


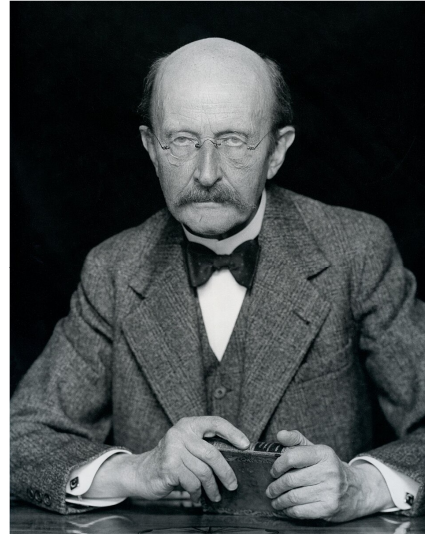
**Quantum Theory**  
aka Quantum Mechanics or Quantum Physics



Quantum theory describes the behavior of matter and energy on very small scales, such as atoms and subatomic particles

## The Birth of Quantum Theory

- 1900 – Max Planck introduces the concept of quanta of energy (Blackbody radiation)
- Light can only be emitted in quantized form → the energy can only be a multiple of a constant
- 1918 Nobel Prize in Physics – discovery of energy quanta



Max Planck 1858 - 1947



## DETOUR: The Nature of Light

Sir Isaac Newton –  
Corpuscular theory  
of light  
→ Light is a **Particle**



## Wave Theory of Light

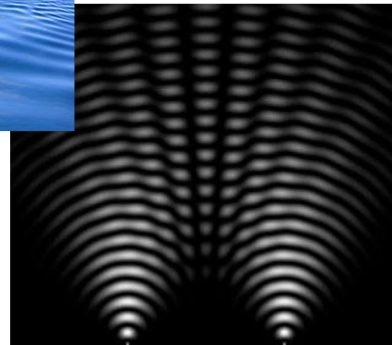


Christiaan Huygens



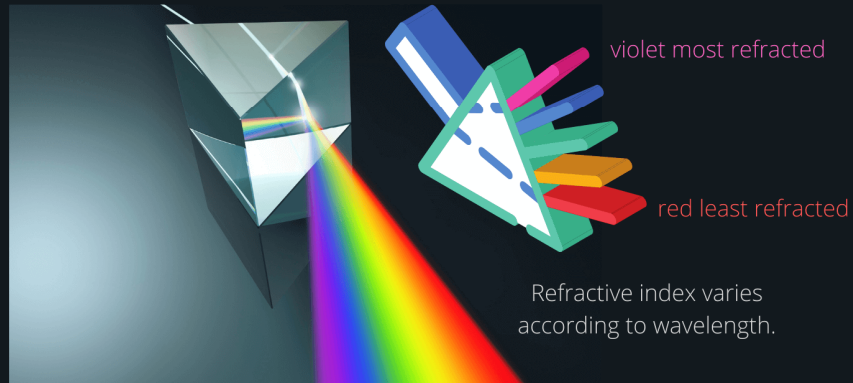
Thomas Young

Light exhibits wavelike properties similar to those of water waves and sound waves  
**Interference**



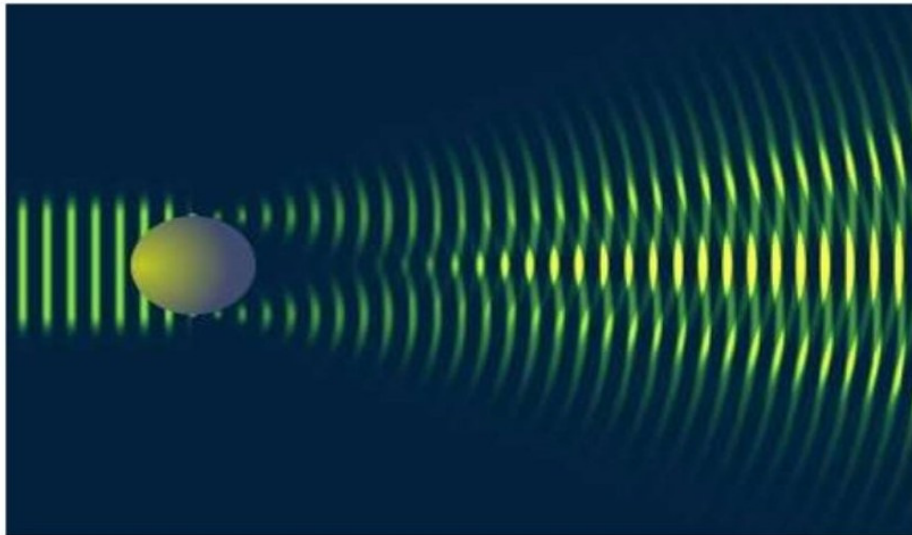
## Refraction

Refraction is the change in the speed and direction of a wave passing from one medium into another.



sciencenotes.org

## Diffraction

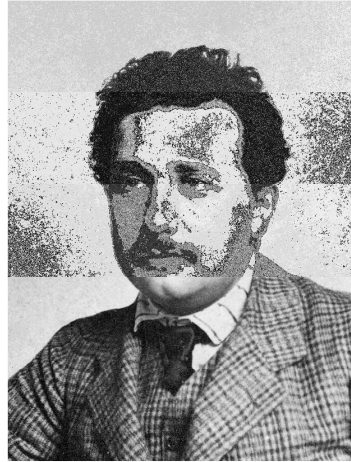


Conclusion: Light is a **Wave**

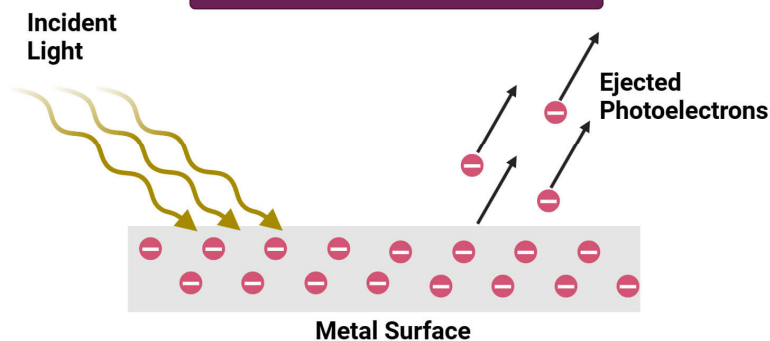
In 1921 Einstein received the Nobel Prize in Physics for "his services to theoretical physics, and especially for his discovery of the law of the **photoelectric effect**."

Light is composed of Particles →  
**Photon**: Particle of light that carries a quantum of energy

Einstein's paper on the photoelectric effect was only 16 pages in length



### Photoelectric Effect



- Photons incident on certain metals can result in atomic electrons being ejected from the metal's atoms.
- Regardless of the intensity of the light beam, photons below a certain energy have no effect

What is it good for?

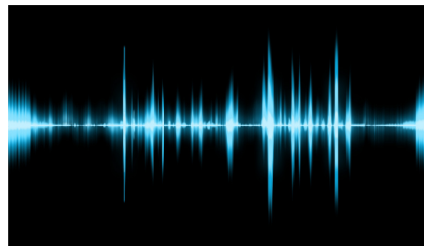
Enough light falling on a 'photoelectric'  
material can produce an electric current



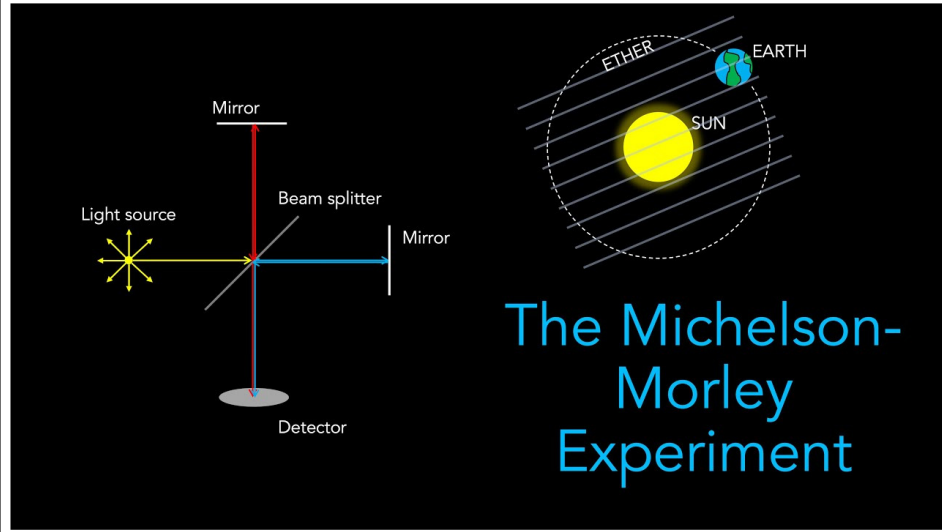
### Is light a Wave or a Particle?

'Mechanical' waves needs a medium to  
travel through

- Ocean waves travel through water
- Sound waves travel through air



Does space contain an Ether through which light propagates as a wave?



**Michelson-Morley Experiment (1887)**

The Earth moving through the ether wind is analogous to a boat moving with or against a current

### Michelson-Morley Experiment conclusions:

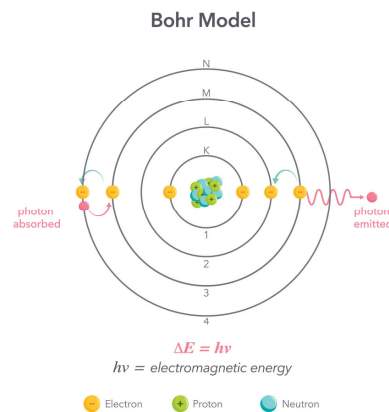
- Evidence in support of the Special Theory of Relativity since it demonstrated that the speed of light is constant regardless of the motion of the light source
- No ether → Light not a wave since there exists no medium for the wave to travel through
- Therefore, light is a Particle (?)

### Niels Bohr (1885 – 1962) and the Bohr Atom



1922 -Nobel Prize in Physics

Bohr Model developed 1911 - 1918

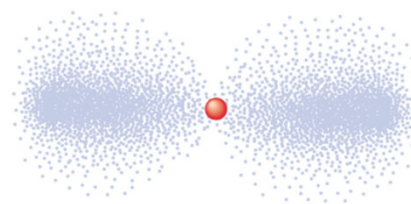


Atomic electrons can only occupy certain discrete (quantized) energy states

- Electrons **don't orbit** the nucleus of an atom like planets orbit the Sun
- Instead, they prefer to 'hang out' in certain regions in the vicinity of the nucleus based on their energy



An s orbital

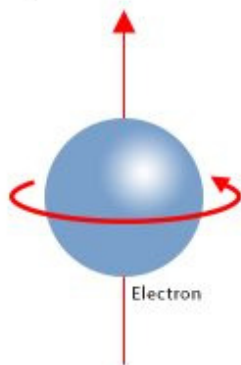


A p orbital

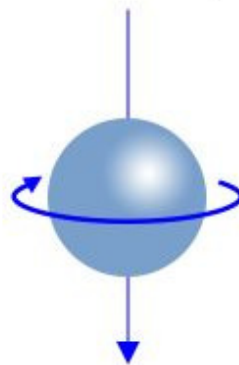
One of the properties of an electron is called **Spin** with values of  $\frac{1}{2}$  or  $-\frac{1}{2}$

### Spin Quantum Number ( $m_s$ )

$m_s$  indicates the orientation of the electron spin



$$m_s = +\frac{1}{2} \Rightarrow \text{"Spin-up"}$$



$$m_s = -\frac{1}{2} \Rightarrow \text{"Spin-down"}$$

ChemistryLearner.com

## The Pauli Exclusion Principle (1924)



Wolfgang Pauli 1900 – 1976  
Nobel Prize in Physics 1945

- Two or more identical particles with half-integer spins (i.e., fermions) cannot simultaneously occupy the same quantum states
- Hence, electron energy shells

Note: Pauli also predicted the **neutrino** (necessary to explain Beta Decay)

## Pauli Exclusion Principle

Electrons don't like crowds; that is, instead of this ...

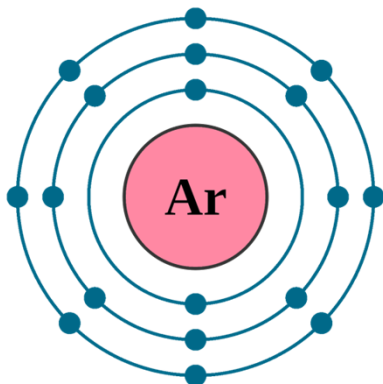


THIS!

Three blue smiley faces representing electrons, each occupying its own separate quantum state, arranged vertically.

## Pauli Exclusion Principle – No two electrons can share the same set of four quantum numbers

Argon Atom  
18 Electrons



Shell	Subshell	# Electrons
K	1s	2
L	2s	2
	2p	6
M	3s	2
	3p	6
	3d	(10)



The presenter apologizes for bringing up any unpleasant memories of High School Chemistry

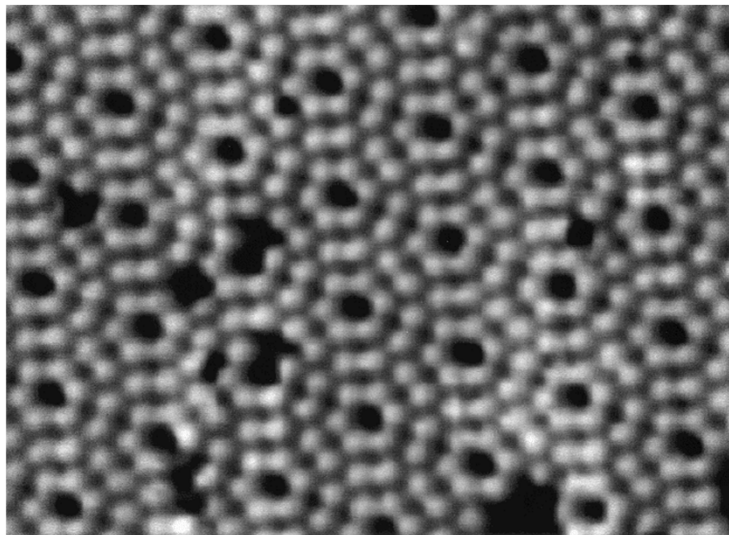
# PERIODIC TABLE OF ELEMENTS

PubChem

1 <b>H</b> Hydrogen Nonmetal																	2 <b>He</b> Helium Noble Gas																		
3 <b>Li</b> Lithium Alkali Metal	4 <b>Be</b> Beryllium Alkali Earth Metal																	10 <b>Ne</b> Neon Noble Gas																	
11 <b>Na</b> Sodium Alkali Metal	12 <b>Mg</b> Magnesium Alkali Earth Metal																	18 <b>Ar</b> Argon Noble Gas																	
19 <b>K</b> Potassium Alkali Metal	20 <b>Ca</b> Calcium Alkali Earth Metal	21 <b>Sc</b> Scandium Transition Metal	22 <b>Ti</b> Titanium Transition Metal	23 <b>V</b> Vanadium Transition Metal	24 <b>Cr</b> Chromium Transition Metal	25 <b>Mn</b> Manganese Transition Metal	26 <b>Fe</b> Iron Transition Metal	27 <b>Co</b> Cobalt Transition Metal	28 <b>Ni</b> Nickel Transition Metal	29 <b>Cu</b> Copper Transition Metal	30 <b>Zn</b> Zinc Transition Metal	31 <b>Ga</b> Gallium Post-Transition Metal	32 <b>Ge</b> Germanium Metalloid	33 <b>As</b> Arsenic Metalloid	34 <b>Se</b> Selenium Nonmetal	35 <b>Br</b> Bromine Halogens	36 <b>Kr</b> Krypton Noble Gas																		
37 <b>Rb</b> Rubidium Alkali Metal	38 <b>Sr</b> Strontium Alkali Earth Metal	39 <b>Y</b> Yttrium Transition Metal	40 <b>Zr</b> Zirconium Transition Metal	41 <b>Nb</b> Niobium Transition Metal	42 <b>Mo</b> Molybdenum Transition Metal	43 <b>Tc</b> Technetium Transition Metal	44 <b>Ru</b> Ruthenium Transition Metal	45 <b>Rh</b> Rhodium Transition Metal	46 <b>Pd</b> Palladium Transition Metal	47 <b>Ag</b> Silver Transition Metal	48 <b>Cd</b> Cadmium Transition Metal	49 <b>In</b> Indium Post-Transition Metal	50 <b>Sn</b> Tin Post-Transition Metal	51 <b>Sb</b> Antimony Metalloid	52 <b>Te</b> Tellurium Metalloid	53 <b>I</b> Iodine Halogens	54 <b>Xe</b> Xenon Noble Gas																		
55 <b>Cs</b> Cesium Alkali Metal	56 <b>Ba</b> Barium Alkali Earth Metal		72 <b>Hf</b> Hafnium Transition Metal	73 <b>Ta</b> Tantalum Transition Metal	74 <b>W</b> Tungsten Transition Metal	75 <b>Re</b> Rhenium Transition Metal	76 <b>Os</b> Osmium Transition Metal	77 <b>Ir</b> Iridium Transition Metal	78 <b>Pt</b> Platinum Transition Metal	79 <b>Au</b> Gold Transition Metal	80 <b>Hg</b> Mercury Transition Metal	81 <b>Tl</b> Thallium Post-Transition Metal	82 <b>Pb</b> Lead Post-Transition Metal	83 <b>Bi</b> Bismuth Metalloid	84 <b>Po</b> Polonium Metalloid	85 <b>At</b> Astatine Halogens	86 <b>Rn</b> Radon Noble Gas																		
87 <b>Fr</b> Francium Alkali Metal	88 <b>Ra</b> Radium Alkali Earth Metal		104 <b>Rf</b> Rutherfordium Transition Metal	105 <b>Db</b> Dubnium Transition Metal	106 <b>Sg</b> Seaborgium Transition Metal	107 <b>Bh</b> Bohrium Transition Metal	108 <b>Hs</b> Hassium Transition Metal	109 <b>Mt</b> Meitnerium Transition Metal	110 <b>Ds</b> Darmstadtium Transition Metal	111 <b>Rg</b> Roentgenium Transition Metal	112 <b>Cn</b> Copernicium Transition Metal	113 <b>Nh</b> Nihonium Post-Transition Metal	114 <b>Fl</b> Flerovium Post-Transition Metal	115 <b>Mc</b> Moscovium Post-Transition Metal	116 <b>Lv</b> Livermorium Post-Transition Metal	117 <b>Ts</b> Tennessine Halogens	118 <b>Og</b> Oganesson Noble Gas																		
																		57 <b>La</b> Lanthanum Lanthanide	58 <b>Ce</b> Cerium Lanthanide	59 <b>Pr</b> Praseodymium Lanthanide	60 <b>Nd</b> Neodymium Lanthanide	61 <b>Pm</b> Promethium Lanthanide	62 <b>Sm</b> Samarium Lanthanide	63 <b>Eu</b> Europium Lanthanide	64 <b>Gd</b> Gadolinium Lanthanide	65 <b>Tb</b> Terbium Lanthanide	66 <b>Dy</b> Dysprosium Lanthanide	67 <b>Ho</b> Holmium Lanthanide	68 <b>Er</b> Erbium Lanthanide	69 <b>Tm</b> Thulium Lanthanide	70 <b>Yb</b> Ytterbium Lanthanide	71 <b>Lu</b> Lutetium Lanthanide			
																		89 <b>Ac</b> Actinium Actinide	90 <b>Th</b> Thorium Actinide	91 <b>Pa</b> Protactinium Actinide	92 <b>U</b> Uranium Actinide	93 <b>Np</b> Neptunium Actinide	94 <b>Pu</b> Plutonium Actinide	95 <b>Am</b> Americium Actinide	96 <b>Cm</b> Curium Actinide	97 <b>Bk</b> Berkelium Actinide	98 <b>Cf</b> Californium Actinide	99 <b>Es</b> Einsteinium Actinide	100 <b>Fm</b> Fermium Actinide	101 <b>Md</b> Mendelevium Actinide	102 <b>No</b> Nobelium Actinide	103 <b>Lr</b> Lawrencium Actinide			

### Photo of Atomic Structure

Each sphere is the electron cloud of an individual atom

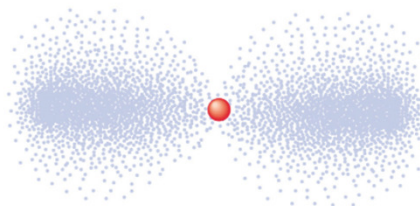


### Quantum Theory Interpretation

- Electrons 'blink on and off' appearing in one location then another
- Can never predict where an electron will be
- Can only predict the probability of it being in a specific location



An s orbital



A p orbital

## The Pauli "Effect"

- Technical equipment suddenly breaking down when Pauli was present: experiments failed, machinery gave up the ghost and appliances got broken.
- Otto Stern wanted to deny Wolfgang Pauli access to his institute for fear of such mishaps.
- Ongoing goal of physicists of the time was to determine the range of the Pauli Effect.

Pauli himself was aware of this strange "gift"



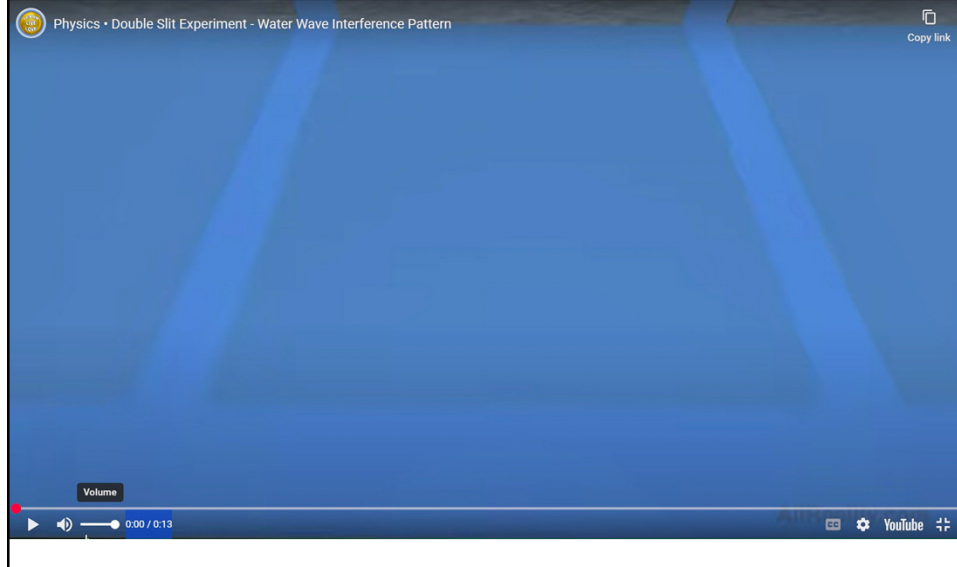
## Is light a Wave or a Particle?

### Interference Patterns

- Throw two stones into a pond
- Resulting circular ripple (wave) water patterns from each stone with Interfere with each other

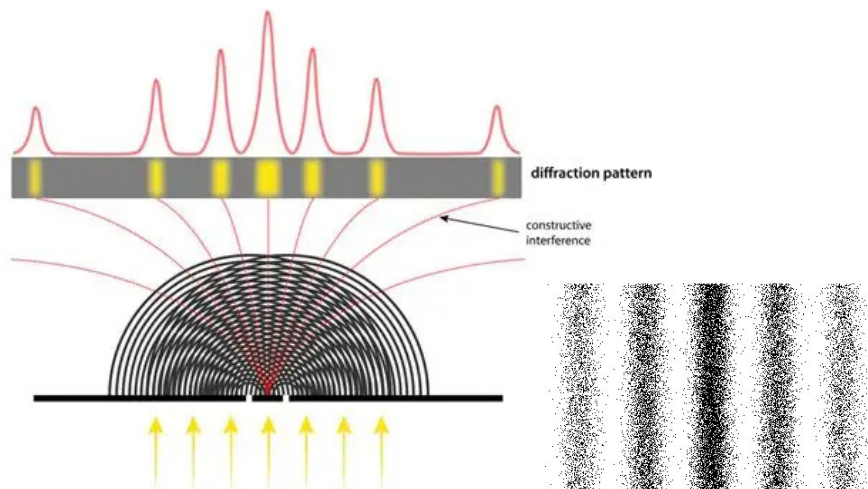


# Double-Slit Experiment



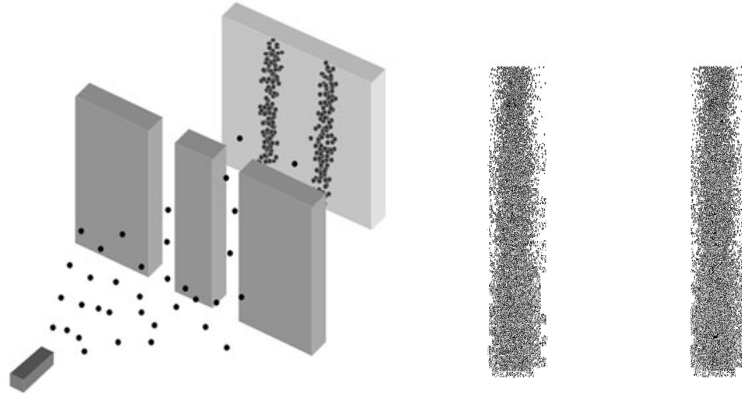
1801 – Thomas Young. Passing light through a double-slit results in an Interference Pattern just like that produced by water waves.

**Light is a Wave**

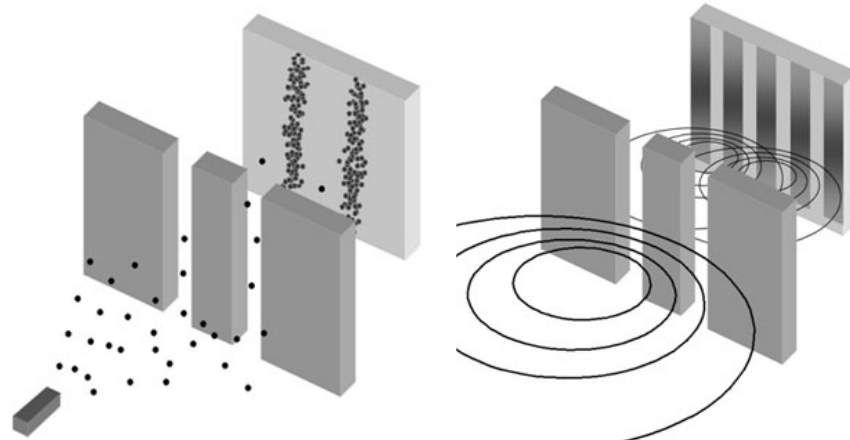


Instead of Light, perform the experiment with  
Bullets.

**Bullets behave like Particles**



Similar experiment using Bullets!  
Bullets behave like particles.



Double-slit with Bullets

Double-slit with Waves



So? Perform the  
experiment with  
Electrons.  
Are Electrons  
Particles or  
Waves?

PARTICLES  
Of Course!



Send Photons through a Single Slit  
**We get an Wavelike Interference Pattern**



Send Electrons through a Single Slit

**We get a Particle-like Pattern**

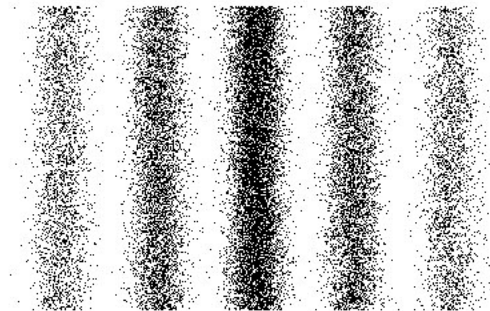
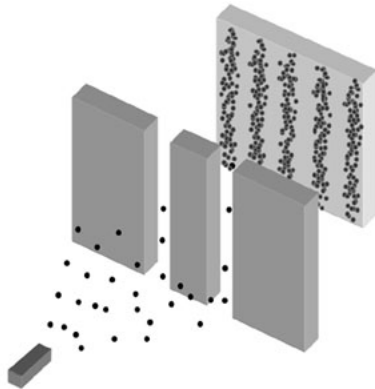


So,  
what's  
the big  
deal?



1927 – Davisson and Germer perform Double-slit Experiment with Electrons.

**GET THE SAME BEHAVIOR AS WITH LIGHT!**



Billy:  
 "Golly, gee, Mr.  
 Wizard. I don't  
 get it.



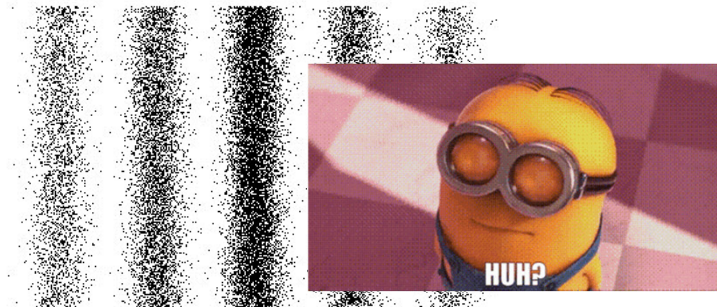
How come electrons act like Particles when there is only one slit open, and act like Waves when there are two slits open?

I have an idea. Suppose we only send one Electron through at a time?"

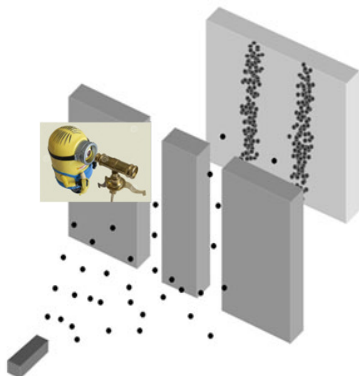
Mr. Wizard: "Great idea, Billy. We have actually done such experiments."

- We send one Electron through at a time and record where each lands on the screen.
- Note that each Electron makes a dot where it lands on the screen; i.e., it does NOT make a blurry pattern like a wave would.
- Eventually we have thousands of dots recorded.
- What we get is ...

**AN INTERFERENCE PATTERN!**

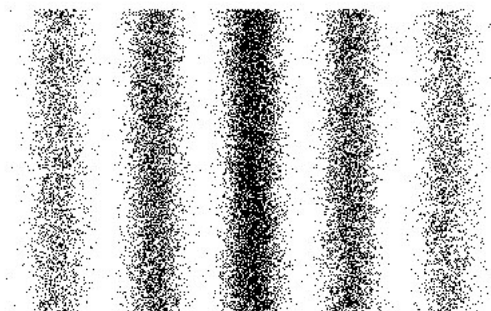


- It's like somehow the Electron "knows" whether or not there is a Second Slit!
- Install a detector at one of the slits to determine which slit each particle passes through.
- The detector records about half of the Electrons pass through its Slit.



**Electrons are  
back to  
behaving like  
Particles!**

- One more try. Tell Stewart (the Minion) to close his eye, that is, don't look.
- Don't tell the Electrons that Stewart isn't looking.
- And the Electrons behave like ...



**WAVES!**

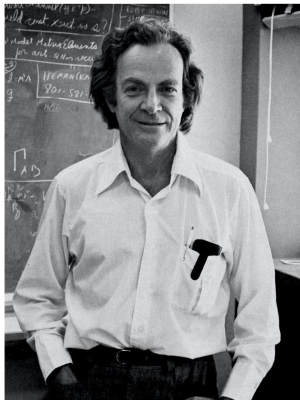
What is going on?  
 Isn't an electron a Particle?  
 How can a Particle act like a Wave?



Even sending one electron at a time through a double slit apparatus showed the same interference pattern—that is, a single electron **interfered with itself**, behaving like a wave.

It just isn't Electrons.  
 Same behavior with any Quantum Entity:  
 Protons, Neutrons, Atoms

**Why?**



“I think I can safely say that nobody understands quantum mechanics ... Do not keep saying to yourself, if you can possibly avoid it, “But how can it be like that?” because you will go “down the drain” into a blind alley from which nobody has yet escaped. Nobody knows how it can be like that.” – Richard Feynman

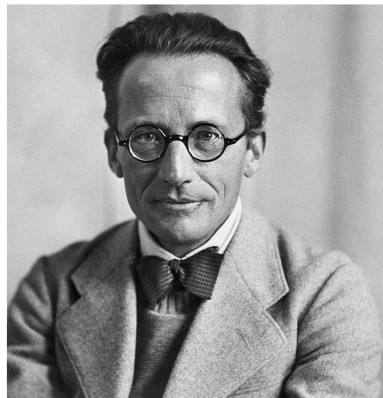
## Wave-Particle Duality of Matter



Louis de Broglie 1892 – 1987  
Nobel Prize in Physics 1933  
(shared with Erwin Schrodinger)

- Like photons, particles such as electrons, neutrons and protons have an associated wavelength depending on their energy (1924).
- 'Explains' why electrons and photons behave similarly in the double-slit experiment.

## The Schrodinger Wave Equation



Erwin Schrodinger  
1887 – 1961  
Nobel Laureate in  
Physics 1933

Every quantum system has associated with it a Probability Wave  $\Psi^*$  or 'wavefunction' (1926, inspired by de Broglie)

\* Not to be confused with the wavelength of a photon

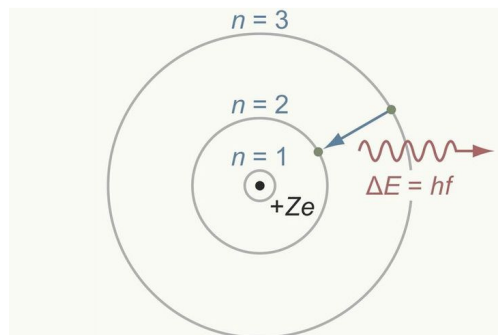
## Statistical Interpretation of Quantum Theory Max Born (1882 – 1970)

- The 'wave' in Schrödinger's wave equation,  $\Psi$ , is related to the location of the subatomic particle it is associated with.
- $\Psi^2$  gives the probability of the particle being at that location.
- Nobel Prize in Physics - 1954



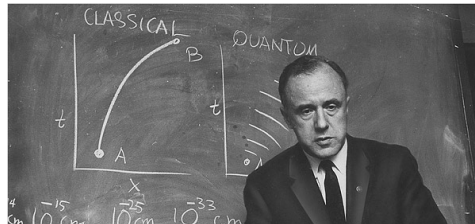
### Quantum Theory Interpretation (cont.)

- Electron 'orbits' correspond to different electron energies
- When an atom emits energy in the form of light, electron **disappears** from one orbit and **appears** in another lower energy orbit
- Electron does not *move* from one orbit to the other



## Quantum Theory Interpretation (cont.)

- Schrodinger intended his wave mechanics to explain what happens during the jump, but it didn't
- "If all this damned quantum jumping were really here to stay, I should be sorry I ever got involved with quantum theory." – Schrodinger
- Turns out, so far *quantum jumping* has been here to stay



John Wheeler  
(1911 – 2008)  
Nuclear fission,  
General Relativity,  
Black Holes

In the fall of 1940, Richard Feynman received a telephone call from Wheeler [Feynman's thesis advisor] at the Graduate College in Princeton, in which he [Wheeler] said that he knew why all electrons have the same charge and the same mass. "Why?" asked Feynman, and Wheeler replied,

**"Because they are all one and the same electron."**

## SUPERPOSITION

- Particle can exist in a superposition of states (both slits) and behave like a Wave
- Once measured, this superposition collapses, and the particle acts like classical Particle
- That is, once you look at (i.e., detect or measure) a particle, the 'wavefunction' collapses into a single point which identifies the particle's location

So... is light a Wave or a Particle?  
Just answer the #%\*@! Question!



- A photon is a quantum entity so it exists in a superposition of states (e.g., both Particle and Wave) until it is measured.
- At that point, depending on what is being measured, it behaves like either a Particle or Wave.



## Heisenberg Uncertainty Principle



Werner Heisenberg 1901 -  
1976  
Nobel Prize in Physics 1932

- Matrix Mechanics – An alternative mathematical formulation of quantum theory (1925) \*
- **Uncertainty Principle** (1927)

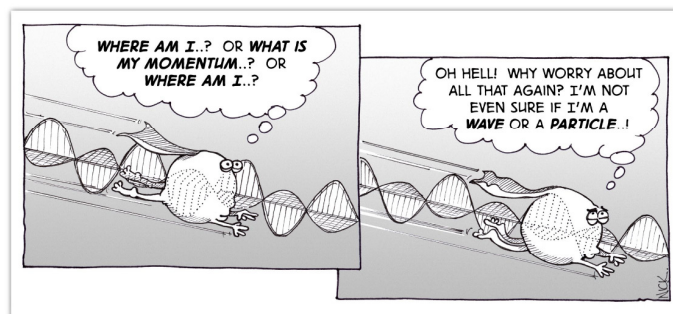
\* Schrodinger showed that Heisenberg's matrix mechanics and his wave mechanics were identical

## Heisenberg Uncertainty Principle

- Cannot exactly determine both location and momentum (speed) of a quantum object simultaneously.
- The more certain where the it is, the less certain about it's speed (momentum)
- The more certain about it's speed (momentum), less certain about where it is
- **The Joke: Heisenberg part**
- To some extent, due to the difficulty of making a measurement (location) of a quantum object (electron) since you need to bounce another quantum object (photon) off it which in turn changes its momentum

## Heisenberg Uncertainty Principle

- Quantum uncertainty is related to wave-particle duality
- Momentum related to motion  $\rightarrow$  wave property since waves must be moving
- Location is a definite particle property



Photon self-identity issues

Uncertainty Principles 'explains' why the probability of certain nuclear reactions is greater than what would be predicted by classical physics

Classical Physics: Little chance of collision



Quantum Physics: Uncertainty in location and momentum of target → greater chance of collision



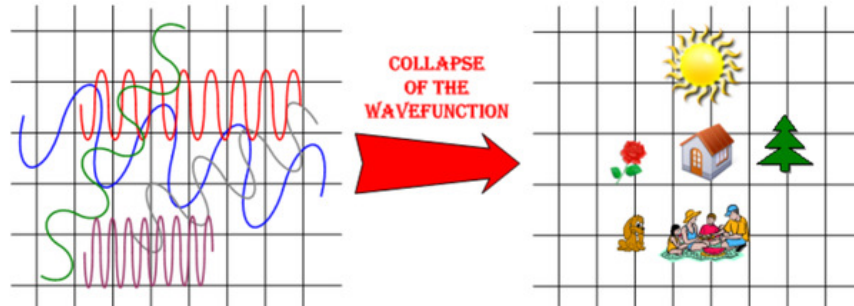
- The state of a subatomic particle is *unknown* until it interacts with its surroundings at which time its wave function collapses.



*The Collapse of the Wave Function*

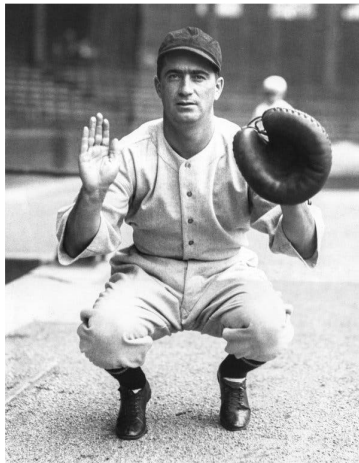
- This interaction is called an *observation*.
- It is essentially the quantum physics equivalent of a measurement that connects the wave function to classical observations such as location and speed.

The universe exists in a fuzzy, wavy state until the wave function collapses.



When does the wave function collapse?  
When one makes an observation.

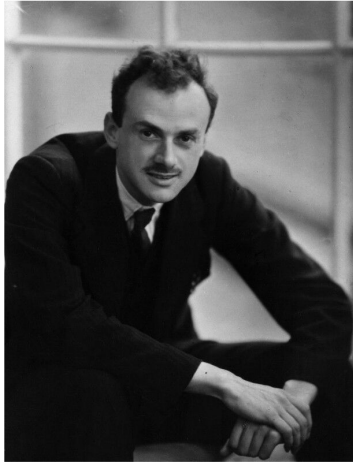
### Heisenberg and the Ballplayer



Morris "Moe" Berg  
1902 – 1972  
2018 film *The Catcher Was a Spy*

- Morris Berg played catcher for both the Boston Red Sox and Chicago White Sox
- Graduate of Princeton University and Columbia Law School
- Spoke several languages and daily read 10 newspapers
- WWII OSS operative to assess German progress on an atomic bomb
- Attended Heisenberg's Dec. 1944 lecture in Zurich

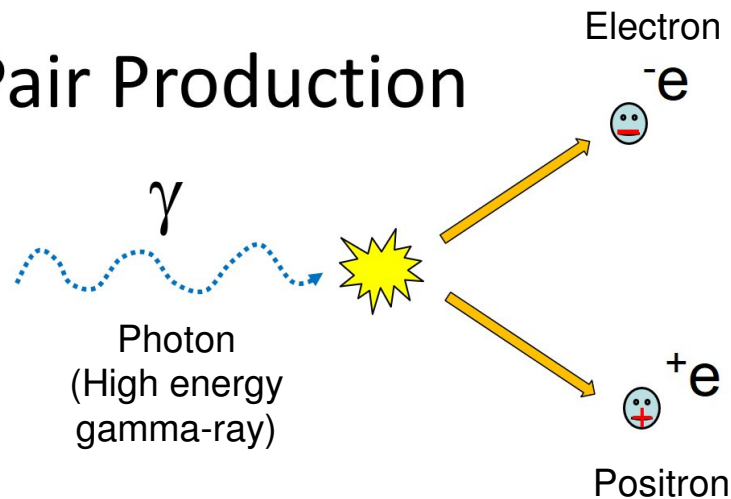
## Anti-Matter



Paul Dirac 1902 - 1984  
Nobel Prize in Physics 1933

- Relativistic quantum theory and prediction of Anti-Matter (1928)
- Foundations of both quantum electrodynamics and quantum field theory
- Every elementary particle has an anti-particle
- Anti-particle of an **electron** is a **positron**—same mass but opposite charge

## Pair Production

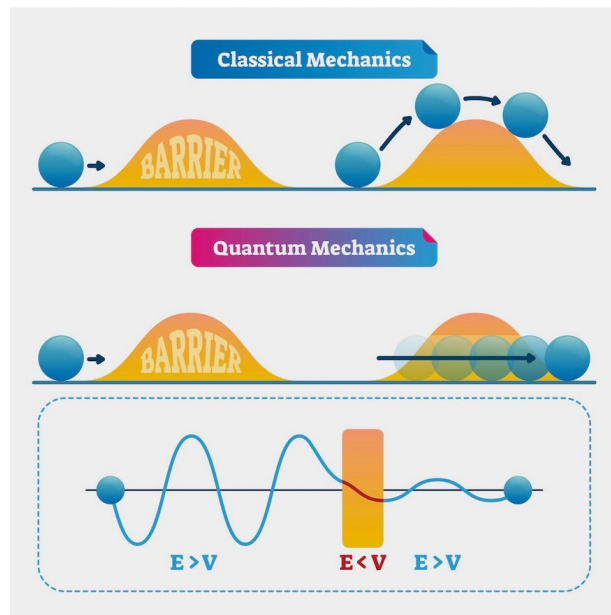


## George Gamow (1904 – 1968)

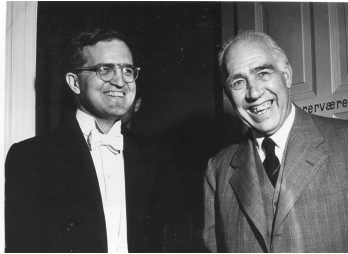
- Alpha decay by quantum tunneling
- Liquid drop model of nucleus
- Developed the Big Bang model of cosmology



## Quantum Tunneling



### Institute of Theoretical Physics Copenhagen, Denmark

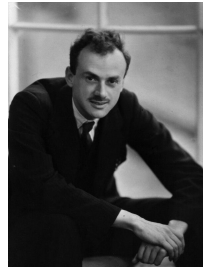


Aage and Niels Bohr

Werner  
Heisenberg



Wolfgang  
Pauli



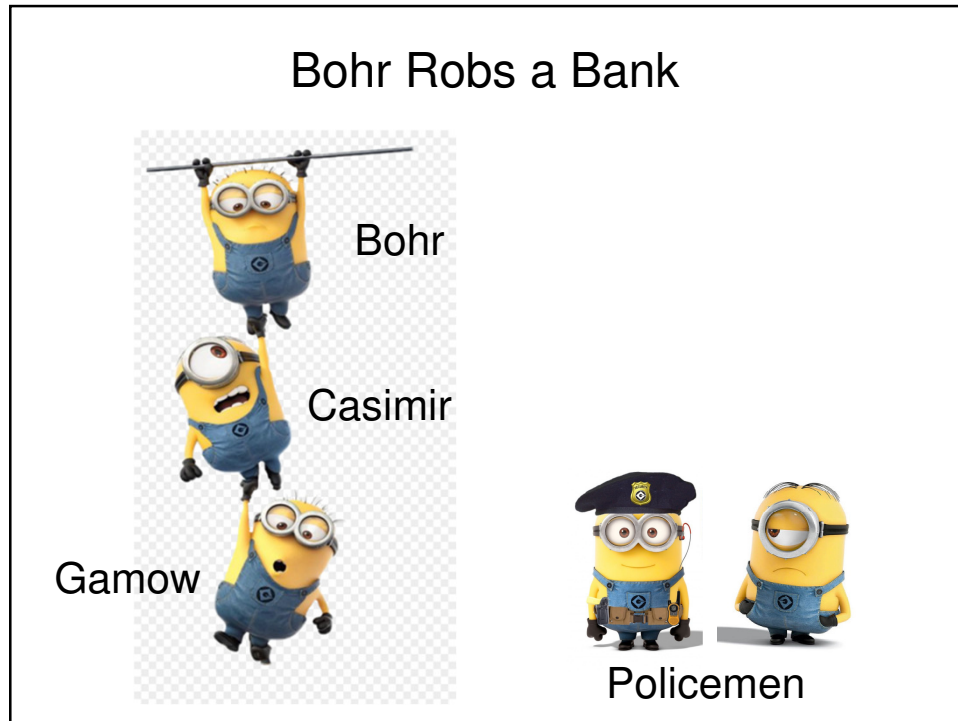
Paul Dirac



George Gamow



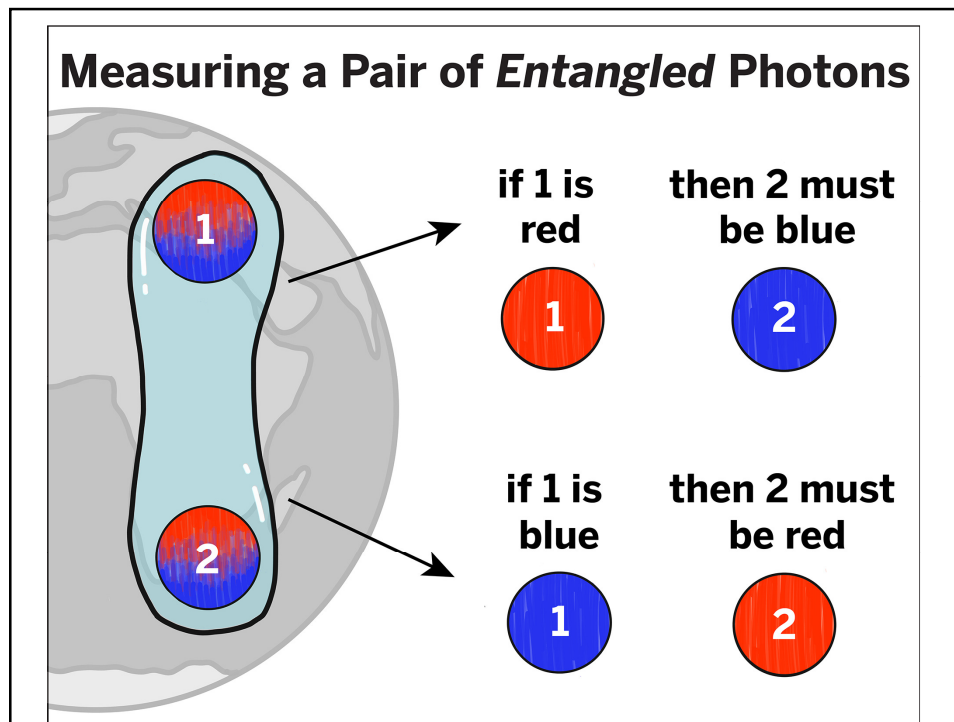
L. Landau, Aage Bohr, George Gamow, Ernest  
Bohr, Edward Teller (1931)



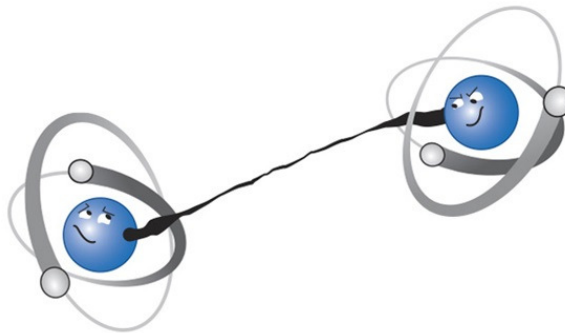
### ***Stranger Still!***

#### **Quantum Entanglement**

- When two particles, such as a pair of photons or electrons, become "*entangled*," they remain connected even when separated by vast distances.
- Spooky "action at a distance"
- 1935, Einstein, Boris Podolsky and Nathan Rosen (EPR) argument: *The elements of physical reality which are objectively possessed cannot be influenced instantaneously at a distance.*

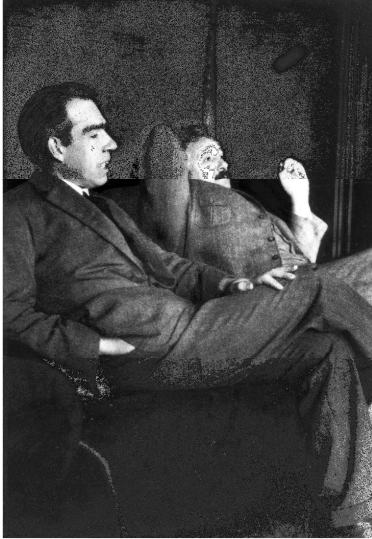


Starting in 1949, many experiments have 'apparently' confirmed that quantum entanglement is real. For example, in 2018, an Austrian Academy of Sciences experiment tested the correlation over 248 kilometers of optical fiber.



## Einstein–Bohr Debate

Solvay Conference 1927



Is the universe deterministic or probabilistic?

"I am at all events convinced that *He* [God] does not play dice." – Einstein to Max Born, 1926

## 1927 Solvay Conference

**17 Nobel Laureates!**



Piccard, Henriot, Ehrenfest, Herzen, De Donder, Schrodinger, Verschaffelt, Pauli Heisenberg, Fowler, Brillouin  
Debye, Knudsen, W. L. Bragg, Kramers, Dirac, Compton, de Broglie, Born, Bohr Langmuir, Planck, Curie, Lorentz, Einstein, Langevin, Guve, Wilson, Richardson



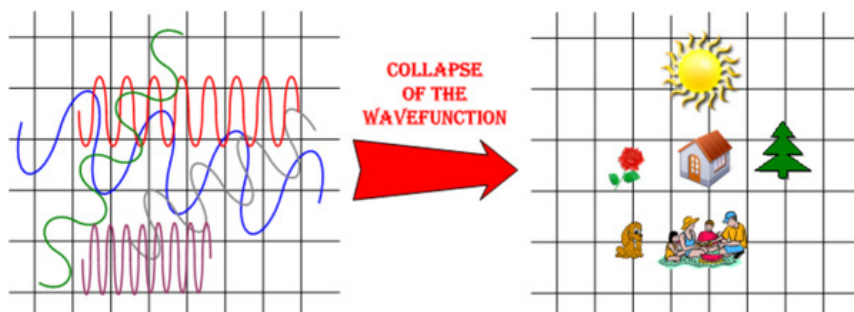
## ***Interpretations of Quantum Mechanics***

***Have we left the realm of science and entered the realm of metaphysics ... or Looney Tunes for that matter?***



- There have been several attempts at interpreting what this all means, the most famous of which is the **Copenhagen Interpretation** of Born, Bohr, and Heisenberg.
- The state of an object does not exist until it is observed (measured).
- The atomic world is not deterministic, that is, future events cannot be predicted at the atomic level.
- The atomic world is stochastic (probabilistic). Nothing is certain!

The universe exists in a fuzzy, wavy state until the wave function collapses.



When does the wave function collapse?  
When one makes an observation.

### Copenhagen Interpretation

- Isolated material particles do **not exist**, but are abstractions which we only identify through their interactions with other systems—e.g., someone measures the location of an electron. (Bohr)
- The Rainbow Analogy.
  - A rainbow does not exist as a material object.
  - It appears in a different place to each observer.
  - No two people see the same rainbow.
  - But it is real—it can be photographed.
  - Then again, it is not real unless it is being photographed or observed. (Frank Herbert)

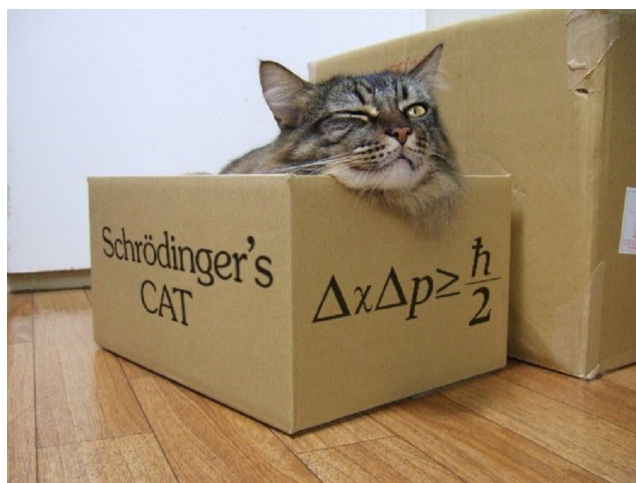
### One way to view the Copenhagen Interpretation



IF A TREE FALLS ON A MIME IN A FOREST  
WOULD ANYONE REALLY CARE?

- "The Universe only exists because we are looking at it." – Physicist John Wheeler
- "Neils Bohr brain-washed a whole generation of physicists into believing that the problem had been solved." – Physicist Murray Gell-Mann
- "More severe is the opinion that Bohr's philosophy is an obscure 'web of words' and mute on crucial foundational issues." – Philosopher of Science Mara Bella
- "It tries to be very deep and tell you that these ambiguities, which you worry about, are somehow irreducible... You shouldn't strive for clarity — that's naive." – Physicist John Bell

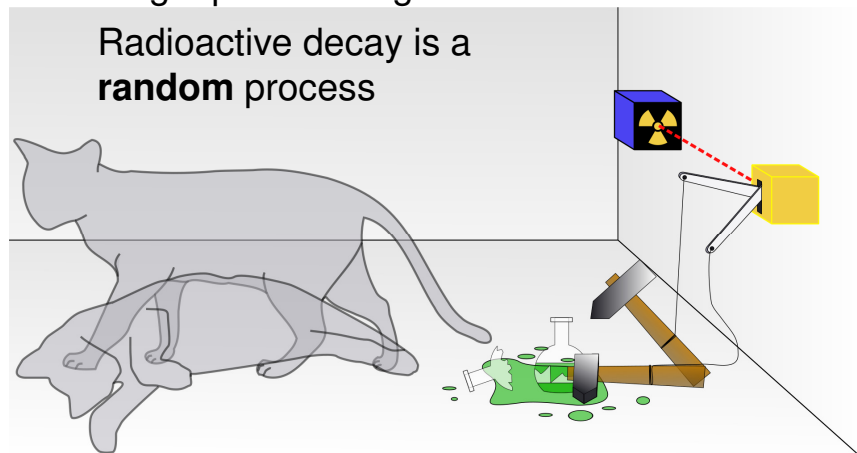
**Warning!**  
**Cat lovers may wish to skip the**  
**next couple of slides.**



## Schrödinger's Cat

- In the thought experiment devised by Schrödinger in 1935 in a discussion with Einstein, a hypothetical cat may be considered simultaneously both alive and dead, while it is unobserved in a closed box, as a result of its fate being linked to a random subatomic event that may or may not occur.
- Schrödinger thought the Copenhagen Interpretation to be nonsense and devised this thought experiment to support that claim.

A radioisotope is also in the box. Should the isotope emit a particle that is detected by the Geiger counter, a signal from the counter triggers a hammer device which smashes a bottle releasing a poisonous gas that kills the cat.

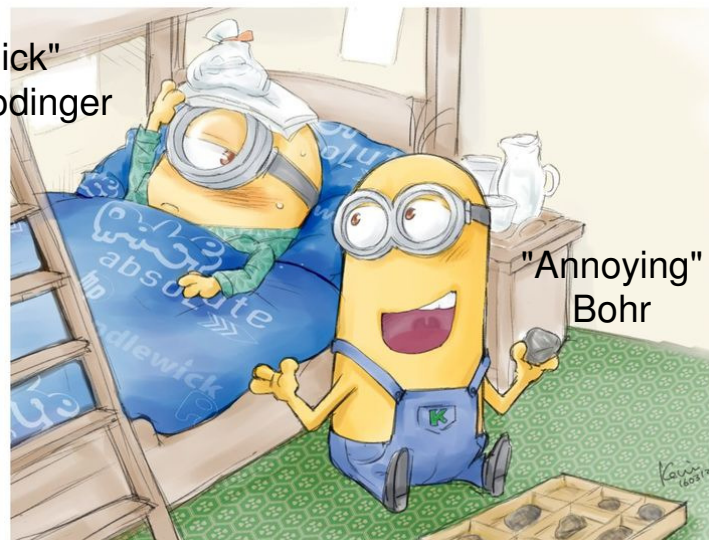


- Schrödinger's point is that the Copenhagen interpretation implies that, after a while, the cat is **simultaneously alive and dead**.
- Yet when one looks into the box, the **cat is either dead or alive**. **The Joke**
- At what point does quantum superposition end and the reality resolves that the cat is either dead or alive?
- Note: Cats are not quantum entities



## Niels Bohr's Beside Manner

"Sick"  
Schrodinger



"Annoying"  
Bohr

### **Multiverse (Many Worlds) Interpretation**

- Originally Schrodinger. Refined by Hugh Everett 1957 and expanded by Bryce DeWitt and David Deutsch in the 1970s.
- Wave function is real but there is nothing in the equations about wavefunction collapse (Bohr addition)
- Schrodinger: the idea that a quantum superposition will collapse just because we look for it is absurd! (1952)
- Every event creates a new branch in reality and both outcomes are equally real but can never interact with each other
- Does away with the need for an observer

### **QUANTUM MECHANICS**



**SUBJECT TO A MANY-WORLDS INTERPRETATION**

© WORDS & UNWORDS

- Everett: Since no observer would ever be aware of the existence of the other worlds, to claim that they cannot be there because we cannot see them is no more valid than claiming that the Earth cannot be orbiting around the Sun because we cannot feel the movement.
- Quantum computing → Evidence for the multiverse?

### Pilot Wave Interpretation

- de Broglie: Quantum entity both a wave and a particle that are both real
- The wave (***pilot wave***) guides the particle to its destination (surfer riding a wave)
- Double-Slit Experiment → pilot wave spreads out through both slits and interferes with itself
- Can measure the properties of the particle but never those of the wave
- Wave is hidden from us until particle detected
- Known as "hidden variables" theory
- Bohr and Pauli attacked the pilot wave idea
- John von Neumann "proved" that hidden variable theories were impossible

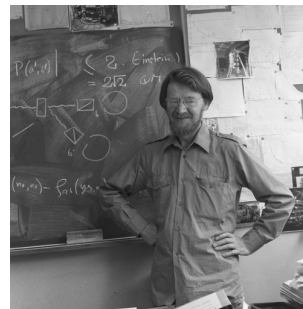


John von Neumann  
(1903 – 1957)  
Mathematician,  
physicist, economist,  
computer scientist,  
statistician



David Bohm (1917  
- 1992)  
Physicist,  
neuropsychologist,  
philosopher of the  
mind

John Bell (1929  
- 1990)  
Physicist



## Pilot Wave Resurrected

- David Bohm theory similar to de Broglie's pilot wave theory
- John Bell finds error in von Neumann's analysis.
- Bell shows that all hidden variables theories are non-local → Bell's Theorem
- "... this idea seems so natural and simple, to resolve the wave-particle dilemma in such a clear and ordinary way, that is a great mystery to me what it was so generally ignored." – John Bell, 1987

## WHY DO WE FIND RELATIVITY AND QUANTUM THEORY SO WEIRD?

Our experience is one of:

- Low Energy and Low Speed compared to the High Energy and High Speed environment where Relativity Effects are observable
- Large Scale compared to the Atomic Scale environment of Quantum Theory



## **Note the Importance of An Observer in both theories!**

- Relativity: The measured mass, rate of time flow, and size of an object moving near the speed of light depend on the speed of an observer relative to the object
- Quantum Theory: The act of observing (measurement) of an event can affect its outcome

