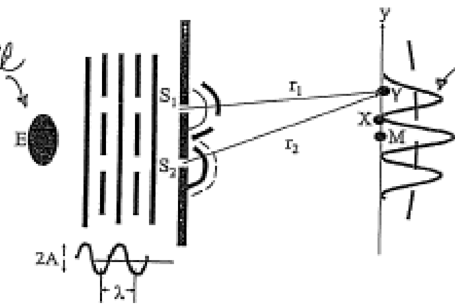
F. Light: Our guiding "light"

Young's Two-slit experiment (~1800)

one source



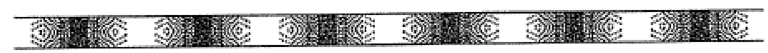
Slit 1 opens half the time

$I_{1+2} \neq (I_1 + I_2)$

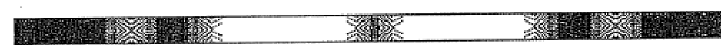
(intensity when slits 1 & 2 are open)

slit 2 opens half the time

Both slits are open

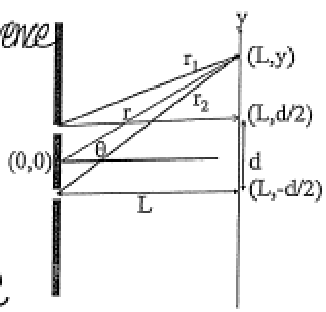


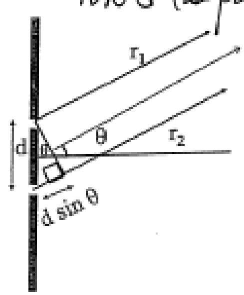
One slit opens for half the time and then the other



Explained by Wave theory (interference)

Path difference $r_2 - r_1$ leads to constructive/destructive interference





For d (separation between slits) ≪ r, see maxima at

$$d \sin\theta = n\lambda$$

n: integer; λ: wavelength

constructive interference

- Technique to find λ
- Don't need to know what is waving!

For EM Waves (~1860 Maxwell)

- What is waving is $\vec{E}$ field ($\vec{B}$-field) [positive → negative → positive → ...]
- It is Intensity that is observed on screen (always positive)
- Intensity[+] $\propto |\vec{E}|^2$
- Key Points:
  - A wave (Maxwell's) theory, with a Wave equation (EM waves), that could evaluate $|\vec{E}(\vec{r},t)|^2$ at positions $\vec{r}$ (e.g. points on screen) at time t that predicts (explains) the observed intensity pattern.

[So far so good!]

[+] Writing it as $|\vec{E}|^2$ is intentional, although one can work with E^2 for real fields in EM. In QM, wavefunctions Ψ are generally complex and we need to work with $|\Psi|^2$.

The Stage is set: Planck (1900), Einstein (1905), Compton (1919)

Particle (Photon) Nature of Light

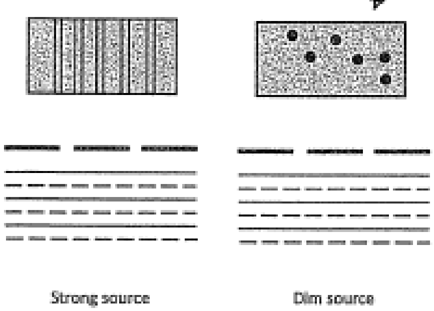
How does the photon (particle nature of light) behave in two-slit experiments?

← Key Question (Must know the phenomena clearly)

How to do it?

- "Dim the light!" [very weak intensity, even only one photon in apparatus at a time]

Standard situation →   dim source

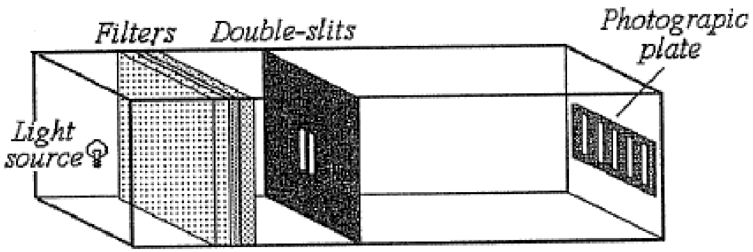


Schematic

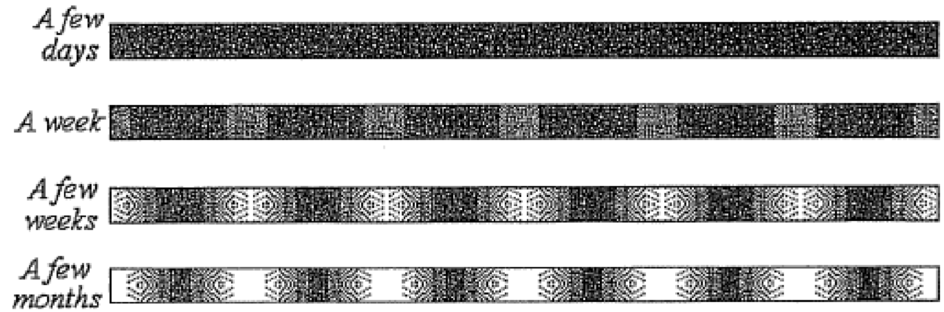
Key phenomena

- One photon in, one photon arrives and detected at a location on screen (i.e. as particle)
- Intensity pattern emerges after sending in many photons one at a time (wave property)
- Modern time: photon detections by electronic devices

- 1909: Earliest attempt by Sir Geoffrey I. Taylor



Filters to dim light
Modern expt's use electronic devices for photon detection



Interference pattern emerges after many photons detected on screen (to the extreme of one at a time)

- The same type of experiments has been refined and done over 100 years!
- All results pointed to the same (unusual) nature of light
- Below is a summary of observations and their implications.

100 years later

The wave-particle duality of light: A demonstration experiment

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[Putting many single-photon events together => interference pattern emerges]

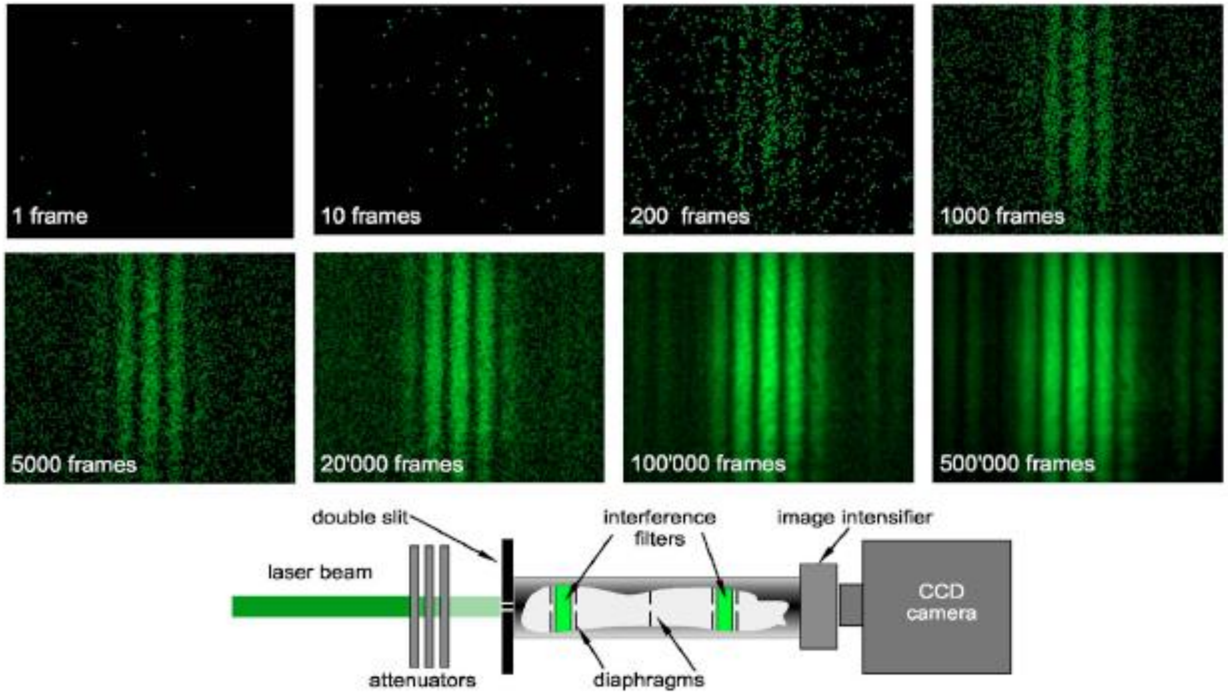

Fig. 1. (Color online) From particles to waves: Detection of light diffracted from a double slit on a photon by photon basis using a single-photon imaging CCD camera. Although single frames show an apparently random distribution of photon impact points, their integration reveals the classical fringe pattern.

Link to paper: http://aapt.scitation.org/doi/abs/10.1119/1.2815364

Key Phenomena and Implications [2-slit exp't with dim source]

Photon is detected at a location one at a time

- Photon is detected at a location one at a time
  - Evidence: detection devices on screen but only one detected photon
  - By product, can also prove $E = hf$ and $p = \frac{h}{\lambda}$
  - Light arrives at screen as particles (one at a time)

Cannot predict where a photon lands

- Big moment in physics: must give up determinism as enjoyed by classical physics
- Particles of light are no ordinary particles
  No trajectory can (to) be predicted

Two open slits required for seeing interference pattern (even one photon in apparatus at a time)

- Close one slit : ruin pattern (thus, wave nature)
- Particle (photon) must have gone through one slit ?
  - Be careful! This is classical physics thinking!
  - Don't know! [this is an honest answer]
  - If we know (spy on which slit photon goes through), the pattern is ruined (tested exp'tally)
  - Many authors described this as:
    "photon interferes with itself"
    "photon knows there are two slits"

Particles of light are ***no ordinary particles***

Probabilistic role of Wave Theory

- No more determinism
- Re-interpret what wave theory <u>can do</u>
  - Wave theory that gives $|\vec{E}(\vec{r},t)|^2$
  - $|\vec{E}(\vec{r},t)|^2 \propto$ <u>Probability</u> of photon to be detected at position $\vec{r}$ at time t
- What wave theory <u>cannot do</u>
  - predict outcome of one run (one photon)
- Probabilistic role
  - can only predict statistically the results after a large number of runs of the same expt (many photons)

Deeper Implications

- In doing/thinking QM, be <u>honest</u>!
  - only say what is actually <u>measured</u> ("reality")
  - <u>don't</u> extend your thought to what is not measured
  - E.g.: "photon is a particle so it must follow a trajectory that passes through one slit"
- Now photon is detected at $\vec{r}$, was it somewhere near (just in front of) $\vec{r}$ just a while ago?
  - No! We don't know!
  - All we know is $|\vec{E}(\vec{r}, t-\delta t)|^2$ (probability!) — δt: "a while ago"
  - Only when we measure, photon shows up as a particle at where it is detected

Let's recap the key implications

Photon is detected at a location one at a time

Can't predict where a photon lands

Two open slits required for seeing interference pattern (even one photon in apparatus at a time)

Particles of light are ***no ordinary particles***

Probabilistic role of Wave Theory

Measurements play a special role

All these are extremely important concepts

Because they also apply to electrons in two-slit experiments

matter (not light)

and inform us what quantum mechanics [wave theory of particles] can do and cannot do!

Remarks:

- These ideas about the physics of light at the microscopic level (photons) are what **experiments** over many years showed us. The quantum mechanics developed based on these ideas has been extremely successful (so far).
- Of course, these experiments can only be carried out using available technologies of the time. [Think: We didn't see quantum effects prior to 1850 because experiments at the time did not probe into the necessary scales.] Will 21st century experiments change our view of photons? Let's wait and see. It is exactly how science develops and what science is about!
- Pictures in this section are taken from: *Shankar, Fundamentals of Physics Vol.II* and *Pfeffer and Nir, Modern Physics: An Introductory Text.*