Wave particle duality for a single photon: from Einstein licht quanten to Wheeler's delayed choice experiment

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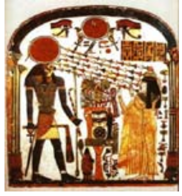
1

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 "riddles on water") Huyghens

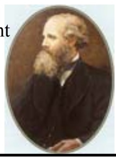
Newton (Opticks, 1702): particles (of various colours)

2

XIXth cent. The triumph of waves

Young, Fresnel (1822): interference, diffraction, polarisation: light is a transverse wave

Maxwell (1870): light is an electro-magnetic wave



1900: "Physics is completed" (Lord Kelvin) … except for two details!??

3

Early XXth: Photons (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?

4

Wave particle duality

Einstein 1909

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

Blackbody 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)

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

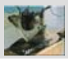
Easy to say the words, but difficult to represent by images

5

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
  - •Stability of atoms, molecules, solids
  - •Electrical, mechanical, thermal properties
  - •Spectroscopic properties
- Understanding "exotic properties"
  - •Superfluidity, supraconductivity, BEC
- Inventing new devices
  - •Laser, transistor

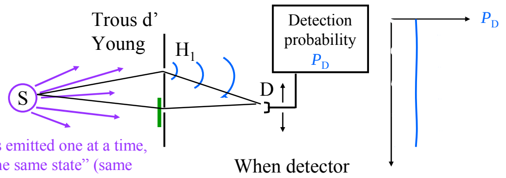


Quantum mechanics applied to large ensembles

How does it work for a single particle? See textbooks (*e.g.* Feynman)

6

Wave particle duality in textbooks
wave-like behaviour for particles



Particles emitted one at a time, all "in the same state" (same origin, direction distribution, energy)

When detector D moves, P_D is modulated

When a hole is closed no modulation (P_D constant)

Interpretation: each particle is described by a wave passing through both holes and recombining on the detector.

P_D depends on the path difference $\Delta = SH_1D - SH_2D$

Wave-like behavior with faint light?

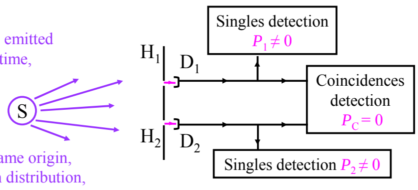
Taylor	1909	Diffraction	Photographic plate	Oui
Dempster & Batho	1927	Grating, Fabry-Perot	Photographic plate	Oui
Janossy and Naray	1957	Michelson interferom.	Photomultiplier	Oui
Griffiths	1963	Young slits	Intensifier	Oui
Dontsov & Baz	1967	Fabry-Perot	Intensifier	NON
Scarl et al.	1968	Young slits	Photomultiplier	Oui
Reynolds et al.	1969	Fabry-Perot	Intensifier	Oui
Bozec, Imbert et al.	1969	Fabry-Perot	Photographic plate	Oui
Grishaev et al.	1971	Jamin interferometer	Intensifier	Oui
Zajonc et al.	1984	Fiber interferometer, delayed choice	Photomultiplier	Oui
Alley et al.	1985	Fiber interferometer, delayed choice	Photomultiplier	Oui

Average distance between photons large compared to interferometer size

Single particle interference?

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

Particles emitted one at a time, all "in the same state" (same origin, direction distribution, energy)

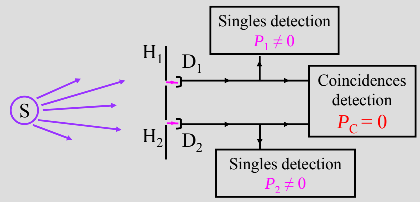


D_1 et D_2 observe random pulses, with a constant mean rate, but no coincidence ($P_C = 0$): anticorrélation

$P_C = 0$: a single particle passes either through H_1, or through H_2, not through both paths simultaneously. A single particle cannot be split.

Opposite behavior predicted for a wave: $P_C \neq 0$

The which path GedankenExperiment



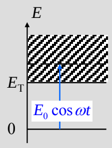
Not realized before 1985

- Particle nature considered "obvious" for electrons, neutrons, atoms, molecules: only wave-like effects searched
- Case of faint light: particle like behaviour considered "obvious" when the average distance between photons is large : only wave-like effects searched with very attenuated light

The particle-like character of faint light is not proved by photoelectric effect

Photoelectric effect fully interpretable by the semi-classical model of photo-ionization (Lamb and Scully, 1964)

- Quantized detector with a ground state and a continuum of excited states (atom, molecule, metal …)
- Light : classical electromagnetic field
- Fermi golden rule: rate of photo ionization proportional to density of final states



Remark: in 1905 (eight years before Bohr's atom) no quantum model, neither for light nor for matter: photoelectric effect impossible to understand in classical physics. Einstein chose to quantize light. He could have chosen to quantize matter.

According to modern quantum optics faint light is not made of single particles

Attenuated light described as a Glauber quasi-classical state, which has the same behavior as a classical electromagnetic wave.

If one insists for speaking of particles: in any interval of time, or space volume, probabilistic distribution of particles

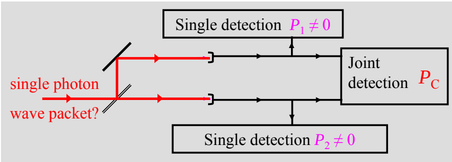
$P(1)$ small but $P(2) \sim P(1)^2$

Probability to have two particles never zero. No anticorrelation expected between two detectors : $P_C \neq 0$

Are there means to produce single photon states of light?
Can we demonstrate experimentally single particle behavior?

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

(AA, Philippe Grangier, 1985)



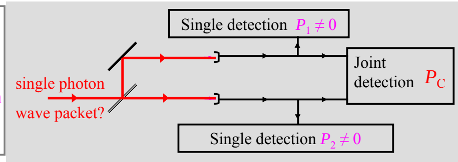
Single particle: one expects $P_c = 0$

13

Wave-like behaviour at a beam splitter

(AA, Philippe Grangier, 1985)

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 $P_c = \eta^2 RT \overline{I^2}$

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

but $\overline{I^2} \geq (\overline{I})^2$

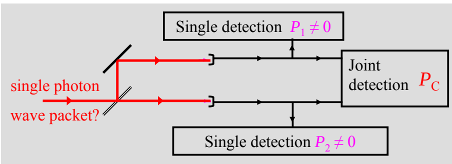
for a wave $\alpha = \frac{P_C}{P_1 P_2} \geq 1$

14

A quantitative criterion to discriminate wave-like *vs.* particle-like behaviour

Particle: one expects $P_c = 0$

Wave: one expects $P_c > P_1 P_2$



Criterion for a particle like behaviour: $\alpha = \frac{P_C}{P_1 P_2} < 1$

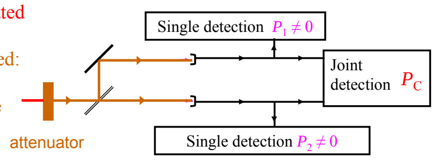
PG, AA, 1985

15

Faint light does not pass single particle test

(AA, Philippe Grangier, 1985)

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



Experimental result: $\alpha_{meas} = 1.07 \pm 0.08$ not single particle behaviour

In agreement with classical description of wave splitting.

Quantum optics: faint light described as a quasi classical "coherent" state. Number of photons is not a "good quantum number": Poisson distribution: $P(2) \sim P(1)^2 \neq 0$ just enough to explain coincidences

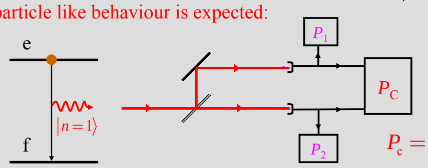
16

Single photon sources

Quantum optics allows us to design sources of single photons ($|n=1\rangle$) for which a particle like behaviour is expected:

Isolated excited atom

Emits one and only one photon



$P_c = 0$

$\Rightarrow \alpha < 1$

In classical light sources (thermal radiation, fluorescence lamp) many atoms simultaneously excited: Poisson distribution (laser also)

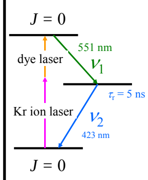
To obtain single photons effects, isolate a single atom emission:

- in space (Kimble, Dagenais, Mandel, antibunching)
- in time (J Clauser 1974, non classical effects in radiative cascade; AA, PG, heralded single photon, $\alpha < 1$)

17

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

Institut d'Optique



Assembly of atoms emitting 10^7 s^{-1} pairs of photons. 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) .

Experimental result:

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

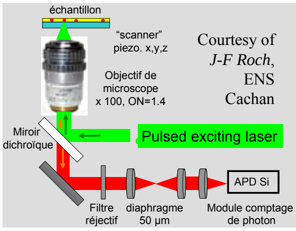
Clear anticorrelation ($\alpha < 1$)

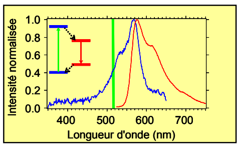
Particle-like behaviour

18

Modern sources: single photons emitters isolated in space and time

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





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

Experimental result

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

Clear anticorrelation ($\alpha < 1$)

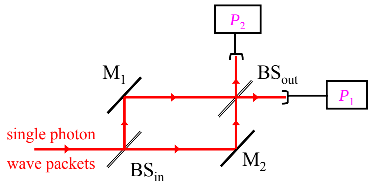
Particle-like behaviour

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

19

Single photon interference?

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

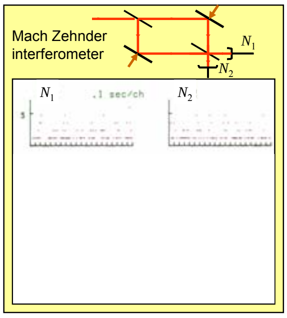


Do probabilities P_1 and P_2 vary (sinusoidally) when one varies the path difference?

20

Single photon interference

Interferometer with single photon source at input



Vary path difference and stay 0.1 second at each position

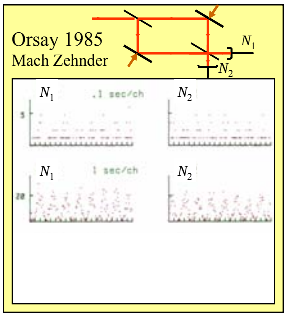
Not much to see!

Grangier, AA, 1985

21

Single photon interference

Interferometer with single photon source at input



Vary path difference and stay 1 second at each position

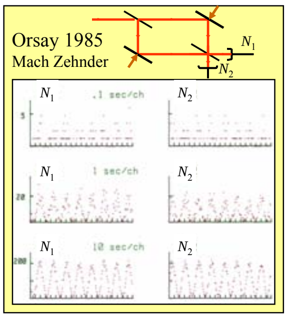
Clear modulation!

Grangier, AA, 1985

22

Single photon interference

Interferometer with single photon source at input



Vary path difference and stay 10 seconds at each position

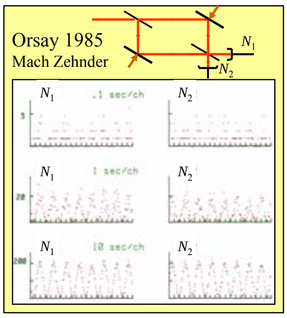
Sinusoidal variation!
Remarkable signal to noise ratio, visibility close to 1.

Unambiguous wave like behaviour

23

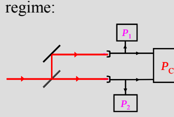
Single photon interference

Interferometer with single photon source at input



Vary path difference and stay 10 seconds at each position

Experiment done in the single photon regime:



$\alpha = \frac{P_C}{P_1 P_2} < 1$

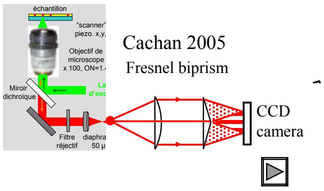
Sinusoidal variation!
Remarkable signal to noise ratio, visibility close to 1.

Unambiguous wave like behaviour in the single photon regime

24

Single photon interference

A more modern implementation (Cachan, 2005)



Cachan 2005
Fresnel biprism

Anticorrelation on detectors D1 and D2: $\alpha_{meas} = 0.132 \pm 0.001$

Observation in the overlap between two beams: interference fringes?

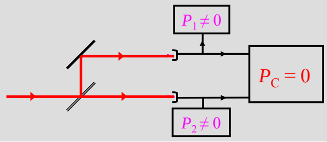
Evidence of single photon behaviour

Unambiguous wave like behaviour in the single photon regime

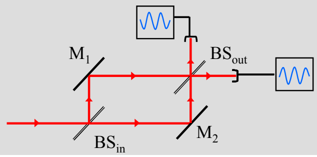
25

Wave particle duality for single particles

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



Second experiment
Wave like behaviour: goes through both paths (output depends on paths difference)



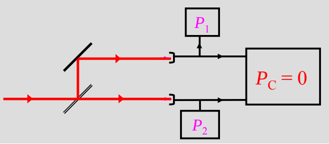
Same single photon wave packets, same beamsplitter, contradictory images

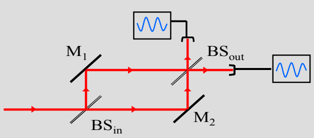
26

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





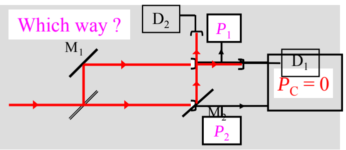
Could it be that the photon behaves according to the question?

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

27

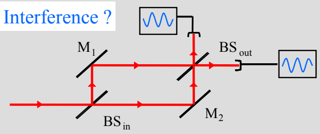
Wheeler's delayed choice experiment

The two experiments are incompatible. One must choose the question:
- Which way ?
- Interference ?



Slightly modify the "which way" experiment

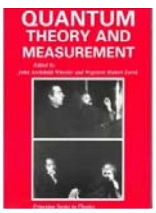
One can choose the question by introducing or removing BS_{out}

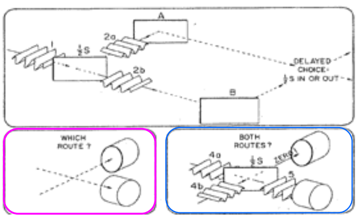


One can make the choice after the photon passed BS_{in}

28

Wheeler's proposal (1978)

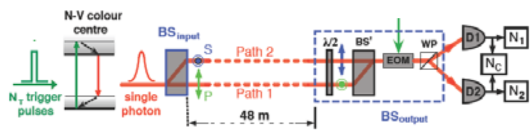




The choice of introducing or removing the second beamsplitter must be space like separated from the passage at first beamsplitter, so when the photon passes the first beam splitter it cannot know which measurement will be done.

29

Experimental realization (ENS Cachan)



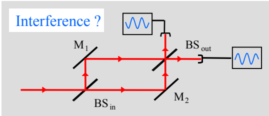
Electro Optical Modulator:
- no voltage = BS_{output} removed
- V_π = BS_{output} recombines the beams

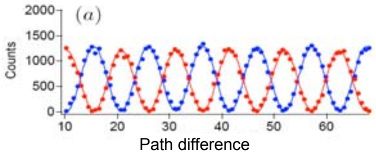
The choice is made by a quantum random noise generator, after the photon passes the first beam splitter.

30

Delayed choice experiment: results

BS_{output} "inserted"



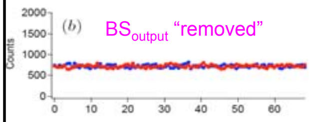


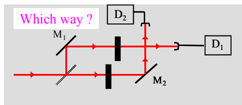
Fringe visibility: 94 %

Wave-like behaviour ⇒ both routes

31

Delayed choice experiment: results





No interference fringes

Alpha parameter = 0.12

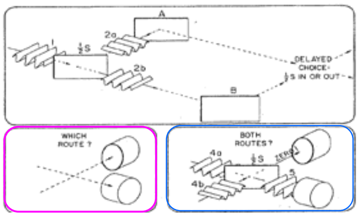
"Which way" parameter = 99%

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.

32

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.

The choice, made by a quantum random noise generator, is separated by a space-like interfal from passage at the first beam splitter.

"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

33

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

Experimental facts force us to accept it. Impossible to reconcile with 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.

Questioning the foundations of quantum mechanics is not only an academic issue. It has led to the development of quantum information, i.e. quantum cryptography and quantum computing.

34

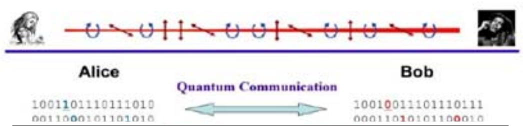
Quantum cryptography with single photons (BB84)

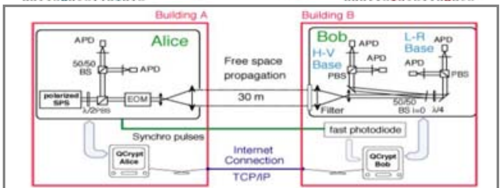
Quantum Key Distribution: produce two identical copies of a random sequence of 0 and 1, without an eaves dropper (Eve!) being able to obtain a copy of the key unnoticed

- perfect security mathematically proven (R. Shannon)
- quantum laws allows one to be sure that there is no eavesdropper looking at a single photon without leaving a trace.

35

Quantum cryptography with single photons (BB84)





http://www.iota.u-psud.fr/~grangier/Photon/QKD-ph-uniques.html

36

Cryptographie quantique: Schéma BB84 avec photon unique

Groupe d'Optique Quantique de l'Institut d'Optique (P. Grangier)

Laboratoire de photonique ENS Cachan (J F Roch)

37

Delayed choice experiment: the team

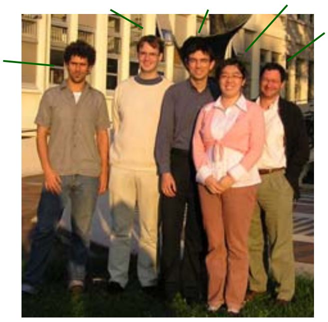
Frederic Groshans

François Treussart

E Wu

Jean-François Roch

Vincent Jacques



and the of that

god fathers experiment

38

Delayed choice experiment: one of the two big quantum mysteries (Feynman, 1960, 1982)

Single particle interference experiment (1 particle)

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.

EPR correlation (2 entangled particles)

I've entertained myself always by squeezing the difficulty of quantum mechanics into a smaller and smaller place, so as to get more and more worried about this particular item. It seems to be almost ridiculous that you can squeeze it to a numerical question that one thing is bigger than another. But there you are—it is bigger than any logical argument can produce, if

39

Delayed choice experiment: one of the two big quantum mysteries (Feynman, 1960, 1982)

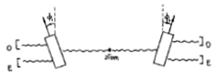
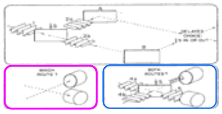


Fig. 4.



EPR correlation (2 entangled particles)

- No local realistic description (violation of Bell's inequalities)
- Bohm's hidden variables description is non-local

Wheeler's delayed choice experiment (1 particle)

- Local realistic description possible (Bohm's hidden variables)

Wave-particle duality (one particle) is not as big a mystery as entanglement (elementary many-body problem)

40

Delayed choice experiment: one of the two big quantum mysteries (Feynman, 1960, 1982)

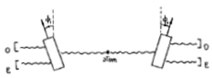
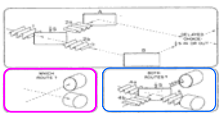


Fig. 4.



Wheeler's delayed choice experiment (1 particle)

EPR correlation (2 entangled particles)

Are they "only" academic (epistemological) questions?

Studies of these questions have led to the development of quantum information: quantum computing (based on entanglement) and quantum cryptography (based on single photons or entanglement)

41