Experiments with Single Photons:
Existence Proof and Interference
(and Entanglement of 2 Photons)

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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

Which experiment should undergraduates perform first?

- Proof of the existence of photons!

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

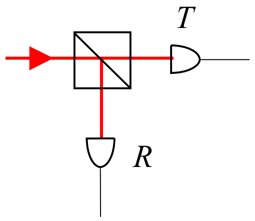
Photoelectric Effect?

- 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

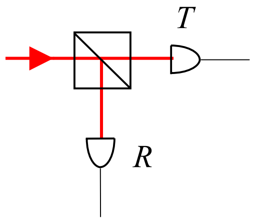


If a single photon is incident on a beamsplitter, what do we know about "clicks" at output detectors?

- 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:

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

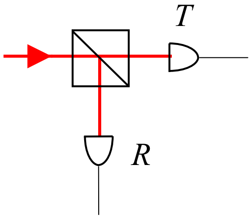
$$= \frac{P_{TR}}{P_T P_R}$$

$$P_{TR} = 0$$

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

The degree of second-order coherence

Classical Wave on a Beamsplitter



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

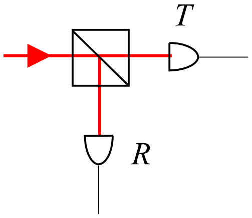
$I_T = \mathcal{T} I_I \quad I_R = \mathcal{R} I_I \qquad \mathcal{T} + \mathcal{R} = 1$

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

$\langle I_I^2 \rangle \geq \langle I_I \rangle^2$ (Cauchy-Schwartz inequality)

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

Distinguishing Classical and Quantum Fields



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

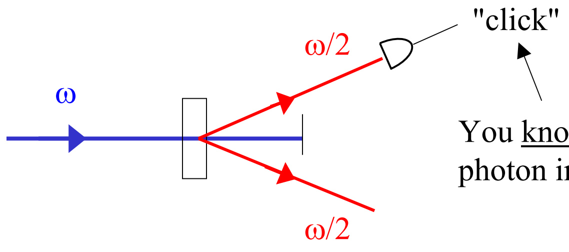
Therefore, any field with $g^{(2)}(0) < 1$ cannot be described classically, and is inherently quantum mechanical.

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

Making a Single-Photon State

Spontaneous parametric downconversion

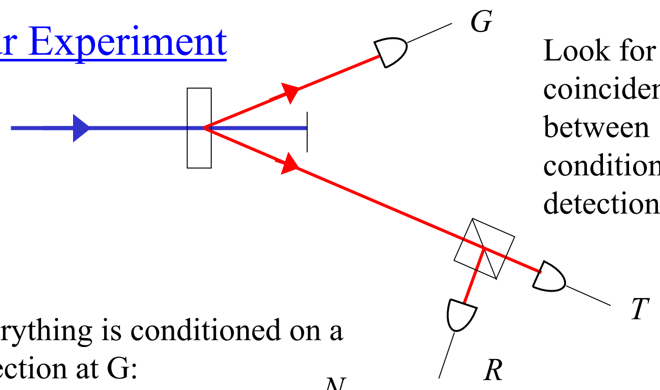
- One photon converted into two
- Photons always come in pairs



You know 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*.

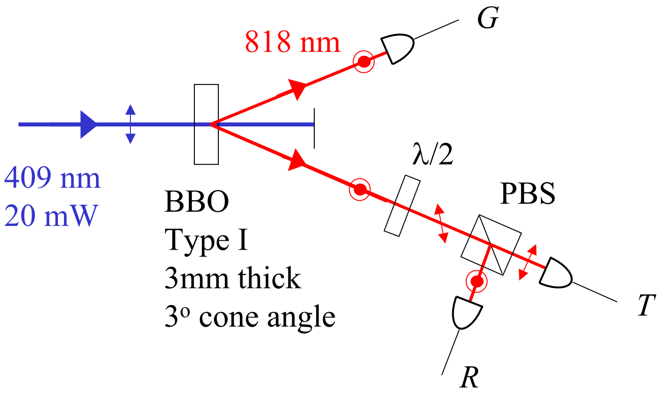
Everything is conditioned on a detection at G:

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

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

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

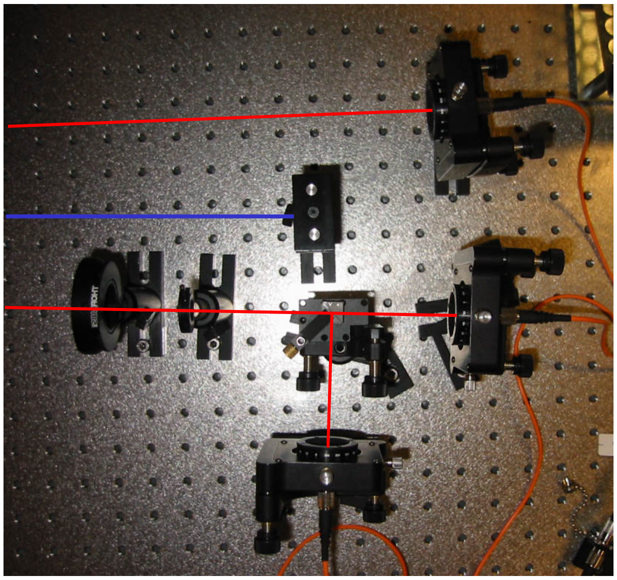
More Details



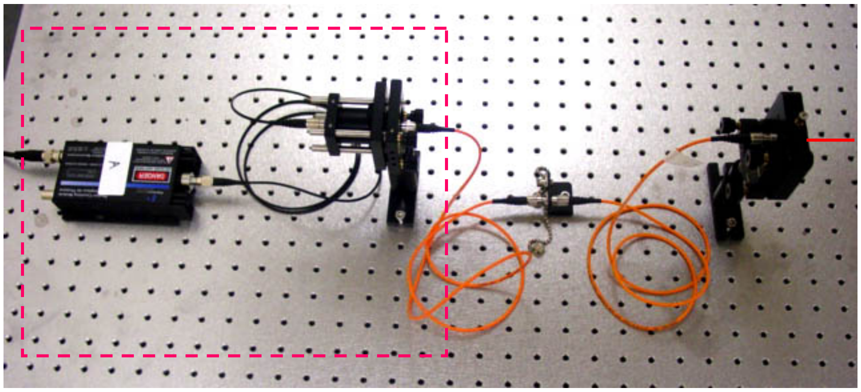
Detectors have RG780 filters

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

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

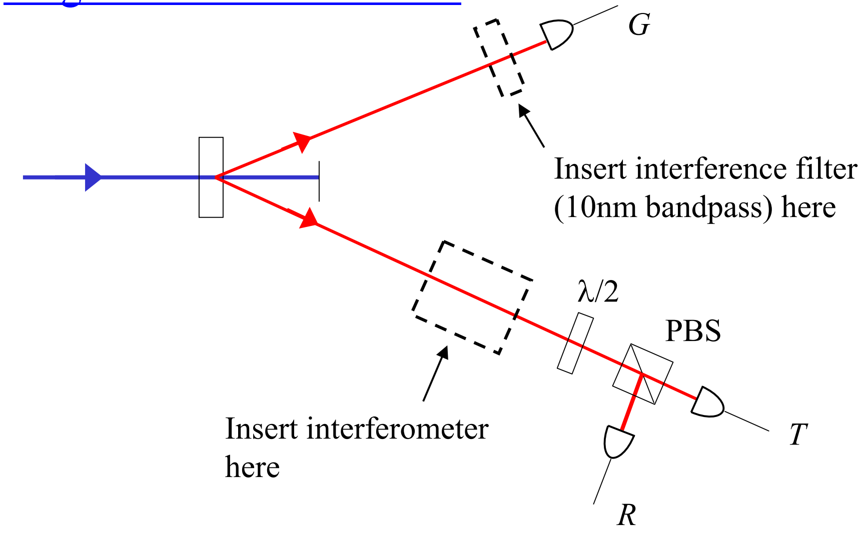
- i.e., we expect no coincidences between T and R

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.

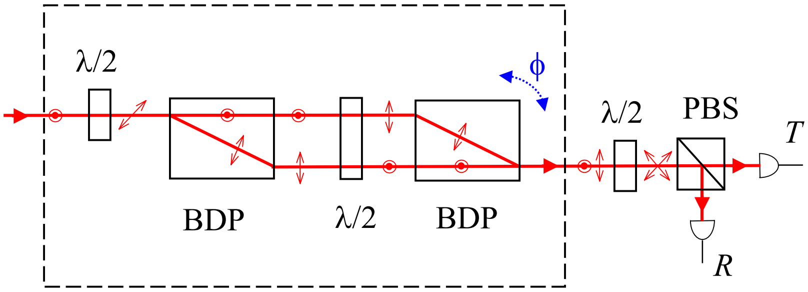
Single Photon Interference



Insert interference filter (10nm bandpass) here

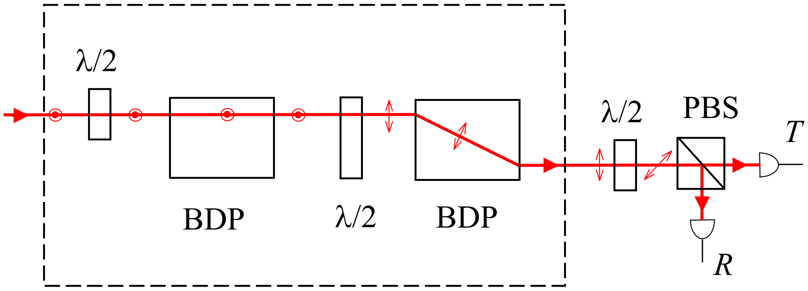
Insert interferometer here

Polarization Interferometer



- Easy to align
  - equal pathlengths
- EXTREMELY stable

No Polarization Interferometer

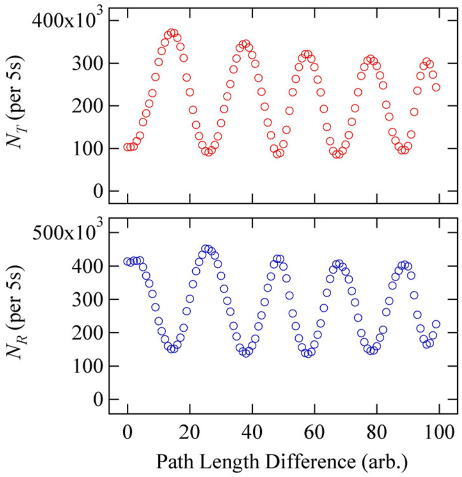


- Remove interferometer by rotating waveplate
- Switch between Grangier expt. and interference expt.

Results — Equal Pathlengths

Raw singles counts, not coincidences.

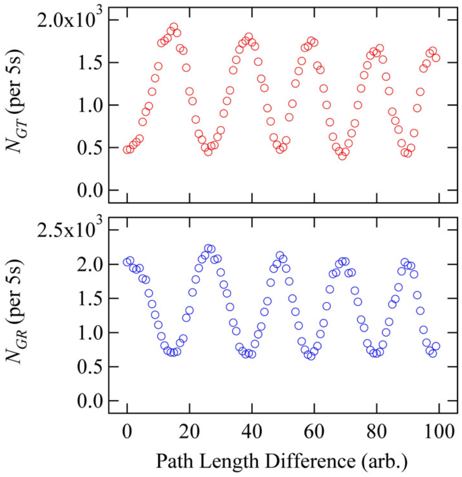
"White-light" fringes.



Results — Equal Pathlengths

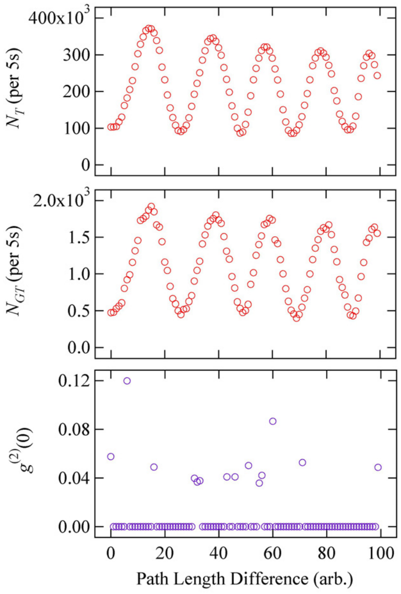
Coincidence counts.

True single photon interference.

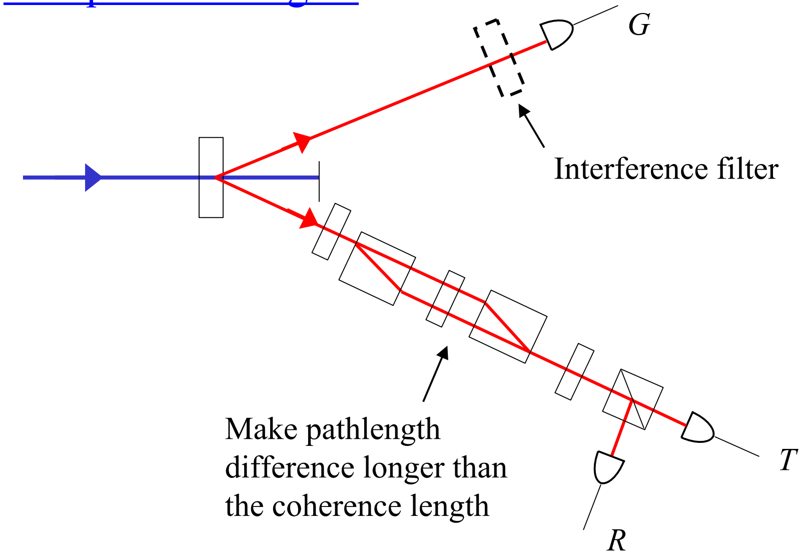


Results — Equal Pathlengths

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



Unequal Pathlengths



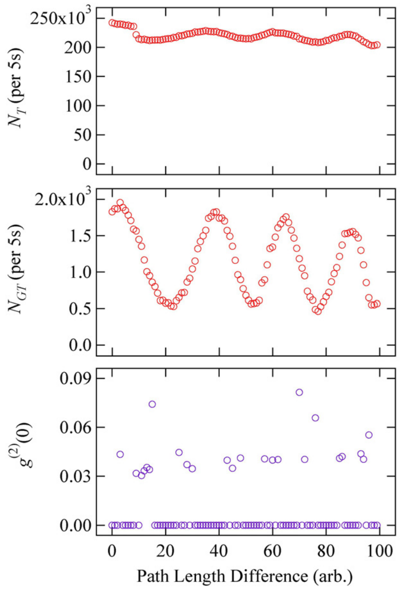
Interference filter

Make pathlength difference longer than the coherence length

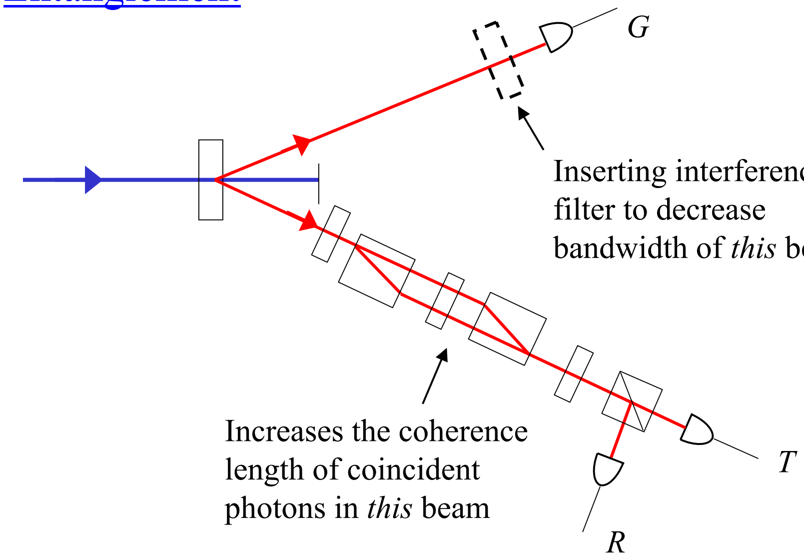
Results — Unequal Pathlengths

Pathlength difference is larger than the coherence length of light in the interferometer.

Why do we still see interference in coincidence?



Entanglement



Inserting interference filter to decrease bandwidth of *this* beam

Increases the coherence length of coincident photons in *this* beam

Entanglement

Frequencies of the two beams are entangled

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

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

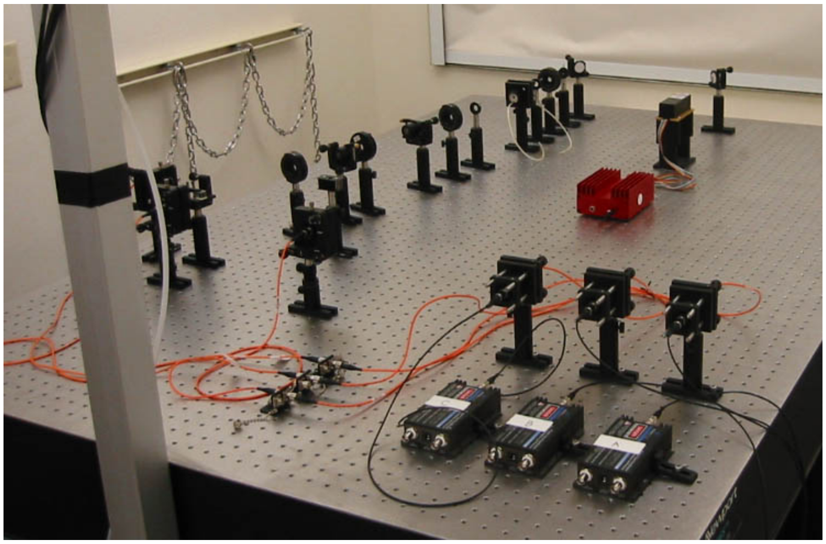
$\omega_G, \omega_I \Rightarrow$ frequencies of gate and interferometer beams

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

Conclusions

- We have performed an experiment that proves that light is made of photons
- We have demonstrated single-photon interference
- We have demonstrated frequency entanglement of two photons
- Experiments were performed by undergraduates, and are suitable for undergraduate teaching labs

Whole Table



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