Complementarity

"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

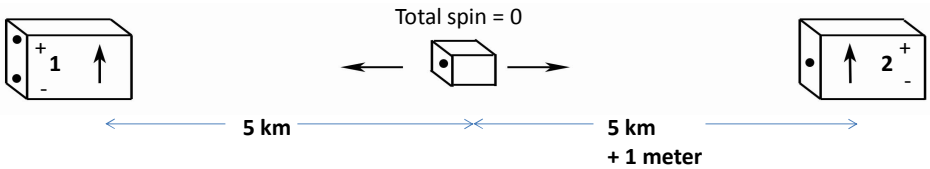
Day 40:
Questions?
Finish/ Review Single-Photon Experiments
Complementarity & Incompatible Observables

Up Next:
Some Cosmology & Grav waves
Next week is review for final

Opening the box on the right revealed to us:
- the color of the sock in the box on the left
- something that was ***real*** and already ***predetermined*** here on Earth.

Albert: ↑

Niels: ↓



Measuring the spin of one particle reveals to us:
- the spin of the other particle
- something that was ***real*** and already ***predetermined*** as the particles separate?

Wheeler's delayed choice gedanken experiment

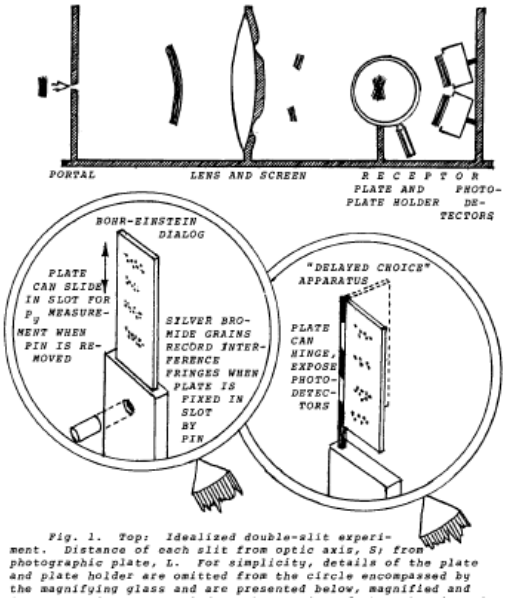
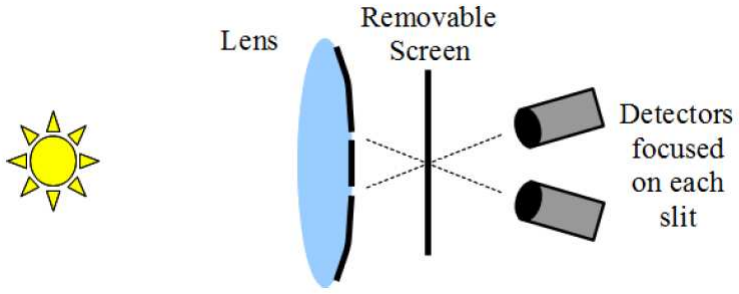


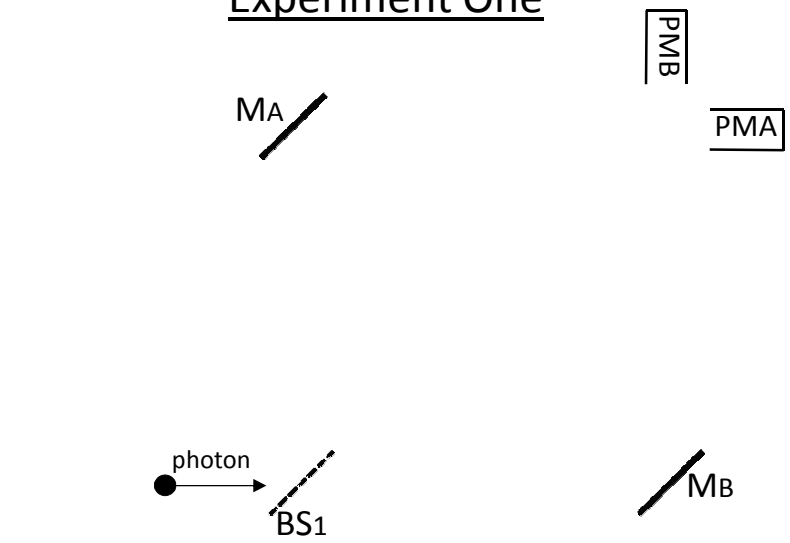
Fig. 1. Top: Idealized double-slit experiment. Distance of each slit from optic axis, S; from photographic plate, L. For simplicity, details of the plate and plate holder are omitted from the circle encompassed by the magnifying glass and are presented below, magnified and

J.A. Wheeler (1978)

Wheeler's delayed choice gedanken experiment



Experiment One

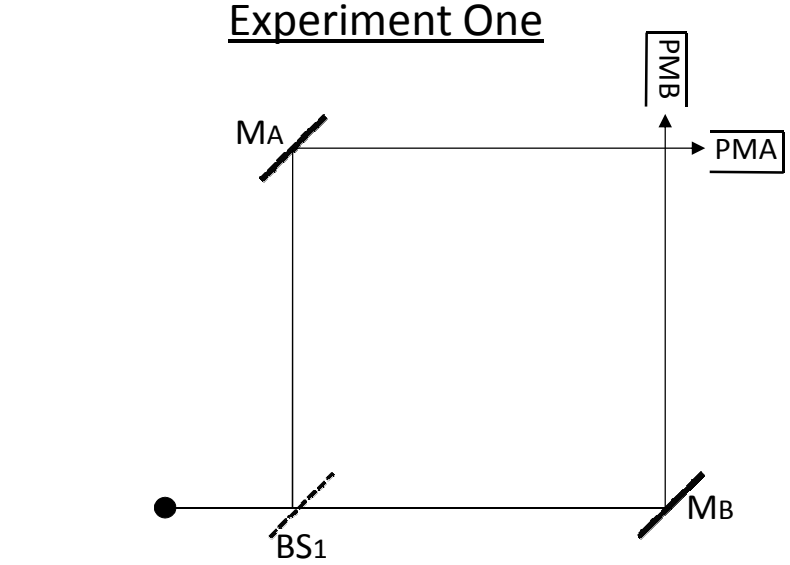


M: Mirror

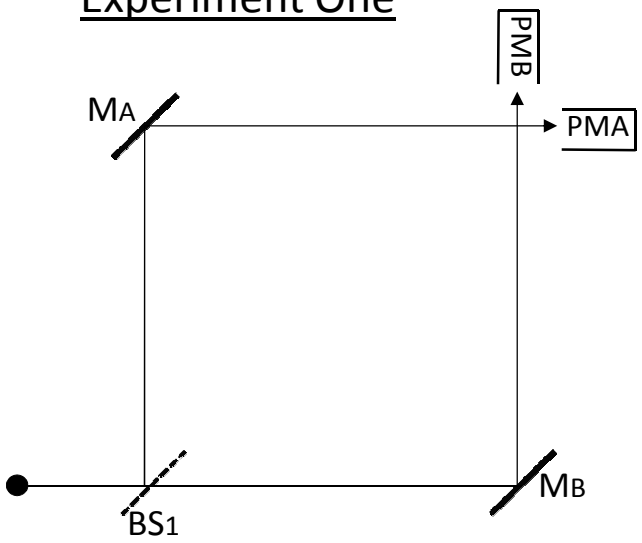
BS: Beam splitter (50% reflected, 50% transmitted)

PM: Photomultiplier (Detector: Counting photons)

Experiment One



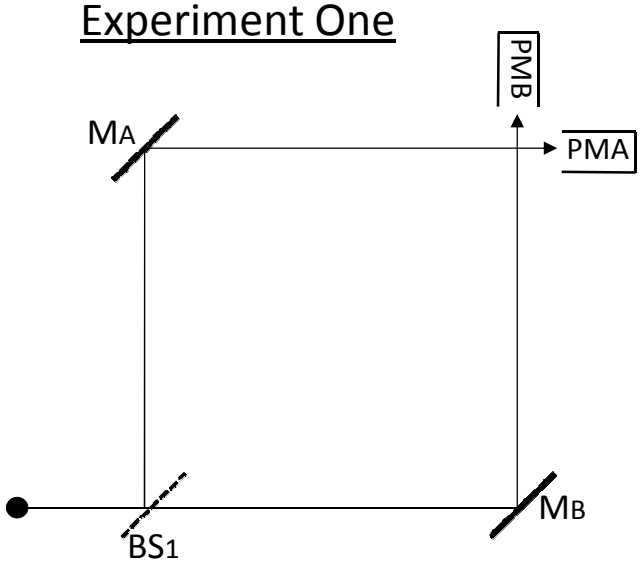
Experiment One



• If the photon is detected by PMA (PMB), then it must have taken path A (B): Particle-like behavior

• Is photon "choosing" path at BS1?

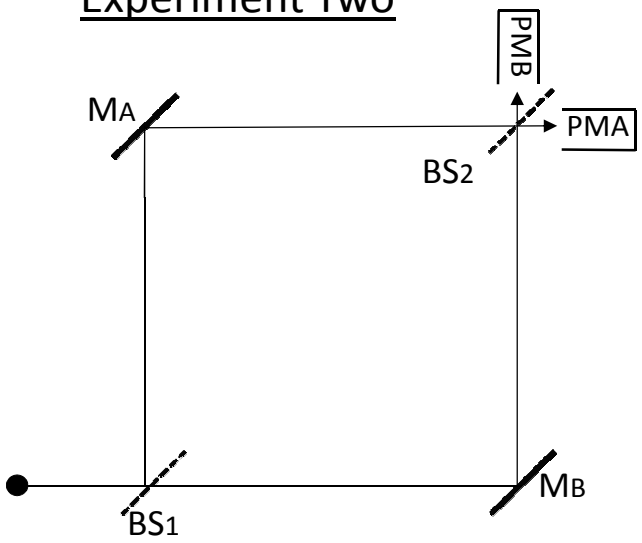
Experiment One



How can we change the experiment to detect wave-like behavior?

Which physical phenomenon do you want to observe for wave-like behavior?

Experiment Two



• Whether the photon is detected by PMA or PMB, both paths are possible

• By "varying the length of one path", interference can be observed

INTERPRETING EXPERIMENTS ONE & TWO

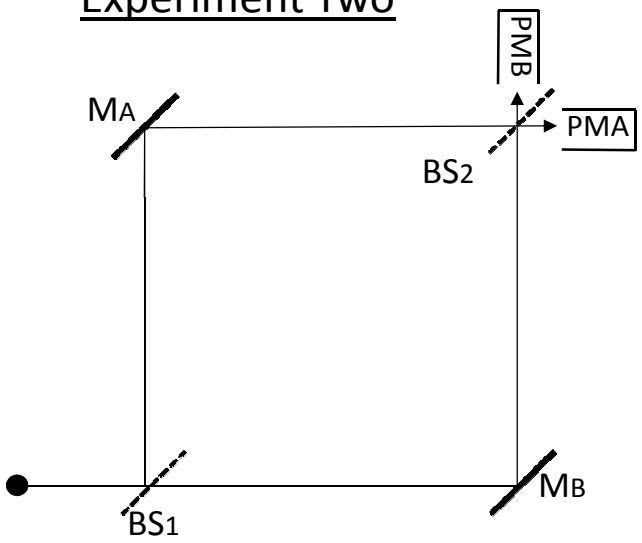
• Photons in **Experiment One** took **either** Path A **or** Path B
when encountering BS1
(reflection or transmission – particle-like behavior)

• Photons in **Experiment Two** took **both** Path A **and** Path B
when encountering BS1
(reflection and transmission – wave-like behavior)

When encountering BS1, how does a photon "know"
whether we're conducting Experiment One or Two?

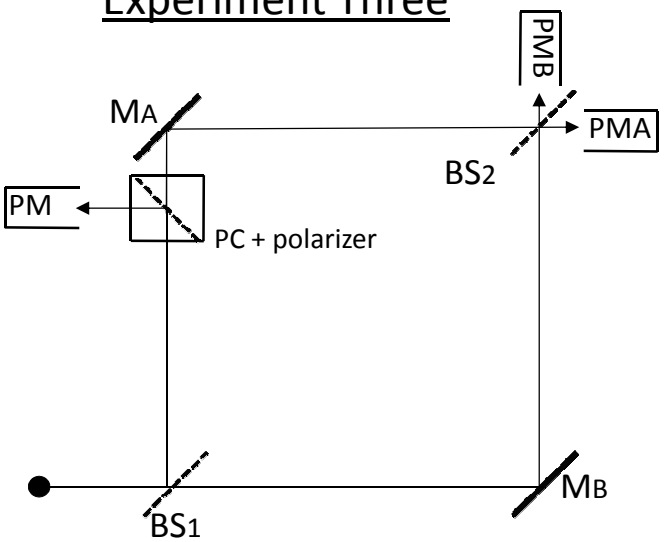
Can we "trick" the photon into behaving one way when
it should be behaving in another?

Experiment Two



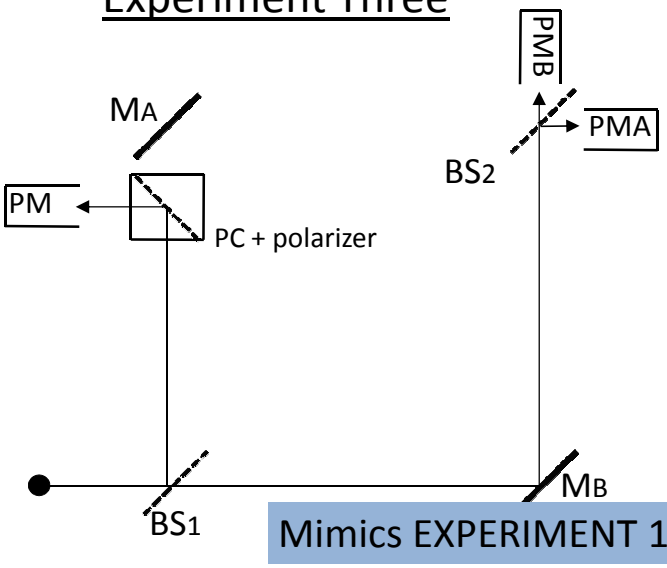
Can we "trick" the photon into behaving one way when it should be behaving in another?

Experiment Three



Insert a Pockels cell and Polarizer in path A
= Switchable beam splitter (either reflects or transmits)

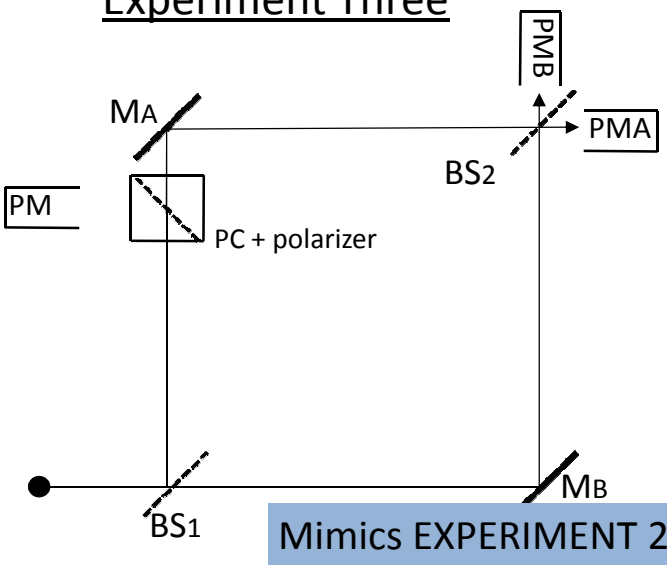
Experiment Three



Mimics EXPERIMENT 1

Voltage applied to PC: Beam splitter reflects

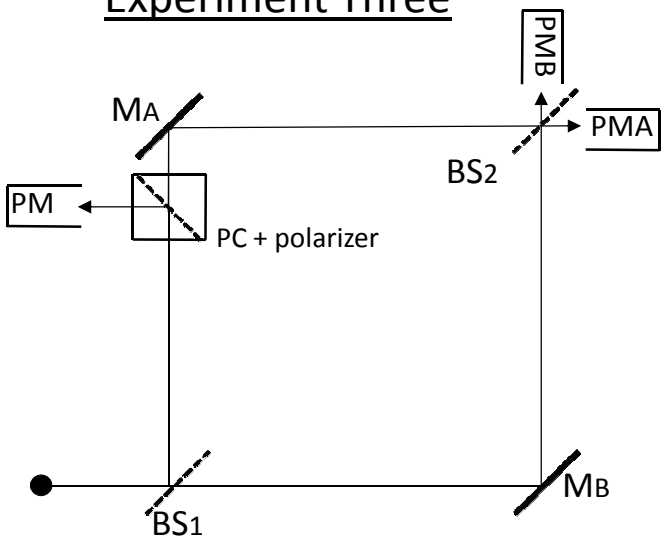
Experiment Three



Mimics EXPERIMENT 2

No voltage applied to PC: Beam splitter transmits

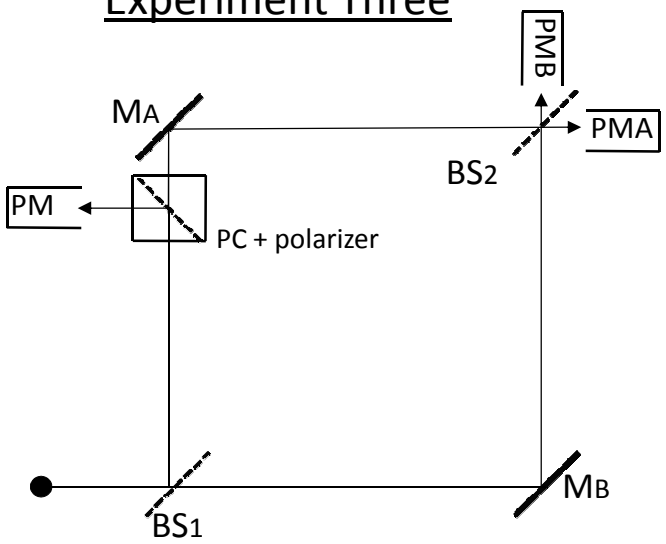
Experiment Three



Voltage applied to PC: One path to BS2 → Particle-like behavior

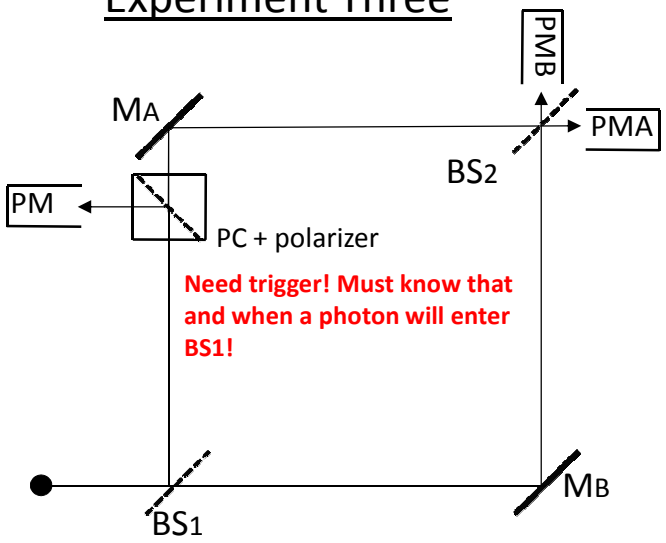
No voltage applied to PC: Two paths to BS2 → Wave-like behavior

Experiment Three



Delayed Choice Experiment:
Photon encounters BS1 with voltage applied, then turn off voltage

Experiment Three



Delayed Choice Experiment:
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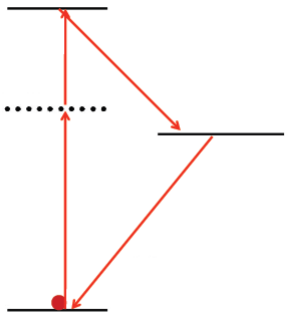
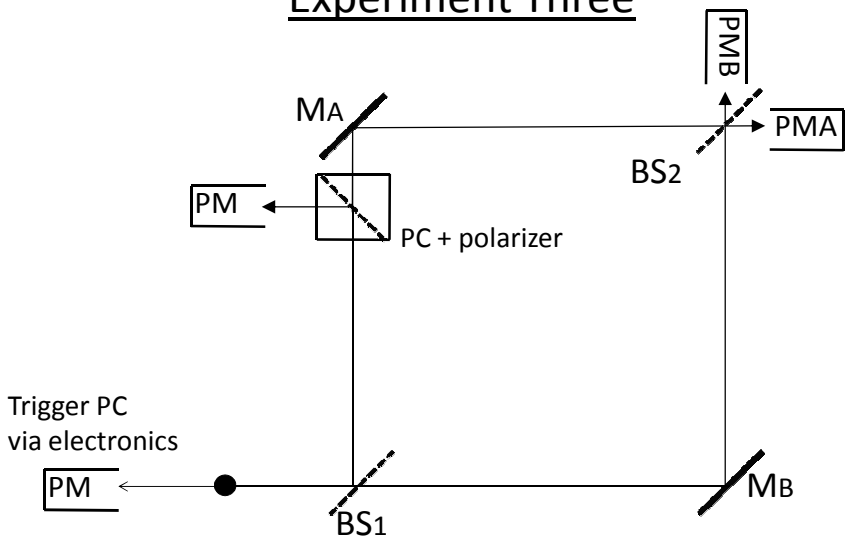
Single Photon Source



- Calcium atoms are excited by a two-photon absorption process
- Excited state first decays by single photon emission
  → use it to trigger Pockels cell
- With high probability second photon is emitted within ~10 ns
  → use it in experiment three

Experiment Three



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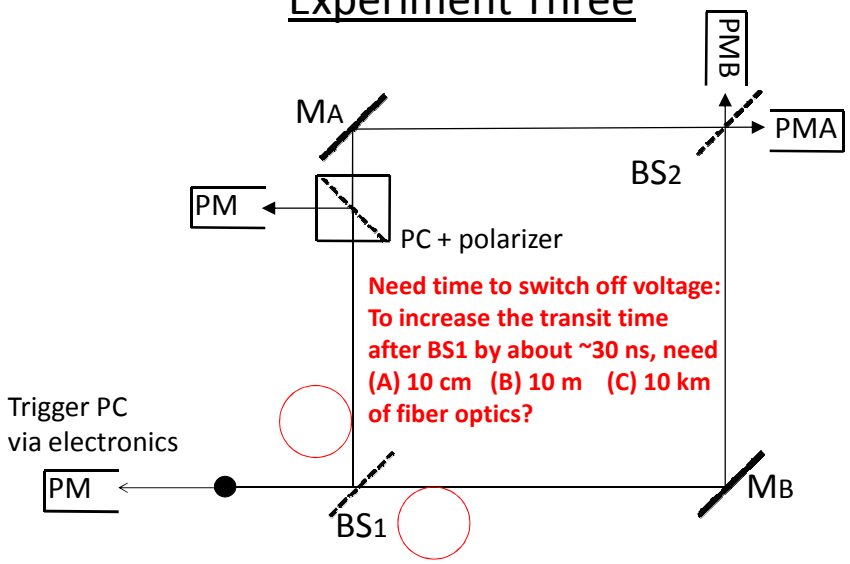

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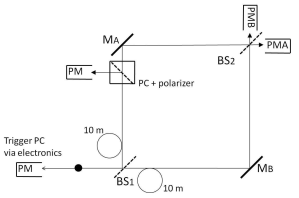


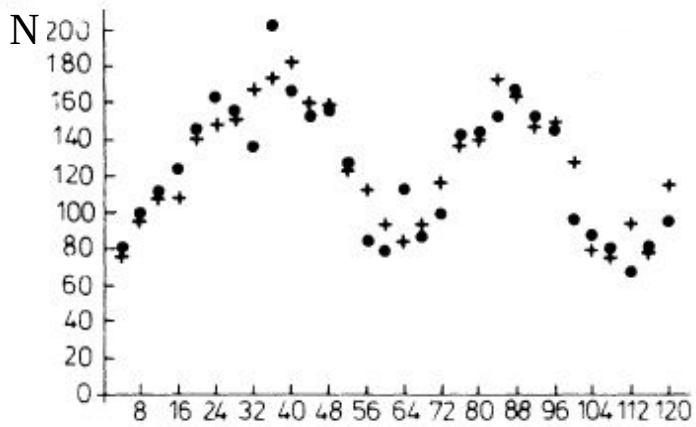
NO VOLTAGE applied to PC
- Two paths to BS2 = Interference

VOLTAGE APPLIED to PC
- One path to BS2 = No interference

"DELAYED-CHOICE" MODE
- Photon encounters BS1 with **VOLTAGE APPLIED** (Experiment One)
- Photon *should* choose either one path (to PM) **or** the other path (to BS2)
- *after* photon encounters BS1 **VOLTAGE TURNED OFF** (switch to Experiment Two)

What would Einstein expect ?
(A) Interference or (B) No interference

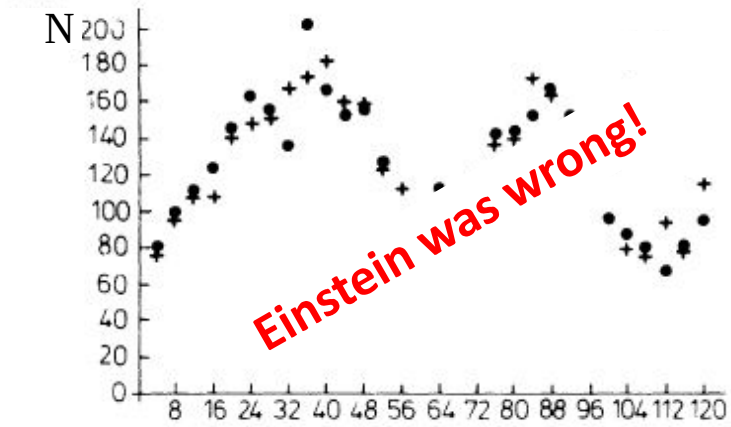
Experiment Three



Dots: apparatus operating in "normal mode" – no voltage applied to PC

Crosses: apparatus operating in "delayed-choice mode"

Experiment Three



Dots: apparatus operating in "normal mode"
– no voltage applied to PC

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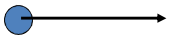
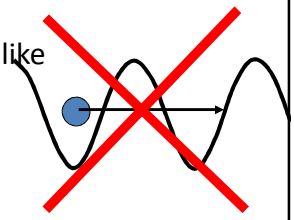
Experiments One & Two & Three

Experiment One says sufficient to think 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.



At at the first beam splitter
Consistent interpretation across all three experiments is:

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

Furthermore:

Experiment Three shows local realism is not a correct assumption
i.e. the EPR paradox doesn't work (no hidden variables!)

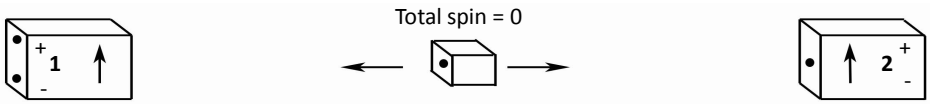
Because...

We changed the behavior of the photon after it should have already been in a certain state
Therefore, there is no set behavior of the photon in advance

Opening the box on the right revealed to us:
- the color of the sock in the box on the left
- something that was ***real*** and already ***predetermined*** here on Earth.

Albert: ↑

Niels: ↓



Measuring the spin of one particle reveals to us:
- the spin of the other particle
- ~~something that was ***real*** and already ***predetermined*** as the particles separate~~

Complementarity

Complementarity applies to what are known as ***incompatible observables***. Examples from class:

- If we know the momentum of a particle, its positions is indeterminate.
- If we know the spin of an atom along one direction, its spin along other directions is indeterminate.
- If we know which path a photon takes, we can't observe its wave behavior.

Classical Systems

For a classical system we can write down a list of all the characteristics of a physical system:

POSITION

LINEAR MOMENTUM

ANGULAR MOMENTUM

ENERGY

etc…

In principle, all of these quantities can be simultaneously measured with as much accuracy as we require.

Classical Systems

For a classical system we can write down a list of all the characteristics of a physical system:

POSITION

LINEAR MOMENTUM

ANGULAR MOMENTUM

ENERGY

etc…

Knowing these quantities initially allows us to predict these quantities at later times.

Quantum Systems

For a quantum system we have to write down **TWO** lists:

A	B
PARTICLE	WAVE
WHICH-PATH	INTERFERENCE
POSITION	MOMENTUM

- For every characteristic in **List A**, there is a corresponding characteristic in **List B**.
- Knowing a lot about one means we know only a little about the other.