Putting Local Realism to the Test

"We can't solve problems by using the same kind of thinking we used when we created them."
- Albert Einstein

Day 39:
Questions?
Revisit EPR-Argument
Testing Local Realism
Single Photon

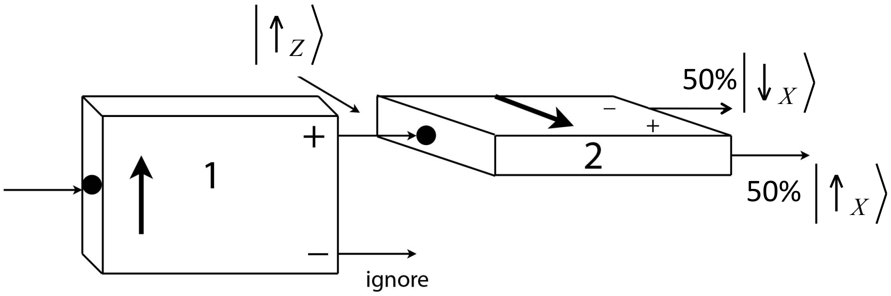
Up Next:
Readings!
Finish Single-Photon Experiments
Wave-Particle Duality

Recently:

1. Hidden variables, locality, quantum interpretations.
2. Entanglement

Today:

1. Revisit the EPR argument.
2. Testing local realism
3. Single photon



What would be the expectation (average) value for m_X?

$$\langle m_X \rangle = P\left[|\uparrow_X\rangle\right](+m_B) + P\left[|\downarrow_X\rangle\right](-m_B)$$

$$= (0.50)(+m_B) + (0.50)(-m_B) = 0$$

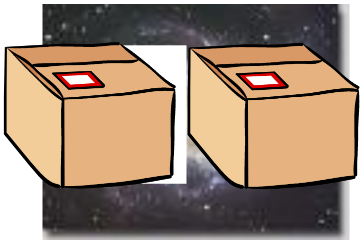
Classical Ignorance vs. Quantum Uncertainty

- Classical Experiment:
  - Take a blue sock and a red sock
  - Seal them up in identical boxes
  - Mix up boxes
  - Take them to opposite ends of galaxy
  - Open just one box, and you know what color sock is in the other box.
- The math we use to describe this is that

  Expectation = 0.5 blue + 0.5 red

  $|\Psi_{12}\rangle = \underline{|\uparrow_1\rangle}|\downarrow_2\rangle + \underline{|\downarrow_1\rangle}|\uparrow_2\rangle$

  Same math as spin up / down … is the PHYSICS the same?



Which interpretation sounds most reasonable to you?

A) **<u>Interpretation One</u>**: An atom with a definite value of m_Z also has a definite value of m_X, but that value changes so rapidly that we can't predict it ahead of time.

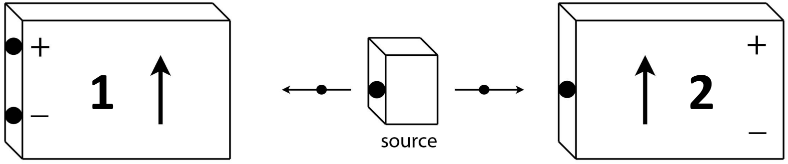
B) **<u>Interpretation Two</u>**: An atom with a definite value of m_Z also has a definite value of m_X but measuring m_Z disturbs the value of m_X in some unpredictable way.

C) **<u>Interpretation Three</u>**: An atom with a definite value of m_Z doesn't have a definite value of m_X until measured.

D) A & B seem equally reasonable.

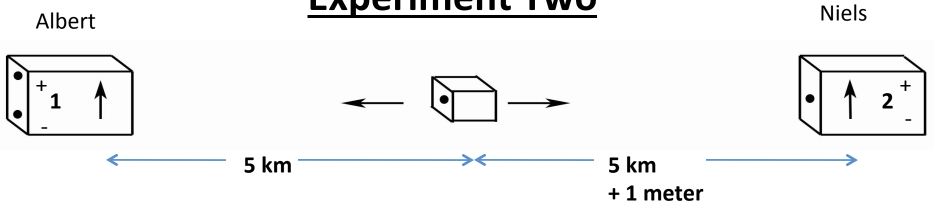
E) Something else…

<u>Experiment One</u>



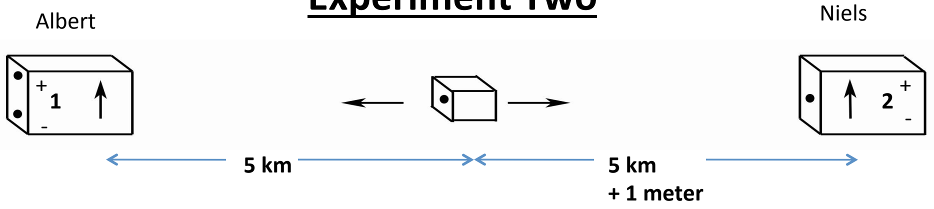
- The results of **Experiment One** show that the measurements performed on **Atom 1** and on **Atom 2** are ***anti-correlated***.
- ***<u>Anti</u>***-correlated means that, whatever answer we get for **Atom 1**, we'll get the ***<u>opposite</u>*** answer for **Atom 2**, as long as we're asking the ***same question***.
- Atom pairs in a correlated state $|\Psi_{12}\rangle = |\uparrow_1\rangle|\downarrow_2\rangle + |\downarrow_1\rangle|\uparrow_2\rangle$ are said to be ***entangled***.

Experiment Two



- **Analyzer 1** (watched by **Albert**) is placed 5 km to the left of the source.
- **Analyzer 2** (watched by **Niels**) is placed 5 km ***plus one meter*** to the right of the source.
- Perform **Experiment One**, exactly as before.
- How is this experiment different from the first?

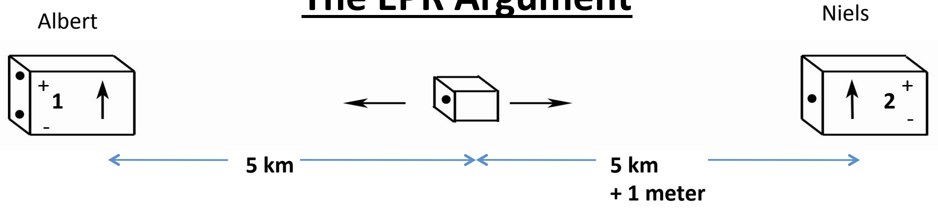
Experiment Two



- **Albert** can tilt **Analyzer 1** any way he wants, and **Niels** can do the same with **Analyzer 2**.
- When **Analyzers 1** & **2** are tilted at different angles, they sometimes get the same answer, sometimes different answers.
- But when they compare their data, whenever the analyzers were tilted at the same angle they got ***opposite*** answers.
- The measurements are still 100% ***anti-correlated***.

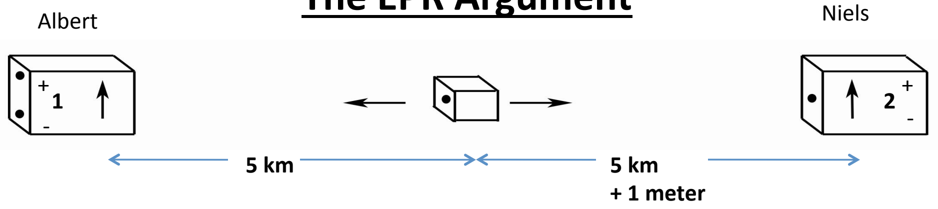
$$|\Psi_{12}\rangle = |\uparrow_1\rangle|\downarrow_2\rangle + |\downarrow_1\rangle|\uparrow_2\rangle$$

The EPR Argument



- **Analyzers 1** & **2** are set at the same angle and **Albert** measures the spin of **Atom 1** ***first.*** He observes $\left|\uparrow_1\right\rangle$.
- **Albert** ***knows*** what the result of **Niels'** measurement will be ***before*** **Atom 2** reaches **Analyzer 2**. [And **Niels** knows he knows it.]
- What will be the outcome of Niels' measurement?
- If we ***assume locality***, then **Albert's** measurement can't change the outcome of **Niels'** measurement! **Niels** observes $\left|\downarrow_2\right\rangle$, and that must have been the state of **Atom 2** all along.

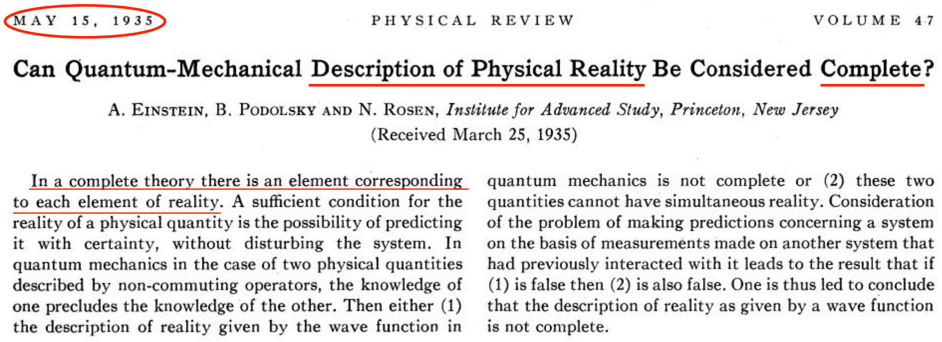
The EPR Argument



- In other words, if **Albert** can predict with 100% certainty that **Niels** will observe $\left|\downarrow_2\right\rangle$ ***before*** he performs the measurement, then $\left|\downarrow_2\right\rangle$ must have been the ***real***, ***definite*** state of **Atom 2** ***at the moment the atom pair was produced***.
- ***Local Realism*** says the atom pair was produced in the state

$$\left|\Psi_{12}\right\rangle = \left|\uparrow_1\right\rangle\left|\downarrow_2\right\rangle$$

and the measurements revealed this ***unknown reality*** to us.



MAY 15, 1935 PHYSICAL REVIEW VOLUME 47

Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

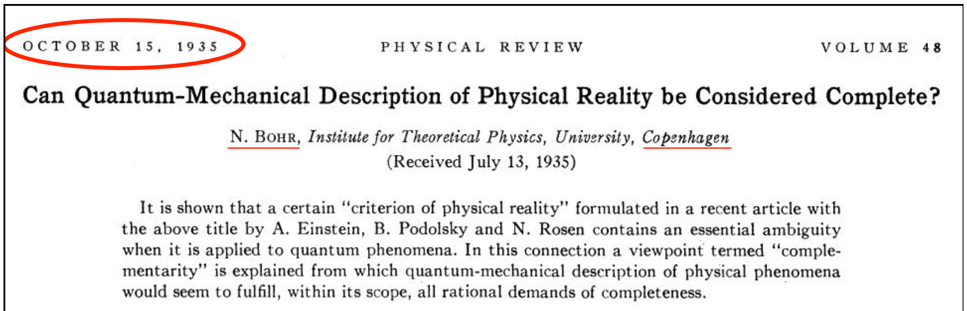
A. Einstein, B. Podolsky and N. Rosen, *Institute for Advanced Study, Princeton, New Jersey*

(Received March 25, 1935)

In a complete theory there is an element corresponding to each element of reality. A sufficient condition for the reality of a physical quantity is the possibility of predicting it with certainty, without disturbing the system. In quantum mechanics in the case of two physical quantities described by non-commuting operators, the knowledge of one precludes the knowledge of the other. Then either (1) the description of reality given by the wave function in quantum mechanics is not complete or (2) these two quantities cannot have simultaneous reality. Consideration of the problem of making predictions concerning a system on the basis of measurements made on another system that had previously interacted with it leads to the result that if (1) is false then (2) is also false. One is thus led to conclude that the description of reality as given by a wave function is not complete.

Albert Einstein believed that the properties of a physical system are ***objectively real*** – they exist whether we measure them or not.

Einstein, ***P***odolsky and ***R***osen (***EPR***) believed in the ***reality*** of hidden variables not described by quantum mechanics.



OCTOBER 15, 1935 PHYSICAL REVIEW VOLUME 48

Can Quantum-Mechanical Description of Physical Reality be Considered Complete?

N. Bohr, *Institute for Theoretical Physics, University, Copenhagen*

(Received July 13, 1935)

It is shown that a certain "criterion of physical reality" formulated in a recent article with the above title by A. Einstein, B. Podolsky and N. Rosen contains an essential ambiguity when it is applied to quantum phenomena. In this connection a viewpoint termed "complementarity" is explained from which quantum-mechanical description of physical phenomena would seem to fulfill, within its scope, all rational demands of completeness.

- ***The Copenhagen Interpretation*** says the atom pair was produced in the ***superposition*** state $|\Psi_{12}\rangle = |\uparrow_1\rangle|\downarrow_2\rangle + |\downarrow_1\rangle|\uparrow_2\rangle$
- Albert's measurement of $|\uparrow_1\rangle$ ***instantly collapses*** $|\Psi_{12}\rangle$ into the ***definite*** state $|\Psi_{12}\rangle = |\uparrow_1\rangle|\downarrow_2\rangle$
- This ***collapse*** must be ***instantaneous***, because there is no time for a signal to travel from **1** to **2**.

Albert Einstein: God does not play dice with the universe.

Niels Bohr: Who are we to tell God how to act?

Niels Bohr and Albert Einstein together at the 1930 Solvay Conference.

Philosophy or Science?

Interpretations One & **Two** involved ***hidden variables***.

Interpretation Three said:
In general, the state of a quantum system is indeterminate until measured.

We can restate this as:
THE OUTCOME OF A QUANTUM EXPERIMENT CANNOT, ***IN GENERAL***, BE PREDICTED EXACTLY; ONLY THE PROBABILITIES OF THE VARIOUS OUTCOMES CAN BE FOUND.

Question: How comfortable are you with **Interpretation Three** (i.e. Finkelstein says Einstein is wrong and Bohr is right)?

A. Very comfortable
B. Getting comfortable, but still not totally convinced
C. On the fence, I can see arguments for both sides
D. No way, Finkelstein (and Bohr) are full of it
E. Don't have any idea which interpretation is right

Dealing with Hidden Variables

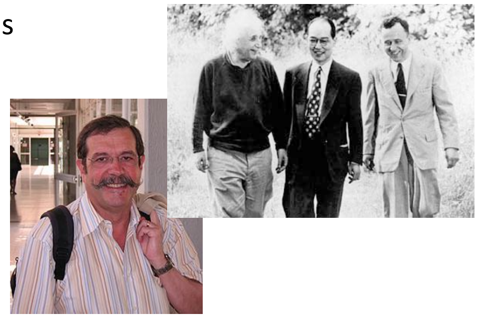
In 1964, J. S. Bell proves *theoretically*:

No <u>local</u> interpretation of quantum phenomena can reproduce all of the predictions of quantum mechanics.

THE paradox of Einstein, Podolsky and Rosen [1] was advanced as an argument that quantum mechanics could not be a complete theory but should be supplemented by additional variables. These additional variables were to restore to the theory causality and locality [2]. In this note that idea will be formulated mathematically and shown to be incompatible with the statistical predictions of quantum mechanics. It is

In 1978, John Wheeler proposes ***delayed choice experiment*** to demonstrate Bell's theorem

In 1986, Alain Aspect, et al. performs set of **single photon experiments**

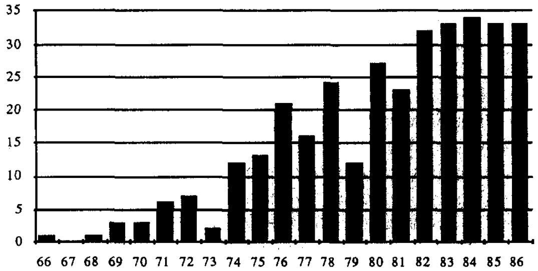


Bell's Theorem

There is a powerful general theorem by J. S. Bell that proves:

No <u>local</u> interpretation of quantum phenomena can reproduce all of the predictions of quantum mechanics.

[We can devise a realistic scheme that is non-local, but most scientists are uncomfortable with this kind of interpretation.]

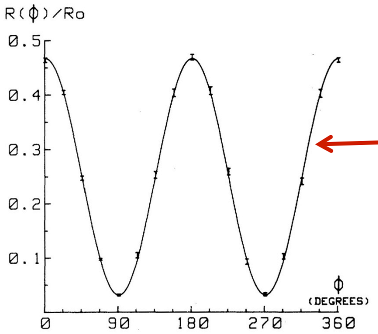


Number of annual citations of "On the Einstein-Podolsky-Rosen Paradox"
J. S. Bell, *Physics* **1**, 195 (1964)

Bell’s Theorem

There is a more general theorem by J. S. Bell that proves:

No local interpretation of quantum phenomena can reproduce all of the predictions of quantum mechanics.



Error bars represent one standard deviation

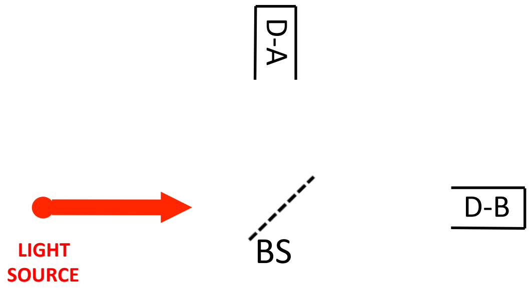
Not a “best-fit” curve !!

A test of Bell’s Theorem performed by A. Aspect (1981)

Single Photon Experiments

“It is wrong to think that the task of physics is to find out how Nature is. Physics concerns what we can say about Nature.

– **Niels Bohr**

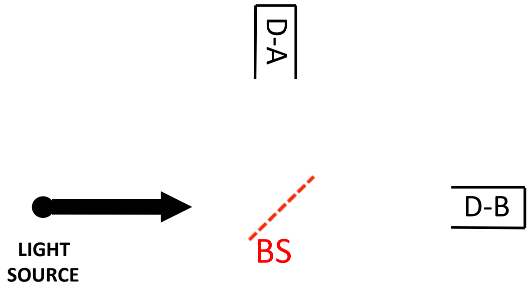


D-A

LIGHT SOURCE

BS

D-B



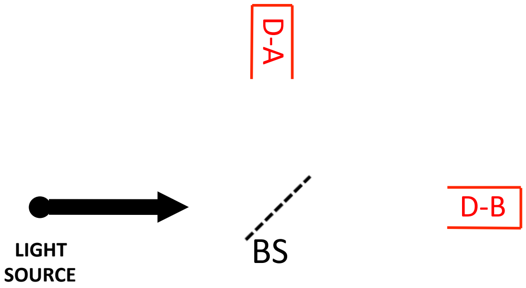
D-A

LIGHT SOURCE

BS

D-B

- BS is a beamsplitter



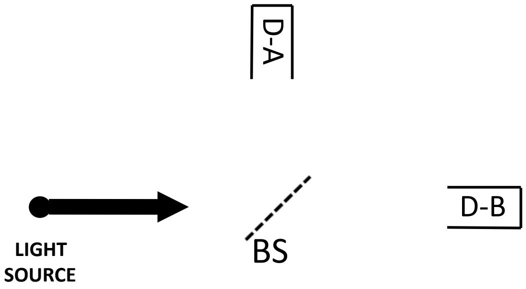
D-A

D-B

LIGHT SOURCE

BS

- BS is a beamsplitter
- D-A & D-B are detectors



D-A

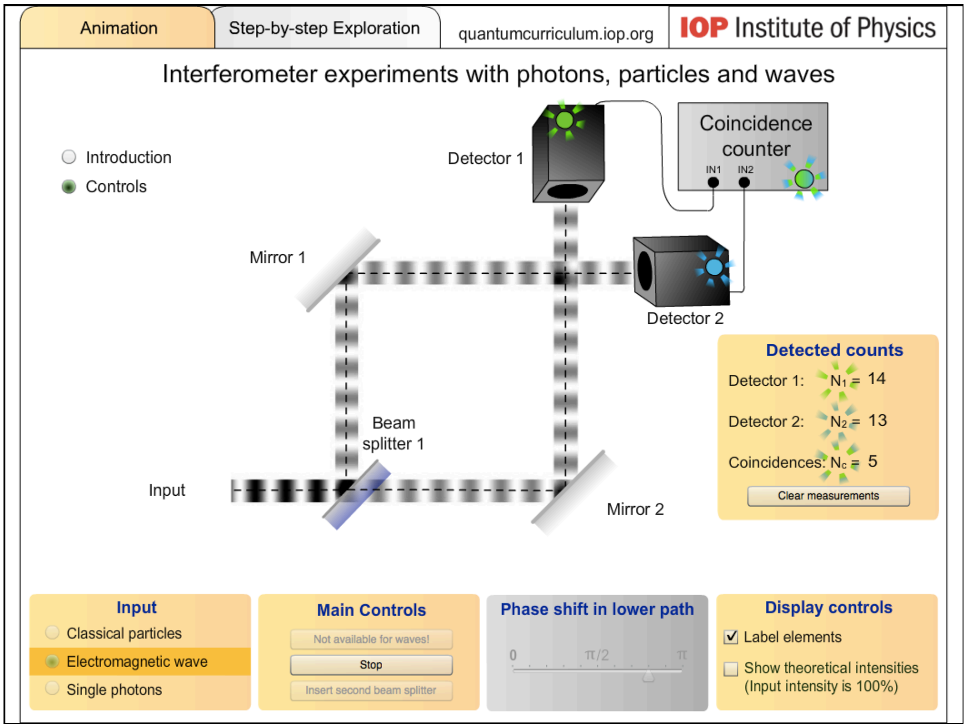
D-B

LIGHT SOURCE

BS

What happens when an EM wave encounters a beamsplitter?

(A) It's reflected towards Detector A.
(B) It's transmitted towards Detector B.
(C) It's reflected & transmitted towards both detectors.
(D) It alternates back and forth between the two with time.
(E) Something else.



Interferometer experiments with photons, particles and waves

Detected counts

Detector 1: $N_1 = 14$

Detector 2: $N_2 = 13$

Coincidences: $N_c = 5$

Input

○ Classical particles

● Electromagnetic wave

○ Single photons

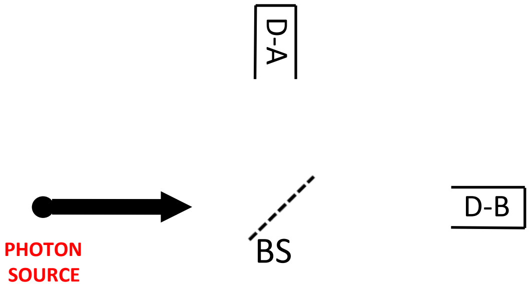
Main Controls

Phase shift in lower path

Display controls

☑ Label elements

☐ Show theoretical intensities (Input intensity is 100%)



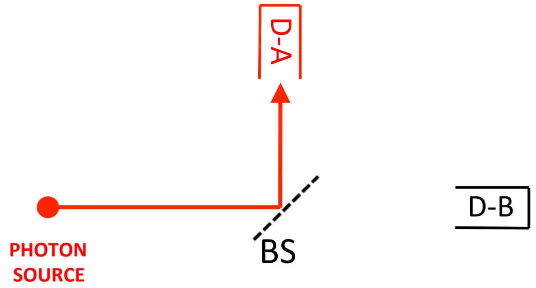
What happens when a single photon encounters a beamsplitter?

(A) Either reflected towards D-A (w/ 50% probability) **or** transmitted towards D-B (w/ 50% probability) at random.

(B) It's reflected & transmitted towards both detectors.

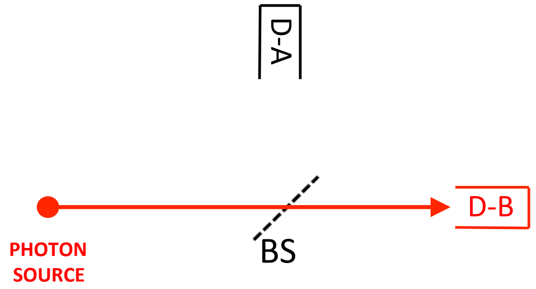
(C) Science has no way of knowing.

Silent / No Discussion Pleas



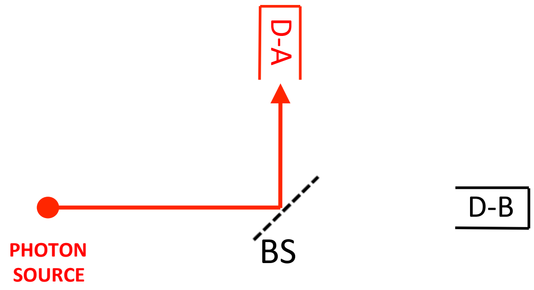
Two possibilities:

1. Photons are **reflected** at the beamsplitter



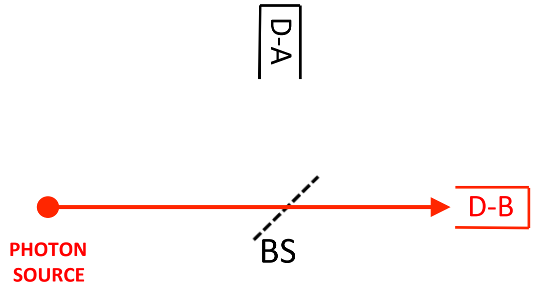
Two possibilities:

1. Photons are **reflected** at the beamsplitter
2. Photons are **transmitted** at the beamsplitter



Reflection: $|\Psi\rangle = |R\rangle$

$P_\mathrm{R} = 0.50$

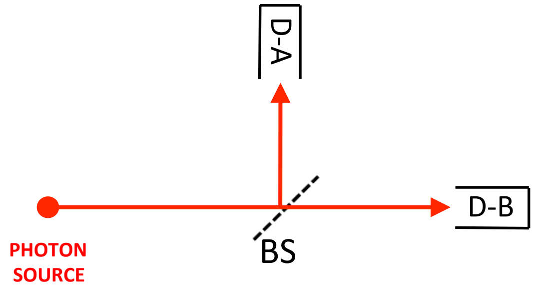


Reflection: $|\Psi\rangle = |R\rangle$

$P_\mathrm{R} = 0.50$

Transmission: $|\Psi\rangle = |T\rangle$

$P_\mathrm{T} = 0.50$



Reflection: $|\Psi\rangle = |R\rangle$ **Transmission:** $|\Psi\rangle = |T\rangle$

$$|\Psi\rangle = \frac{1}{\sqrt{2}}|R\rangle + \frac{1}{\sqrt{2}}|T\rangle$$

Interpretation

Statistical: Each photon is **either** reflected **or** transmitted at the beamsplitter (but not both). The superposition state represents our ignorance of its actual state.

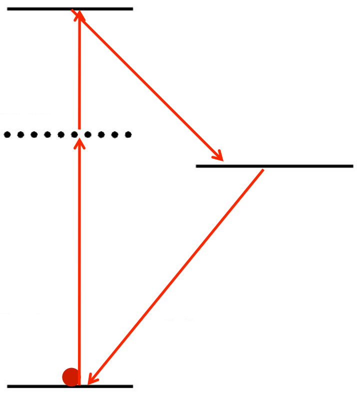
Quantum Wave: Each photon is **both** reflected **and** transmitted. The superposition state represents the actual state of each photon after encountering the beamsplitter.

Copenhagen: We can't describe what we can't observe. The superposition is the correct mathematical description of the possible measurement outcomes, but we can't ever know more than that.

"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."

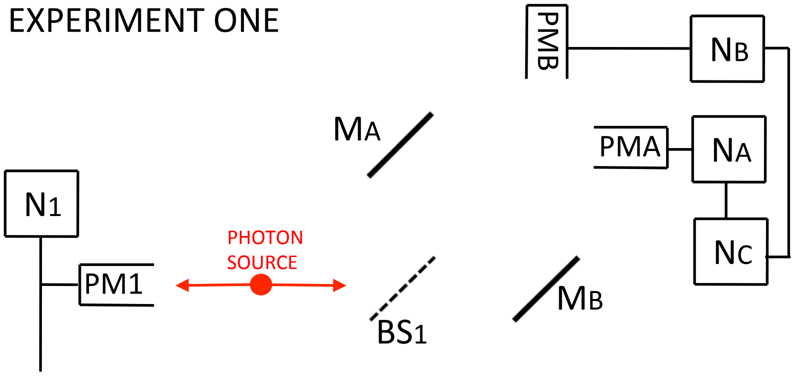
P. A. M. Dirac, *The Principles of Quantum Mechanics* (1930, p. 8)

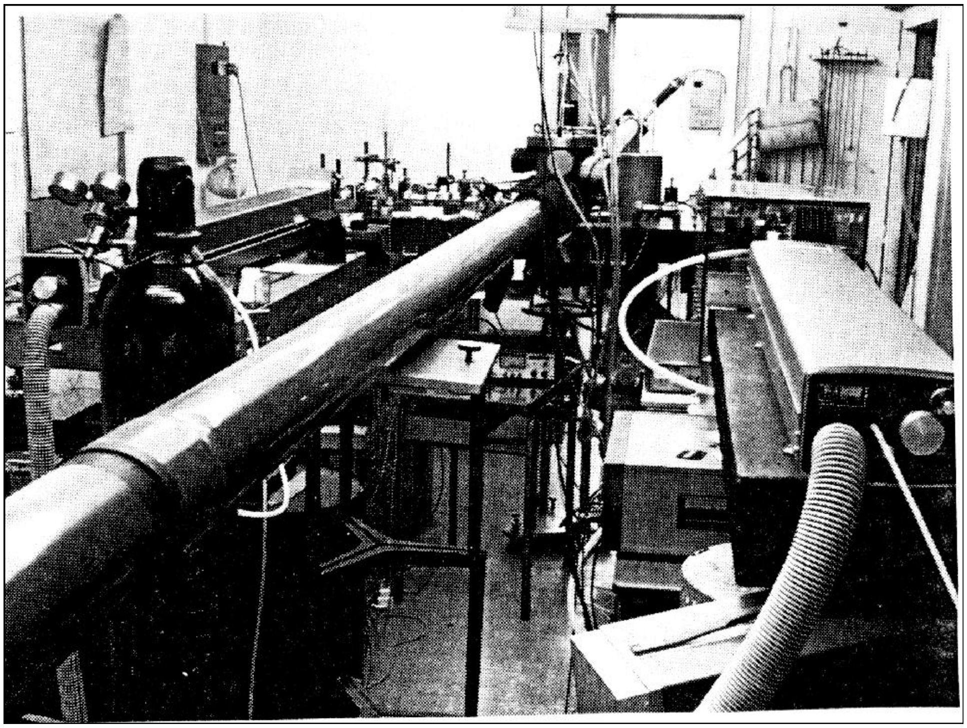
Single Photon Source (1986)

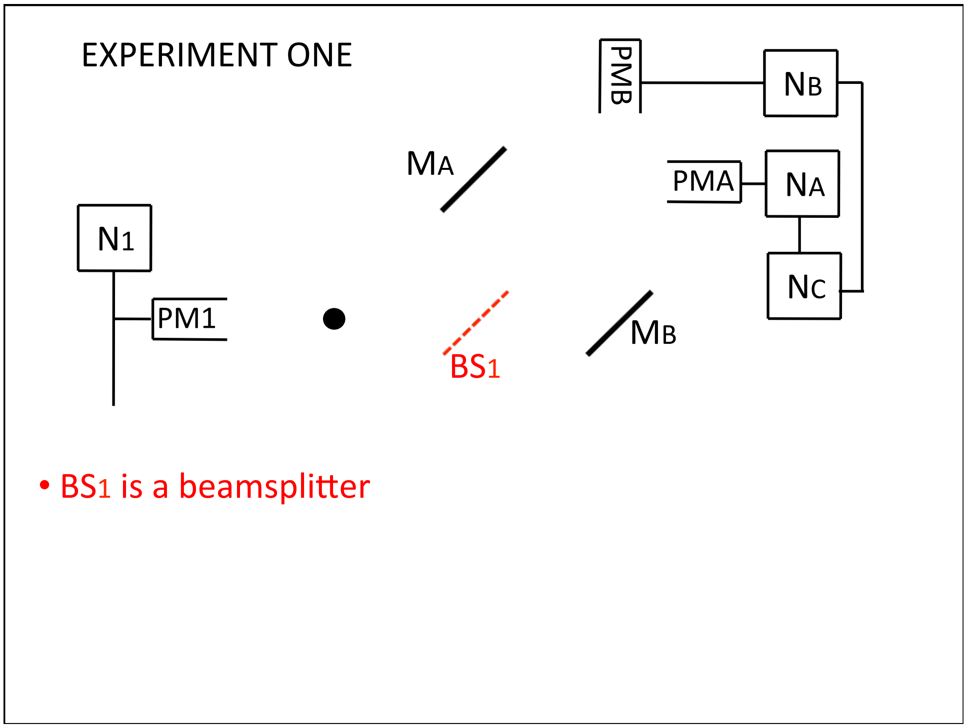


- Calcium atoms are excited by a two-photon absorption process (E_K = 3.05 eV) + (E_D = 2.13 eV).
- The excited state first decays by single photon emission (E_1 = 2.25 eV).
- The lifetime of the intermediate state is $\tau \sim 5$ ns.
- High probability the second photon (E_2 = 2.93 eV) is emitted within $t = 2\tau$

EXPERIMENT ONE

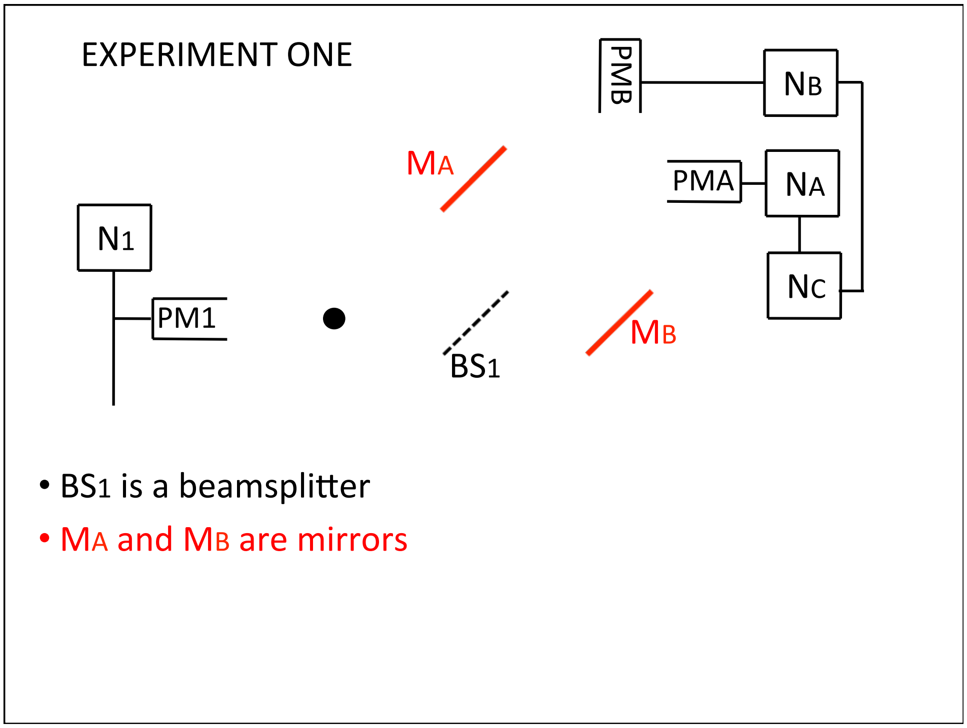






EXPERIMENT ONE

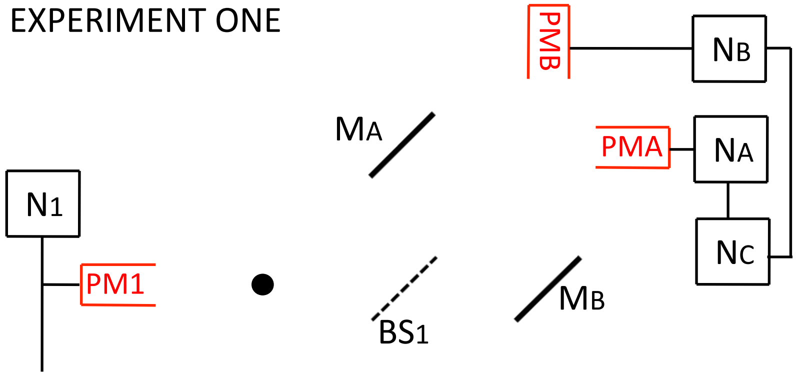
- BS_1 is a beamsplitter



EXPERIMENT ONE

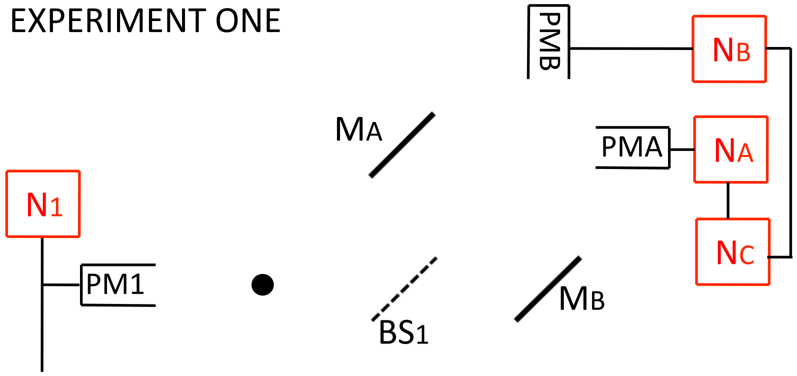
- BS_1 is a beamsplitter
- M_A and M_B are mirrors

EXPERIMENT ONE



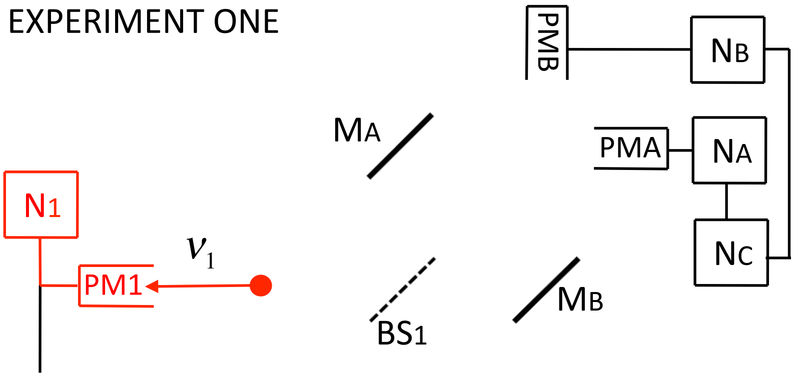
- BS1 is a beamsplitter
- MA and MB are mirrors
- PM1, PMA & PMB are photomultipliers

EXPERIMENT ONE



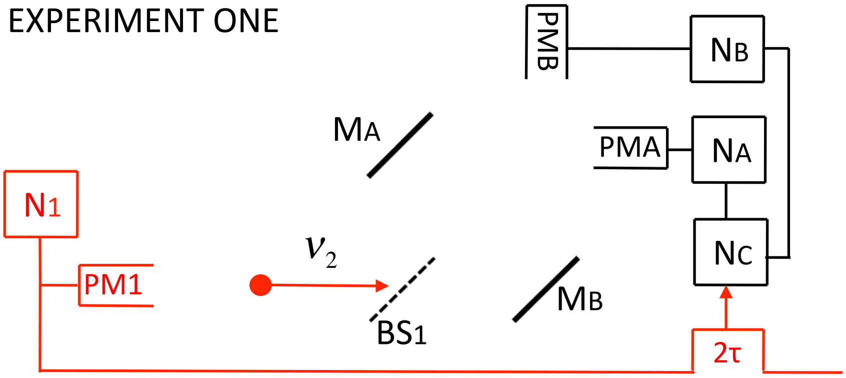
- BS1 is a beamsplitter
- MA and MB are mirrors
- PM1, PMA & PMB are photomultipliers
- N1, NA, NB & NC are counters recording photon detections

EXPERIMENT ONE

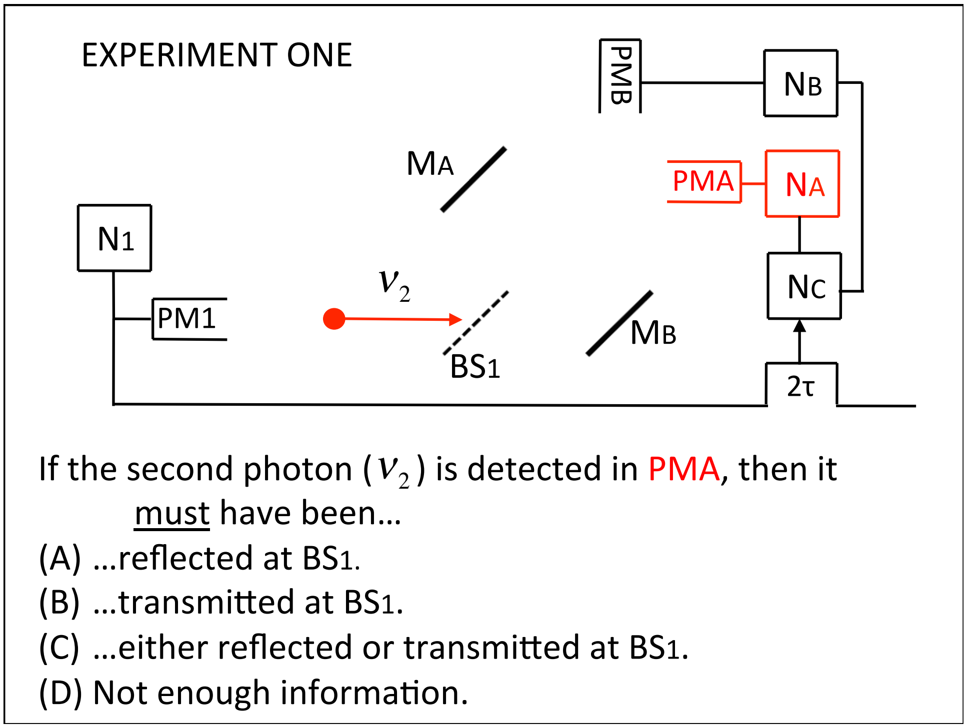


- Detection of first photon (ν_1) is counted by N1

EXPERIMENT ONE



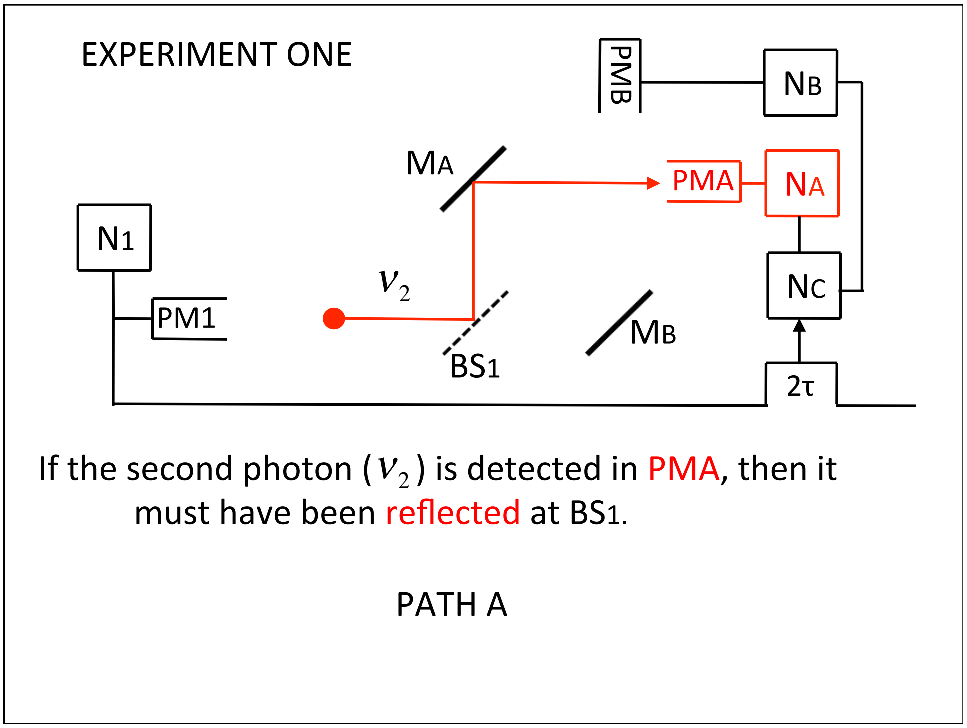
- Detection of first photon (ν_1) is counted by N1
- A signal is sent to tell the other counters (NA, NB & NC) to expect a second photon (ν_2) within a time 2τ



EXPERIMENT ONE

If the second photon (ν_2) 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.

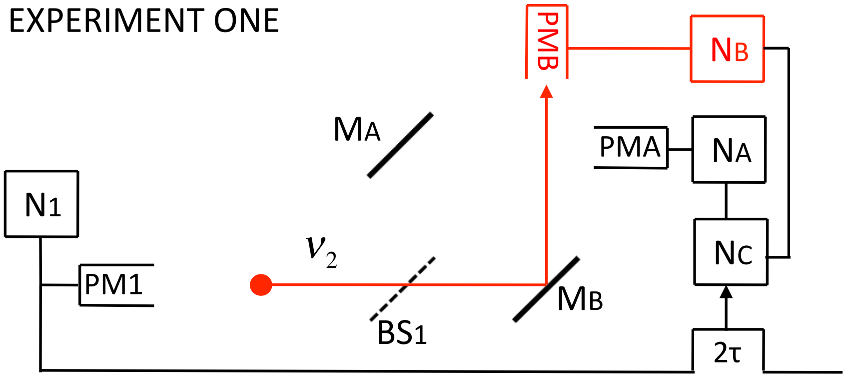


EXPERIMENT ONE

If the second photon (ν_2) is detected in PMA, then it must have been reflected at BS1.

PATH A

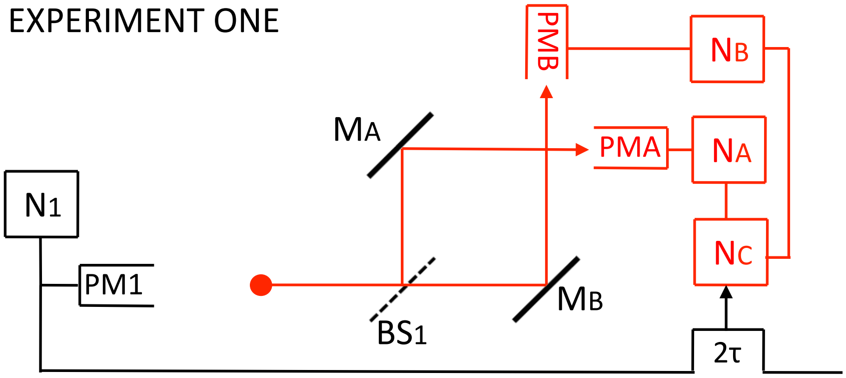
EXPERIMENT ONE



If the second photon (ν_2) is detected in PMB, then it must have been transmitted at BS1.

PATH B

EXPERIMENT ONE



If <u>both</u> PMA and PMB fire within t = 2τ, then the coincidence counter (NC) is triggered

Many photons…

…or classical wave-like behavior at the beamsplitter

ANTI-CORRELATION PARAMETER (α)

Want some kind of measure of how often PMA & PMB are firing simultaneously (within t=2τ)

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

- $P_A = \frac{N_A}{N_1}$ = probability for NA to be triggered
- $P_B = \frac{N_B}{N_1}$ = probability for NB to be triggered
- $P_C = \frac{N_C}{N_1}$ = probability for coincidence counter (NC) to be triggered (PMA & PMB during t=2τ)

ANTI-CORRELATION PARAMETER $\boxed{\alpha \equiv \frac{P_C}{P_A \cdot P_B}}$

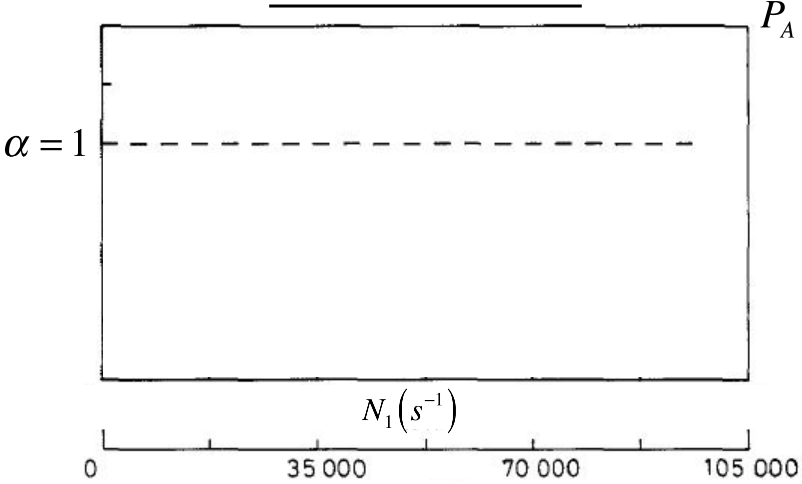
- If NA & NB are being triggered randomly and independently, then $\alpha = 1$ $P_C = P_A \cdot P_B$
- If NA & NB are being triggered separately (reflection **or** transmission) then $\alpha \geq 0$

  $P_C = 0$ when photons are detected by either PMA or PMB, but never both simultaneously
- If NA & NB are being triggered together (reflection **and** transmission) then $\alpha \geq 1$

  $P_C > P_A \cdot P_B$ means PMA & PMB are firing together more often than random.

EXPERIMENT ONE

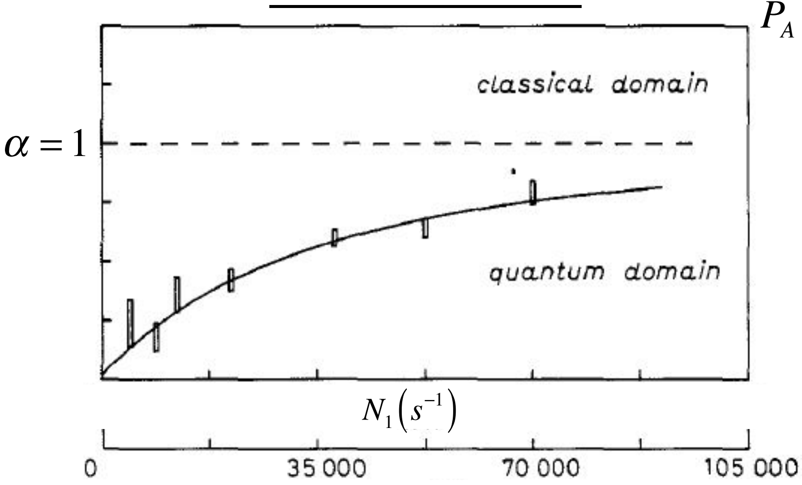
$$\alpha \equiv \frac{P_C}{P_A \cdot P_B}$$



What do you expect for the experimental results?

EXPERIMENT ONE

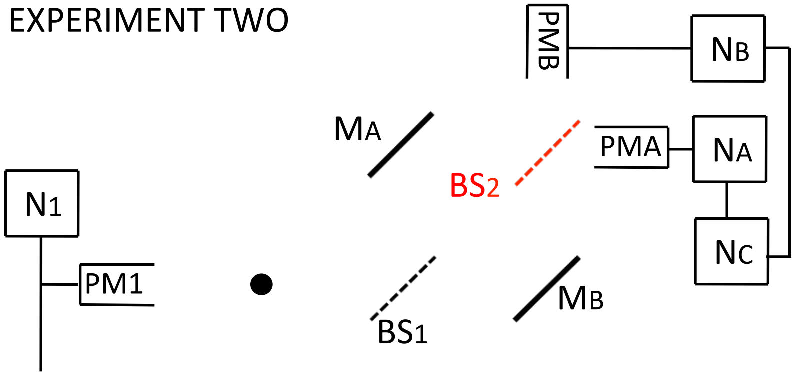
$$\alpha \equiv \frac{P_C}{P_A \cdot P_B}$$



Photons are detected in <u>either</u> PMA or PMB, but <u>not</u> both!!

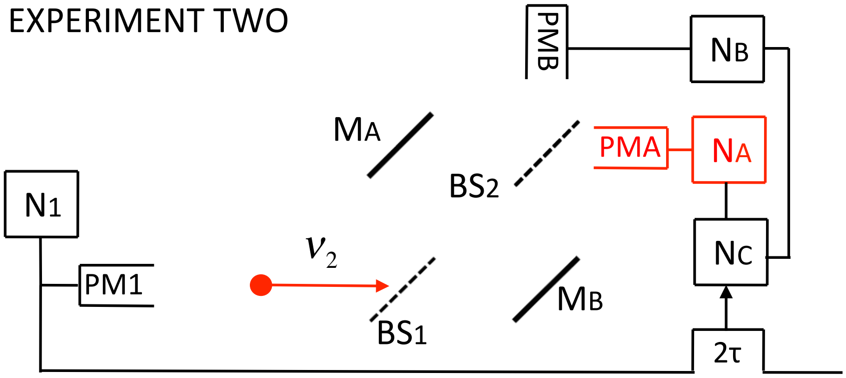
If photons are particles, why don't we <u>always</u> measure α = 0?

EXPERIMENT TWO



- Same setup as before, but now insert a second beamsplitter (BS2)

EXPERIMENT TWO



If the second photon (ν_2) is detected in PMA, then it must have been…

(A) …reflected at BS1.
(B) …transmitted at BS1.
(C) …reflected and transmitted at BS1.
(D) Not enough information.