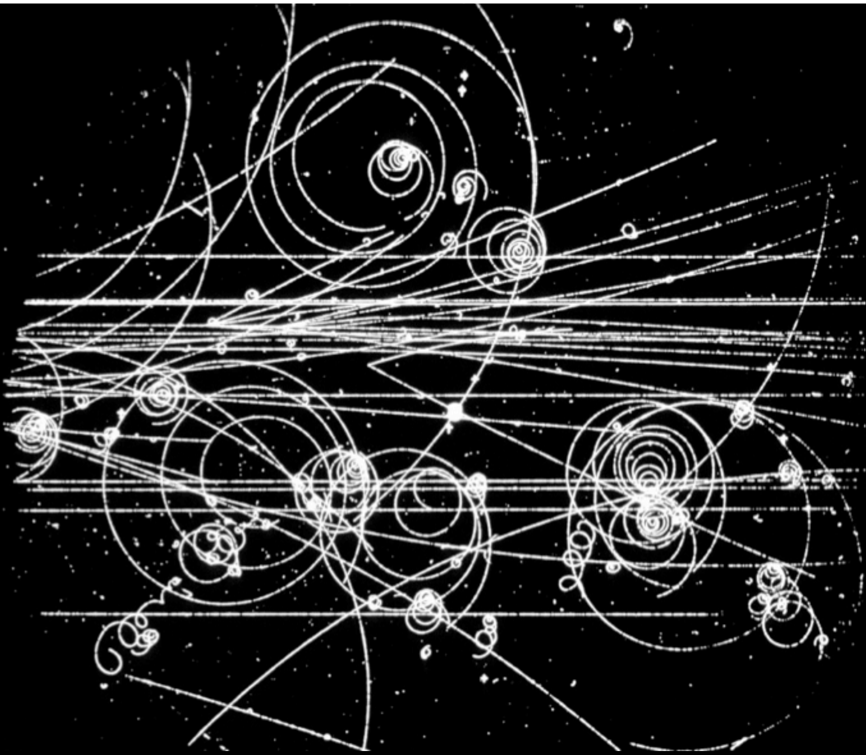
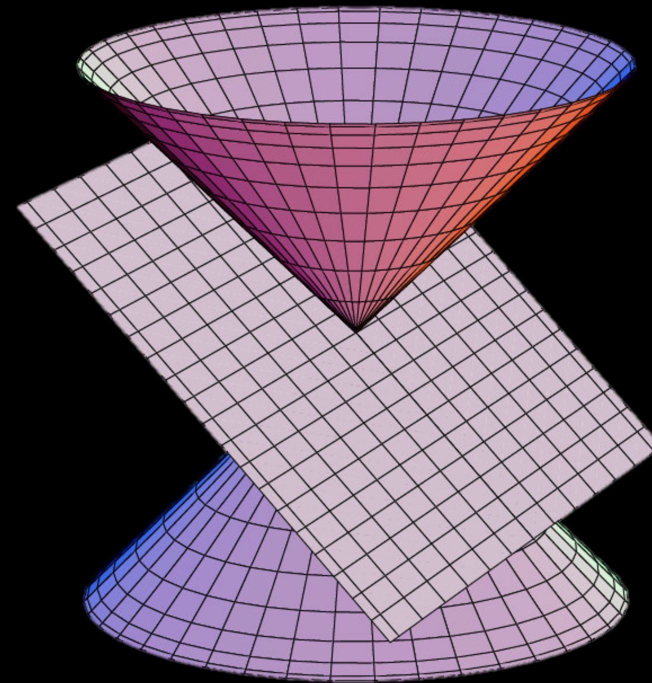


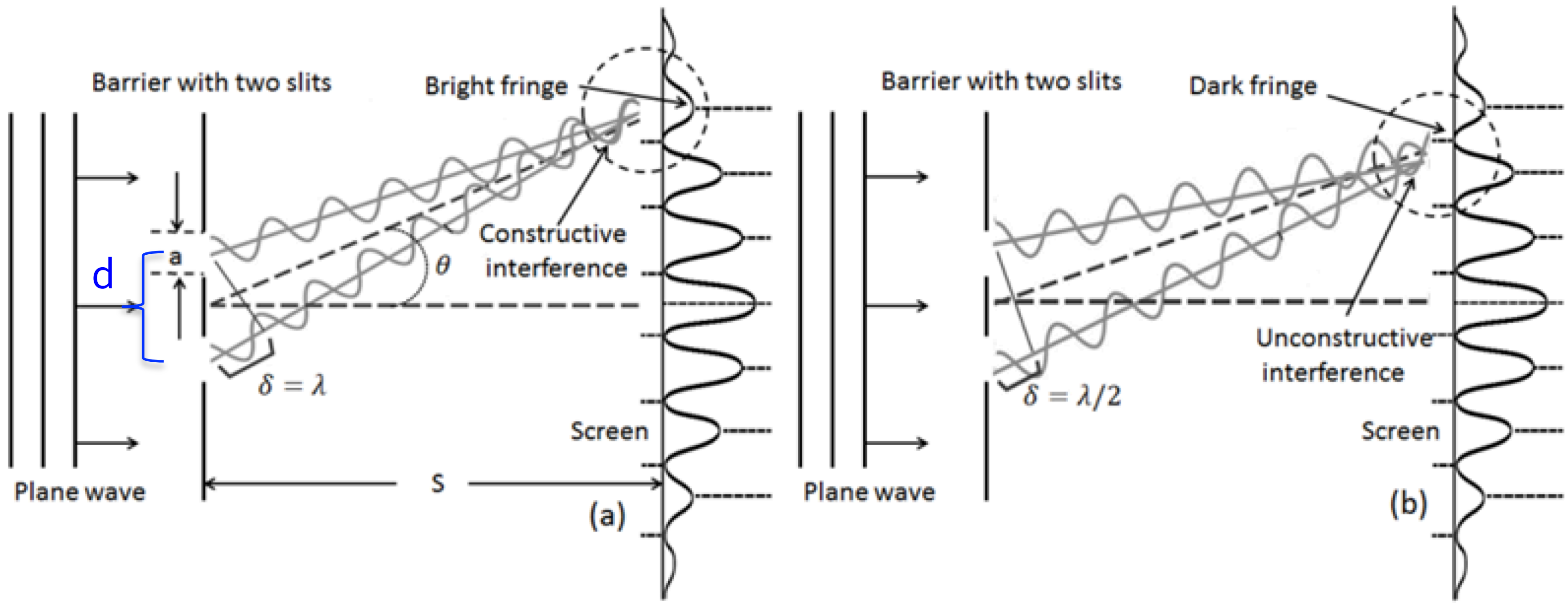


Modern Physics (Phys. IV): 2704

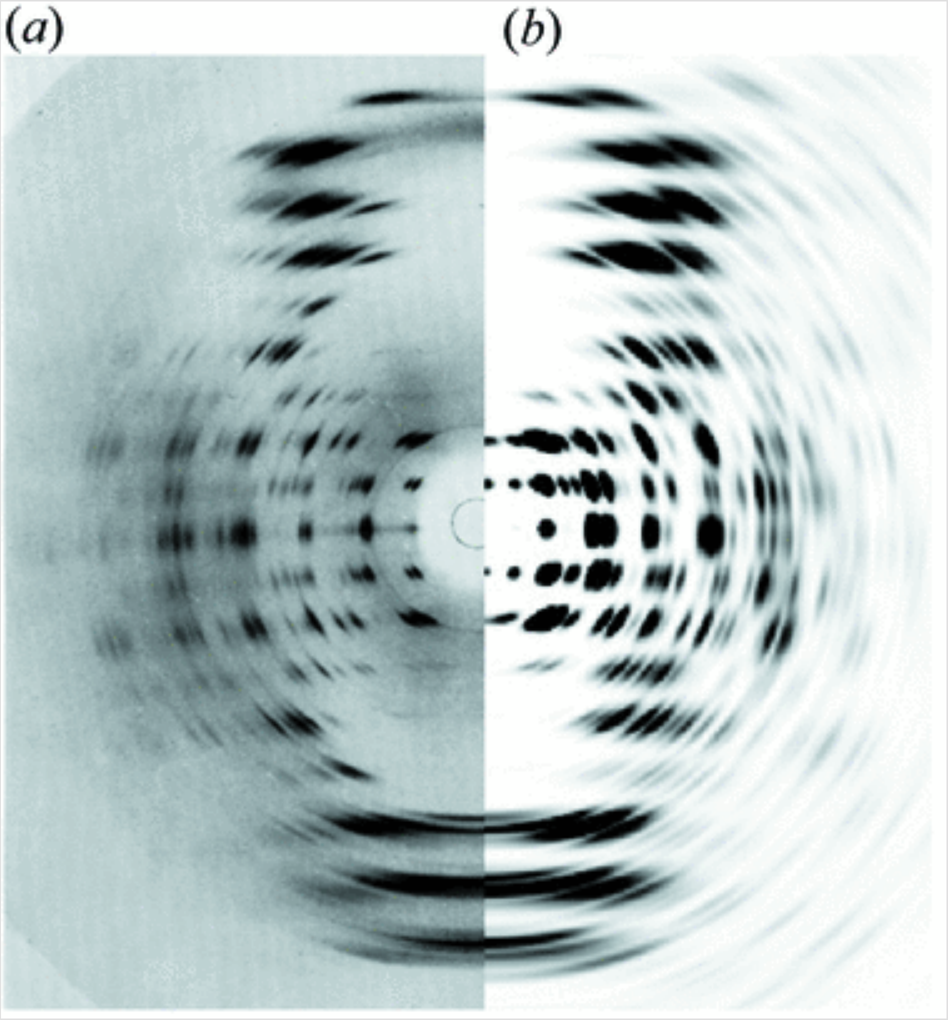
Professor Jasper Halekas
Van Allen 70
MWF 12:30-1:20 Lecture

Diffraction

Maxima for $\delta = d \sin\theta = n\lambda$ Bigger λ => fringes farther apart



X-Ray Diffraction DNA!! (Crick, 1952)



(a)represents actual measurement
(b)represents theoretical prediction for a double-helix

De Broglie

Light is sometimes like a particle

What if particles are sometimes like waves?

De Broglie Wavelength

- $p = h/\lambda$ for a massless photon
- By analogy, De Broglie proposed $\lambda = h/p$ for particles with mass

Concept Check

- Suppose an electron and a baseball are moving at the same speed. How does the deBroglie wavelength of the baseball compare to that of the electron?

A. $\lambda_{baseball} = \lambda_e$
B. $\lambda_{baseball} = 10^{30}\,\lambda_e$
C. $\lambda_{baseball} = 10^{10}\,\lambda_e$
D. $\lambda_{baseball} = 10^{-10}\,\lambda_e$
E. $\lambda_{baseball} = 10^{-30}\,\lambda_e$

$m_e \sim 9.1 \times 10^{-31}$ kg

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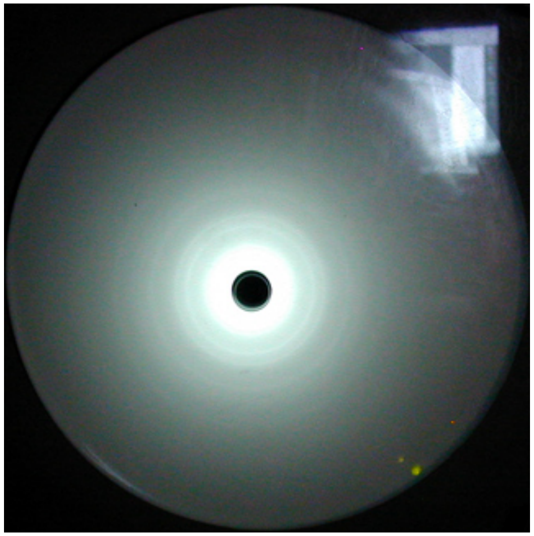
Concept Check

- If you increase the energy of the electrons, how should the diffraction fringes change?



A. Move farther apart
B. Move closer together
C. Stay at the same spacing
D. Turn pink and dance the Macarena

Concept Check

- If you increase the energy of the electrons, how should the diffraction fringes change?

A. Move farther apart
B. Move closer together
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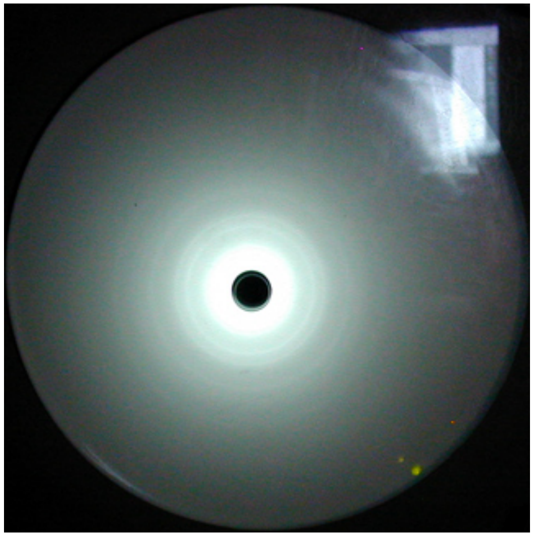
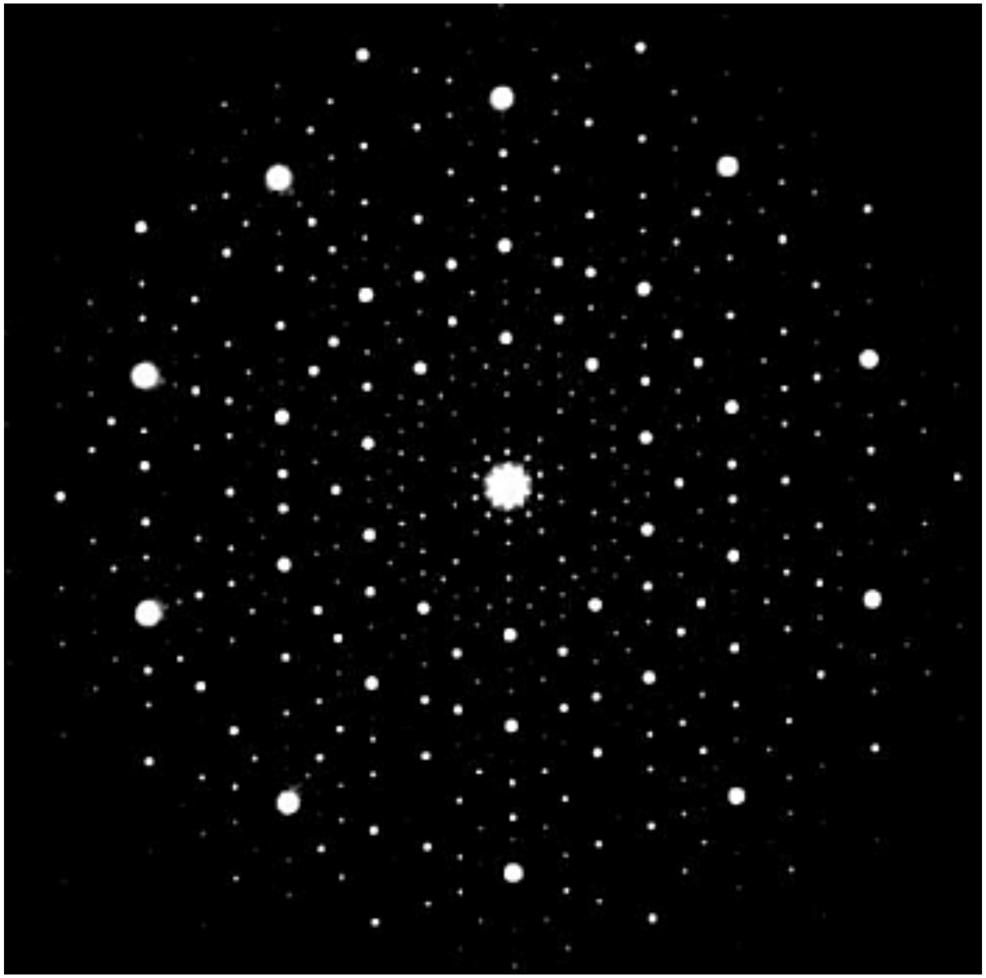
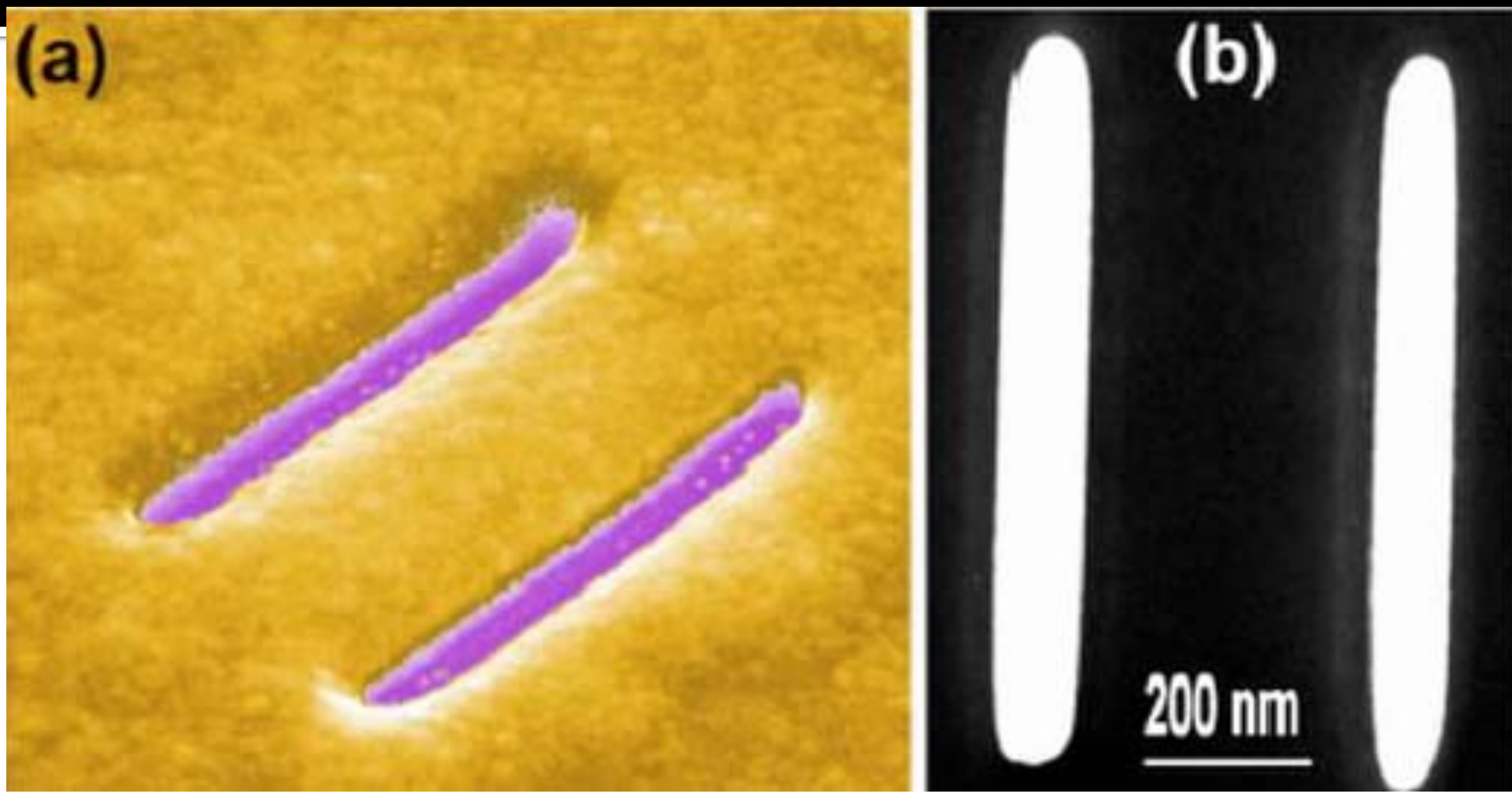


Electron Diffraction as a Probe



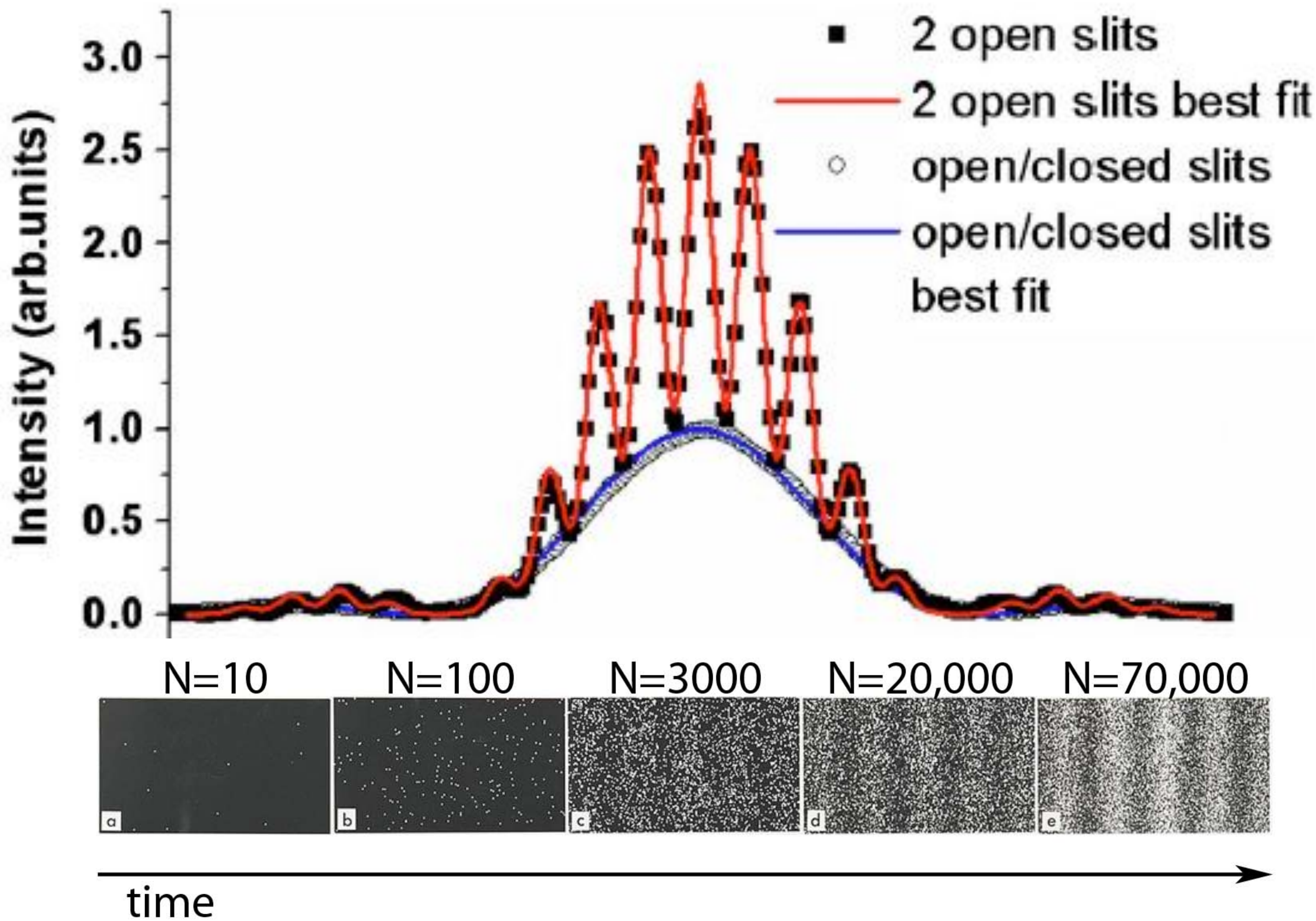
Electron diffraction pattern of an aluminum-manganese alloy

Miniature Double Slit

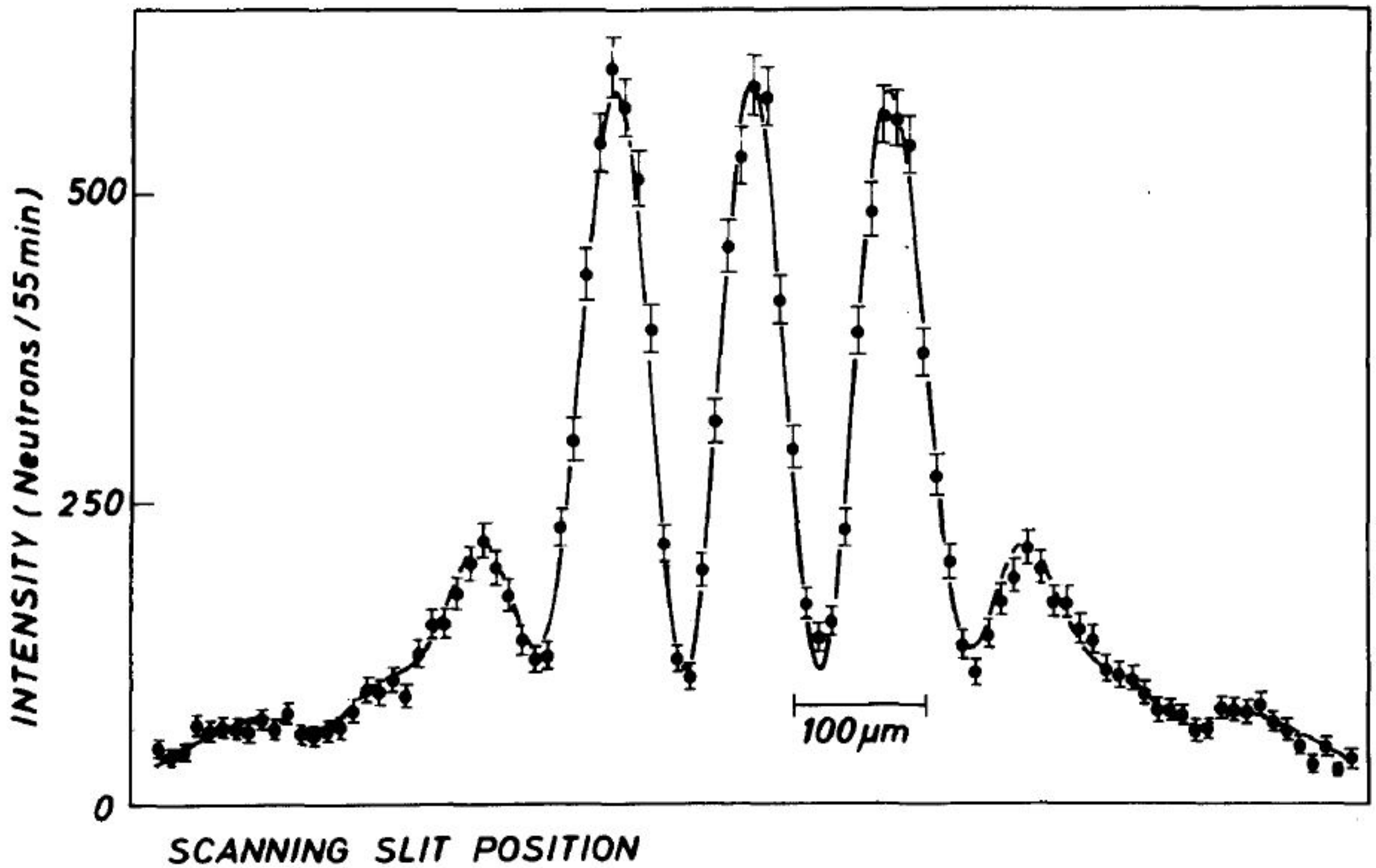


- Images of a nanometer scale double-slit system created using gold foil and a focused ion beam (2008).
- Slits are 83 nm wide and spaced 420 nm apart

Electron Double-Slit Observations



Neutron Double Slit Experiment

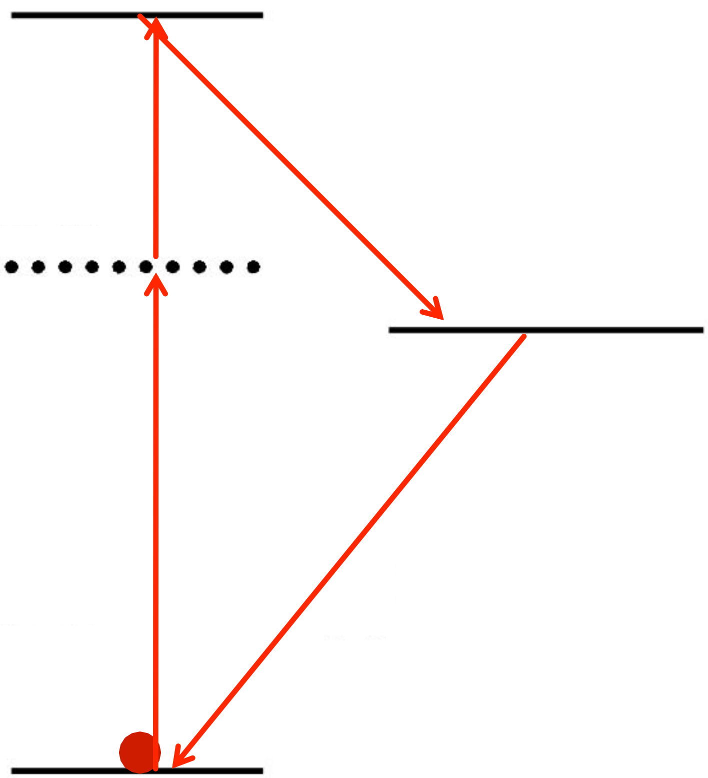


Double Slit: Particle Interpretation?

"…each photon interferes only with itself. Interference between different photons never occurs."

P. A. M. Dirac, *The Principles of Quantum Mechanics* (1947).

Experimental Setup



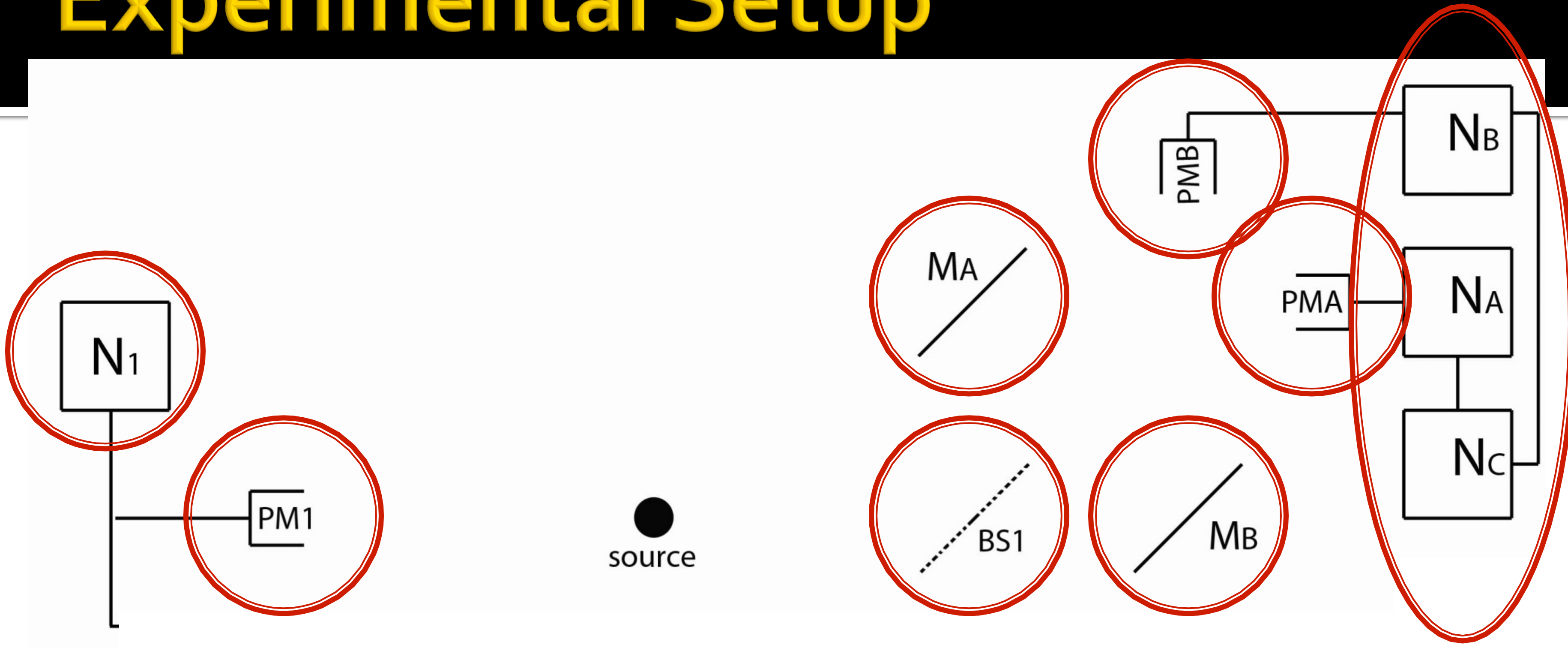
- Calcium atoms are excited by a two-photon absorption process (E_K = 3.05 eV) + (E_D = 2.13 eV).

- The excited state first decays by single photon emission (E_1 = 2.25 eV).

- The lifetime of the intermediate state is $\tau \sim 5$ ns.

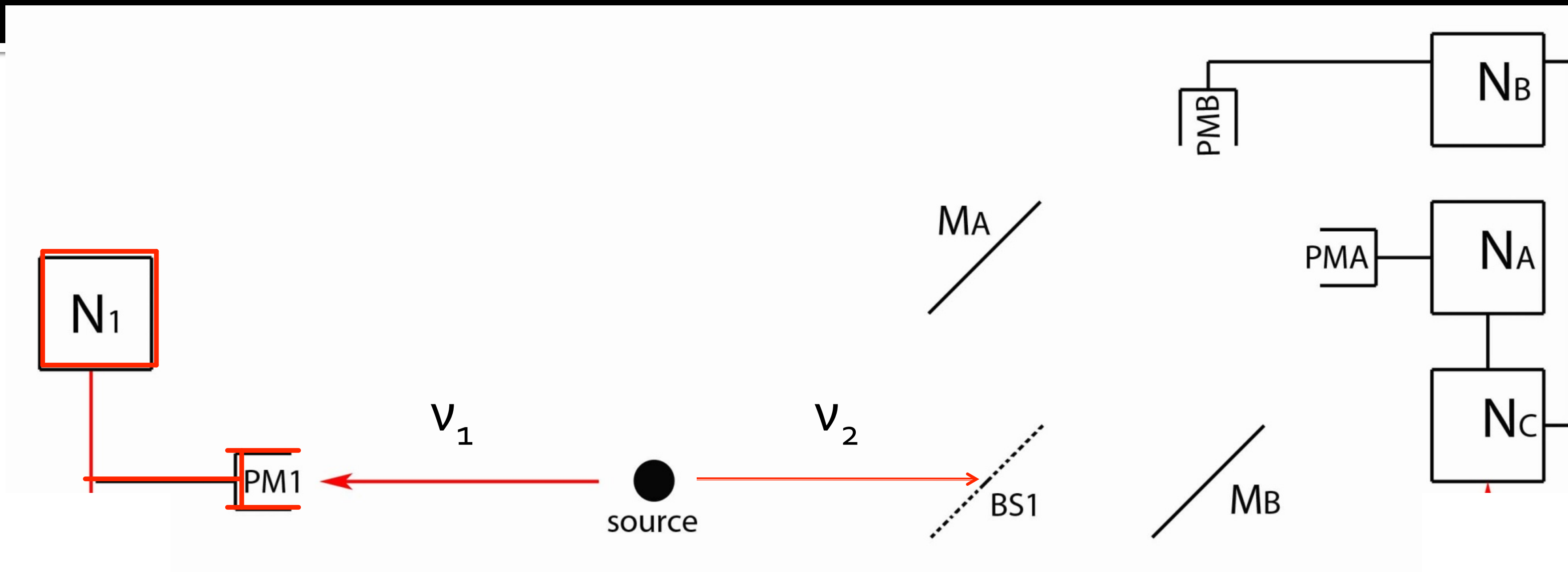
- High probability the second photon (E_2 = 2.93 eV) is emitted within $t = 2\tau$

Experimental Setup



- M_A and M_B are mirrors.
- BS1 is a beam splitter.
- PM1, PMA & PMB are all photomultipliers.
- N_1, N_A, N_B & N_C are counters that record photon detections.

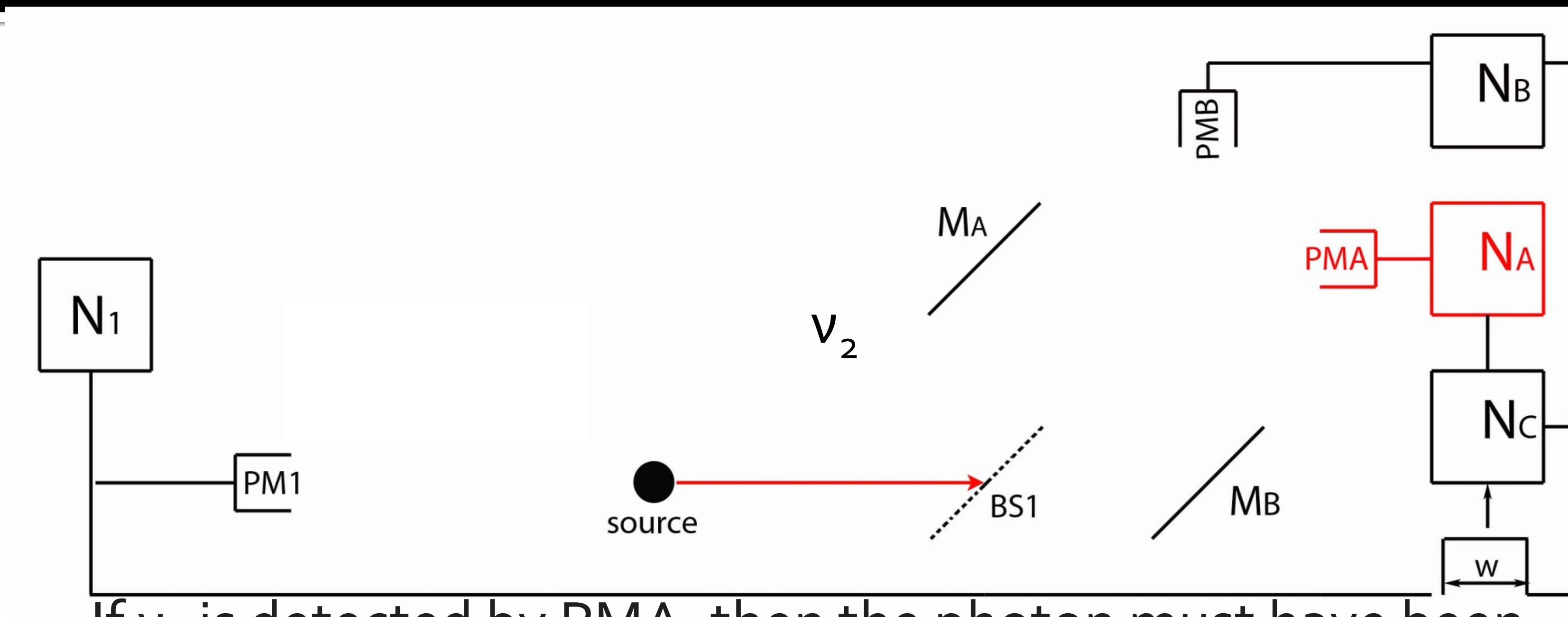
Experimental Setup



ν_1 and ν_2 are emitted back-to-back.

- Detection of first photon (ν_1) is counted by N_1.
- A signal is sent to tell the counters (N_A, N_B & N_C) to expect a second photon (ν_2) within a time $w = 2\tau$.

Concept Check



If ν_2 is detected by PMA, then the photon must have been…

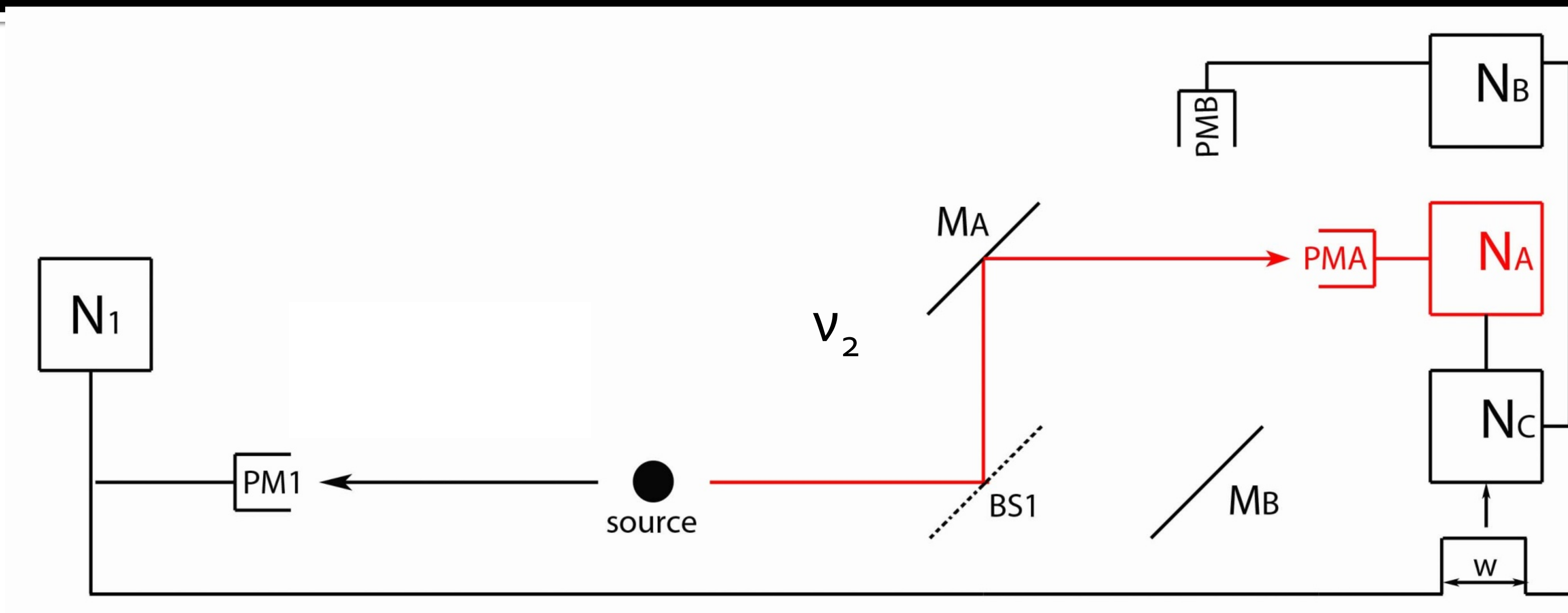
A) …reflected at BS1

B) …transmitted at BS1

C) …either reflected or transmitted at BS1

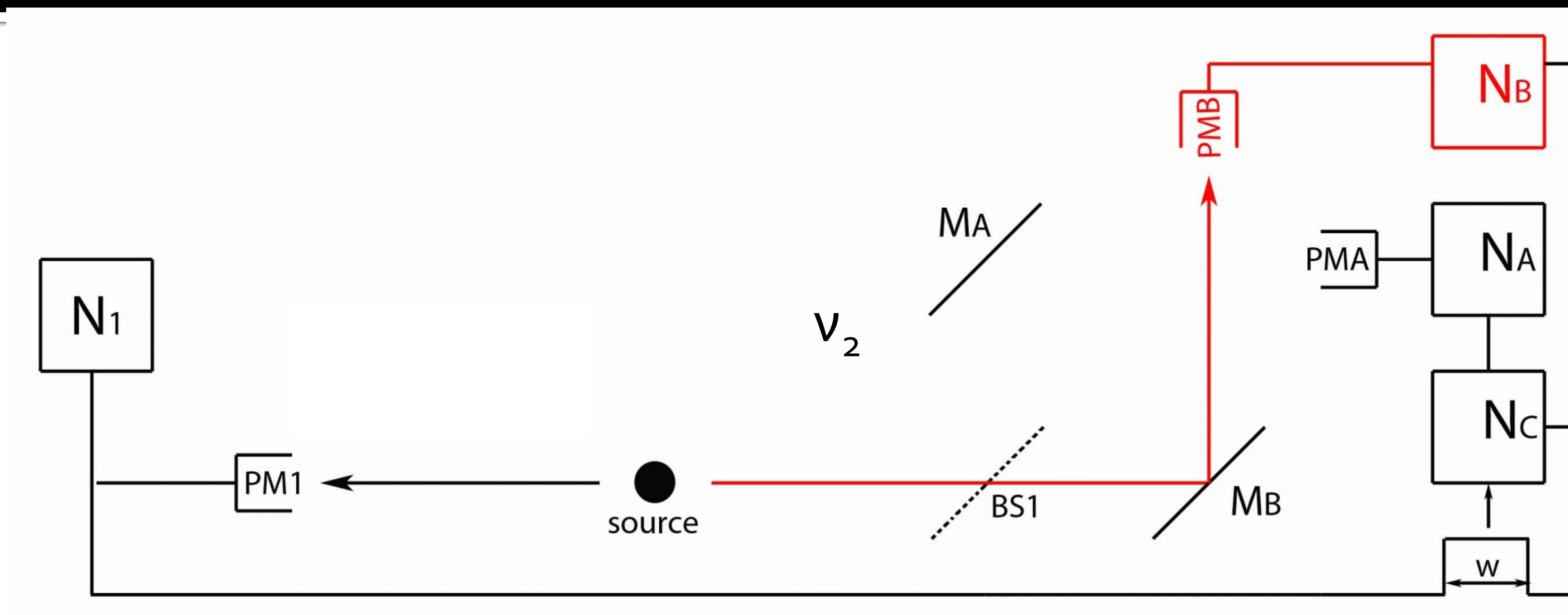
D) Not enough information.

Concept Check



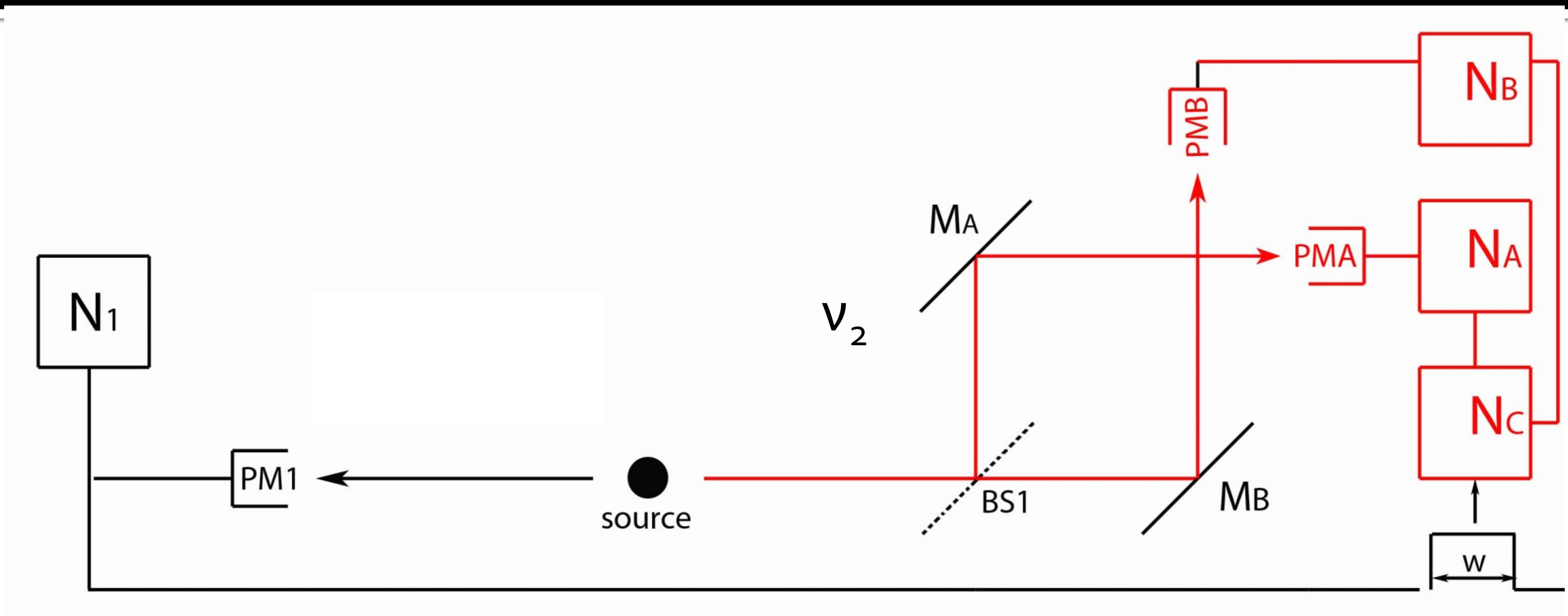
- If the second photon (ν_2) is detected by PMA, then the photon must have traveled along Path A (via M_A), so . it was reflected at BS1.

Other Path



- If the second photon (ν_2) is detected by PMB, then the photon must have traveled along Path B (via M_B).

Both Paths



- If both PMA & PMB are triggered during $w = 2\tau$, then the coincidence counter (N_C) is triggered.

Correlation Measure

- Need some kind of measure of how often PMA & PMB are being triggered at the same time.
- Let $$\alpha \equiv \frac{P_C}{P_A P_B}$$
- P_A is the probability for N_A to be triggered.
- P_B is the probability for N_B to be triggered.
- P_C is the probability for the coincidence counter (N_C) to be triggered (both N_A and N_B during $t = 2\tau$).

Interpretation

$$\alpha \equiv \frac{P_C}{P_A P_B}$$

- If N_A and N_B are being triggered randomly and independently, then $\alpha = 1$.

  $P_C = P_A \times P_B$ which is consistent with:
  - Many photons present at once
  - EM waves triggering N_A & N_B at random.

- If photons act like single particles, then $\alpha \sim 0$.

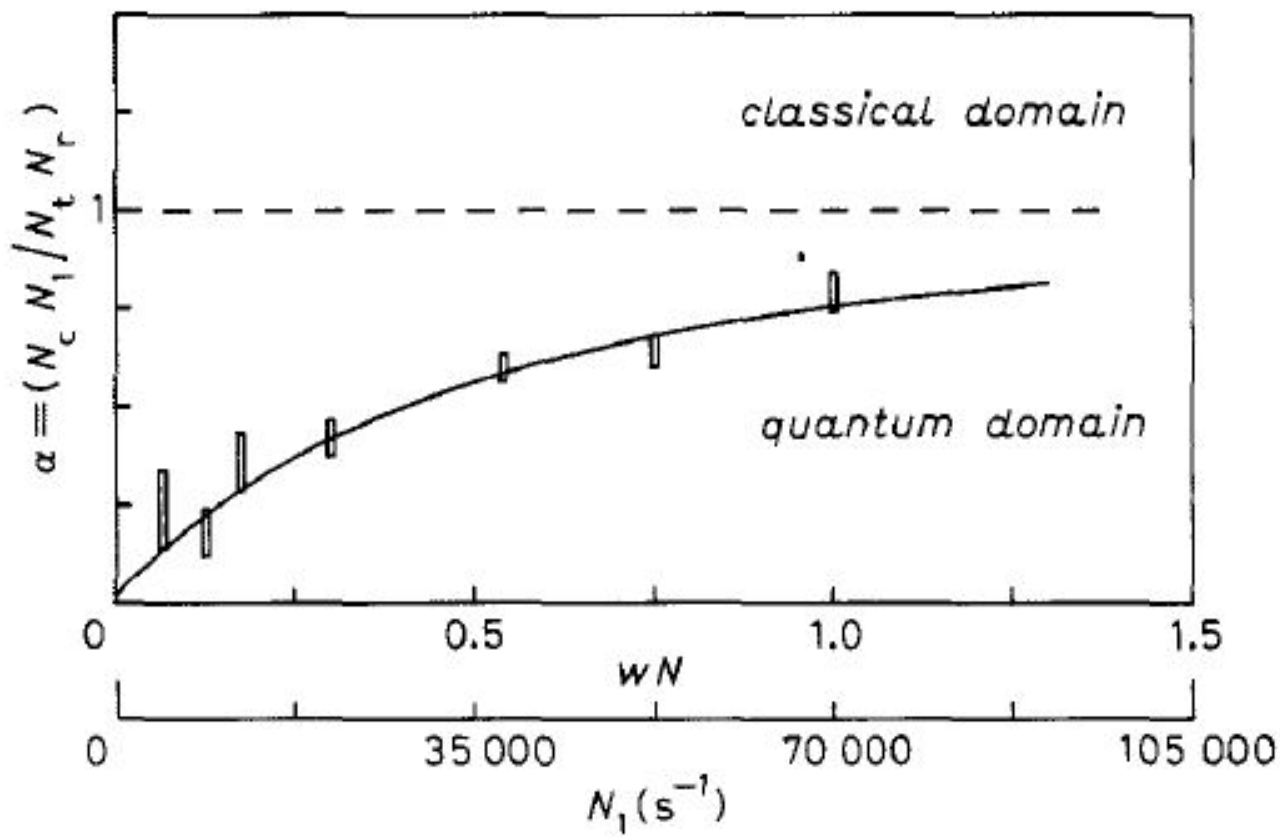
  $P_C = 0$ when photons are always detected by PMA or by PMB, but not both simultaneously.

- If photons act like waves, then $\alpha \geq 1$.

  $P_C > P_A \times P_B$ means PMA and PMB are firing together more often than by themselves ("clustered").

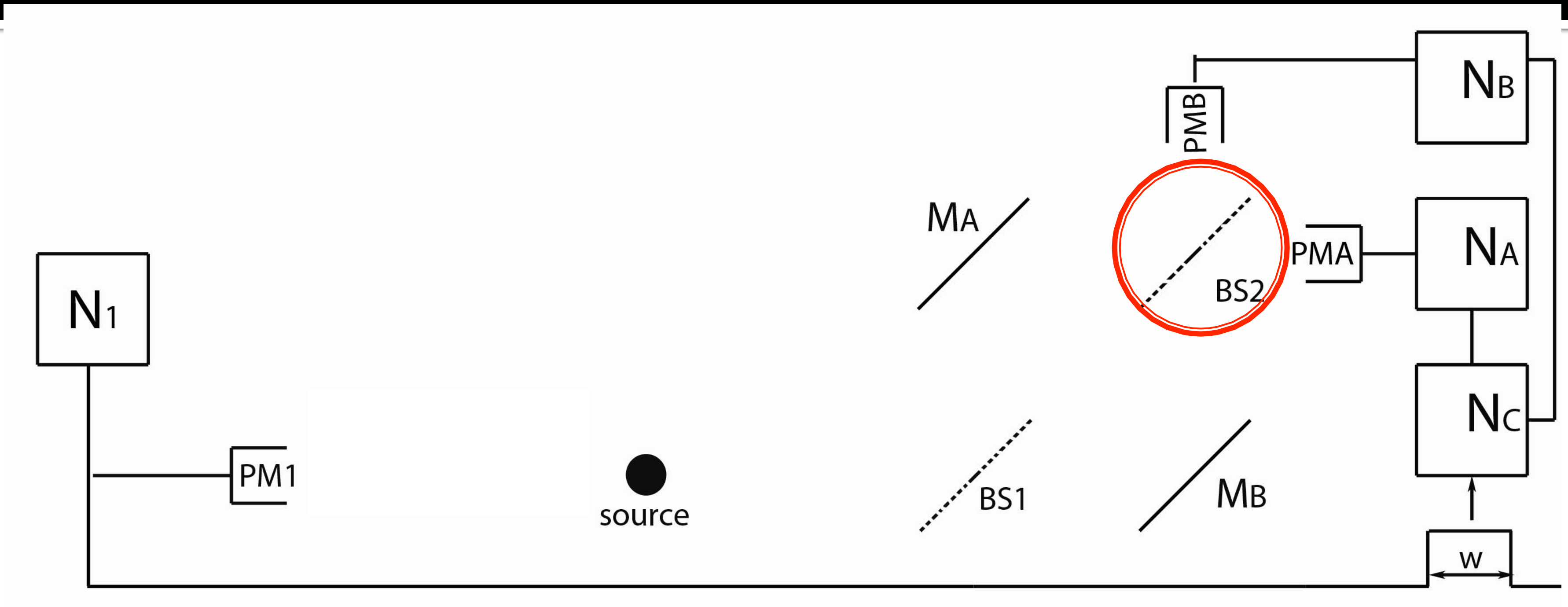
Experimental Results

Photons take ***<u>either</u>*** **Path A *<u>or</u>* Path B**, but not both!!



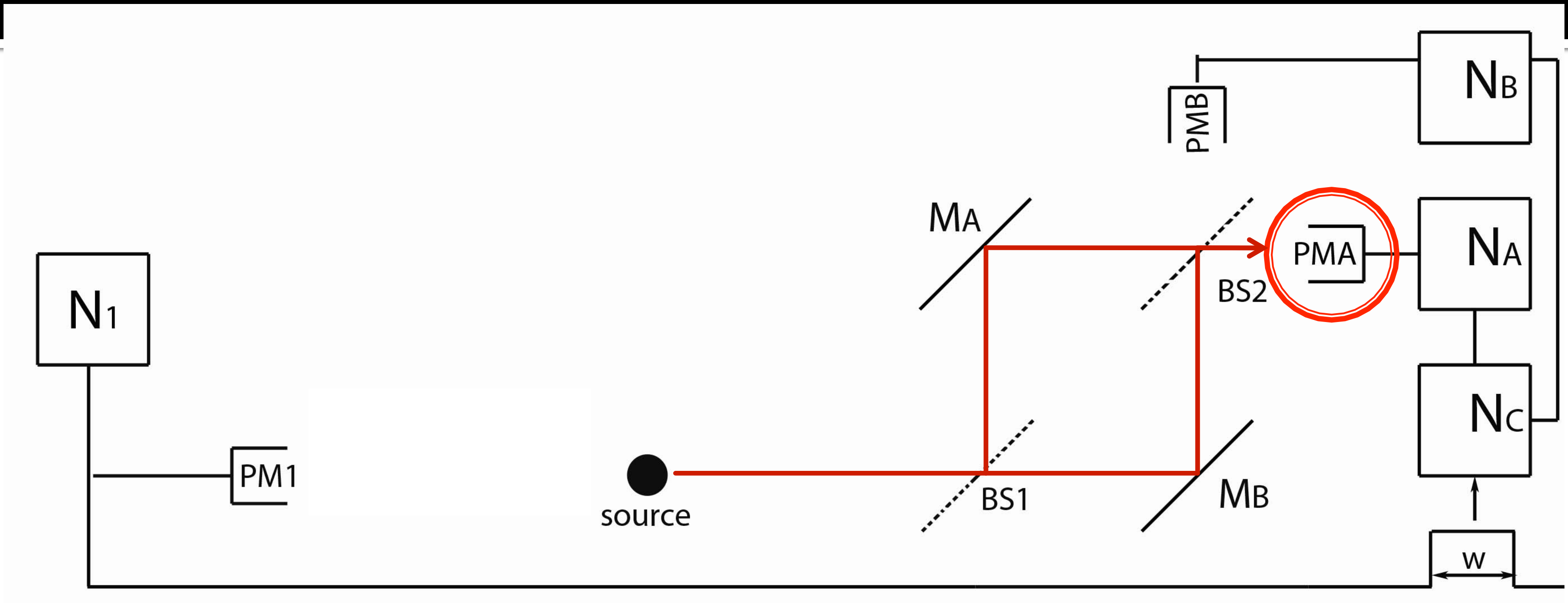
Event Rate

Add an Extra Feature



- Use same single-photon source, but now insert a second beam splitter. (BS2)
- Run experiment as before…

Concept Check



If the photon is detected in PMA, then it must have been...

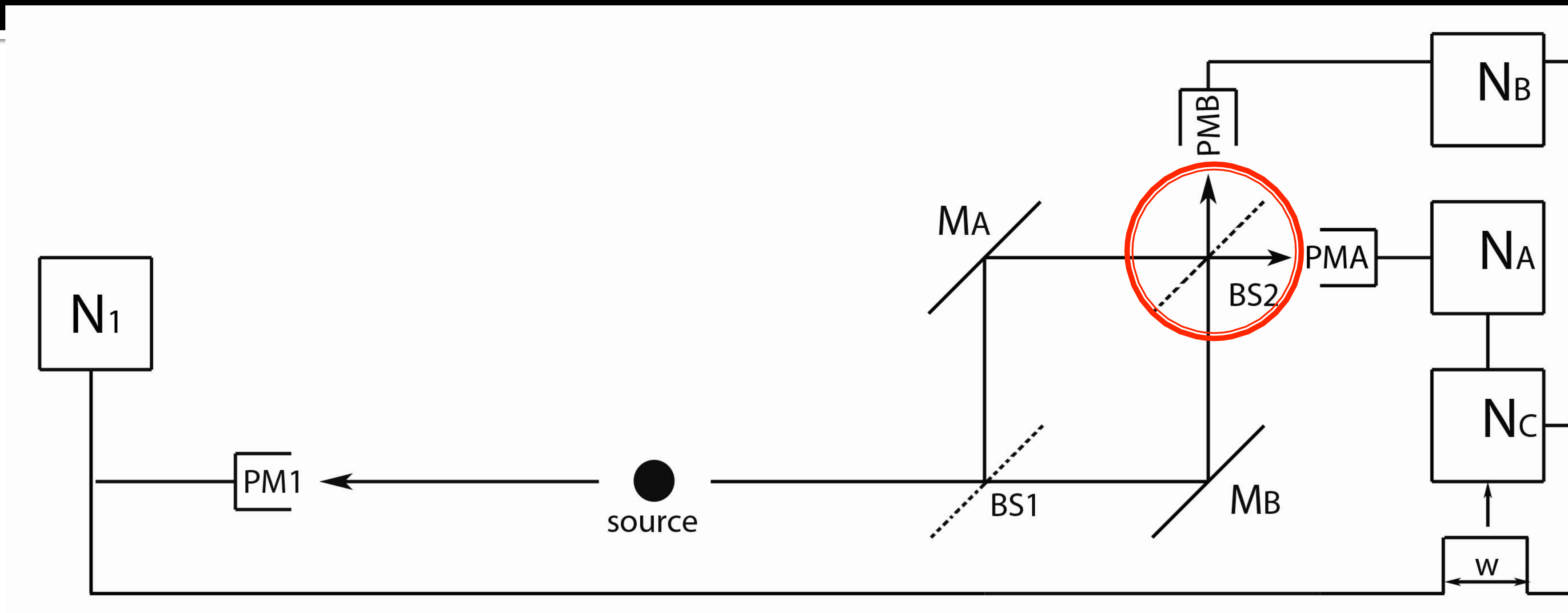
A) ...reflected at BS1.

B) ...transmitted at BS1.

C) ...either reflected or transmitted at BS1

D) Not enough information.

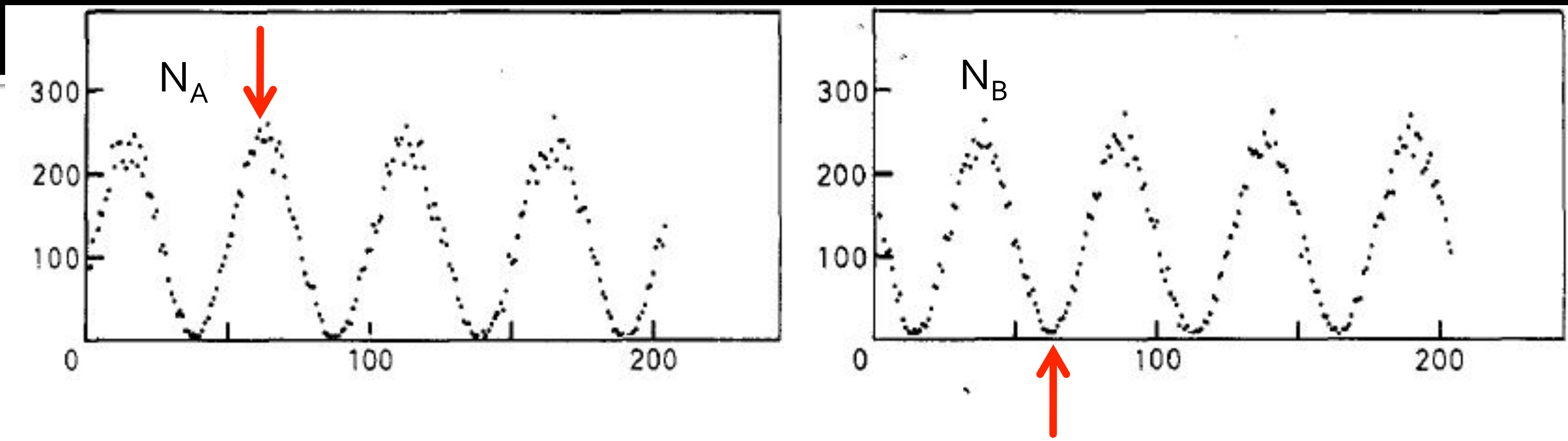
New Setup



- Whether the photon is detected in PMA or PMB, we have ***no information*** about which path (**A <u>or</u> B**) any photon took.

- What do we observe when we compare data from PMA & PMB?

Quantum Interference



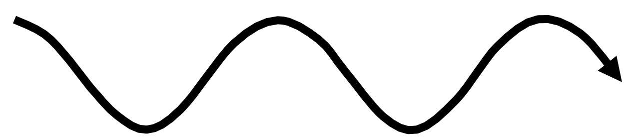
- Slowly change one of the path lengths (Move M_B, for example), and we observe interference!
- For some path length differences, all the photons are detected by PMA and none in PMB
- For some path length differences, there is an equal probability for either detector to be triggered.
- Each photon is somehow "aware" of ***both paths***!

Wrap Up

- Photons in **Experiment One** took **only** **Path A** **or** **Path B.**
  (which-path information – a particle encounters BS1 and takes either one path or the other)
- Photons in **Experiment Two** take **both** **Path A** **and** **Path B**.
  (no path information – a wave encounters BS1 and splits equally to take both paths)

Experiment One says photons behave
like ***particles*** at BS1.

Experiment Two says photons behave
like ***waves*** at BS1.



Quantum Weirdness

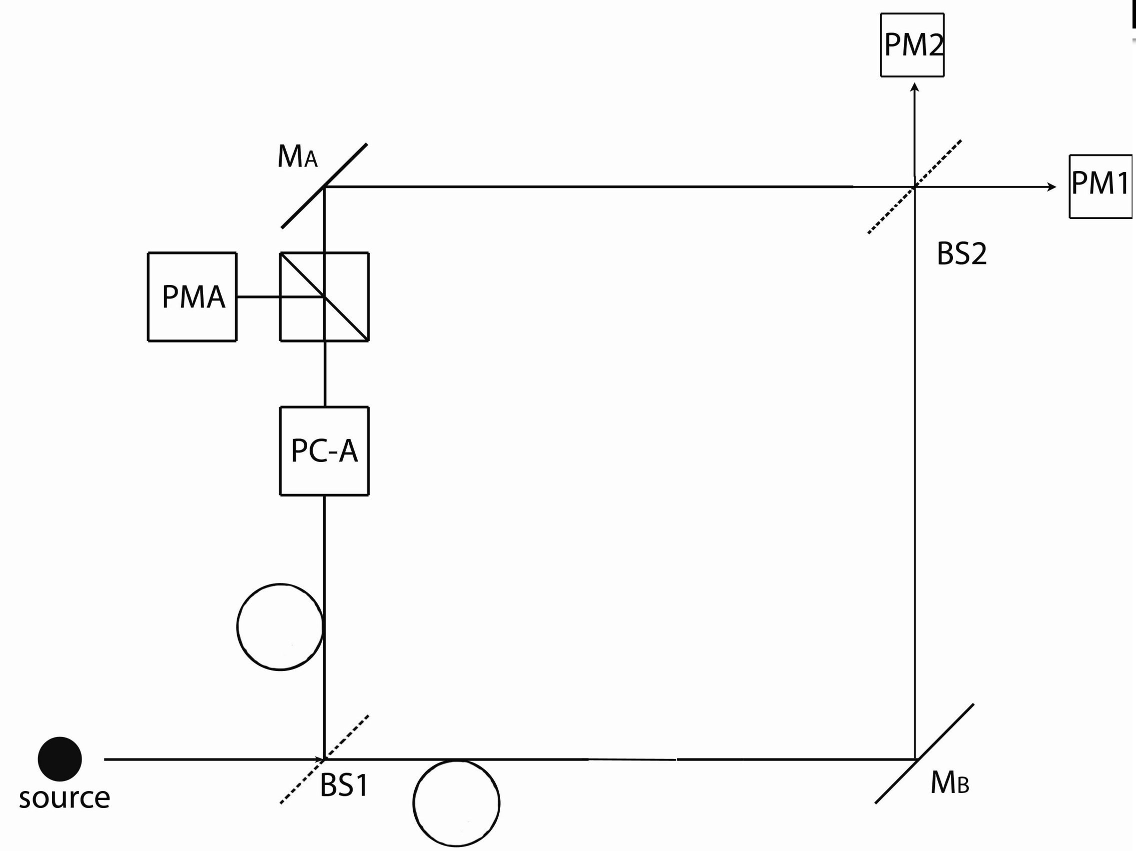
How can the photon "know" whether we are conducting Experiment One or Experiment Two when it encounters BS1?

Perhaps each photon "senses" the entire experimental apparatus and always behaves accordingly.

Can we "trick" a photon into acting like a particle at BS1 when it should act like a wave, or the other way around?

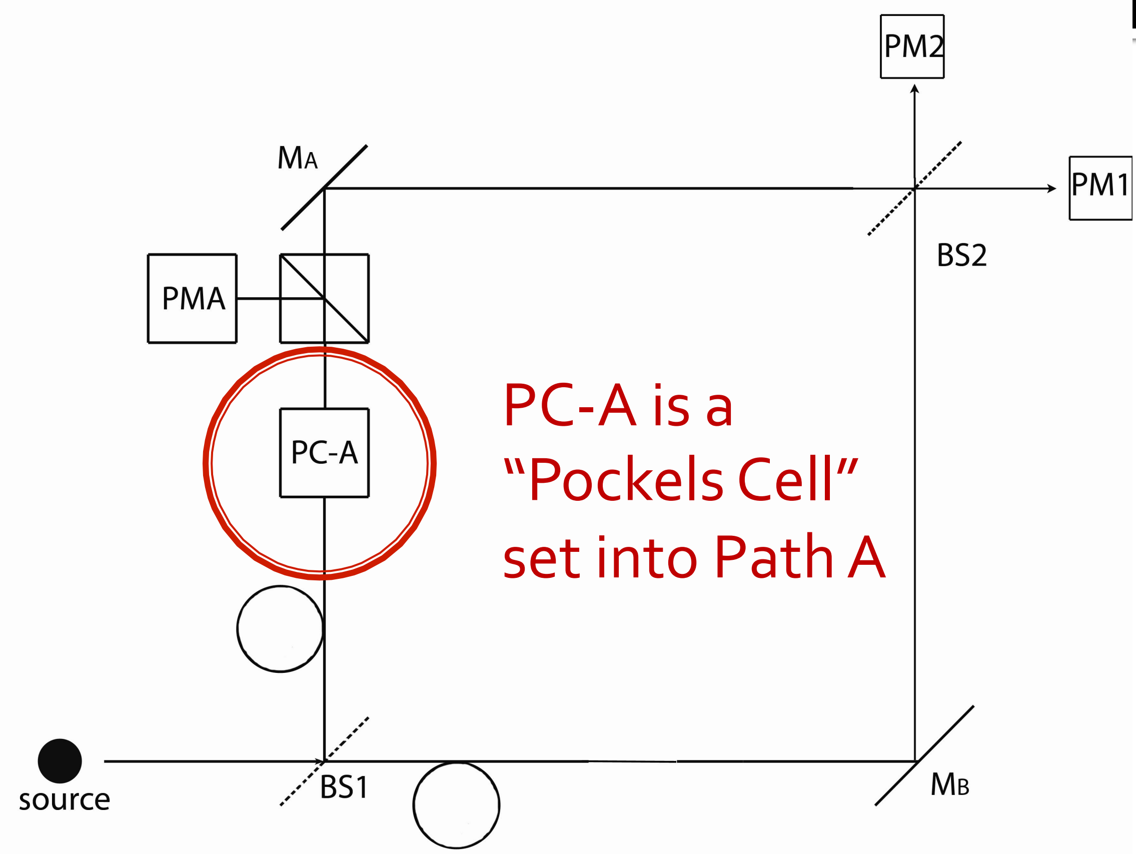
Suppose we let the photon enter the apparatus when only one path is available, but then open up a second path at the last moment.

Delayed Choice Experiment



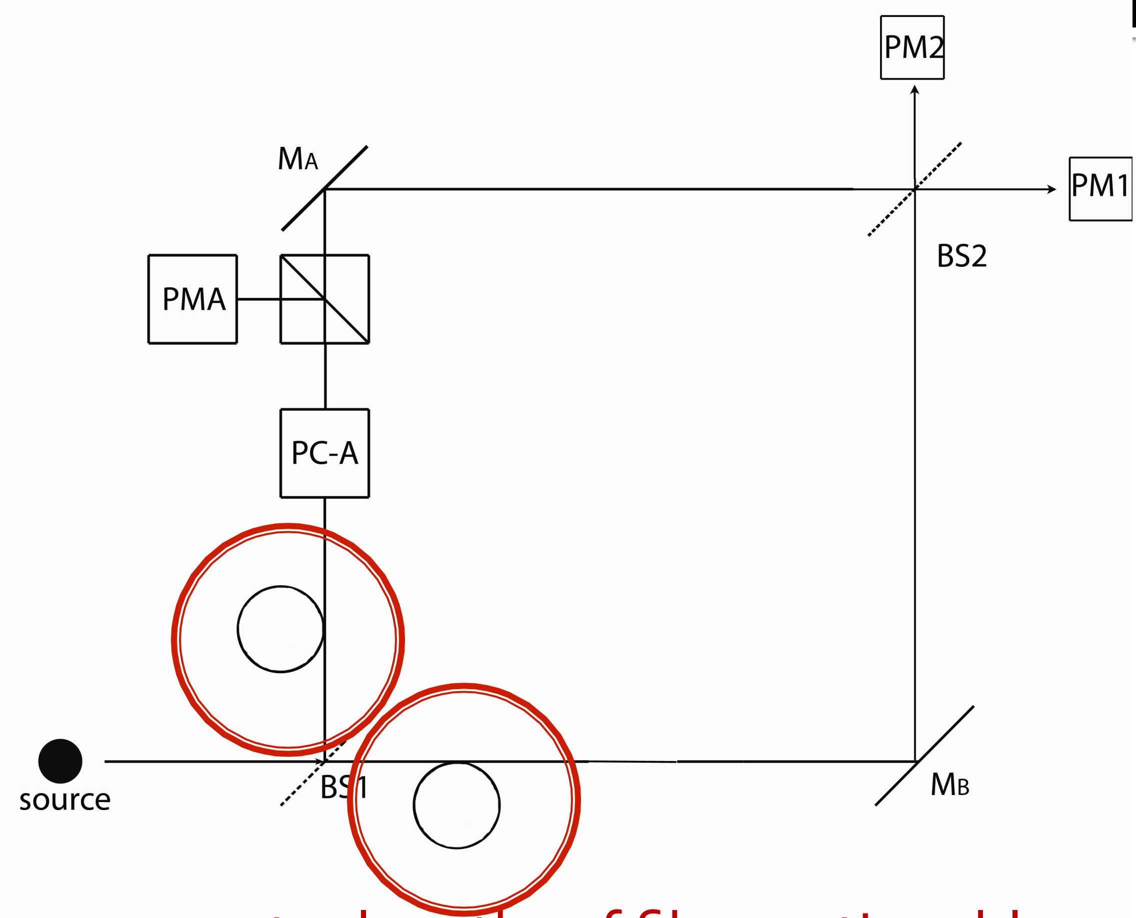
Impossible to insert/remove a path at the necessary speed, but the above setup is equivalent to what we just described.

Delayed Choice Experiment



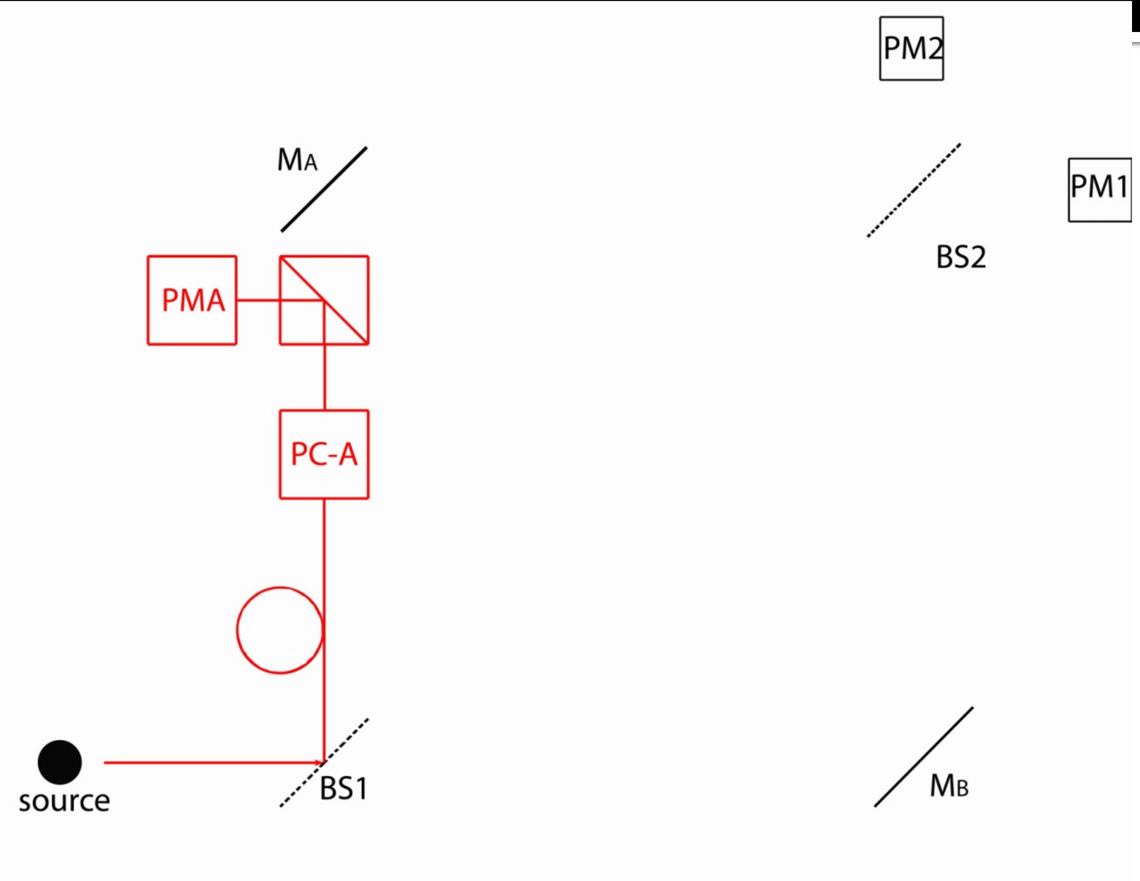
When voltage applied to PC-A, it deflects the photon to PMA. We can turn this voltage on and off very quickly (and randomly).

Delayed Choice Experiment



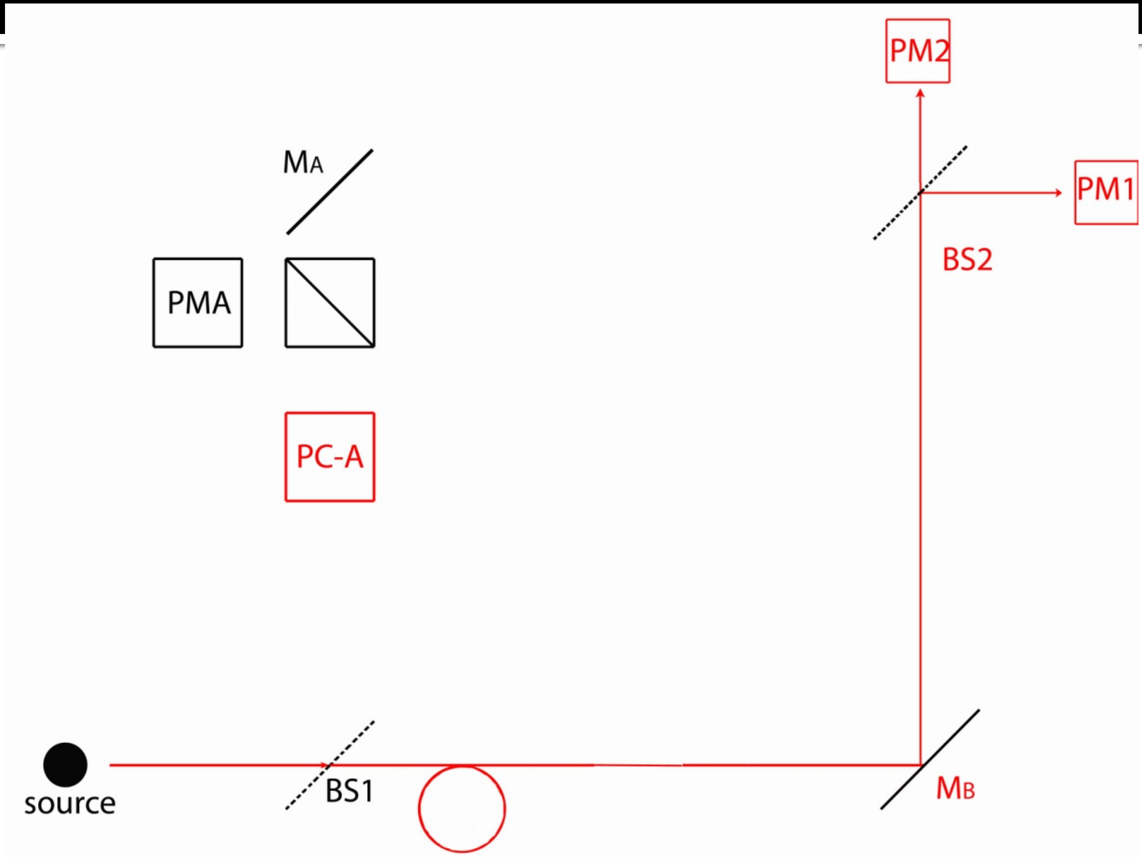
10 meter lengths of fiber optic cable are inserted into both paths to give us time.

Delayed Choice Experiment



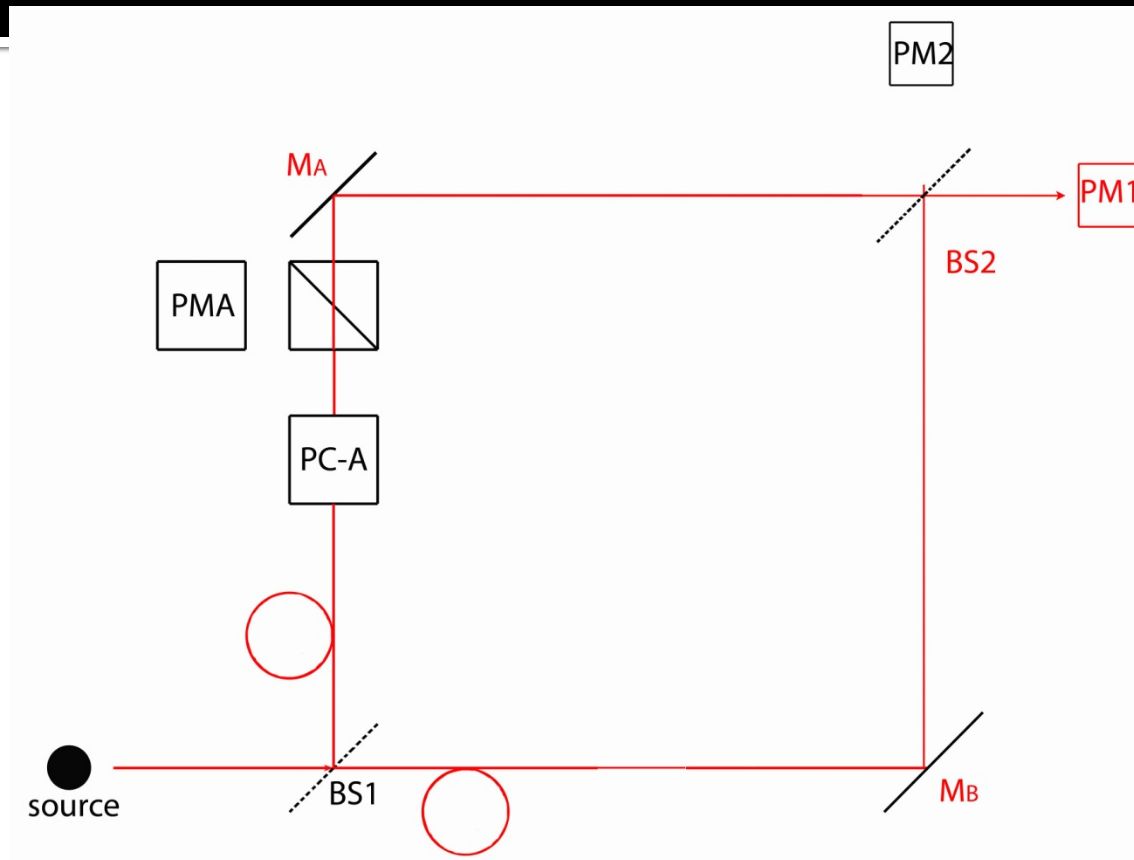
If the photon is reflected at BS1 with voltage applied to PC-A, then the photon is always detected in PMA.

Delayed Choice Experiment



If the photon is transmitted at BS1 with voltage applied to PC-A, then the photon is detected in PM1 or PM2 with equal probability (no interference).

Delayed Choice Experiment



When ***NO*** voltage applied to PC-A, both Paths A & B are possible.
We'll fix mirrors so photons are always detected in PM1 (Interference).

Delayed Choice Wrap Up

No voltage applied to PC-A:

Both paths are possible and photon is detected in PM1 only.

TWO PATHS = INTERFERENCE

Voltage applied to PC-A:

If photon detected in PMA ⟵⟶ Photon took Path A

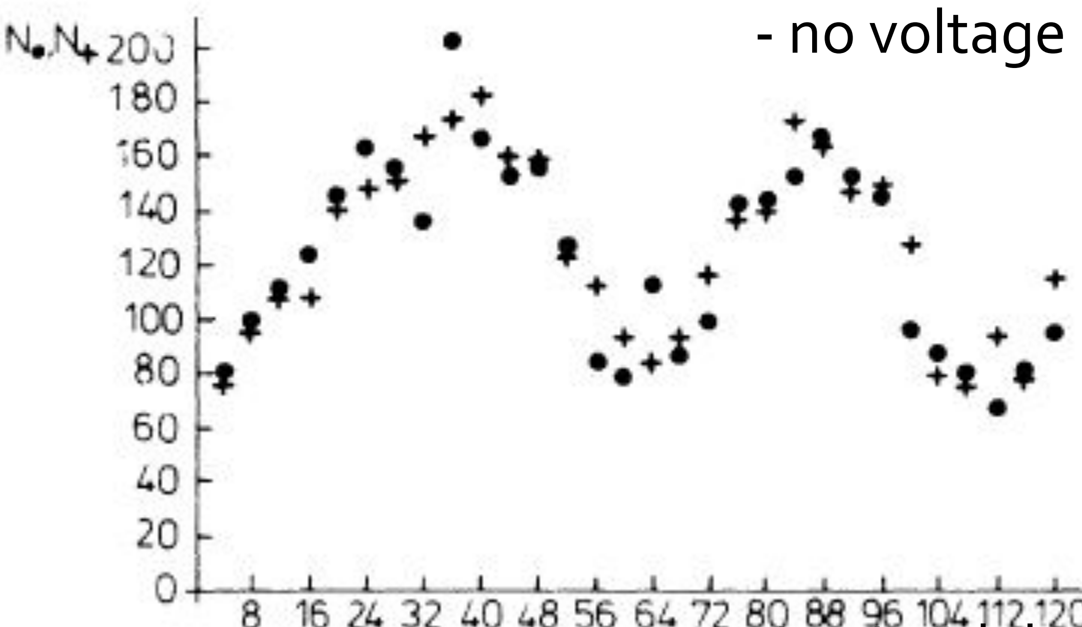
If photon detected in PM1 or PM2 ⟵⟶ Photon took Path B

ONE PATH = NO INTERFERENCE.

Delayed Choice Experimental Data

- Dots represent apparatus operating in “normal” mode

  - no voltage applied to PC-A.



- Crosses represent apparatus operating in “delayed-choice” mode
  - photon enters apparatus with only one path open.
  - photon should choose one path or the other at BS1
  - paths are unblocked after delay, interference is still observed.

Interpretation?

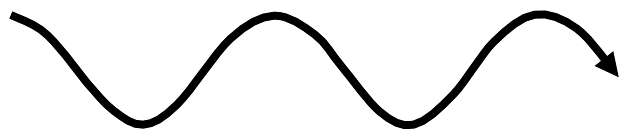
"The result of [the detection] must be either the whole photon or nothing at all. Thus the photon must change suddenly from being partly in one beam and partly in the other to being entirely in one of the beams."

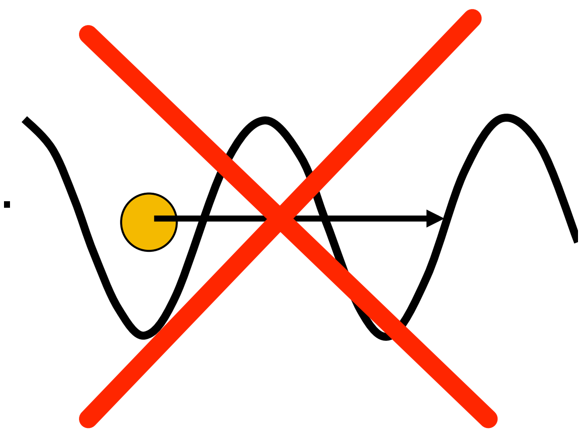
P. A. M. Dirac, *The Principles of Quantum Mechanics* (1947).

Great Gadzooks

Experiment One says photons behave like ***particles***.

Experiment Two says photons behave like ***waves***.

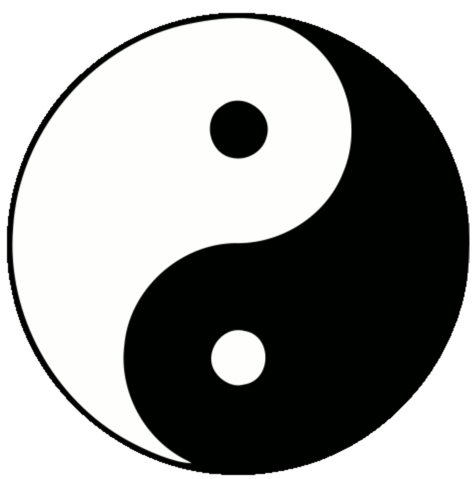




Experiment Three says photons ***do not*** behave like particle ***and*** wave at the same time.

Complementarity

- ***Sometimes*** photons behave like ***waves***, and ***sometimes*** like ***particles***, but ***never both*** at the same time.
- According to Bohr, ***particle*** or ***wave*** are just classical concepts, used to describe the different behaviors of quanta under different circumstances.
- Neither concept by itself can completely describe the behavior of quantum systems.



Contraria sunt Complementa

Latin for: opposites are complements

Wave-Particle Duality

- Light sometimes has particle-like behavior
- Particles sometimes have wavelike behavior