Horizon Lecture

Quantum Superposition, Quantum Entanglement and Quantum Technologies

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Indian Institute of Technology Kanpur

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Outline

Quantum Superposition

- What is it?
- Difference from Classical Superposition
- Applications/Technologies

Quantum Entanglement

- What is it?
- Is there any classical analog?
- Application/Technologies

Declaration

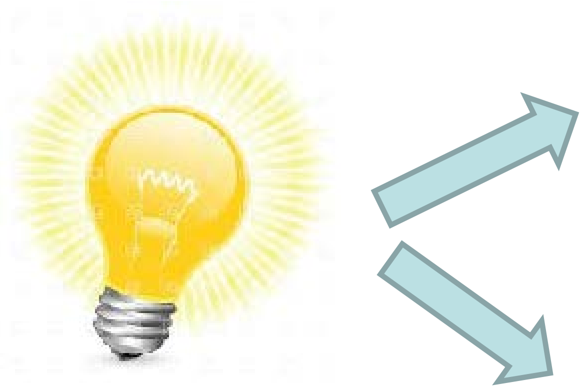
“..it is safe to say no one really understands quantum mechanics”

– R. P. Feynman

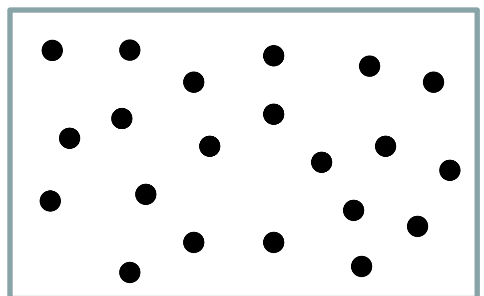
“ All these fifty years of conscious brooding have brought me no nearer to the answer to the question, 'What are light quanta?' Nowadays every Tom, Dick and Harry thinks he knows it, but he is mistaken.”

--- Albert Einstein

What is light ??



waves



particles

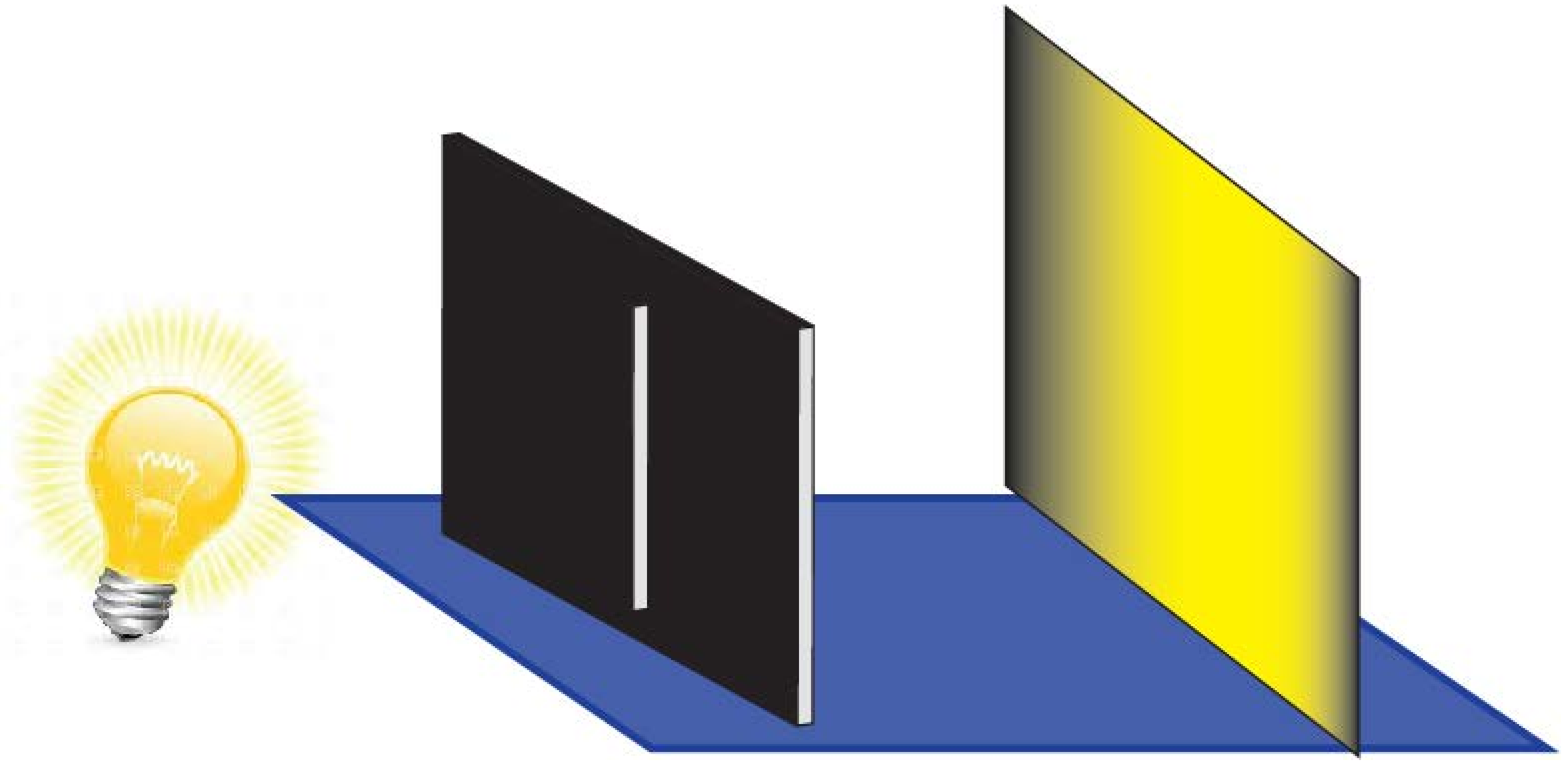
17^{th} Century: Light was made up of Particles (Newton’s theory)

1801-1900: Light was a wave (Young’s double slit experiment)

1900- : Light is wave as well as particle (Planck’s hypothesis: $E=nh\nu$; Photoelectric effect.)

Image source: Wikepedia and google images

Light is wave (Young's double slit experiment)



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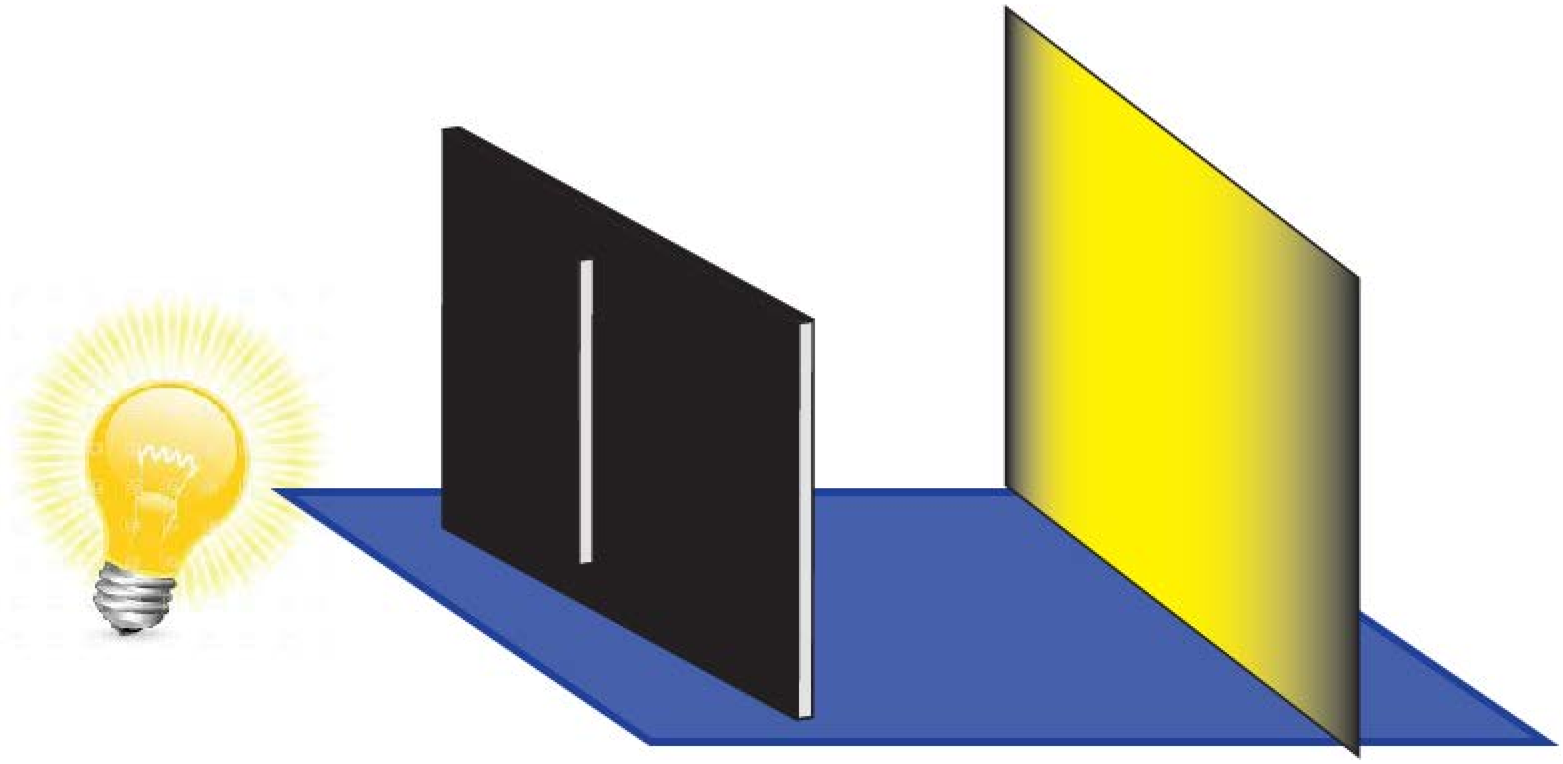

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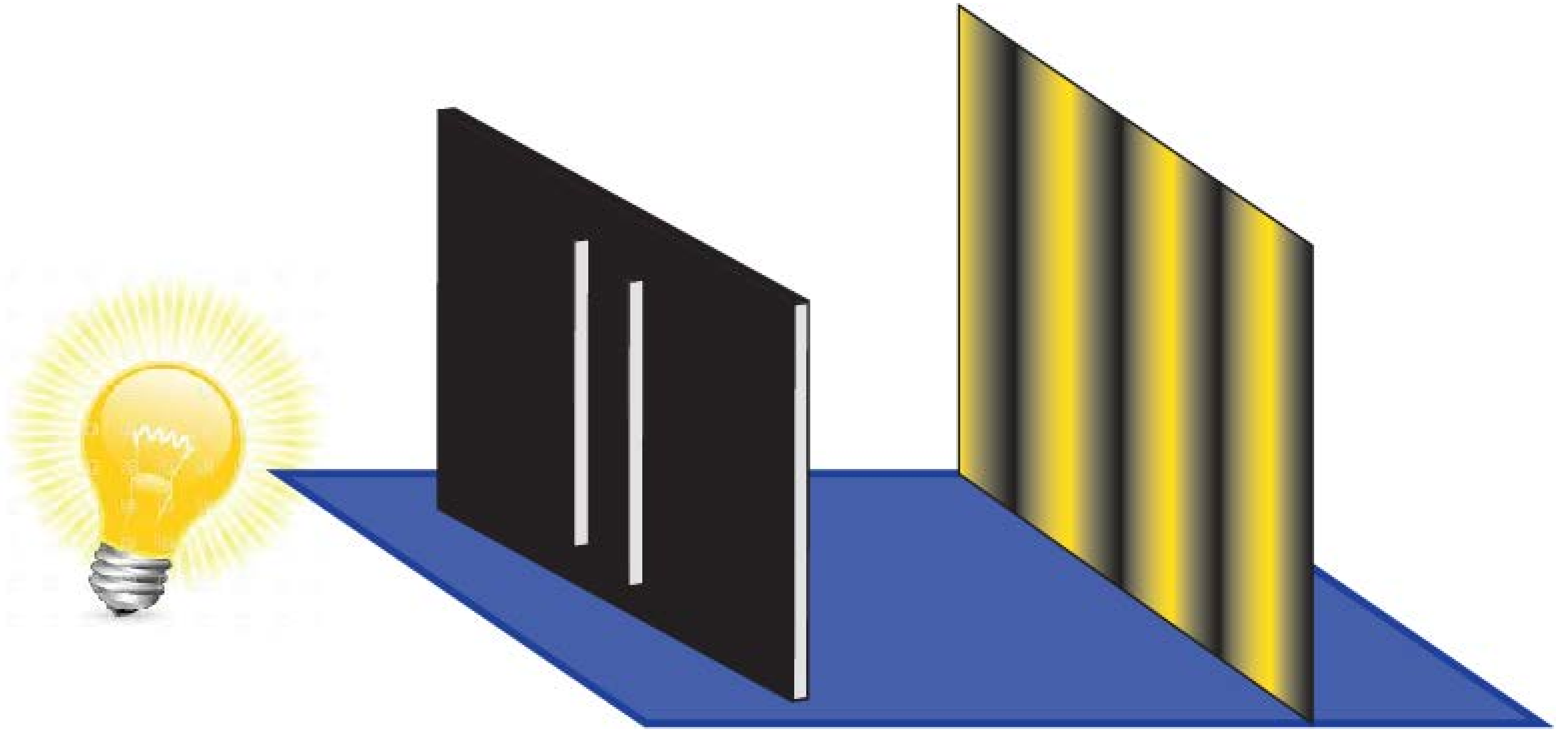


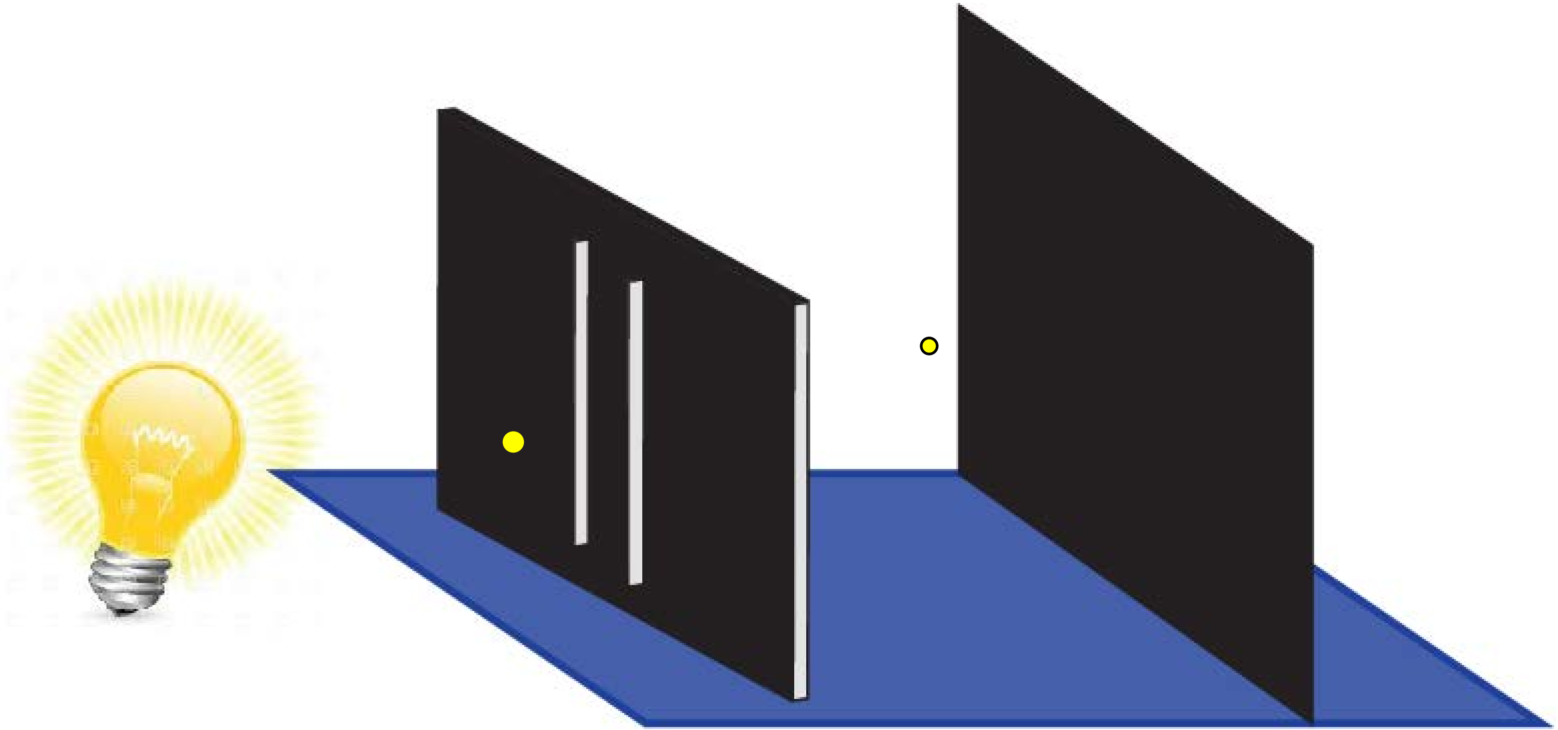
Superposition (Classical Wave theory):

Division of amplitude (= Division of energy)

⇩

Superposition of amplitudes (Interference)

Light is Particles (Young's double slit experiment)



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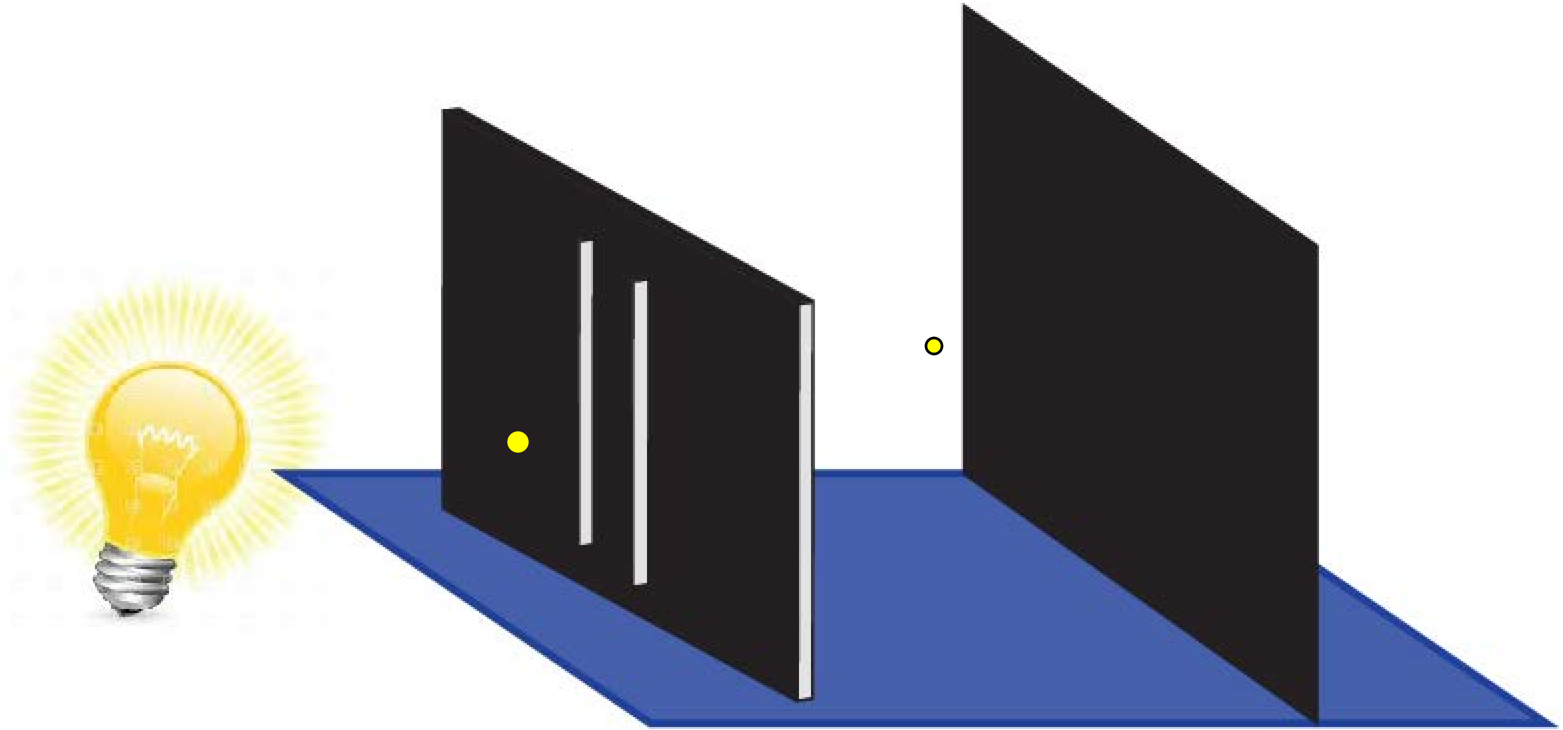

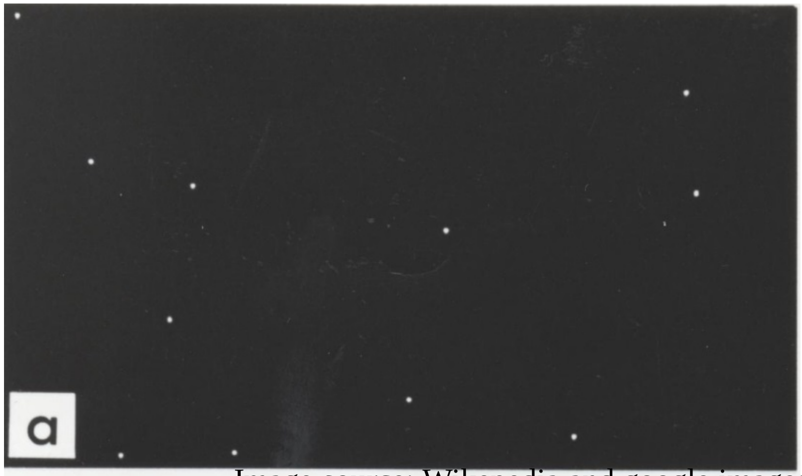

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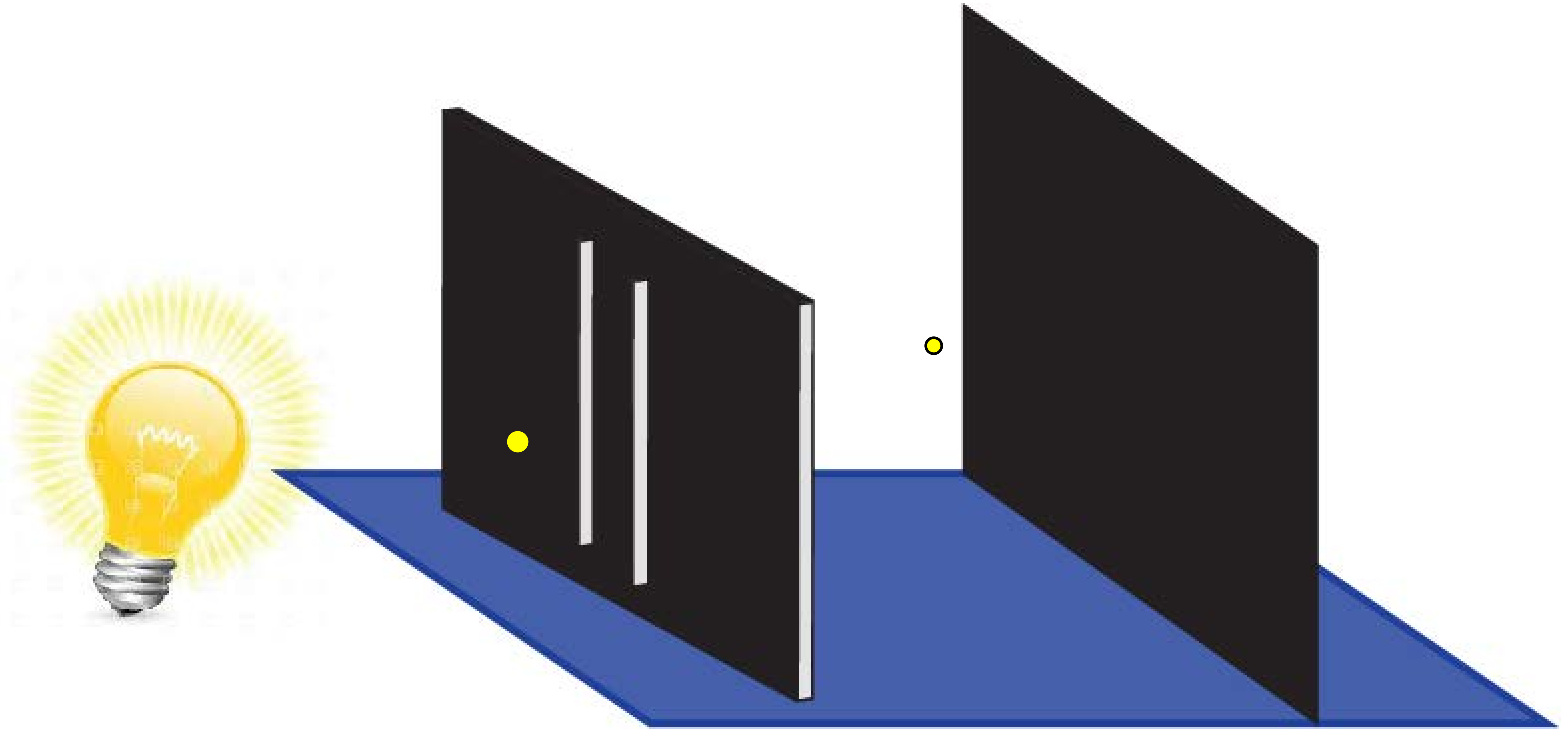
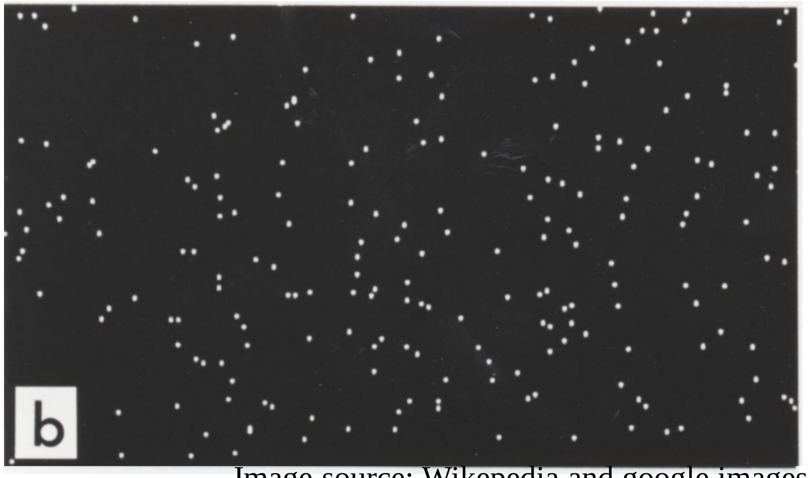
Light is Particles (Young's double slit experiment)





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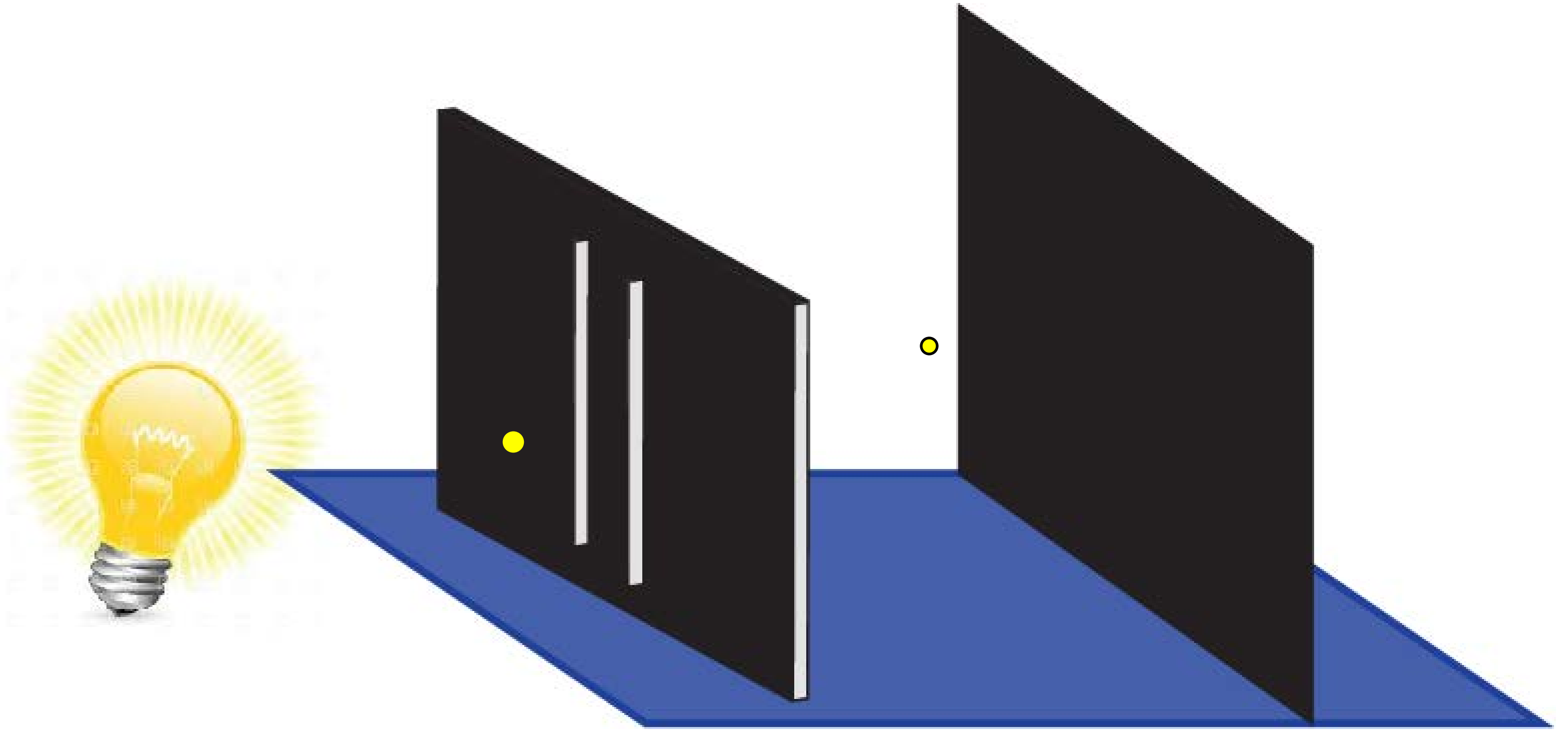

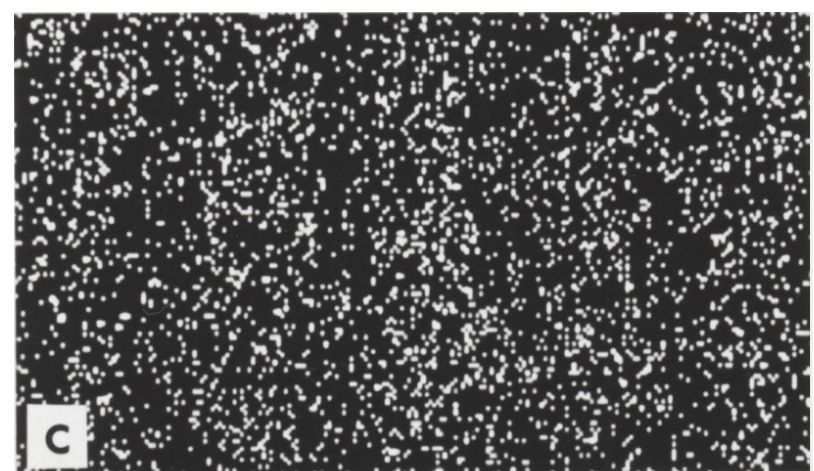

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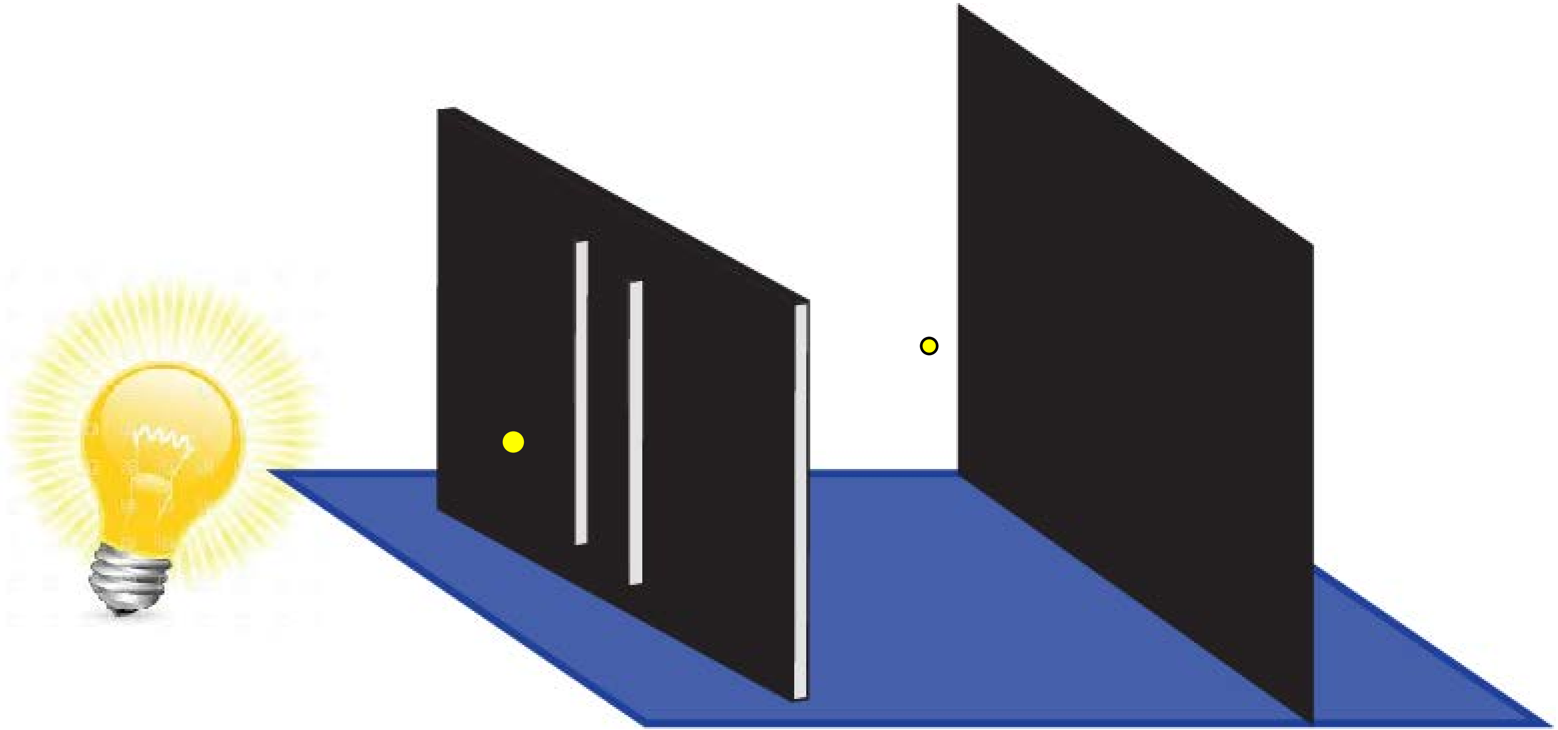

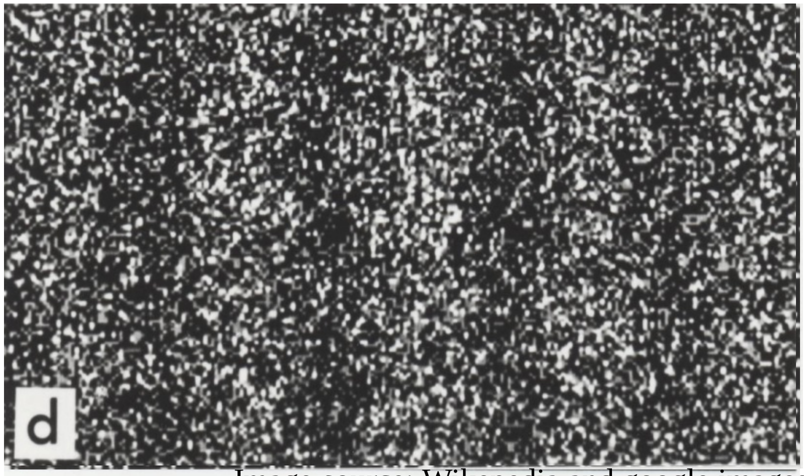

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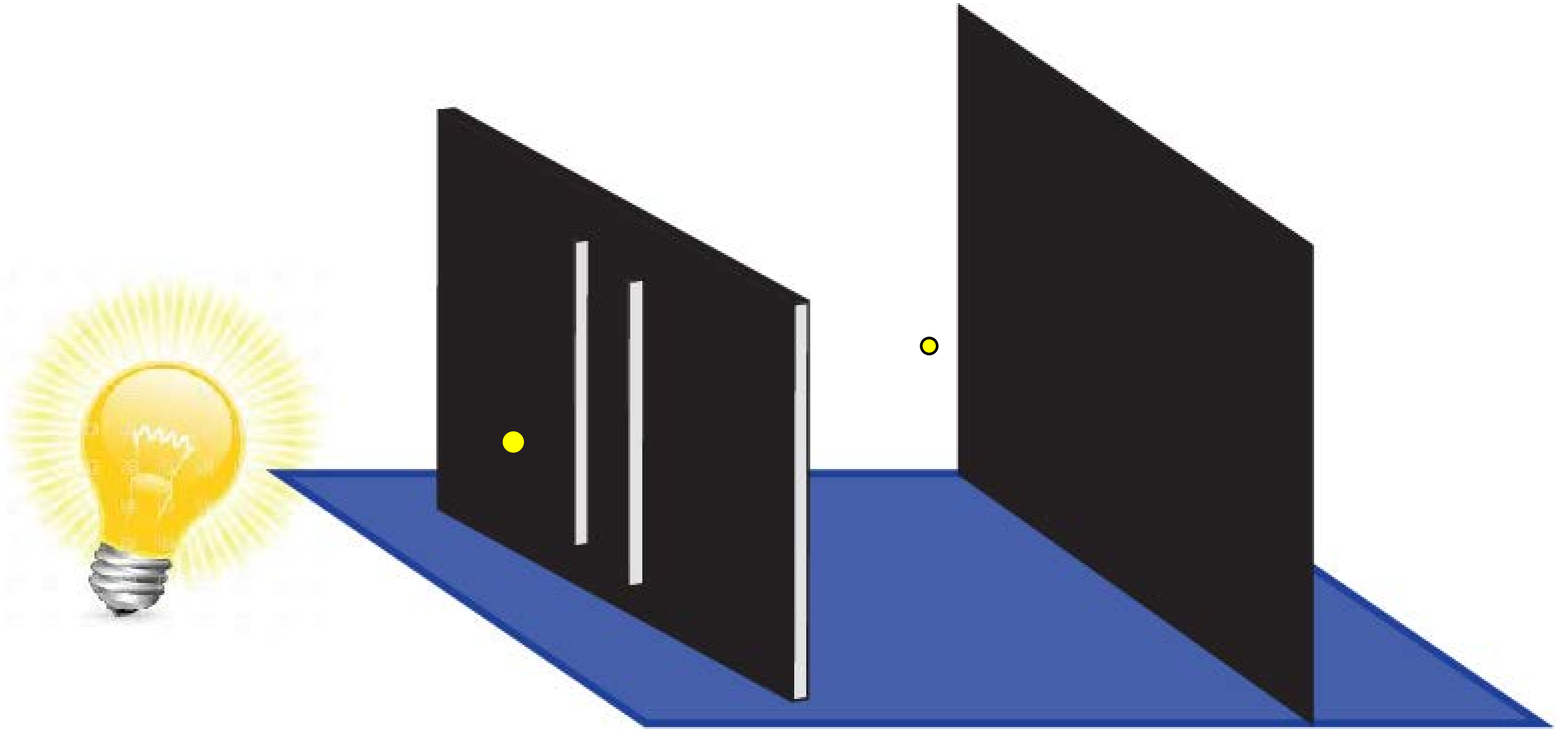

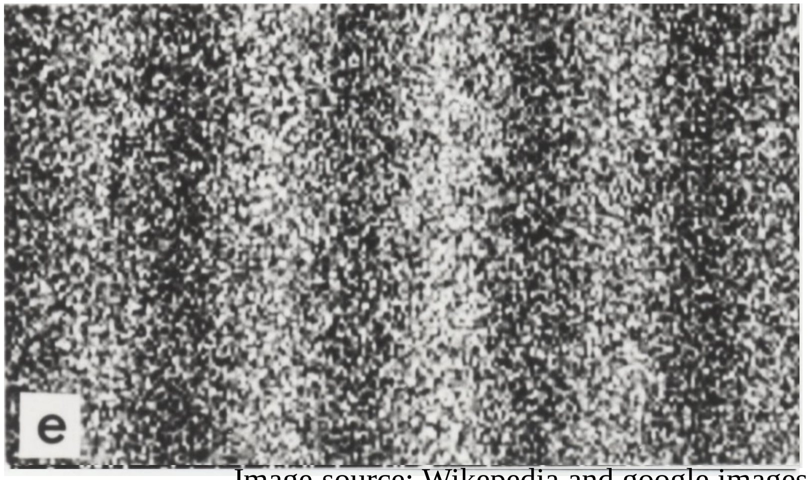

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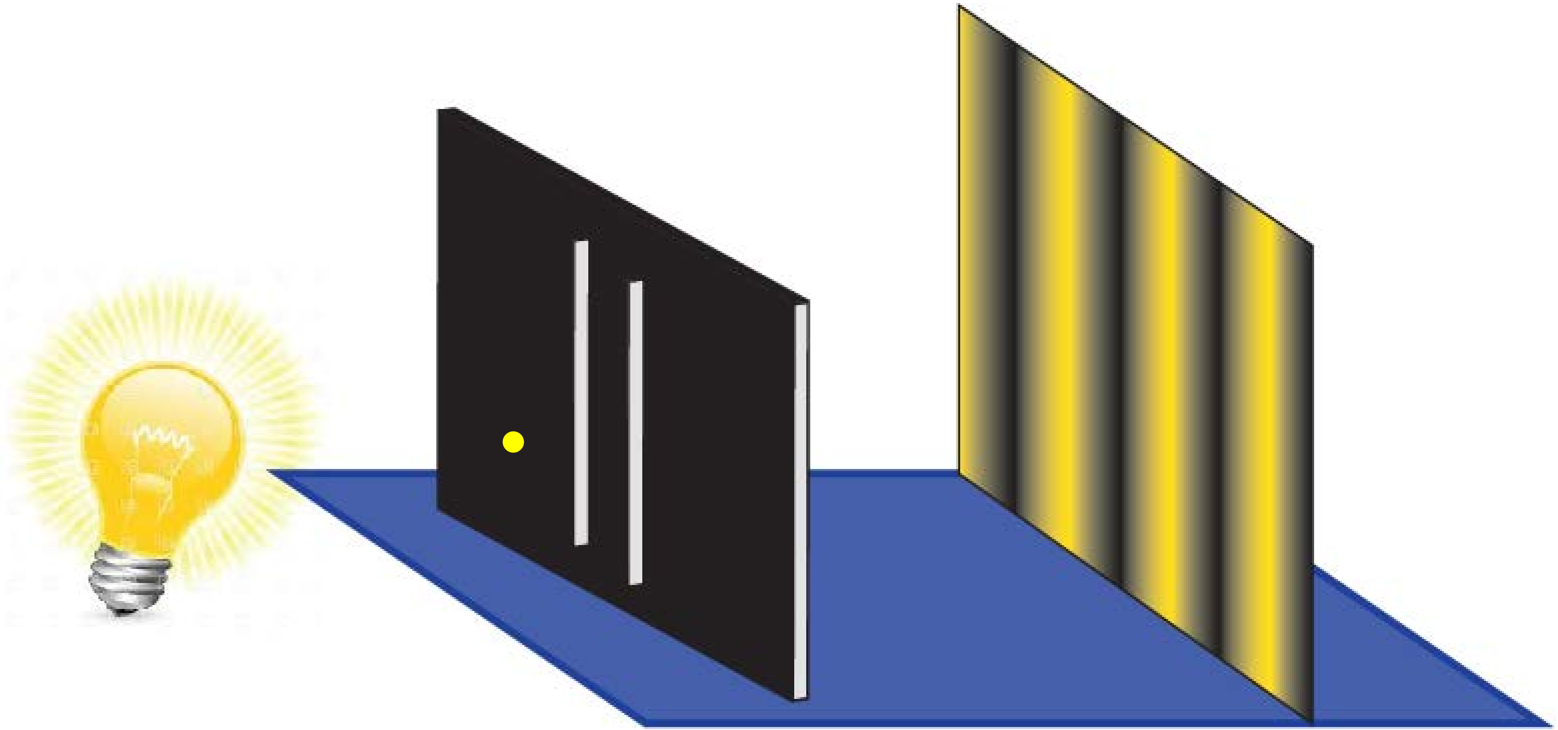
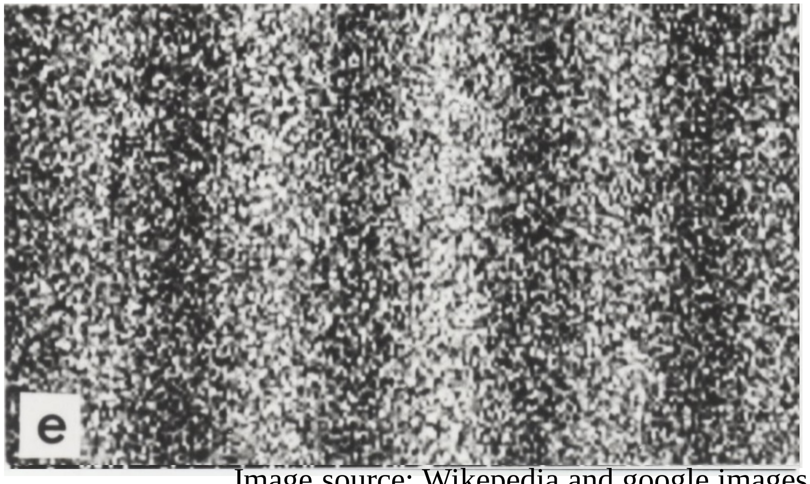
Light is Particles as well as Waves



Superposition (Quantum)??



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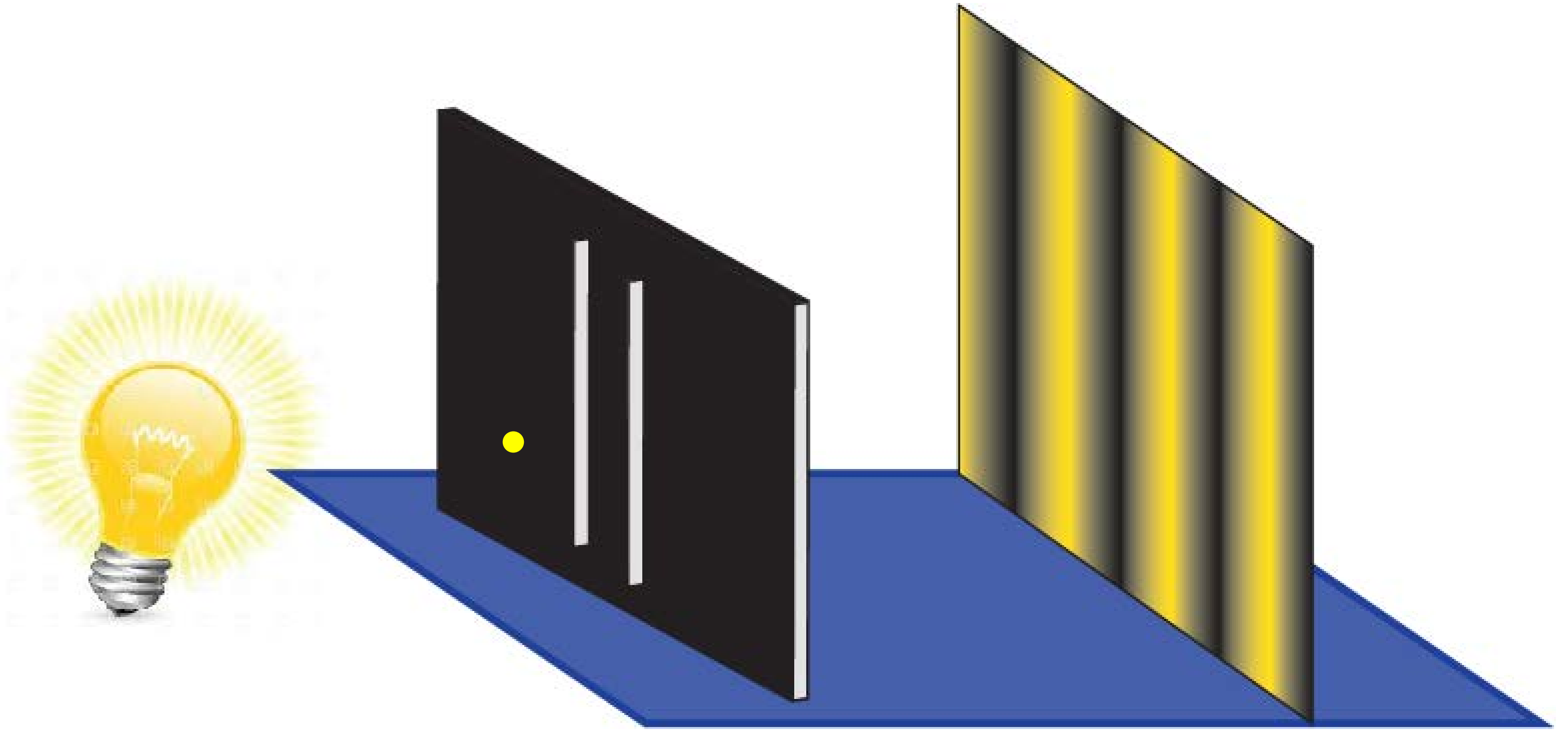
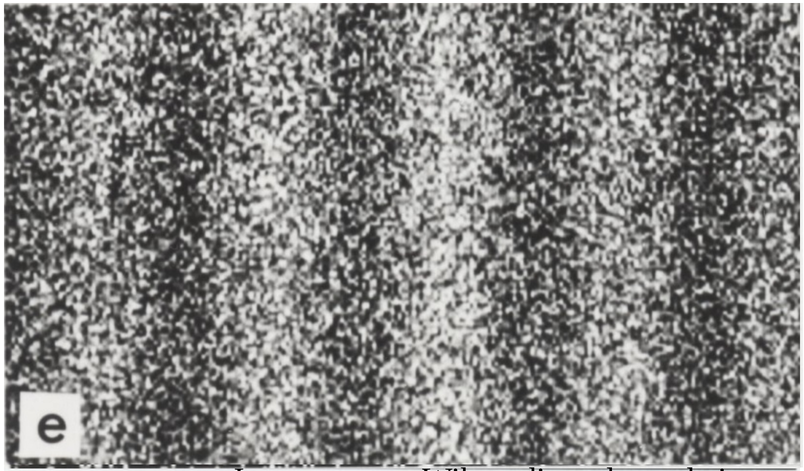


Superposition (Quantum)

- A photon goes through either slit#1 or slit#2

- Photons hit the screen at well localized points

- Photon distribution is the interference pattern



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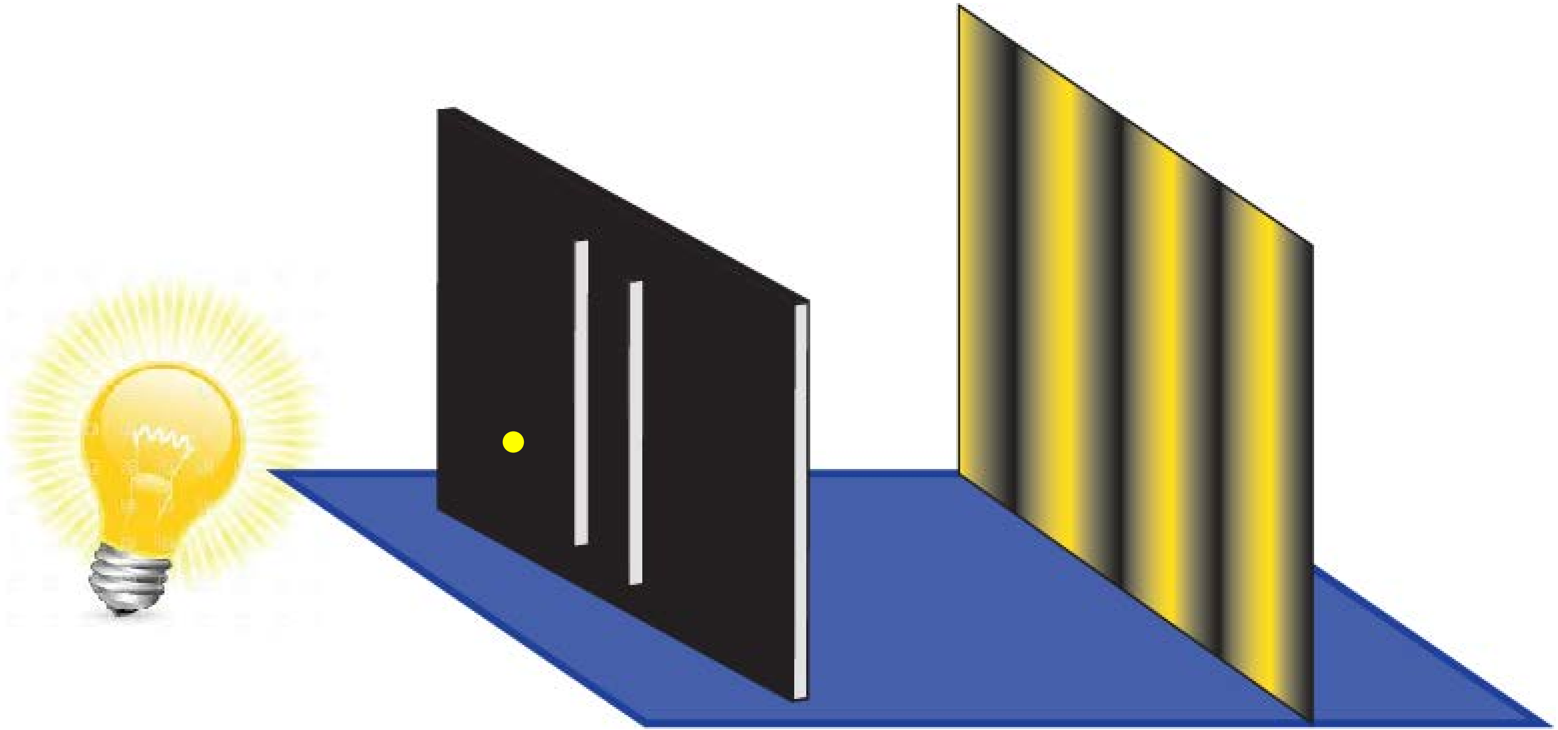
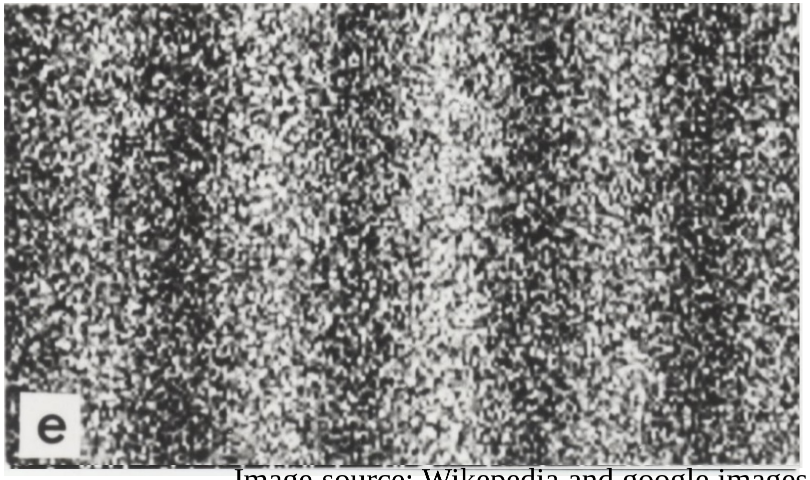
Light is Particles as well as Waves



Superposition (Quantum)

- Any effort to get the which-slit (particle) information destroys the interference (wave) information to the same degree.

--- Bohr's Complementarity Principle



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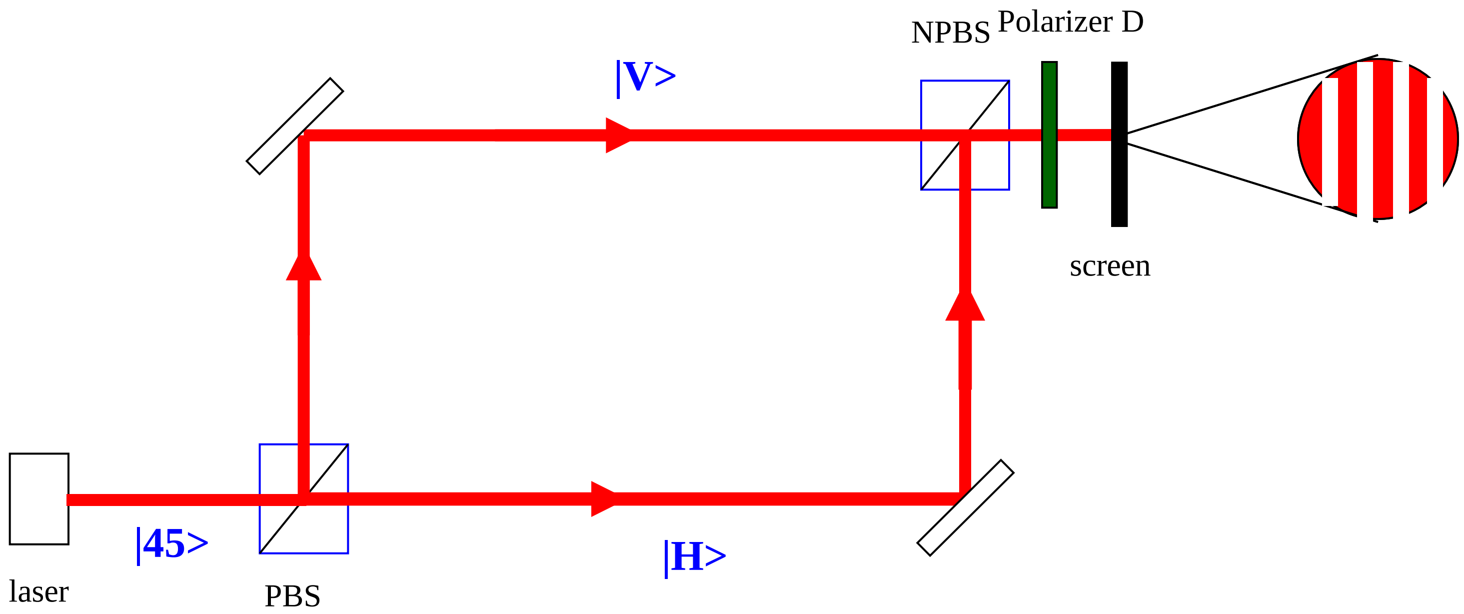
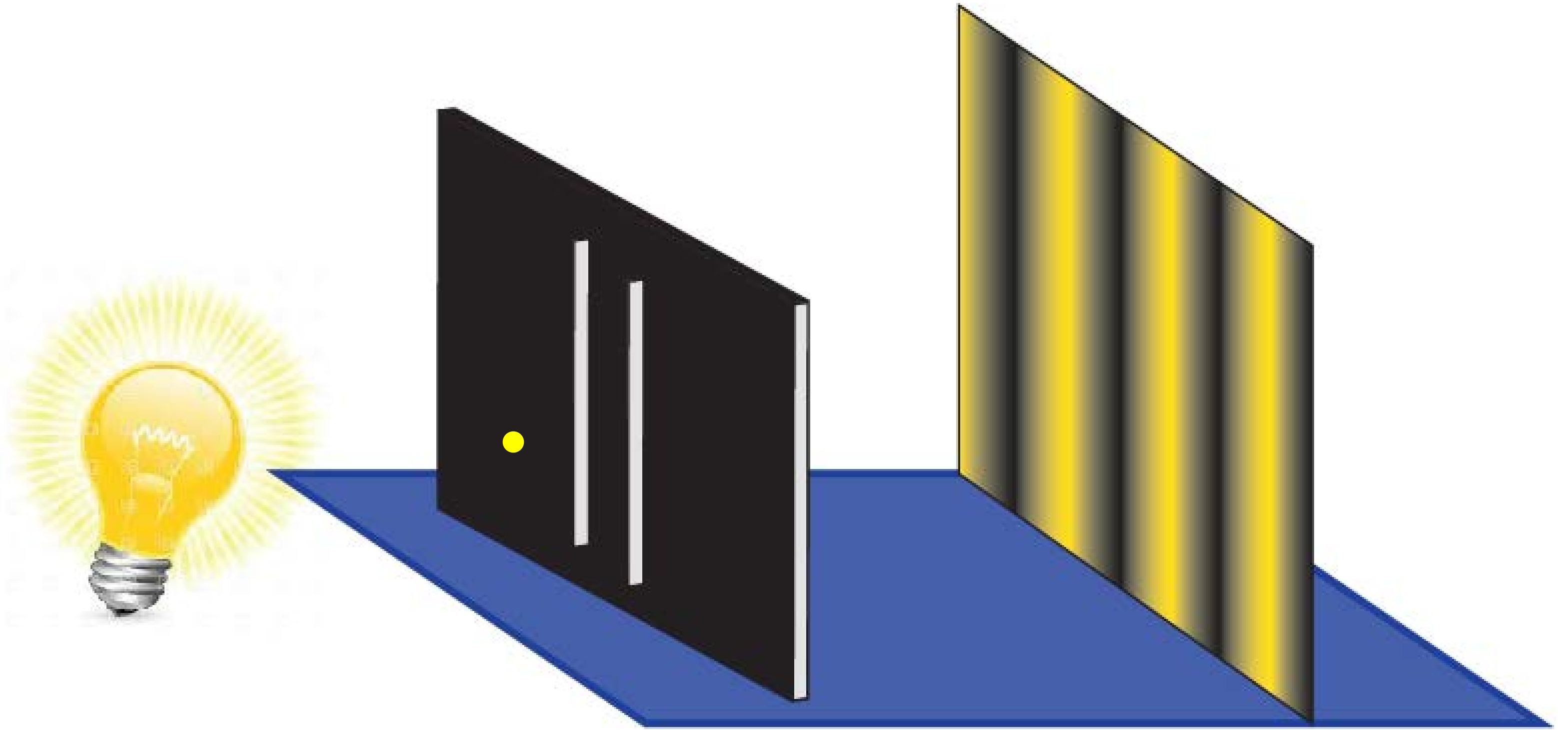
Bohr’s Complementarity Principle



Polarizer D, absent → **No Fringes**

Polarizer D at 45 → **Fringes**

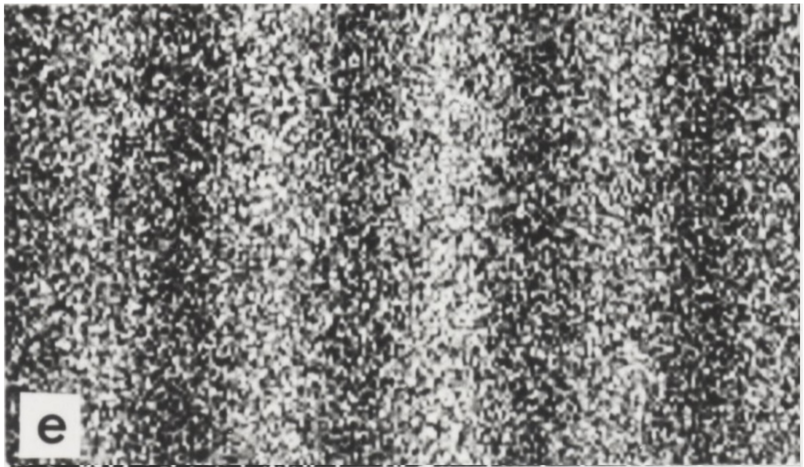
Light is Particles as well as Waves



Superposition (Quantum):

"Each photon then interferes with itself. Interference between two different photons never occur."

--- Dirac (in Principles of Quantum Mechanics)



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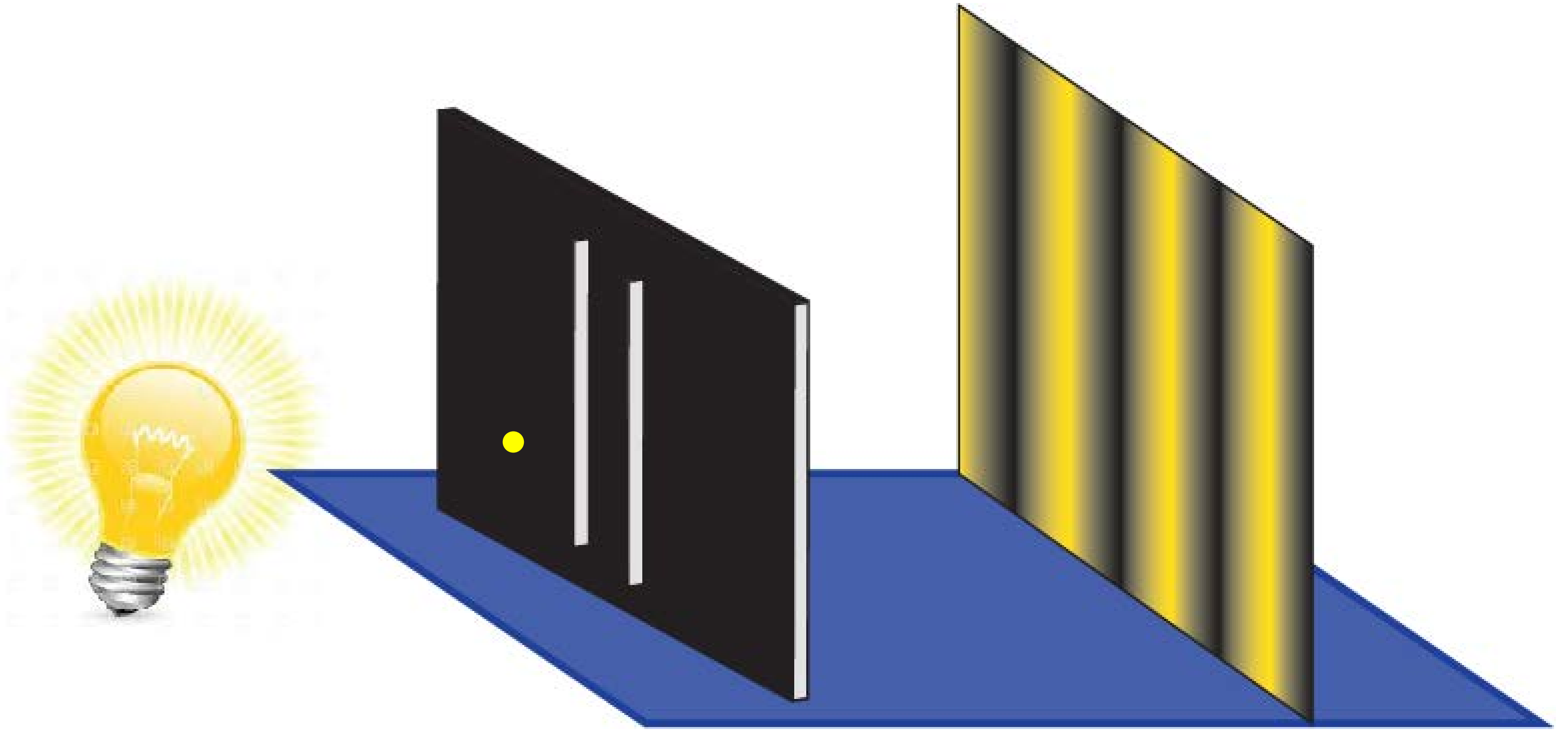
Light is Particles as well as Waves



Superposition (Quantum):

Division of wave-function (≠ Division of energy)

⇩

Superposition of wave-functions (Interference)

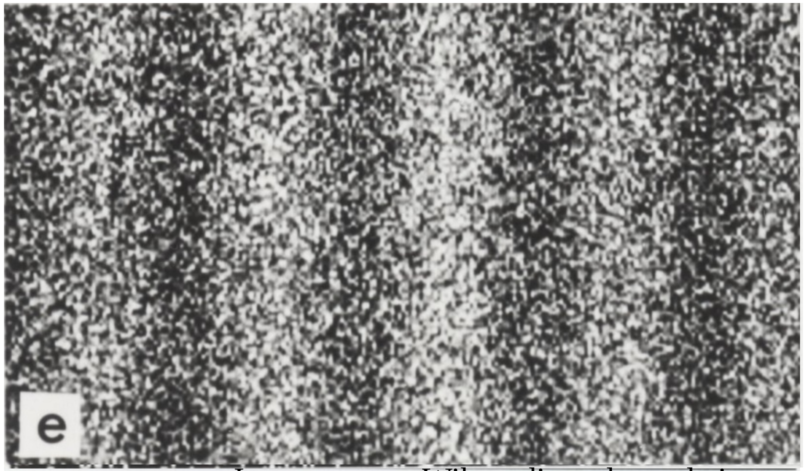


Image source: Wikepedia and google images

Light is Particles as well as Waves

Superposition (Classical Wave theory):
Division of amplitude (= Division of energy)
⇩
Superposition of amplitudes (Interference)

Fundamentally incorrect, but applicable at high light-levels. Inadequate at single-photon levels.

Superposition (Quantum):
Division of wave-function (≠ Division of energy)
⇩
Superposition of wave-functions (Interference)

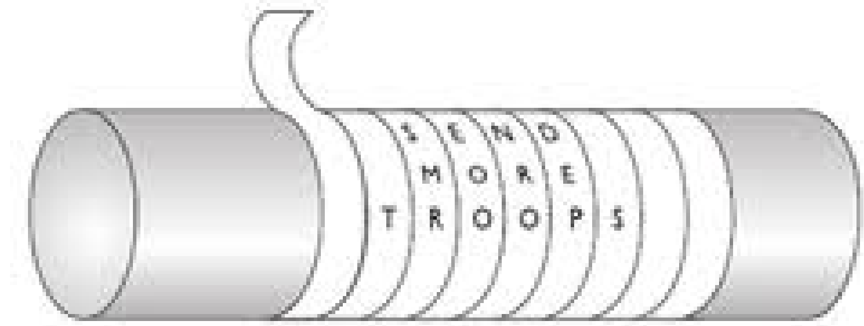
Fundamentally correct, but may be necessary only at single-photon levels.

Quantum Superposition: Application (Quantum Cryptography)

Older Method

(scylate)

A



B

Modern Method

Message: **OPTICS**

Encrypt with Key: **010110**

Encrypted message: **OQTJDS**

Encrypted message: **OQTJDS**

Decrypt with Key: **010110**

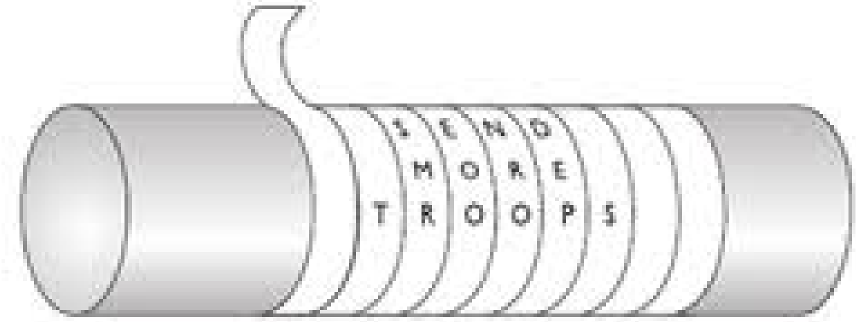
Decrypted Message: **OPTICS**

Image source: Wikepedia and google images

Quantum Superposition: Application (Quantum Cryptography)

Older Method
(scylate)

A



B

Modern Method

Message: **OPTICS**

Encrypt with Key: **010110**

Encrypted message: **OQTJDS**

Encrypted message: **OQTJDS**

Decrypt with Key: **010110**

Decrypted Message: **OPTICS**

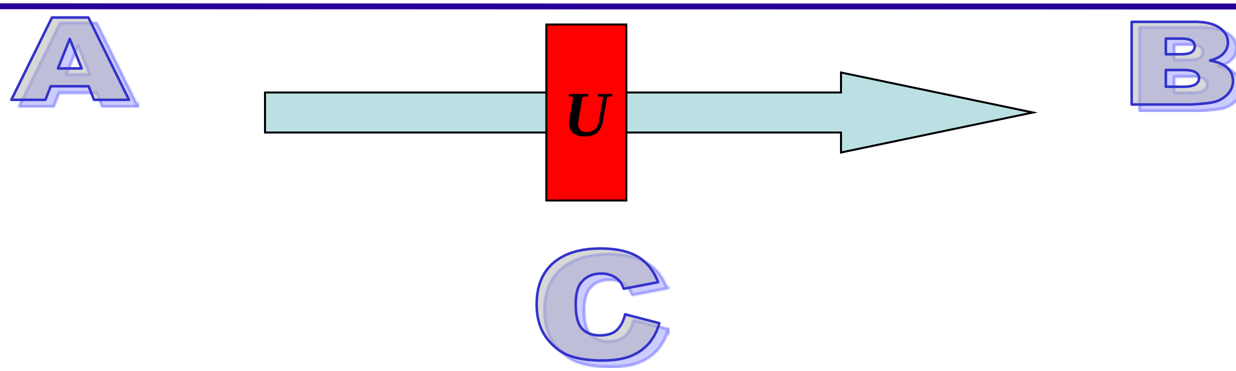
Main issue: Security

Future?

“Quantum Cryptography”
--- perfectly secure because of the laws of quantum mechanics.

Image source: Wikepedia and google images

Quantum Superposition: Application (Quantum Cryptography)



What are those laws ?

1. Measurement in an incompatible basis changes the quantum state
2. No Cloning Theorem:

$$\hat{U}|S\rangle|H\rangle \rightarrow |0\rangle|HH\rangle$$

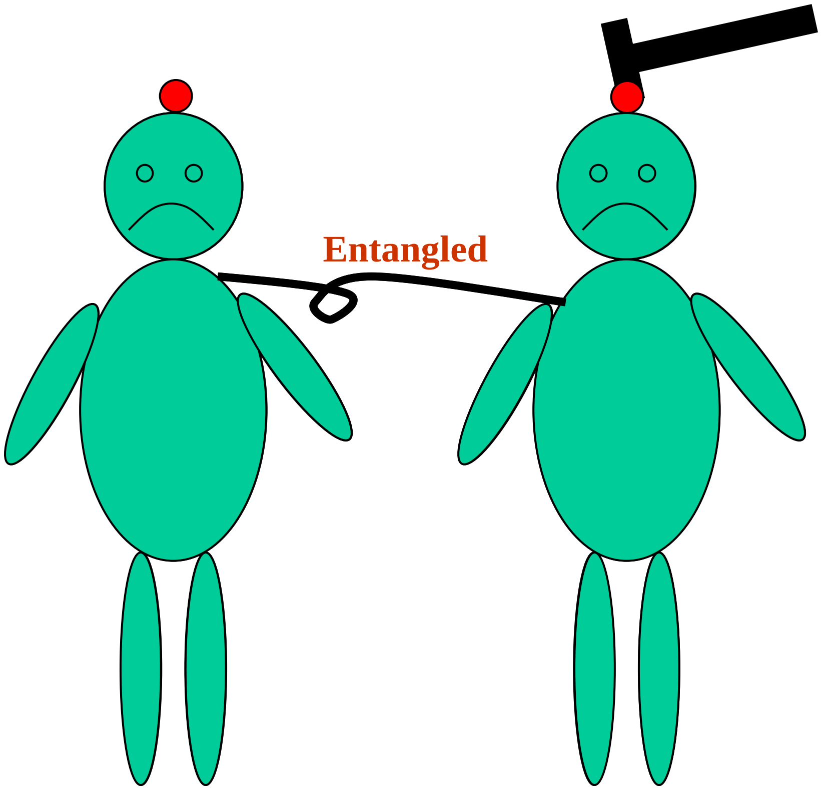
$$\hat{U}|S\rangle|V\rangle \rightarrow |0\rangle|VV\rangle$$

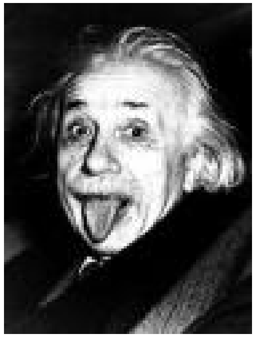
$$\hat{U}|S\rangle(|H\rangle + |V\rangle) \rightarrow |0\rangle(|HH\rangle + |VV\rangle)$$

$$\neq |0\rangle|(H+V)(H+V)\rangle$$

- C cannot clone an arbitrary quantum state sent out by A

Quantum Entanglement

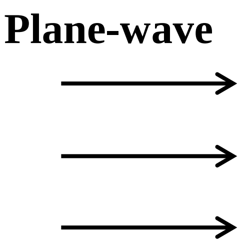




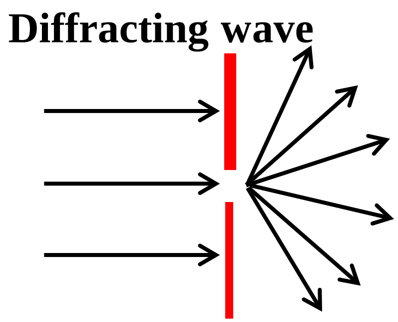
Einstein objected to this kind of phenomenon

EPR Paradox

One photon system:



Momentum is the Physical Reality

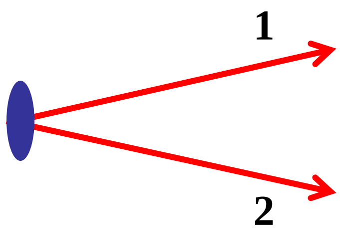


Position is the Physical Reality

$$\Delta x \, \Delta p \geq \hbar/2$$

"When the operators corresponding to two physical quantities do not commute the two quantifies cannot have simultaneous reality." -- EPR rephrasing the uncertainty relation.

Two-photon system (Entangled):



$$\Delta x^{(1)}_{cond} \;\; \Delta p^{(1)}_{cond} < \hbar/2$$

Non-local correlation ???

EPR's Questions: (1) Is Quantum mechanics incomplete??

(2) Does it require additional "hidden variables" to explain the measurement results.

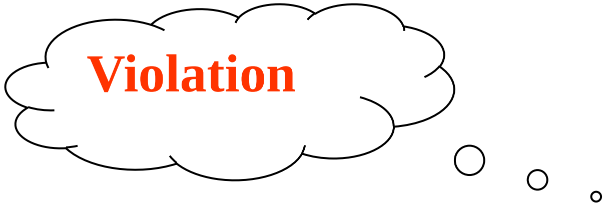
Quantum Entanglement Verified

- **1950s: hidden variable quantum mechanics by David Bohm**

- **1964: Bell’s Inequality--- A proposed test for quantum entanglement**

- **1980s -90s --- Experimental violations of Bell’s inequality.**

$\lvert S \rvert \leq 2$	For hidden variable theories
$\lvert S \rvert \leq 2\sqrt{2}$	For quantum correlations



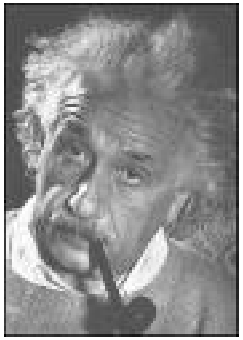
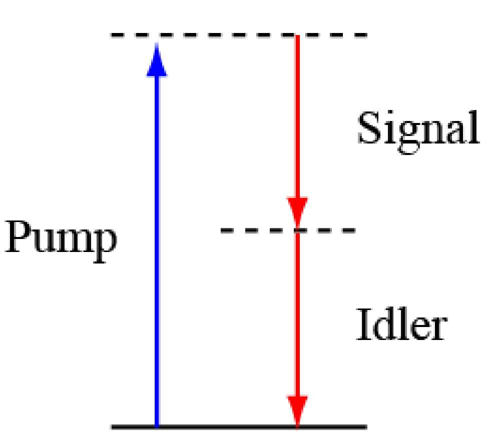
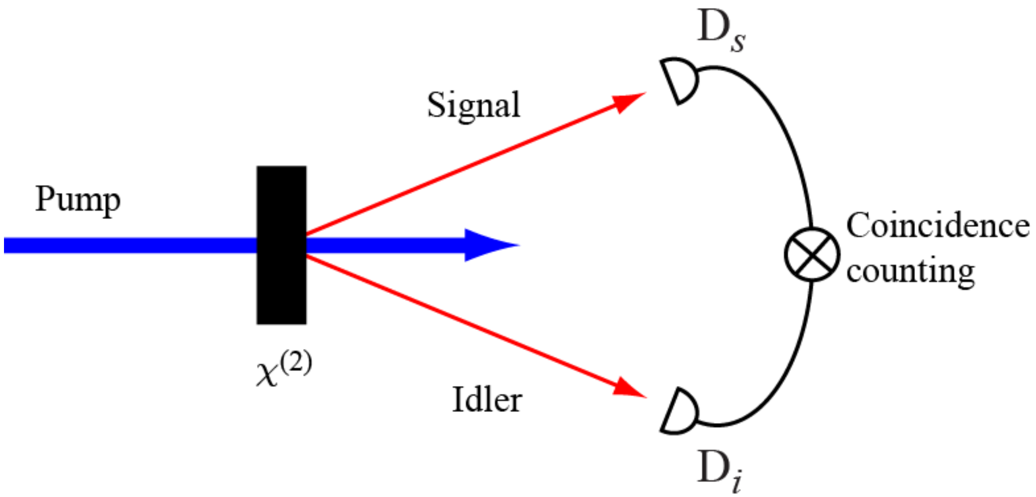


Image source: Wikepedia and google images

Source of Entanglement/ Type of Entanglement





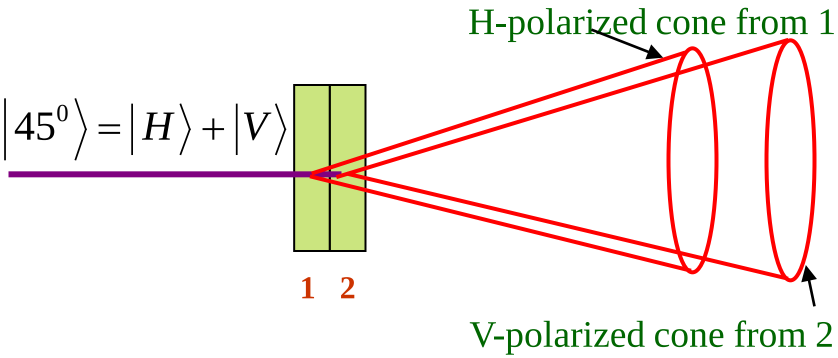
- Entanglement in position and momentum
- Entanglement in time and energy
- Entanglement in angle and orbital angular momentum

} **Continuous-variable entanglement**

- Entanglement in Polarization

} **Two-dimensional entanglement**

What is Entanglement (Polarization)



$$\left|45^0\right\rangle = \left|H\right\rangle + \left|V\right\rangle$$

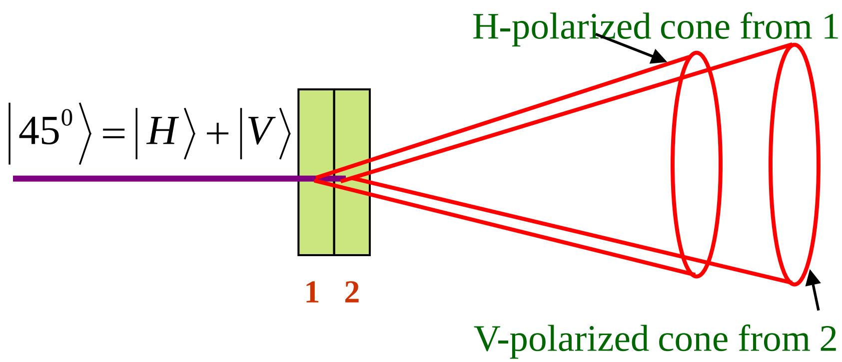
$$\left|\psi\right\rangle = \left|H_s H_i\right\rangle + \left|V_s V_i\right\rangle$$

(1) If signal photon has horizontal (vertical) polarization, idler photon is guaranteed to have horizontal (vertical) polarization

--- Is this entanglement ?? NO

--- Two independent classical sources can also produce such correlations

What is Entanglement (Polarization)



$$|\psi\rangle = |H_s H_i\rangle + |V_s V_i\rangle$$

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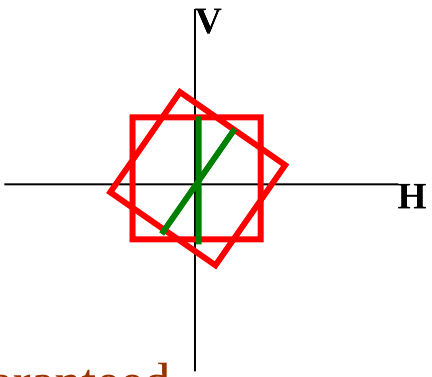
$$|\psi\rangle = |H_s\rangle |H_i\rangle + |V_s\rangle |V_i\rangle$$

$$|\psi\rangle = |45\rangle_s |45\rangle_i + |-45\rangle_s |-45\rangle_i$$



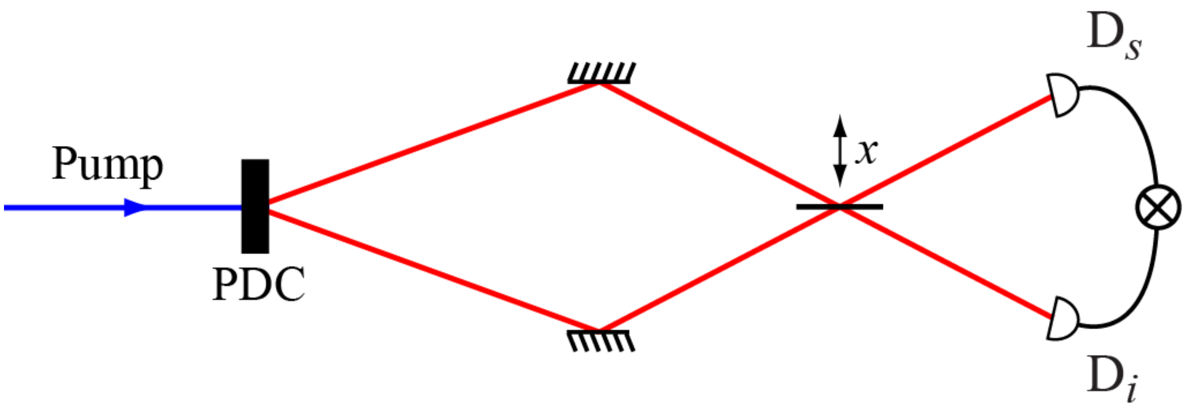
(2) If signal photon has 45^0 (-45^0) polarization, idler photon is guaranteed to have 45^0 (-45^0) polarization --- Is this entanglement ?? NO

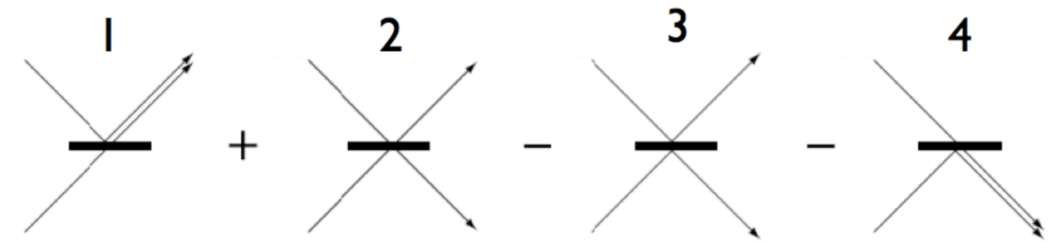
If correlations (1) and (2) exist simultaneously, then that is entanglement

Quantum Superposition with Entangled Photons

Hong-Ou-Mandel Effect

C. K. Hong et al., PRL 59, 2044 (1987)





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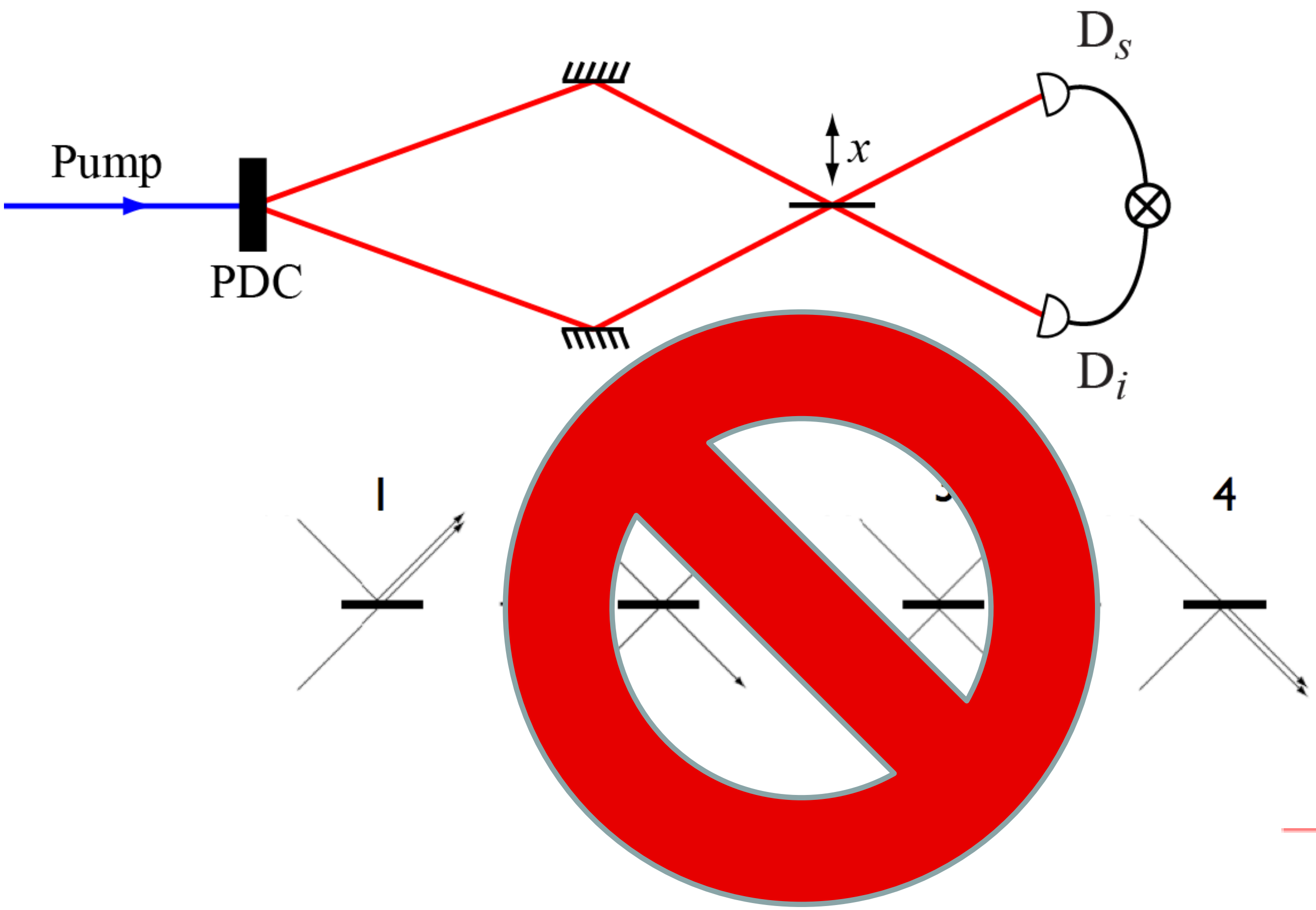
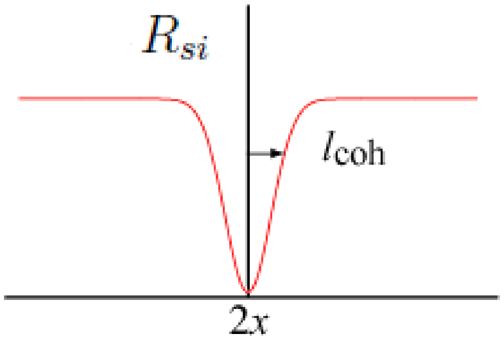




Bunching of photons at a beam splitter

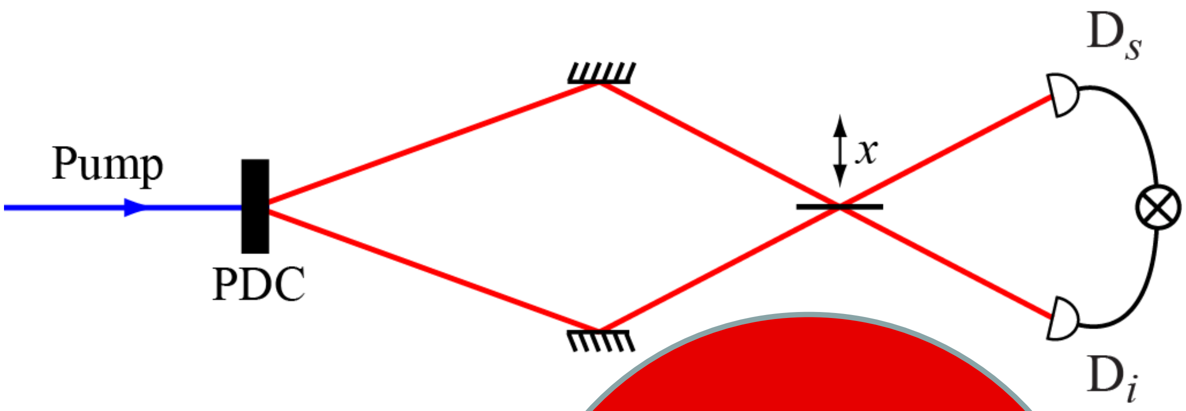
---- Applications in quantum metrology

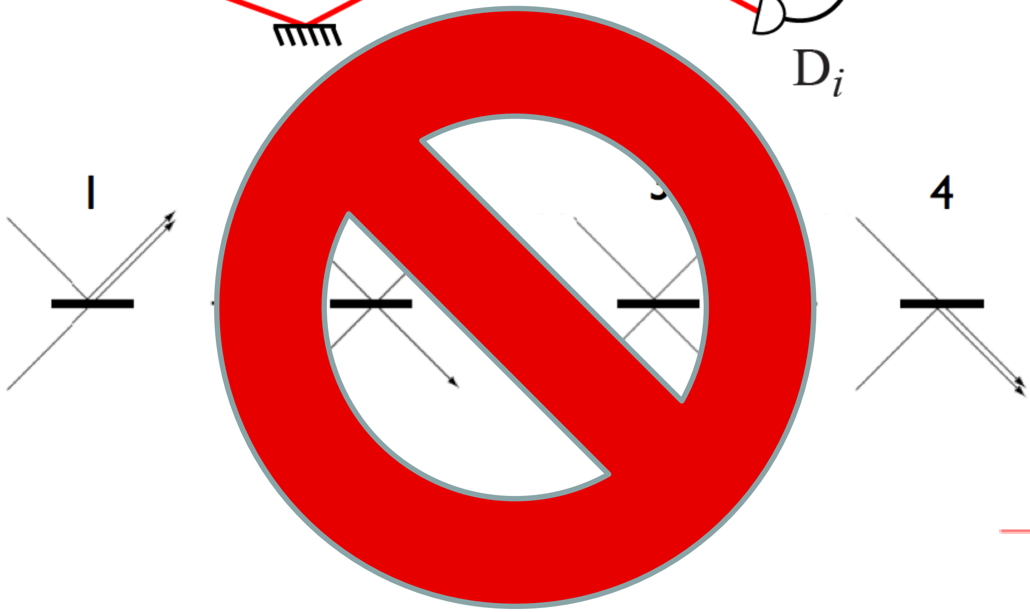
Image source: Wikepedia and google images

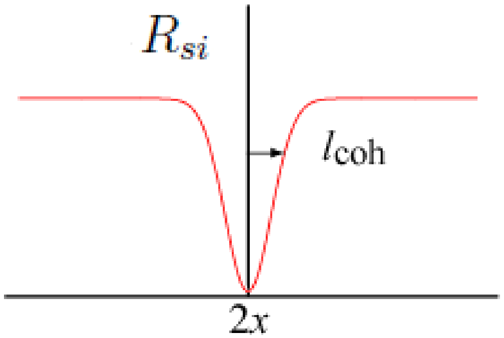
Quantum Superposition with Entangled Photons

Hong-Ou-Mandel Effect

C. K. Hong et al., PRL 59, 2044 (1987)







Is this interference between two different phtons?

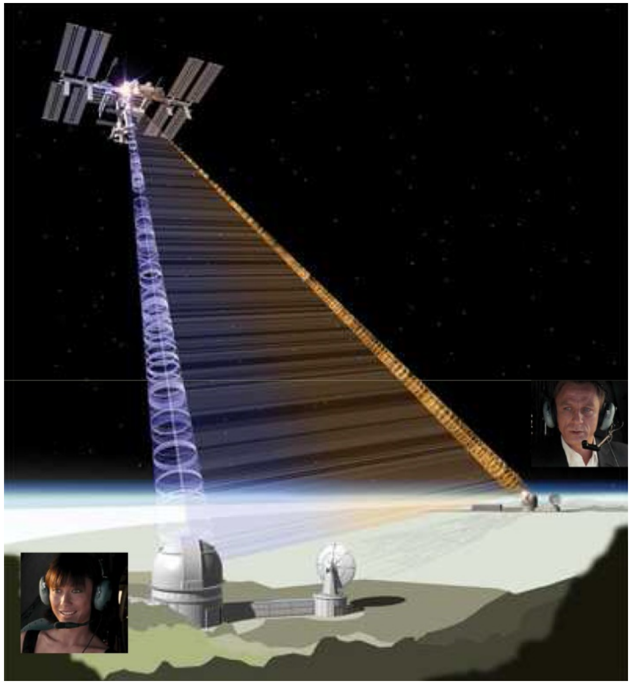
Is Dirac's statement incorrect? - NO

Here, a two-photon is interfering with itself

Image source: Wikepedia and google images

Quantum Entanglement: Applications

1. Quantum Cryptography with Entangled photons



A. Zeilinger. Oct. 20, 2008. “Photonic Entanglement and Quantum Information” Plenary Talk at OSA FiO/LS XXIV 2008, Rochester, NY.

2. Quantum Teleportation

- **Quantum states (not system) can be teleported from point A to point B**
- **Record is Teleportation over 144 km ---** Ursin et al., *Nature Physics*, *3*(7), 481-486 (2007).

3. Quantum Computing (building a quantum computer)

- **Solving quantum-mechanical problem, Prime factorization, Database search**

4. Quantum Metrology

Imaging with enhanced resolution and/or sensitivity.

Conclusions

- Superposition principle and entanglement and the two hallmark effects of quantum mechanics.

- The next-generation quantum technologies could be based on these two effects.

Acknowledgments:

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- The Physics department

Further Interactions:

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