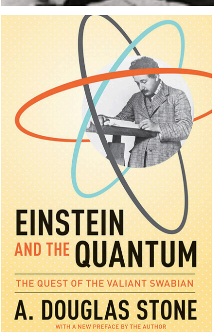
From Einstein's LichtQuanten to Wheeler's delayed choice experiment: wave-particle duality for a single photon

https://www.coursera.org/learn/quantum-optics-single-photon

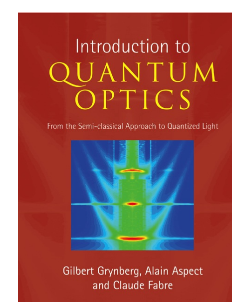
symposium: Optics in the Quantum World

Oberkochen, 18/04/2018



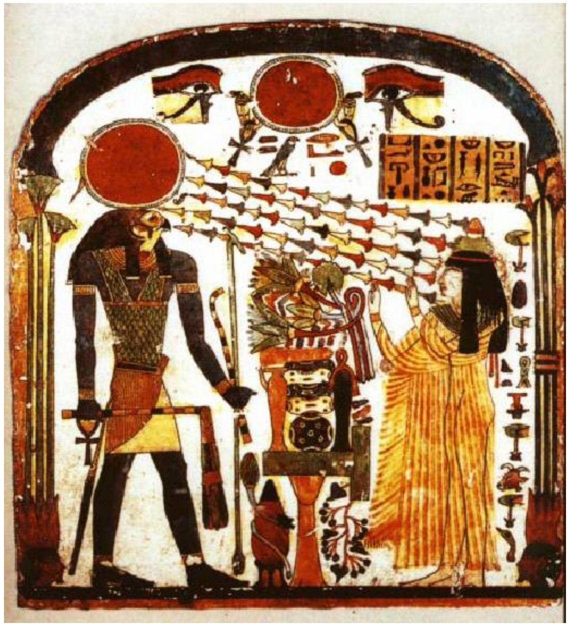
Alain Aspect , Institut d'Optique, Palaiseau, France

http://www.lcf.institutoptique.fr/Alain-Aspect-homepage



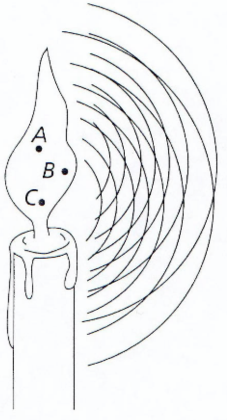
Light across ages: wave or particle?

Antiquity (Egypt, Greece): particles towards or from the eye (Epicure, Aristotle, Euclid)

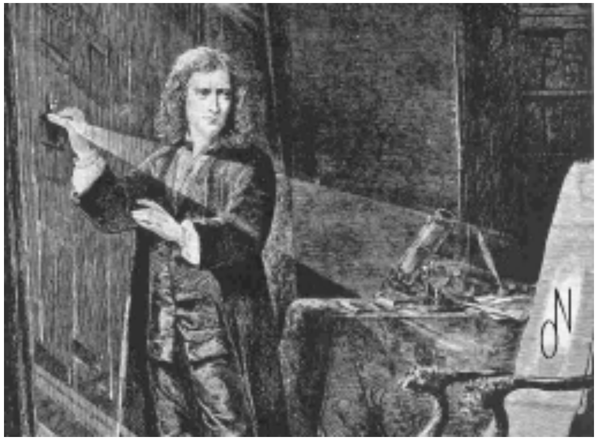


Middle age, renaissance: engineering: corrective glasses, telescope (Al Hazen, Bacon, Leonardo da Vinci, Galilée, Kepler…)

XVIIth cent.: Waves (as “ripples on water”) Huyghens



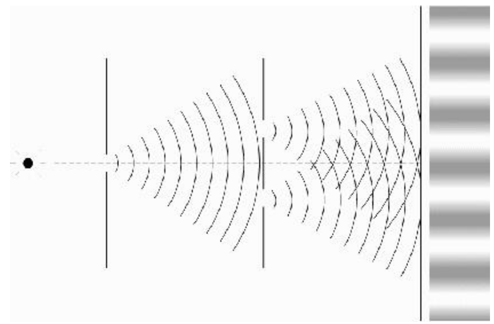
Newton (Opticks, 1702): particles (of various colours)



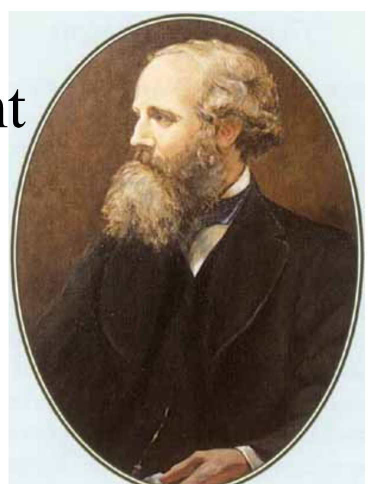
XIXth cent. The triumph of waves

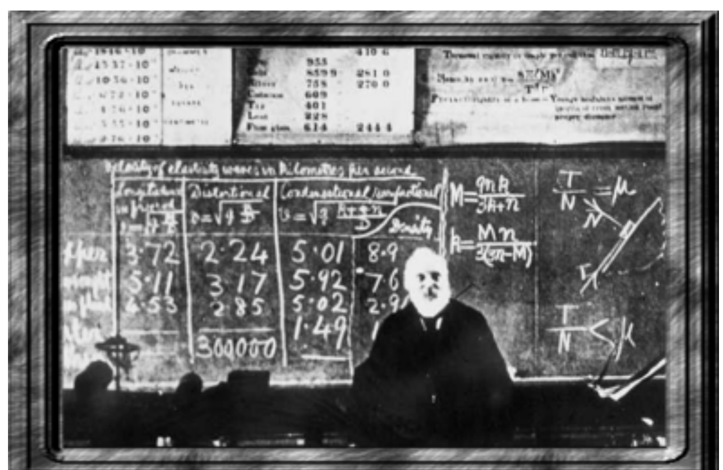
Young, Fresnel (1822):

interference,
diffraction,
polarisation:
light is a
wave



Maxwell (1865): light is an electro-magnetic wave



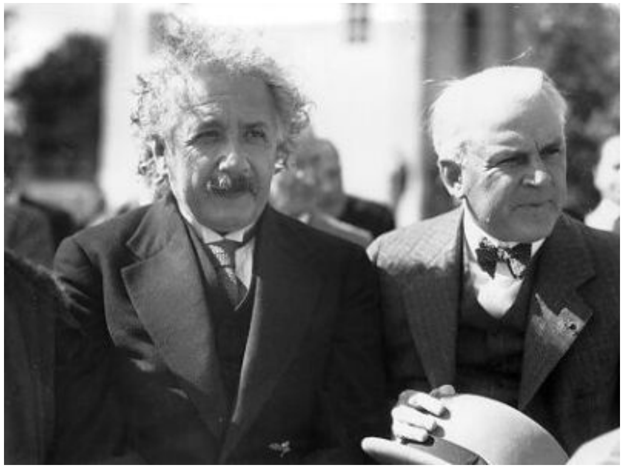


1900: “Physics is completed” (Michelson) … except for two clouds (Kelvin) !!!

Early XXth: particles come back

- Einstein (1905). Light made of quanta, elementary grains of energy $E = h\nu$ and momentum $p = h\nu / c$ (named "photons" in 1926 only).

➢ Quantitative predictions for the photoelectric effect



➢ Ideas not accepted until Millikan's experiments on photoelectric effect (1915).

➢ Nobel award to Einstein (1922) for the photoelectric effect

➢ Compton's experiments (1923): momentum of photon in the X ray domain

How to reconcile the particle description with typical wave phenomenon of diffraction, interference, polarisation?

Particle or wave?

Wave particle duality

Einstein 1909
Salzburg

Light is both waves (capable to interfere) and an ensemble of particles with defined energy and momentum…

Thermal radiation fluctuations

$$\overline{\varepsilon^2} = \left(h\nu\rho + \frac{c^3\rho^2}{8\pi\nu^2} \right) d\nu$$

Random particles ("shot noise")

Random waves ("speckle")

Louis de Broglie 1923

Similarly particles such as electrons behave like a wave (diffraction, interference)

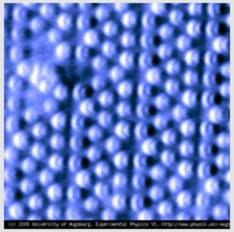
$$\lambda = \frac{h}{p}$$

Easy to say the words, but difficult to represent by images

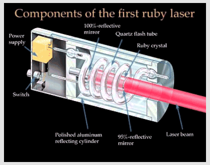
Wave particle duality: fruitful

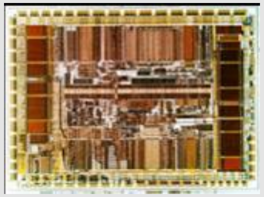
A very successful concept at the root of the quantum revolution:

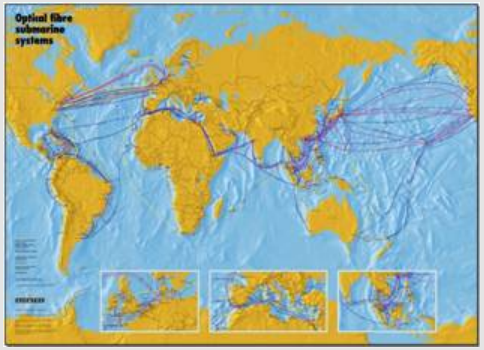
- Understanding the structure of matter, its properties, its interaction with light
  - Electrical, mechanical properties



- Understanding "exotic properties"
  - Superfluidity, supraconductivity, BEC
- Inventing new devices
  - Laser, transistor, integrated circuits







- Information and communication society

Quantum mechanics applied to large ensembles

Does it work for a single particle?

From Einstein to Wheeler: wave-particle duality for a single photon

1. Light: wave or particle?

   Newton, Hughens, Young, Fresnel, Maxwell, Einstein…: both

2. Single photon experiments

   Quantum weirdness brought to light

3. Wheeler's delayed choice experiment

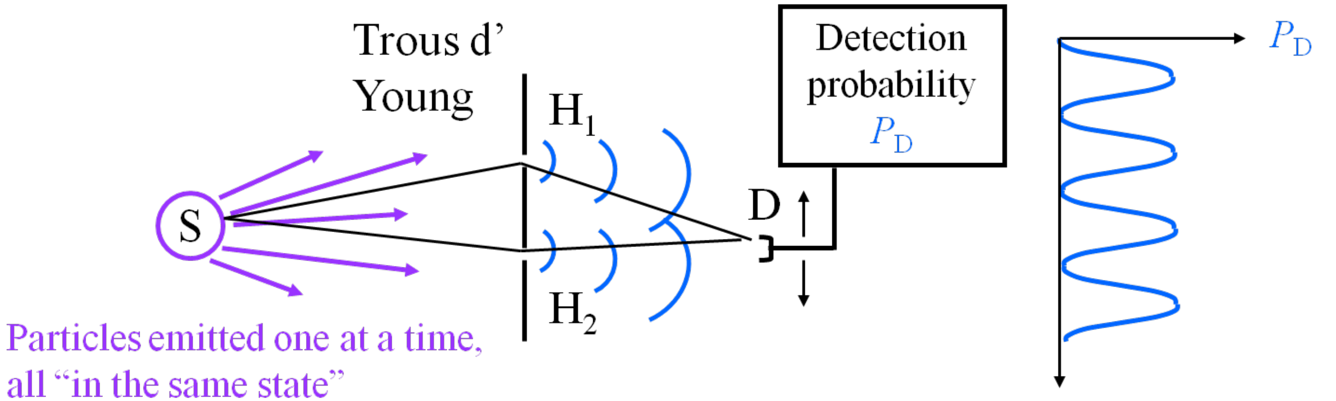
   Yet more quantum weirdness

4. From fundamental tests to applications

   Quantum information

Wave particle duality in textbooks

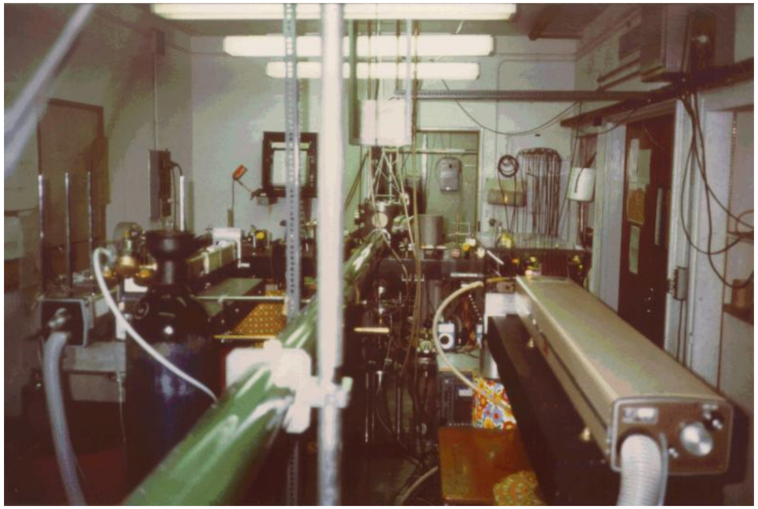
wave-like behaviour for single photons



Has it been observed in real experiments?

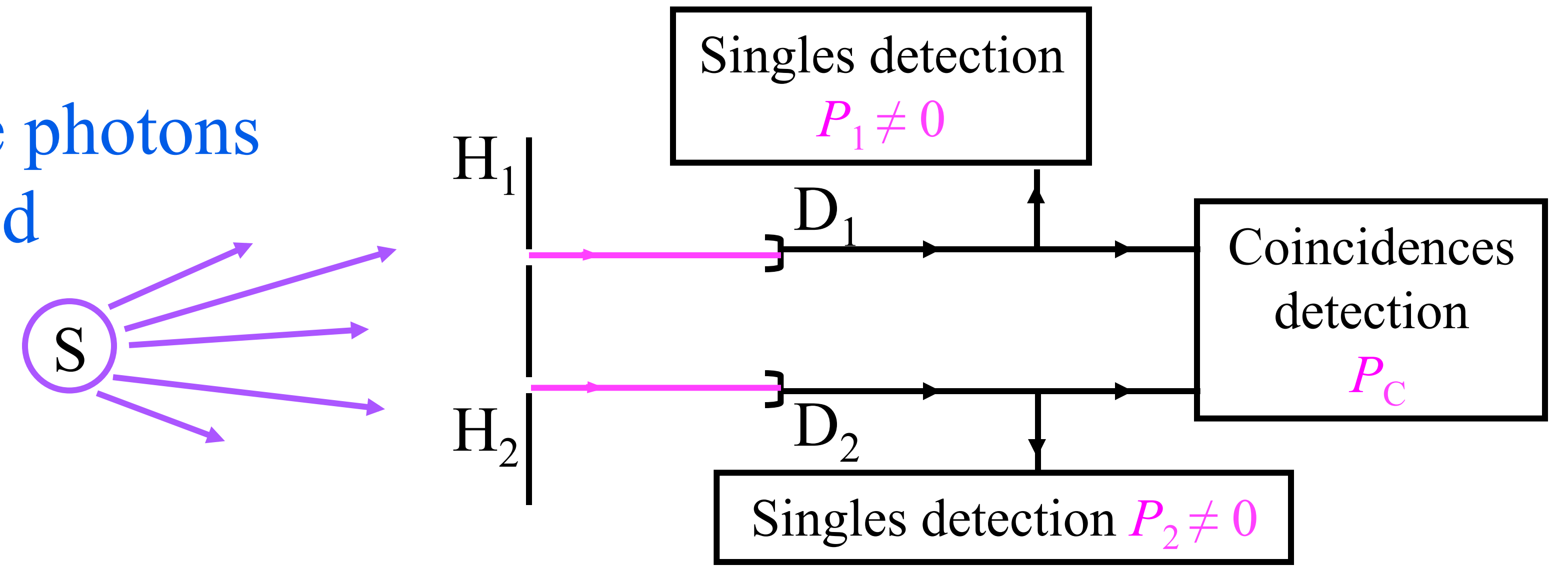
For the first time in 1985 (AA, P Grangier), with the first source of single photons (sim. with Hong and Mandel)

How could we prove we had realized a source emitting single photons?



How to know one has single particles?
The "which path" GedankenExperiment

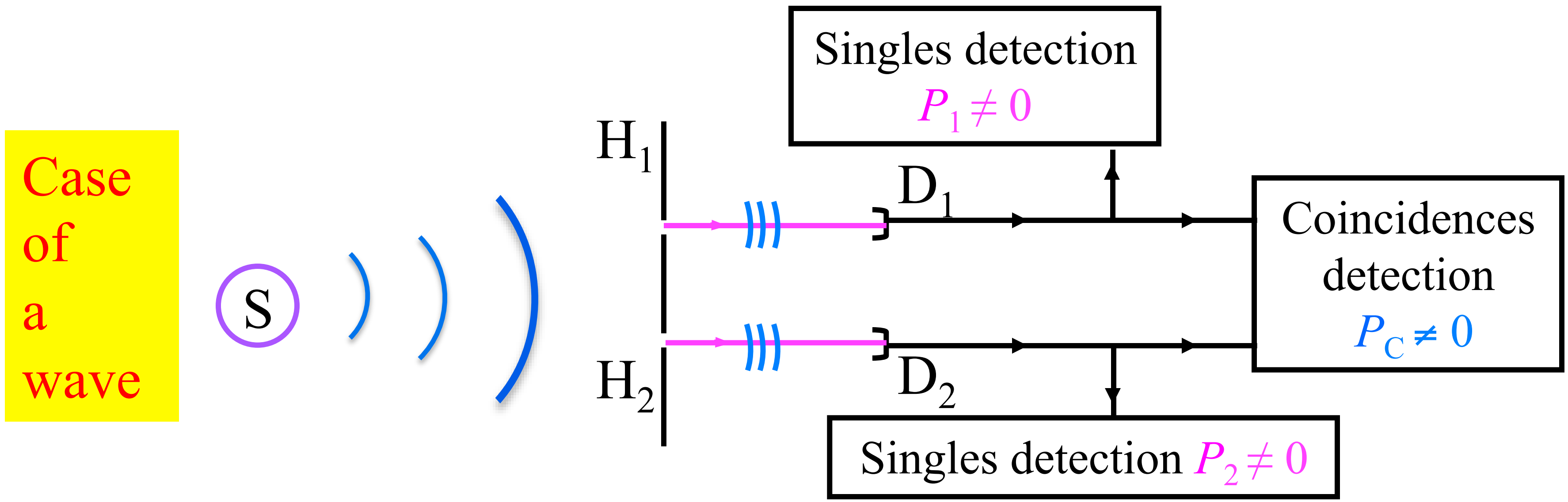
Single photons emitted one after one



What do we expect

- for a wave?
- for a particle?

The "which path" GedankenExperiment in the case of a wave

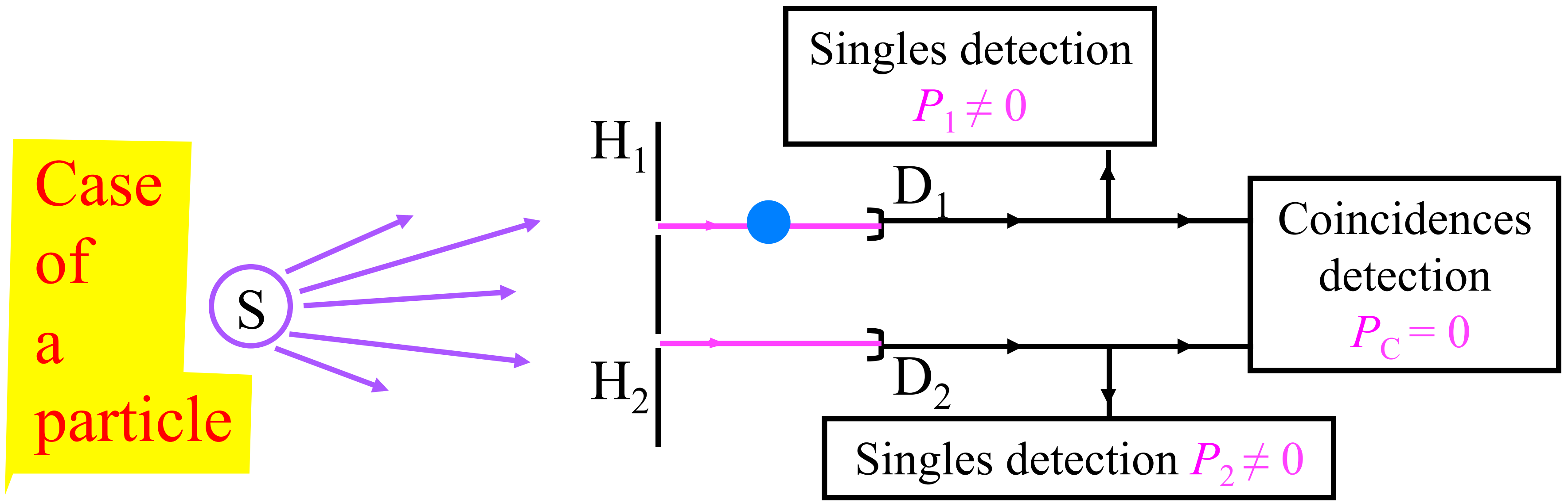


A wave passes through both holes, and falls simultaneously on both detectors. Simultaneous detection can happen.

Wave $\Rightarrow$ $P_C \neq 0$: Simultaneous detection observed

Case of all light sources known until end of 1970's : wave-like behavior

The "which path" GedankenExperiment in the case of a single particle

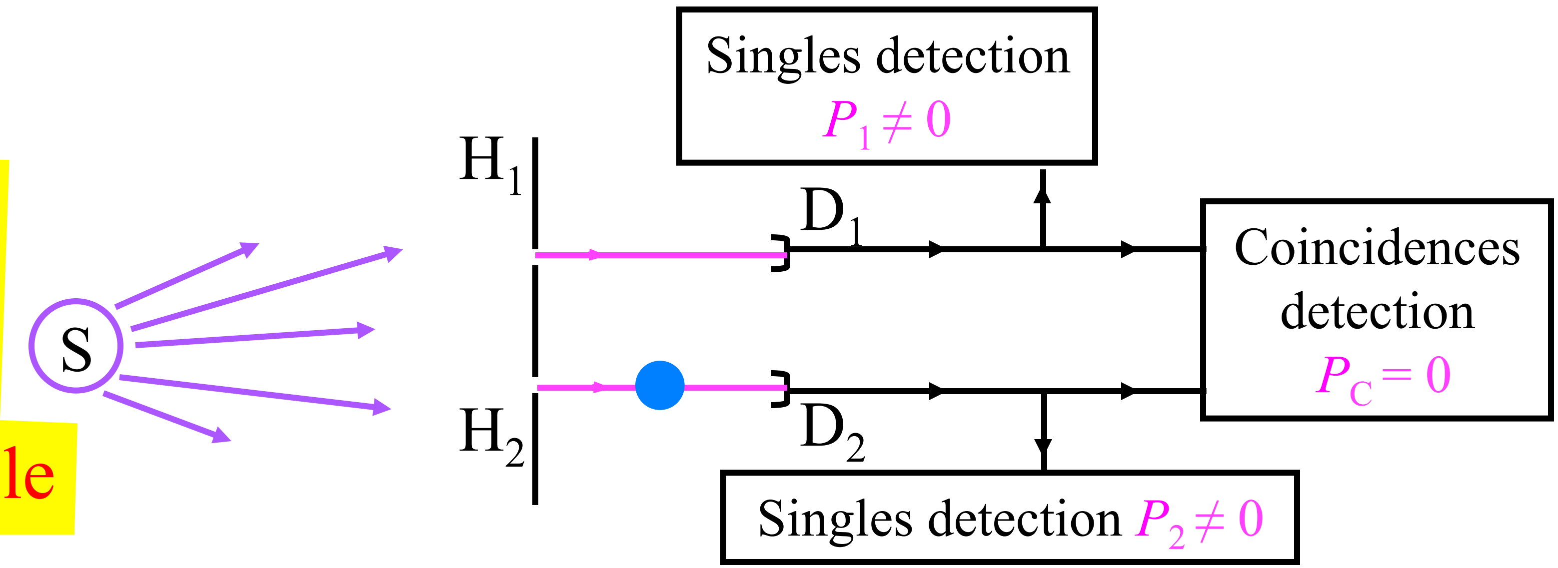


A single particle passes either through H_1, or through H_2, not through both paths simultaneously. A single particle cannot be split.

Single particle $P_C = 0$: No simultaneous detection

The “which path” GedankenExperiment in the case of a single particle

Case of a particle



A single particle passes either through H$_1$, or through H$_2$, not through both paths simultaneously. A single particle cannot be split.

Single particle $P_C = 0$: No simultaneous detection

Lack of coincidences:
smoking gun for single photon source

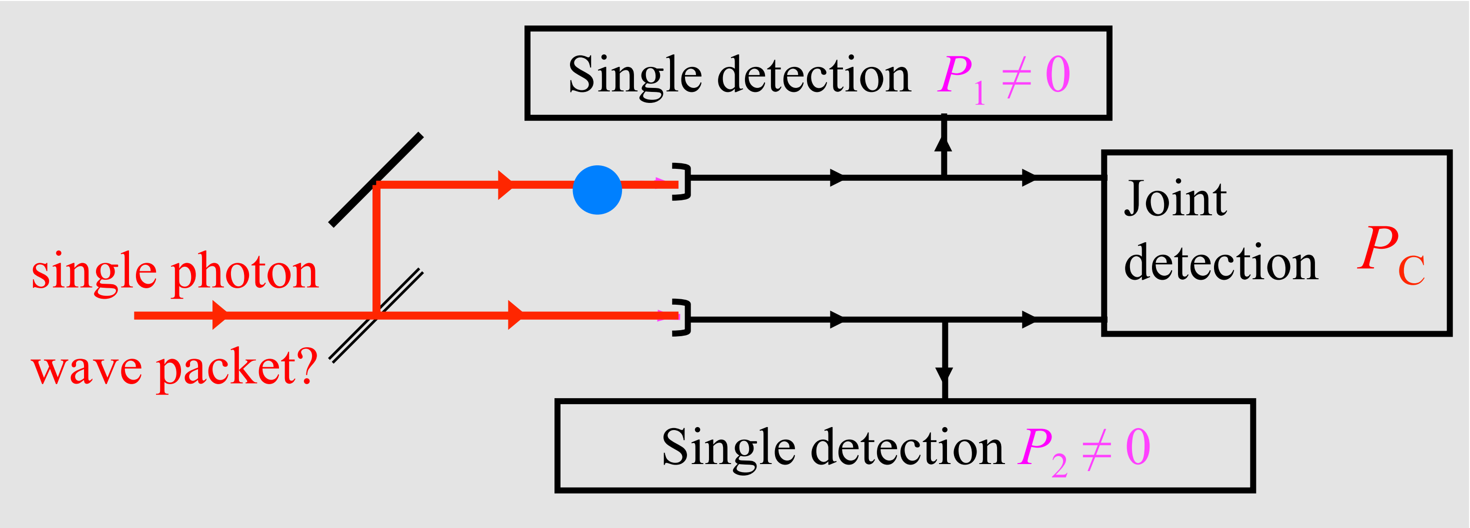
The which path GedankenExperiment with a beam splitter

A beam-splitter to discriminate between a particle-like and a wave-like behaviour

(AA, Philippe Grangier, 1985)

Case of a single particle: one expects

$P_c = 0$



If light behaves as a single particle, it can be detected only once.

$$P_C = 0$$

A beam-splitter to discriminate between a particle-like and a wave-like behaviour

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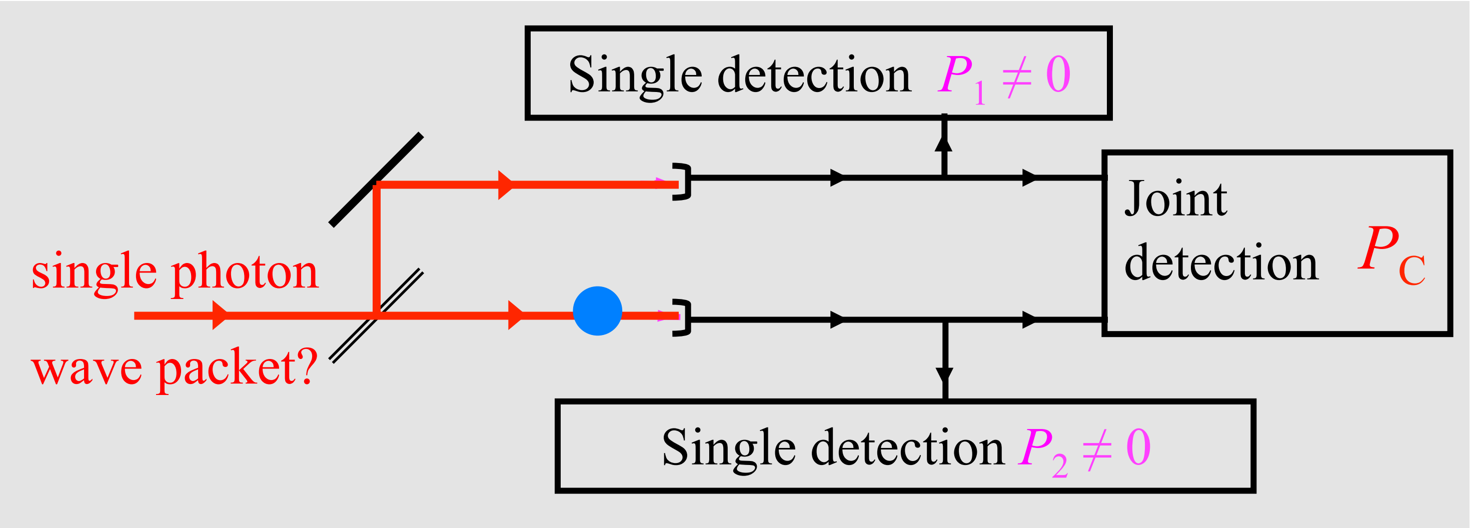

If light behaves as a single particle, it can be detected only once.

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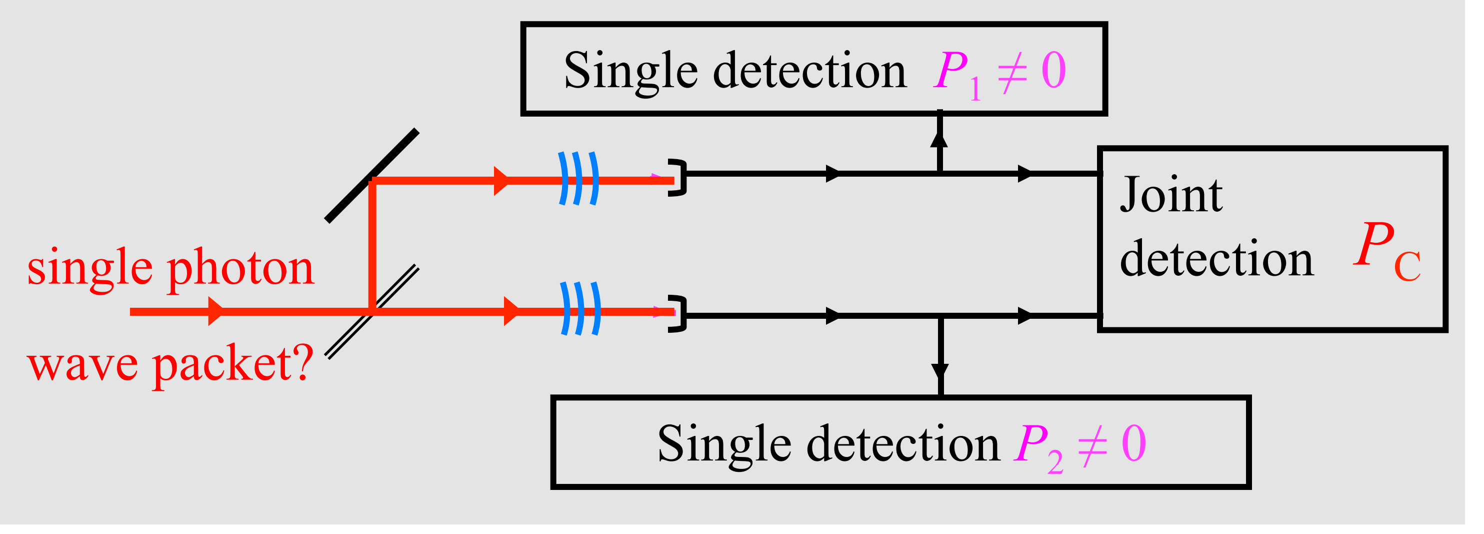
A beam-splitter to discriminate between a particle-like and a wave-like behaviour

(AA, Philippe Grangier, 1985)

Case of a wave split in two at BS: one expects joint detection $P_c \neq 0$

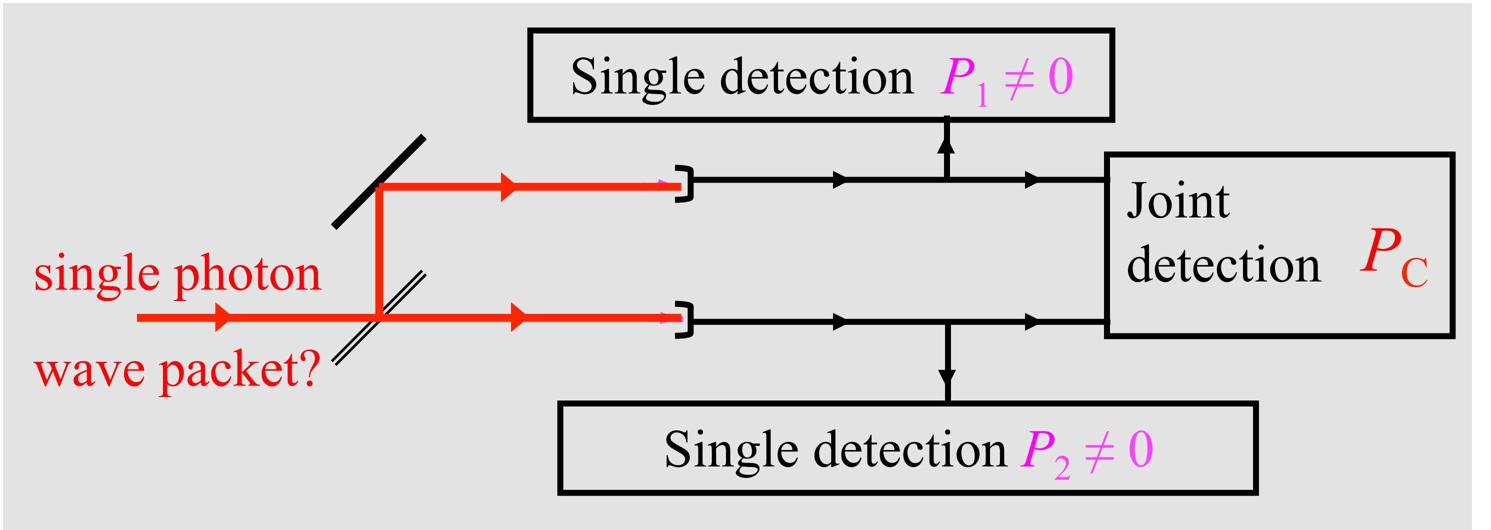


If light behaves as a wave, it can be detected on both sides of the beam splitter: joint detections

$$P_C \neq 0$$

A beam-splitter to quantitatively discriminate particle-like from wave-like behaviour

(AA, Philippe Grangier, 1985)



Single particle $P_C = 0$

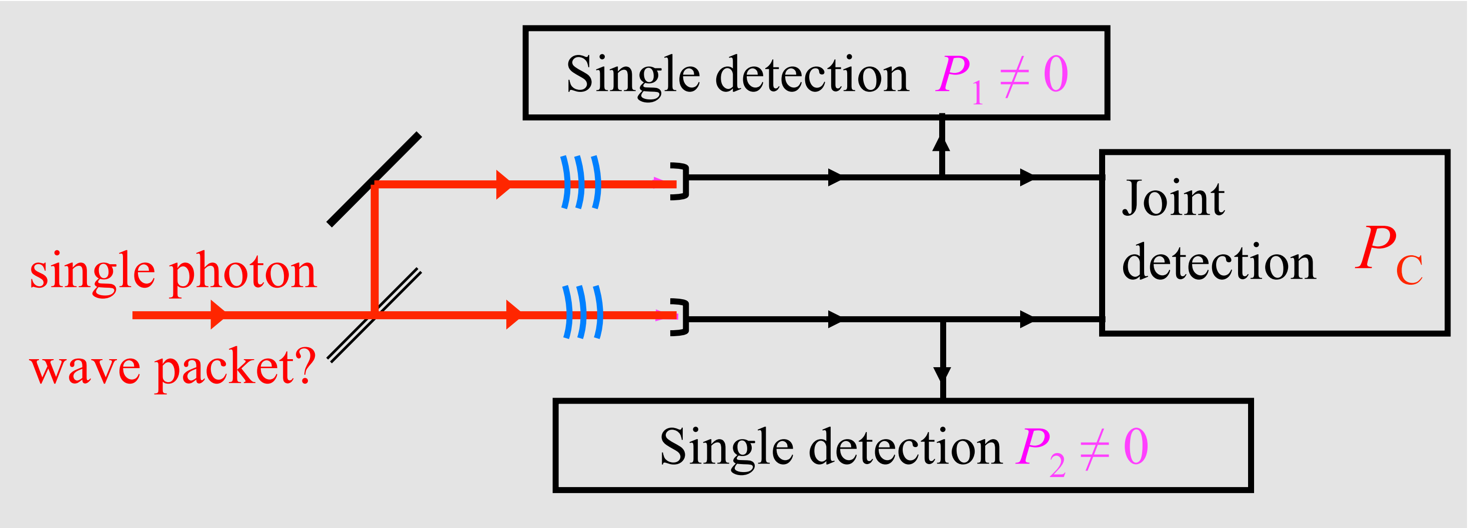
Wave $P_C \neq 0$

In a real experiment, how to distinguish zero from non-zero?

A quantitative criterion for a wave

(AA, Philippe Grangier, 1985)

Case of a wave split in two at BS: one expects joint detection $P_c \neq 0$



More precisely, joint photodetection probability proportional to mean square of wave intensity $P_c = \eta^2 R T \overline{I^2}$

while $P_1 = \eta R \overline{I}$, $P_2 = \eta T \overline{I}$

but $\overline{I^2} \geq \left(\overline{I}\right)^2 \Rightarrow P_C \geq P_1 \cdot P_2$

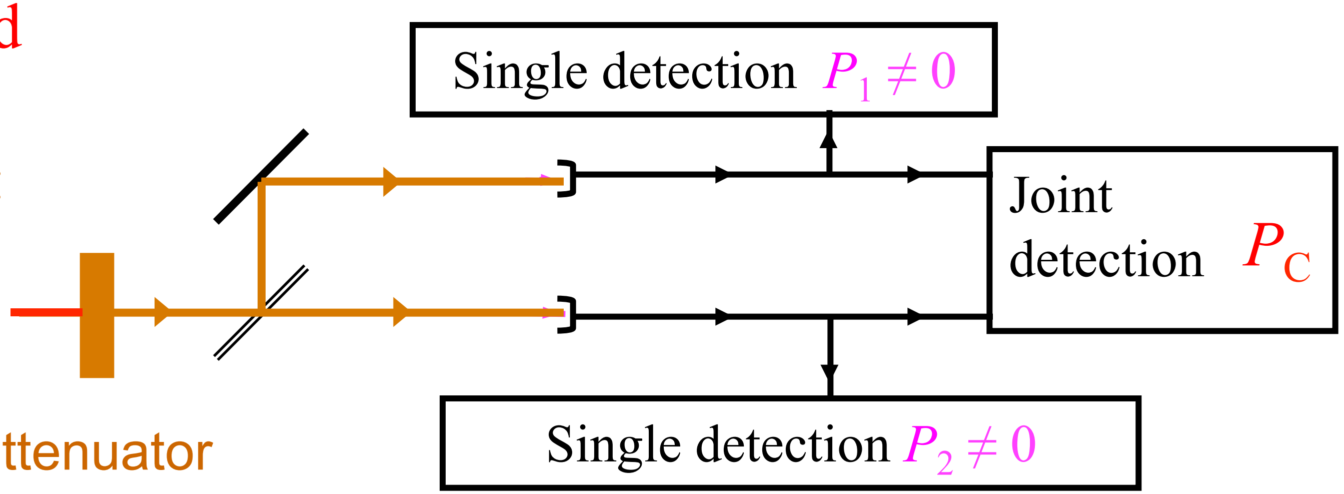
for a wave $\boxed{\alpha = \dfrac{P_C}{P_1 P_2} \geq 1}$

$\alpha < 1$ particle like behavior; cannot be a wave

How to obtain single photons?
Strongly attenuated light ?

Light pulses emitted by a LED and strongly attenuated: 0,01 photon per pulse, on average

AA, P. G., (1985)



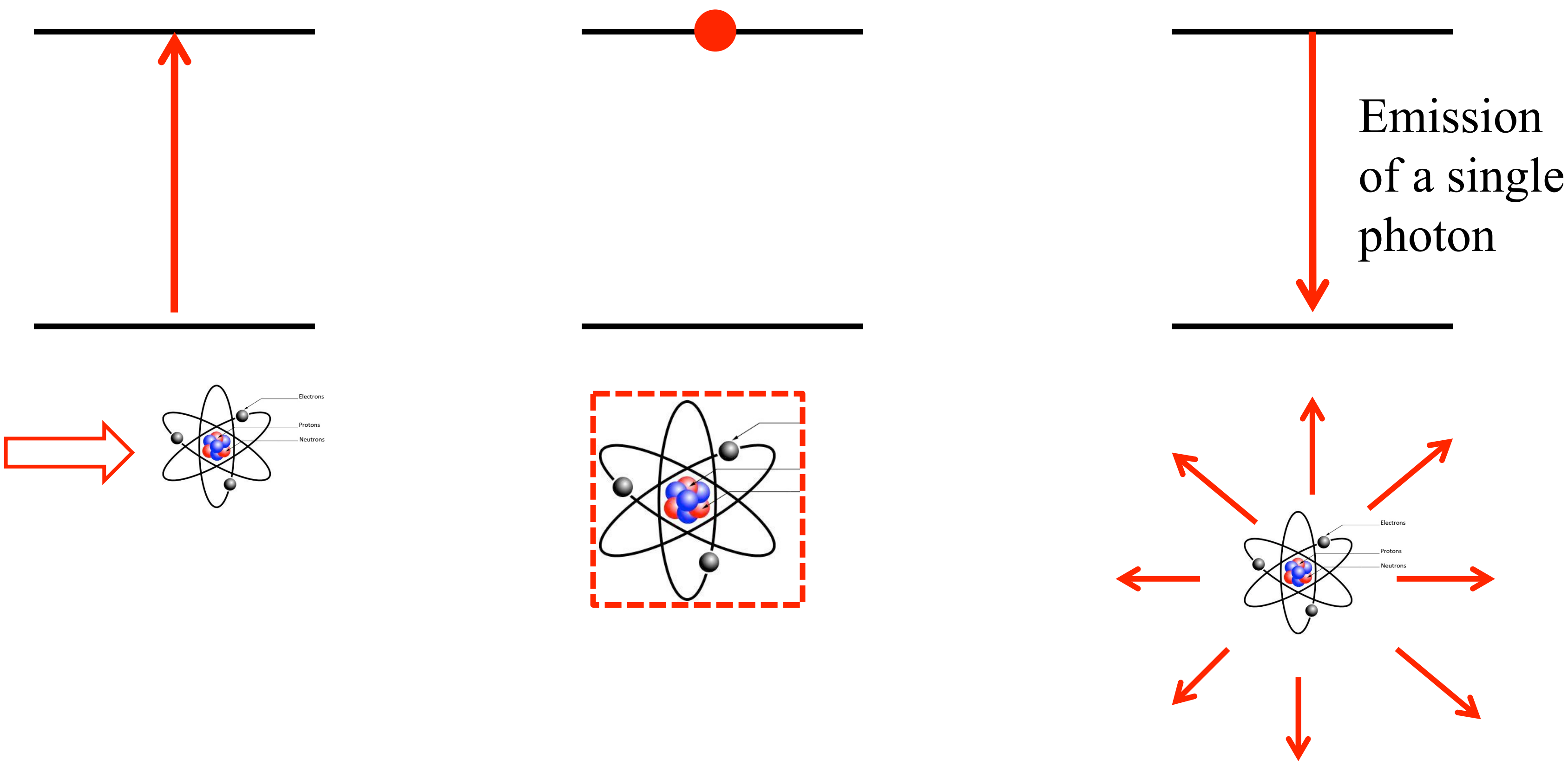
Experimental result: $\alpha = 1.07 \pm 0.08$ NOT single particle behaviour

Attenuated light pulses behave like a wave

Quantum optics: faint light described as a quasi classical "coherent" state. Number of photons is not a "good quantum number": Poisson distribution: $P(2) \sim P(1)^2$: just enough to explain coincidences

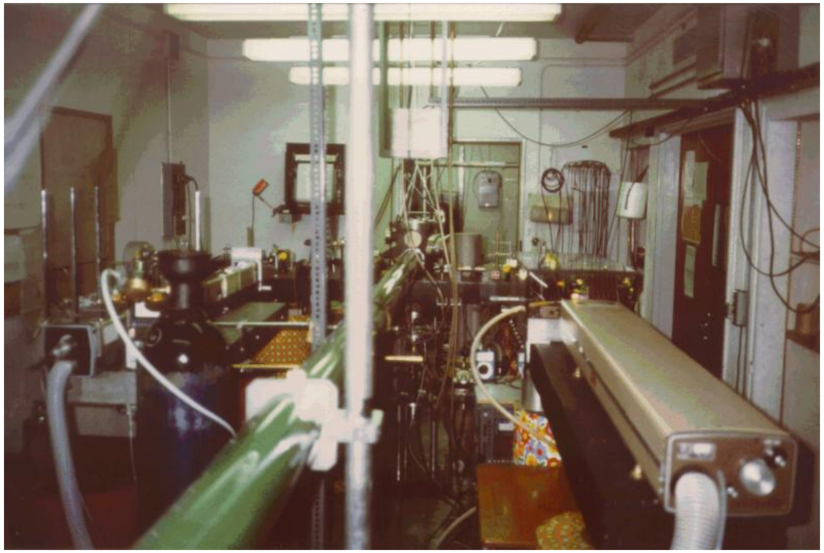
How to emit a single photon?

Take a single atom, excite it, and wait

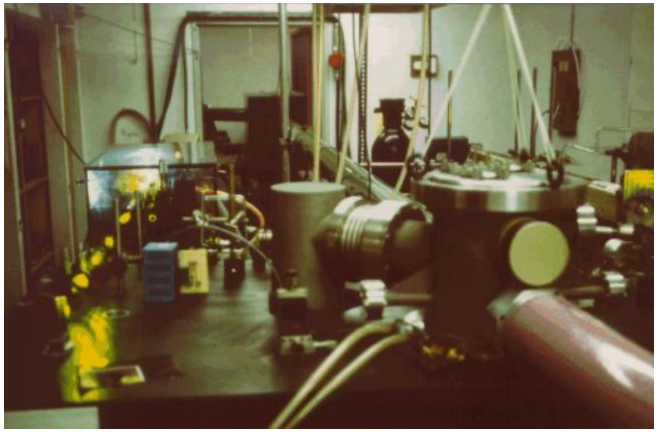


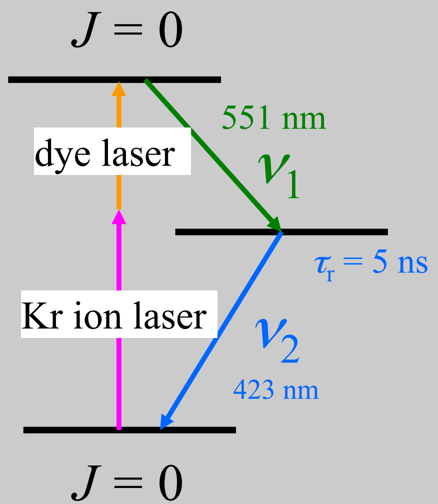
How to isolate a single atom?

Isolating single photons emitters in time (AA, Philippe Grangier, 1985)



Assembly of atoms emitting pairs of photons at a rate of $10^7\ s^{-1}$





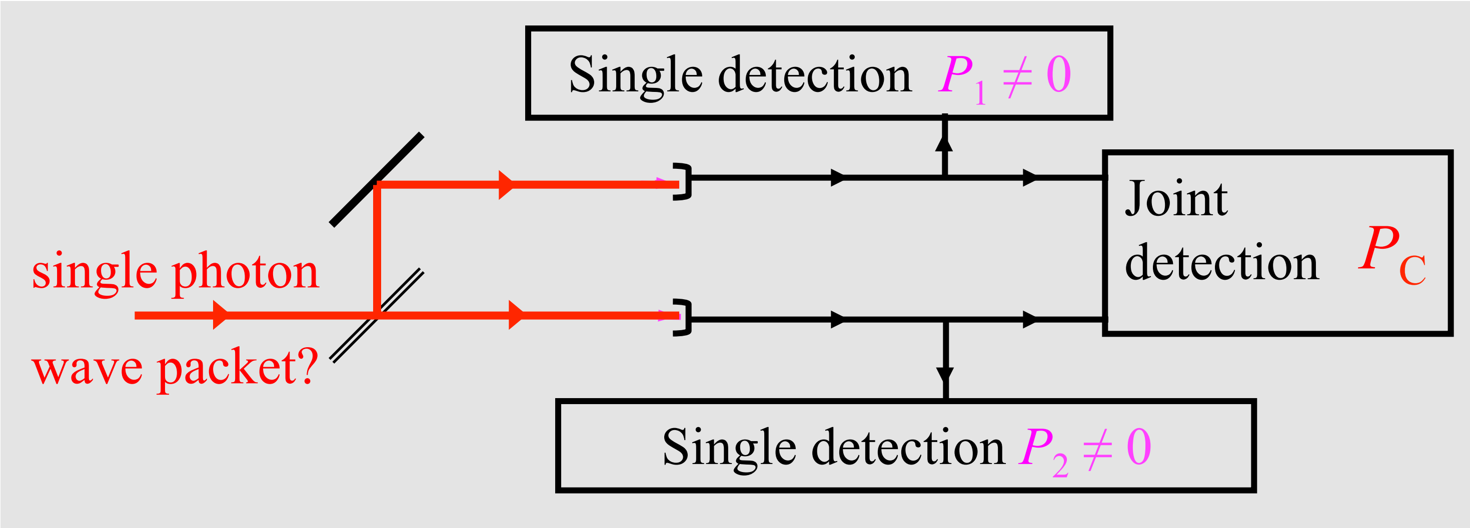
Radiative cascade. In the 5 ns time window following detection of ν_1, only one atom is likely to emit a photon ν_2 (cf J Clauser, 1974) .

First single photon source : isolating single atom emission in time (heralding)

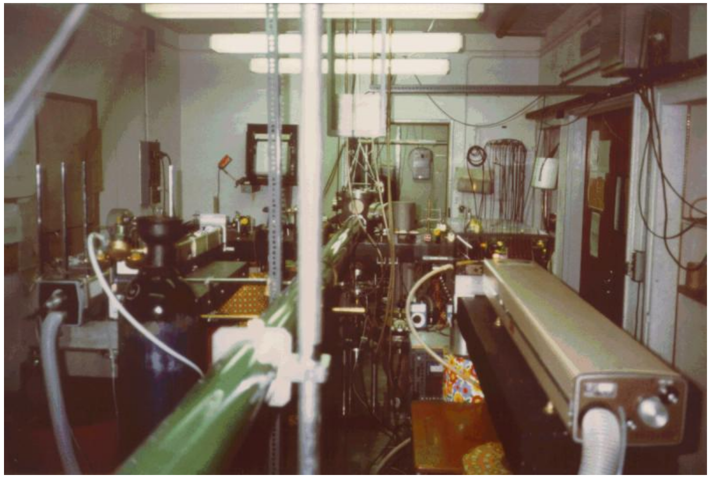
A beam-splitter to quantitatively discriminate particle-like from wave-like behaviour

Particle: one expects $\alpha = \frac{P_C}{P_1 P_2} < 1$

Wave: one expects $\alpha > 1$



First single photon source : isolating single atom emission in time



Experimental result (AA PG 1985):

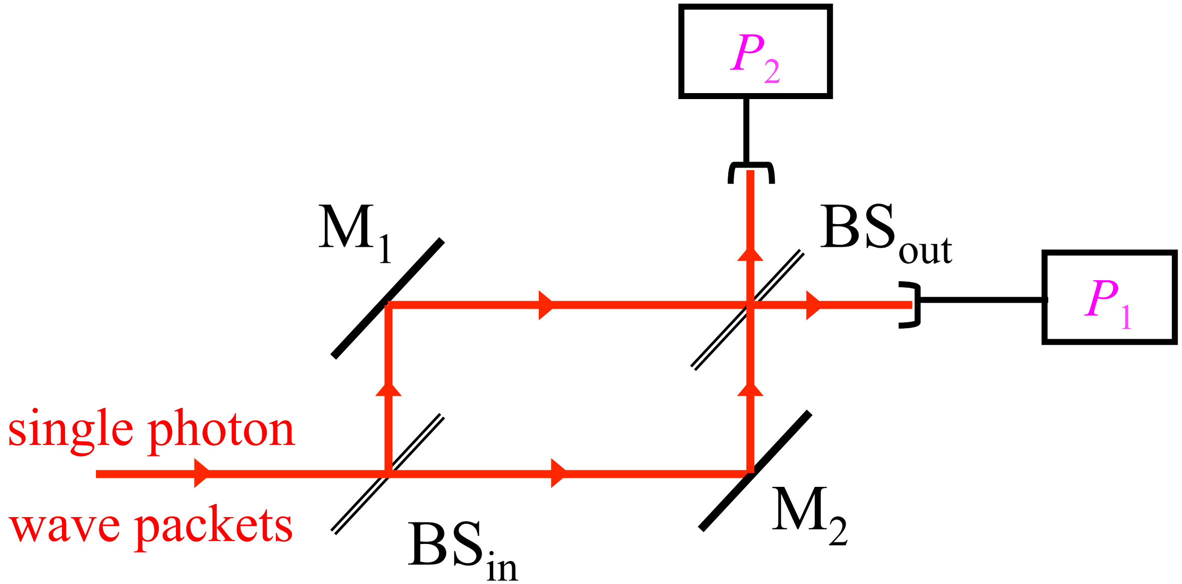
$\alpha_{meas} = 0.18 \pm 0.06$

Clear anticorrelation ($\alpha < 1$)

Particle-like behaviour

Single photon interference?

Can we observe interference with single photon wave packets ($\alpha < 1$)?



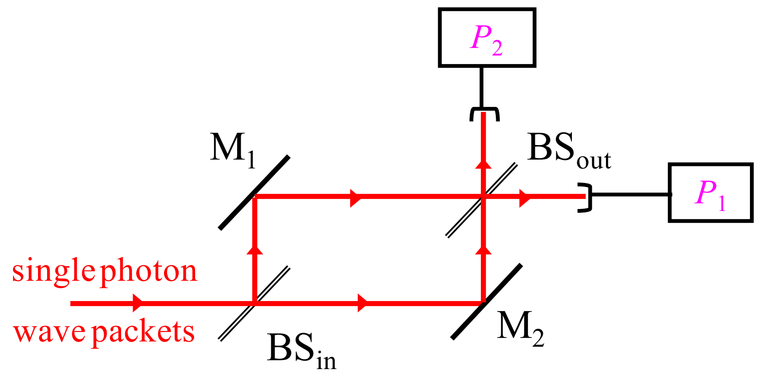
Do probabilities P_1 and P_2 vary (sinusoidally) when one varies the path difference?

Single photon interference?

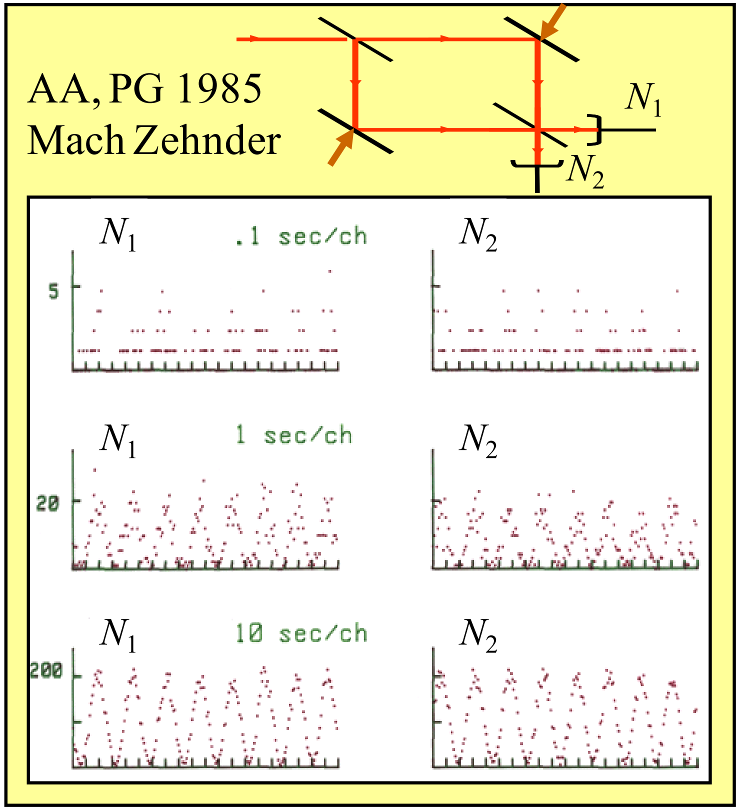
Can we observe interference with single photon wave packets ($\alpha < 1$)?

Yes!

(AA, PG 1985)



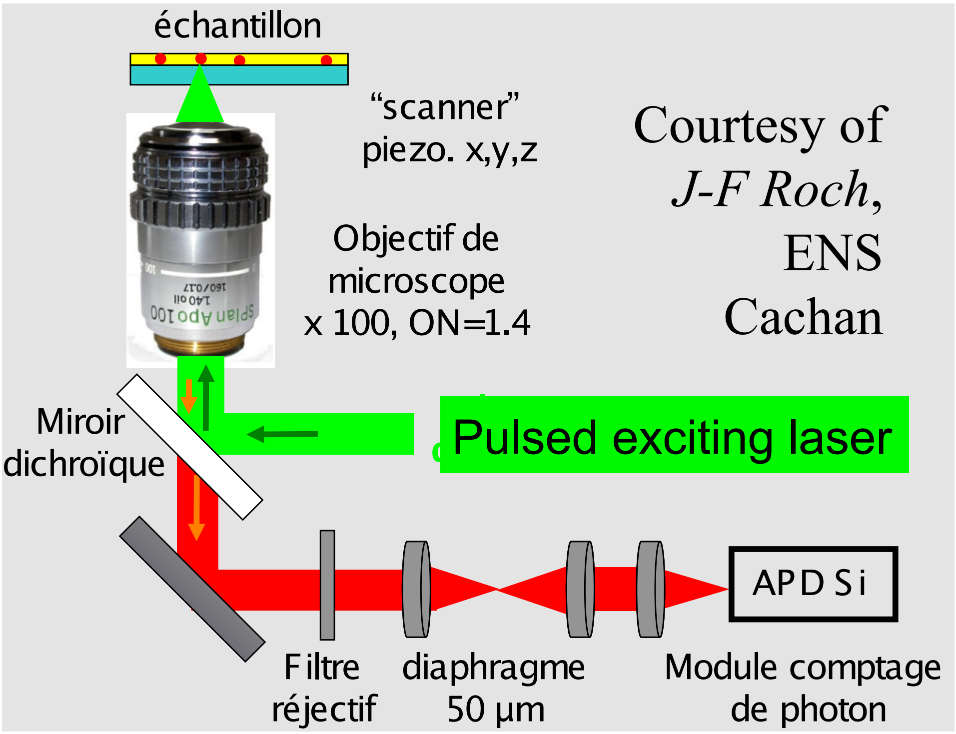
Probabilities P_1 and P_2 vary (sinusoidally) when one varies the path difference



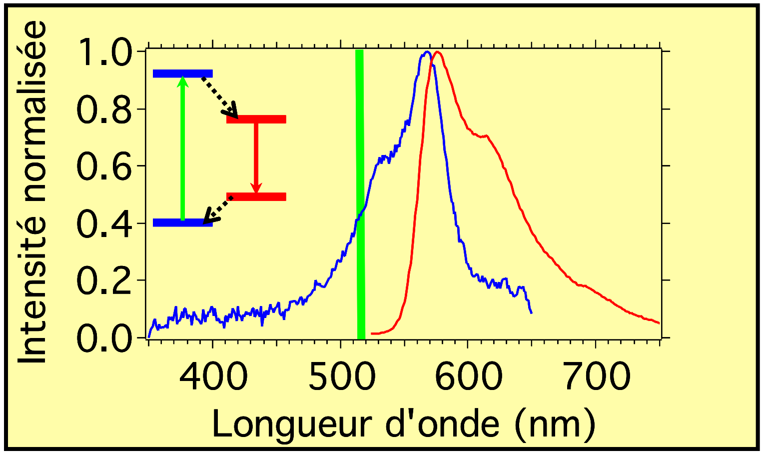
Unambiguous wave like behaviour for single photon

Modern sources: single photons emitters isolated in space and time

Isolated 4-level emitter + pulsed excitation (*Lounis & Moerner*, 2000)



Courtesy of *J-F Roch*, ENS Cachan



V. Jacques et al., EPJD 35, 561 (2005)

For a review: *B. Lounis and M. Orrit*, Rep. Prog. Phys. 68, 1129 (2005).
P. Grangier and I. Abram, Phys. World, Feb. 2003

Experimental result

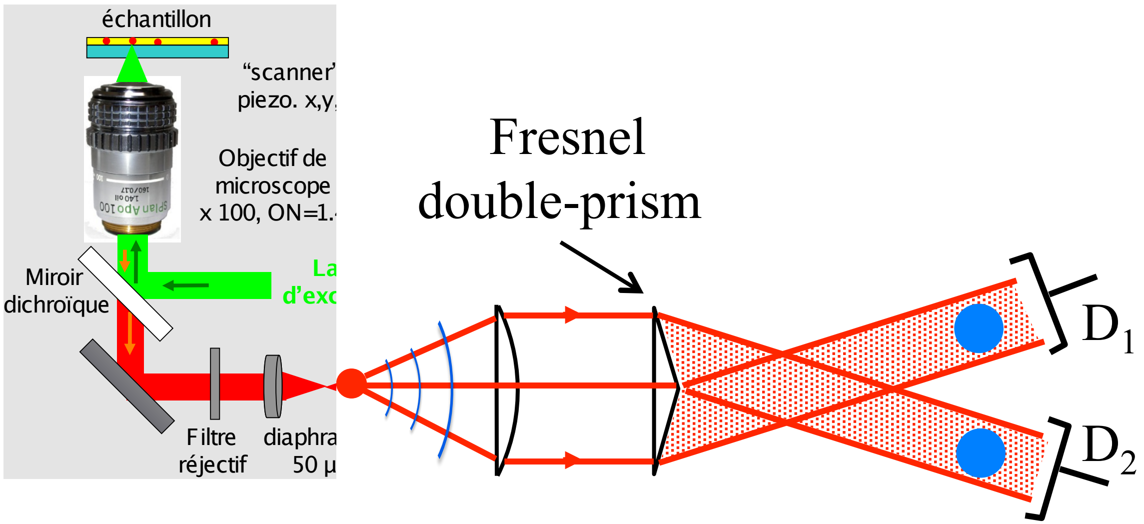
$\alpha_{meas} = 0.132 \pm 0.001$

Clear anticorrelation ($\alpha < 1$)

Particle-like behaviour

A modern single photon source

A modern implementation (V. Jacques, J-F. Roch et al., Ecole Normale Supérieure de Cachan, 2005)



Anticorrelation on detectors D1 and D2: joint detections suppressed

The photon passes either up (detected in D2) or down (detected in D1)

Experimental result

$\alpha_{meas} = 0.132 \pm 0.001$

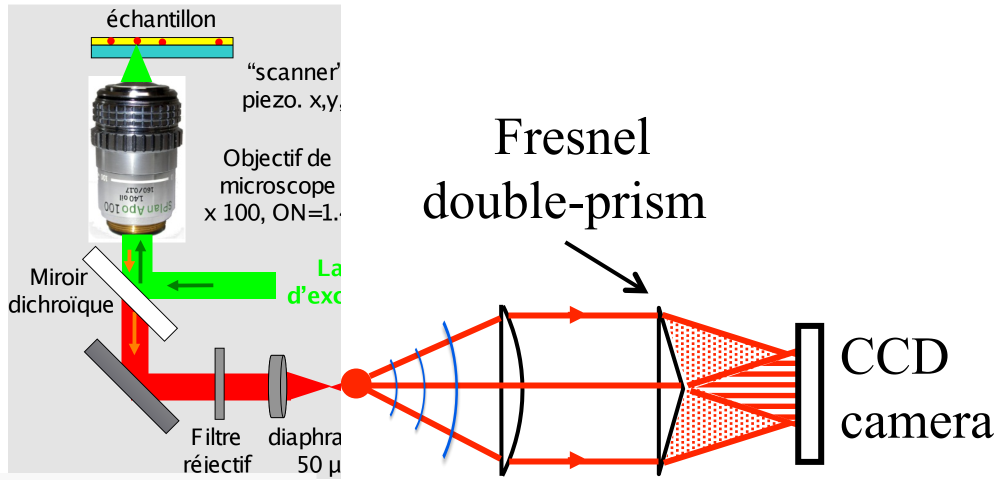
Clear anticorrelation ($\alpha < 1$)

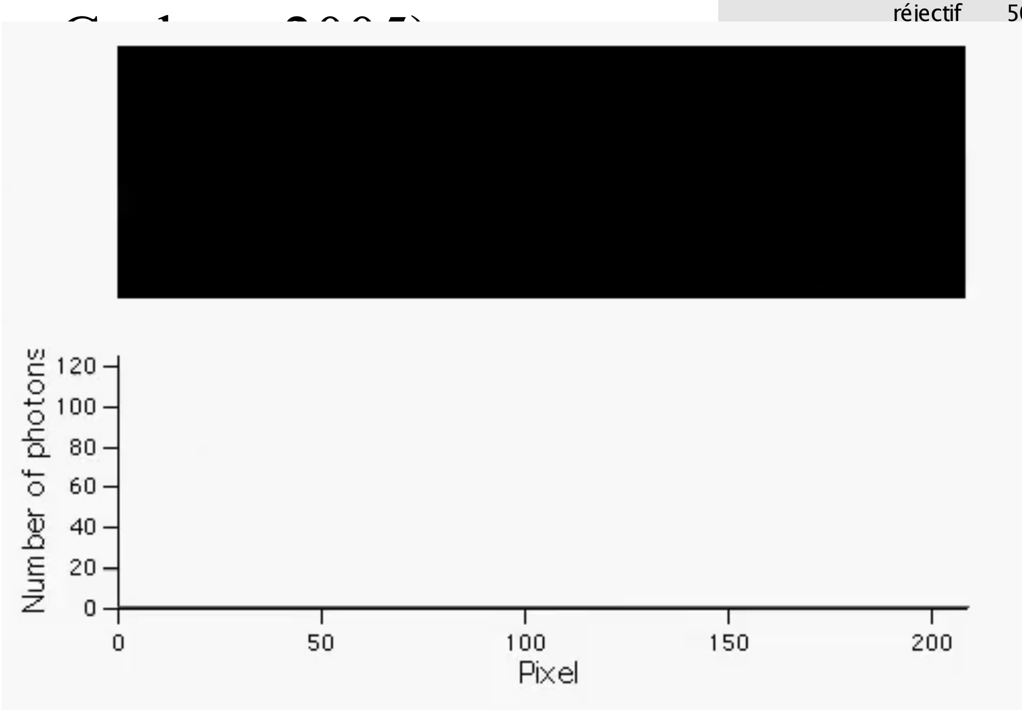
Particle-like behaviour

Evidence of single photon behaviour

Single photon interference experiment

A modern implementation
(V. Jacques, J-F. Roch et al., Ecole Normale Supérieure de





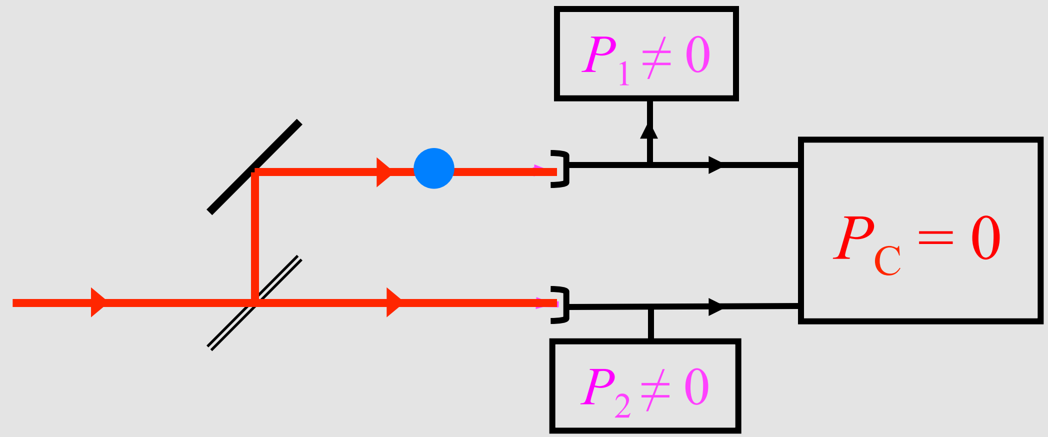
Observation in the overlap between two beams: interference fringes?

r in the single photon regime

Wave particle duality for single photons: weird

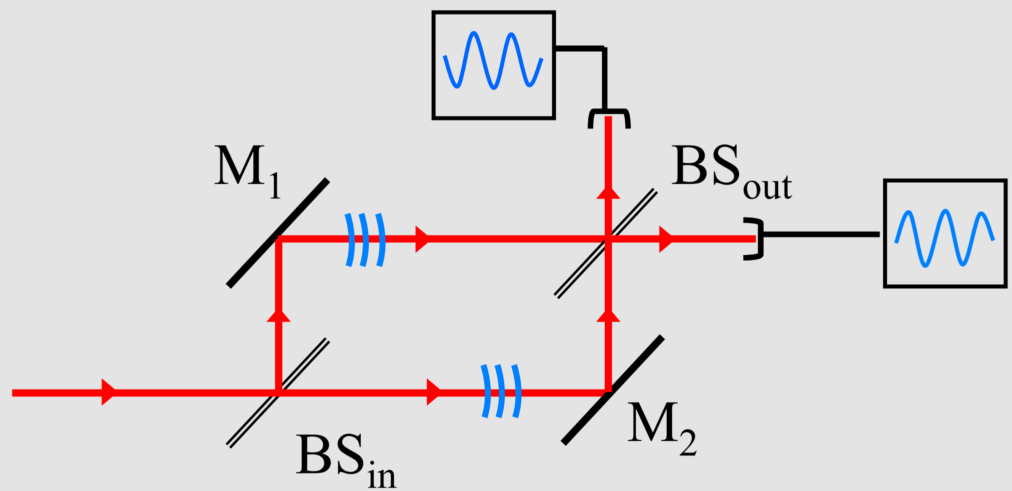
First experiment

Particle like behaviour: goes either to one side, or the other, not both.



Second experiment

Wave like behaviour: Travels along both paths (output depends on paths difference)



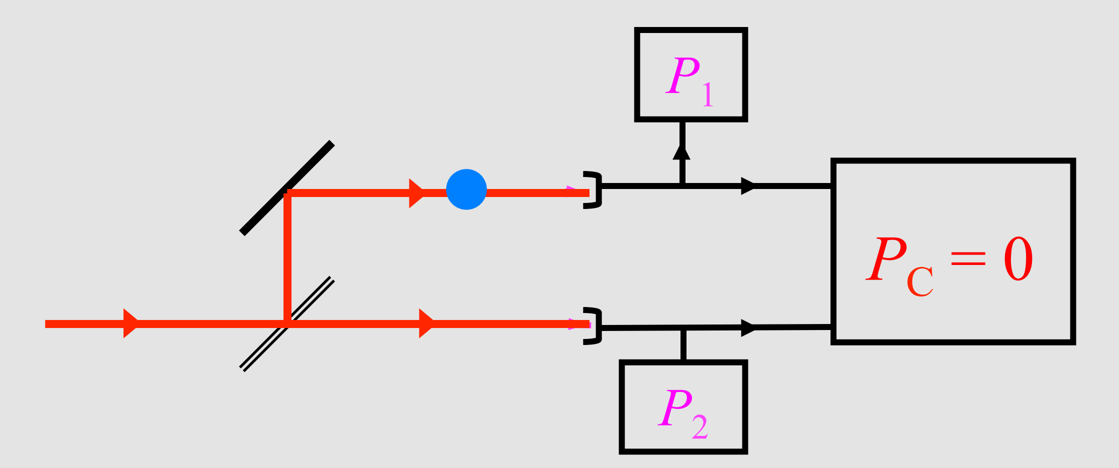
Same single photon wave packets, same beamsplitter, contradictory images

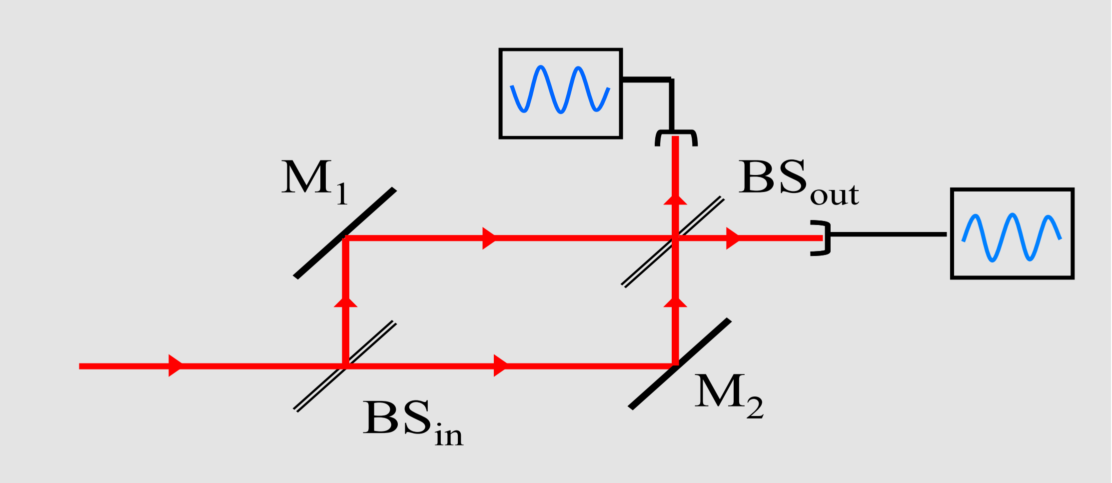
To comfort oneself: Bohr's complementarity

The two experiments are incompatible. One must choose the question:

- Which way ?
- Interference ?

The two questions cannot be asked simultaneously





Could it be that the photon behaves according to the question?

What would happen if the question was chosen after passage at the input beamsplitter? Wheeler's delayed choice experiment.

From Einstein to Wheeler: wave-particle duality for a single photon

1. Light: wave or particle?

   Newton, Hughens, Young, Fresnel, Maxwell, Einstein…: both

2. Single photon experiments

   Quantum weirdness brought to light

3. Wheeler's delayed choice experiment

   Yet more quantum weirdness

4. From fundamental tests to applications

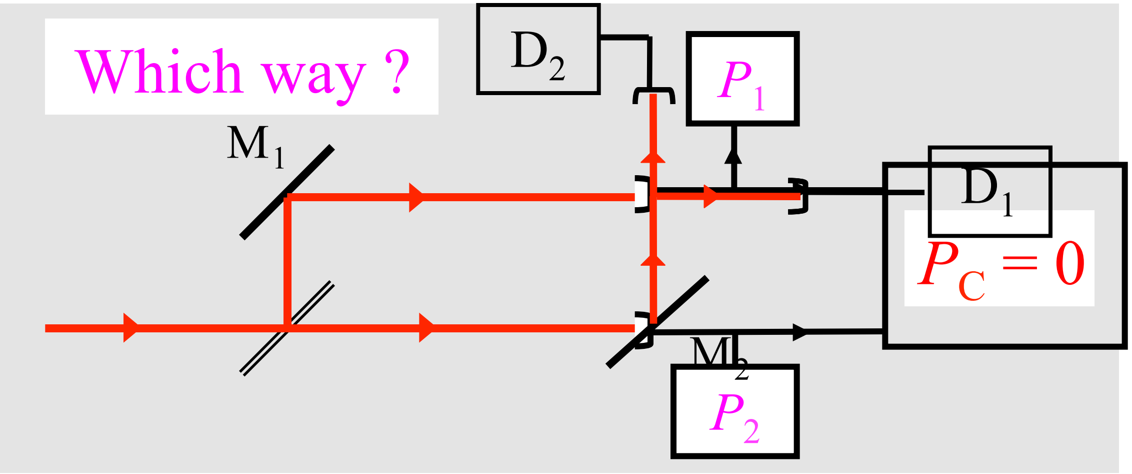
   Quantum information

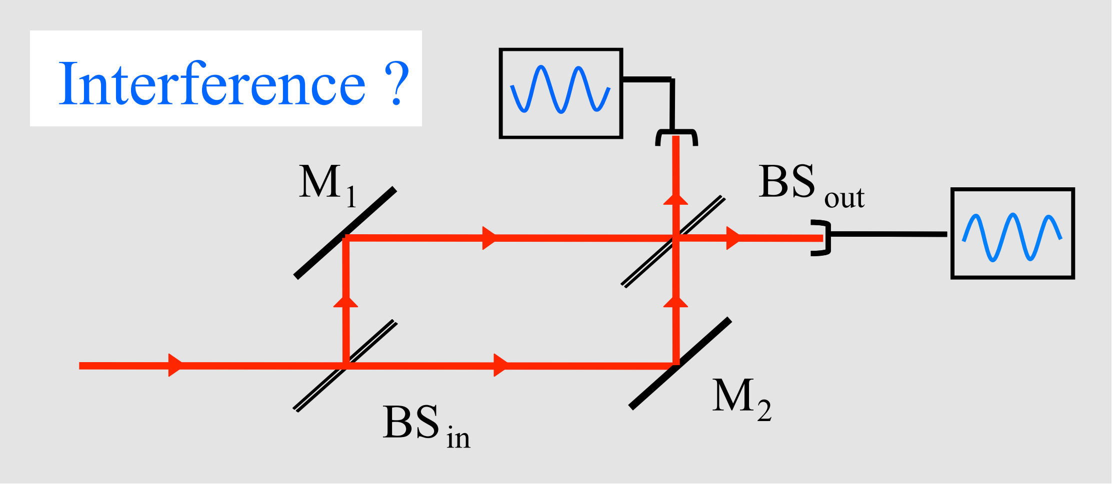
Wheeler's delayed choice experiment

The two experiments are incompatible. One must choose the question:

- Which way ?
- Interference ?

Can we ask the question after passage at the first beam splitter?



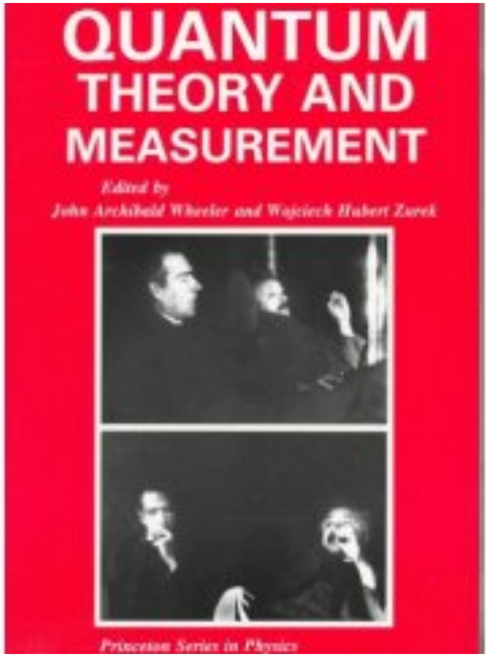


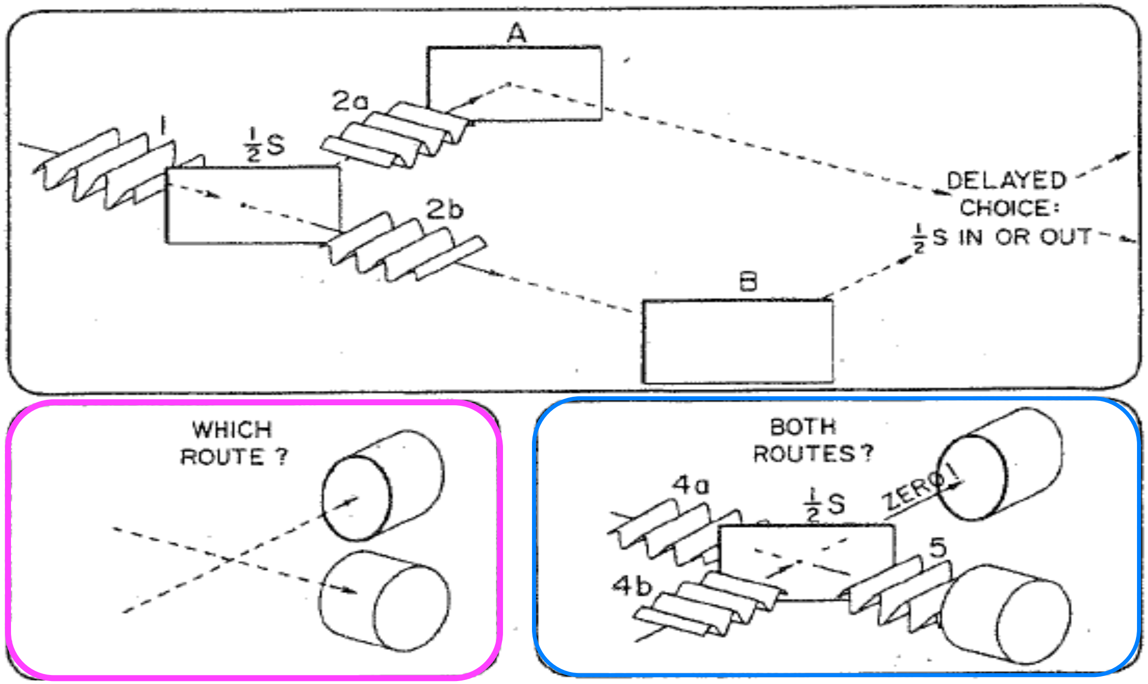
Slightly modify the "which way" experiment

One can choose the question by introducing or removing BS_{out}

One can make the choice after the photon passed BS_{in}

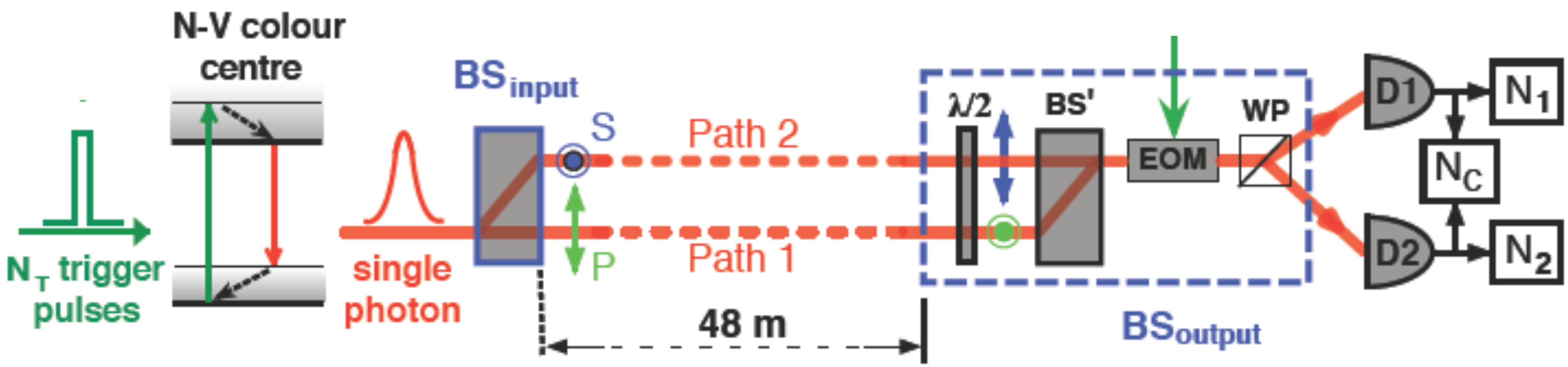
Wheeler's proposal (1978)





The choice of introducing or removing the second beamsplitter must be space like separated from the passage at first beamsplitter, so when the photon passes the first beam splitter it cannot know which measurement will be done.

Experimental realization (ENS Cachan / Institut d'Optique)



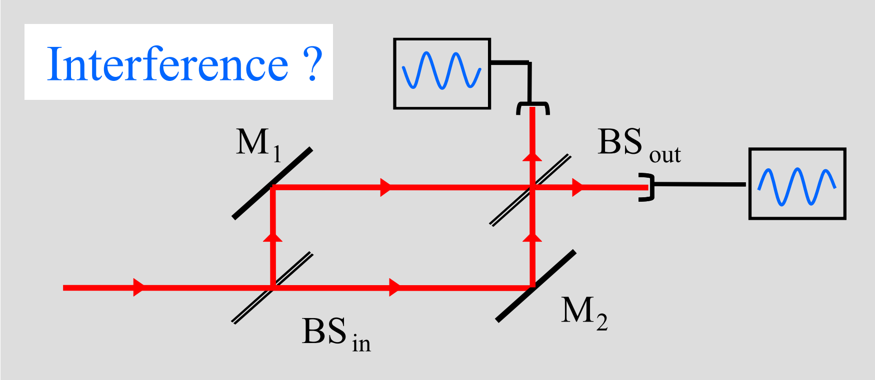
Electro Optical Modulator:

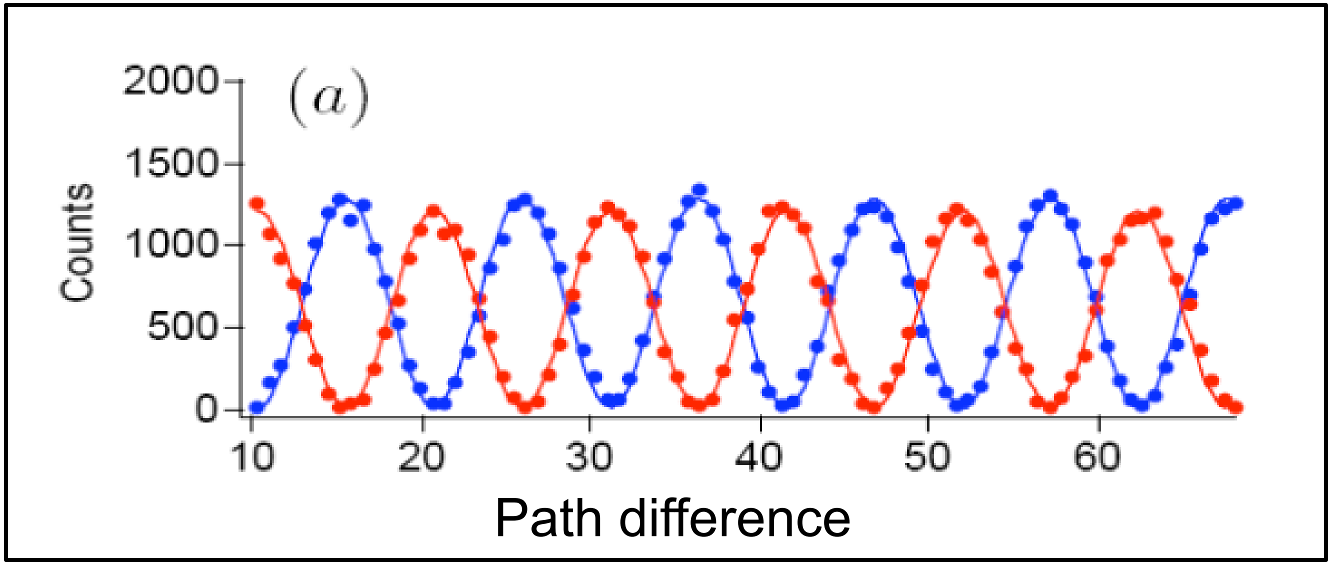
- no voltage = BS_{output} removed
- V_π = BS_{output} recombines the beams

The choice is made by a quantum random noise generator, after the photon passes the first beam splitter.

Delayed choice experiment: results

Observations with BS_{output} "inserted"



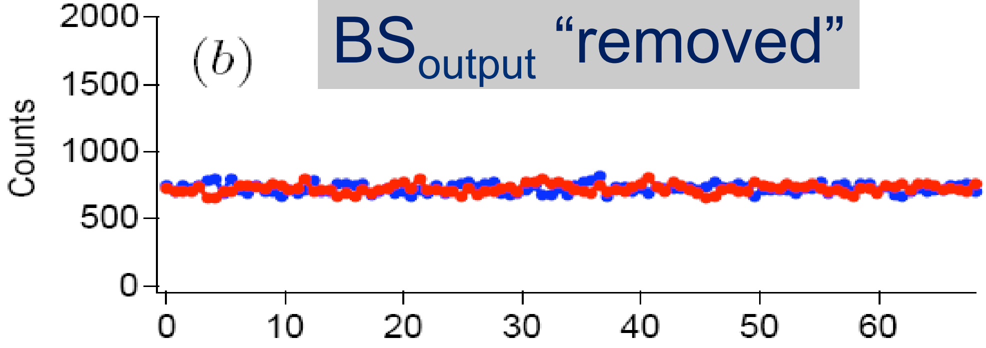


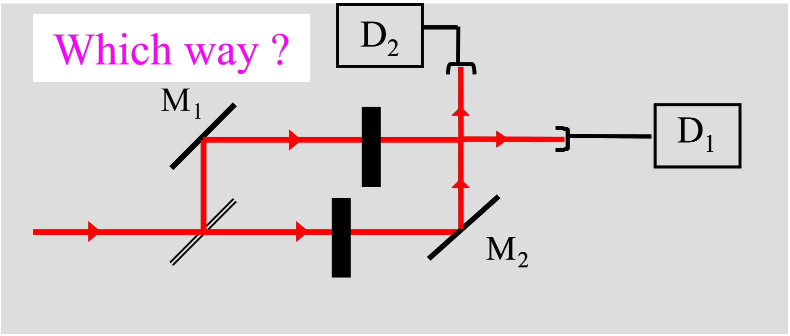
Fringe visibility: 94 %

Wave-like behaviour ⇒ both routes

Delayed choice experiment: results

Observations with BS$_{output}$ "removed"





No interference fringes

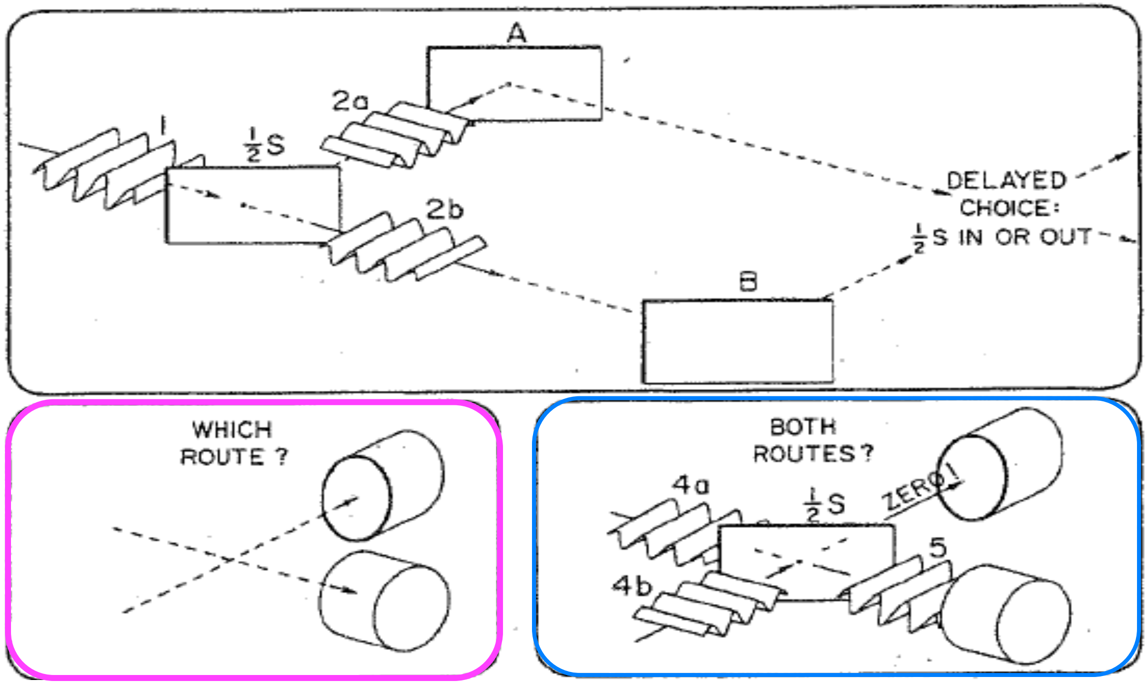
Alpha parameter = 0.12

"Which way" parameter = 99%

correlation between detection rate at either detector and blocking of one path or the other

The photon travels one route or the other… and we can tell which one.

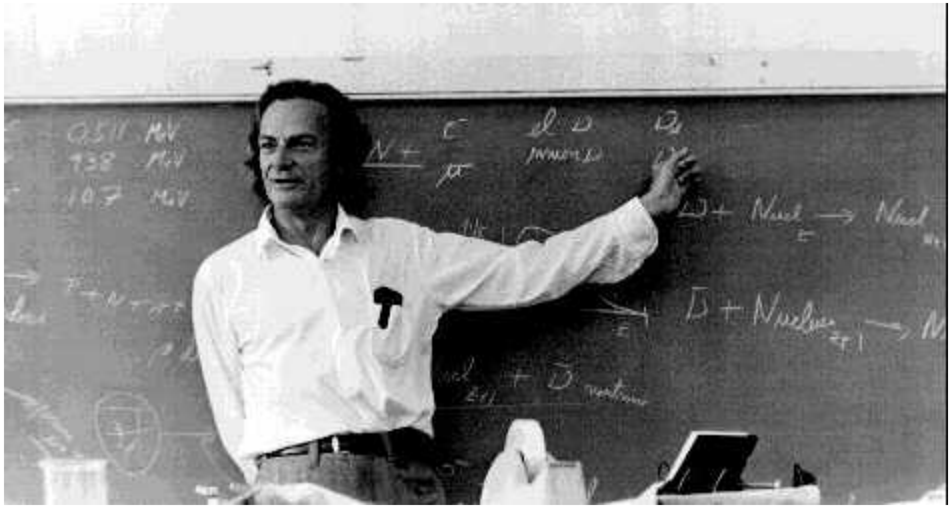
Delayed choice experiment: conclusion

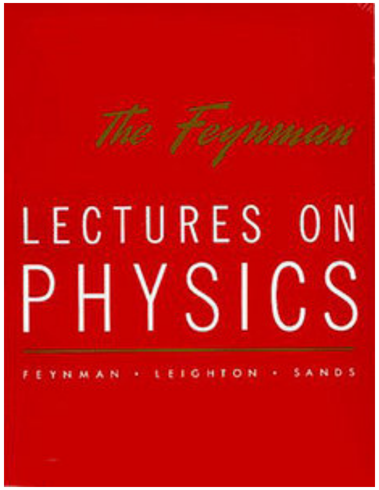


The photon travels one way or both routes according to the setting when it arrives at the position of the output beamsplitter.

"Thus one decides the photon shall have come by one route or by both routes after it has already done its travel" J. A. Wheeler

Wave particle duality: one of the "great mysteries" of quantum mechanics





In this chapter we shall tackle immediately the basic element of the mysterious behavior in its most strange form. We choose to examine a phenomenon which is impossible, *absolutely* impossible, to explain in any classical way, and which has in it the heart of quantum mechanics. In reality it contains the only mystery*.Vol. 3, chapter 18

* Entanglement the other great mystery. Int. Journ. Th. Phys.21, 467 (1982): founding paper on quantum computing

Wave particle duality: one of the "great mysteries" of quantum mechanics

Experimental facts force us to accept it. Impossible to reconcile with consistent images coming from our macroscopic world. To comfort ourselves:

- Quantum optics formalism gives a coherent account of it (one has not to choose one image or the other).
- Bohr's complementarity allows one to avoid too strong inconsistencies but...
- The delayed choice experiment shows that complementarity should not be interpreted in a too naïve way.

Wave particle duality: one of the "great mysteries" of quantum mechanics

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- The delayed choice experiment shows that complementarity should not be interpreted in a too naïve way.

Questioning the foundations of quantum mechanics is not only an academic issue. Clarifying the concept of single photon has led to applications.

From Einstein to Wheeler: wave-particle duality for a single photon

1. Light: wave or particle?

   Newton, Hughens, Young, Fresnel, Maxwell, Einstein…: both

2. Single photon experiments

   Quantum weirdness brought to light

3. Wheeler's delayed choice experiment

   Yet more quantum weirdness

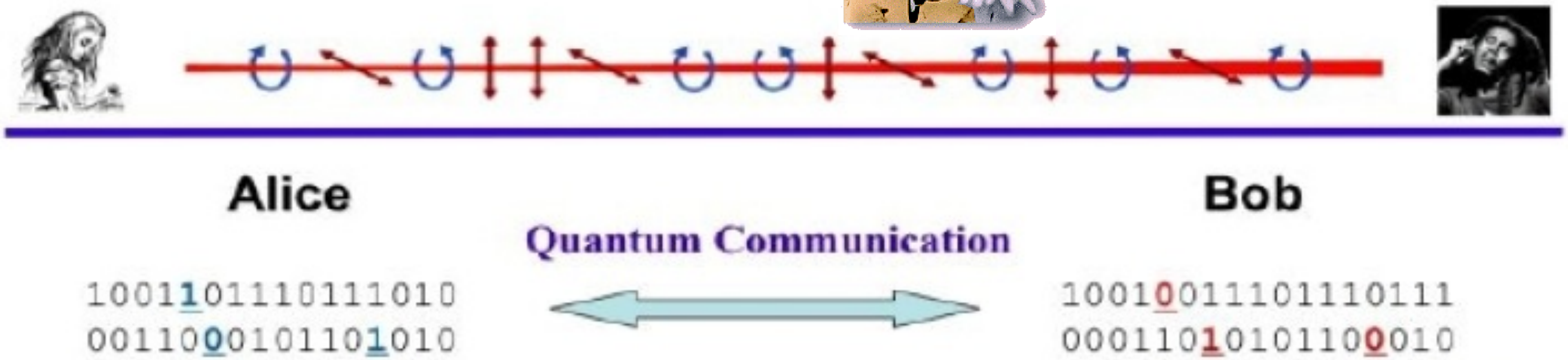
4. From fundamental tests to applications

   Quantum information

Gilles Brassard Charles Bennet

Quantum cryptography with single photons (BB84)

Eve (eavesdropper)

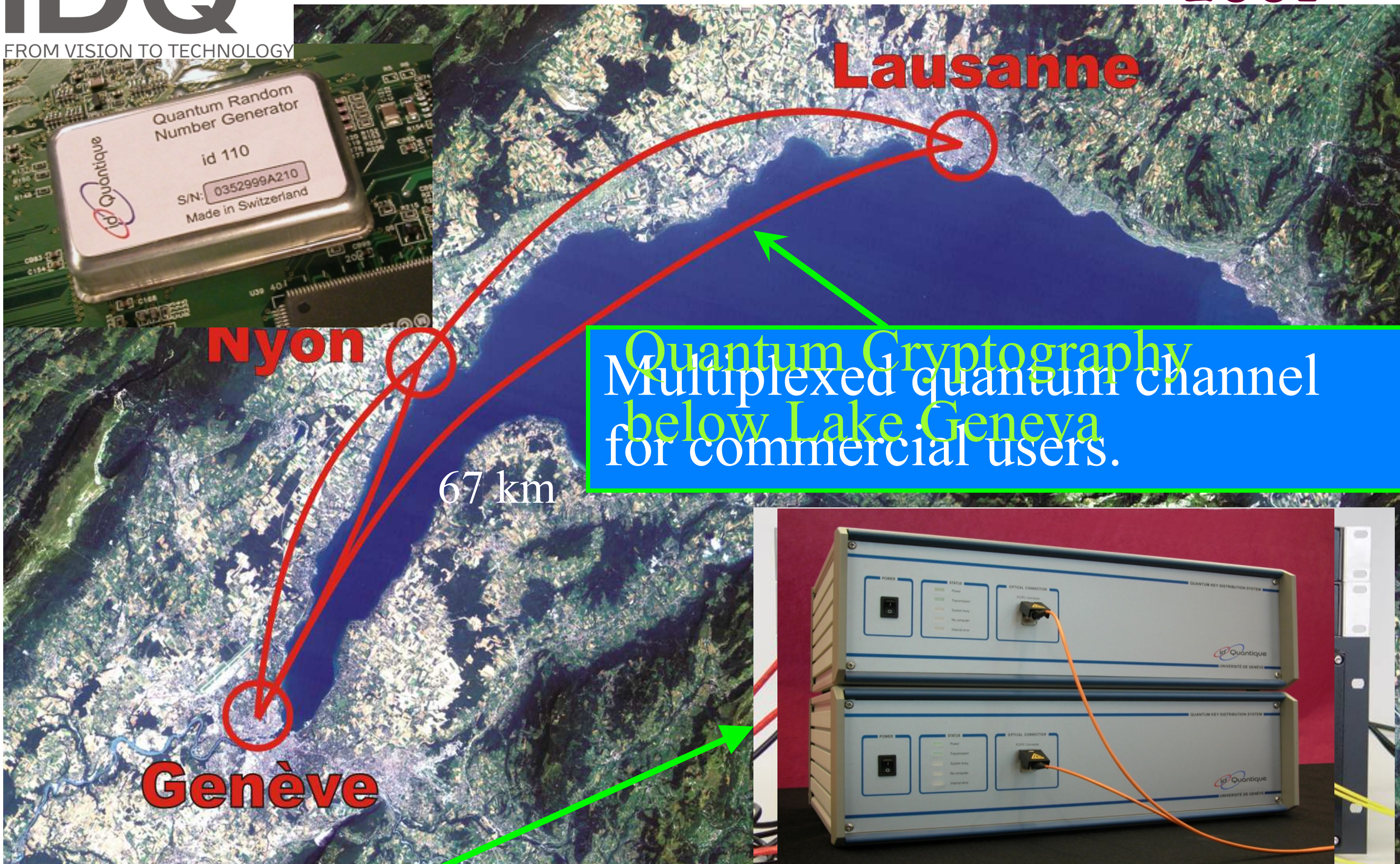


Quantum Key Distribution: produce two identical copies of a random sequence of 0 and 1: security mathematically proven (R. Shannon)

- quantum laws allows one to be sure that there is no eavesdropper obtaining a copy of the key remaining unnoticed
- One cannot look at a single photon without leaving a foot print:

FROM VISION TO TECHNOLOGY

Spin-off, University of Geneva 2001



Quantum Cryptography below Lake Geneva

Multiplexed quantum channel for commercial users.

Used daily by some commercial customers

From Einstein to Wheeler: wave-particle duality for a single photon

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One of the great quantum mysteries experimentally demonstrated

Asking fundamental questions may lead to applications

Delayed choice experiment: the family

Frederic
Groshans

François
Treussart

E
Wu

Jean-François
Roch

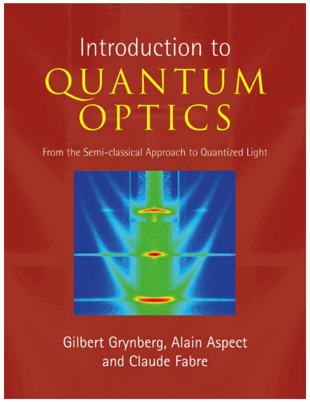
Vincent
Jacques

and the
of that

god fathers
experiment

More material about this talk

- https://www.coursera.org/learn/quantum-optics-single-photon
- Single interference fringes movie
- Excerpts from « Introduction to quantum optics »
- Link to more material at ENS Cachan
- Link to the « Histoire d'un photon » (with English subtitles) by Anne Papillault and Jean-François Dars

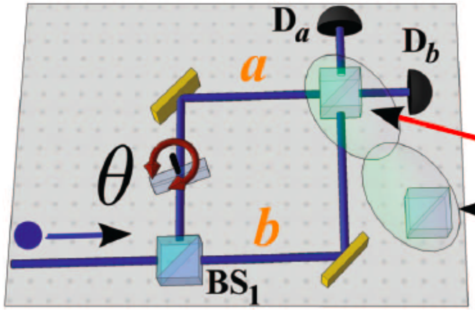


available at http://www.lcf.institutoptique.fr/Alain-Aspect-homepage

Recent delayed choice experiments

Entanglement-Enabled Delayed-Choice Experiment

Florian Kaiser,[1] Thomas Coudreau,[2] Pérola Milman,[2,3] Daniel B. Ostrowsky,[1] Sébastien Tanzilli[1]*



A Quantum Delayed-Choice Experiment

Alberto Peruzzo,[1]* Peter Shadbolt,[1]* Nicolas Brunner,[2]† Sandu Popescu,[2] Jeremy L. O'Brien[1]‡

SCIENCE VOL 338 2 NOVEMBER 2012

References

Video of the single photon fringes, and some supplementary material, accessible at http://www.physique.ens-cachan.fr/old/franges_photon/index.htm

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V.Jacques et al., SCIENCE 315 966 (2007): *Experimental realization of Wheeler's delayed-choice gedanken experiment*

Grangier p., Roger G., Aspect A., Europhys. Lett., 1 (1986) p.173-179: *"Experimental evidence for a photon anticorrelation effect on a beam splitter: a new light on single-photon interferences“*

A related paper:

Grangier P., Aspect A., Vigue J., Phys. Rev. Lett., 54 (1985) p.418: "*Quantum interference effect for two atoms radiating a single photon*”

General references on single photons

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P. Grangier and I. Abram, Phys. World, Feb. 2003

T. Legero, T. Wilk, A. Kuhn, and G. Rempe, in Advances in atomic molecular, and optical physics, vol 53, Vol. 53, 2006, p. 253.