Clicker

What is the rest mass of a photon?

a) Meaningless question, since a photon cannot be brought to rest.

b) Zero.

c) $E = mc^2$, and $E = hf$, so $m = hf/c^2$.

d) The same as its relativistic mass.

e) It must be nonzero, since "the Higgs particle gives mass to all particles".

Clicker

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$\boxed{\text{b) Zero.}}$

$$E = hf = \gamma m_0 c^2 \qquad m_0 = \frac{hf}{\gamma c^2} = \frac{hf}{c^2}\sqrt{1 - \left(\frac{v}{c}\right)^2} = 0$$

c) E = mc^2, and E = hf, so m = hf/c^2.

d) The same as its relativistic mass.

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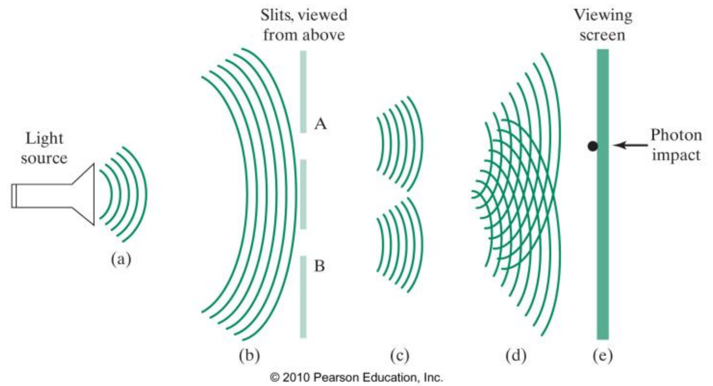
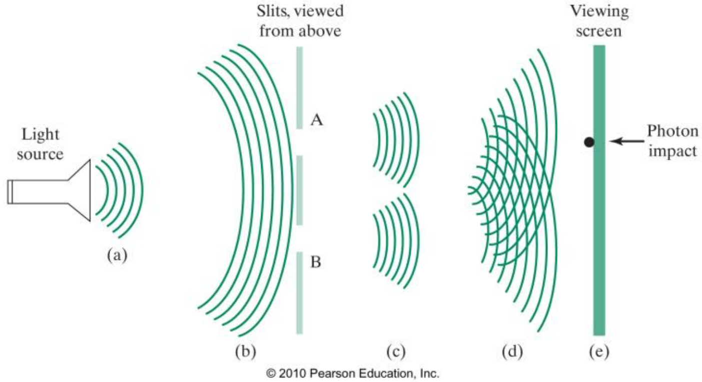
Clicker



In a double slit interference experiment, the light intensity between interference fringes is low because

A. The waves from the two slits arrive in phase, causing constructive interference.
B. The waves from the two slits arrive out of phase, causing constructive interference.
C. The waves from the two slits arrive in phase, causing destructive interference.
D. The waves from the two slits arrive out of phase, causing destructive interference.

Clicker



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If waves can act like particles,

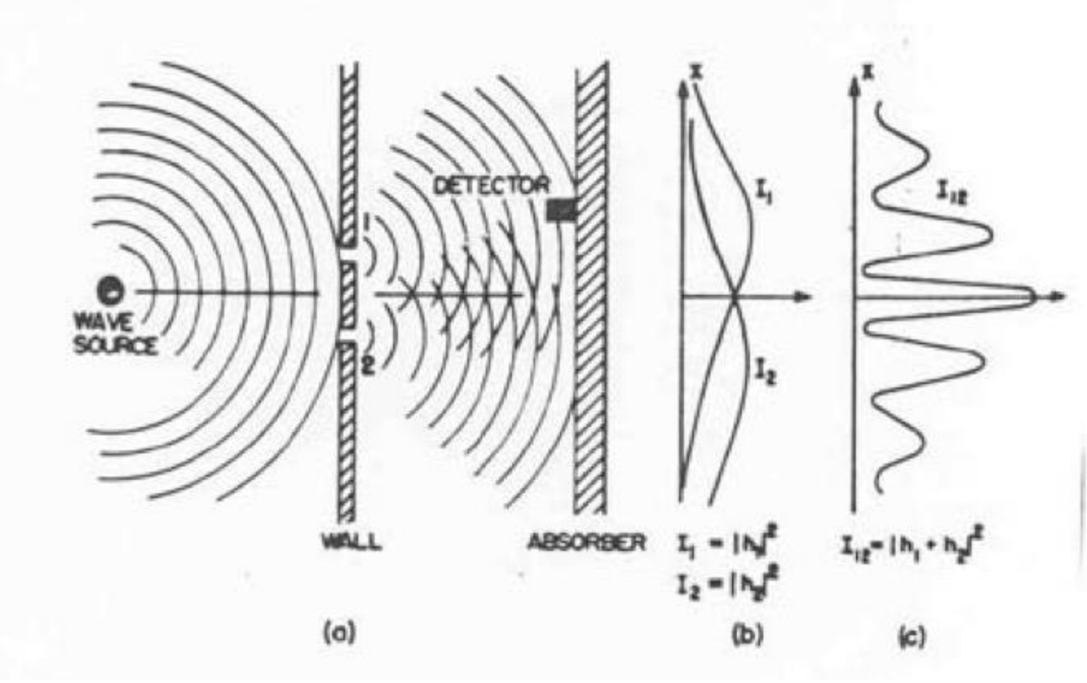
then is it also possible that

particles can also act like waves?

Wave-Particle Duality

(From Feynman Lectures on Physics)

- How a **wave** behaves in a double-slit experiment:

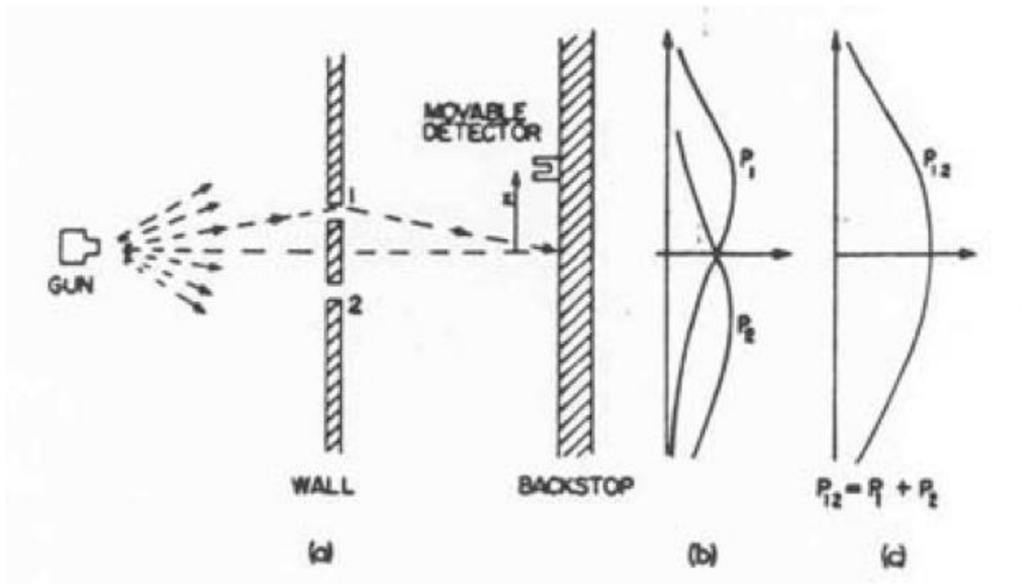


- A wave will pass through **both** slits simultaneously, resulting in an interference pattern. Light is **wavelike.**

Wave-Particle Duality

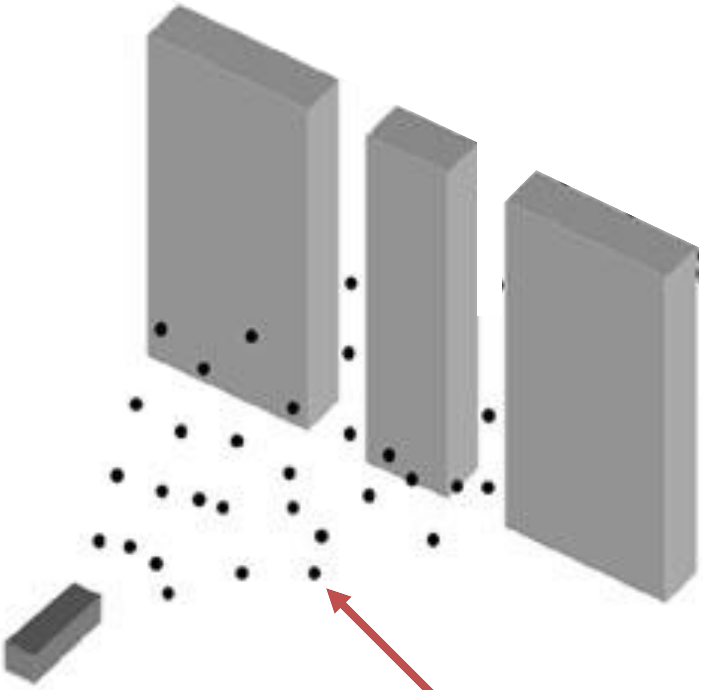
(From Feynman Lectures on Physics)

- How a **bullet** behaves in a **double-slit experiment**:



- The bullet's behavior is **particle-like**.

Double slit experiment (this time with electrons)

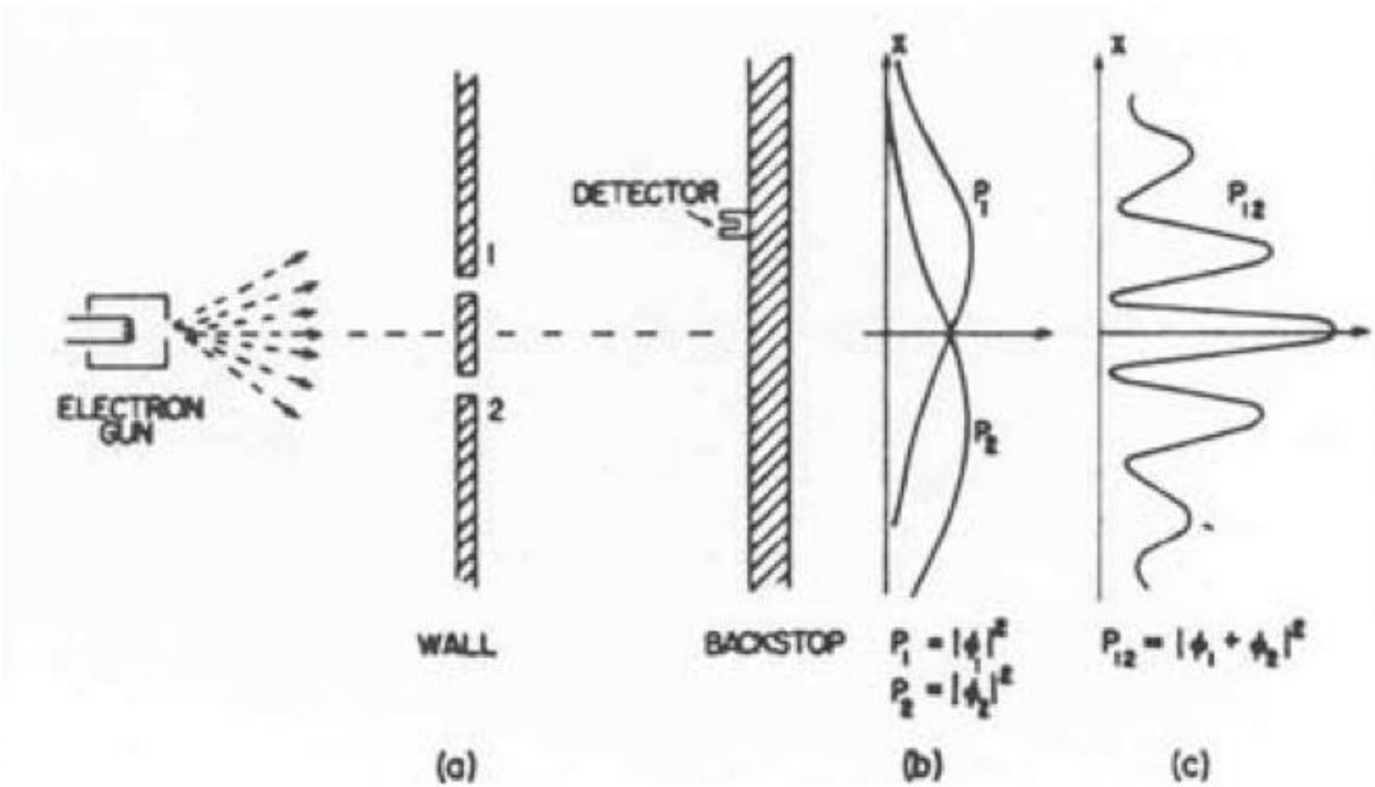


particles! (e.g. electrons)

Wave-Particle Duality

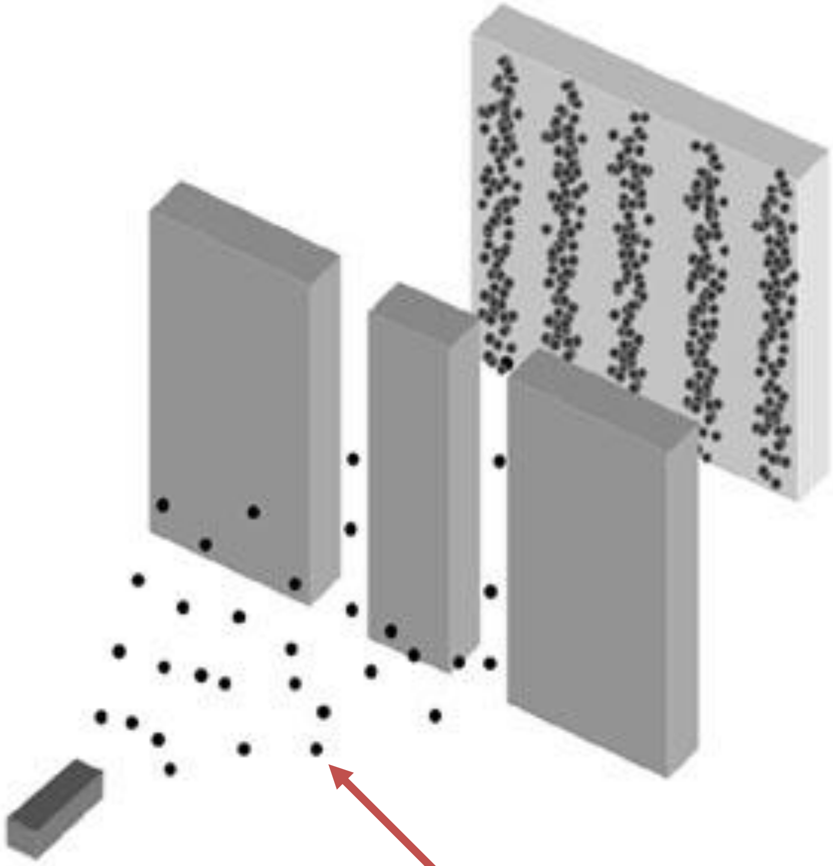
(From Feynman Lectures on Physics)

- What happens if you "shine" **electrons**?



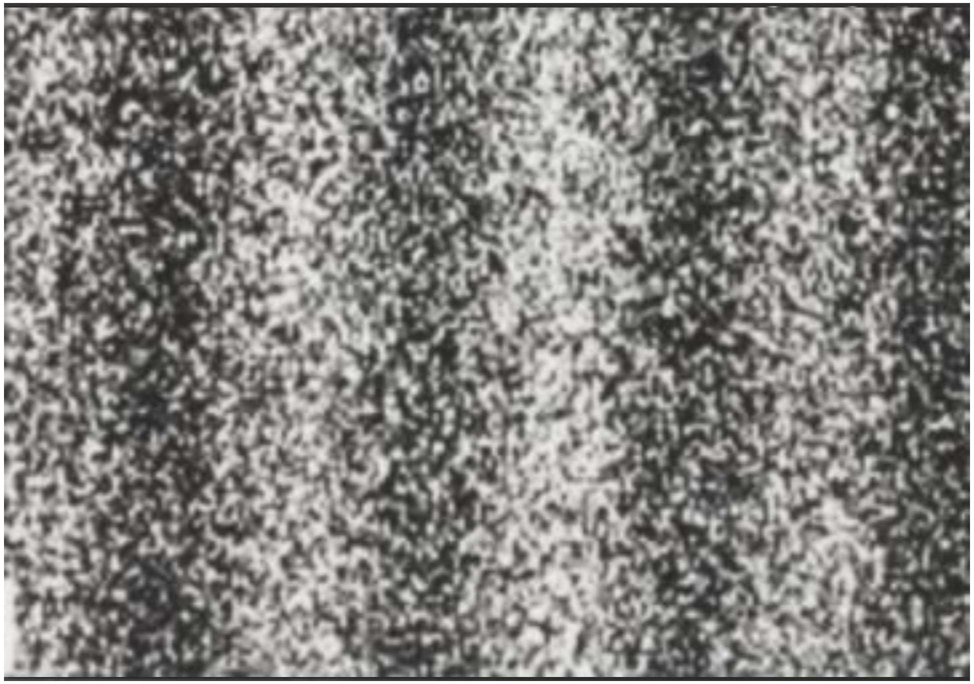
- But

Double slit experiment



particles! (e.g. electrons)

Double slit experiment



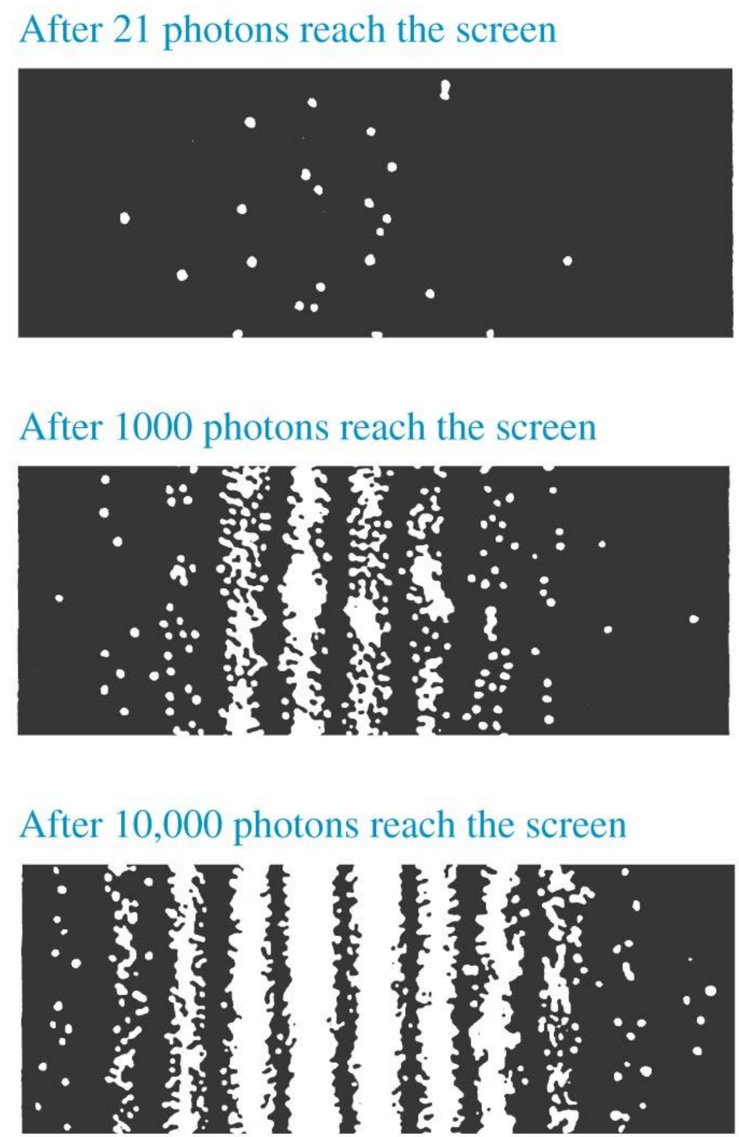
There is a randomness to arrival of electrons!
But it is a randomness with a pattern!

Wave-Particle Duality

- But wait! The interference pattern emerges because a wave passes through **both slits at the same time**. But an electron (and a photon) is a particle, too.
- So the interference pattern must result because multiple electrons/photons are passing through the slits and interfere with each other, right?
- Not really - interference happens even for a single electron:

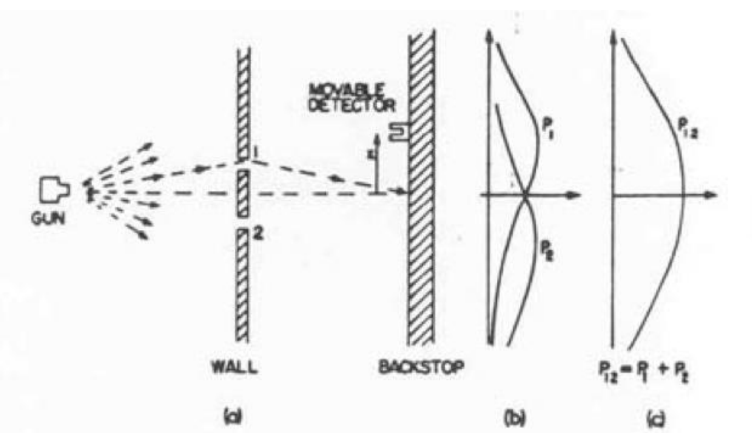
Wave-Particle Duality

- As we have seen, the interference pattern is defined by the wave nature of light/electrons.
- However, with a sensitive detector, we can see individual photons/electrons appear at distinct spots.
- Does an individual photon/electron interfere only with other photons/electrons, or with itself?
- It appears that each photon/electron "knows" where to go, even if no other particles are in the apparatus at the same time!

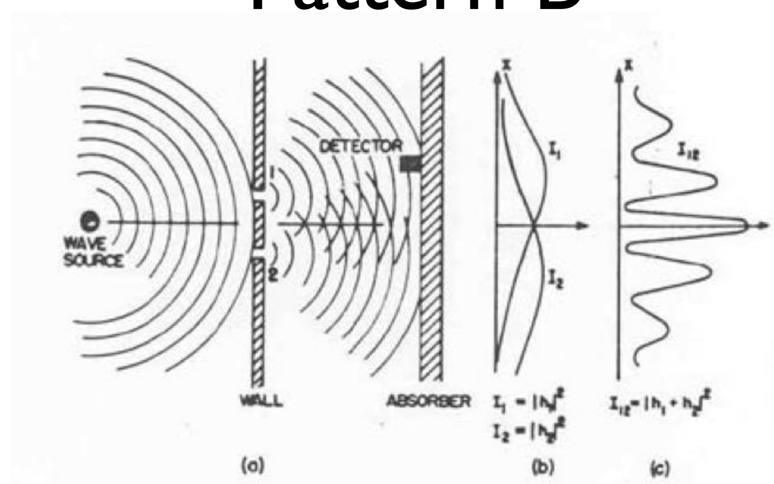


- Suppose we limit the number of electrons so that **only one electron passes the slits at a time**. Which pattern do you get?
  A. Pattern A (particle-like)
  B. Pattern B (wavelike)
  C. Neither

Pattern A



Pattern B



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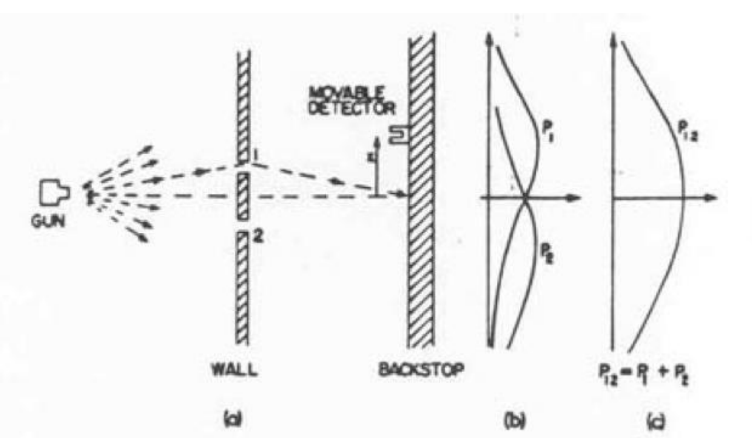
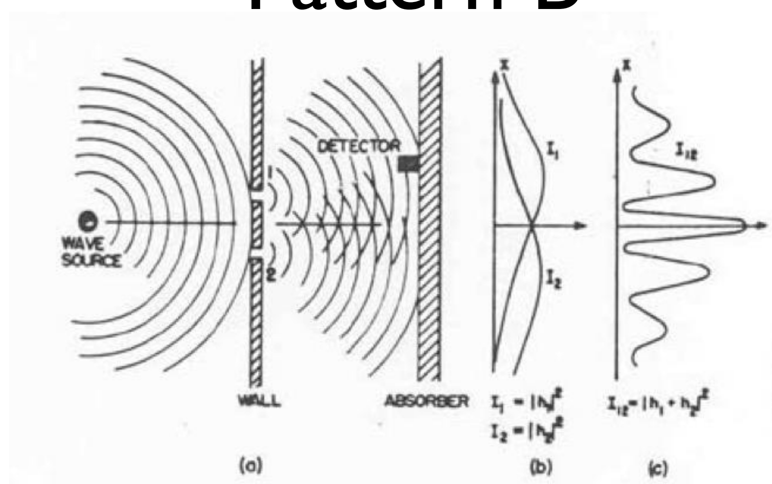
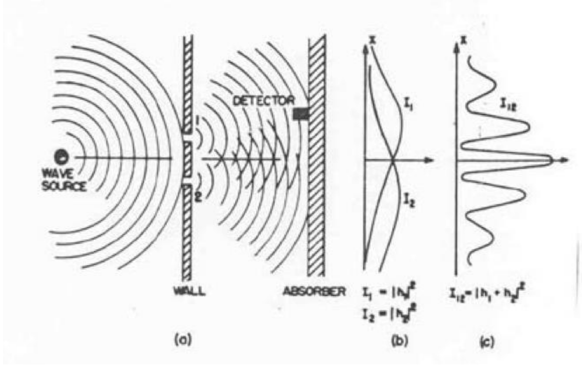
Pattern A



Pattern B

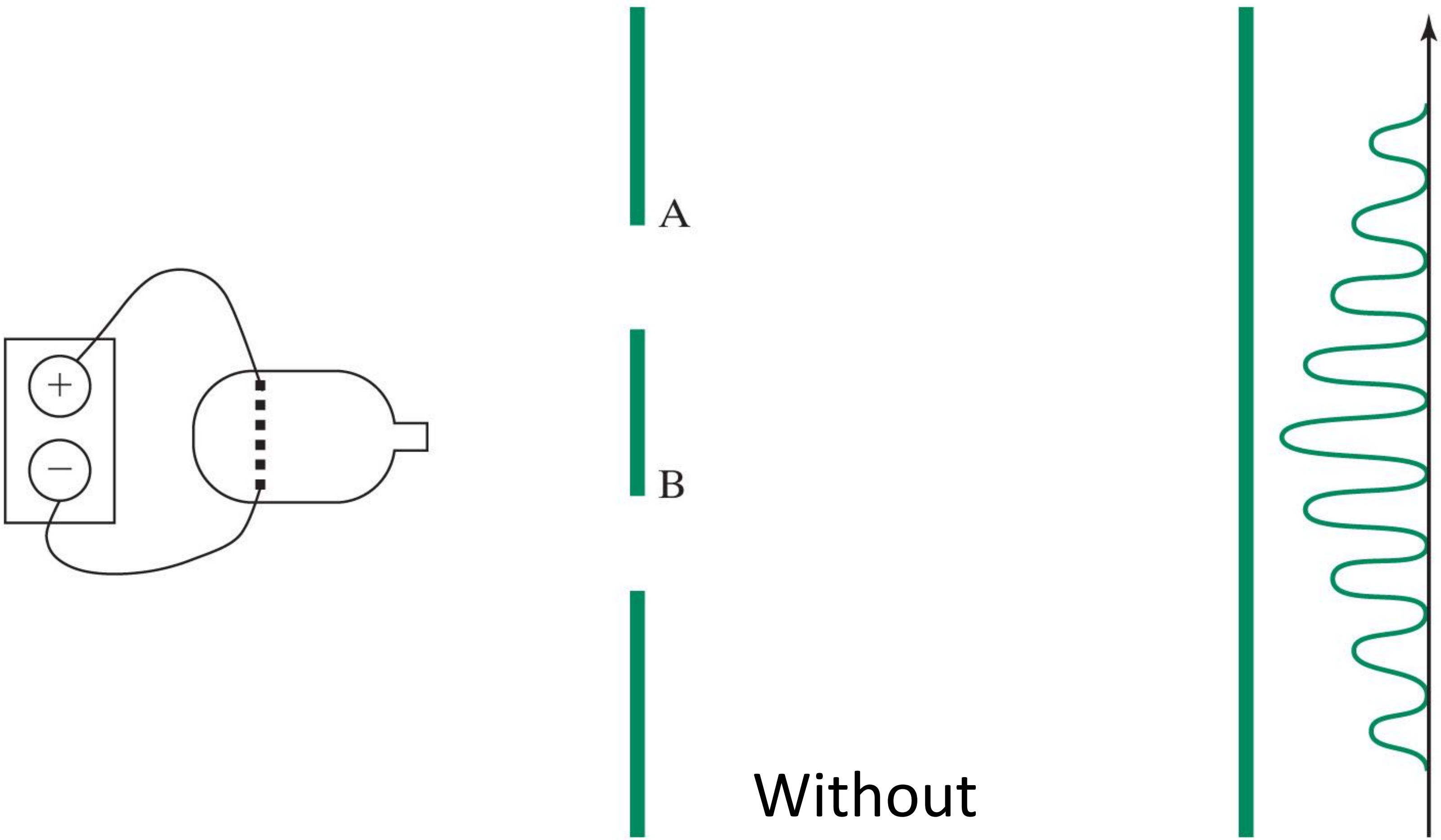


Pattern B

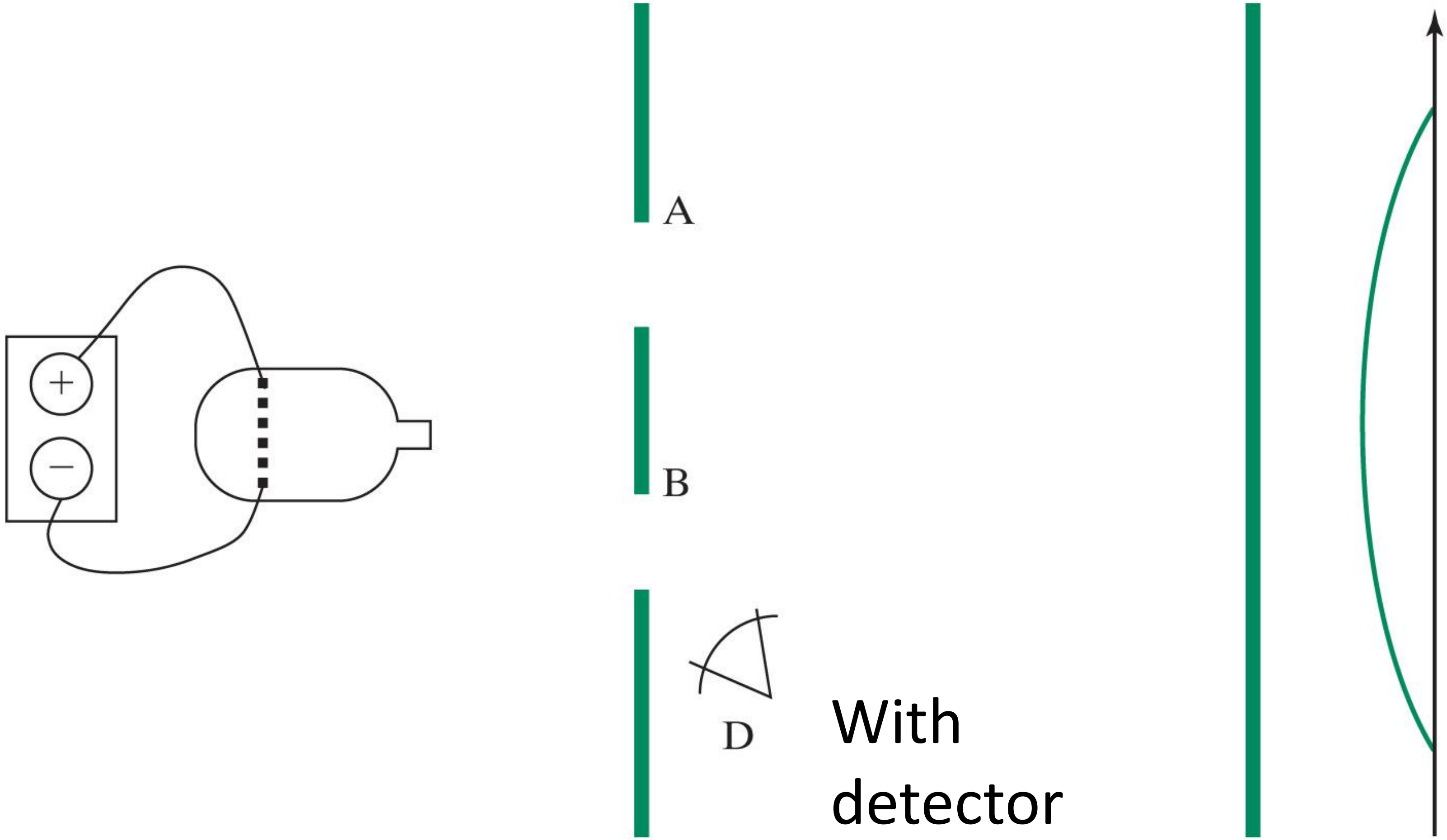


- This was experimentally tested in 1961. It turns out that all particles are **fundamentally wavelike.** Even if you limit the electrons so that only one passes at a time, an interference pattern emerges.
- This means that a **single** electron is affected by **both slits**. Does it actually pass through both slits at once, or is it that we just don't know (and can't possibly know) which slit it passed through? That's a philosophical question!

What happens if you "look" to see which slit the electron passed through?



Without detector



With detector

You destroy the interference pattern!

Clicker

What best describes what happens to an individual electron in the double-slit experiment?

A) It goes through one or the other slit, and even though we don't know which one, we could find out with a clever setup.

B) It goes through one slit and interferes with another electron going through the other slit.

C) It goes through neither slit.

D) It goes through both slits and interferes with itself.

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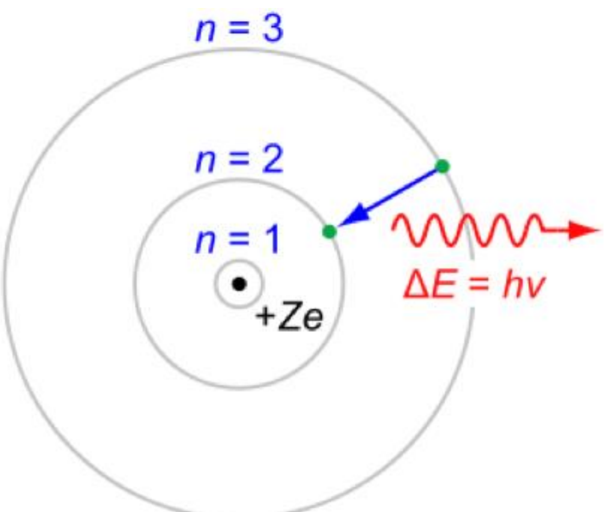
De Broglie: Electrons as standing waves!

1913

1924

DeBroglie Wavelength

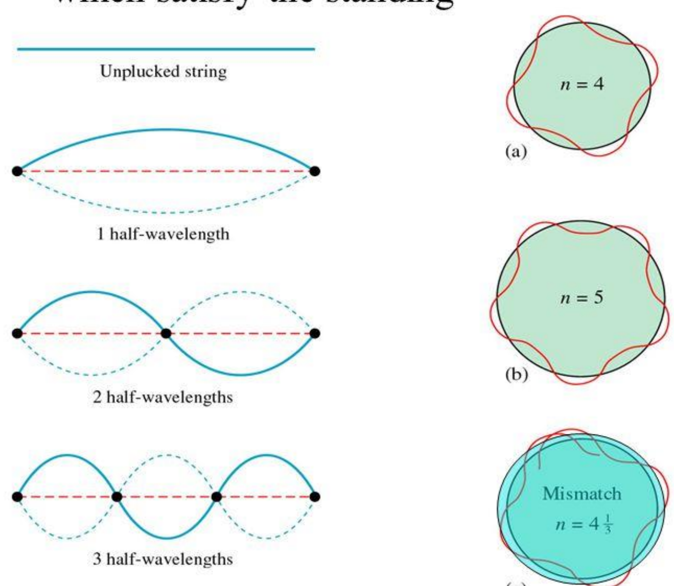
$$\boxed{\lambda = \frac{h}{p}}$$



Bohr picture:

Classical orbits

- Louis de Broglie suggests that for the e^- orbits envisioned by Bohr, only those orbits are allowed which satisfy the standing wave condition.

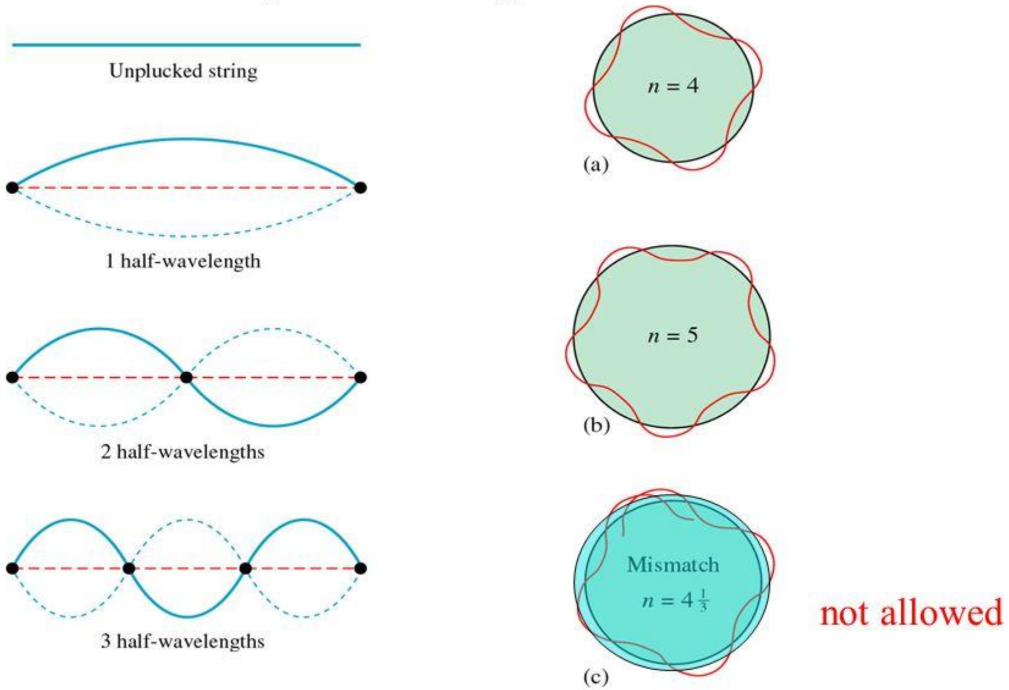


not allowed

De Broglie: Atoms are Like Guitars

Guitar - standing waves on a string.
Atom - standing waves on a ring!

- Louis de Broglie suggests that for the e^- orbits envisioned by Bohr, only those orbits are allowed which satisfy the standing wave condition.



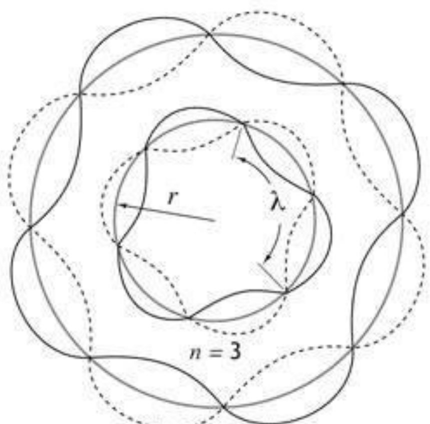
De Broglie: Electrons as standing waves!

MODERN PHYSICS • XXIII.iii • *Wave Mechanics and Atomic Theory* [472]

The De Broglie Wavelength

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

λ = wavelength
h = Planck's constant (6.63×10^{-34} J • s)
p = momentum
m = mass
v = speed



De Broglie's extension of the concept of particle-wave duality from photons to include all forms of matter allowed the interpretation of electrons in the Bohr model as standing electron waves. De Broglie's work marked the start of the development of wave mechanics.

New theory explains:

- Why there are special orbits
- The meaning of the integer *n*
- Why the electron doesn't spiral down onto the nucleus

- 1895-1925: Something big is cooking…
  - Line spectra of atoms.
  - Thompson: electron.
  - Rutherford: atomic nucleus.
  - Planck: blackbody radiation – energy quanta.
  - Photoelectric effect: waves as particles.
  - De Broglie atom: particles as waves.
  - Randomness and precision all at once…
- 1926-29: New paradigm: “Quantum Mechanics”
  - Erwin Schrödinger
  - Werner Heisenberg
  - Paul Dirac
  - Wolfgang Pauli
  - Max Born

1927-1929 : The Quantum Revolution

Werner Heisenberg

Erwin Schrödinger

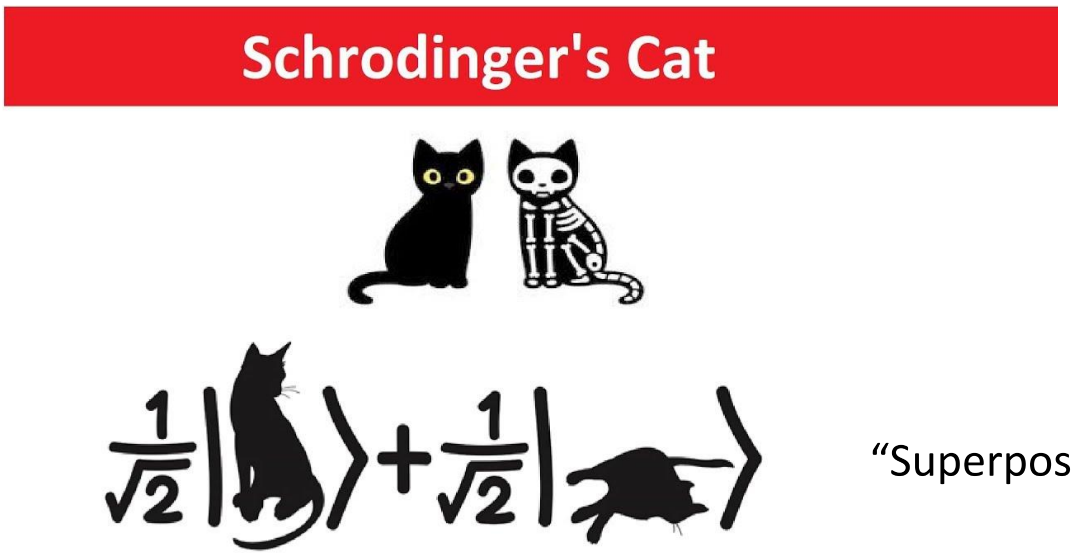
Paul Dirac

Wolfgang Pauli

- Quantum theory predicts the ***probability*** of experimental outcomes (e.g. the probability of finding a particle at this place at that time).
- Predicts these probabilities very accurately!
- Correctly predicts the behavior of light, atoms, and subatomic particles.

Weirdness of Quantum Mechanics

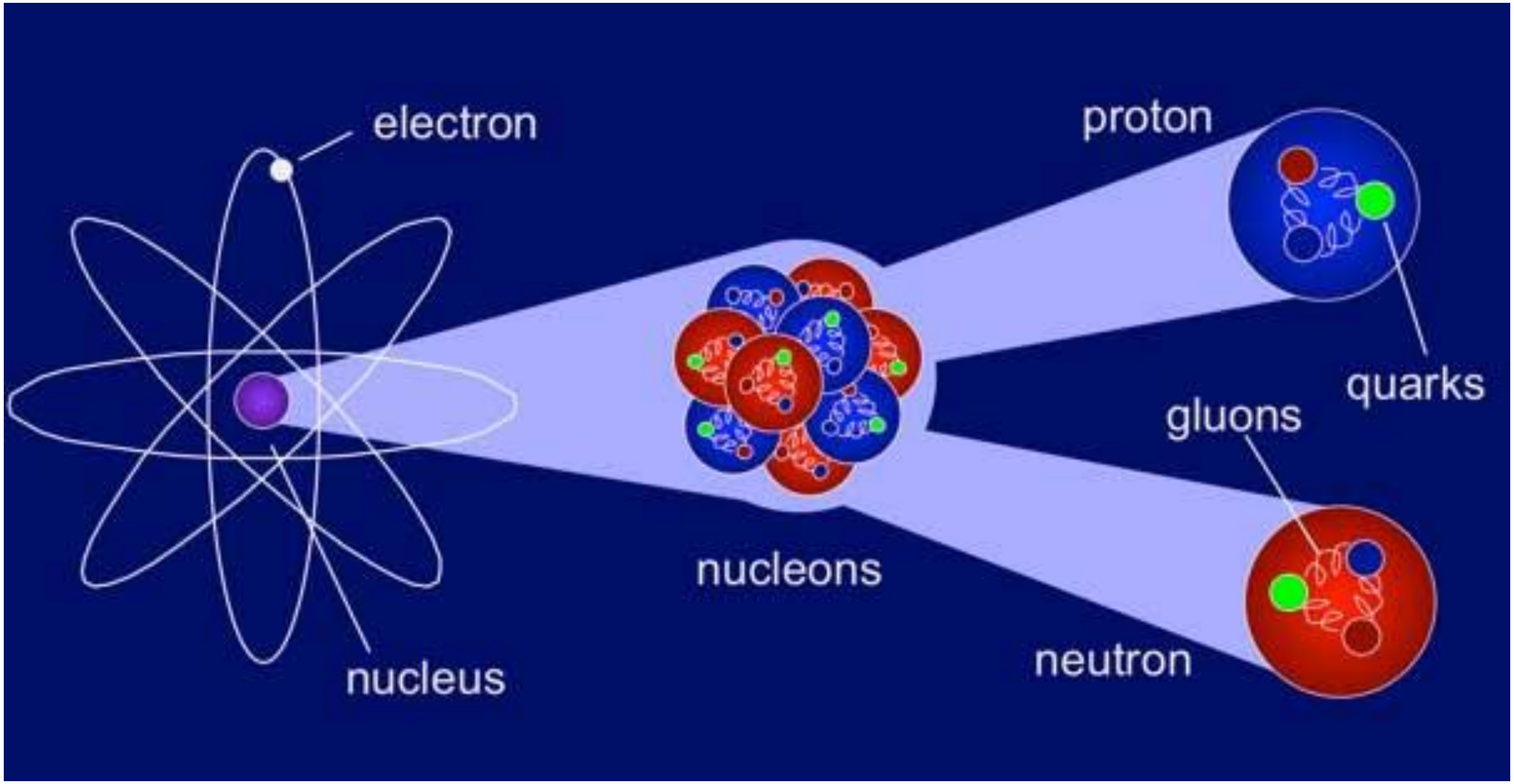
- Quantum mechanics ***works extremely well*** to describe microscopic phenomena.
- When applied to macroscopic phenomena, it predicts some really weird things, such as an animal being simultaneously dead and alive!



"Superposition State"

- Macroscopic superposition states are not being observed. This points to deep connections between physical reality, measurement, and consciousness.
- There are many competing interpretations, heavily debated among physicists.

Nuclei and Radioactivity



1897-1906: Marie Curie

Discovery of new “radioactive” elements

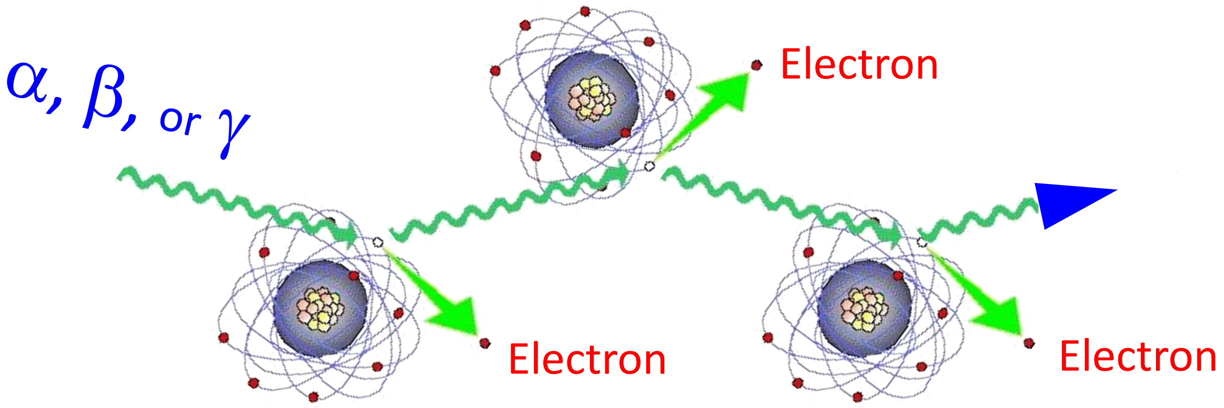

1911 photograph of Maria Skłodowska Curie

- Thorium
- Polonium
- Radium

Died at age 67 from radiation exposure.

Ionizing radiation

- 3 types of radiation: α, β, γ radiation.
  - Also X-rays (not produced by nuclei)
- Repeatedly knock electrons off atoms/molecules.
- Breaks chemical bonds.
- Causes mutations, genetic damage, cancer.



Demo

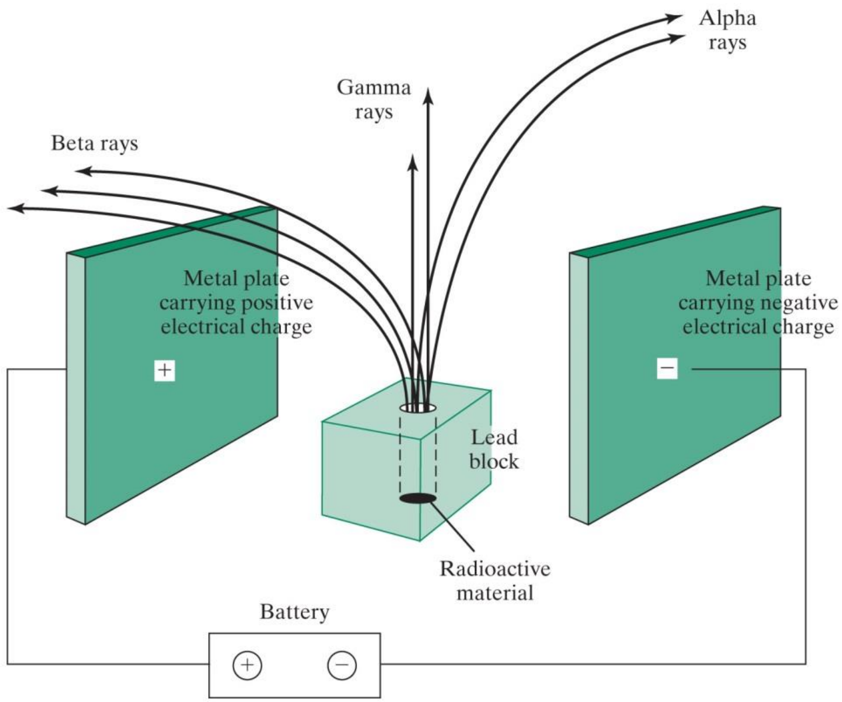
Let’s use a Geiger counter

Geiger counter is sensitive to all three!

γ (neutral)

β (–)

α (+)



Geiger counter

- Each click is one α, β, or γ ray entering the detector
- Say, 20 clicks a second: How can there be so many? Won't the sample disappear after a while?
- Let's see how many atoms are gone after a year:
  - 20 x 60 x 60 x 24 x 365 = 6×10^8 decays
  - Compare with 10^{23} atoms; no problem!

Results from Demo

- ^{241}Am (americium 241):

  α emitter

  Air, cardboard will stop it
- ^{90}Sr (strontium 90):

  β emitter

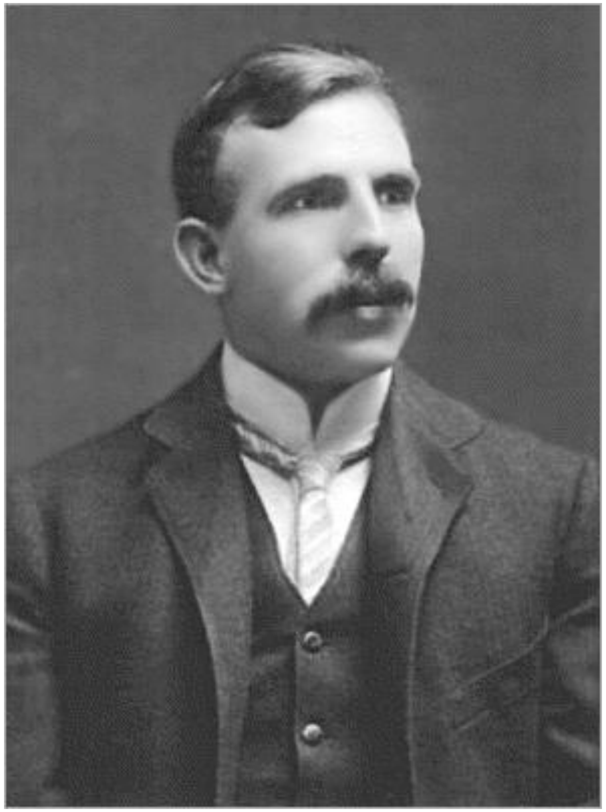
  Need lead sheet to stop it
- ^{60}Co (cobalt 60):

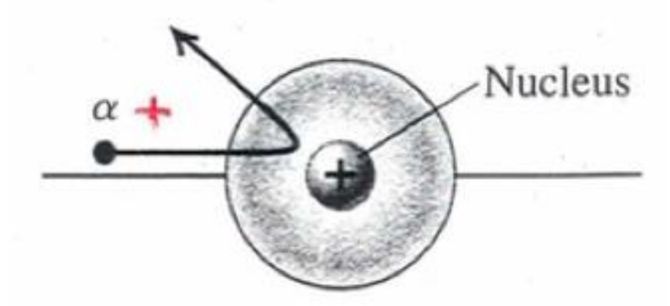
  γ emitter

  Need several lead sheets to stop it

1909: Ernest Rutherford

- Nucleus is tiny!
- Nucleus contains the positive charge.
- Nucleus contains almost all the mass of the atom.

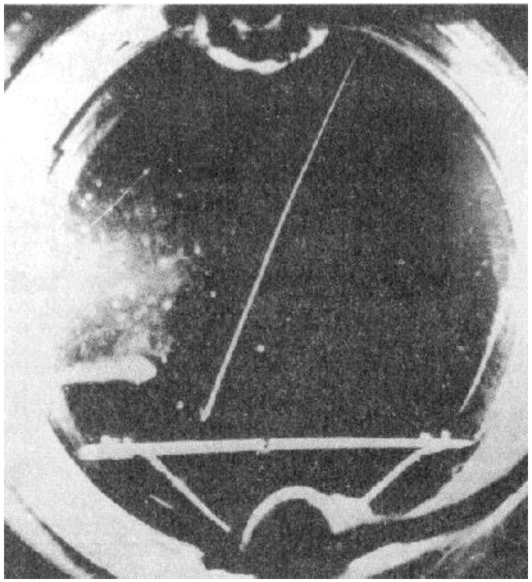


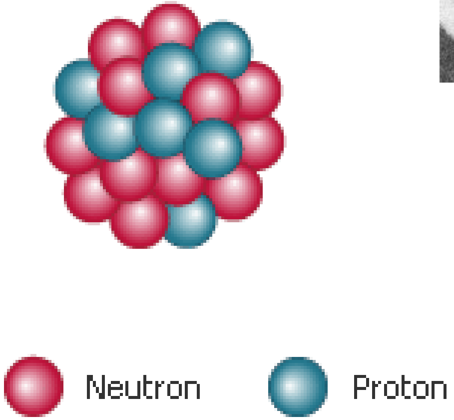


Discovery of Neutron

James Chadwick 1932

Alpha particles interacting in air found to knock out neutral particles.

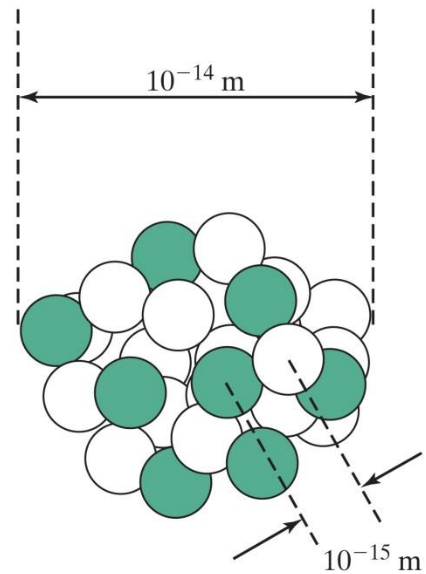




Atoms made out of:
protons, neutrons, electrons

What holds the nucleus together?

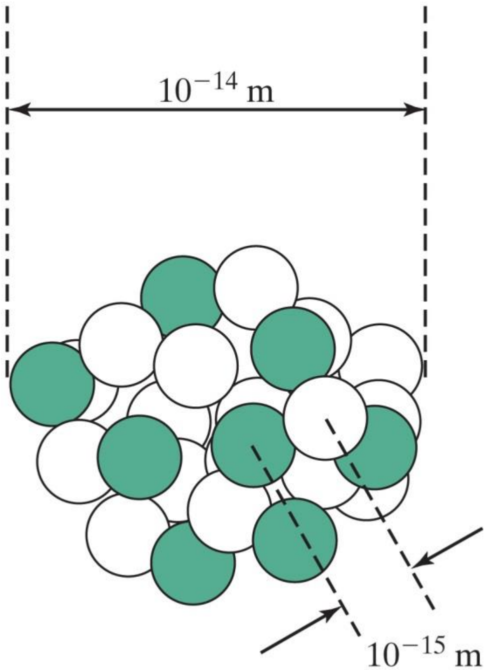
- Interesting facts:
  - Nucleus is 1000 times smaller than atom (~10^{-10} m).
  - Nucleus contains positively charged protons and neutral neutrons.
  - Nucleus stays together despite extremely strong proton-proton repulsion!



- What can we conclude?
  - There must be another force, in addition to electric forces.
  - It must be much stronger than electric forces.
  - It must only act at nuclear distances.
  - We call it the "strong force".

Strong Nuclear Force

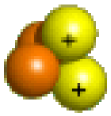
- One of the four fundamental forces of nature: (*gravitational*, *electromagnetic*, *strong*, and *weak*)
- Acts only on protons (*p*) and neutrons (*n*), not on electrons.
- Doesn't care whether *n* or *p.*
- Always attractive.
- Much stronger than electric at short distances.
- But quickly vanishes at longer distances (>10^{-14} m).



Identities of α, β, and γ revealed

Basic ingredients:

Particle	Symbol	Rest Mass (u)	Charge (e)
Neutron	n	1.0087	0
Proton	p or ${}^{1}_{1}\mathrm{H}$	1.0073	$+1$
Alpha	α or ${}^{4}_{2}\mathrm{He}$	4.0026	$+2$
Electron	β or e^{-}	0.0005	-1
Photon	γ	0	0



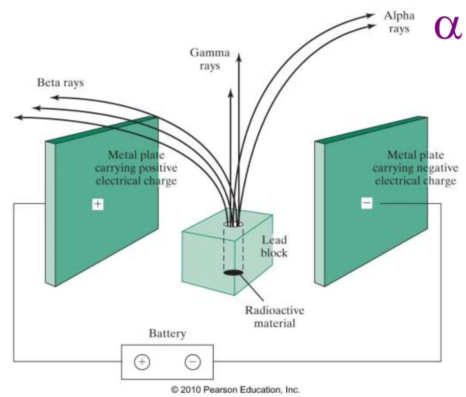
Units:

- $e = 1.602 \times 10^{-19}$ C
- $\mathrm{u} = 1.6605 \times 10^{-27}$ kg

γ (neutral)

β (–)

α (+)



Terminology for Nuclei

“Mass number” = number of protons + neutrons

Carbon 14

6 protons
8 neutrons
14 total

$$^{14}_{6}\mathrm{C} \quad \text{or} \quad ^{14}\mathrm{C}$$

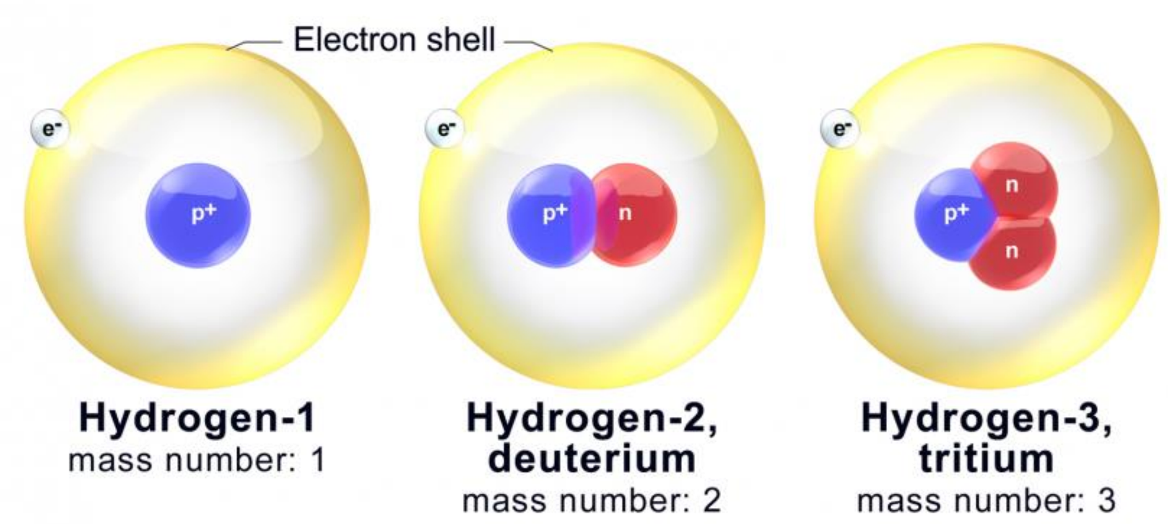
“Atomic number” = number of protons ⇔ Name of element

Isotopes

Isotopes of an element correspond to nuclei with the same atomic number (i.e., protons) but have different mass numbers (different numbers of neutrons).

Examples:

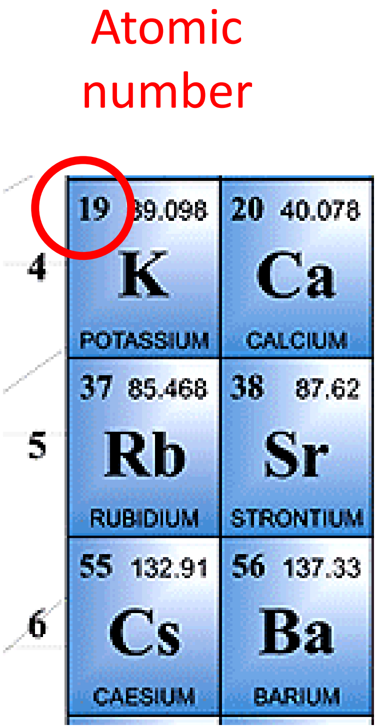
- ^{12}C and ^{14}C
- ^{235}U and ^{238}U
- ^{1}H, ^{2}H (deuterium), and ^{3}H (tritium)



Clicker

Potassium (K) has atomic number 19. Calcium (Ca) has atomic number 20. Which is true about these nuclei?

A. ^{40}K and ^{40}Ca are isotopes of each other.
B. ^{40}K has 19 neutrons.
C. ^{40}Ca has 21 neutrons.
D. ^{40}K has 21 neutrons.
E. ^{40}K and ^{40}Ca have the same number of protons.



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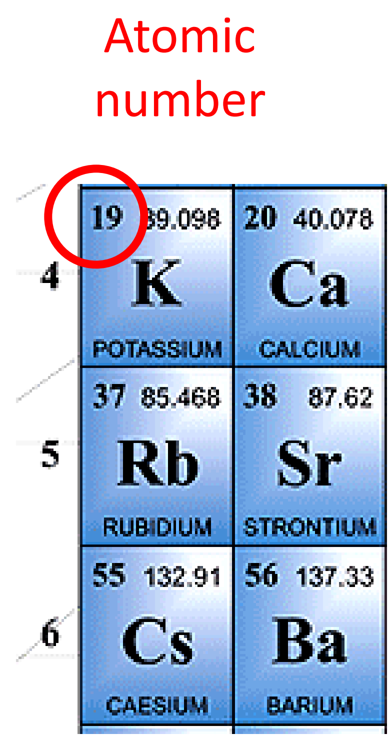
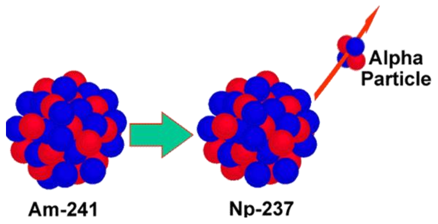
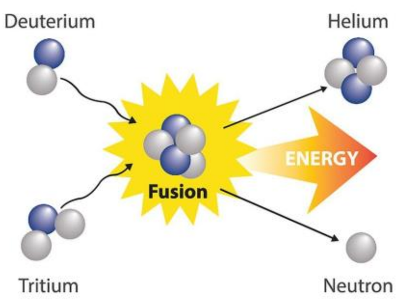


Three kinds of nuclear reactions

- Radioactive decay of unstable nuclei (today).



- Fusion: Next week!



- Fission: Next week!