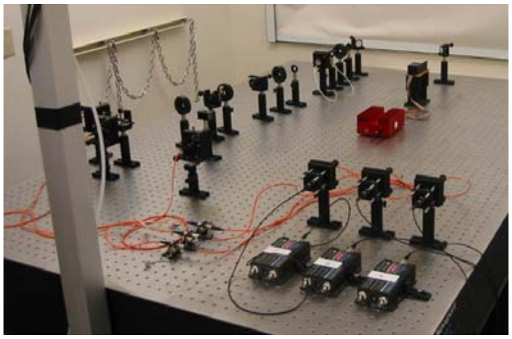
Conclusions

We have performed the following experiments

- Proof of the existence of photons
- Single-photon interference
- Quantum eraser
  - A classical mixed state can mimic certain aspects of the eraser behavior
- Test of Bell inequality
  - $S=2.467\pm0.015$
  - Violates $S\leq2$ by 30 standard deviations

All experiments have been performed by under-graduates, and are suitable for an undergraduate laboratory

Whole Table



http://www.whitman.edu/~beckmk/QM/