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Wave-particle duality

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Research Area

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We are investigating the dual nature of electrons as both particles and waves, with a focus on the experimental evidence supporting wave-particle duality in different context (light and electrons) and its implications for quantum mechanics and the nature of reality.

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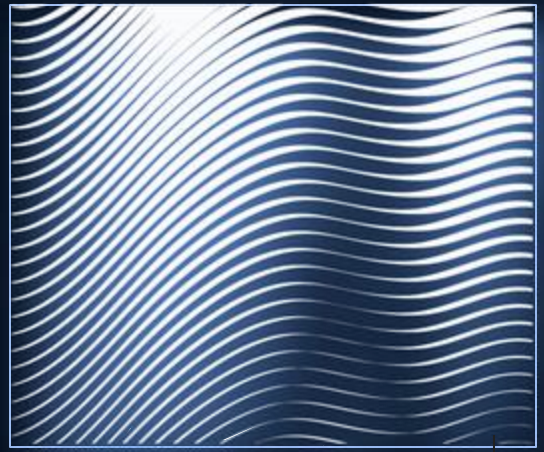

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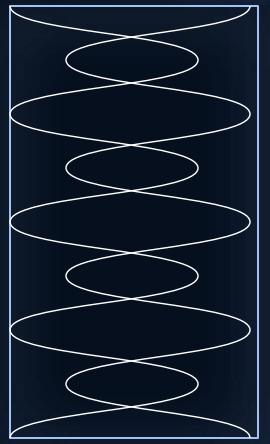
01- Nature of waves and particles

What are they

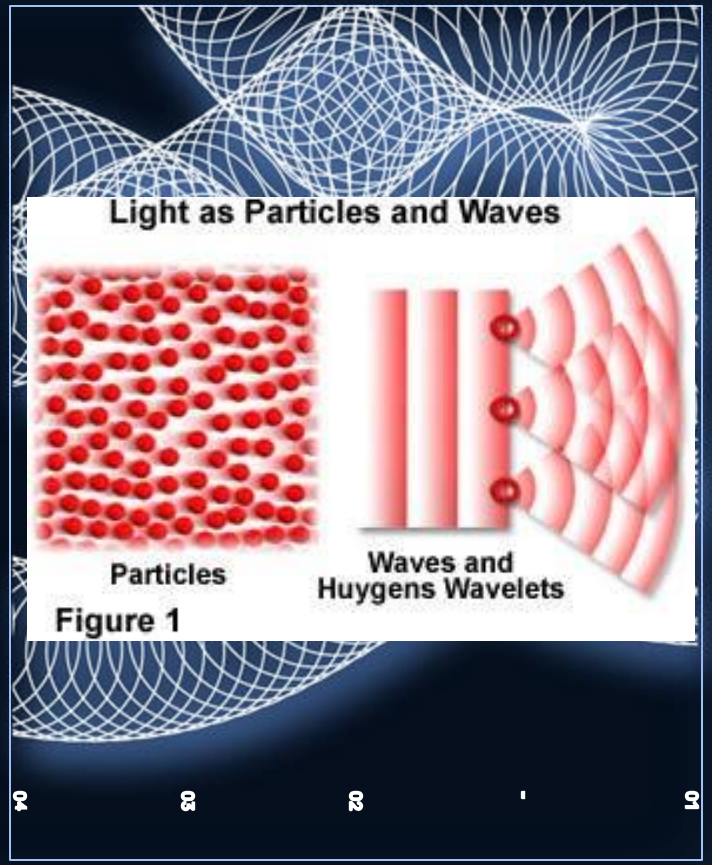


Physics definition of a wave

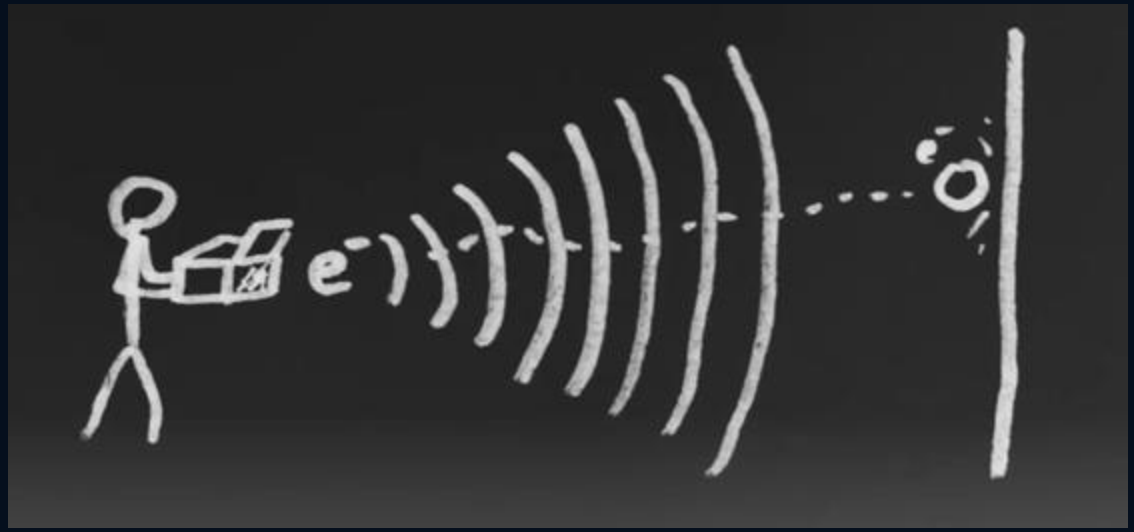
Spread-out disturbances
They have properties like frequency, wavelength, and interference.

Physics definition of a particle

A small localized object to which physical properties such as mass, charge, momentum, and energy can be assigned.



How can we visualise wave particle duality of electrons?



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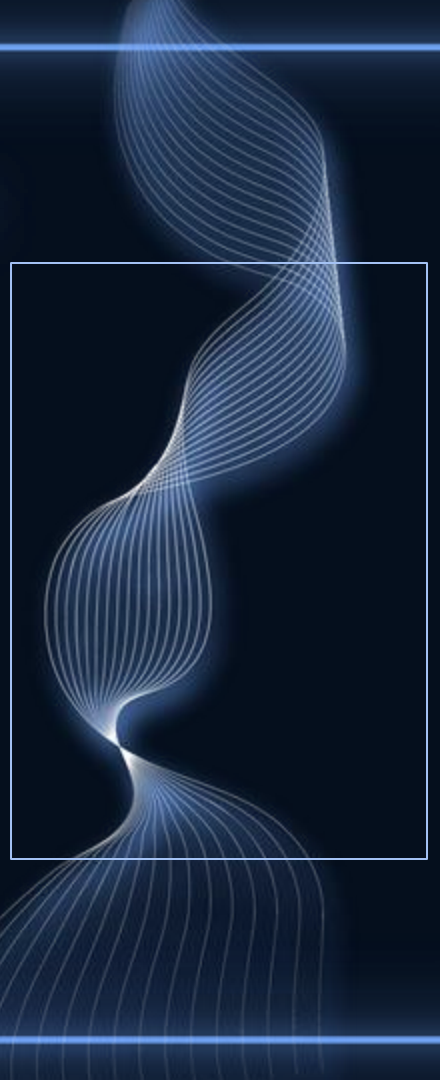
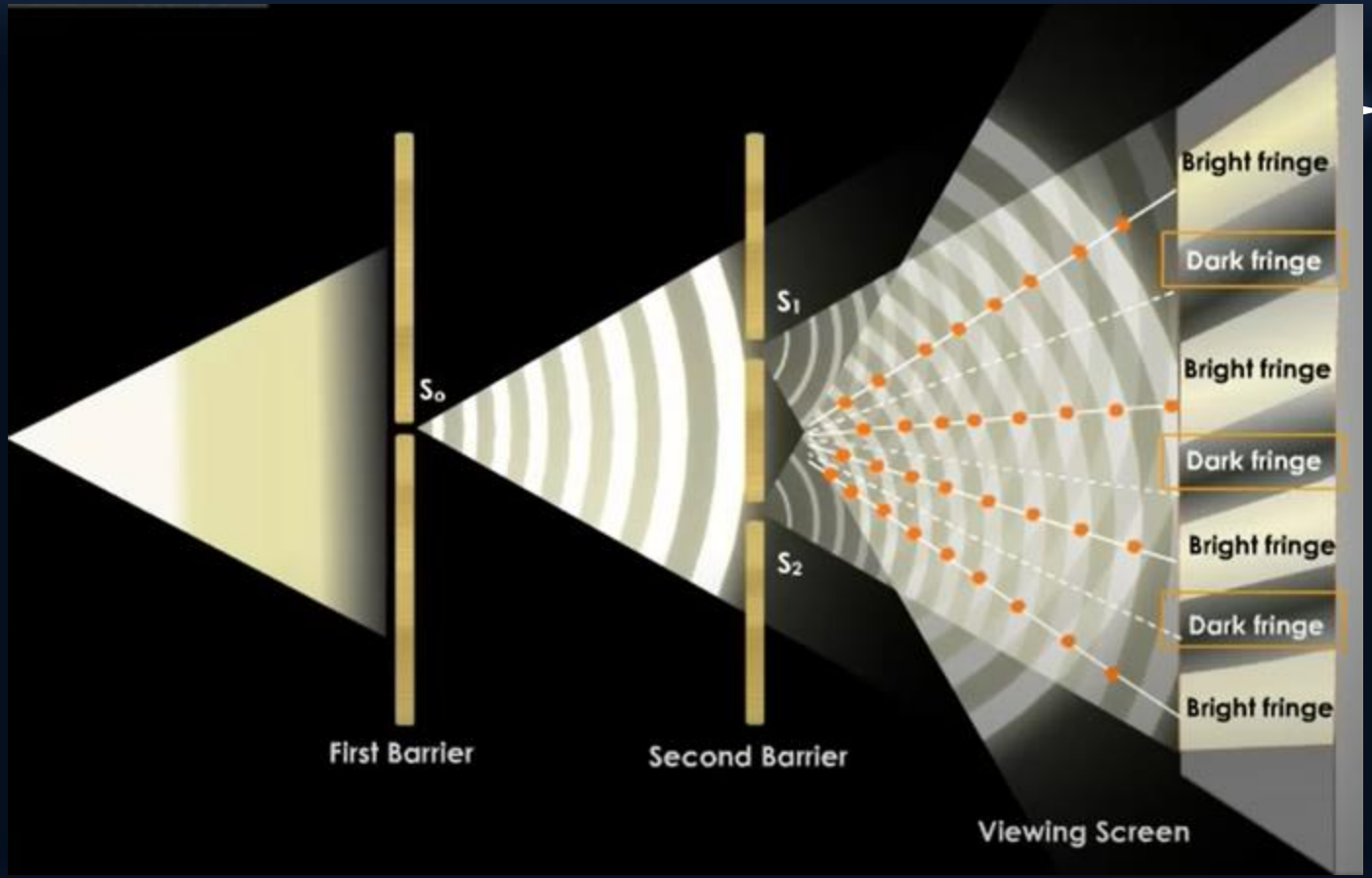
02- History



Pre- 20th Century

- Debate about whether light was a particle or a wave
- Thomas Young (1801) demonstrated the wave nature of light through the what is known now as the double-slit experiment:


Bright fringe
Dark fringe
Bright fringe
Dark fringe
Bright fringe
Dark fringe
Bright fringe
S_1
S_0
S_2
First Barrier
Second Barrier
Viewing Screen

1905

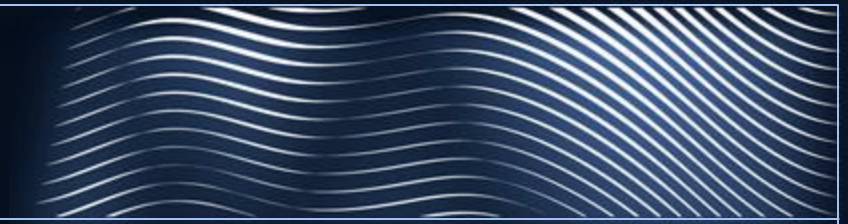
Experiment: light was shined onto metal surface → electrons absorb energy and get emitted

Initial understanding:

- Light as a wave
- Brighter light -> more energetic electrons
- The rate of electron emission should increase as the light frequency is increased.

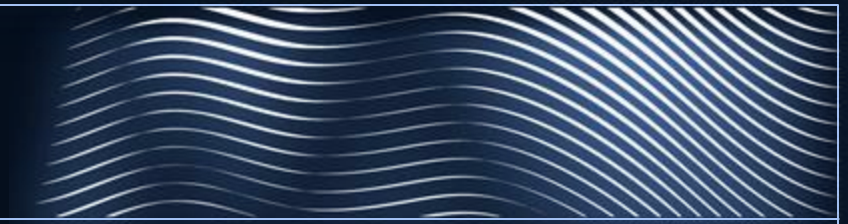
Photoelectric Effect (Einsten) showed ***the opposite***:

- If the light's frequency is below a threshold → **no electrons are emitted**, no matter how bright the light.
- Above threshold → electrons emitted **instantly**, even with very weak light.
- Higher intensity just produced more electrons, not more energetic ones.



The **photoelectric effect** showed that light's energy comes in **discrete packets (photons)** rather than being spread smoothly like a wave. Electrons are knocked out by **individual photon impacts**, not by gradually absorbing wave energy.

1924



de Broglie extended the idea: matter (like electrons, protons, and even atoms) previously thought to be only particles, can behave like waves.

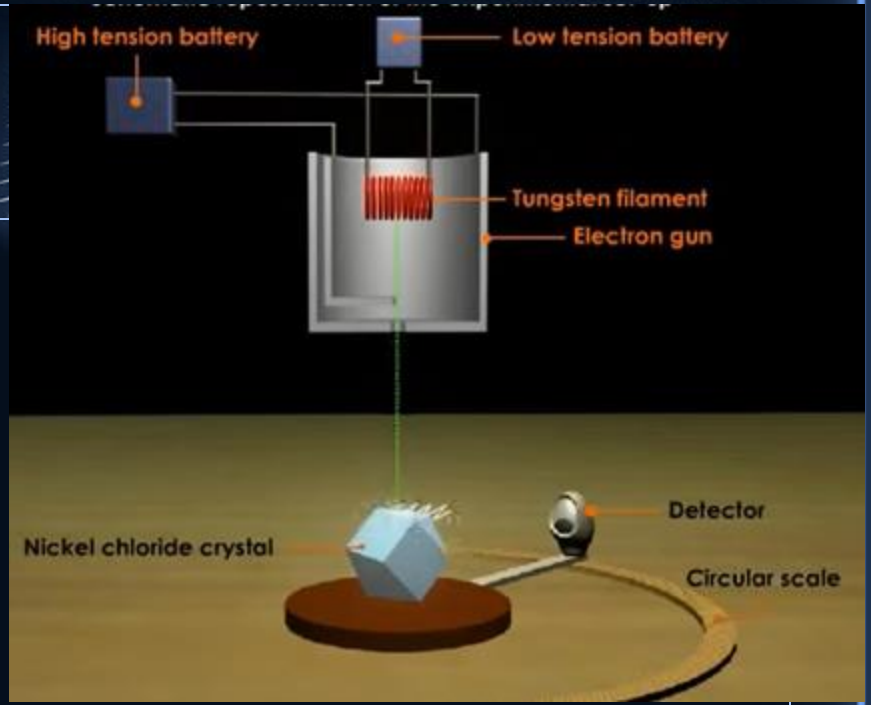
Formula $\lambda = h\ p$

(where λ = wavelength of the particle, h = Planck's constant, p = momentum of the particle)

1927

First experiment: Davisson–Germer Experiment (Clinton Davisson and Lester Germer at Bell Labs)

- Fired electrons at a nickel crystal
- Found electrons diffracted just like as they produced interference patterns (which is phenomenon only confined to waves !)



Proof of wave - particle duality of electrons

1927

Experiment 2: George P. Thomson

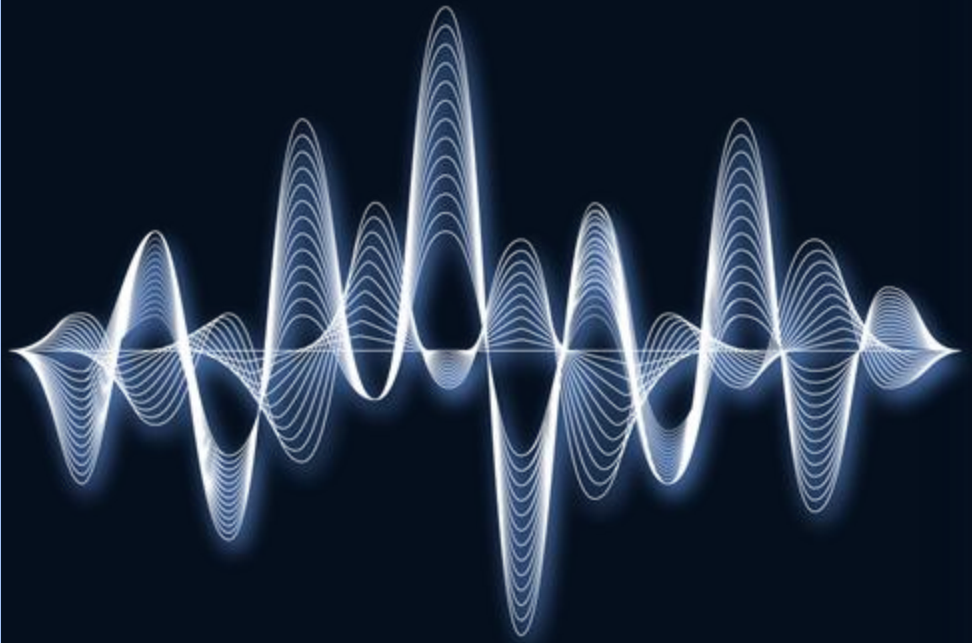
He fired a beam of high-energy **electrons** at a very **thin metal foil** (e.g., gold or aluminum).

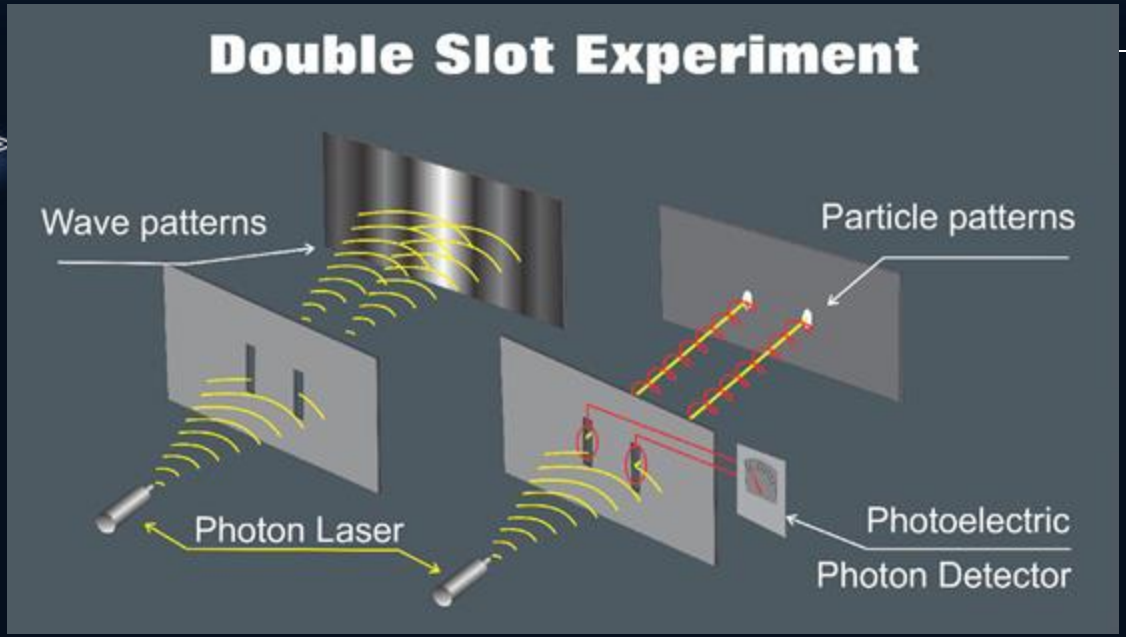
- If electrons were *only* particles, they should just pass through or scatter randomly, like bullets through paper.
- Instead, what he observed:
  On a screen placed behind the foil, the electrons produced a **diffraction pattern** (bright and dark rings), just like **X-rays** or light waves passing through a diffraction grating.

03

Double-Slit Experiment

Modern version used today





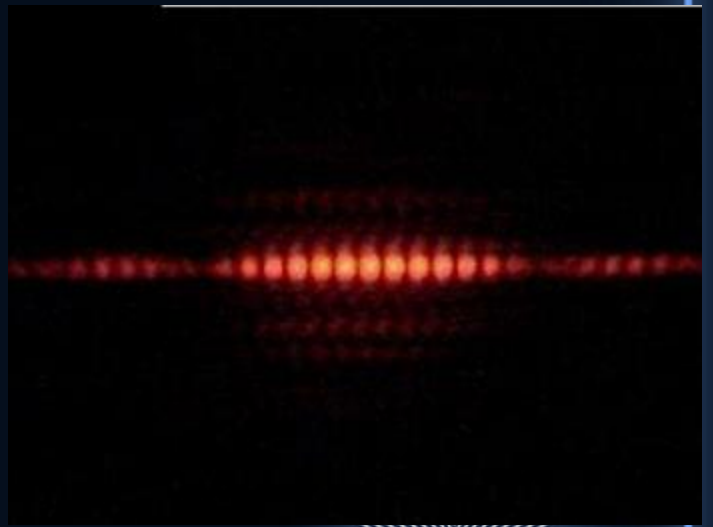
The double-slit experiment is carried out by directing a beam of particles or waves, such as light or electrons, through two narrow, parallel slits in a barrier onto a screen.

Observations

1. With Photons (Light)

- **Laser beam**: A very weak laser is often used
- **Two slits**: The photons pass through the slits.
- **Detection screen**: Even if photons are sent one by one, over time they form an **interference pattern** (bright and dark bands), as though each photon interfered with itself like a wave.

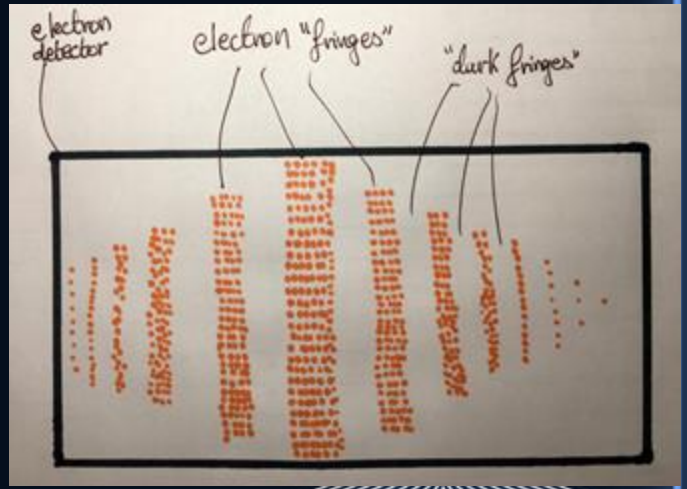
- **If detectors are placed at the slits** to check “which slit” each photon went through, the interference pattern disappears. Instead, you just see two bands (particle behavior).

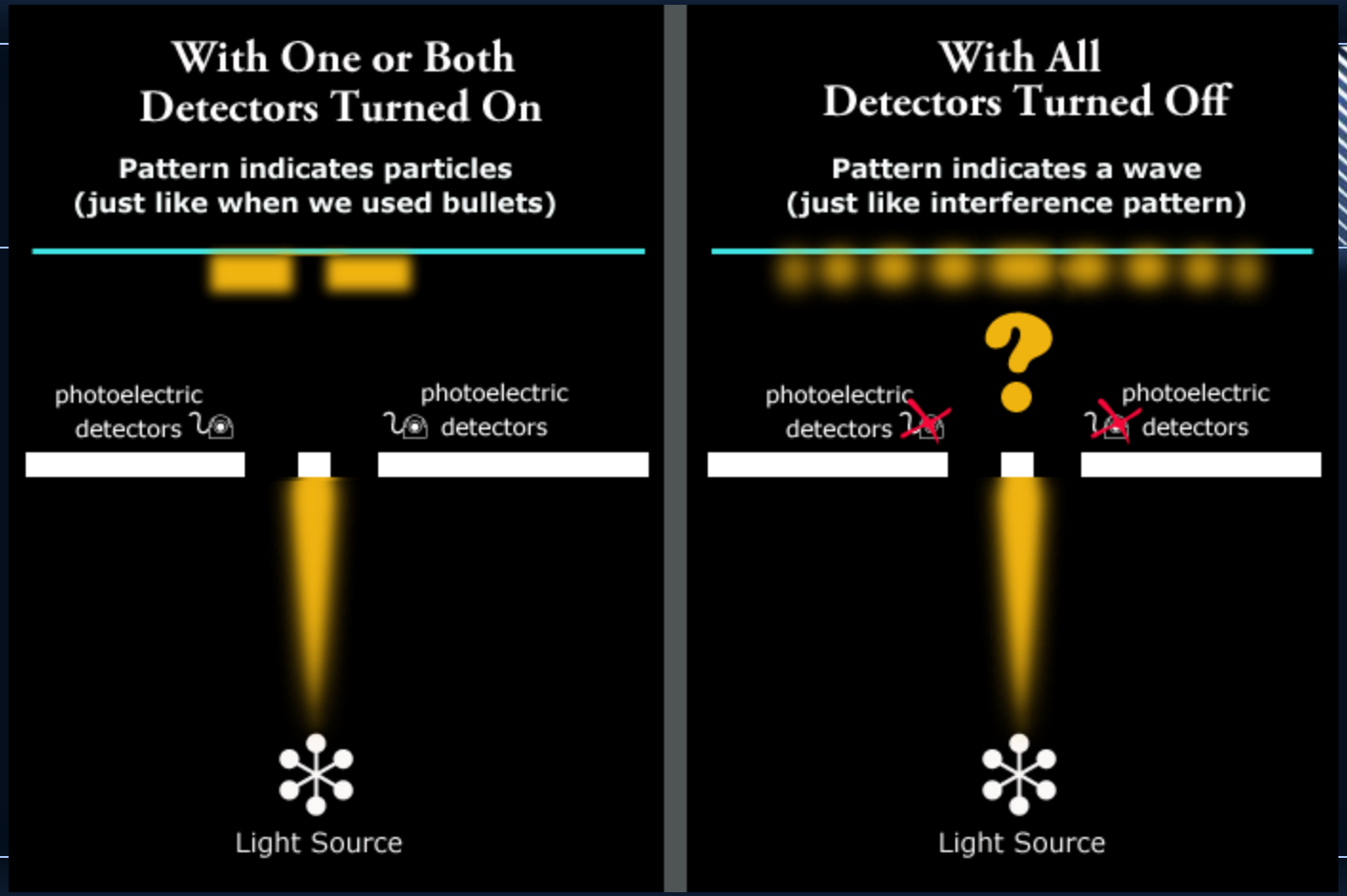


Observations

2. With Electrons (Matter)

- **Electron gun**: A machine shoots electrons at a thin film or barrier with two slits.
- **Detection screen**: They strike a phosphor screen or electronic detector one by one as single dots.
- At first, the dots look random. But as more and more electrons are fired, a **wave-like interference pattern emerges**, proving that electrons, which we usually think of as solid particles, also behave like waves.
- Again, if you try to measure which slit the electron went through (using detectors at the slits), the interference pattern disappears, leaving two simple stripes.

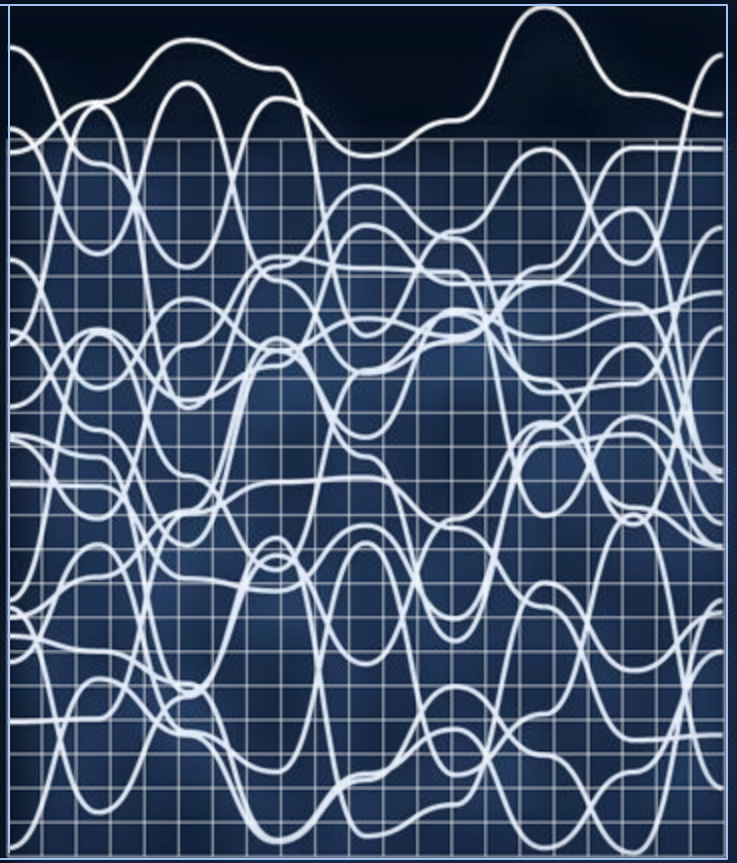



With One or Both Detectors Turned On
Pattern indicates particles (just like when we used bullets)
photoelectric detectors
photoelectric detectors
Light Source
With All Detectors Turned Off
Pattern indicates a wave (just like interference pattern)
photoelectric detectors
photoelectric detectors
Light Source

04

Theories

The observers effect (Feynman’s Mystery)



Observation meaning in quantum mechanics

in quantum mechanics, “observation” doesn’t necessarily mean a human watching

- It means any **interaction that extracts information** about the system (like a detector that records which slit an electron passes through).
- The act of measurement changes the wavefunction:
    - Before measurement → the electron exists in a **superposition** of paths (both slits).
    - After measurement → the wavefunction “collapses” to a definite path.

3. Feynman’s “Mystery”

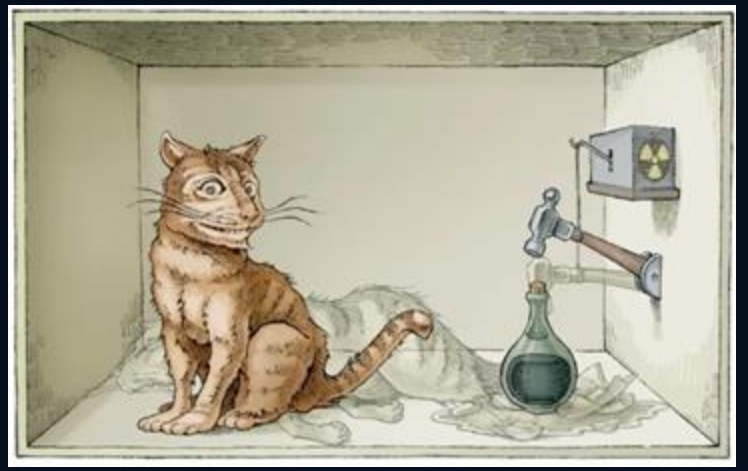
Richard Feynman famously said the **double-slit experiment** “contains the only mystery” of quantum mechanics:

- If we don’t look → the world seems probabilistic and wave-like.
- If we do look → the world looks deterministic and particle-like.
- And there’s no classical explanation for why *asking the question* (which path?) changes the outcome.

Schrodinger’s cat

In classical physics: particles have definite paths, and measuring them just *reveals* what’s already there.

In quantum physics: the path isn’t definite until measured. Measurement itself creates the outcome.



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Thank you