Single Photon Interference

JHU Advanced Lab

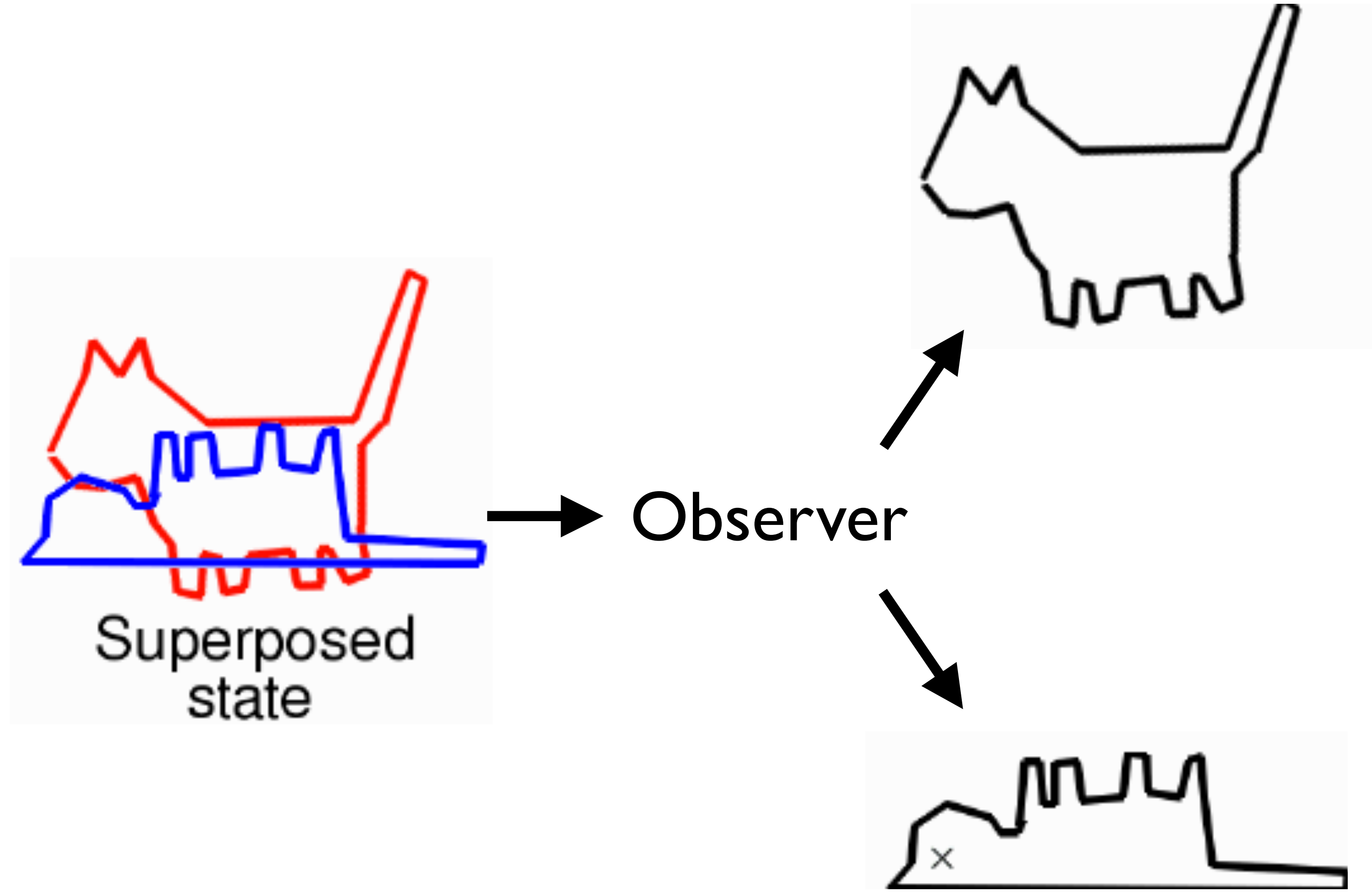


Image from http://randombio.com/subjectivity.html

As I have said so many times, God does not play dice with the world.

-Albert Einstein from Hermanns' *Einstein and the Poet* (1965)

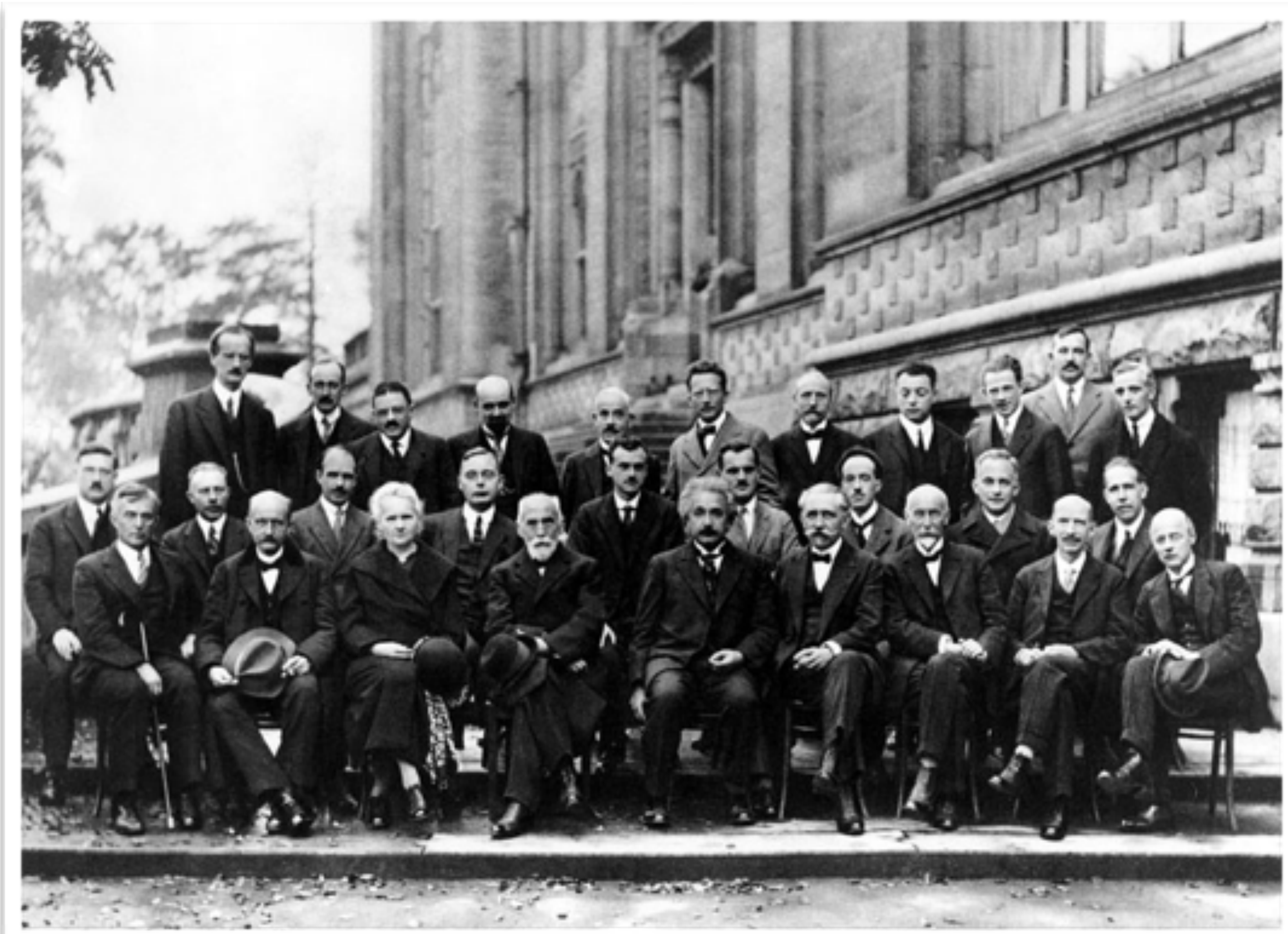
I think I can safely say that nobody understands quantum mechanics.

-Richard Feynman in *The Character of Physical Law* (1965)

...the "paradox" is only a conflict between reality and your feeling of what reality "ought to be."

-Richard Feynman in *The Feynman Lectures on Physics, Vol. 3* (1965)

Introduction: The Rise of Quantum Mechanics



The 1927 Solvay Conference in Brussels.

Architects of quantum mechanics establish the foundational principals in the first half of the twentieth century.

Max Planck, Niels Bohr, Werner Heisenberg, Louis de Broglie, Arthur Compton, Albert Einstein, Erwin Schrödinger, Max Born, John von Neumann, Paul Dirac, Enrico Fermi, Wolfgang Pauli, Max von Laue, Freeman Dyson, David Hilbert, Wilhelm Wien, Satyendra Nath Bose, Arnold Sommerfeld and others

Schrödinger Equation

$$H(t)\,|\,\psi(t)\rangle = i\hbar \frac{d}{dt}\,|\,\psi(t)\rangle$$

Operator

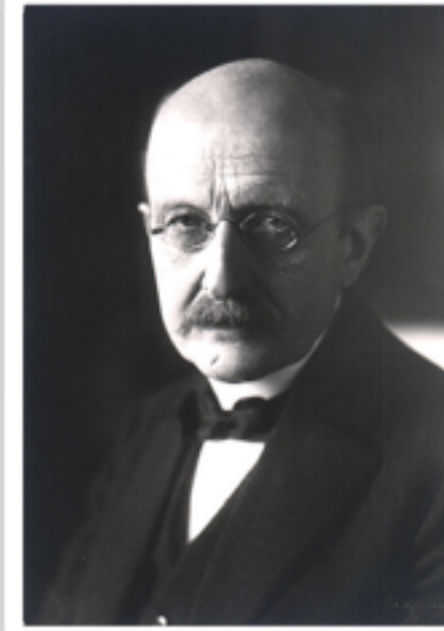
State

Light as Quanta: the Photon

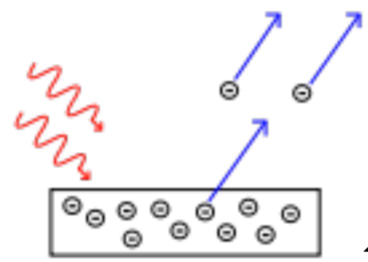
1888 - Heinrich Hertz observes enhanced spark gap emission when his apparatus was exposed to ultraviolet (high frequency) light: the first photoelectric effect.

1901 - Max Planck solves the ultraviolet catastrophe associated with blackbody radiation by quantizing the electromagnetic field:

$E_n = h\nu_n$. (Though still considered light a wave.)



1902 - Philipp Lenard observes that photoelectrons emitted by incident light have energies that increase with the light's frequency.

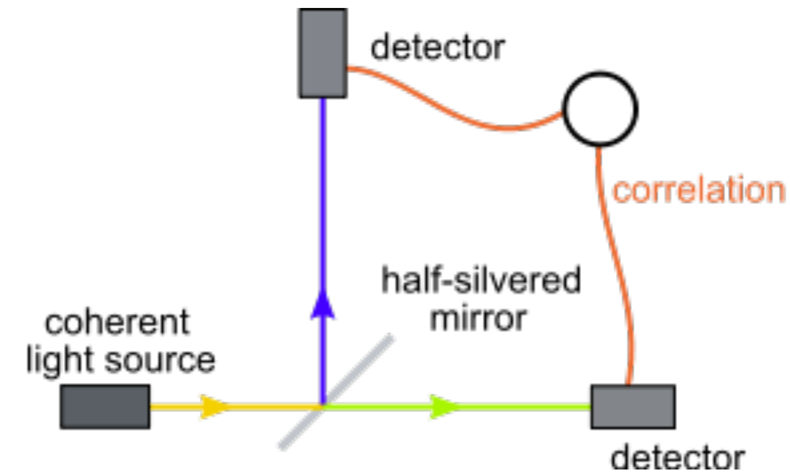


1905 - Einstein explains the photoelectric effect using light quanta.

1922 - Arthur Compton observes X-rays scattering electrons with energetics consistent with Planck's relation

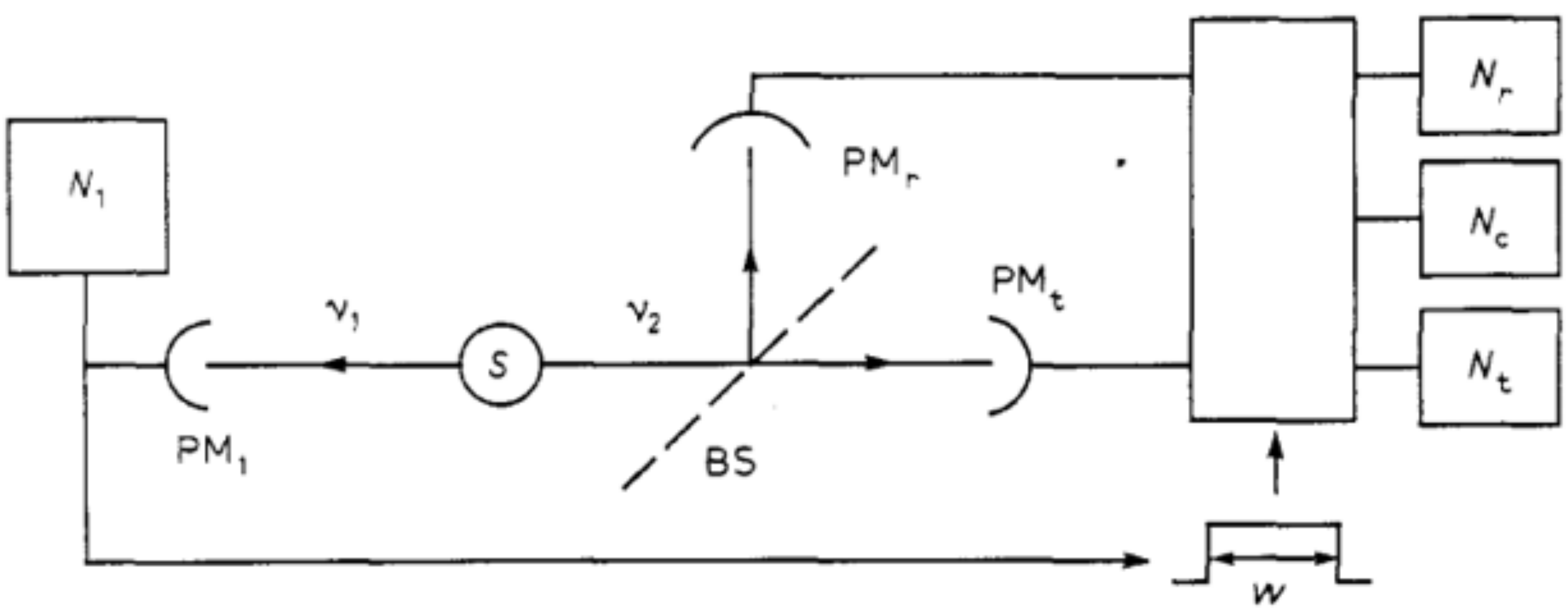
1926 - Frithiof Wolfers and Gilbert N. Lewis coined the name ***photon*** for the light quantum.

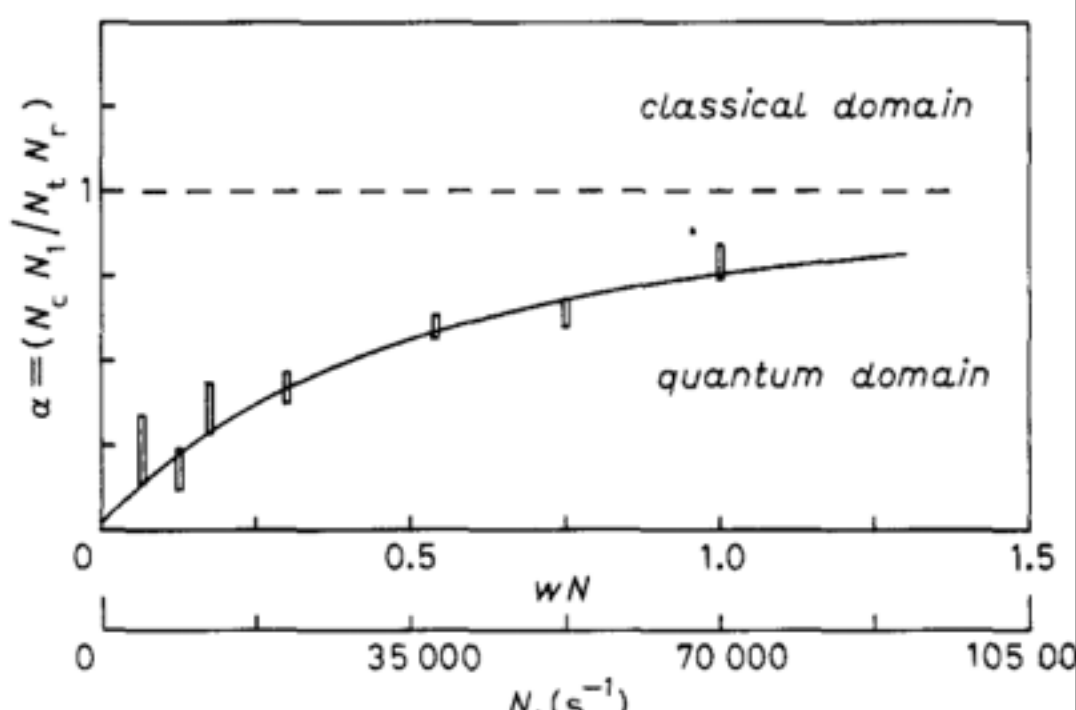
1956 - Robert Hanbury Brown & Richard Twiss observe correlations between photons in coherent light beams (generally thermal sources). The effect is explainable by "photon bunching" in Bose statistics or classical theory of light.



Semiclassical theories of light (not requiring the photon) were still able to explain observed phenomena.

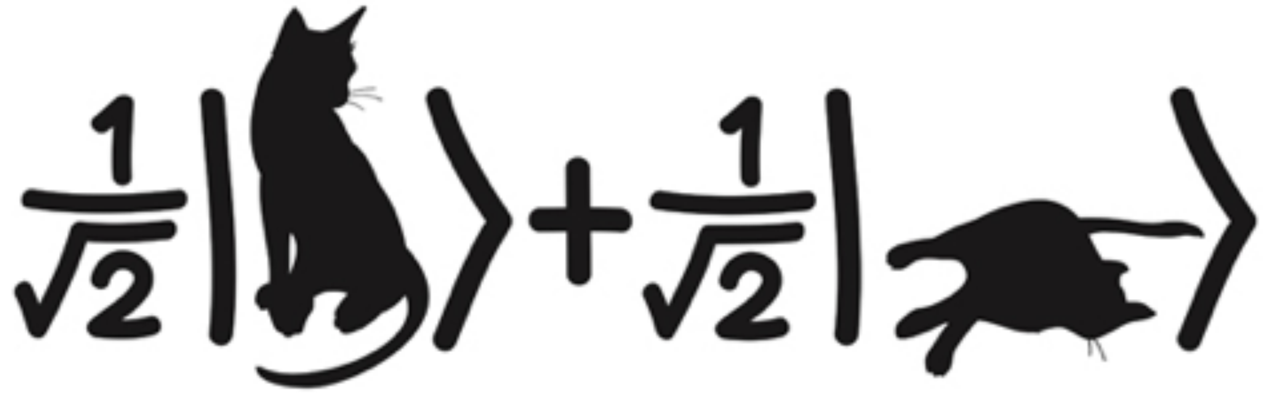
1986 - P. Grangier, G. Roger, & A. Aspect use a two-photon radiative cascade in Calcium to isolate photons and observe anticorrelation of beams (reflected & transmitted) from beam splitter. "A single photon can only be detected once!" Results *inconsistent* with semiclassical theory.





Theory

Quantum System is a Superposition of States

$|\Psi_{in}\rangle \rightarrow$ 

Orthogonal States: Schrödinger's cat is either dead or alive.

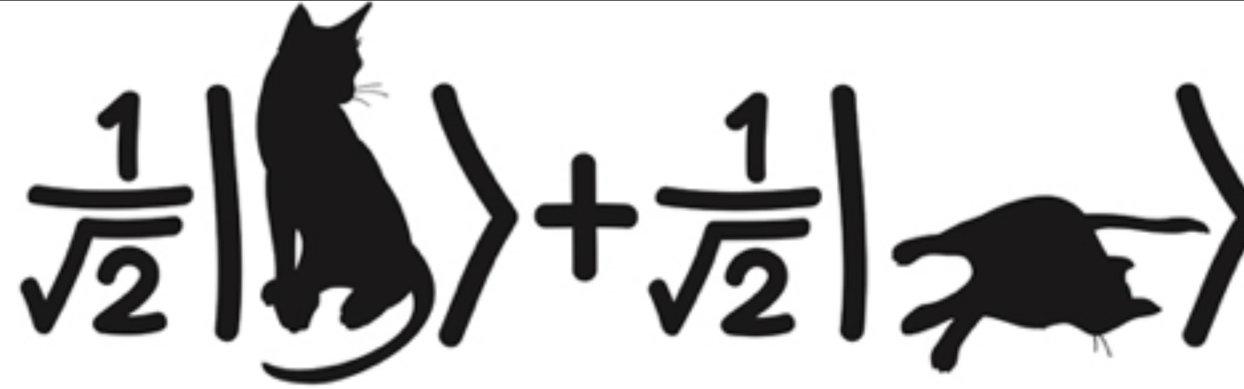
 $=1$  $=0$

QM predicts the probability of an outcome
(or equivalently the number of expected outcomes given N experiments).

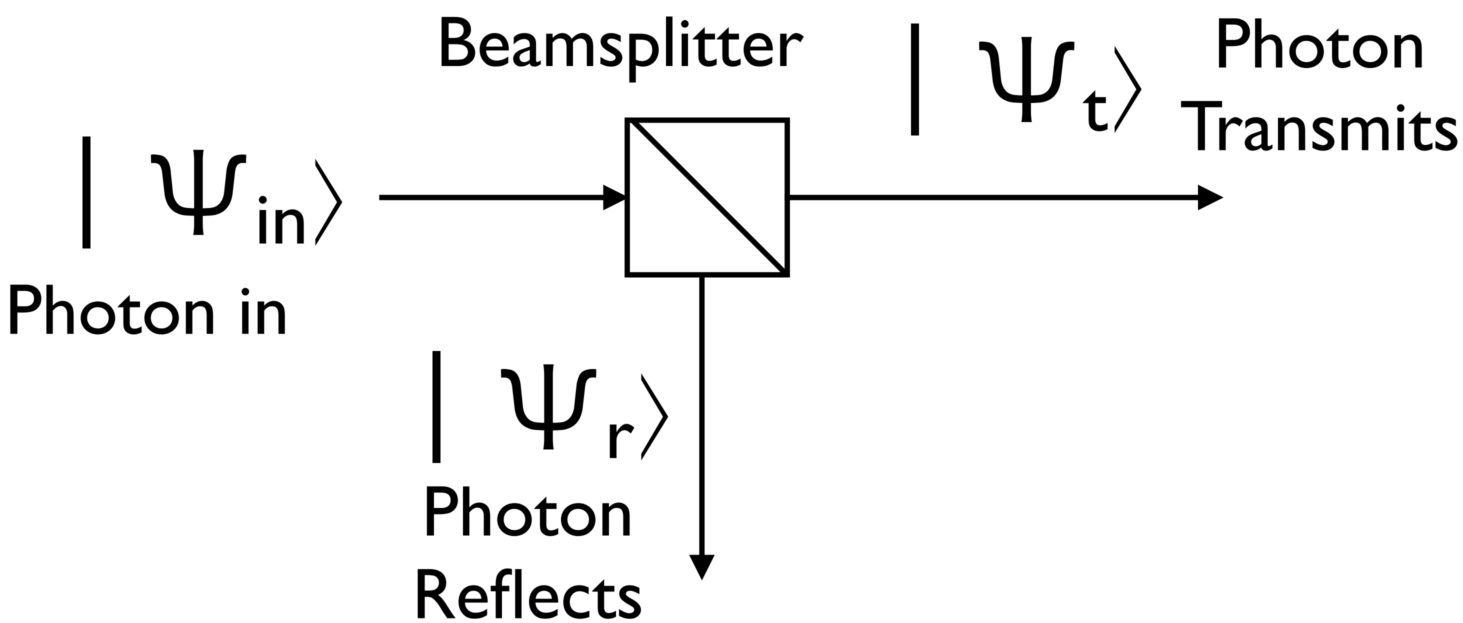
$P_{alive} = |$  $)|^2$

$= 1/2$ **(Half the cats come out alive.)**

Theory



Photon as Schrödinger's Cat



Orthogonal States:
Photon Transmits or Reflects

$$\langle\Psi_t | \Psi_r\rangle=0$$

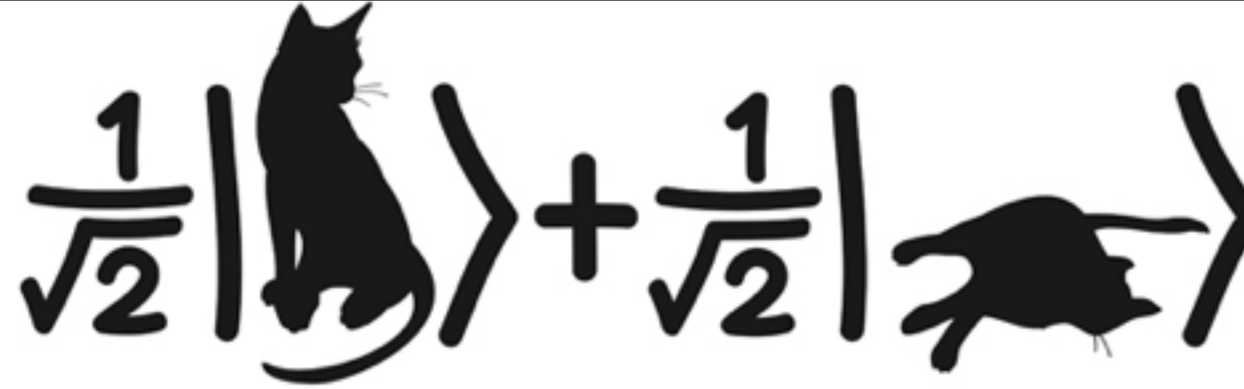
$$\langle\Psi_t | \Psi_t\rangle=1$$

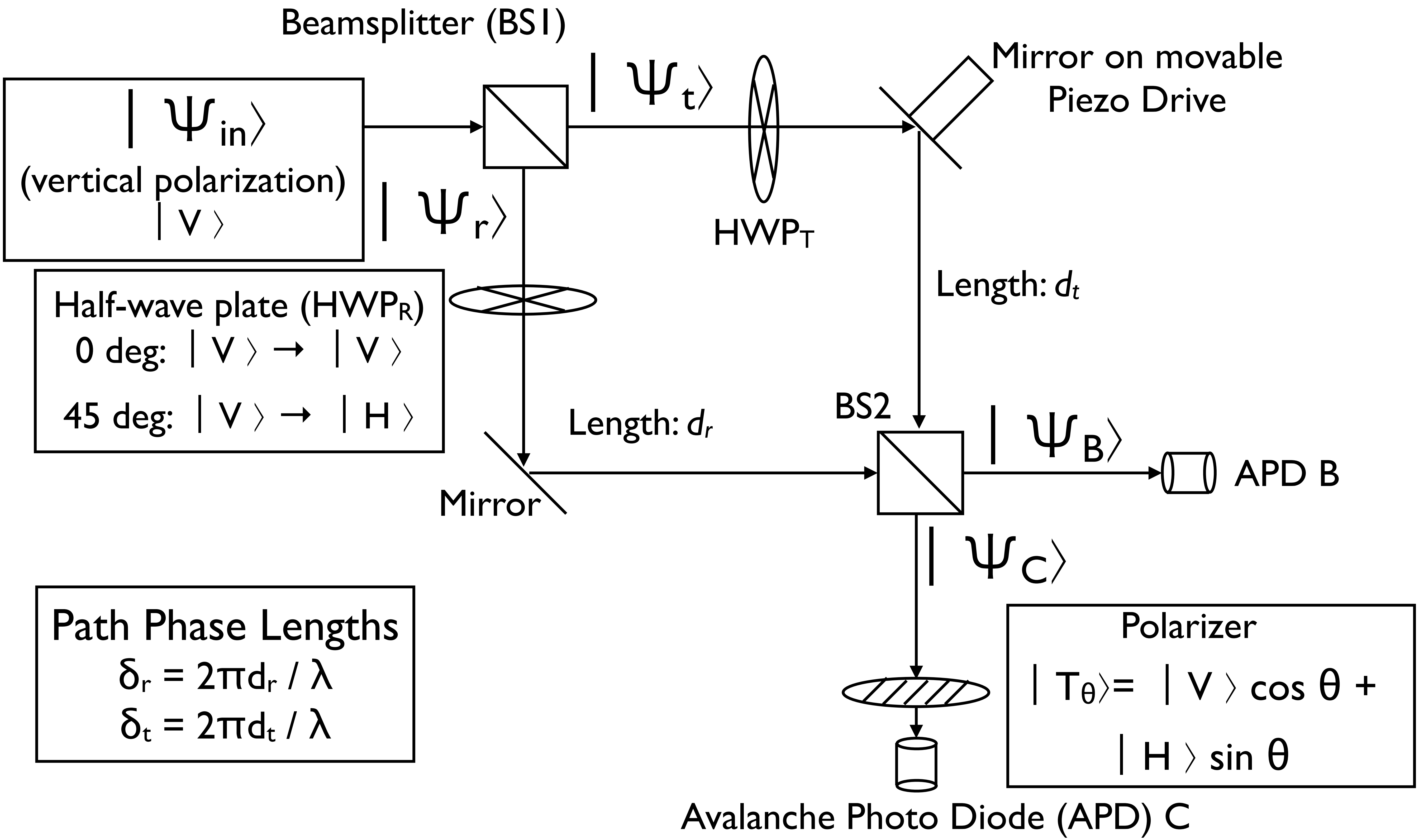
$$| \Psi_{in}\rangle \rightarrow t | \Psi_t\rangle+r | \Psi_r\rangle \qquad t=| t | e^{i\varphi_t} \qquad r=| r | e^{i\varphi_r}$$

$$P_{transmit} = | \langle\Psi_t | \Psi_{in}\rangle |^2 = | t |^2 \equiv T$$

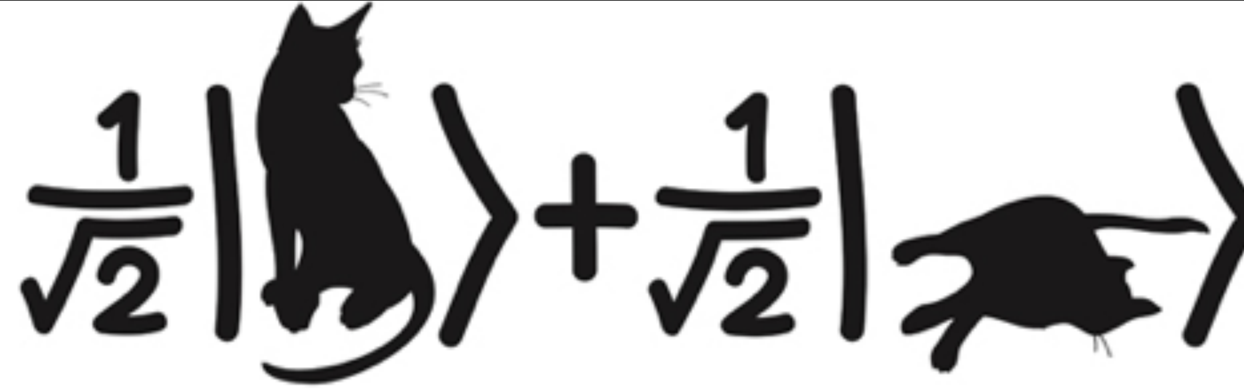
$$P_{reflect} = | \langle\Psi_t | \Psi_{in}\rangle |^2 = | r |^2 \equiv R$$

Theory




Beamsplitter (BS1)
| Ψt⟩
Mirror on movable Piezo Drive
| Ψin⟩
(vertical polarization)
| V ⟩
| Ψr⟩
HWPT
Length: dt
Half-wave plate (HWPR)
0 deg: | V ⟩ → | V ⟩
45 deg: | V ⟩ → | H ⟩
Length: dr
BS2
| ΨB⟩
APD B
Mirror
| ΨC⟩
Polarizer
| Tθ⟩= | V ⟩ cos θ + | H ⟩ sin θ
Avalanche Photo Diode (APD) C
Path Phase Lengths
δr = 2πdr / λ
δt = 2πdt / λ

Theory



Quantum Mechanics predicts the fraction of photons reaching APD C

$$P_{C}= |\langle \Psi_C | \Psi_{in}\rangle|^2$$

Indistinguishable Paths: HWP_R @ 0; HWP_T @ 0; Polarizer @ 0

$$P_{C}=[1-\cos(\delta_r-\delta_t)]/2 \qquad (T=R=1/2)$$

Distinguishable Paths: HWP_R @ 45; HWP_T @ 0; Polarizer @ 0

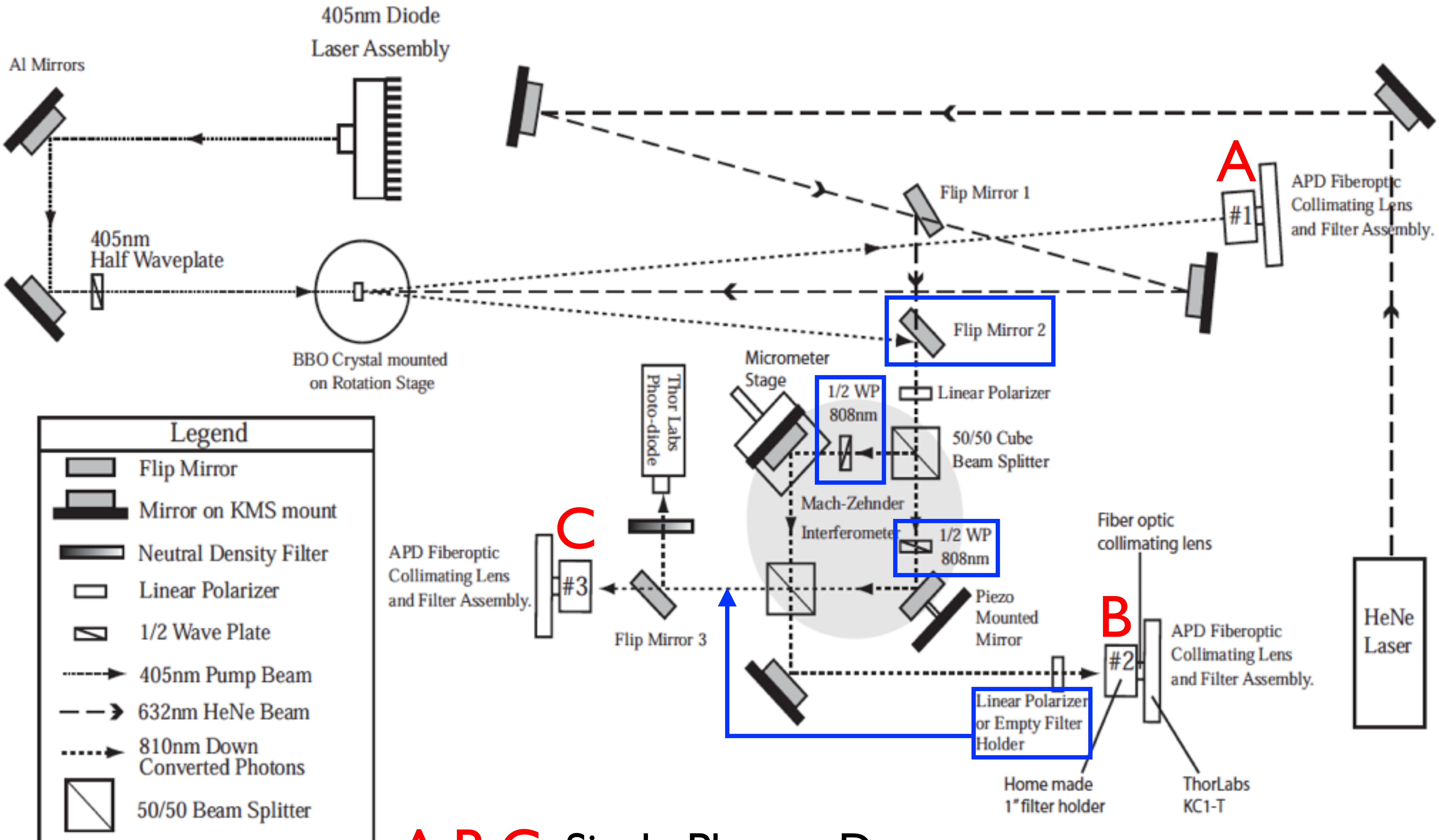
$$P_{C}=1/4 \qquad (T=R=1/2)$$

Quantum Eraser: HWP_R @ 45; HWP_T @ 0; Polarizer @ 45

$$P_{C}=[1-\cos(\delta_r-\delta_t)]/4 \qquad (T=R=1/2)$$

[See Pearson & Jackson 2010 for sketch of derivation.]

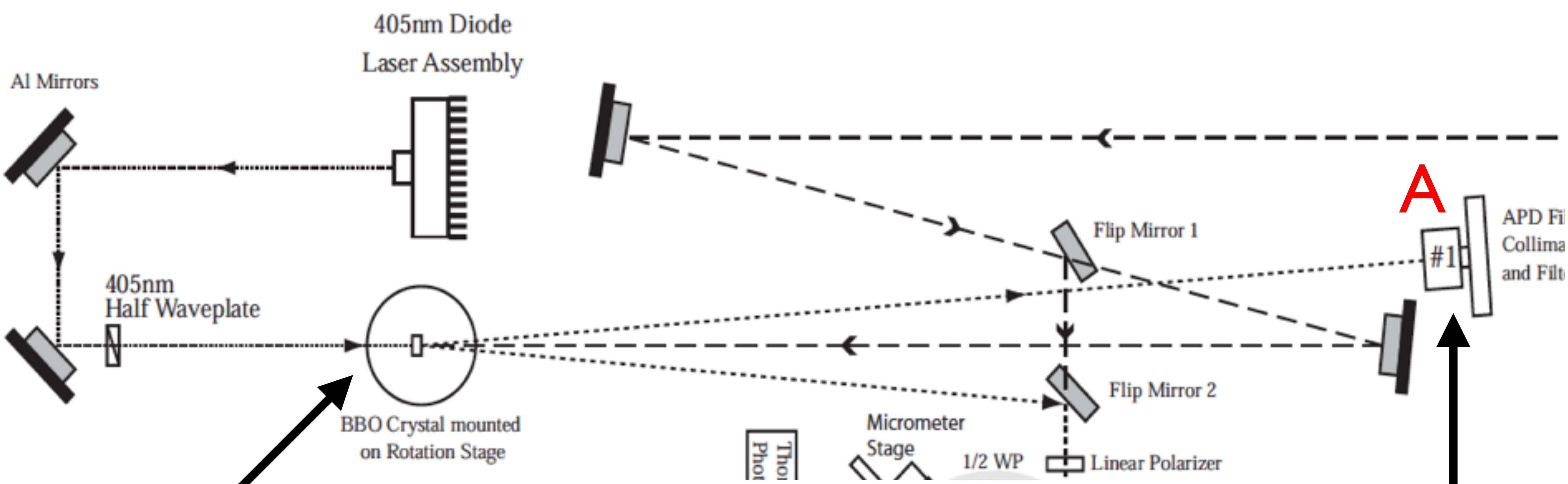
Experiment & Data



A,B,C Single Photon Detectors

Adjustable Elements (HWP, Polarizer)

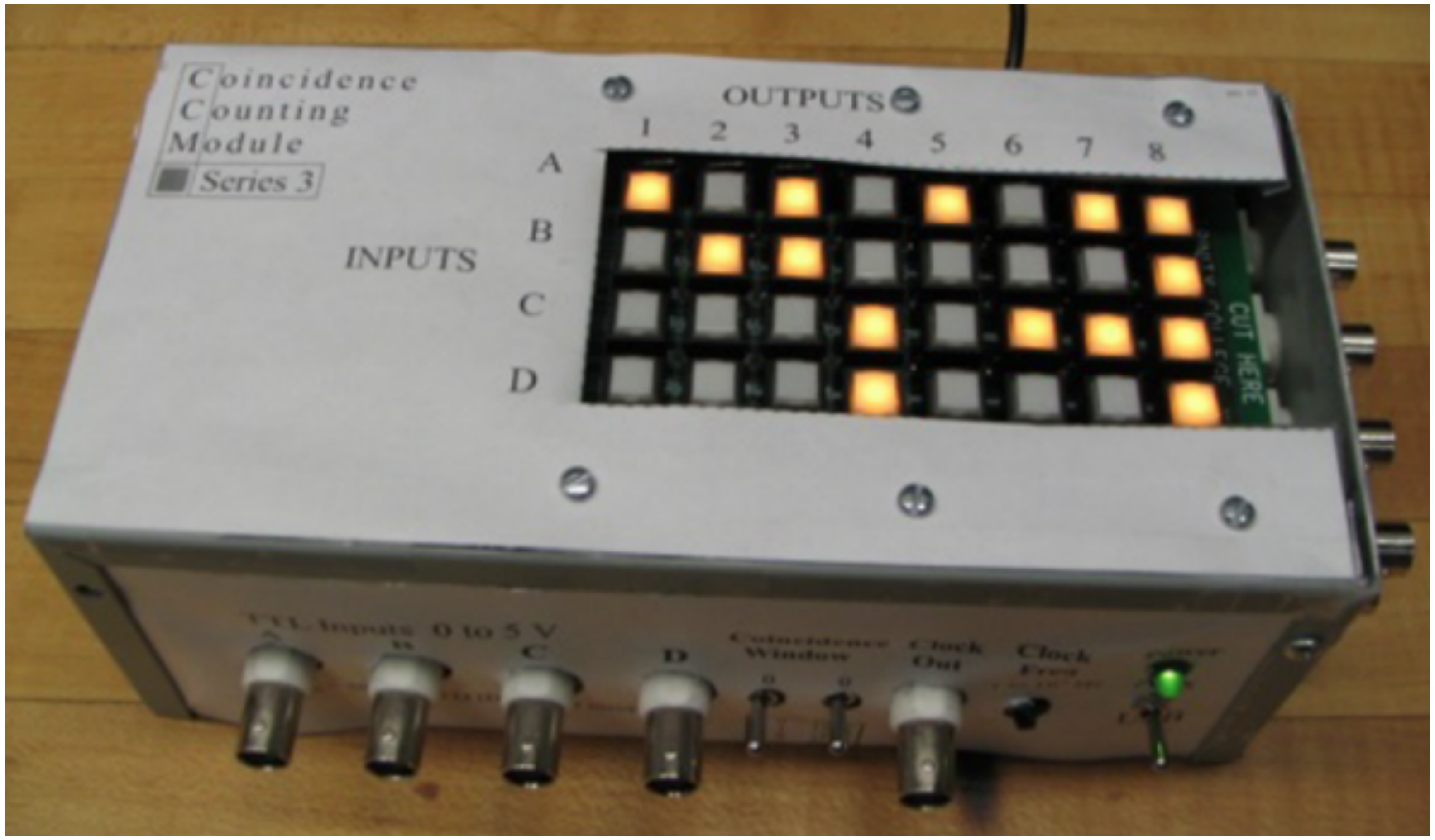
Isolating the Photons



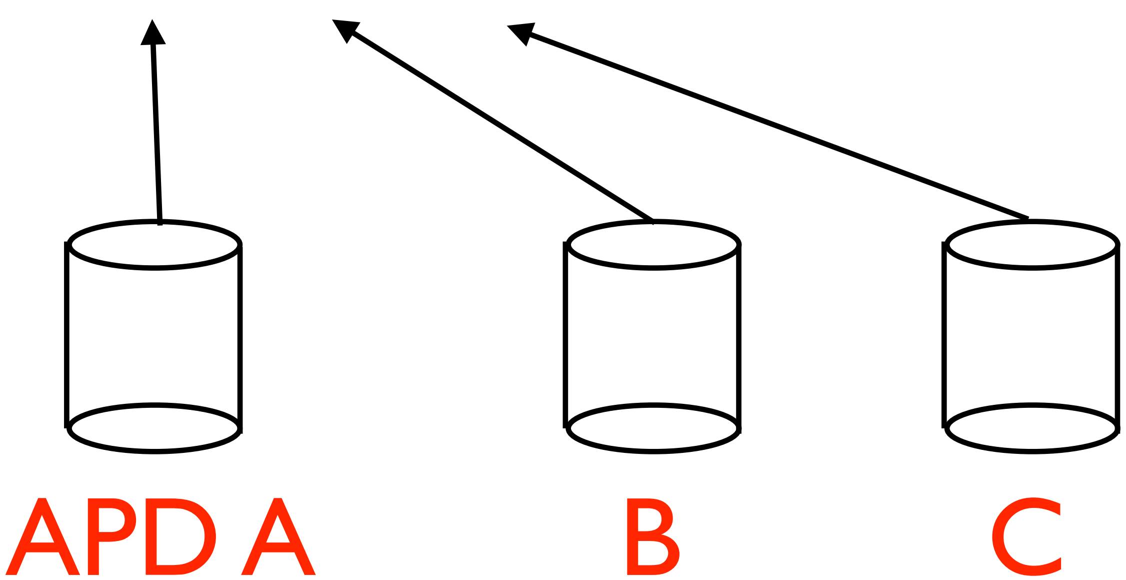
Parametric down-conversion:
A nonlinear crystal: β-Barium Borate (BBO) transforms minute fraction of 405 nm photons into two 810 nm photons.

Gate Detector :
Avalanche Photo Diode A detects "idler" photon while the "signal" photon travels through the interferometer. The signal from APD A will be used a "gate" APD C,D to decrease background.

Measuring Photon Coincidence



Coincidence Counting Module (CCM) counts when a photon is detected by A, B, or C as well as simultaneous detections:
A+B, A+C, B+C, A+B+C



“Simultaneous” is determined by a settable coincidence window (12ns, 14ns, 20ns)

Data!

Step 1:

It is crucial that you only have one photon in the interferometer at a time. Always record the A+B+C channel and make sure it is much smaller than the A+C channel under study.

Step 2:

Take three datasets corresponding to “indistinguishable paths”, “distinguishable paths”, and “quantum eraser” cases.
For each piezo voltage (interferometer phase difference), compute average A+C count and estimate error from scatter.

Step 3:

Consider effect of different coincidence windows.

Data Analysis

Fit interference data with suitable model. A linear model may be okay or may want flexible (non-linear) model, e.g.,

$$P_{C=}(A+Bx)[1\text{-}C\cos(Dx\text{-}E)].$$

A, B, D, E are examples of "nuisance parameters", which parametrize less-than-interesting aspects of the interferometer. **The key parameter, which quantifies quantum interference, is C.** Be sure to propagate all errors to the model parameters.

In your Discussion section compare the model results to the predictions of quantum mechanics.

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Schedule

Week One: 1) Obtain all interference data.
2) Upload plot of A+C coincidences for indistinguishable, distinguishable and eraser.
3) Write draft report through procedure in Experiment and Data section.

Week Two: 1) Fit Data.
2) Upload plot/table of results.
3) Write draft report through end of Data Analysis section.

Week Three: Finish up!