Quantum Mechanics

Karan Kumar

Class Policy

- Classes from 10:00 AM to 12:30 PM (5 min break at ~ 11:00 AM, 5 min break at noon).
- Up to four absences
- Lateness or leaving early counts as half-absence.
- Send email notifications of all absences to shpattendance@columbia.edu

Class Policy

- No cell phone uses during the class
- Feel free to step outside to the hallway in case of emergencies, bathroom, and starvations.
- Feel free to stop me and ask questions / ask for clarifications.

Curriculum

Lecture	Topic
~~1~~	~~Introduction~~
~~2~~	~~History of Particle Physics~~
~~3~~	~~Special Relativity~~
4	Quantum Mechanics
5	Detectors By Sarah Vicker
6	Standard Model
7	Beyond the Standard Model
8	Neutrino Theory
9	Neutrino Experiment
10	Large Hadron Collider (LHC)
11	Higgs Boson and Beyond
12	Cosmology

Outline

- History of Quantum Mechanics
- The Bohr Model of Atom
- Introduction to Quantum Mechanics
- The Interpretations of Quantum Mechanics
- Spin
- The EPR paradox
- Bell's Theorem
- Tunneling
- Schrodinger Cat

History of Quantum Mechanics

Book Reference

- Introduction to Quantum Mechanics by David J. Griffiths
- Introduction to the Quantum Theory by David Park
- Principles of Quantum Mechanics by Ramamurti Shankar
- Modern Quantum Mechanics by J. J. Sakurai
- Introduction to Elementary Particles by David J. Griffiths

Everything in these lectures is taken from these books

History of Quantum Mechanics

- Quantum mechanics, like relativity, started with scientists studying light.
- In 1900 Max Planck faced a tough puzzle in physics. He was trying to explain the blackbody spectrum, which describes how hot objects give off light and heat.
- None of the existing theories worked.

History of Quantum Mechanics

Blackbody Radiation

- Every object gives off electromagnetic waves, which is called **blackbody radiation**.

History of Quantum Mechanics

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- The name is a little misleading, because even the Sun counts as a blackbody in this sense.
- At first, the term **“blackbody”** makes you think of something black, like an object that doesn’t glow at all. But in physics, a blackbody means an *ideal radiator* that gives off light based only on its temperature.

History of Quantum Mechanics

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Source: Wikipedia

History of Quantum Mechanics

- He was trying to explain the blackbody spectrum—the pattern of radiation given off by hot objects.
- Scientists had already used statistical mechanics very successfully to explain many thermal processes, but when they applied it to electromagnetic radiation, the results made no sense.

History of Quantum Mechanics

Experimental Data

Theoretical Prediction

Source: Wikipedia

- The equations predicted that a hot object should give off infinite energy at short wavelengths, especially in the ultraviolet.
- This impossible result became known as the **ultraviolet catastrophe**.

History of Quantum Mechanics

- Planck discovered that he could solve the ultraviolet catastrophe and match the experimental data if he assumed that electromagnetic radiation comes in tiny "packages" of energy. Each package has an energy

$$E = h\nu$$

h is Plack Constant and ν is frequency of the radiation.

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h is Plack Constant and ν is frequency of the radiation.
- Planck himself did not claim to understand why radiation was quantized. He thought it was just a strange detail of how hot surfaces emit light — that they can only give it off in little bursts, not continuously.

History of Quantum Mechanics

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- Planck had suggested that light was emitted in little packets, but Einstein argued that quantization was not just about the emission process.
- Instead, he proposed that light itself is made up of particles—what we now call **photons**.
- Einstein used this idea to explain the **photoelectric effect**.

History of Quantum Mechanics

- When light shines on a metal surface, electrons can be ejected.
- He suggested that a single photon hits an electron, giving it an energy:

$$E = h\nu - w$$

Here $h\nu$ is the energy of the photon, and w is the “work function,” the energy needed for the electron to escape the metal.

Source: Wikipedia

History of Quantum Mechanics

This explanation had a surprising consequence:

- The maximum energy of the electrons depends only on the **color** (frequency) of the light, not on the **brightness** (intensity).

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- Brighter light knocks out more electrons, but each one's energy depends only on the frequency.

This was strong evidence that light behaves like particles, not just waves.

History of Quantum Mechanics

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- To see why this was so shocking, remember the history. For centuries scientists argued about whether light was made of waves or particles. Thomas Young’s double-slit experiment in 1801 seemed to settle it: light showed interference, so it had to be a wave.

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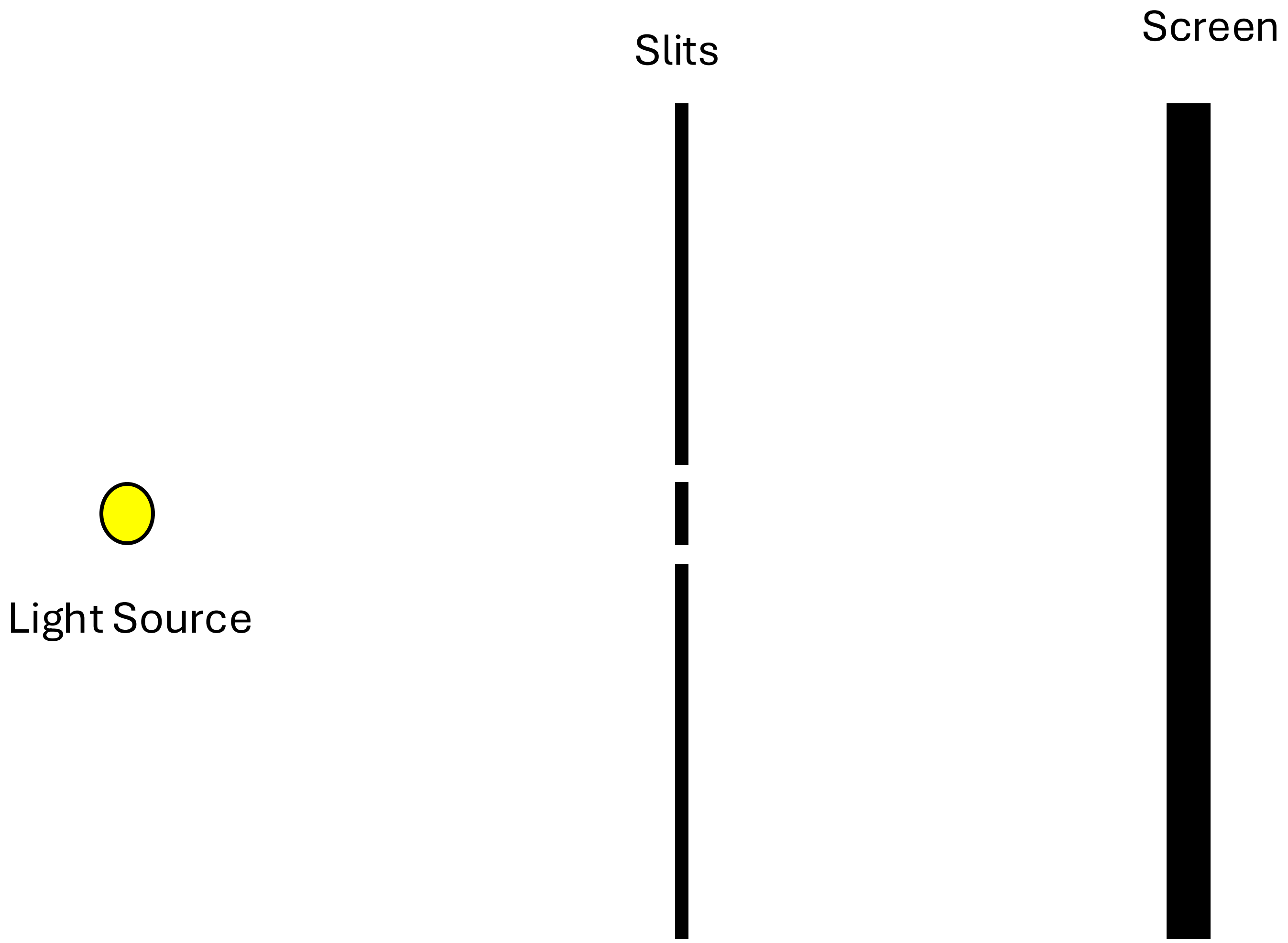
- Later, Maxwell’s theory of electromagnetism explained light beautifully as an electromagnetic wave. The case looked closed.

History of Quantum Mechanics

Young's double-slit experiment

The setup

- A **screen** at the back that records where particles hit, and
- A **barrier** with **two very thin slits** cut into it,
- And you send **light** or **particles** (like electrons) toward it.



History of Quantum Mechanics

What we expect (classical thinking)

- If light were just a **particle**, you'd expect it to behave like tiny pellets fired from a gun:
- Some go through the **left slit**,
- Some through the **right slit**,
- You'd see **two bright spots** on the screen behind the slits.

Source: https://profmattstrassler.com/2025/01/16/double-trouble-the-quantum-two-slit-experiment-1/

History of Quantum Mechanics

What we expect when water wave passes through and when light passes through

Animation: https://phet.colorado.edu/sims/html/wave-interference/latest/wave-interference_all.html

History of Quantum Mechanics

- But when you do the experiment with **light** (or later, with **electrons**), you don't get two spots.
  You get a **pattern of many bright and dark bands** — called an **interference pattern**.
- That pattern looks just like what you'd get if **waves** of water or sound passed through two openings and interfered:
- Where crests meet crests → bright region (constructive interference)
- Where crests meet troughs → dark region (destructive interference)
- So, light behaves like a **wave.**

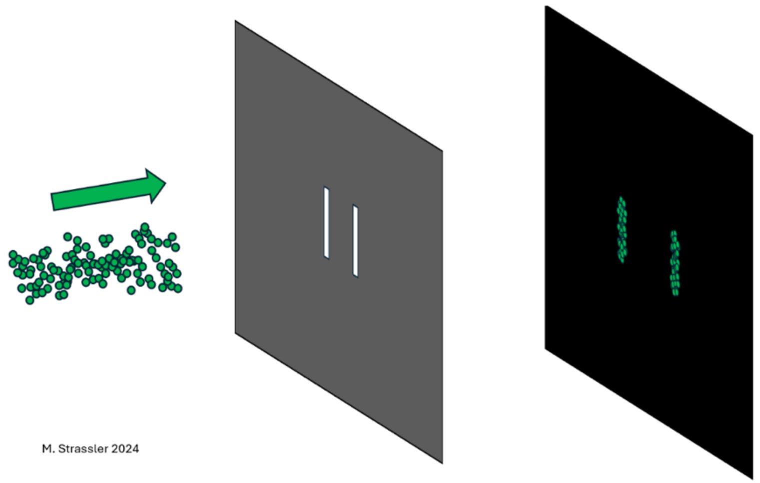


Figure 5: If balls, bullets or other particle-like objects are thrown at the wall, those that pass through the slits will arrive at the screen in two slit-shaped regions.

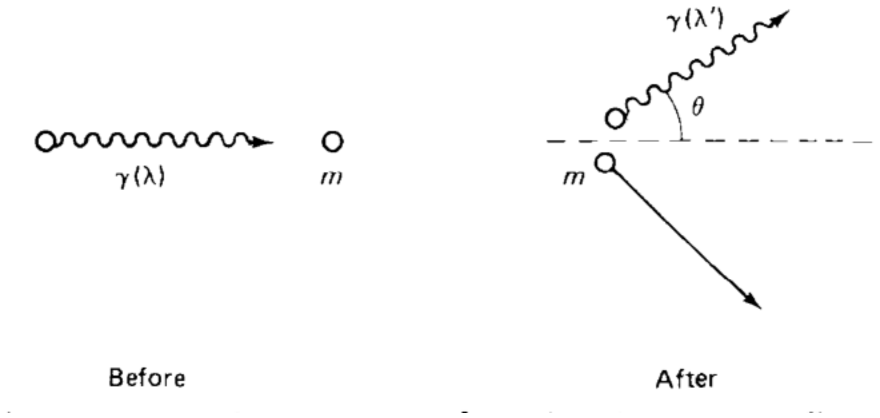
Source: https://profmattstrassler.com/2025/01/16/double-trouble-the-quantum-two-slit-experiment-1/

History of Quantum Mechanics

- Then along came Einstein, claiming that light is actually made of particles—what we now call photons. At the time, this sounded completely absurd.

History of Quantum Mechanics

- What finally settled this debate was **Compton scattering**, discovered by **Arthur H. Compton in 1923**.



Source: Introduction to Elementary Particles by David J. Griffiths

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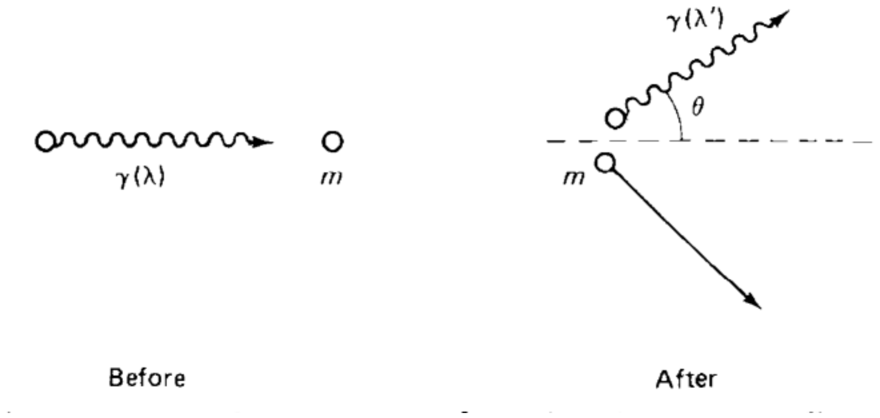
- In this experiment, high-energy X-rays were fired at electrons, and the scattered light was found to have a slightly **longer wavelength** (lower energy) than the incoming light.



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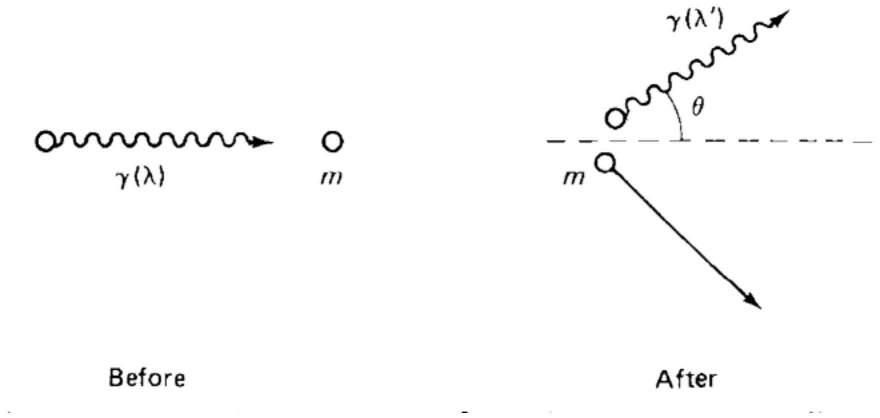
- In this experiment, high-energy X-rays were fired at electrons, and the scattered light was found to have a slightly **longer wavelength** (lower energy) than the incoming light.
- This shift depended on the **scattering angle**, exactly as predicted if light were made of **particles (photons)** that collide elastically with electrons, conserving energy and momentum.



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History of Quantum Mechanics

- In 1924, a French physicist named **Louis de Broglie** had a bold thought:
- If light — which we used to think was a wave — can behave like a particle, maybe **particles** (like electrons) can behave like **waves** too!
- This was a completely new way of thinking at the time.

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

History of Quantum Mechanics

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- In 1925, Davisson and Germer tested this by shooting electrons at a crystal. The atoms in the crystal acted like tiny slits, similar to the double-slit experiment with light.
- The electrons created an interference pattern—just like waves do. This proved that particles such as electrons have wave-like behavior.

History of Quantum Mechanics

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- It inspired scientists like Heisenberg, Schrödinger, and Born to develop **quantum mechanics** between 1925 and 1927.
- But before getting there, we need to go back and look at **Bohr's model of the hydrogen atom**.

The Bohr Model of Atom

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- But according to classical physics, any charged particle moving in a circle should give off energy as light.
- That means the electron would quickly lose energy and spiral into the nucleus. If that were true, atoms couldn't exist for more than a tiny fraction of a second — which clearly isn't the case.

The Bohr Model of Atom

- What's even more interesting is that atoms don't emit or absorb all colors of light — only specific ones.
- Each element, like hydrogen, gives off its own unique set of colors, called its **spectrum**.
- This pattern acts like a fingerprint for that element. For example, hydrogen gives off five distinct colors in the visible range of light.

The four visible hydrogen emission spectrum lines in the Balmer series. H-alpha is the red line at the right.

Source: Wikipedia

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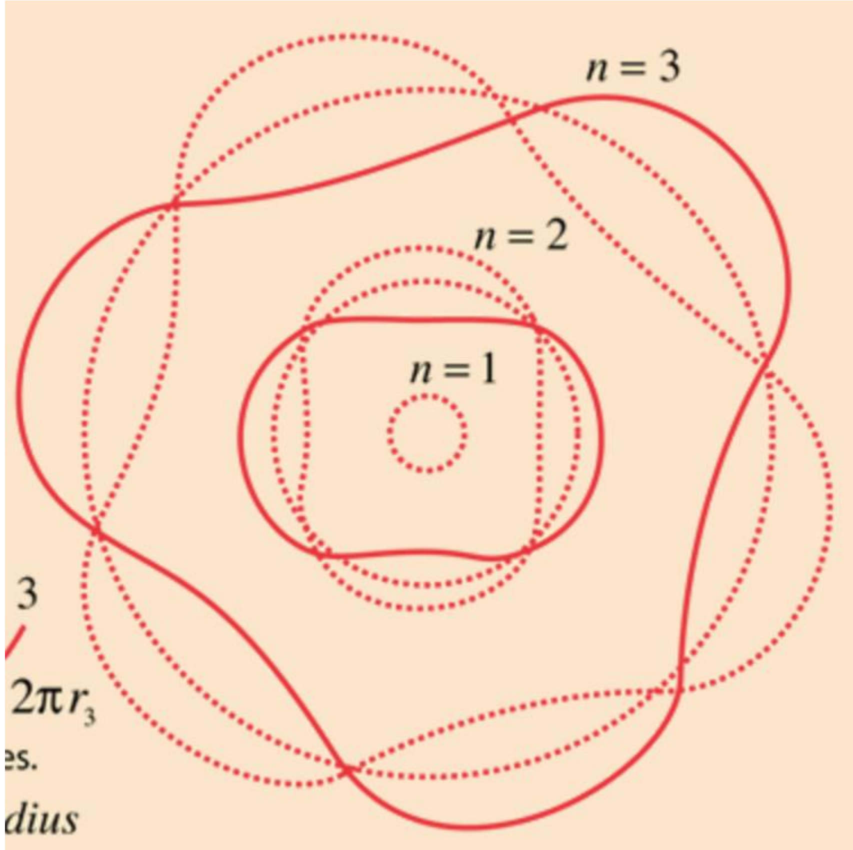

Source: http://hyperphysics.phy-astr.gsu.edu/hbase/Bohr.html

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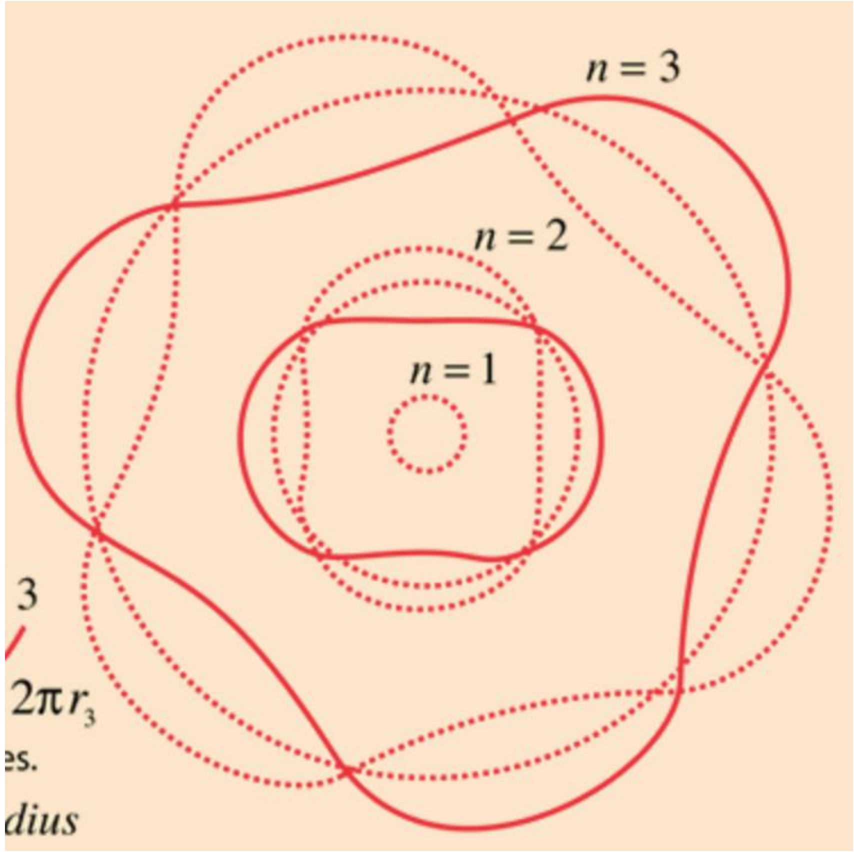

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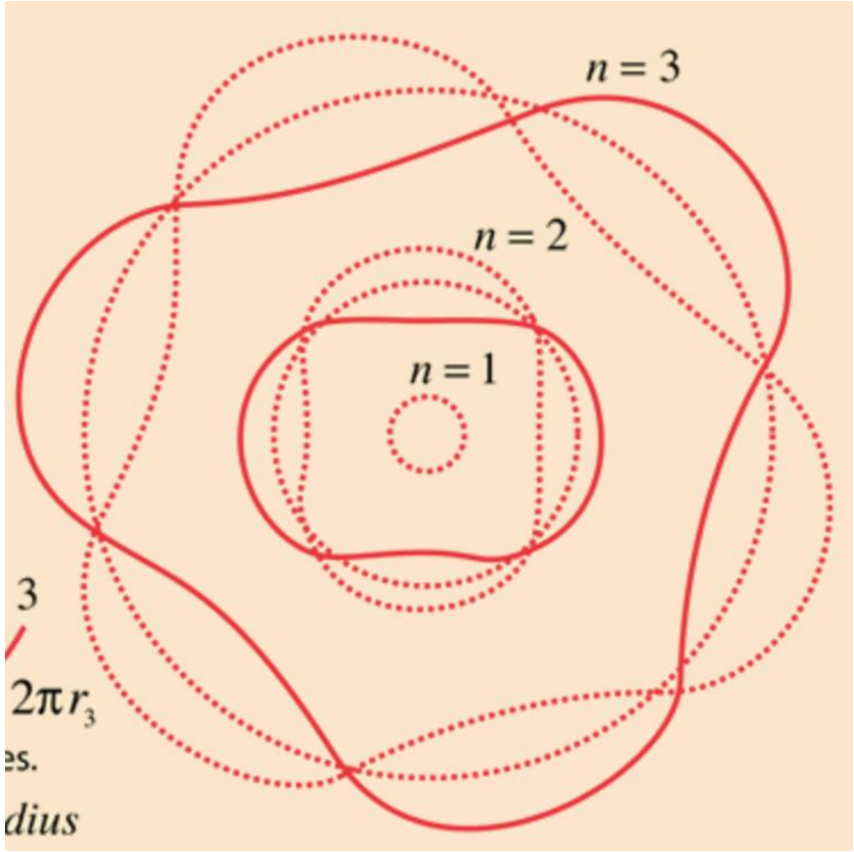

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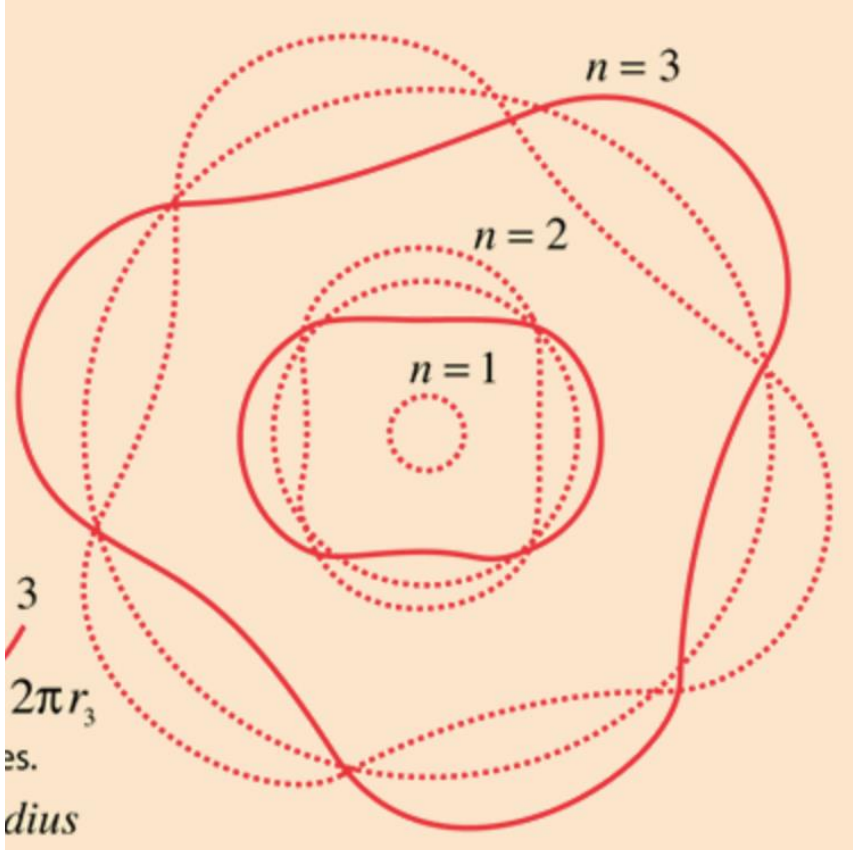
- In these special orbits, the wave lines up with itself perfectly, creating stable energy levels for the atom.



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Introduction to Quantum Mechanics

Wave–particle Duality

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- This strange idea, called **wave–particle duality**, means that everything in nature — light or matter — has both wave-like and particle-like properties.
- Light and electrons **travel or spread out like waves**, showing interference and diffraction, but **exchange energy like particles**, in discrete amounts (quanta).
- So, light and matter are not sometimes waves and sometimes particles — they are **quantum objects** that can show either behavior.

Wave–particle Duality

- The problem is: how do we describe these quantum objects? If we look back, physics used to be written around *what kind of object* something was — either a wave or a particle.

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- It clearly isn't a wave in water or air.
- It isn't an electromagnetic wave either — electrons have mass and charge, not oscillating electric and magnetic fields.
- De Broglie couldn't say what *medium* the wave existed in, or even what was physically "waving."

The Schr$\ddot{o}$dinger's Equations

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This equations is plays a role what F = ma plays in classical physics.

The Schrödinger's Equations

- Newton's second law,

$$F=ma$$

tells you **how a particle moves** when you know the forces acting on it.
If you know where a particle starts (its position and velocity), this equation lets you predict exactly where it will be at any later time.

The Schr$\ddot{o}$dinger's Equations

- In Quantum Mechanics, Schrödinger's equation do that job.

$$i\hbar\frac{\partial\psi}{\partial t} = -\frac{\hbar^2}{2m}\frac{\partial^2\psi}{\partial t^2} + V\psi$$

plays the **same kind of role**, but for the **wave function** ψ .

- Given initial conditions ψ(x,0) , this equations determine ψ(x,t) at later times.

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- By distribution, I mean they are spread out in space. How does this function represent the state of a particle which are localized at the point?
- This is was confusing.

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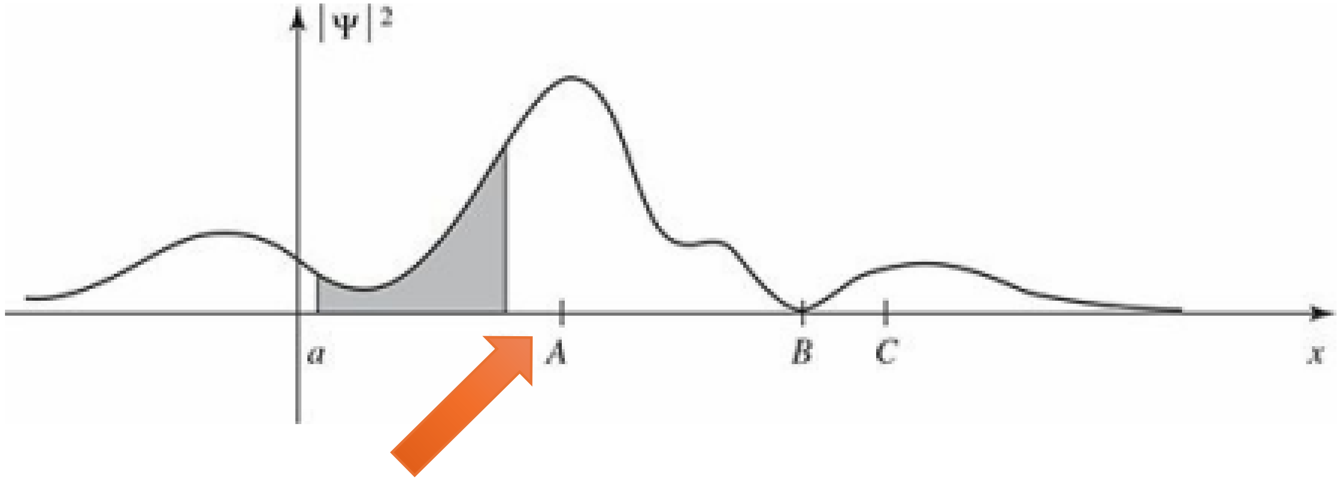
- Born's says that $\psi(x, t)$ is not physical wave but mathematical tool.
- But when you take a square $|\psi(x, t)|^2$, the square of this wave function probability density of finding the particle at x.
- It describes a **wave of probability**.

The Schrӧdinger's Equations

Source: Introduction to Quantum Mechanics by David J. Griffiths



You are mostly like to find particle at A.

The Schrödinger's Equations

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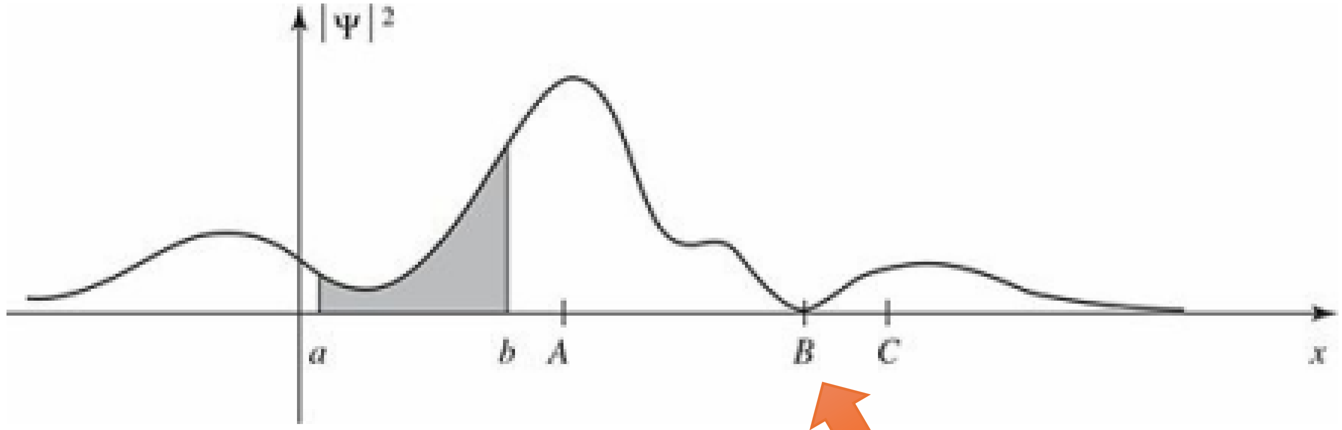

Never at B

The Schrödinger's Equations

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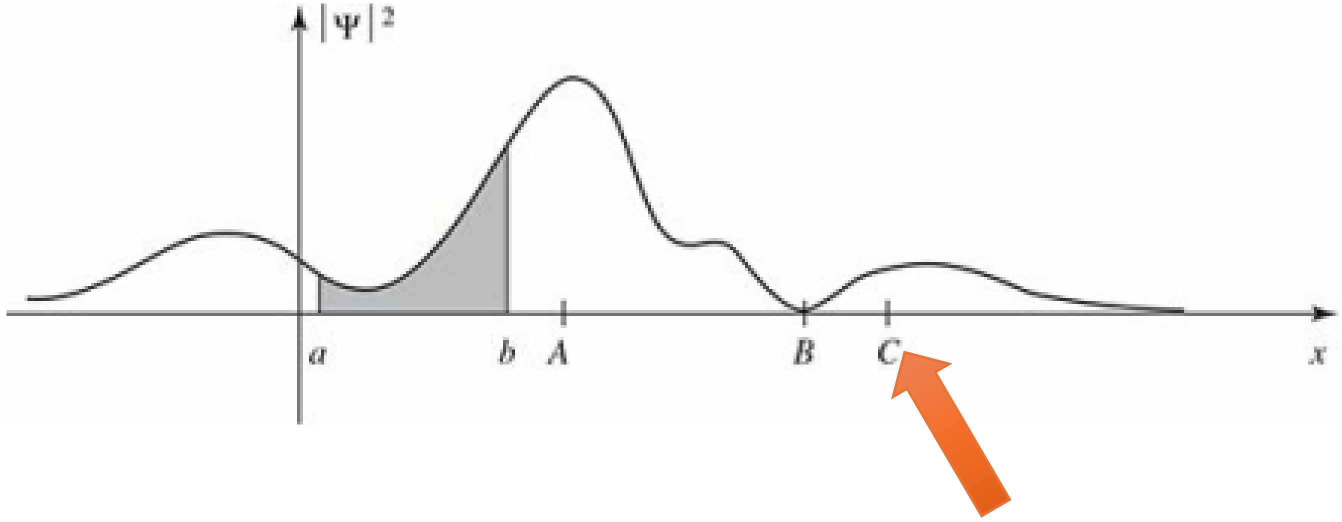

You could also find at c but unlikely.

The Schrödinger's Equations

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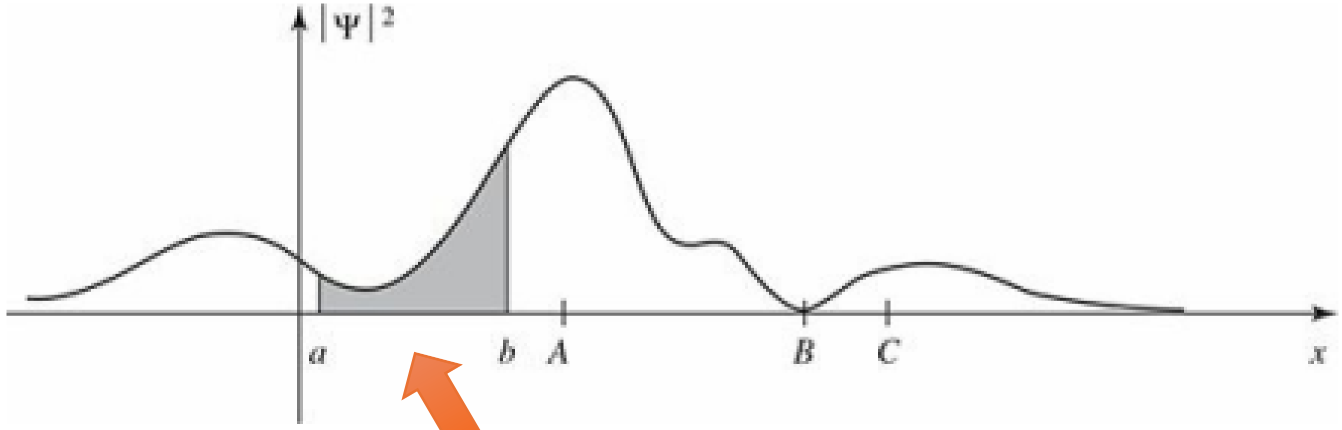

$$\int_a^b |\Psi(x,t)|^2\,dx = \left\{ \begin{array}{l} \text{probability of finding the particle} \\ \text{between } a \text{ and } b, \text{ at time } t. \end{array} \right\}$$

Probability is the area under the graph.

Interpretations of Quantum Mechanics

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- Born’s statistical interpretation adds an element of uncertainty to quantum mechanics.
- Even if we know everything there is to know about a particle—its wave function—we still can’t predict exactly where it will be found when we measure it.
- The best we can do is calculate the probabilities of different outcomes.
- This built-in indeterminacy has puzzled scientists and philosophers ever since. It raises a deep question: is this uncertainty truly a feature of nature itself, or does it reveal a limitation in our theory?

Interpretations of Quantum Mechanics

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There are three possible answers and each one reflects a different way of thinking about quantum mechanics:

1. The realist Position
2. The orthodox Position
3. The agnostic Position

Interpretations of Quantum Mechanics

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- But if this is true, then quantum mechanics must be **incomplete**, because it couldn’t tell us that the particle was already there.
- According to the realist view, the uncertainty in quantum mechanics doesn’t reflect nature itself but it only reflects **our lack of knowledge**.

Interpretations of Quantum Mechanics

The realist position:

- The particle *was* at point **C**. That seems like the most straightforward answer and it's the one Einstein supported.
- But if this is true, then quantum mechanics must be **incomplete**, because it couldn't tell us that the particle was already there.
- According to the realist view, the uncertainty in quantum mechanics doesn't reflect nature itself but it only reflects **our lack of knowledge**.
- In this view, there must be some **hidden information** (often called *hidden variables*) that would, if known, give a complete description of the particle's state.

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- This view, known as the **Copenhagen interpretation**, is most closely associated with **Niels Bohr** and his followers. Among physicists, it has long been the most widely accepted interpretation.
- Still, if this view is correct, it means something very strange is happening during the act of measurement — something we still don't fully understand.

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The agnostic position:

- From this perspective, such questions don't belong to physics at all, because they deal with things that can never be observed or tested. They belong to **metaphysics** and not the useful kind.

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- For many physicists, this has been the **practical stance**: avoid unanswerable questions and focus on what can actually be measured. If pushed too far, they simply reply, “It’s not a meaningful question,” and move on.

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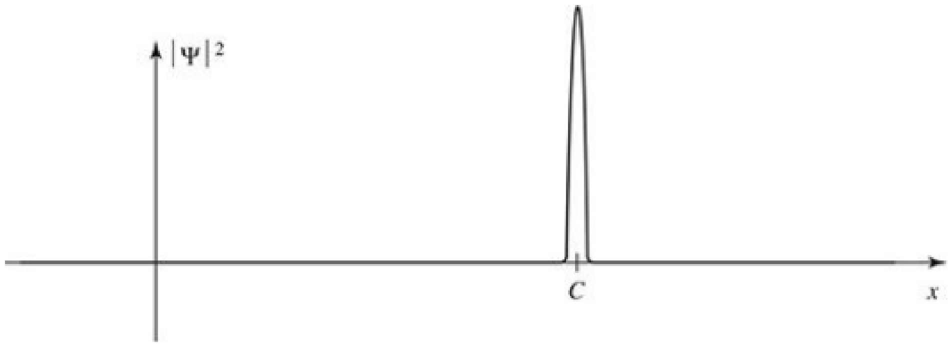
- For a **realist**, this is no surprise: the particle was already sitting at C before the first measurement, you simply discovered it, and when you looked again, it hadn't moved.
- But for the **orthodox (Copenhagen)** interpretation, this needs an explanation. If the particle didn't have a definite position before you measured it, then why does the second measurement always give the same answer?

Interpretations of Quantum Mechanics

- According to this view, the **first measurement collapses the wave function.** It forces the particle's wave, which was once spread out, to become sharply focused around point C. After that, the particle really *is* at C, so the next measurement naturally gives the same result. You have to measure immediately after the first measurement because wave function will evolve with time. If you wait little, you might not get the same answer.



Interpretations of Quantum Mechanics

- So, Copenhagen Interpretation need to add this weird wave function collapse.
- Einstein and even Schrödinger hated this idea.
- Einstein, Podolsky, and Rosen came up with EPR paradoxes to prove Copenhagen interpretation wrong.
- Schrödinger came with Schrödinger’s cat thought experiments.

Spin

- Before we study paradoxes, I want to talk about spin. You need to understand spin to understand the Einstein, Podolsky, and Rosen (EPR) paradox.

Spin

In classical mechanics, a solid object can have **two kinds of angular momentum**:

- **Orbital angular momentum (L):** motion of the whole object around some external point.
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In classical physics, this difference is mostly one of convenience — the Earth's "spin" is really just the total orbital motion of all its rocks and dirt circling around the axis.

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An electron, for instance, has **two** separate kinds of angular momentum:

- **Orbital angular momentum** comes from its motion around the nucleus (like a planet around the Sun) and is described by mathematical functions called **spherical harmonics**.
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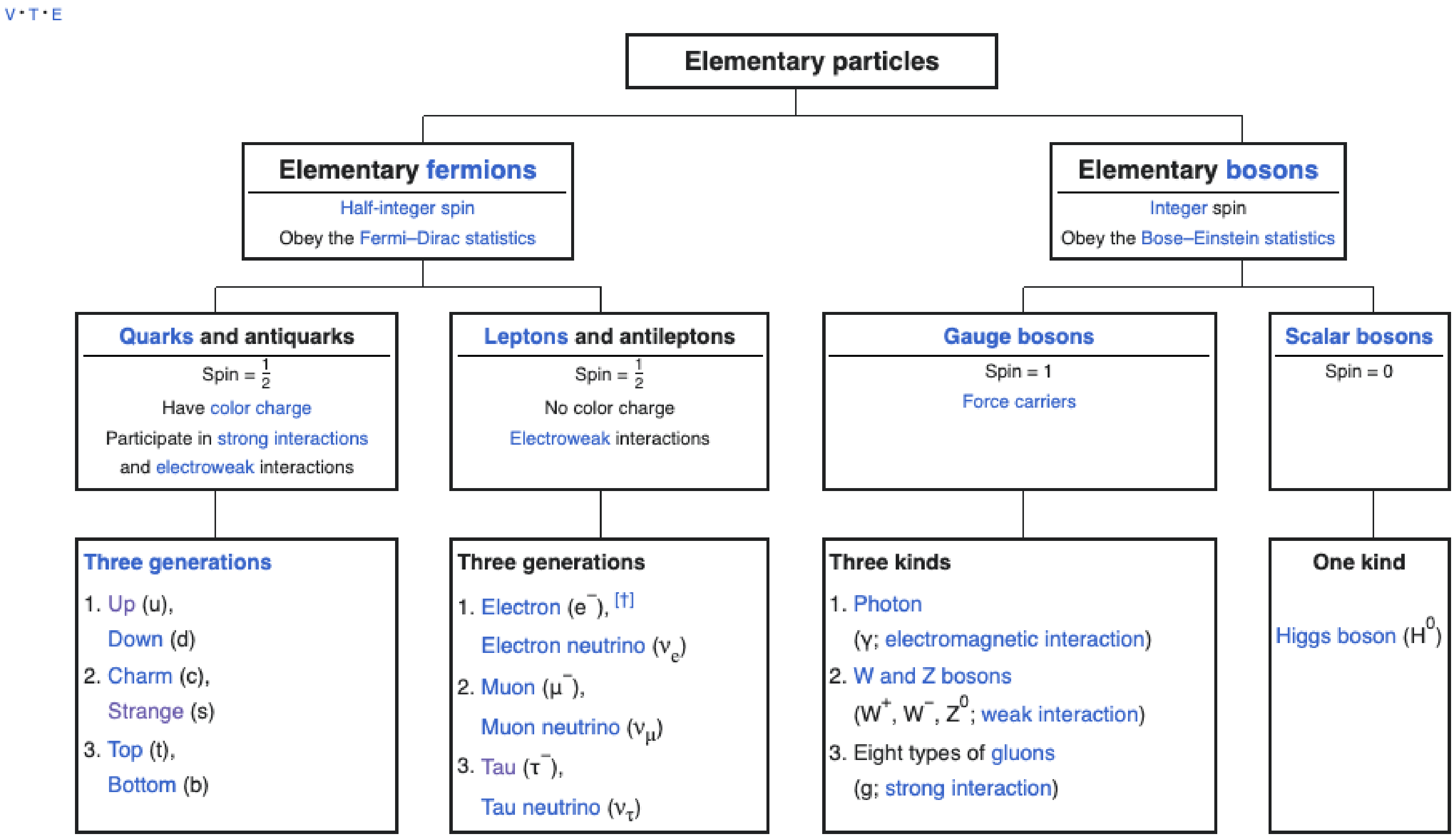
- So in quantum physics, we say that particles carry **intrinsic angular momentum (S)**, in addition to the **extrinsic angular momentum (L)** that comes from motion through space.

Spin

- Spin is an intrinsic angular momentum with a **fixed magnitude** for each particle,though its **direction** can flip (up or down). For example, electron have ½ , pion have spin 0 and photon have spin1.

- Orbital angular momentum, however, **depends on motion** and its **magnitude can change** as the particle moves or interacts.

Spin



Source: Wikipedia

The EPR paradox

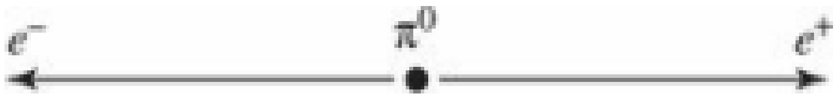
- In 1935, **Einstein, Podolsky, and Rosen (EPR)** published a famous paper that questioned whether quantum mechanics gives a complete description of reality.
- They argued that something must be missing ,some hidden information and that the **realist view** (that particles have definite properties before we measure them) must be correct.

The EPR paradox

- A simpler version of their idea, later described by David Bohm, involves the decay of a neutral pi meson (π^0) into an electron and a positron.

$$\pi^0 \rightarrow e^- + e^+$$

Assuming the pion was at rest before it decayed, the electron and positron must fly off in opposite directions to conserve momentum.



The EPR paradox

- Because the pion had no spin to begin with, the total spin of the two particles after the decay must also add up to zero.
- So when you measure the **electron** and find its spin to be “up,” the **positron’s** spin must immediately be “down.”

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  And at that very instant, the positron's spin must also become definite, no matter how far away it is, so that the total still adds to zero.
- It's as if the measurement on one particle **instantly influences** the other — even if they're on opposite sides of the universe.

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- That influence would have to travel faster than the speed of light, something Einstein’s theory of relativity strictly forbids.
- So he concluded that the orthodox view couldn’t be right — the two particles must have had their specific spins from the moment they were created.

Bell's theorem

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- Only in 1952 did David Bohm propose a valid hidden-variable theory. It was deterministic but nonlocal, involving the same “spooky action at a distance” Einstein disliked.
- For about thirty years after EPR, no one found a local hidden-variable theory that worked.

Bell's theorem

- Finally, in 1964, physicist John Bell showed that no local realist theory — one in which particles have definite properties and no influence travels faster than light — can ever fully agree with the predictions of quantum mechanics.

Bell's theorem

- He showed that if local hidden variables really exist — meaning that each particle carries its own secret "instructions" and nothing travels faster than light — then the correlations between the measurements of two distant particles can never exceed certain limits. These limits are known as Bell inequalities.

$$|P(\vec{a},\vec{b}) - P(\vec{a},\vec{c})| \leq 1 + P(\vec{b},\vec{c}).$$

Source: Wikipedia

Bell’s theorem

- If quantum mechanics were really a local hidden-variable theory then it must satisfy Bell’s inequality.
- But in real experiments, quantum mechanics violates that inequality.
- That means the world cannot be explained by any local hidden-variable theory — nature is either nonlocal (allowing instant connections) or not determined until measurement.

Bell's Theorem

- If the electron's measurement could actually cause the positron's result in a way that the electron's side could control and the positron's side could detect just by looking at its own data, then quantum mechanics would truly conflict with special relativity, because that would mean information traveling faster than light.
- But quantum mechanics is still compatible with special theory of relativity.

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- The positron's result will always match (be opposite, if that's how they're entangled), but neither side can choose what result to get.
- Because the outcomes are random, no one can control what happens — so you can't use this effect to send a message faster than light.

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- We probably need a deeper theory to understand this measurement and wave function collapses.

Uncertainty Principle

- On Blackboard

What is Quantum in Quantum Mechanics?

- Electron has a wave function associated with it.
- For example, a guitar string can only vibrate in certain ways — only those that make the ends stay fixed.
- That means it can only have certain wavelengths, and therefore certain frequencies (or energies).

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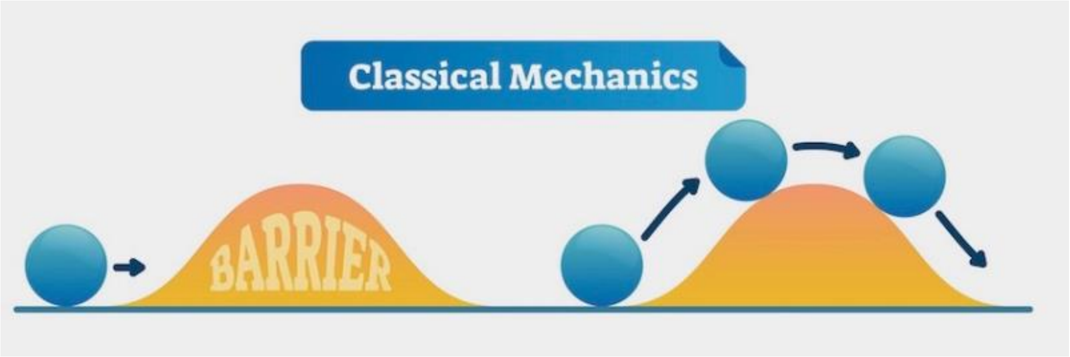
- Only specific wave patterns “fit” around the atom — so the electron can only have certain allowed energies.
- That’s why energy levels in atoms are quantized: they come in discrete steps, just like the notes of a guitar string.
- Quantization is not mysterious — it’s exactly what you’d expect when nature behaves like waves that have to fit certain boundary conditions.

Quantum Tunneling



Source: https://cosmosmagazine.com/science/physics/quantum-tunnelling-is-instantaneous-researchers-find/

In classical physics, if a particle doesn’t have enough energy to climb over a barrier, it just stops — like a ball that rolls up a hill and rolls back down.

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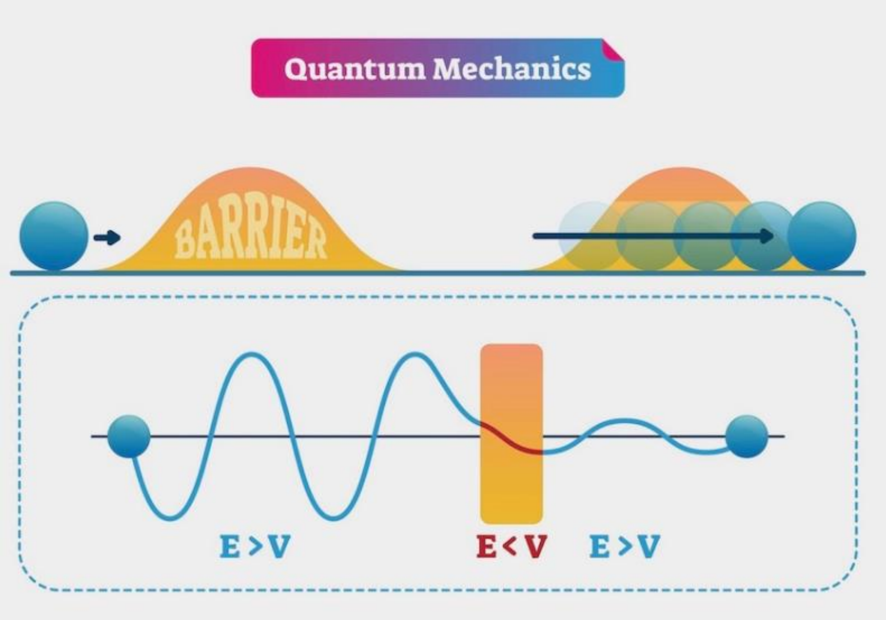

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But in quantum mechanics, particles behave like waves.
A wave doesn't suddenly end at a barrier — it can extend a little bit inside, even into regions where the particle *shouldn't* be allowed.
If the barrier is thin enough, part of that wave can actually leak through to the other side — and there's a small chance the particle will appear there.
That's called **quantum tunneling.**

Quantum Tunneling

- Like most quantum effects, tunneling doesn’t really happen for large, everyday objects such as roller coasters or people.
- The chances are so incredibly tiny that, for all practical purposes, they’re zero — it’s more of a thought experiment than a real possibility.

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- In radioactive decay, particles tunnel out of the nucleus constantly.
- In modern electronics, tunneling is used in tunnel diodes and scanning tunneling microscopes (STM), where electrons pass through barriers only a few atoms thick.

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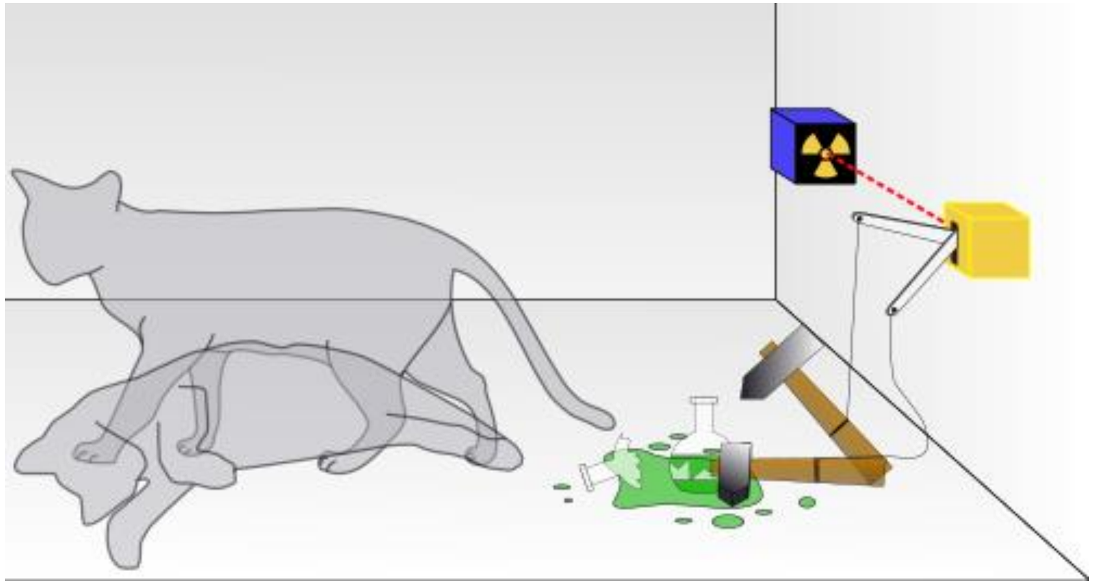

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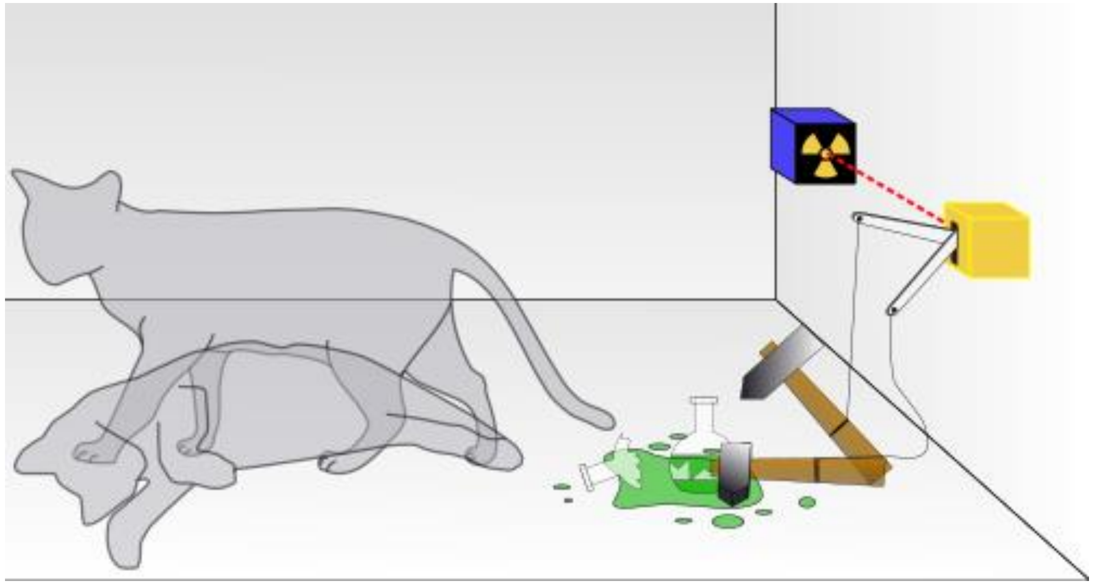

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- After an hour, there's a 50% chance the atom has decayed and a 50% chance it hasn't.
  According to quantum mechanics, before we open the box, the atom is in a superposition — both decayed and not decayed — and therefore, the cat should also be both alive and dead at the same time.
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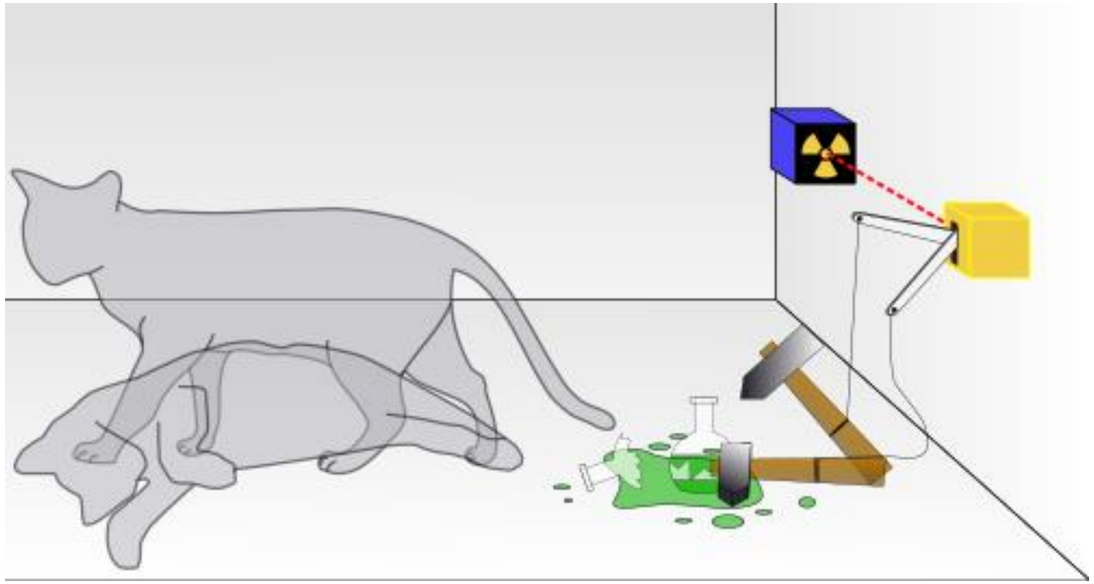

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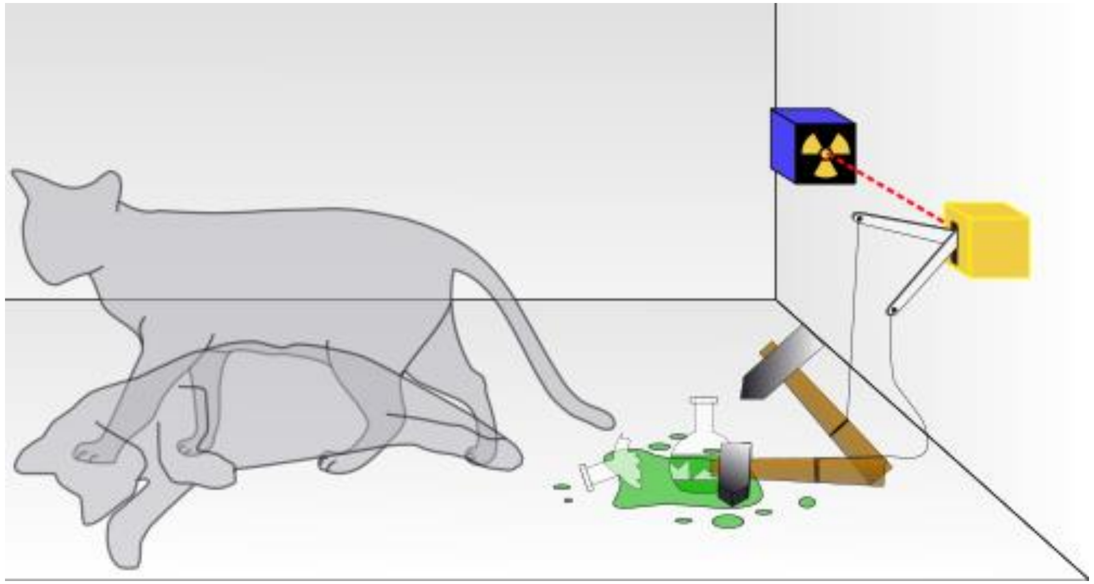
  Only when we look does the wave function "collapse," and the cat becomes definitely alive *or* dead.
- Schrödinger thought this was nonsense. He argued that while an electron might exist in a mix of "spin up" and "spin down," a cat cannot literally be both alive and dead. And the idea that simply *looking* at the cat could decide its fate seemed ridiculous.



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- Some say measurement occurs when an irreversible record is made (for instance, when the vial of poison breaks).
- Most physicists today agree that the collapse happened long before you opened the box — when the poison was released, not when you peeked. So, you're not guilty of "killing" the cat!

Questions

- Why macroscopic object like human, table, chair don’t have quantum superposition of different states?