How Small Is It

This is the companion hard copy for the "How Small Is It" video book that is available on YouTube. This book contains the full text for each of the 7 "How Small Is It" video segments. It also includes notes on additional information and on the musical selections associated with each segment. A full list of sources is included in the Credits segment.

http://howfarawayisit.com

Dedication:

This work is dedicated to my two sons Michael and Sean, and to my grandchildren, Shannon, Tristan, Ashleigh, and Caitlyn. I trust my sons will bring this video book to their children's attention when they are old enough to understand.

Acknowledgements:

Thanks to my wife Elizabeth Butler and Jonathan Onstead for their patience and reviews.

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Preface

Hello and welcome to the "How Small Is It" video book. This is a sequel to my first video book on "How Far Away Is It", where we started in my backyard and went all the way to the edge of the physical universe, explaining along the way how we knew how far away things were.

In this video book, we'll start again from my backyard, but we'll move down to how small the smallest things can get.

I've been motivated by two things to do this video:

- One is the success of "How far away is it" - hundreds of thousands of hits and over two million minutes watched. It's been very gratifying.
- The second is that in 1972 I studied Quantum Field Theory for my Master's degree at Oxford University, and recently, the Higgs boson has been discovered. It's the boson for a field that was just beginning to be talked about back in the early 70s. So it's very exciting.

But I noticed that explanations are so over simplified that they are actually misleading. I heard one explanation that called the Higgs boson a kind of molasses that slowed things down. It's not anything like that. But it's not so mysterious, that we can't understand it.

So as we get down to how small things can get, we'll finish with: the Higgs boson – what it is; the Higgs field – what it does; and the CERN hadron collider that finally found it.

In our first chapter on the microscopic, we'll use microscopes and the wave-particle duality for electrons to understand how an electron microscope works. And then use the electron microscope to see down to a carbon atom.

In the second chapter, we'll go into the atom. We'll scatter alpha particles into the atom to find the nucleus. We'll cover the rules of quantum mechanics as we get deeper and deeper into the working of an atom to help us understand how fields can have sizes, and to set the stage for the Higgs Boson.

In the third chapter, we'll find a whole lot of new elementary particles (some of them not so elementary) - a lot more than the electron, proton, photon, and neutron that came from cosmic rays bombarding us from outer space. We'll also probe the proton - much like Rutherford scattering probed the atom. We'll discover quarks on the inside of the proton and the neutron. And we'll lay the stage for the Standard Model of Particle Physics.

In the final chapter, we'll finish off the standard model by explaining force particles – bosons: the gluons that bind the quarks, and the photon for the electromagnetic force. And then, we'll get into the Higgs boson.

Like we did with "How far away is it", we'll explain along the way how we know how small things are.

The pictures aren't as grand as the Hubble pictures of grand spiral galaxies, but I trust you'll find the story is interesting and informative.

Thank you.

The Microscopic

***{Abstract** – In this first segment of our "How small is it" video book, we cover the microscopic world.*

We start with optical microscopes and take a look at some of the things that you can see with light. We also cover light diffraction and show how it sets a limit on the size of objects we can see.

To understand how we can go further than light can take us by using electrons, we cover wave-particle duality. For that we cover particle momentum and wave interference. For a closer examination of waves, we show the famous Young Double Slit experiment that illustrates the wave nature of light. We also cover Airy Disks as a wave effect to further illustrate the limits of light microscopes. Then we go deeper into the nature of electromagnetic radiation. Here we show how it is the very nature of empty space with its permittivity and permeability that determines the speed of light in a vacuum.

For the particle nature of light, we cover Blackbody Radiation, the radiation catastrophe and how Planck solved the problem by showing that light is created in integer multiples of a constant now called Planck's constant. We then cover Einstein's photo-electric effect that showed that light was absorbed in the same multiples of light quanta. We now call these light quanta photons.

To reconcile these two views of light, we return to Young's double slit experiment and fire photons one at a time. The interference pattern appears over time. We cover how Louis Broglie extended this wave-particle duality to include electrons and other particles, and calculated the Broglie wavelength. The conclusion is that objects interact at points like a particle, but travel through space as a wave.

We then dig a little deeper into the nature of an electron starting with J.J. Thompson's discovery using a mass spectrometer. We then cover how Robert Milliken found the charge of an electron. With the electron's mass and charge known, we calculate its wavelength and find it much smaller than an optical photon's wavelength. This makes it ideal for breaking through the diffusion limit to see much smaller objects.

*We end by covering how a scanning electron microscope works and using it to view very small things - down to a carbon atom!***}**

Introduction

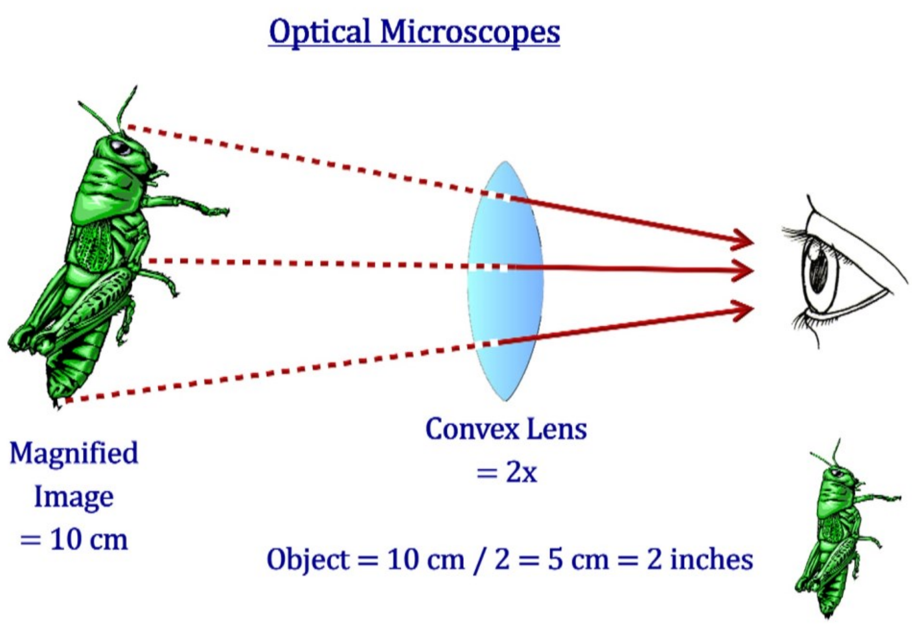
Hello and welcome to the first segment of our video book "How small is it". Here we'll examine the size of things from where we see them around us – very day things down to the smallest things that exist. For that we'll be using a meter stick. A meter is roughly the same size as a yard. It's just 3 inches longer. In addition to how much space an object might take up, we'll going to be looking at how little its mass and energy might be. For that, take a look at the apple - a hundred grams roughly. And to raise a hundred-gram apple one meter is the energy of one Joule. We'll get much smaller than that as we move into additional segments.

We see things because light bounces off an object and into our eye. But the smaller things get, the harder they are to see. A human hair is about one tenth of a millimeter. A millimeter is a thousandth of a meter. In order to see things this small, or smaller, we use lenses. Like this lens here, to get a better look at the size of a hair. But how far can we go bending light. And just how small can things get. We'll be using microscopes various kinds of microscopes to see down to the nanometer level. A nanometer is one billionth of a meter. There are 25,400,000 nanometers in an inch. So, let's get started with optical microscopes.

> **[Music @02:38:** *Tchaikovsky – "Swan Lake" – This 1876 ballet was fashioned from Russian folk tales and tells the story of Odette, a princess turned into a swan by an evil sorcerer's curse. Its variety of melodies fit the themes of science and beauty in our opening chapter.***]**

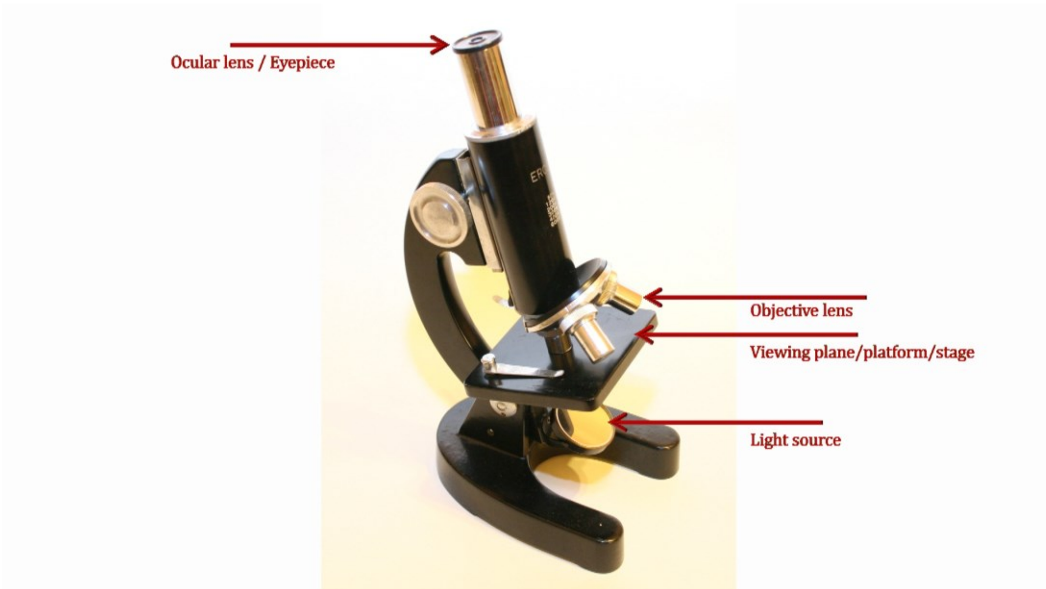
The light microscope

Magnifying tools use lens combinations to bend light at an angle to increase the size of the image that's sent to the eye. The eye traces the light rays back to a virtual image larger than the actual object. The more we bend the light, the larger the image appears. We use x after the number to represent the expansion factor of a microscopic image. For example, the magnifying glass we used in my backyard can double the size of an image, so it would be designated 2x. Therefore, if we divide the apparent size of the image by the magnifying power of the lens, we get the object's actual size.

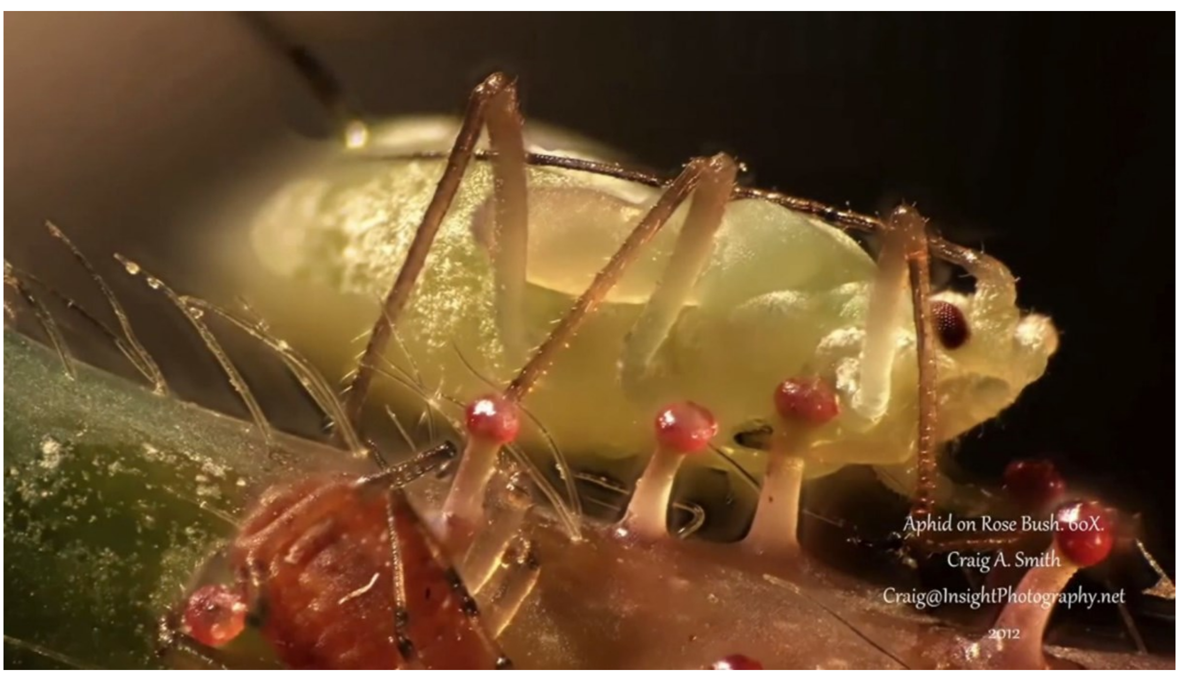


Evidence points to the first microscope appearing in the Netherlands in the late 1500s, probably an invention of eyeglass makers. We know that Galileo used them in the early 17th century. The discovery of things like blood cells and micro-organisms in the late 1600s really accelerated interest and development.

There are a wide variety of optical microscopes, but they all have these basic parts: A quality light source with focusing capabilities; a focal plan for the specimen, the key magnifying lens called the objective and the eyepiece.

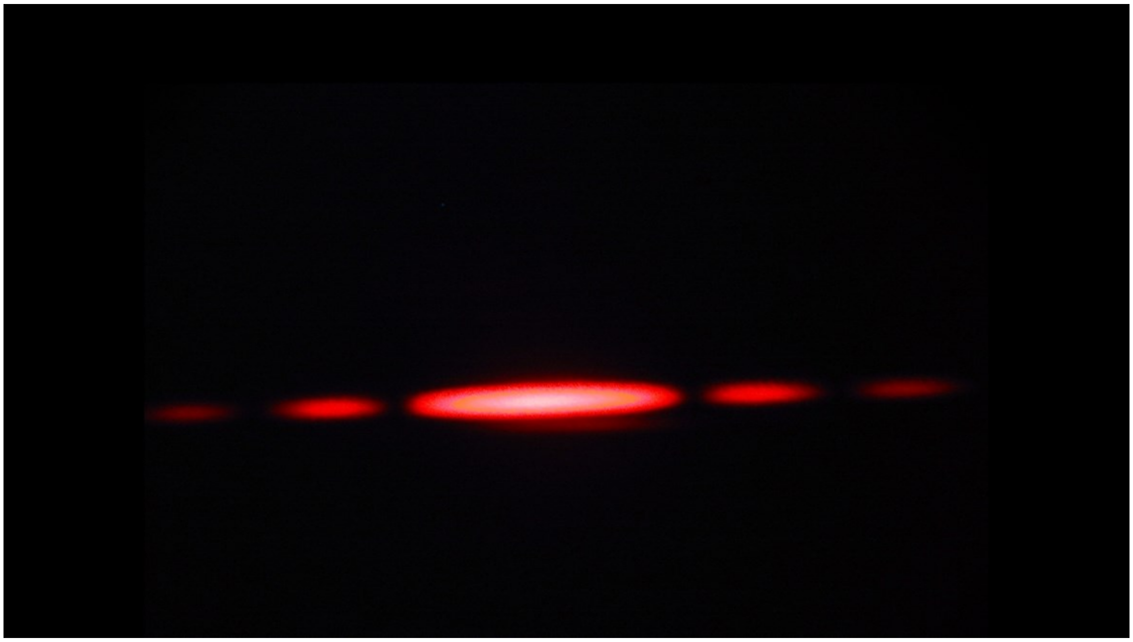


Thanks to Graig A. Smith, we have a fantastic microscopic look at what's in a backyard. **[**You'll find contact information for Graig and additional links in the Credits and Research segment at the end of the video book.**]**



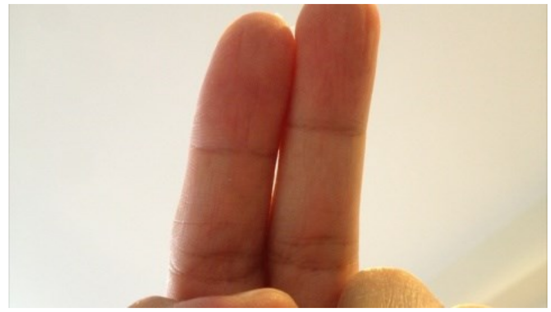
Diffraction

With standard microscopes we can see things as small as 0.2 µm. That's .2 millionths of a meter. Along with factors such as lens size and quality, the limit is hard wired due to a light effect called diffraction. Diffraction of light occurs when a light wave passes by a corner or through an opening or slit that is approximately the size of the light's wavelength.



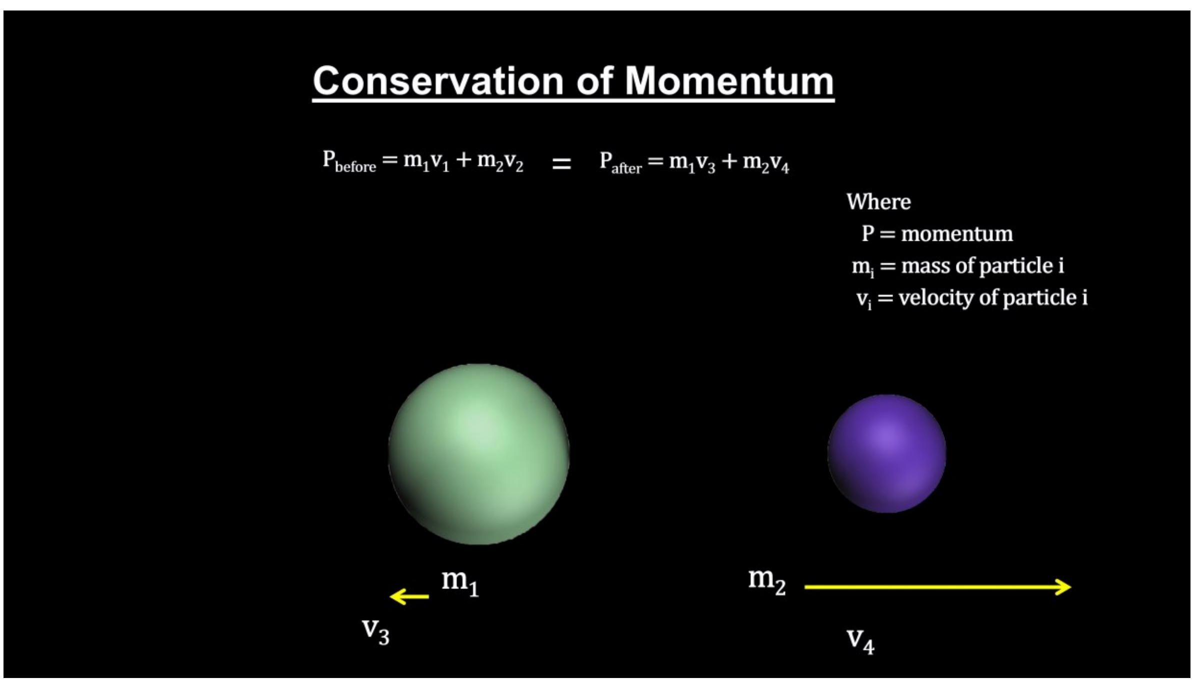
We see this in daily life all the time. For example, diffraction through clouds causes this common yet beautiful sight.

A very simple demonstration of diffraction can be conducted by holding your hand in front of a light source and observing the light transmitted between the fingers. As your face approaches your fingers, you begin to see a series of dark lines parallel to the fingers. The parallel lines are actually diffraction patterns. To understand how this works, we need to take a look at the difference between particles and waves.



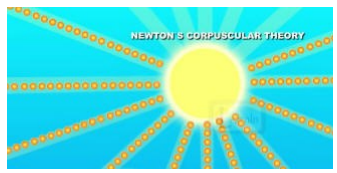
Microscope Resolution Power

Particles are localized and bounce off each other. An important aspect of collisions between particles like these is that the momentum of the system is the same before and after the collision. Momentum is the mass times the velocity. In nature, this quantity is conserved. We'll use this law of nature later on when we start colliding particles to see what happens.

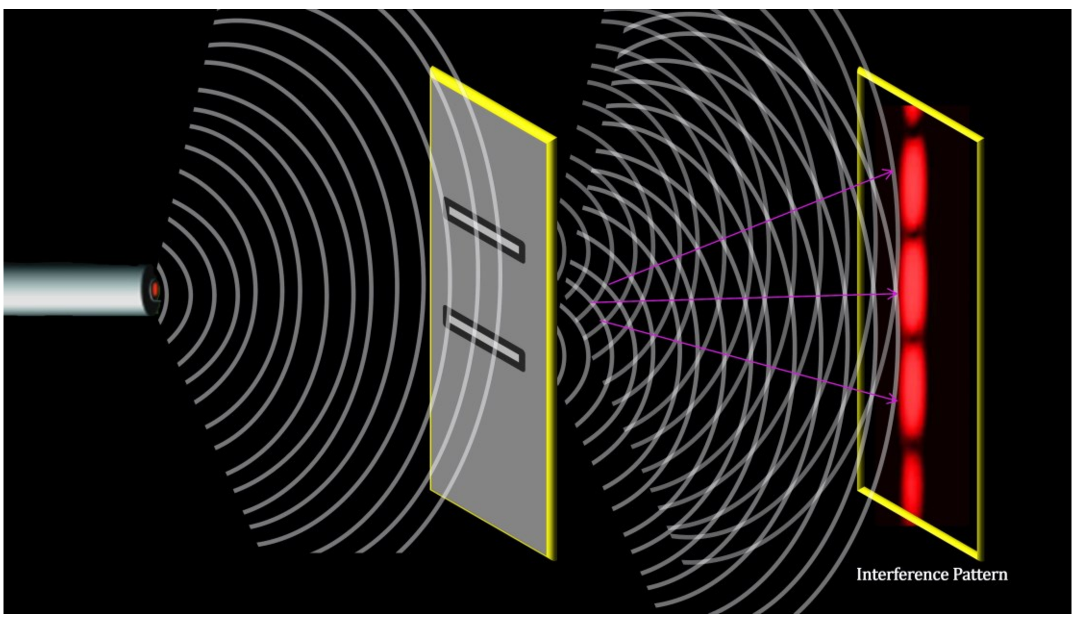


Waves are spread out and pass right through each other. When they move through each other, they interfere with each other. They can even interfere with themselves creating interesting patterns.

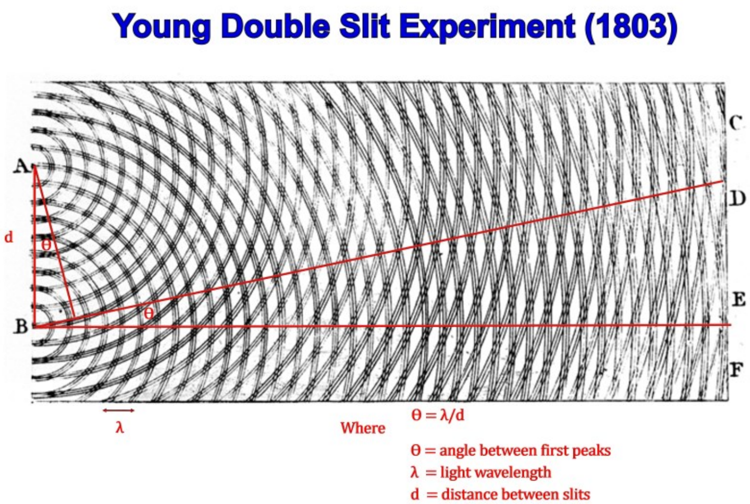
Newton thought light was a particle because he never witnessed light diffraction. The wavelength of light was too small for the experiments he ran. For decades, his view was never questioned.

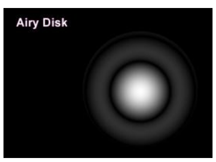


But in the early 1800s, that changed based on experiments by Thomas Young. Here we see light traveling through two slits and then interfering with itself on the other side. An interference pattern is etched onto the back screen. This is the famous double slit experiment.



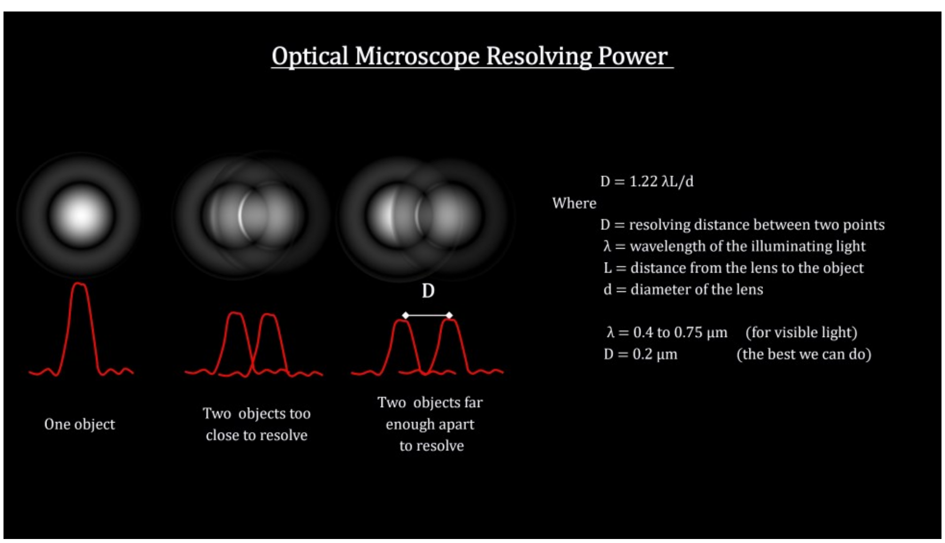
When Thomas Young did his double slit experiment, he showed conclusively that light diffracted and therefore was a wave. Here's his sketch of two-slit diffraction that he presented to the Royal Society in England in 1803.





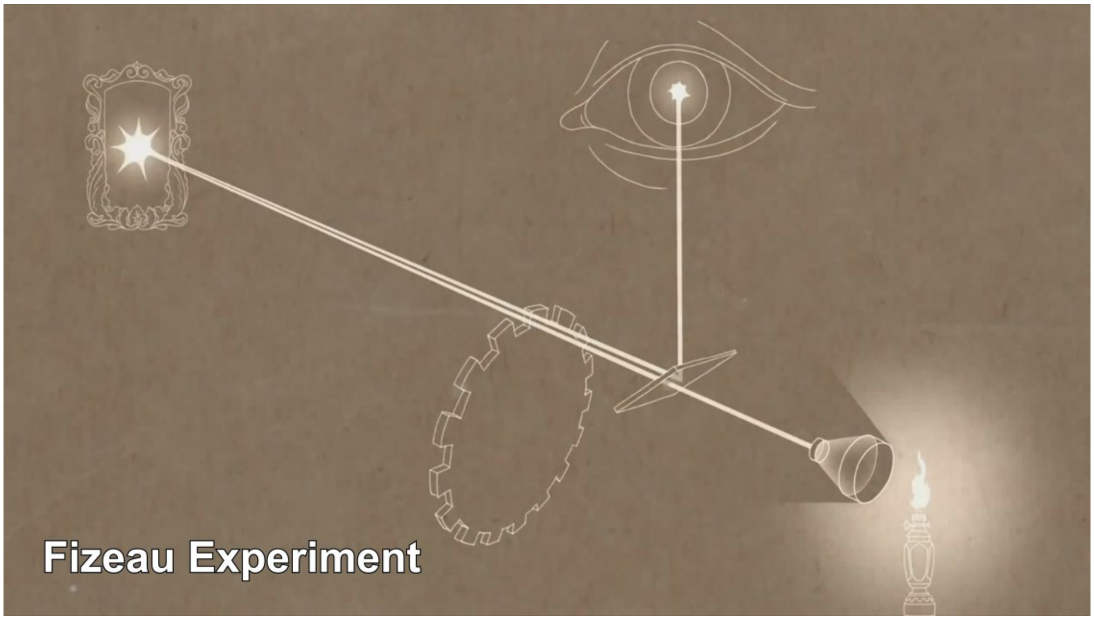
Because of diffraction, instead of seeing points, each point is spread out into a disk called an Airy disk.

The resolving power of any optical instrument is its ability to produce separate images of two adjacent points. This resolving power of optical microscopes is about 0.2 micrometers. The bottom line is that you can't see a thing that is smaller than the wavelength of the light used to illuminate it. If we're going to do better than 0.2 micrometers, we'll need to use something else to do the illuminating. And for that, we'll need to get a better handle on the nature of waves vs. particles.

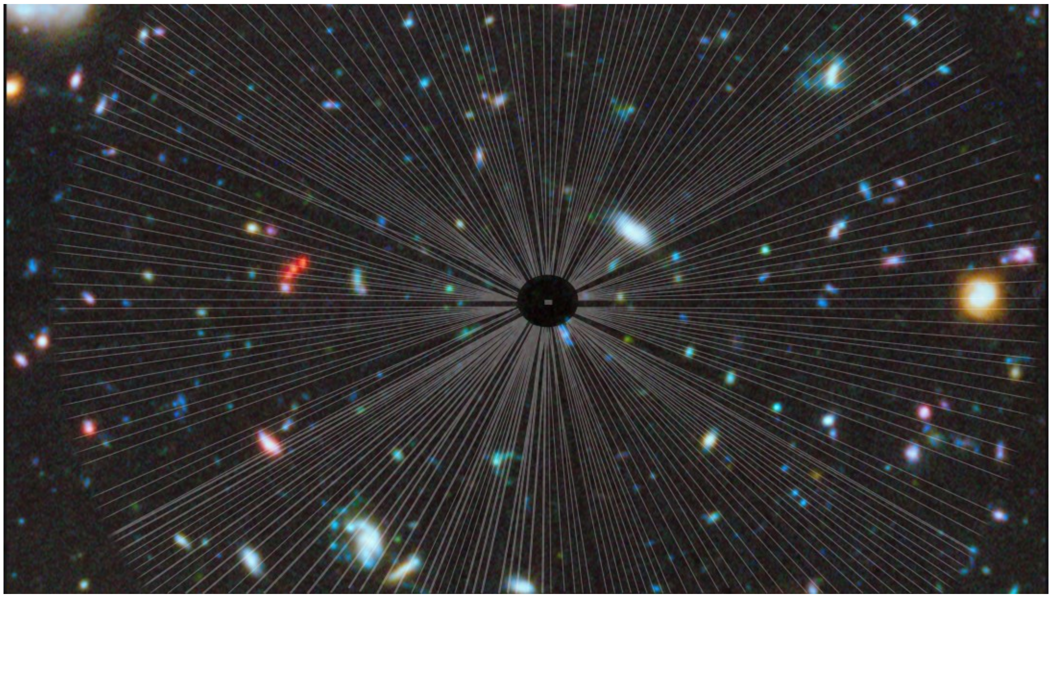


Electromagnetic Radiation

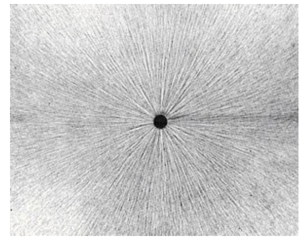
Forty-two years after Young proved that light traveled as a wave, the French physicist Hippolyte Fizeau measured the speed of light to be just under 300,000 km/s (That's 186,000 mi/s). We cover how he did it in the "Speed of Light" chapter of the "How Fast Is It" video book.



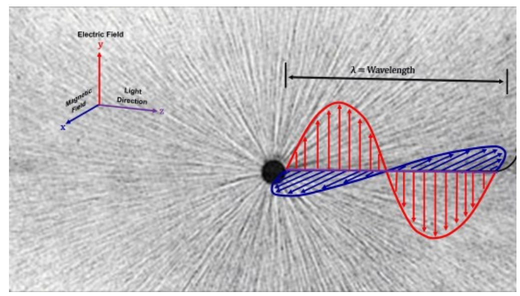
Over that period and into the 1860s, people like Michael Faraday, Andre Ampere and James Maxwell and others were studying electric and magnetic fields. Because waves were known to need a medium to propagate through (like water waves or sound through air), it was assumed that all space was filled with a massless substance that was given the name aether. Then in the mid-1800s, Maxwell proposed that the existence of an electric charge filled empty space with an electric field.



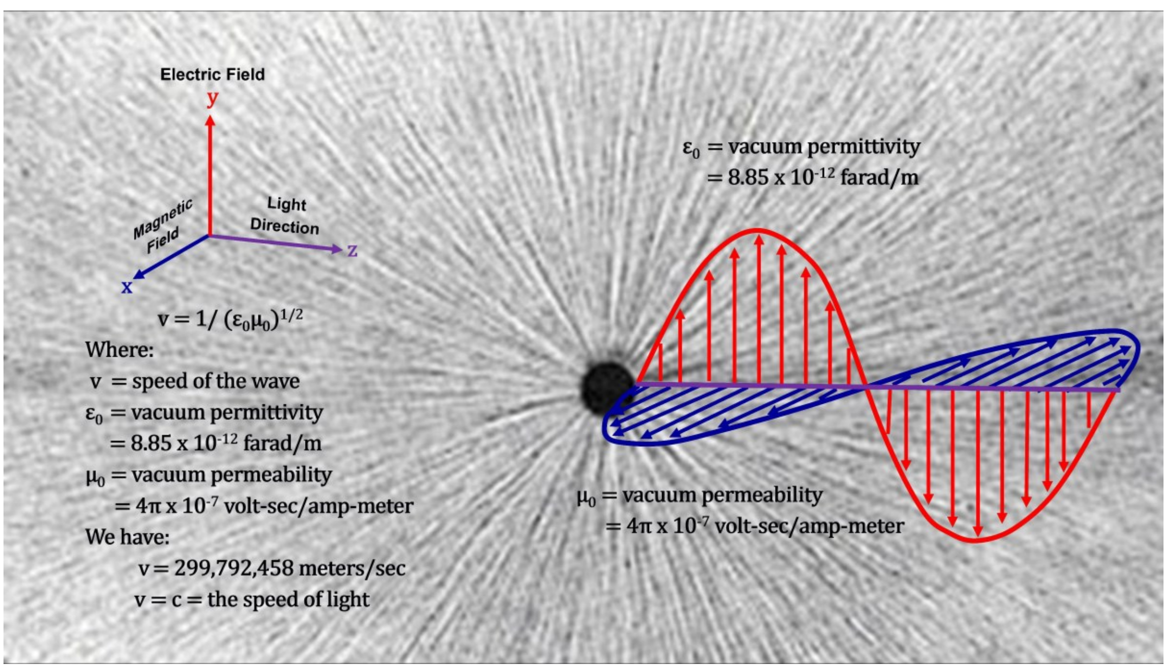
Here's a NASA picture of small threads suspended in an oil aligned with the electric field of a charge.



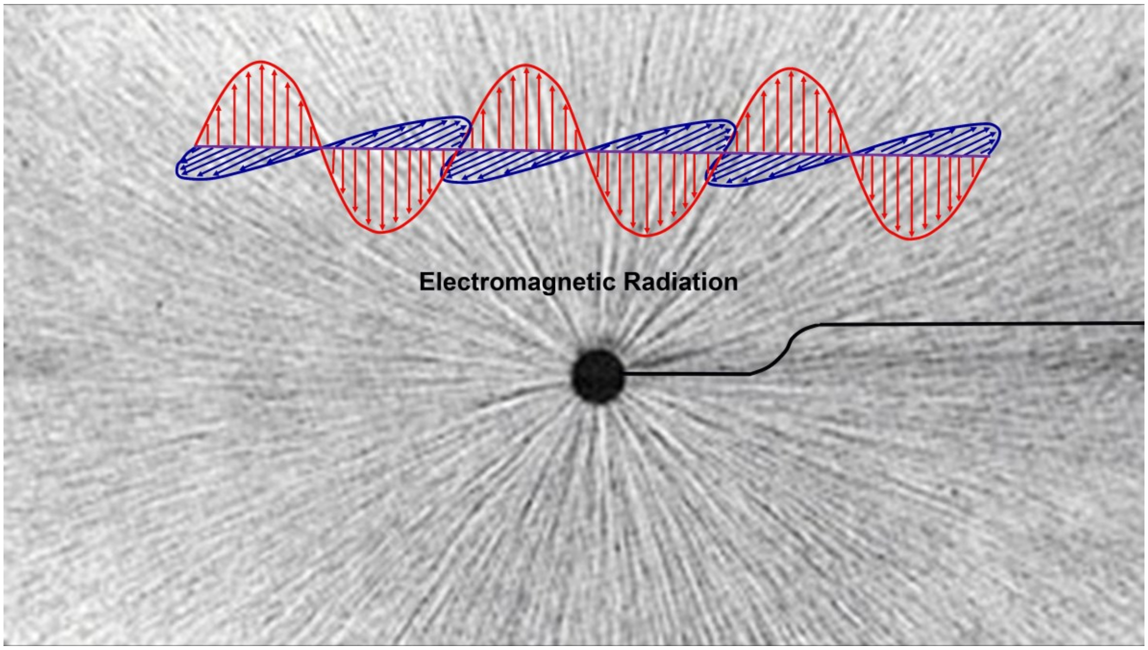
Accelerating the charge causes the electric field to change. Furthermore, he showed that a changing electric field created a magnetic field. And a changing magnetic field created an electric field. So, the accelerated electron creates a disturbance in the electric field that propagates itself through space as an electromagnetic wave.



Earlier, Faraday had measured the resistance of empty space to the forming of an electric field called permittivity and Ampere had measured the resistance of empty space to the forming of a magnetic field called permeability. In 1864, using their numbers, Maxwell calculated the speed of his waves. He found that his velocity was in agreement with Fizeau's for light! He had demonstrated that light is indeed an electromagnetic wave!

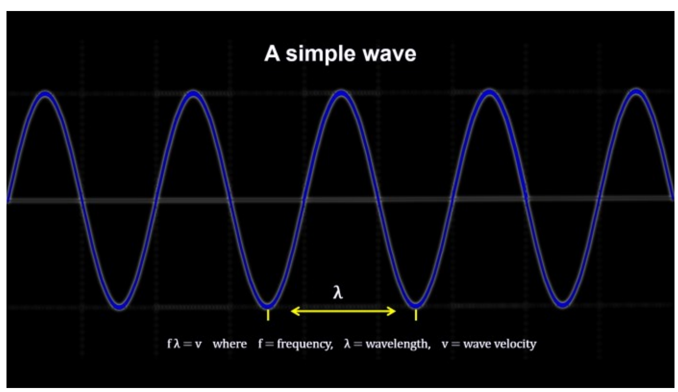


The idea of an aether filling otherwise empty space was rendered un-needed for light propagation once electromagnetic radiation was understood. So, it faded from our vocabulary - replaced by the idea that empty space supported magnetic and electric fields and light represented a disturbance in the electric field. The exact characteristics of so-called empty space will be a recurring subject for us as we approach our segment on the Higgs Boson.



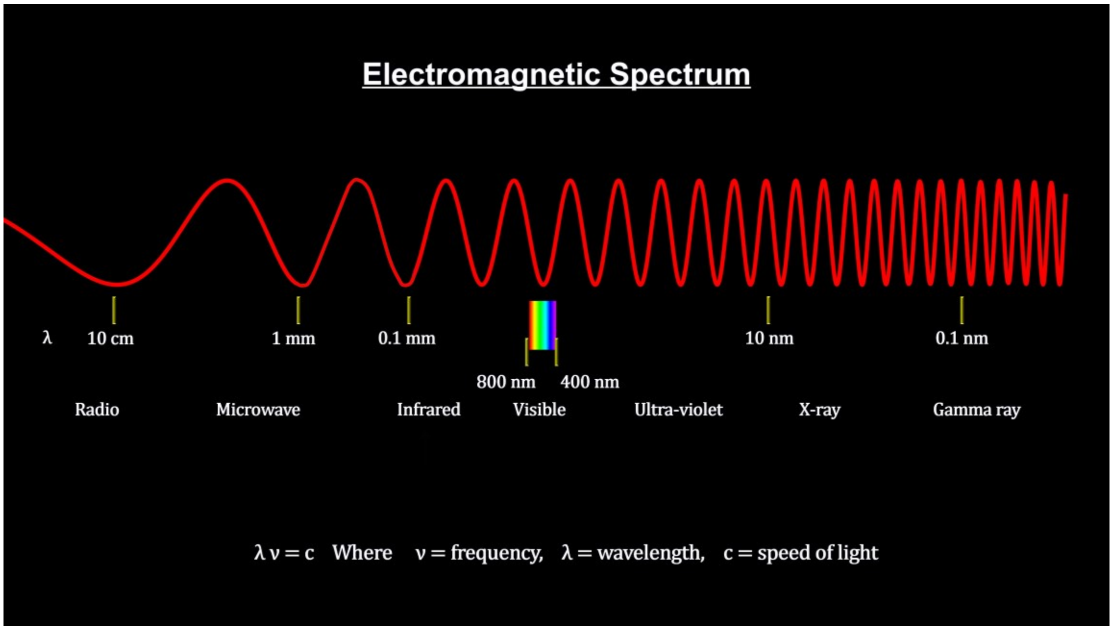
Here's a simple wave. It has:

- a repeating cycle
- a wave length;
- and a frequency in cycles/second



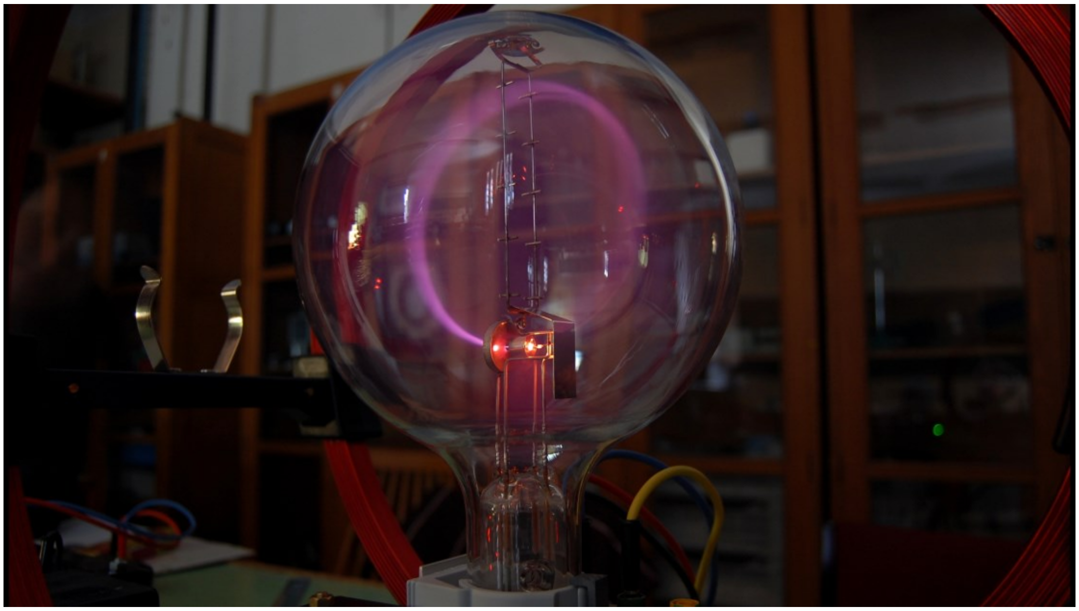
Here we see the full electromagnetic spectrum with visible light in the middle; light with longer wavelengths and smaller frequencies than red light is called *infrared*; radiation with longer wavelengths than infrared is called *microwaves*; and still longer wavelengths are called *radio waves*.

Moving up the energy scale, radiation with shorter wavelengths than violet light is called *ultraviolet*; still shorter wavelengths are called *X-rays* and the maximum energy radiation is called *gamma Rays*.

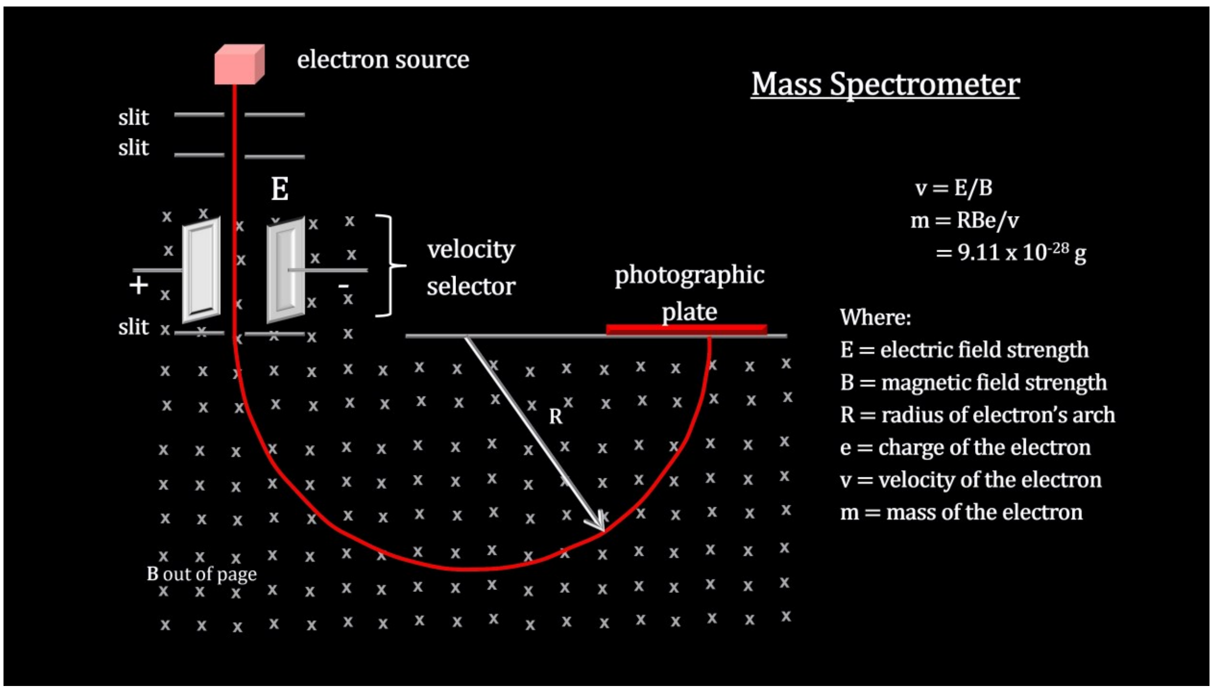


Electron Mass

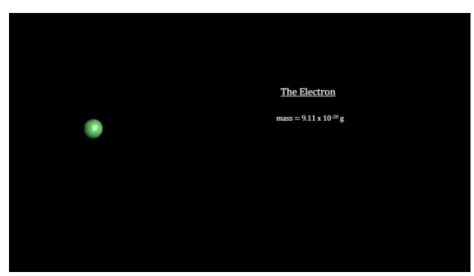
In the early 1800s, most people thought that the atom (the most fundamental unit of matter) was indivisible. Also, a lot was known about electricity, but no one knew what was carrying the electric current. For example, highly charged cathode rays were produced inside vacuum tubes in the mid-1800s, but it wasn't until the late 1800s that anyone figured out what was carrying the charge.



In 1897, J.J. Thompson used a mass spectrometer to measure the mass of cathode rays. Here's how it works. Acceleration is a change in an objects speed or a change in its direction. From Newton, we know that force equals mass times acceleration. So mass equals force divided by acceleration. If we exert an exact amount of force on a particle and carefully measure its acceleration, we'll know its mass. So, we: 1) Fix the particle velocity with an electric field, 2) measure the radius of the resulting curves as it moves through a magnetic field, and 3) use the basic electric, magnetic and centripetal forces equations to calculate mass.



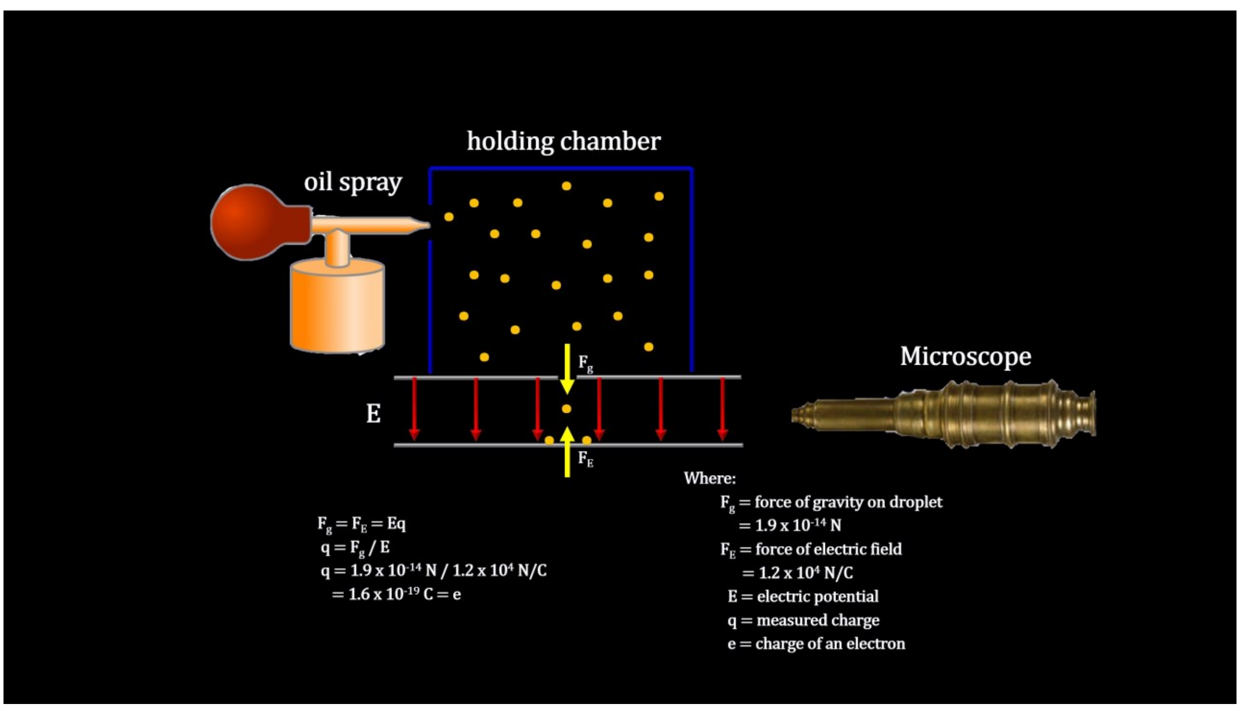
Thompson showed that the rays were made of particles that were around 9.11 x 10^{-28} g. That's 1,800 times lighter than the lightest atom (hydrogen) that had also been measured with mass spectrometers. Therefore, the particles were not atoms. He had discovered a new particle, later named - the electron.



Electron Charge

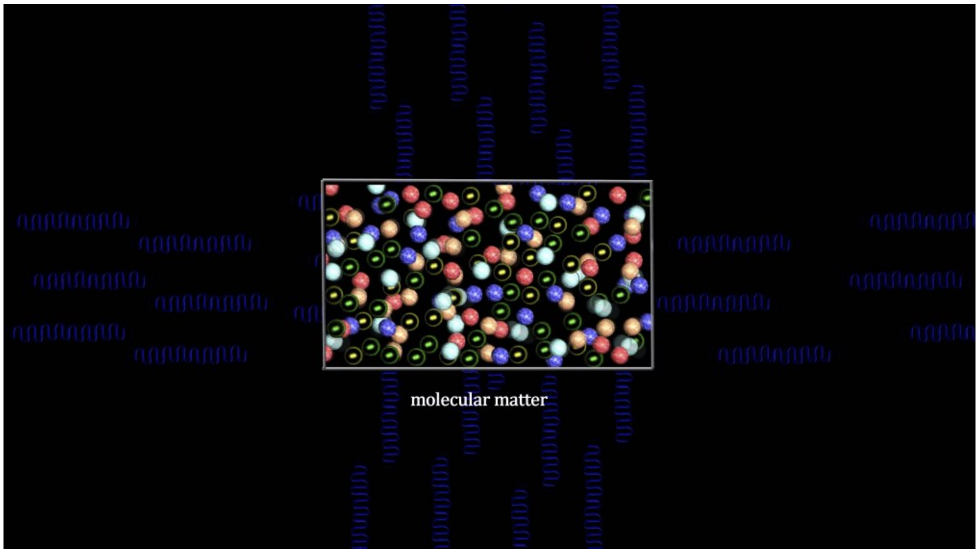
With the mass known, Robert Millikan, a contemporary of Albert Einstein, found a way to measure the charge of an electron. This is the original equipment he used in 1909.

The experiment was performed by spraying a mist of oil droplets into a chamber above two metal plates. Some of the oil droplets become electrically charged by friction as they were sprayed through the nozzle into the holding chamber. A few droplets would enter the space between the parallel plates. Controlling the electric potential across the plates would cause any charged droplets to rise or fall. Finding the voltage that causes a droplet to be suspended above the bottom plate indicates that the downward force of gravity was equal to the upward electrical force. Once Millikin had arduously and meticulously determined the weight of a droplet, he could solve for the charge on the droplet. It was not known just how many electrons would attach to each droplet, maybe one, maybe more. So, the experiment was carried out a large number of times. The smallest charge found was 1.6×10^{-19} C. And all the other charges on oil drops were found to be whole number multiples of this one indicating that it was the charge on a single electron.



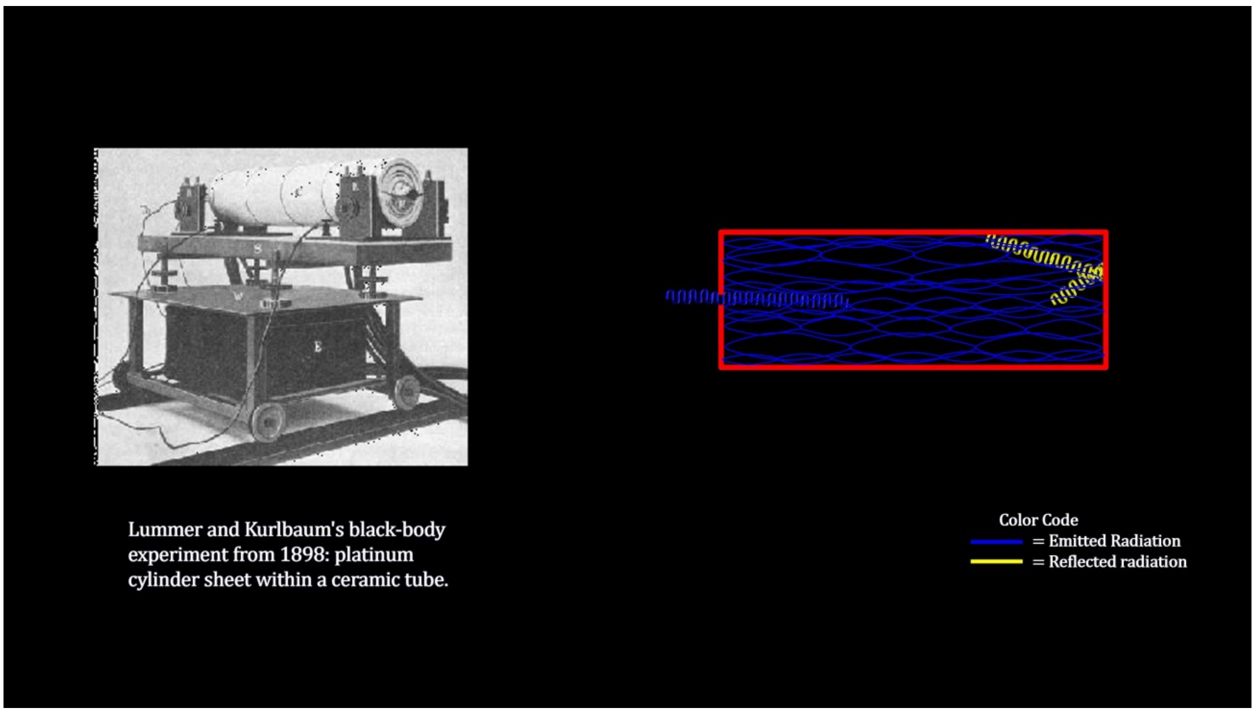
Blackbody Radiation

With the knowledge that the electric charge was carried by the electron, our first elementary particle, Once we understood that light was electromagnetic waves with a wide range of frequencies created by accelerating electric charge, a great deal of research went into studying the nature of this radiation as it related to matter and temperature. Because all matter above absolute zero contains vibrating or oscillating molecules colliding with each other, all matter radiates.



Take a look at this iron rod. At the ends, where it's cool, its radiating in the infrared so we can't see it. Its gray color is based on reflected light. As it heats up it turns red, then orange, yellow and at the hottest is it white. If we could get it hot enough, you'd see it turning blue. These colors are emitted, not reflected.

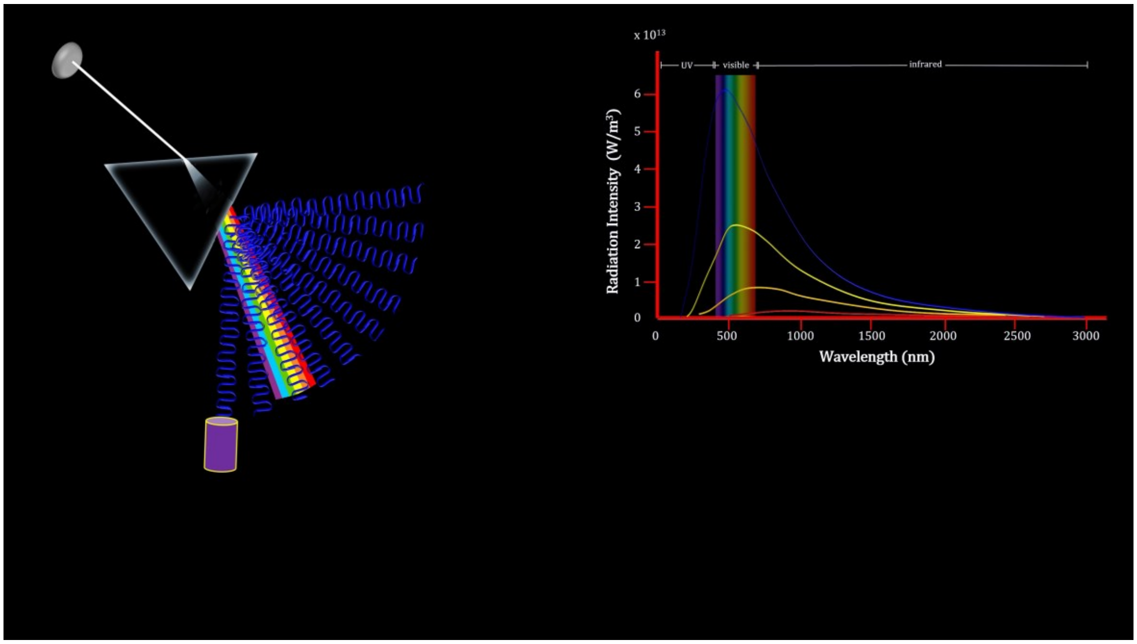
The problem with studying the emitted radiation is that you can't separate out the reflected radiation. What you need is a body that emits without reflecting. Such a body is called a blackbody and its radiation is called blackbody radiation. Here's an example of an early construction of such a device. It's a closed container with platinum interior walls and a small hole at one end. The ceramic exterior keeps the temperature constant throughout the device. Inside, it is literally filled with a wide array of 3-demensional standing waves emitted by the hot platinum walls. Any radiation entering the device through the small hole will have little chance of finding its way back out through the hole. So, for all practical purposes, all the radiation that leaks out through the hole will be radiation emitted by the platinum walls of the device. This makes the hole itself a blackbody.



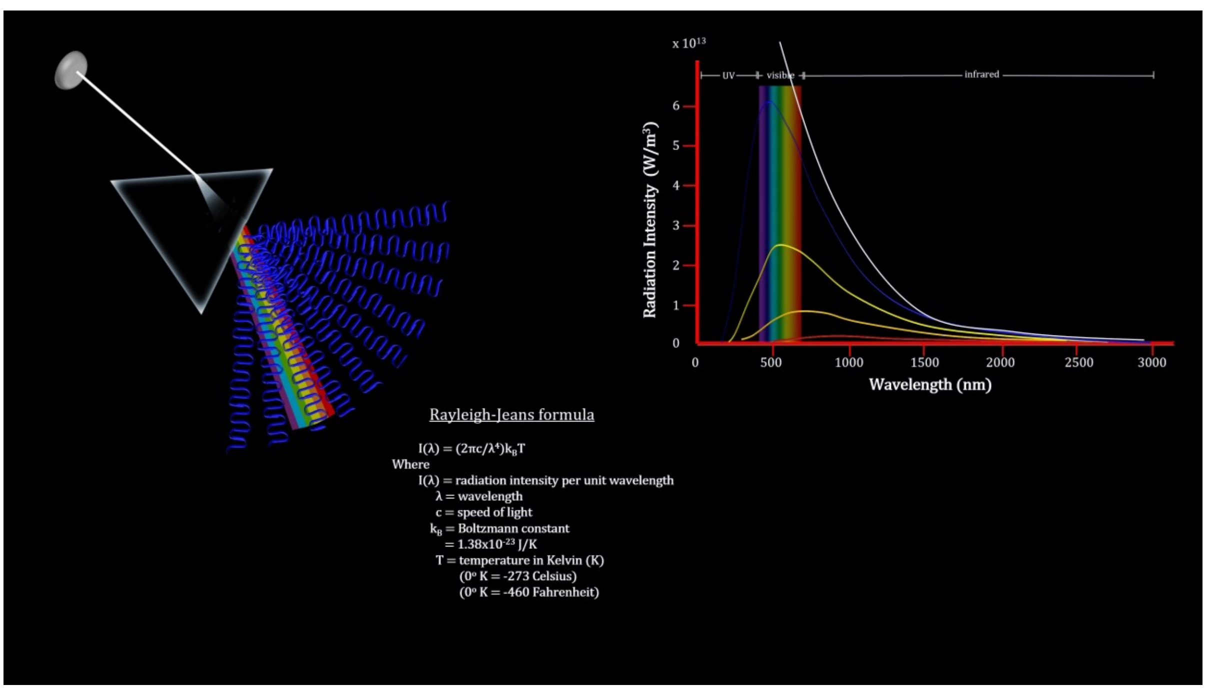
Lummer and Kurlbaum's black-body experiment from 1898: platinum cylinder sheet within a ceramic tube.

We knew that the amount of radiation, its intensity, goes up with temperature. The question was do all frequencies or wavelengths increase in intensity at the same rate. Here's how this is measured. A blackbody is heated to a known temperature. It radiates a beam out the opening. We then pass this beam through a prism to separate the various wavelengths. As we move a detector across the output, we measure the intensity at each selected wavelength. Then, repeat the process with ever increasing temperatures. We see that three things happen:

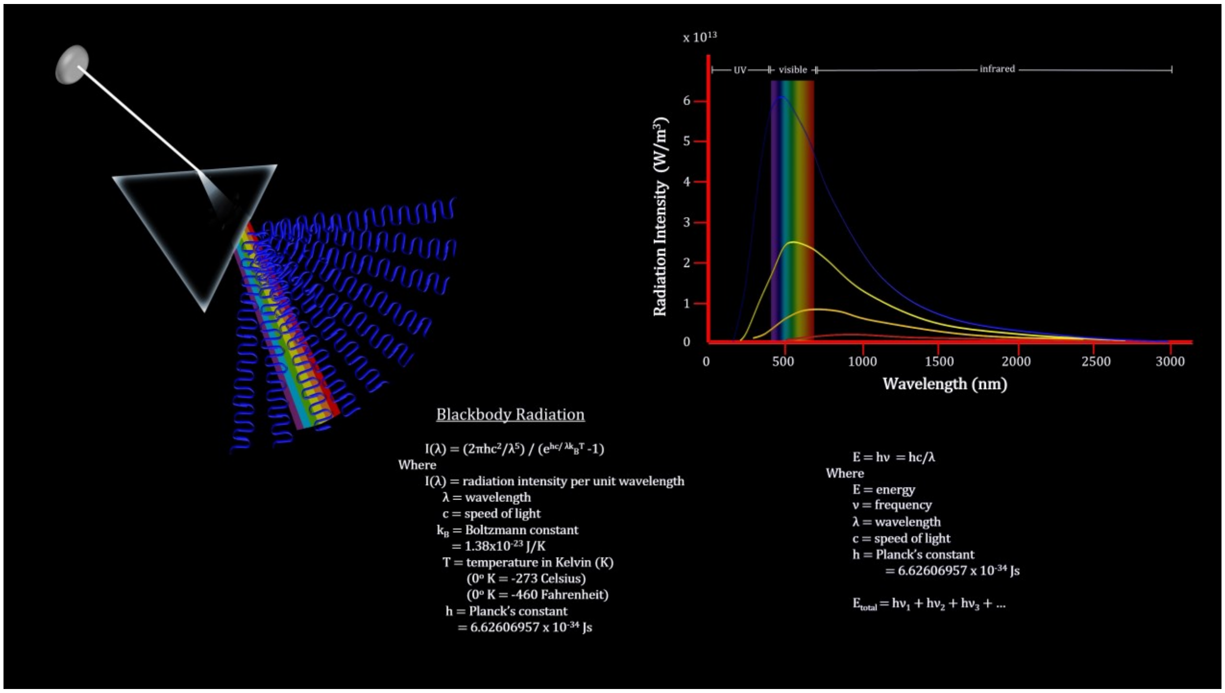
1. The object emits more radiation at all wavelengths.
2. The peak emission frequency shifts toward shorter (blue) wavelengths.
3. The intensity drops precipitously as the wavelengths enter the ultra-violet range.



Using Maxwell's equations and the laws of thermodynamics, physicists developed the equation that should describe blackbody radiation behavior. It's based on the assumption that each wave contributes equally to the total radiation energy and the electromagnetic spectrum is continuous. But the equation predicts an increase in intensity in the ultra-violet range – not the drop-off we see. This dramatic inconsistency between the theory and observation became known as the "ultraviolet catastrophe." Something was dramatically wrong with our understanding.



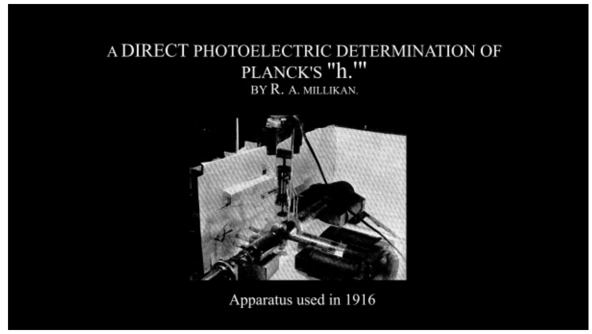
In 1900, Max Planck came up with a solution for blackbody radiation that fit the observations, but he had to brake with two universally accepted fundamentals. He proposed that electromagnetic wave energy was not averaged over a range. Instead, it's a function of each wave's frequency. And he proposed that electromagnetic waves emitted by oscillating atoms are not continuous. Instead, they come in discrete multiples of a minimum quantity. In particular, he proposed that wave energy was described by the simple formula Energy equals a constant times the frequency. The new constant h is now known as Planck's constant, the fundamental constant in quantum mechanics.



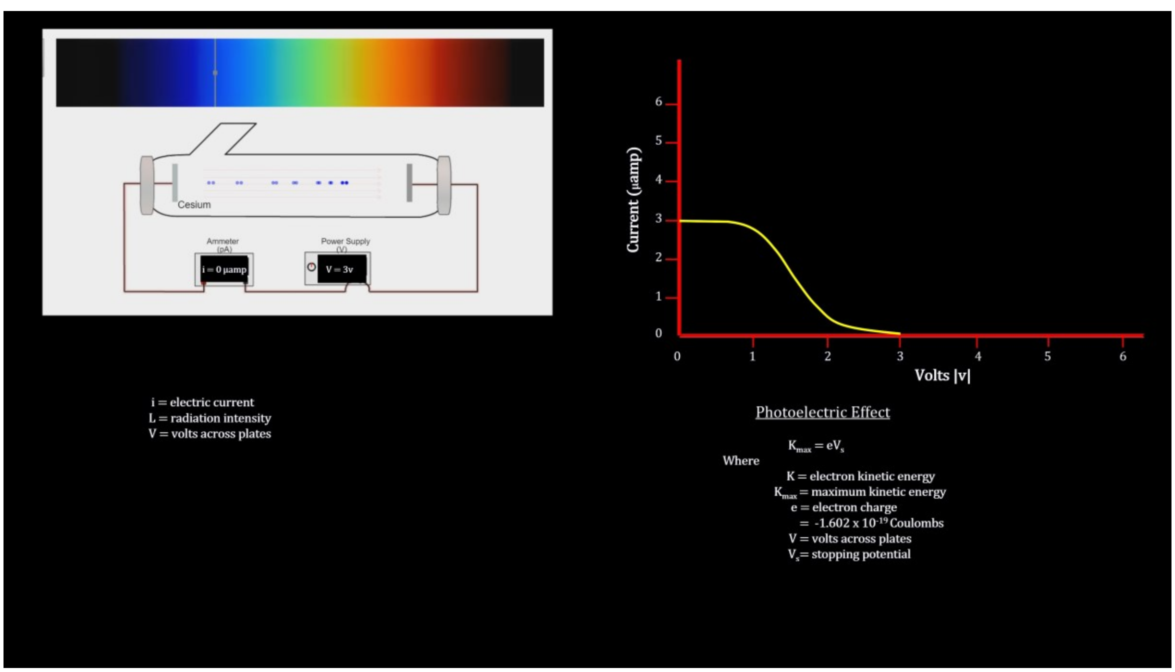
Unlike the speed of light, that's a really big number, Planck's constant is a really small number. Remember that a Joule was the energy needed to lift an apple one meter. Planck's constant is 66 billion trillion trillion times smaller than that. That's why we don't see the effects in everyday life.

Photoelectric Effect

The Photoelectric effect is the ability of light to dislodge electrons from a metal surface. The effect was discovered in 1887 and the emitted electrons are called photoelectrons. In 1915, Robert Millikan developed an experiment to study this effect.

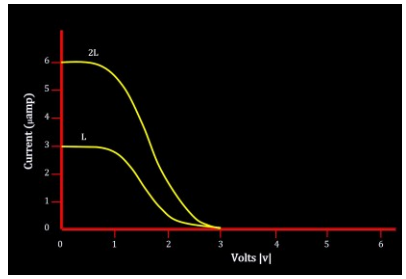


Here's a virtual reproduction of his photoelectric effect experiment. A vacuum tube contains two plates connected to an external circuit that produces a voltage between the plates to oppose the flow of electrons. When a light source shines on the emitting plate, energy is transferred from the light to electrons in the plate. If an electron gains enough energy to overcome the plate's binding energy, it will be dislodged. Furthermore, if such an electron has enough additional kinetic energy left to overcome the voltage, it will reach the other plate. This is then measured as an electric current. At very low voltages, we get plenty of electrons with enough energy to create a current. As the voltage is increased, the number of electrons that can make it across goes down. At some point, the voltage is large enough so that only the most energetic electrons can make it across. Any additional increase will stop all electrons and the current will stop. This is called the Stopping Potential and the energy of those most energetic electrons is the maximum kinetic energy.

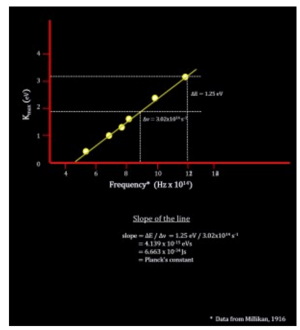


Classical wave theory predicted that light energy would take some time to build up in the electrons before they can escape and the maximum kinetic energy of the electrons would be proportional to the intensity of the light that shines on the metal no matter what the light frequency might be. [That is, as the brightness of the light source is increased, more energy will be delivered to the surface and the electrons should be released with greater kinetic energies.]

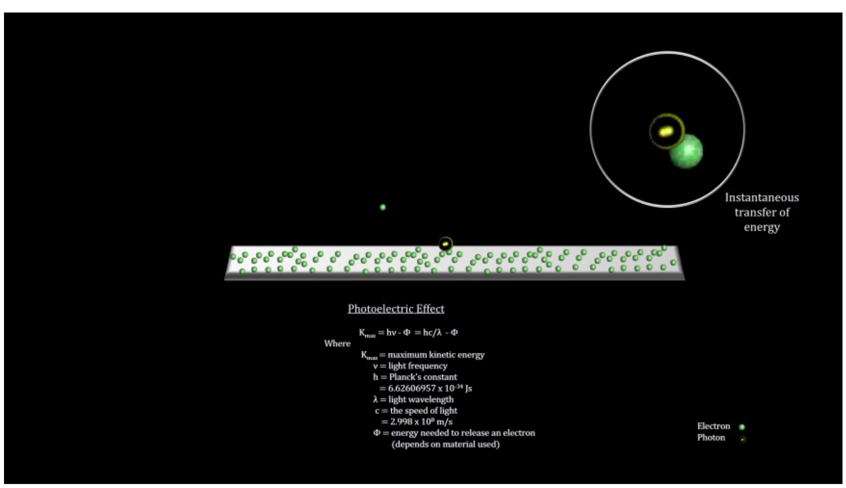
But what we actually see is that although the number of electrons varies with the light intensity, the maximum kinetic energy of these electrons remains the same. In addition, electrons are immitted without any delay except that for really low frequency light, no electrons are emitted at all, no matter how intense the light!



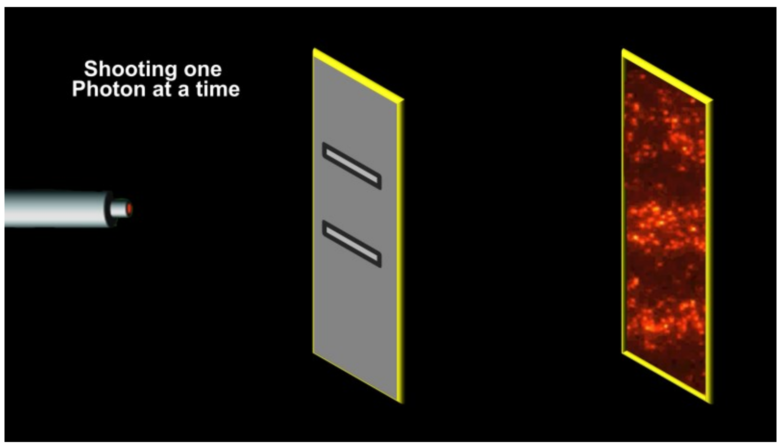
To find out what is actually going on, Millikan measured and graphed this effect for varying light frequencies. Here are his six definitive data points. They create a straight line! The maximum kinetic energy is equal to the frequency times a constant. Careful measurement found that this constant was equal to Planks' constant developed earlier from blackbody radiation.



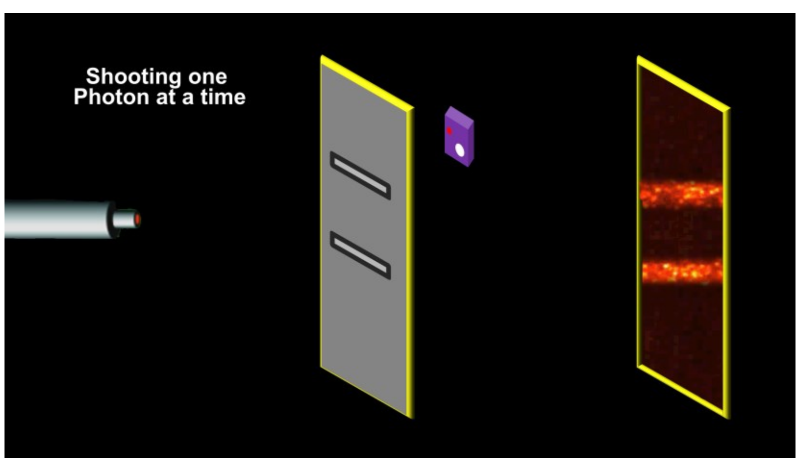
10 years earlier, in 1905, Einstein had proposed that the light impacting the plate was quantized into chunks he called quanta or photons. A photoelectron is released as a result of an encounter with a single photon. The entire energy of the photon is delivered instantaneously to a single photoelectron. If the photon energy is large enough, the photoelectron will be released. If the photon energy is too small, the photoelectric effect will not occur. This explained all the photoelectric effect observations. Millikan (much to his own surprise) proved that Einstein was correct.



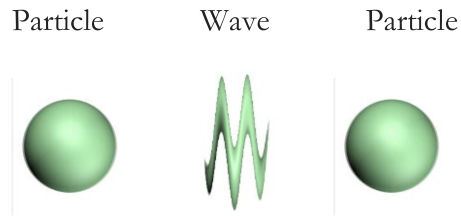
Wave Particle Duality **[Music @25:57** Dvorak – "Symphony No 9 The New World" **]**
Light starts out quantized (as demonstrated by blackbody radiation) and is absorbed quantized as demonstrated by the photoelectric effect, so it stood to reason that it travels quantized as well. In other words, it's a particle – not a wave! But what about the earlier proof that light was a wave? For that we revisit the Young double slit experiment. We've seen Young's diffraction pattern that told us light was a wave. So now let's fire photon particles one at a time at the slits. What happens is that for each photon, the detector registers a hit at a single point. And at first, with a small sample, the hits seam random. But over time, we see that the interference pattern re-emerges! This reminds me of the H-R diagram that looked random after a small sampling, but showed a clear pattern with enough data points. It's as if each photon was contributing to the interference pattern even though there wasn't another photon to interfere with. The conclusion is that photons interfere with themselves! It turns out that they only interfere with themselves, never another photon.



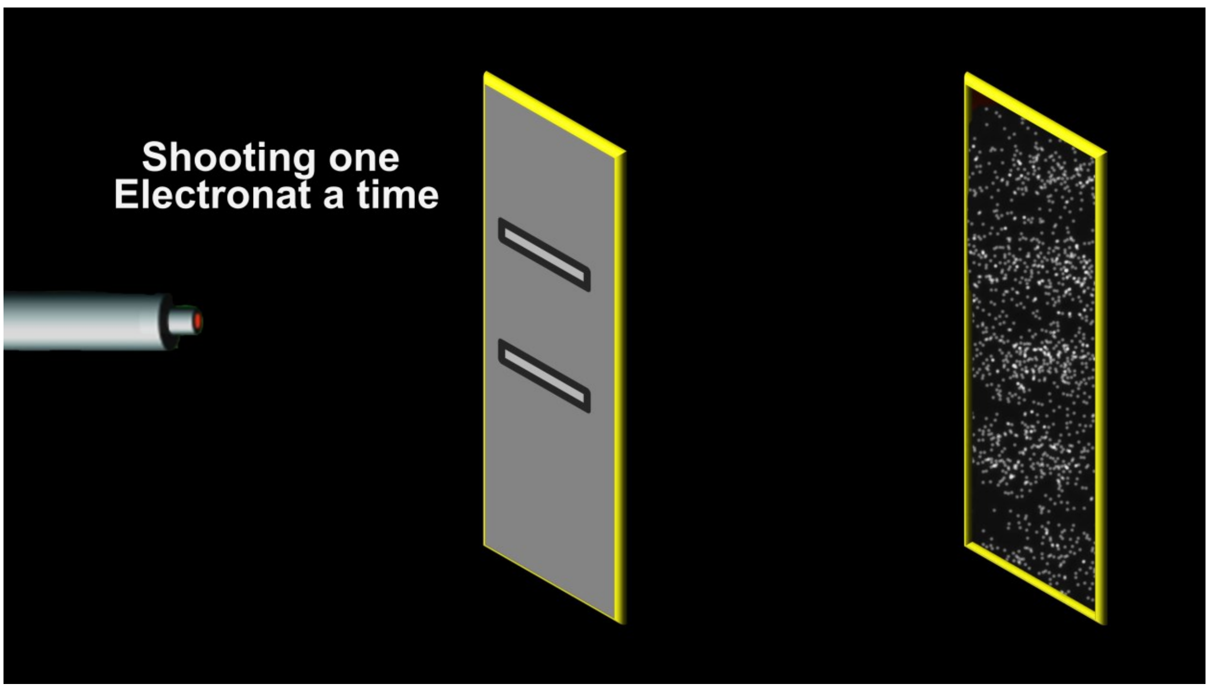
Now look what happens if we detect which slit the photon went through. Here the detector registers yes if the photon went through the upper slit and no if it didn't. The detector sees a photon coming through the top slit around half the time. [The technique for detection uses light polarization and quantum entanglement that we'll cover in an appendix.] We assume that if a photon went through one of the slits, and it was not the top slit, then it must have gone through the bottom slit. The resulting pattern is the pattern for particles! If we turn off the detector, we get the pattern for waves again! This duality puzzled scientists for years, and is argued about to this day.



A good way to look at it is light propagating through space as a wave, but at any time it interacts with something, it interacts as a particle. In other words, it is created as a particle and absorbed as a particle, but travels through space as a wave.



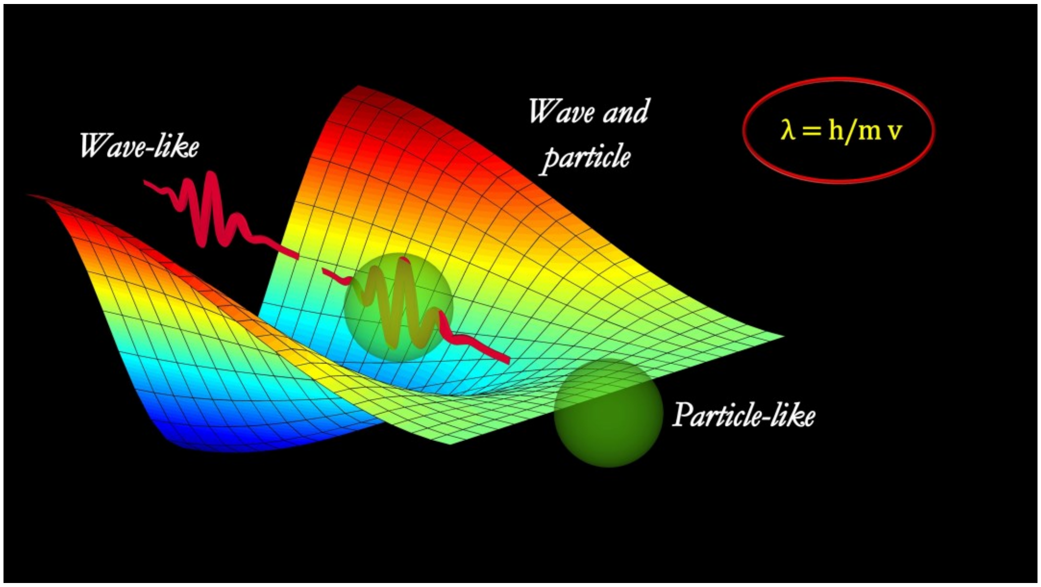
In 1924, Louis de Broglie predicted that this wave-particle duality will work the same for particles like electrons and atoms [and in fact all things]. By 1927, this had been demonstrated for electrons and atoms. With today's equipment, we can even see it for large 20 atom carbon molecules. **[**Anything larger than that has a wavelength too small to detect.**]**



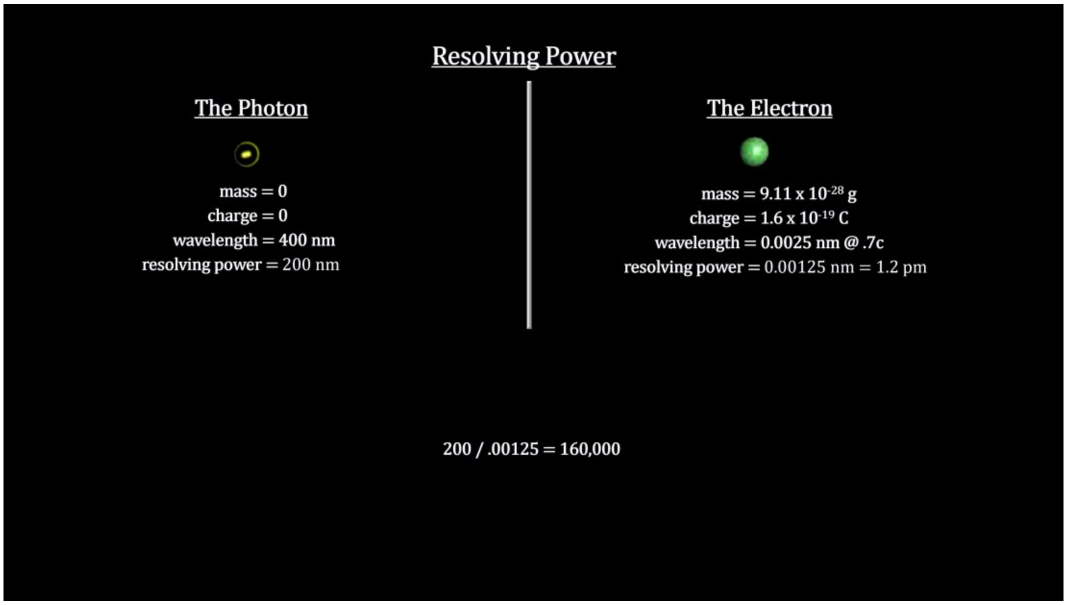
So, we have light waves acting like particles and particles acting like waves. We call it particle wave duality, and it is a fundamental aspect of quantum mechanics and these were the experiments that started it all. Once we understood that electrons travel as waves, they will have a wavelength. Here's the simple derivation conducted by de Broglie.

- The momentum for light is Planck's constant divided by the wavelength ($p = h/\lambda$).
- So, the wavelength is equal to Planck's constant divided by the momentum ($\lambda = h/p$).

- And we know that for particles, momentum is equal to its mass times its velocity ($p = mv$).
- So, a simple substitution gives us the wavelength of the particle as Planck's constant divided by the mass times velocity of the particle ($\lambda = h/mv$).



Microscope resolving power in general is limited to about ½ of the wavelength of the illuminating source. We saw earlier that visible photon wavelengths gave us a resolving power of around 200 nm. Using around 200 keV we can accelerate an electron to 70% of the speed of light. With that, we can use de Broglie's equation along with relativistic adjustments for space contraction and time dilation to calculate its wavelength. We get a wavelength of .0025 nanometers for a resolving power that's 160,000 times smaller than light.



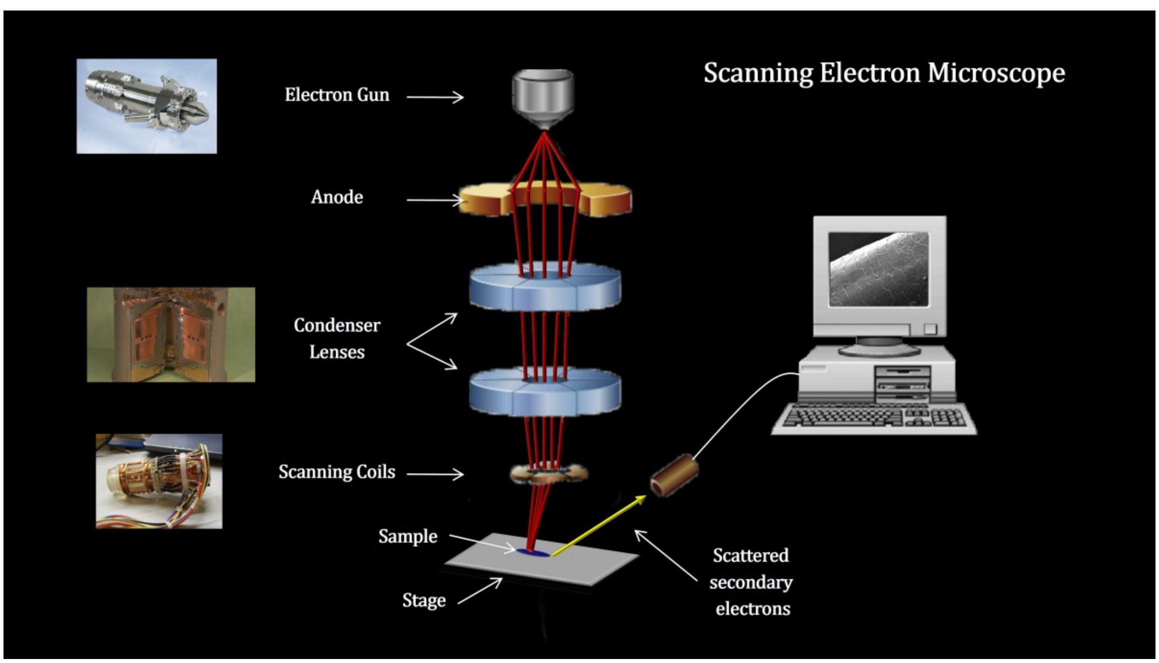
Scanning Electron Microscope

[Music @30:09 Chopin – "Piano Concerto No II Romance" **]**

With such a dramatic increase in resolving power over light, we'll use electrons instead of photons to illuminate the objects.

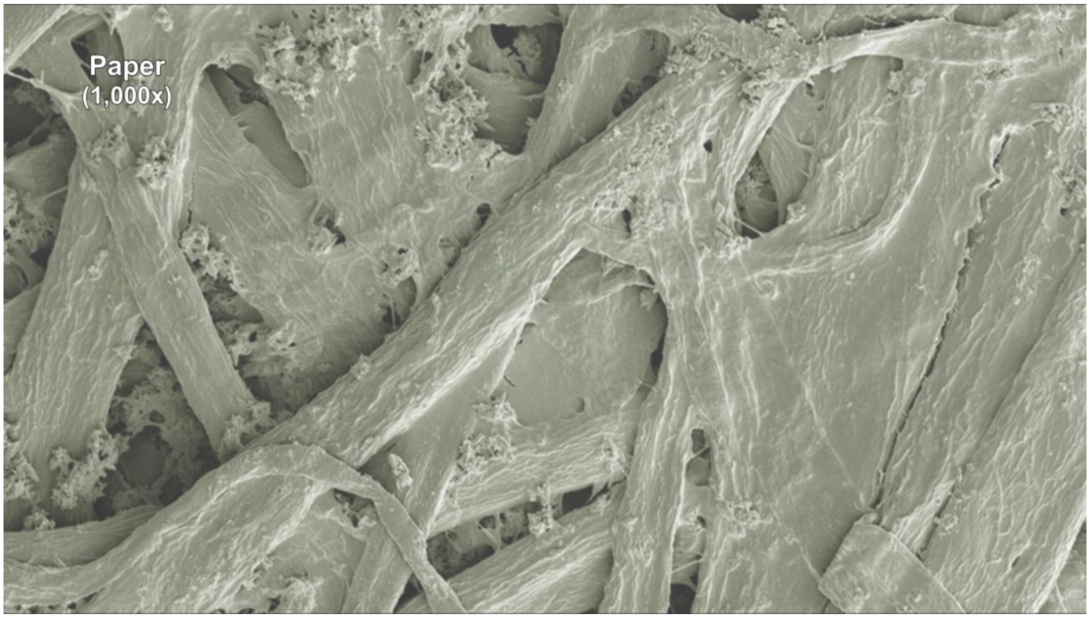
The most common electron microscope is called a scanning electron microscope (SEM).

Here's how they work. An electron gun heats up a metal, such as tungsten, to a temperature where it releases its electrons. An Anode with a large charge accelerates the electrons to a very high speed. Where glass lenses are used in an optical microscope to bend and focus the light, electron microscopes use powerful magnetic and electric field generators bend and focus the electron beam. Scanning coils are then used to focus the electrons onto a tiny spot on the specimen and move it across for a full picture of the surface. Different wavelengths penetrate the surface of the specimen and provide information on its structure. Here we are detecting the secondary electrons that define the surface of the specimen. The results are fed into a computer for processing and color additions.

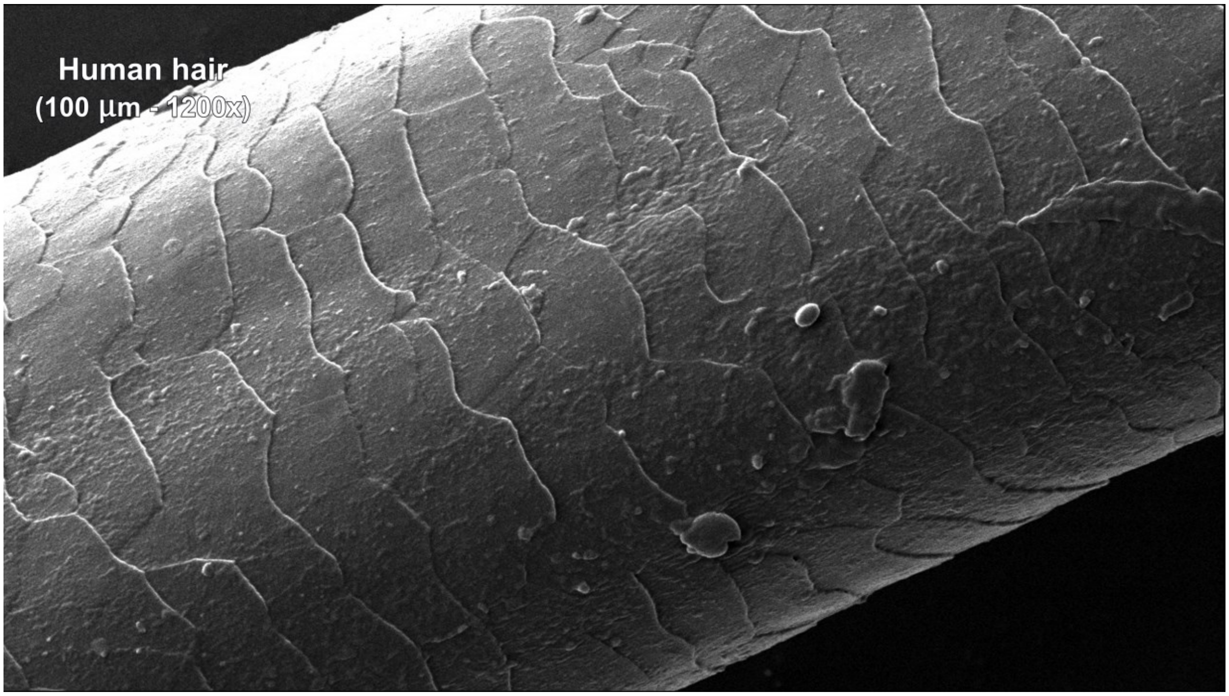


So, let's take a look at what we can see with electron microscopes. Here's an interesting look at bees through an electron microscope magnified 150 times. As you'll see, the resolving power of the electron microscope process provides images with dramatic clarity and detail not possible with optical tools. Because it's not light, there is no color associated with the images. But like we did with astrophotography, color can be added after the image is created by the electron microscope. Here's some honey bee images.

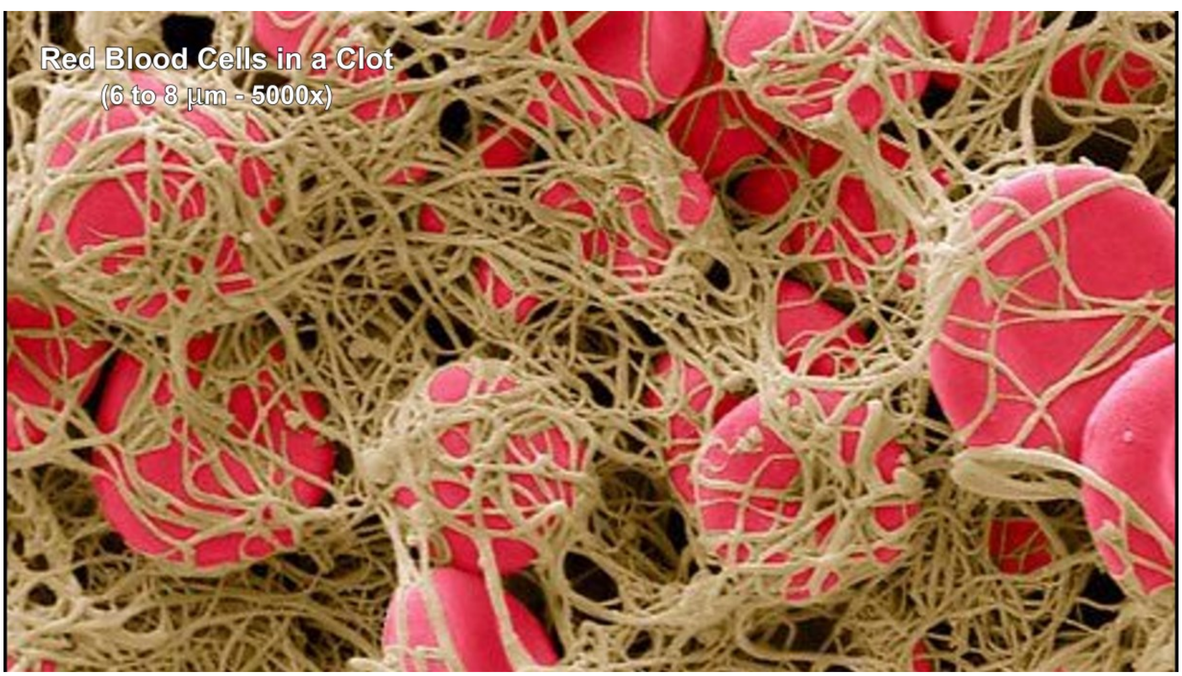
Here's what a sheet of paper looks like at 1000x magnification.



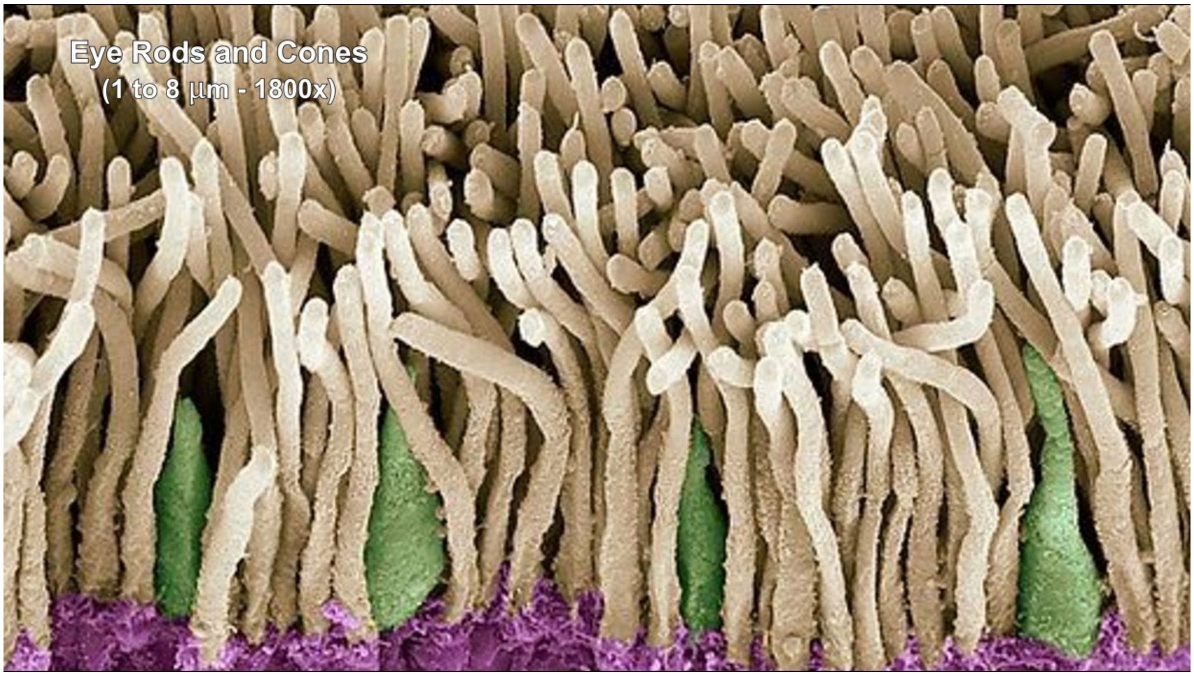
Here's a human hair magnified 1,200 times.



This is a colored SEM micrograph of red blood cells clumped together with fibrin to form a blood clot.

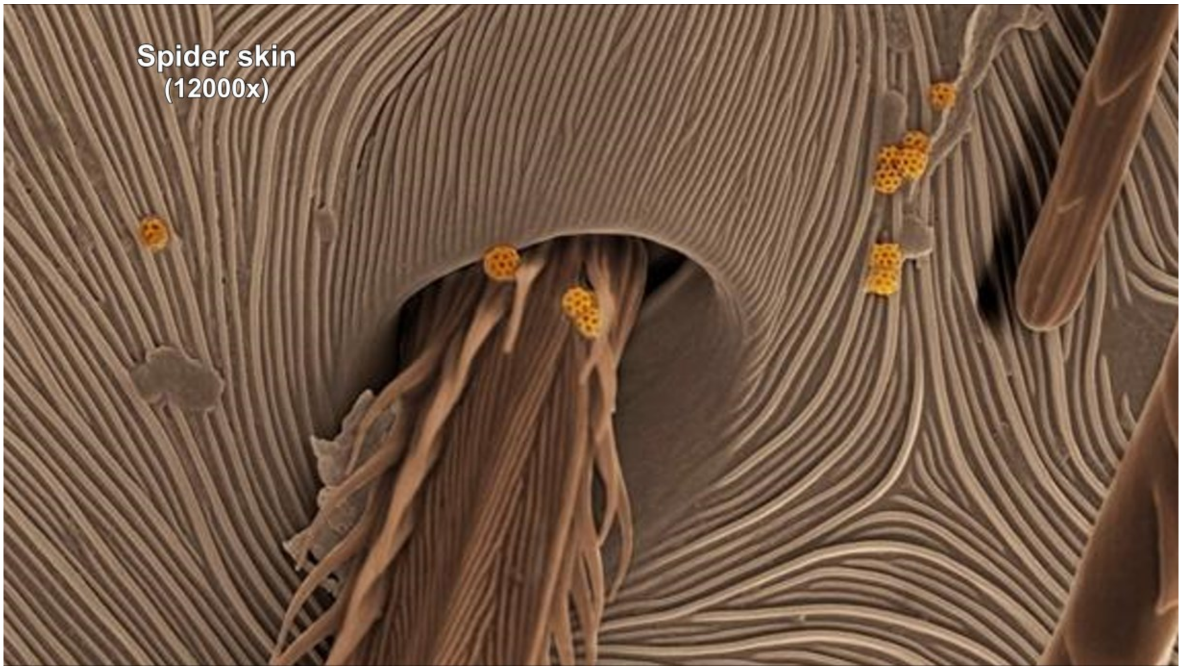


This colored SEM micrograph shows the rods and cones in the retina of the eye. The rods are tan and measure around 1 μm in diameter. The cones are green and measure around 8 μm in diameter.

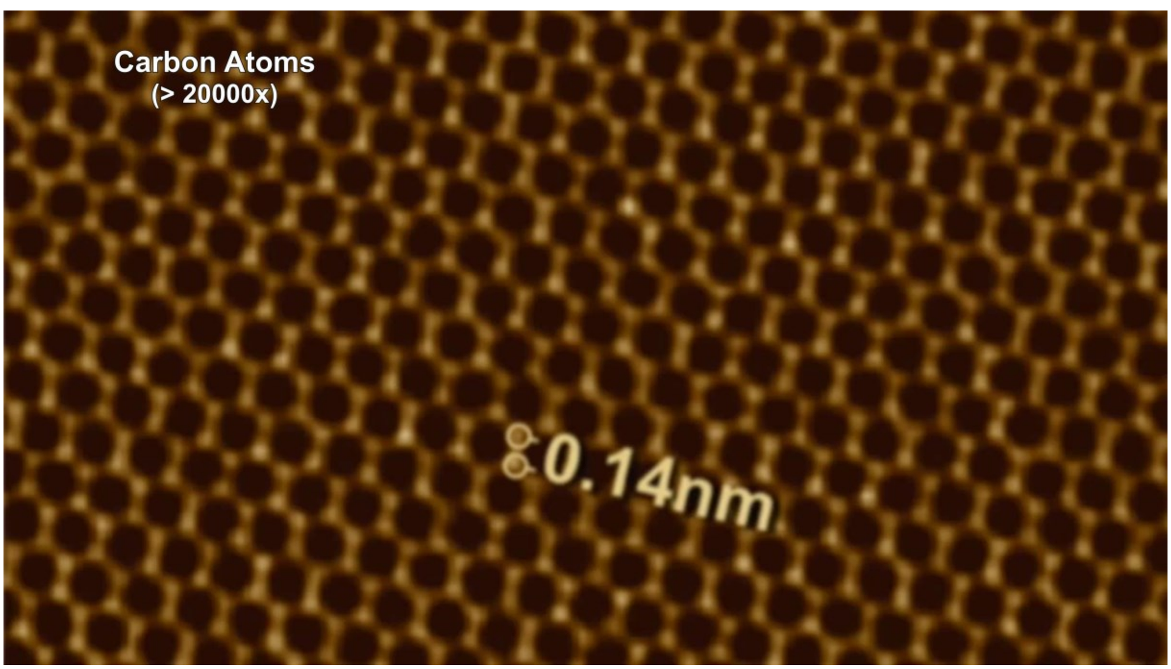


A nerve fiber is a threadlike extension of a nerve cell. Here's a colored scanning electron micrograph of myelinated nerve fibers. The myelin sheath is grey, the nerve inside is pink and the connective tissue is yellow.

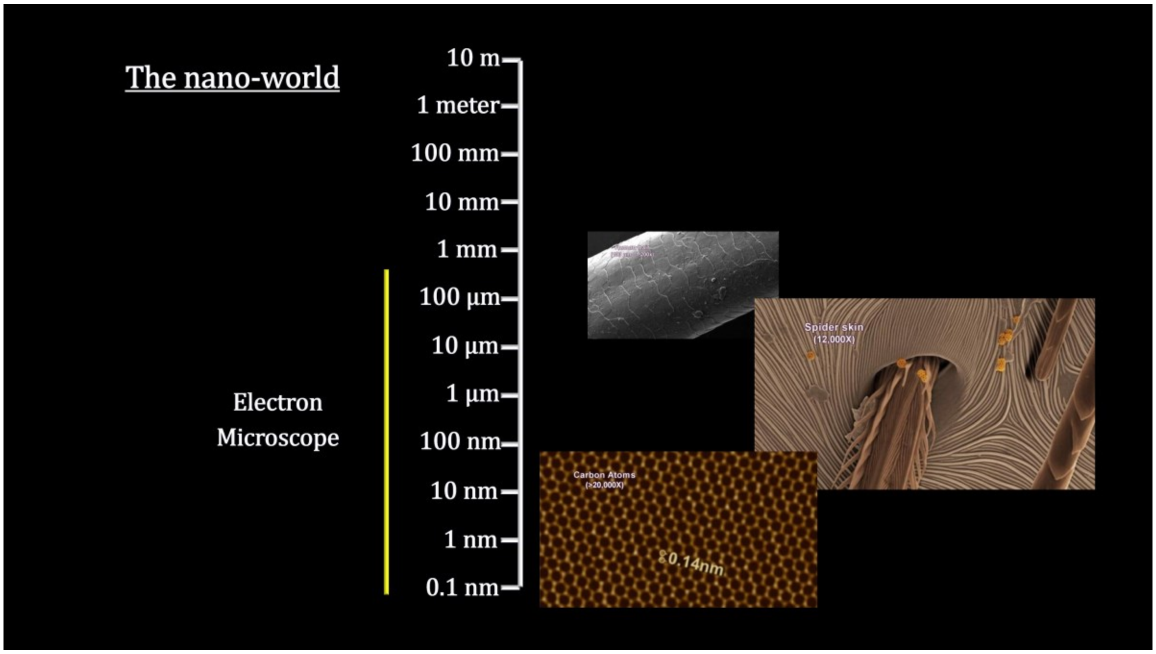
Here is the texture of the skin of a spider, magnified 12,000 times.



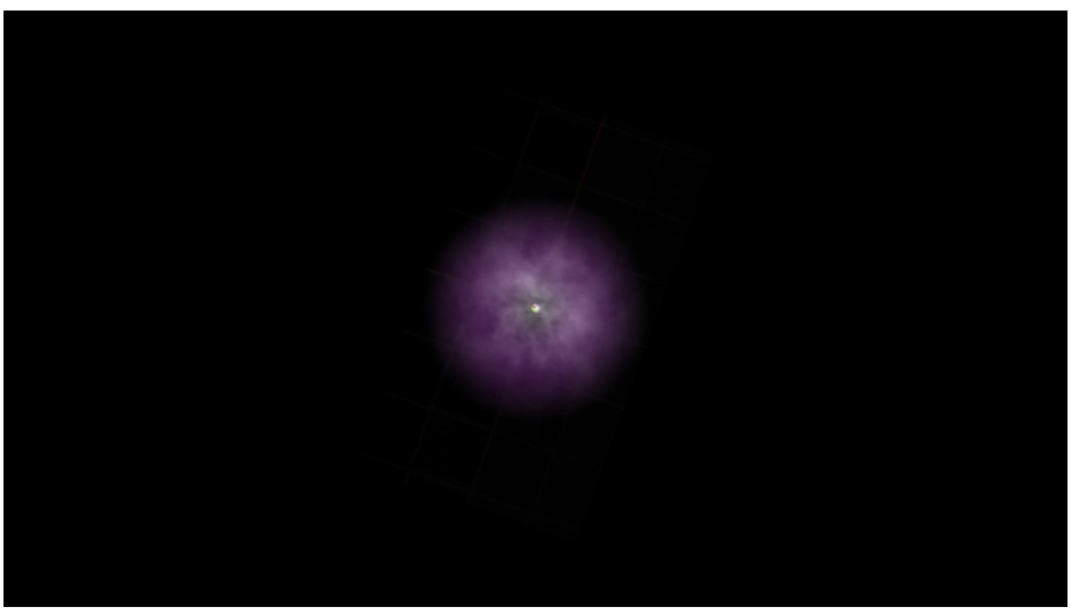
The most powerful electrons microscopes can resolve things as small as carbon atoms. Here's a sheet of carbon atoms with each atom around 0.14 nm in diameter. That's around a billion times smaller than the human hair we saw earlier.



In this segment we've gone from what we can see with the human eye, to what we can see with optical microscopes to what we can see with electron microscopes. Given the electron wavelength, this is about as good as we can do.



In our next segment, we'll take a closer look at atoms and their sub-atomic parts.



Music

@02:38: Tchaikovsky – “Swan Lake”: New Symphony Orchestra from the album “Tchaikovsky’s Greatest Ballets”, 2009

@25:57 Dvorak – “Symphony No 9 The New World”: Oslo Philharmonic Orchestra; Mariss Jansons; from the album “Essential Adagios”, 2010

@30:09 Chopin – “Piano Concerto No II Romance” : Martha Argerich; Orchestre Symphonique de Montréal; Charles Dutoit; from the album “Essential Adagios”, 2010

Greek letters:
- α β γ δ ε ζ η θ ι κ λ μ ν ξ ο π ρ σ τ υ φ χ ψ ω
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The Atom

*{**Abstract** – In this segment of our "How small is it" video book, we cover the atom.*

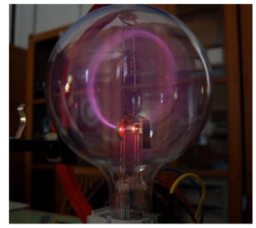
We start with J.J. Thomson's Plum Pudding model of the atom. We then introduce Alpha, Beta and Gamma radiation, and show how Ernst Rutherford used Alpha Particles in his scattering experiments to develop his version of the atom. We then cover Niels Bohr's quantized atomic model along with input from Louis de Broglie who used the wave nature of electrons to show that they take the form of standing waves enveloping the nucleus instead of point particles orbiting the nucleus. We then introduce Schrodinger's Equation, the Heisenberg Uncertainty Principle and the Pauli Exclusion Principle together with electron spin to fill out what we know about electrons around atoms. We explain electron tunneling as an example of these concepts and introduce the Scanning Tunneling Microscope based on these concepts to see atoms by "feeling" them. In closing, we introduce the atomic nucleus and Chadwick's discovery of the neutron, review how small the nucleus is and ask how is possible for protons to hold together in the nucleus when there like charges should push them apart.}

Introduction

[Music: Joseph Haydn – "*Cello* Concerto No. 2 in D" –**]**

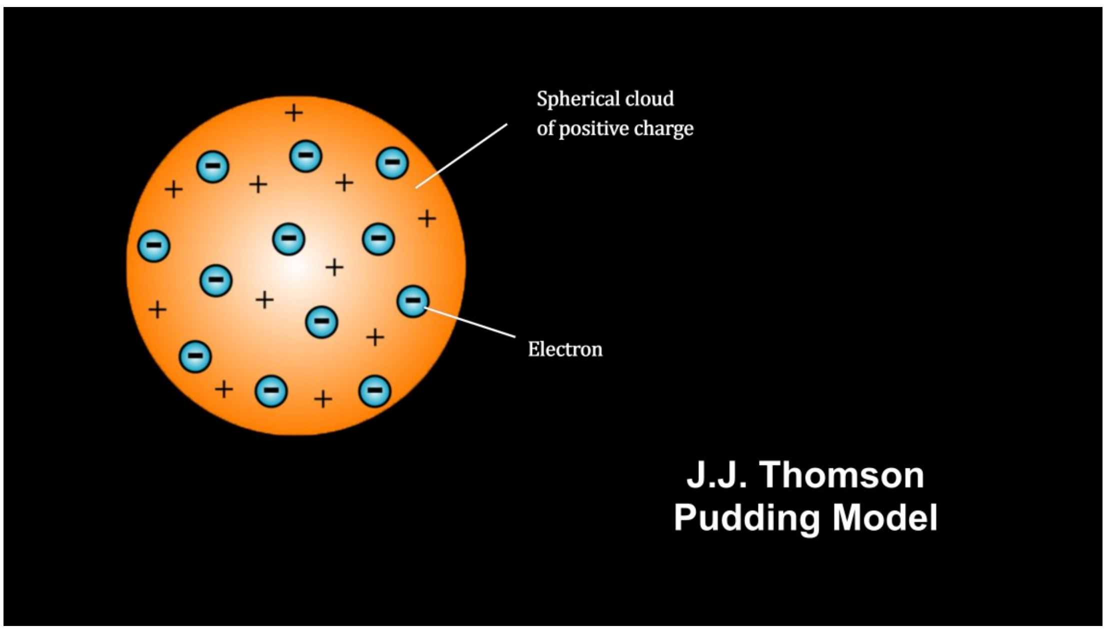
The ancient Greeks wondered how small things can get. One school of thought proposed that a substance such as water could be cut in half infinitely. Others thought that you could only take it to a point and then you would one 'atom' of water. If you split that, you wouldn't have water any more. They were right but they didn't have the tools to prove it. In our first segment, we used photons and electrons to see things down to the size of a carbon atom - 0.14 nanometers. That's small. Atoms are so small, that there are as many atoms in your DNA as there are stars in the Milky Way galaxy. In fact, there are more atoms in the breath of air I just took than there are stars in the visible Universe! The structure of the atom is responsible for nearly all the properties of matter that have shaped the world around us and within us. But what do we actually know about atoms and how small are the particles that combine to create an atom? That's what this segment is all about. We'll start with early guesses about atomic structure and show how we figured out how it actually works. It's a fascinating story and it will put us on the path to understanding elementary particles and the Higgs Boson.

The Thomson Atom



In the 19th century, it was well understood that the chemistry of substances consisted of atoms. But we knew very little about atoms themselves. It was the discovery of the electron by JJ Thomson that first introduced the idea that an atom had parts.

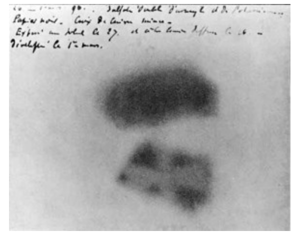
In 1898, with the electron being so light compared to the atom, Thomson suggested what is called the "plum-pudding" model of the atom – with a uniform mass of positively charged matter containing spots of electrons imbedded in it like plumbs in a pudding.



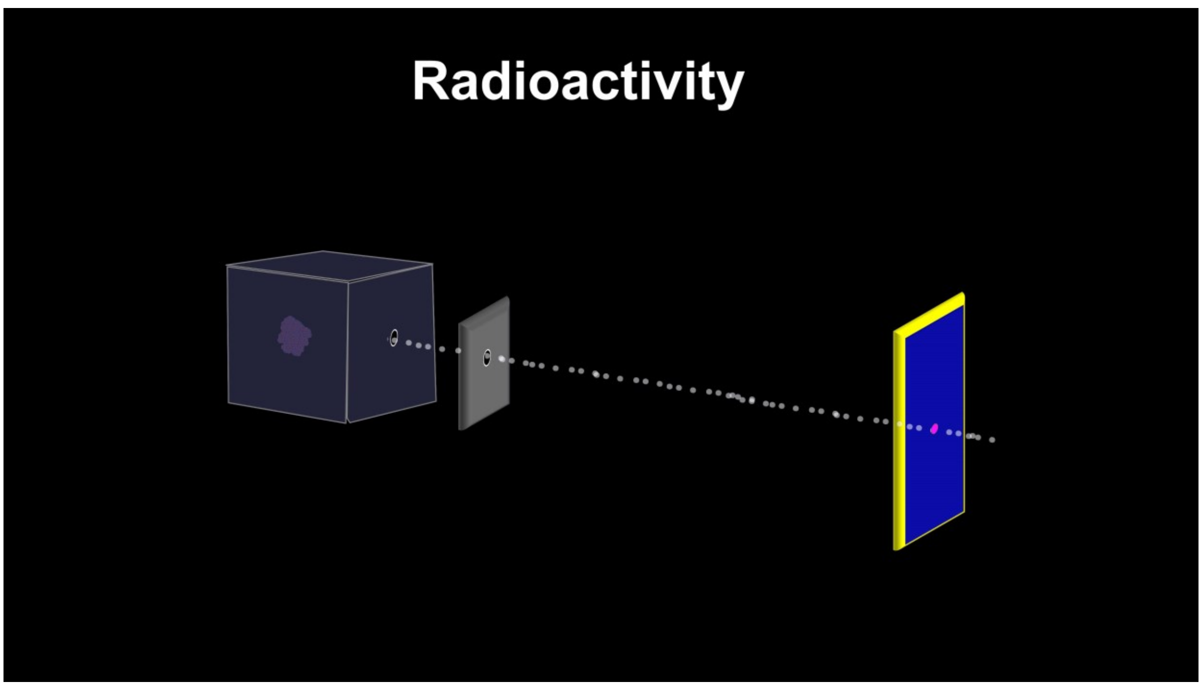
A way to find out if this model is correct or not, is to probe the pudding. But you need to probe with something smaller than the object being probed. For example, you can't probe a grain of sand with your finger. In 1898, there simply wasn't anything smaller than atoms that could be use to probe an atom.

Radioactivity

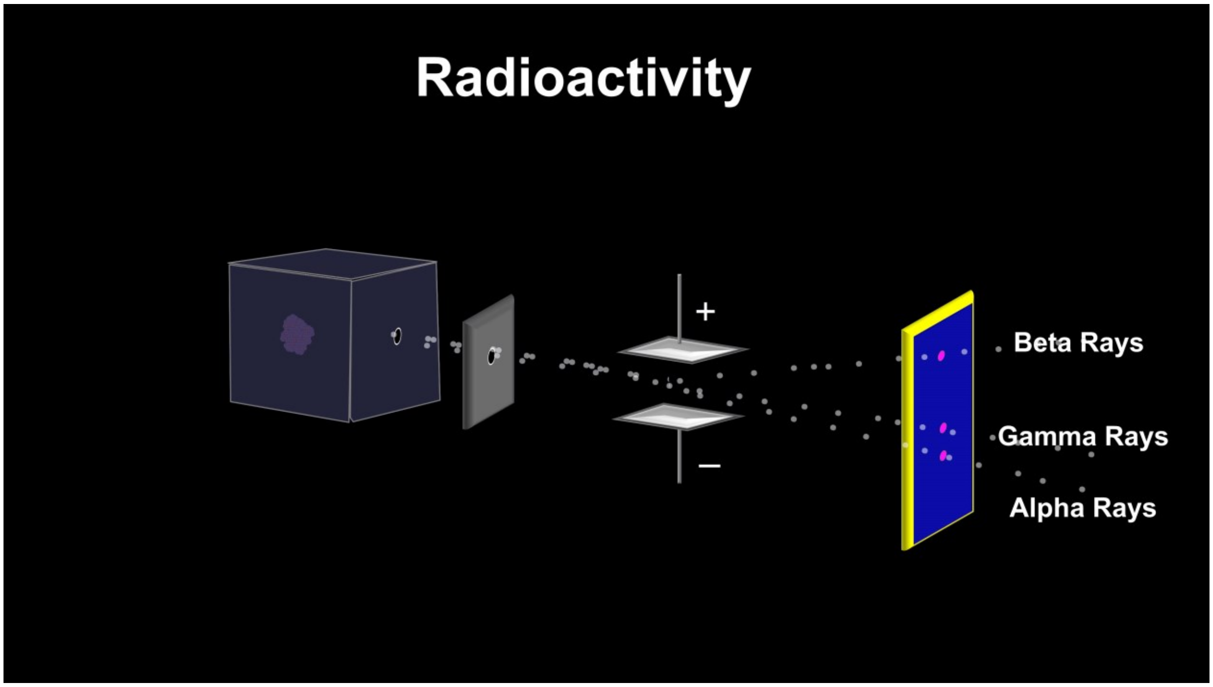
But around that time, radioactivity was discovered by the French scientist Henri Becquerel. Using uranium salts, he was able to blacken a photographic plate. Here's a photograph of the plate.



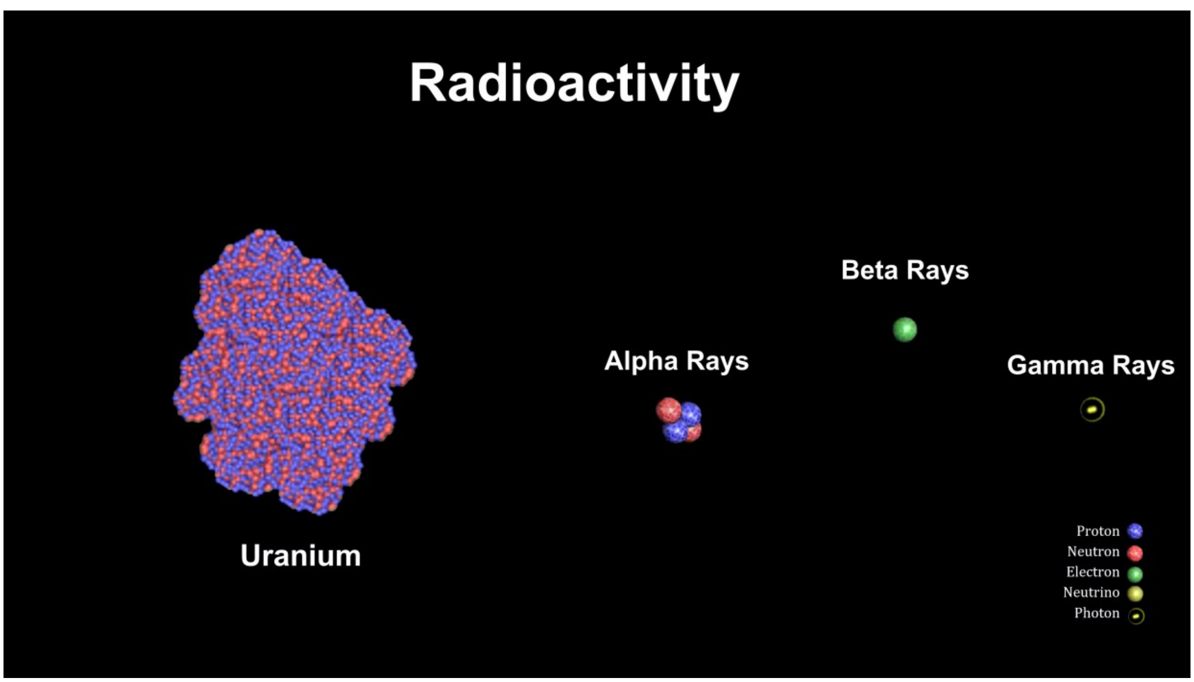
Further research by Becquerel, Ernest Rutherford, Madam Curie, and others discovered 3 types of radiation. Here's how they did it. A radiation source shines on a lead plate with a small hole in it to create a beam. The beam is directed at a florescent screen. The screen flashes when it is struck. Without any electric field present, the beam illuminates a single point on the screen.



When an electric field is applied, the beam is separated into three components. One is deflected upward by the electric field indicating that it is negatively charged. These were named beta rays. One is deflected downward, indicating that it is positively charged. These were named Alpha rays. The radiation that continued to hit the center was not affected by the electric field and therefore has no charge. These emissions were named gamma rays. It was noted that the Alpha rays were deflected far less than the beta rays. This was because the alpha particles are more massive than the beta particles. You'll recall the mass spectrometer we used to measure the mass of electrons in our previous segment.

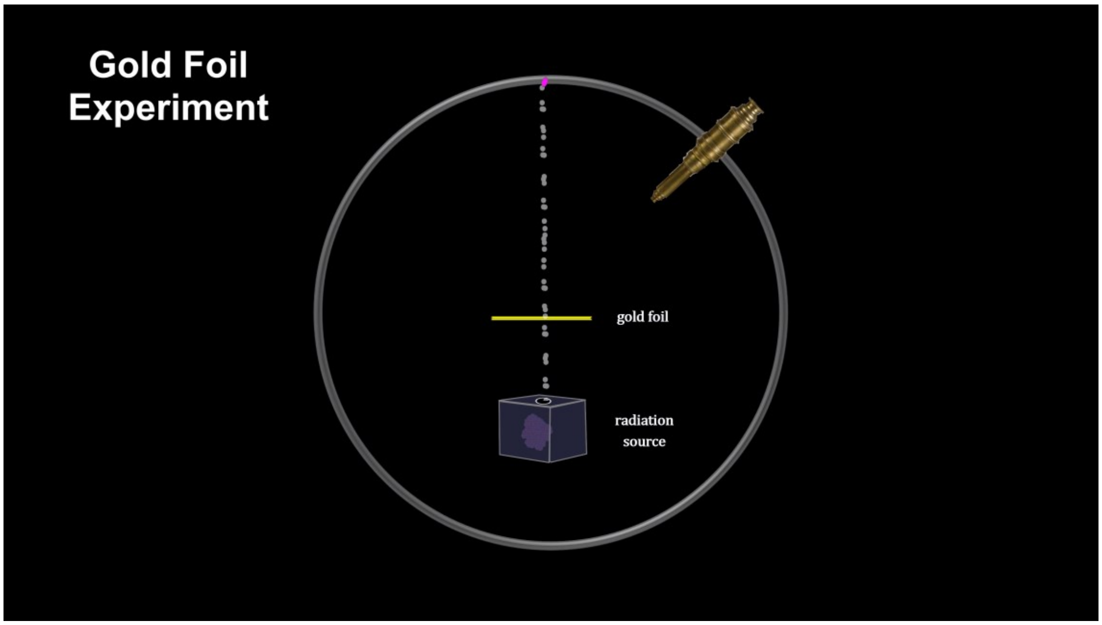


It turned out that beta rays are high speed electrons. The alpha particles were later found to be helium atoms without their electrons. The gamma rays turned out to be high energy photons, more energetic than x-rays.

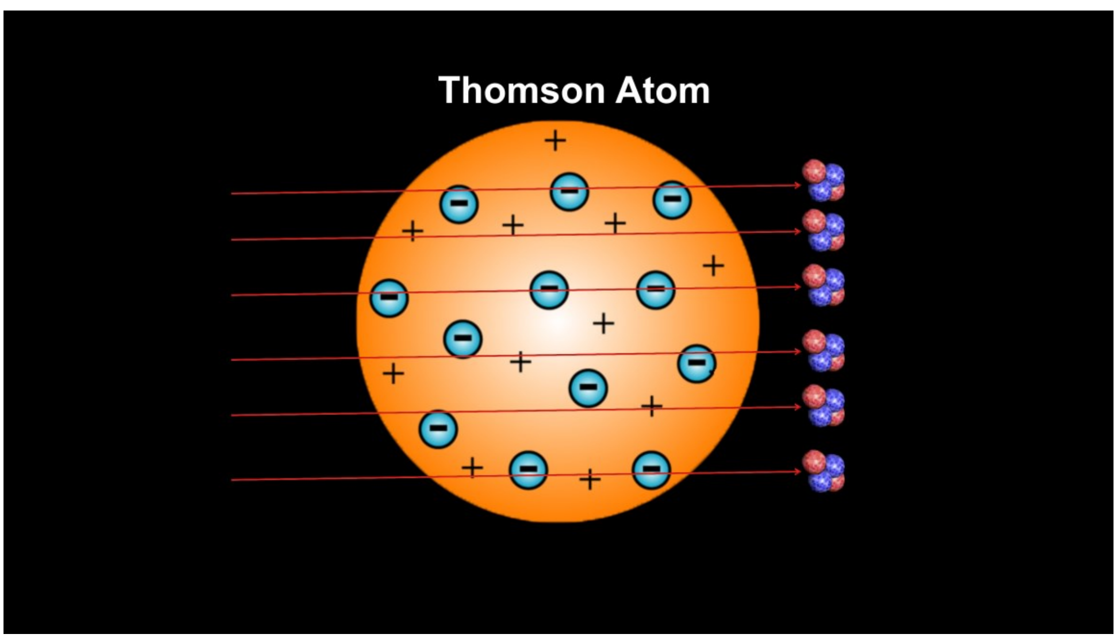


The Rutherford Atom **[Music:** Mozart – "Violin Concerto No. 3" – **]**

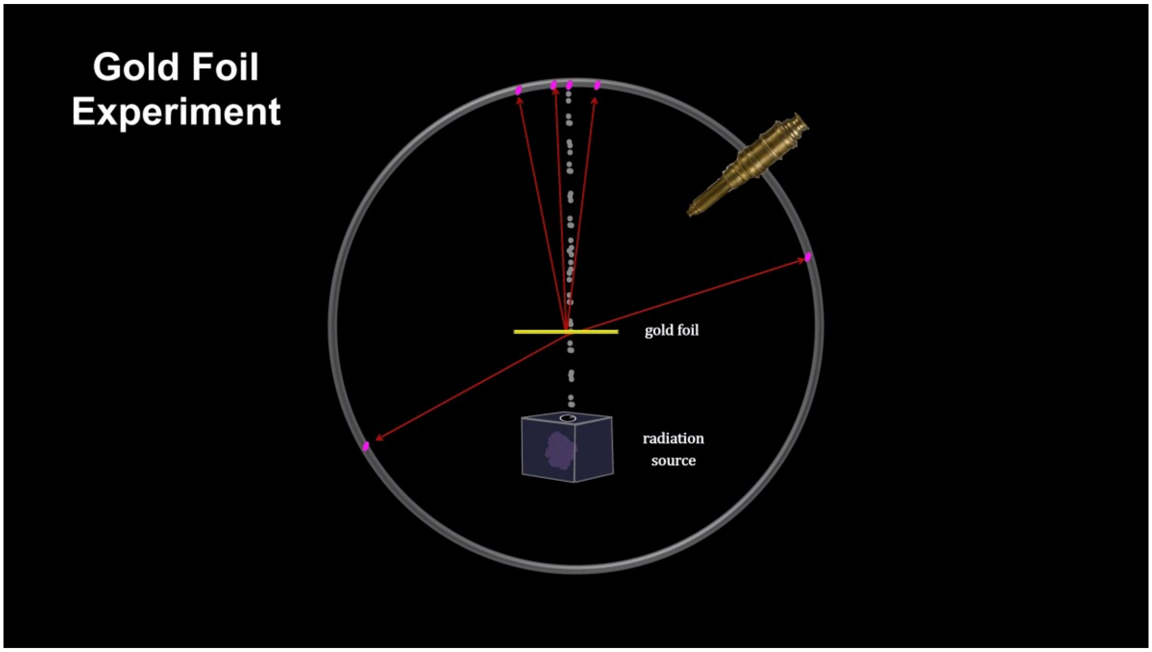
With Alpha particles, Rutherford had something to fire at atoms to see if they were indeed like a positive pudding with imbedded electrons. Here's a graphic of the apparatus used to run the experiment. An alpha particle emitting substance is placed behind a lead screen with a small hole in it to enable a narrow beam of particles to flow through. This beam is directed at a very thin gold foil. A movable zinc sulfide screen is placed on the other side of the foil. Zinc sulfide flashes when hit by an alpha particle. A microscope swivels to view all scattering angles.



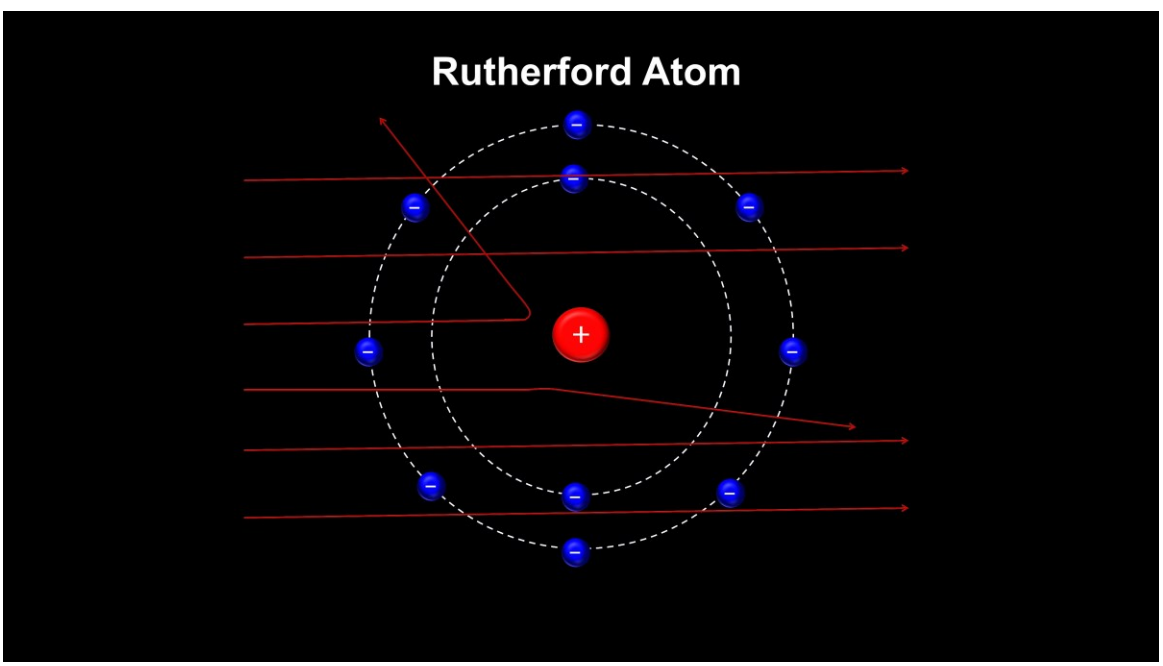
If the Thomson model was correct, the positively charged alpha particles would pass through the distributed and therefore diluted positive charge in the gold atoms with little or no deflections.



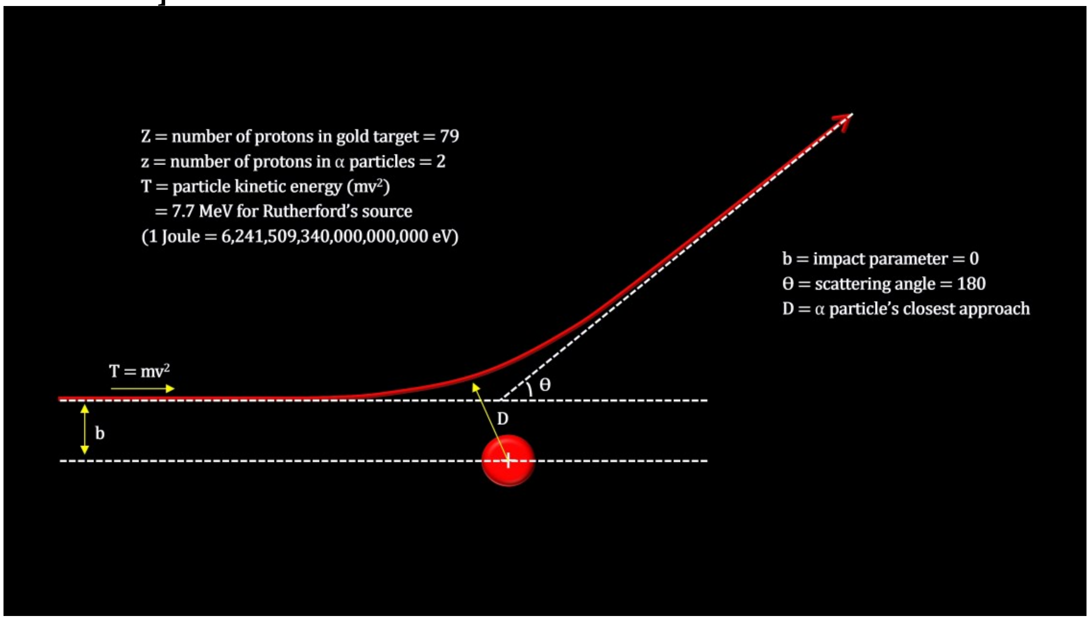
But after days of observations here's what they found. While most of the alpha particles do go right through with only minor deflections, some were scattered through very large angles. A few were even scattered in the backward direction! Rutherford described it as "almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back at you.'



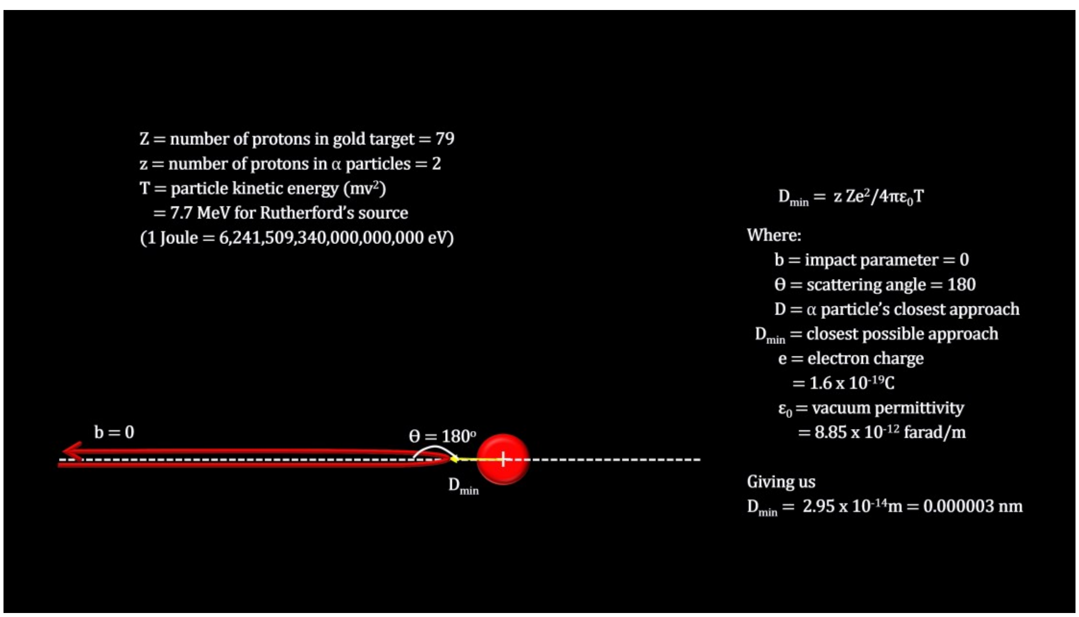
To explain these results, Rutherford was forced to picture an atom as being composed of a tiny nucleus where the positive charge and nearly all of its mass are concentrated, with electrons some distance away. Note that the closer the alpha particle is to the nucleus the greater the angle of the deflection. We can use this angle to measure the maximum possible size of the nucleus.



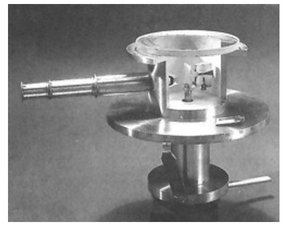
Here we have an alpha particle trajectory with an 'impact parameter' b that scatters at the angle theta and reaches a closest distance labeled D. The number of protons in the alpha particle is 2 and the number of protons in gold is 79. The energy of the naturally occurring alpha particles used by Rutherford where 7.7 million electron volts. An electron volt is the energy it takes to move one electron across one volt. **[**There are 6,240 trillion electron volts in one joule. So, you can see it is a very small number.**]**



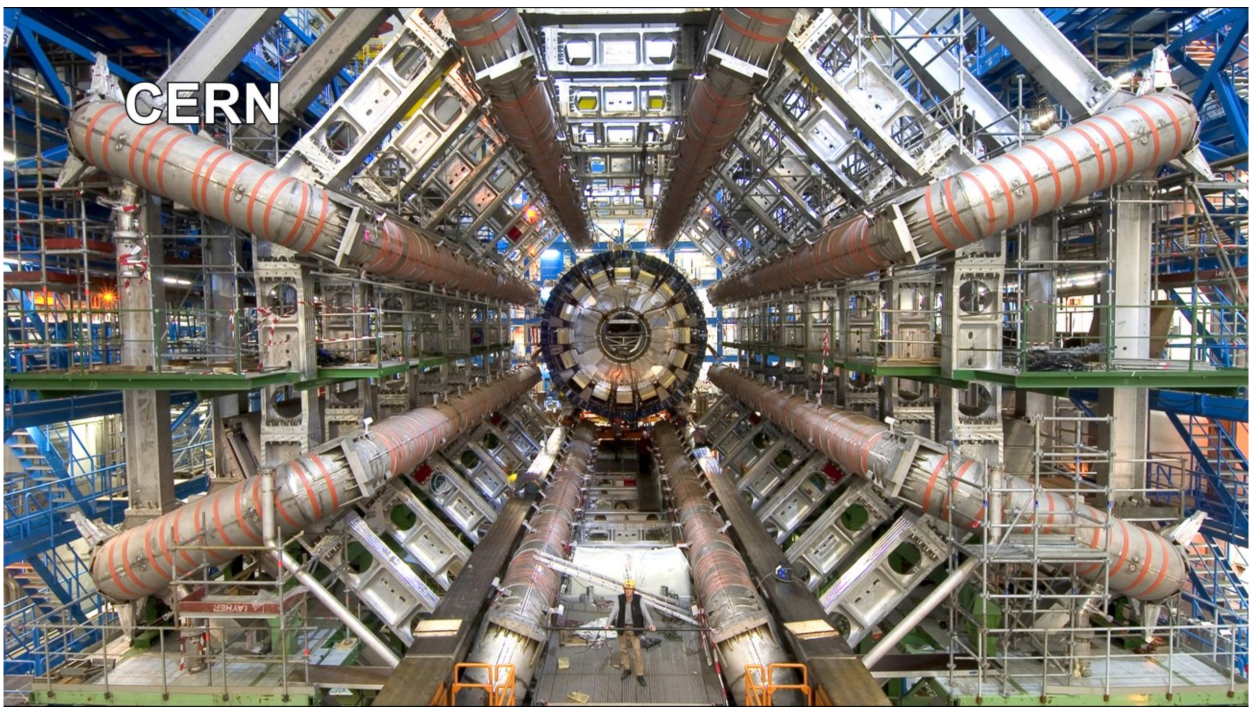
If we consider the direct hit trajectory, the initial kinetic energy of the alpha particle will drop to zero when it reaches its closest possible distance to the nucleus. All its kinetic energy would have been converted to electric field potential energy. Conservation of energy tells us that these two numbers must be equal. Rutherford's calculations showed that the radius of a gold atom nucleus cannot be any larger than 0.00003 nanometers. That was ten thousand times smaller than the size of a gold atom.



Here's a picture of the test apparatus Hans Geiger (of Geiger counter fame) and Ernest Marsden built to look for scattered alpha particles from every angle. The microscope could be swiveled all the way around the gold foil.



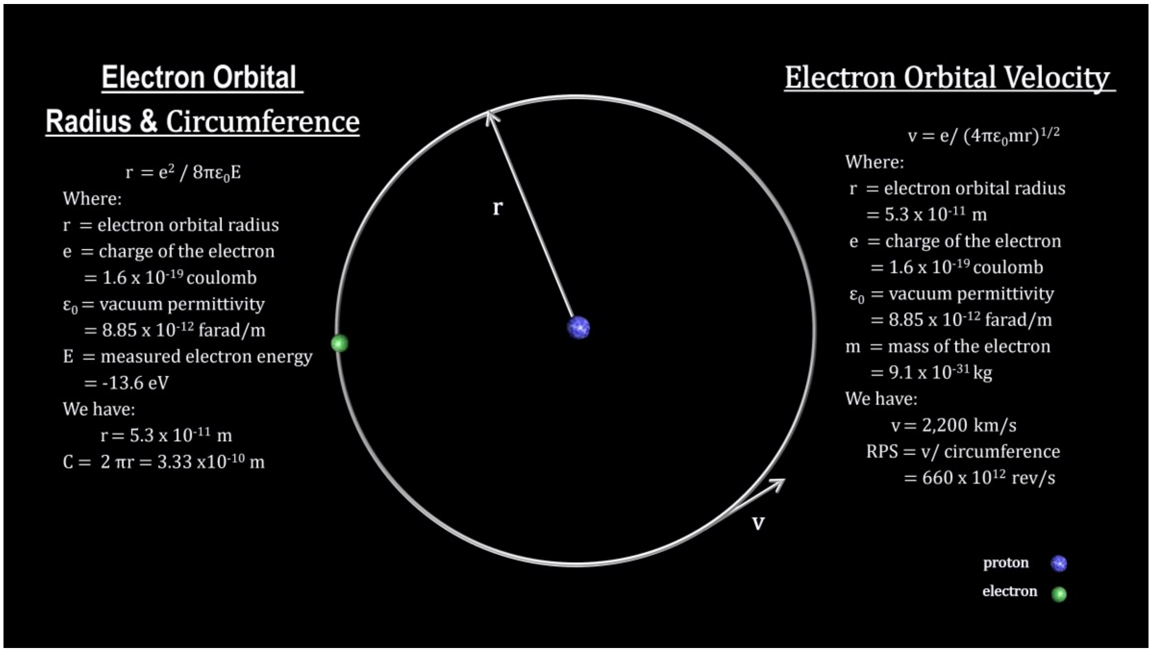
This is the first experiment that fired a beam of particles at a target to detect the scattering effects and deduce what is going on. That was around a hundred years ago. This is exactly what we are doing today at the European Center for Nuclear Research (CERN) to analyze the Higgs Boson. We'll return for a deeper look at Rutherford scattering when we get to particle accelerators.



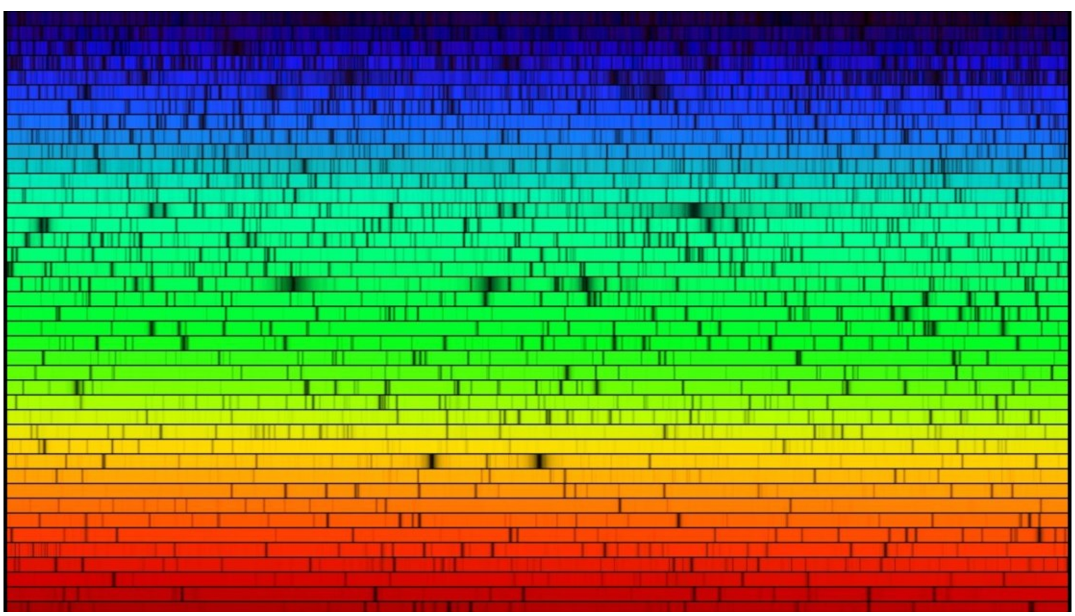
The Bohr Atom **[Music:** Tomaso Albinoni – "Adagio in G minor" –**]**

The Rutherford model of the atom left one outstanding problem. In the Thomson model, the electrons were stationary in the positively charged pudding. But what keeps a negatively charged electron from falling into the positively charged nucleus - given that opposite charges attract each other. The first proposed solution was to assume that the electron is in orbit around the nucleus like the Earth around the Sun. Just as we can use gravitational and centripetal forces to calculate the radius and velocity of a planet around the Sun, we can use electric and centripetal forces to calculate the radius, circumference, velocity, and revolutions per second of an electron around the nucleus.

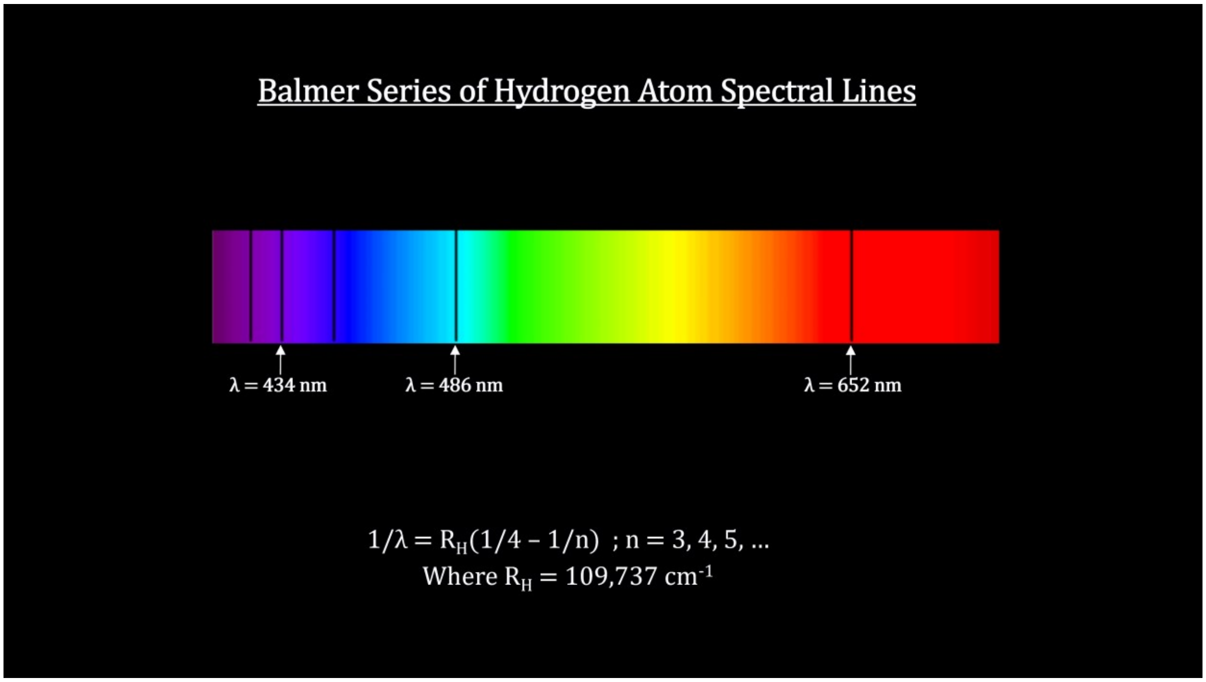
For Hydrogen, we get a very small circumference of around a third of a nanometer and a very large velocity of around 1% of the speed of light. That combination gives us a fantastically large 660 trillion revolutions every second.



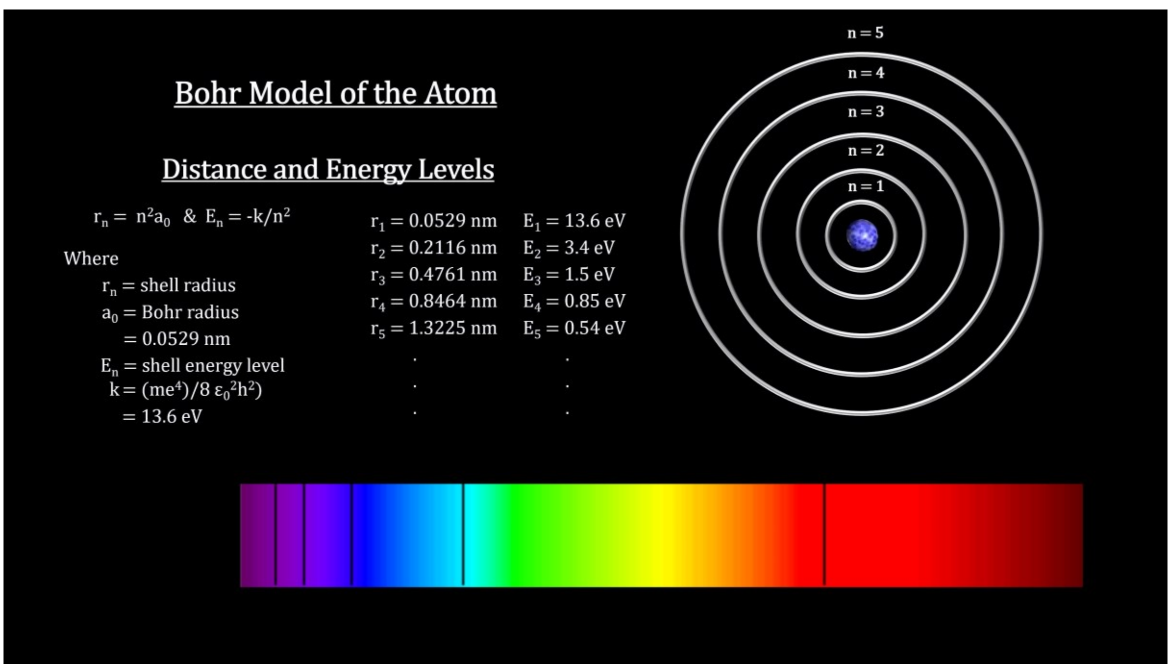
This would create a stable atom if the electron didn't have a charge. But classical electromagnetic theory points out that an accelerating charge radiates energy. Theoretically, the electron should collapse into the nucleus in less than a trillionth of a second. And yet, we see that it does not collapse. You'll recall from our "How far away is it" segment on "Distant Stars", that the light spectrum from stars was covered by thousands of dark lines called Fraunhofer lines or spectral lines. Although these lines had been studied for over a hundred years, no one understood what they were.



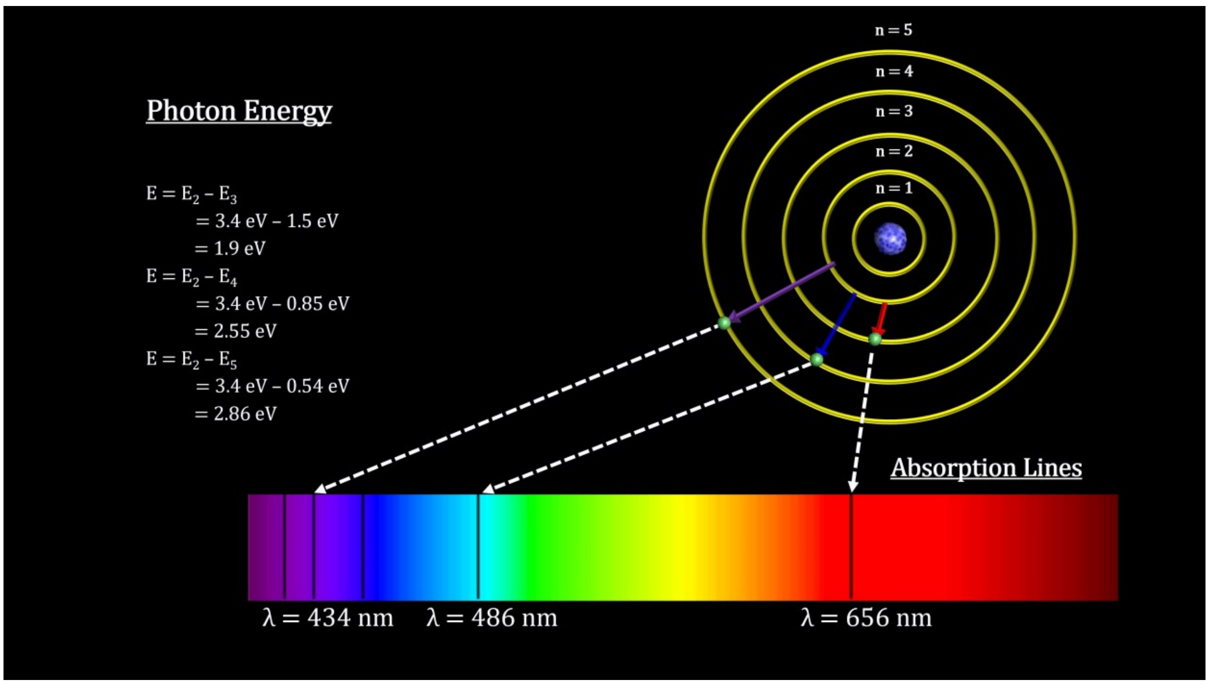
In 1885, Johann Balmer broke out a subset of these lines for Hydrogen and developed some mathematical interrelationships between them.



Then, almost 30 years later, Niels Bohr developed a quantized momentum theory for the atom that partially explained these lines. His model still had the electrons orbiting the nucleus, but they could only orbit at certain specific distances from the nucleus called shells. Each shell had its own unique energy level n, where n was a positive integer = 1, 2, 3, etc. These were called the atom's quantum numbers.

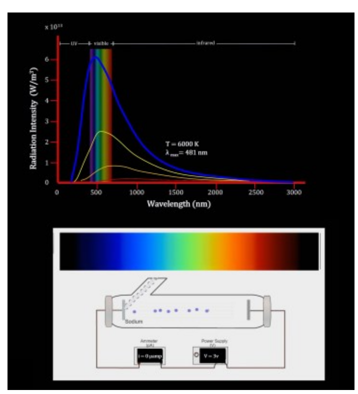


Electrons radiated or absorb energy when they change energy levels. The emitted or absorbed light has the energy difference between the levels. This energy is equal to Planck's Constant times the frequency of the emitted light. Here's how it works. When a photon with an energy E, hits an electron in a shell around a nucleus that has a higher shell it can reach with this same exact energy the photon's entire energy is transferred to the electron instantaneously. This jumps the electron to a higher energy level with a larger quantum number. The photon is eliminated. This creates 'absorption lines' in a star's spectrum as light from the star travels through the star's atmosphere. When the electron drops from this excited state back to a lower energy level, a photon with the exact difference between energy levels is emitted. This creates emission lines that we can see in the lab.

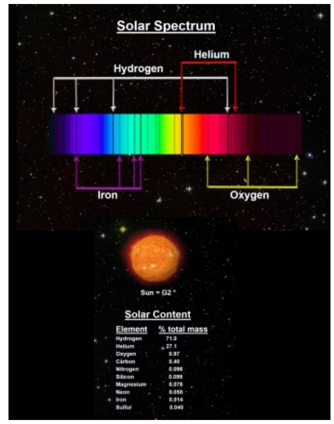


Bohr's model explained the Balmer series for Hydrogen spectra.

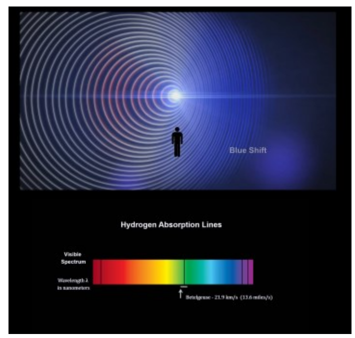
In addition, it provided the physical mechanism for Planck's quantized emission Blackbody Radiation and Einstein's quantized absorption Photelectric Effect.



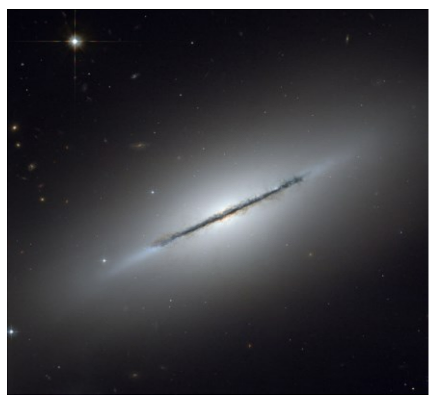
It was also momentous for astronomy. Every atom and molecule have their own unique spectral line signature. So, by observing the absorption lines in a star's spectrum, we can tell what the star is made of!

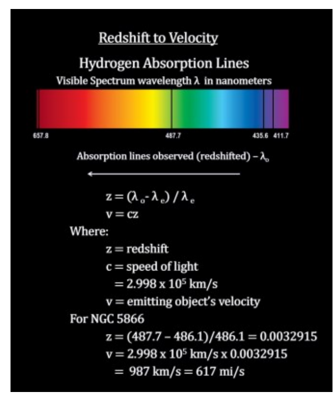


And not only that, by analyzing how these lines shift, we can calculate star radial velocities via the doppler effect,



and even use them to measure the expansion of the Universe.

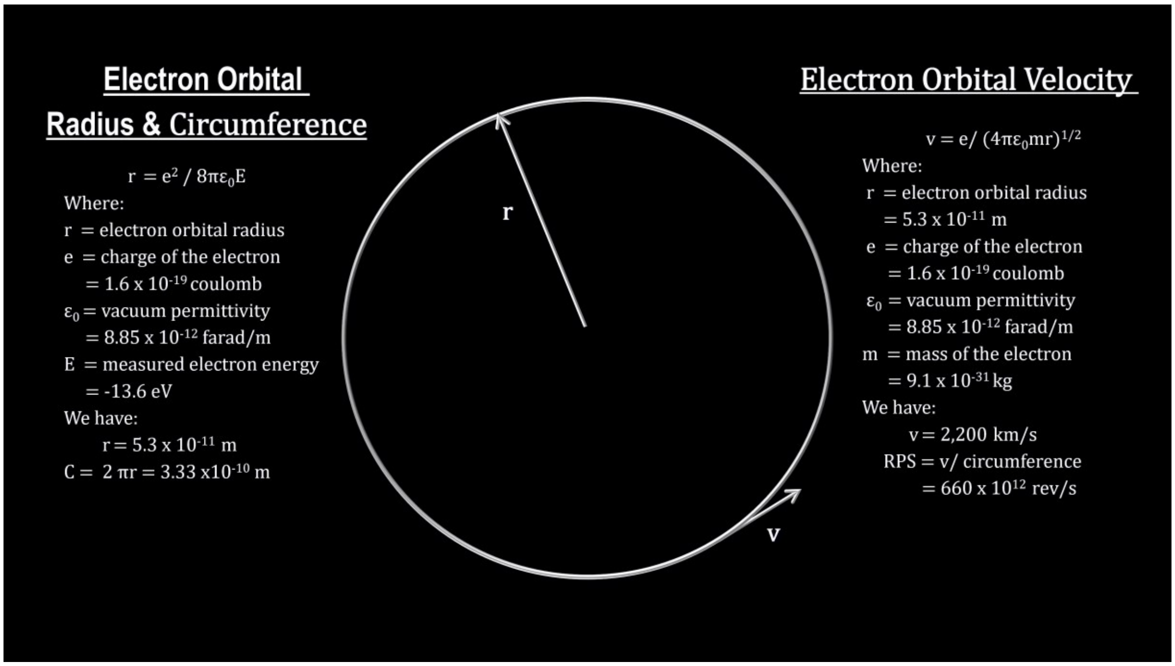




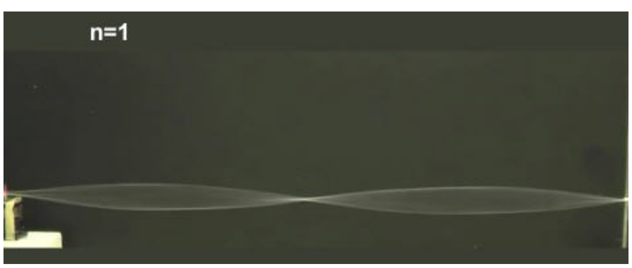
Indeed, Bohr's model explained a great deal. But there was no explanation for why the shell distances from the nucleus were as described, and there was no explanation for why the orbiting electrons didn't radiate away their energy and collapse into the nucleus.

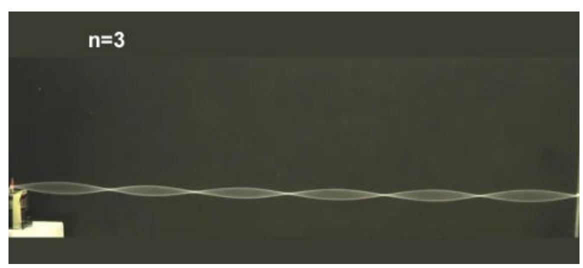
The de Broglie Atom

In 1925, Louis de Broglie came up with the model that explained how electrons avoid falling into the nucleus. Earlier, we calculated the circumference and velocity of the electron, so like we did for electron microscopes in the previous segment, he calculated its wavelength. He found that it was exactly the length of the electron orbit's circumference as enumerated by Bohr! In other words, the wavelength of the electron is exactly the length of one revolution. This would create a standing wave!



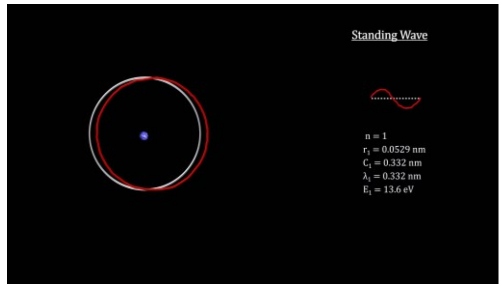
Here are a couple of standing waves on a string.



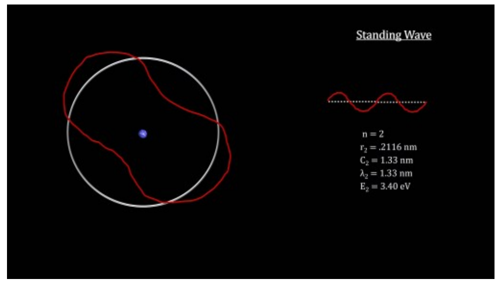


Here's a water standing wave. A standing wave is a wave constrained to vibrate in a distance that's an exact multiple of its wavelength. Anything more or less would create destructive interference and the wave would collapse.

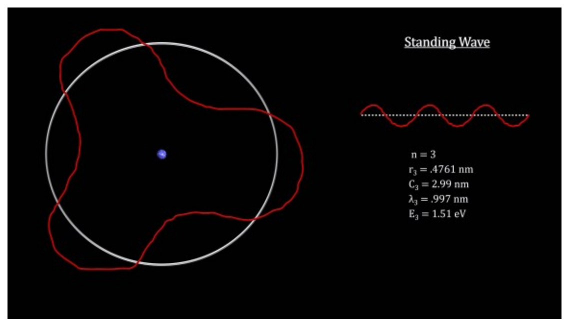
So, the first energy shell would have to have the radius that creates the circumference that exactly fits one wave.



The second shell would have to have the radius that creates the circumference that exactly fits two wavelengths.

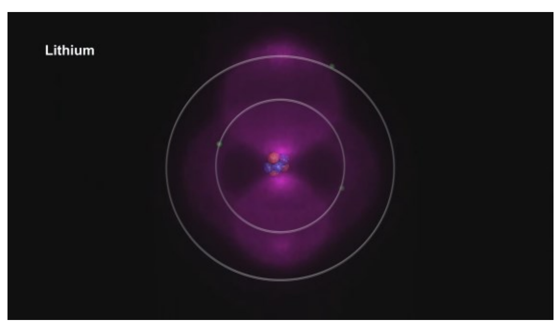


The third shell would have to have the radius that creates the circumference that exactly fits three wavelengths, and so on.



So, the proposed answer to the question "How can an electron sit way outside the nucleus without orbiting away its energy?" is that the electrons exist as standing waves that envelop the nucleus. No orbital motion is required and therefore, no radiation is emitted. Remember that: electrons in an atom do not 'orbit' the nucleus like planets around the sun – they exist as standing waves.

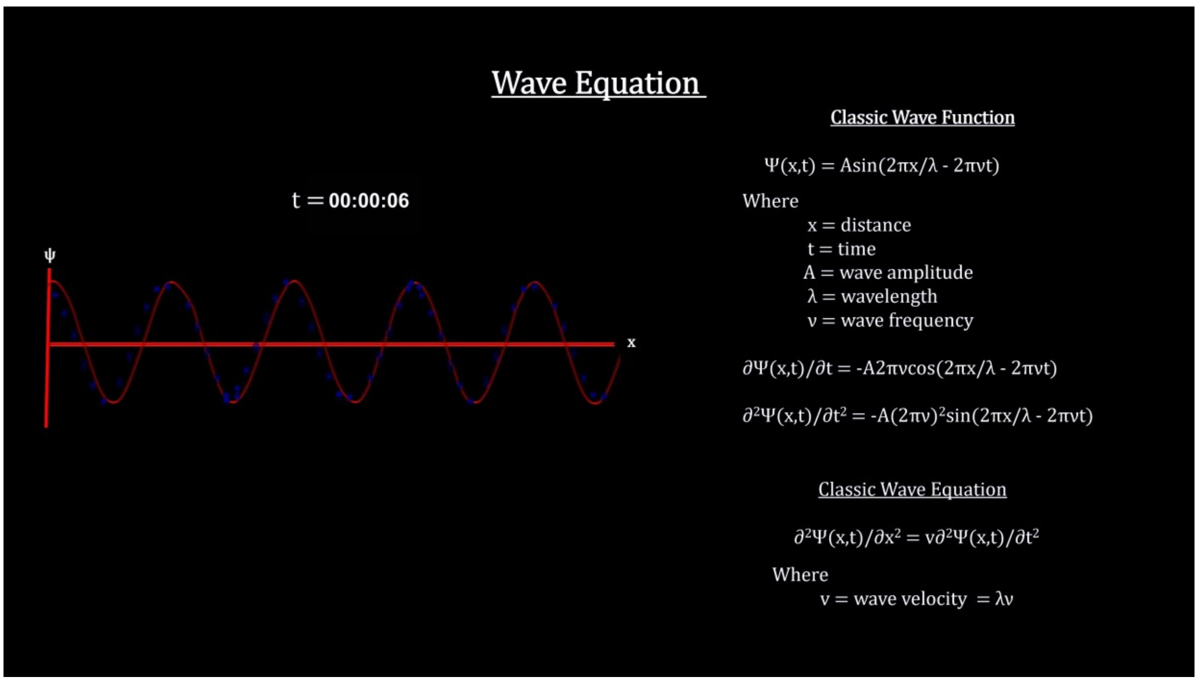
de Broglie's simple geometry elegantly explained the reason for each energy shell's distance from the center and its corresponding energy. But it didn't scale to explain the spectra of more complex atoms that have more electrons. [And it could not explain how individual atoms interact with one another to produce the physical and chemical properties that we observe in everyday life.]



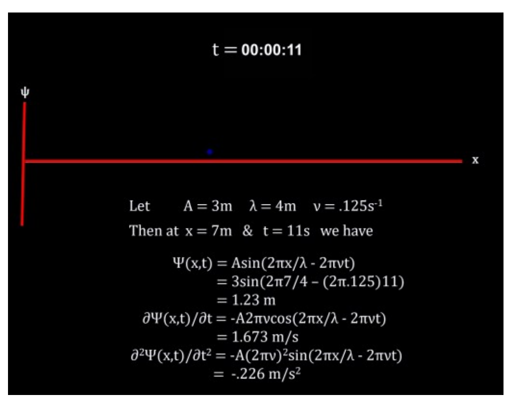
Schrodinger's Equation

Given that particles travel as waves, and are confined in atoms as standing waves, it followed that a generalized wave equation was needed to describe them. Building on the works of Planck, Einstein, Rutherford, Bohr, de Broglie and others, Erwin Schrodinger an Austrian physicist developed just such an equation, now bearing his name.

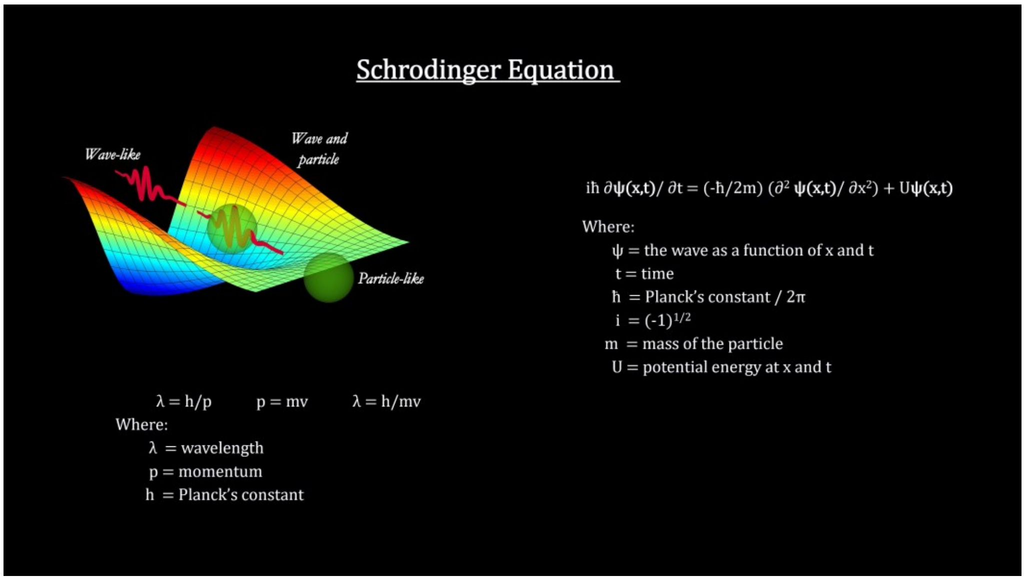
Here's a simple sine wave in water. It's described by a wave function. The function tells us the displacement of every water particle in the wave at any time t. If we take the change in a particle's displacement with respect to time, we get its velocity. And if we take the change in a particle's velocity with respect to time, we get its acceleration. A generalization called the wave equation describes how a wave function evolves over time.



Here's an example. If we take a look at the particle 7 meters down the line and take a snapshot at the 11 second mark, we see that it is just above the line, heading up rapidly and slowing down slightly.

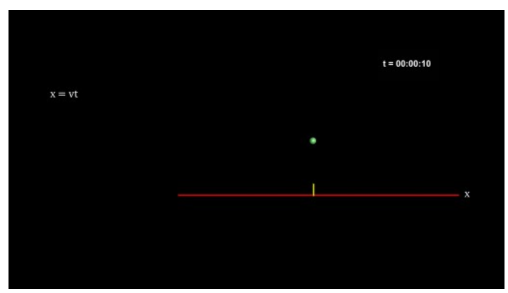


Schrodinger used the fundamental relationships between energy and wave frequency and quantized momentum to develop a quantum mechanical equivalent of the wave equation. Importantly, it had one critical difference with the classical model - it did not produce a location for a particle. In fact, it did not represent an observable physical quantity at all. Instead, it produced a probability curve for particle location.

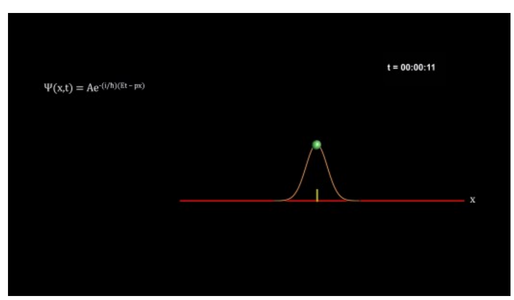


For free particles, the square of the wave function gives us the probability of experimentally finding the particle at a particular location at a particular time.

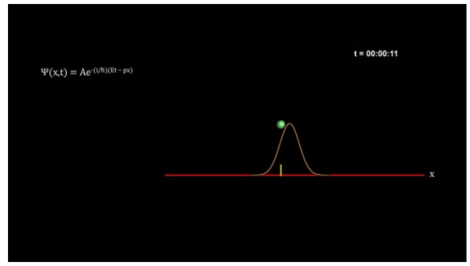
For example, suppose we had a particle moving from left to right at a specific speed. From Newton's equations, the distance x is equal to the speed v times the time t. After 24 seconds, we would say that the particle is here.



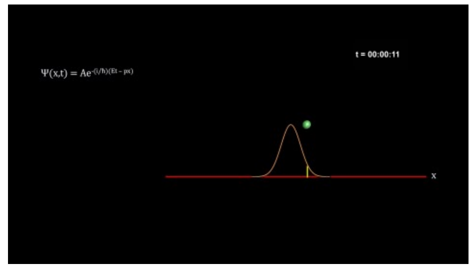
But, because the particle moves as a matter wave, we need to use Schrodinger's equations. So, when you touch the wave at time t, it collapses into a particle. Where classical physics says it is here, quantum mechanics says that 'here' is the most likely place.



But there is a smaller probability that it is here.

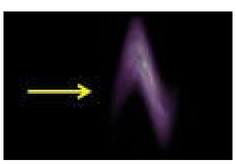


Or an even smaller probability that it is here. In fact, there is a chance that it may be anywhere along this probability curve, with the probabilities dropping rapidly as we move away from the most probable point.

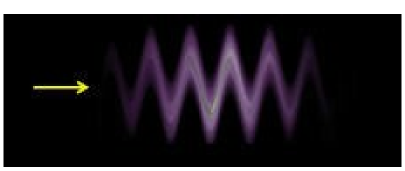


Heisenberg Uncertainty Principle **[Music:** Dave Porter – "Breaking Bad" –**]**

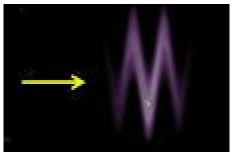
This brings us to the Heisenberg Uncertainty Principle. In our quest to understand how small things can get, we need to know if there is a measure of size below which we can't go. We see from our little thought experiment that, as a wave, a particle's location is not fixed. The wave is spread out. Here we see three different wave packets for an electron.



The wave packet at the top is narrow and therefore easier to locate, but it is less than one wavelength, so its momentum is impossible to figure out.

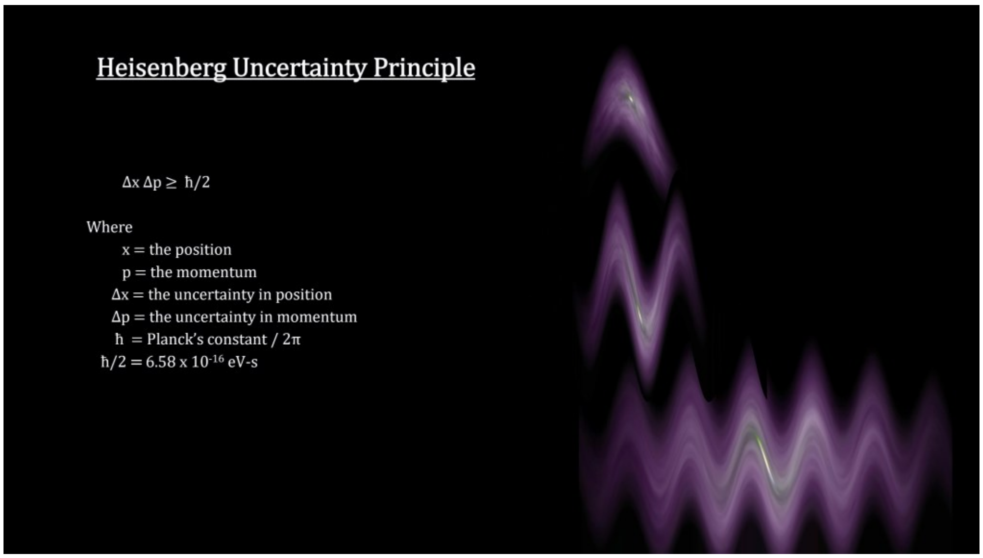


The bottom wave packet contains plenty of wavelength information, but it is quite spread out and its location is more uncertain.

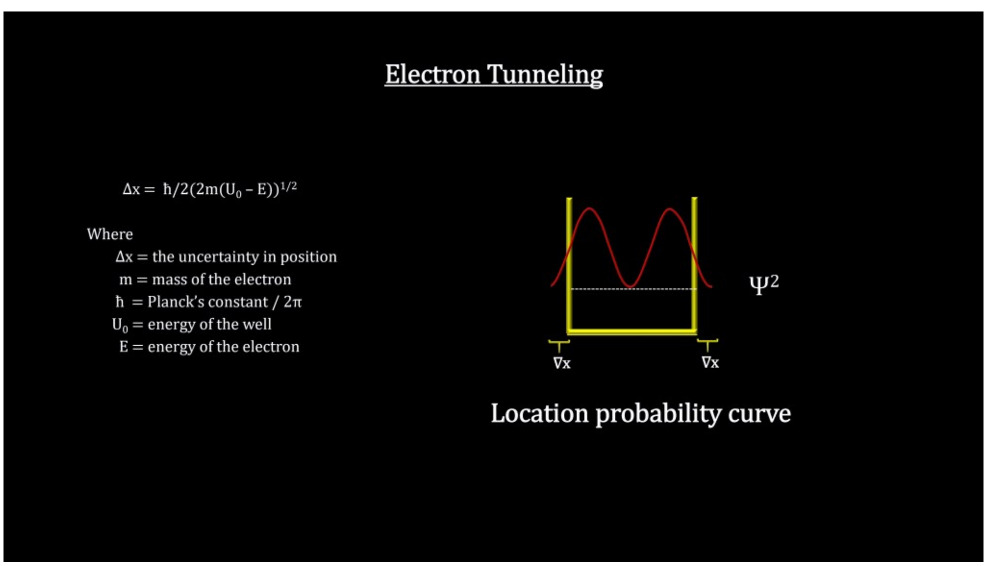


The wave packet in the middle has enough wavelength information to make its momentum less uncertain, and it is less spread out than the one on the bottom making its location less uncertain.

But, due to the spread-out nature of matter waves, we still can't know both the location and momentum at the same time. Mathematically stated, the uncertainty in position times the uncertainty in the momentum is always greater than or equal to Planck's constant divided by 4 π. This is the Heisenberg Uncertainty Principle. It has nothing to do with the accuracy of our instruments and everything to do with the wave nature of matter.

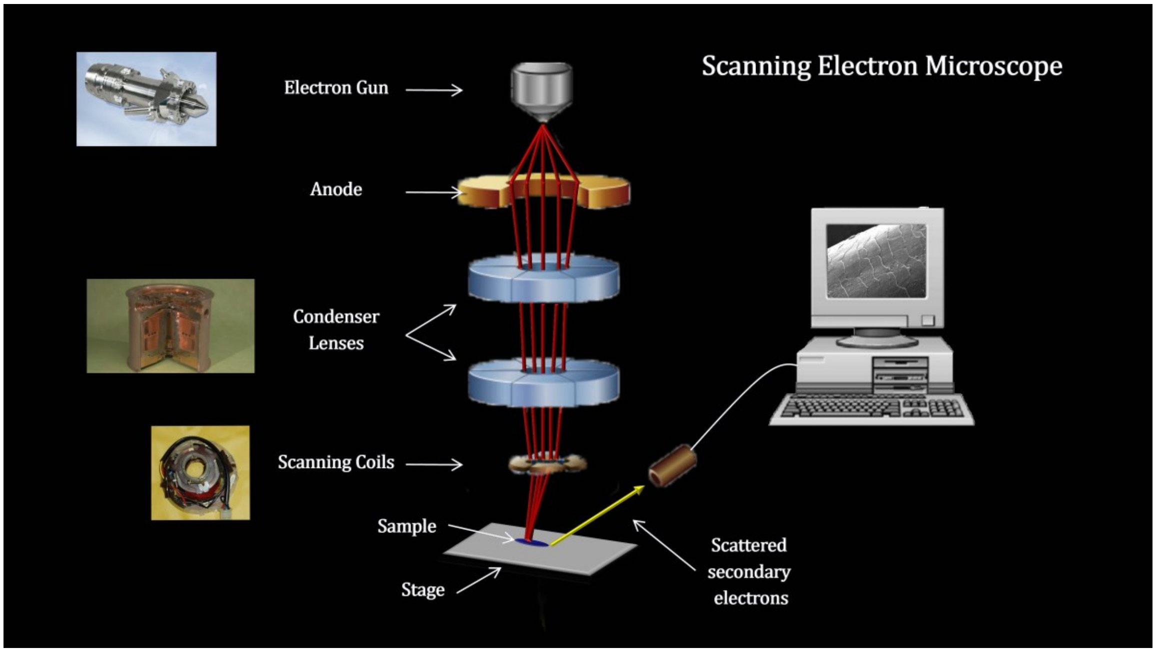


A good way to illustrate this is to look at an electron in an energy well too deep for it to get out. But remembering that the electron has a wave function that gives the probability of finding it at any given point, and some of these points (admittedly with very very low probability) can be found outside the walls of the well – as if it had tunneled through the wall when in fact it did not.

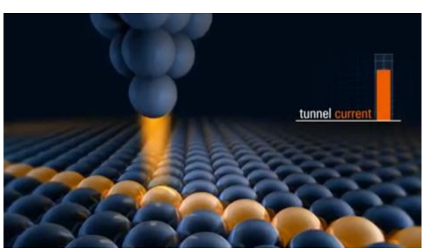


Scanning Tunneling Electron Microscope (STM) **[Music:** Georges Bizet – "L'Arlésienne" –**]**

In our 'How Small Is It' chapter on the microscopic, we covered scanning electron microscopes that mapped the surface of an object by using the wave nature of electrons and analyzing their scattering properties.



Here we will cover Scanning Tunneling Microscopes or STM for short, that use the quantum mechanical tunneling property. Here's an STM at the Max Planck Institute.



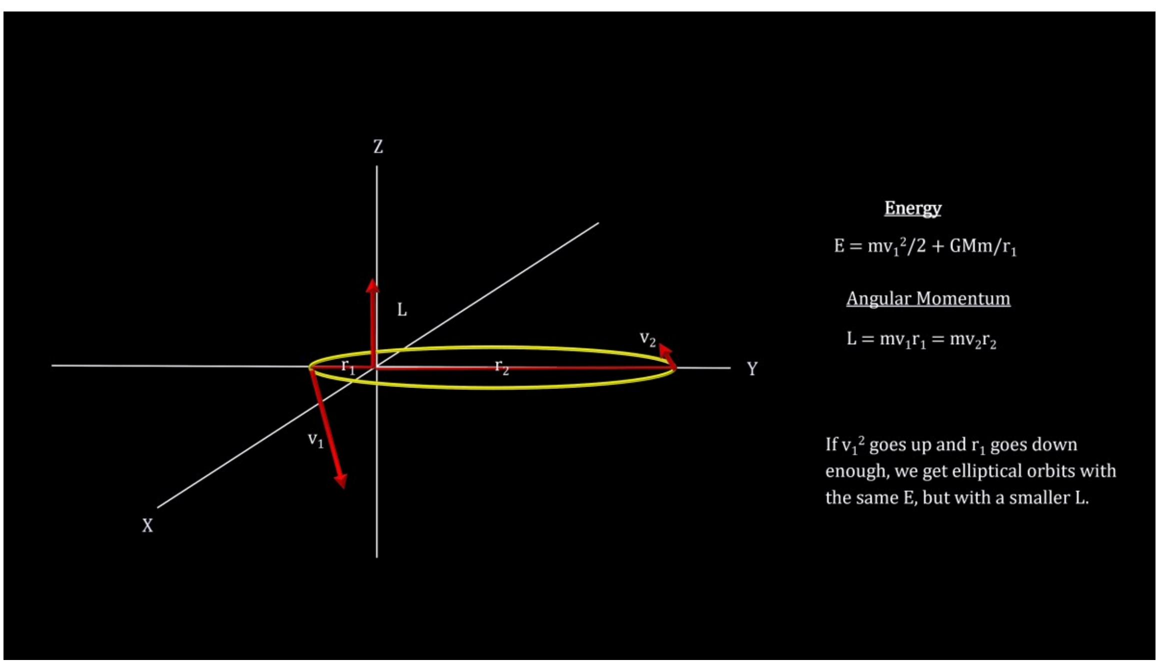
It has a small pin head that is actually one single atom at its tip. The tip is brought close enough to the object for electrons to tunnel across the space exactly in accordance with Schrodinger's equation. This creates an electric current.

As the tip scans across the object, the current will go up or down depending on weather an atom is under the tip or not. This is repeated over and over till the entire surface is mapped. What we are doing is actually feeling the surface of the object to see and measure the atoms. The resolution reaches 0.01 nm. That's about 1/100th the diameter of an atom.

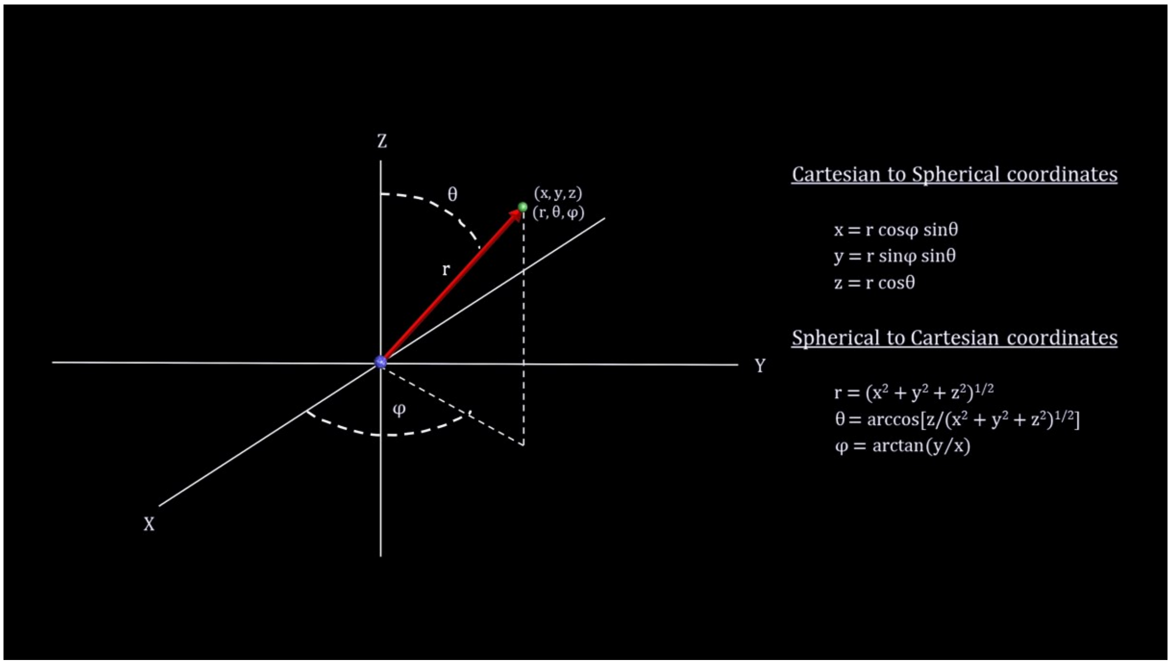
With a little stronger pull, we can even dislodge and move atoms. Here we see that the scientists at the Max Planck Institute moved the atoms one by one to spell their institute's initials MPI. The tag is just 6 nanometers wide.

Schrodinger's Atom

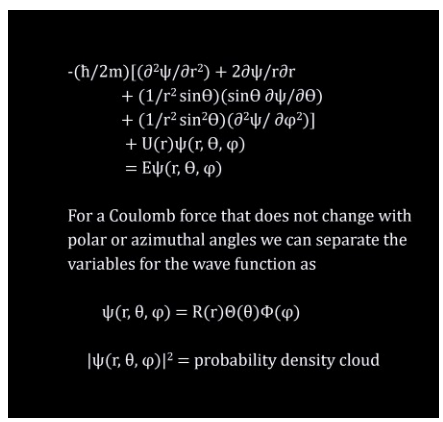
Before we get back to the atom, it's helpful to examine macroscopic orbital systems to see what varies with respect to energy, angular momentum, and orientation. In Newtonian Mechanics, we can calculate the angular momentum L for an elliptical orbit and its energy E. [The system depends on mass, the distances from the center mass, and the velocity of the orbiting objects. It turns out there are no limits on the number of combinations of distance and velocity that can produce the same value for energy.] We see that there are no limits to the number of angular momentum values L that can be associated with any particular system energy E. We also note that there are no restrictions on the orientation or azimuth angel for any angular momentum L.



Because we are dealing with a spherical system with the bulk of the mass at the center, it is common practice to use spherical coordinates. **r** is the vector specifying the position of the electron relative to the proton. Its length is the distance between the two and the direction is the orientation of the vector pointing from the proton to the electron. Theta is the polar angle most closely related to angular momentum. And Phi is the azimuthal angel associated with orientation.



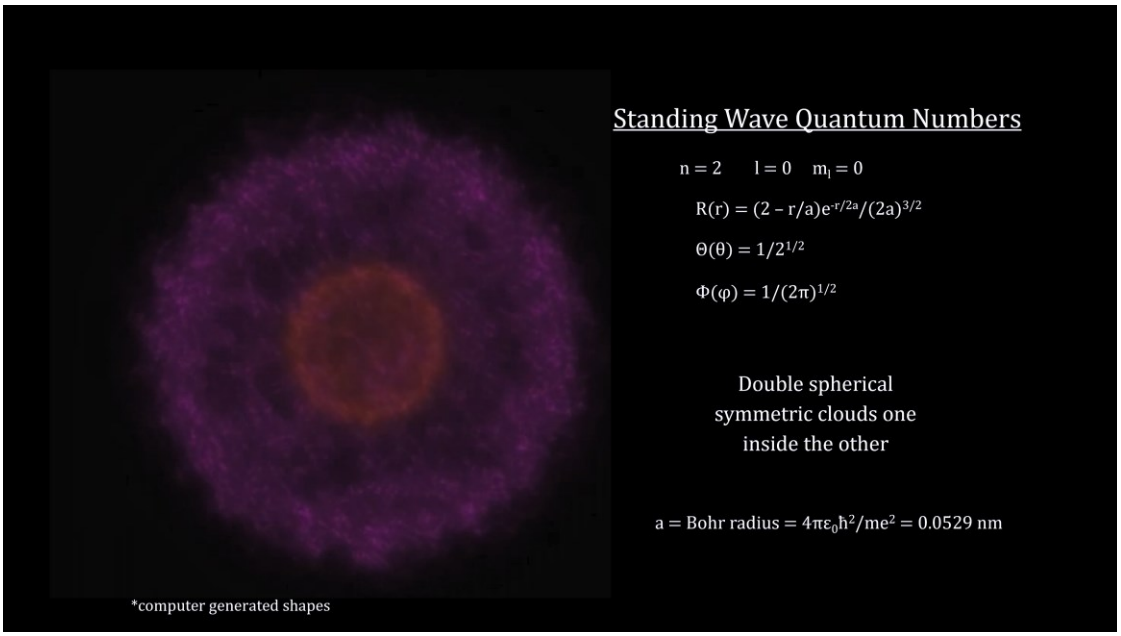
But when we move from matter systems to matter wave systems, we move from Newtonian equations for gravitationally bound systems to Schrodinger equations for negatively charged electrons bound by a positively charged nucleus. The relationships between energy, angular momentum and orientation are quite different. With Schrodinger's equation for the Hydrogen atom in spherical coordinates, we can separate the variables R, Theta and Phi.



Solving Schrödinger's equation yields multiple wave functions as solutions. They define an electron's probability density cloud.

- Energy is quantized into electron shells designated by the letter n. It determines the distance the electron is from the nucleus. These energy levels match the ones proposed by Bohr.
- For each energy level n, the associated angular momentum is also quantized into electron sub-shells designated by the letter ℓ. It determines the shape of the orbital.
- And surprisingly, for each quantized angular momentum sub-shell, even the allowed orientations are quantized into orbitals and designated by the letters m_ℓ. It determines the orientation of the orbital.

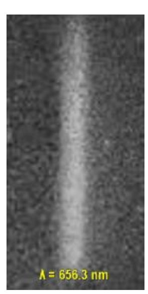
In chemistry, an atomic orbital is defined as the region within an atom that encloses where the electron is likely to be 90% of the time. It is these radii with their binding energies and interesting geometries that give atoms their chemical properties.

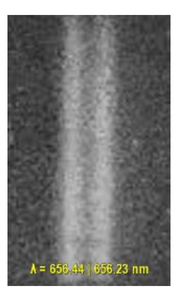


The Pauli Exclusion Principle

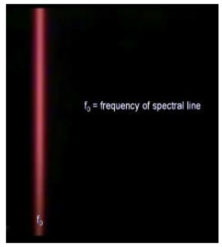
Although Schrodinger's equation went a lot further than Bohr and de Broglie, there were still a couple of things about the atom that were not completely explained.

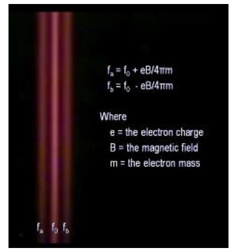
1. When examined very closely, many spectral lines showed up as pairs instead of single lines as called for by Schrodinger's equation.





2. The splitting of spectral lines by magnetic fields was not accounted for. This is known as the Zeeman effect.

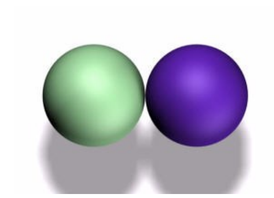




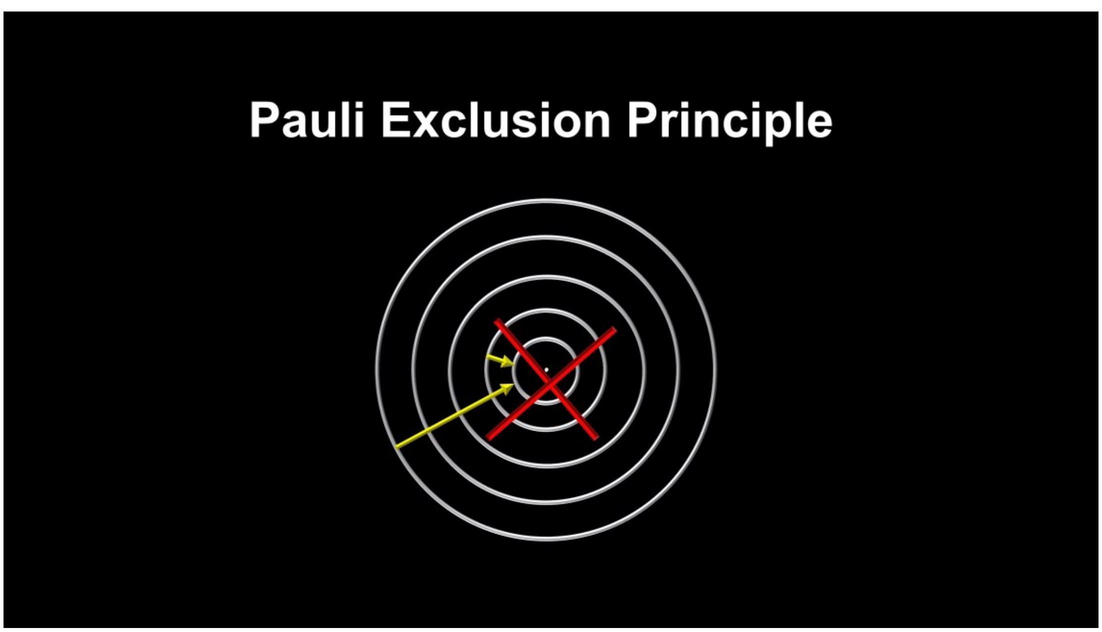
3. It was not understood why all the electrons didn't all move to the innermost lowest energy orbital.

In order to deal with these issues, Wolfgang Pauli proposed a fourth quantum number and his exclusion principle.

In classical physics, the exclusion principle states that no two objects can occupy the same space at the same time.



Pauli's exclusion principle stated that no two particles could occupy the same quantum state at the same time. But Pauli could find no physical explanation for the fourth quantum number.

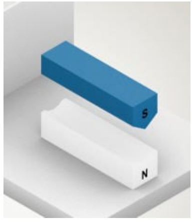


Electron Spin - Stern-Gerlach experiment

The physical explanation turned out to be electron spin. Electrons have an intrinsic property that is best observed with a modern version of the Stern-Gerlach experiment that used silver atoms.

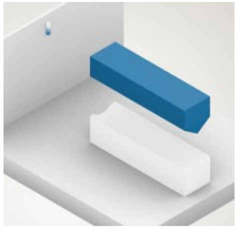
Here we use magnets and electrons directly.

The device has a north and south pole shaped to create a magnetic field that is stronger near the tip. This varies the forces on charged particles passing through.

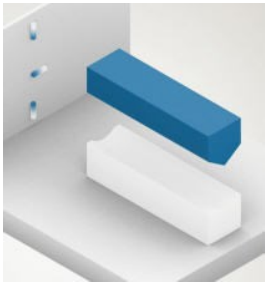


A magnet is sent through with the north pole up and the south pole down.

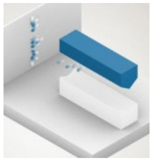
The magnetic field creates a force that deflects the magnet upward as it passes through the field.



As we change the orientation of the magnets being sent through, we see the change in the amount and direction of the deflections. The deflections depend on the orientation. This is as expected.

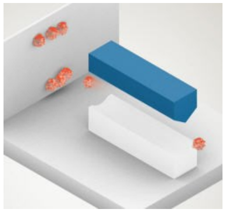


When we send large numbers of randomly oriented magnets through the field, they arrive anywhere vertically.

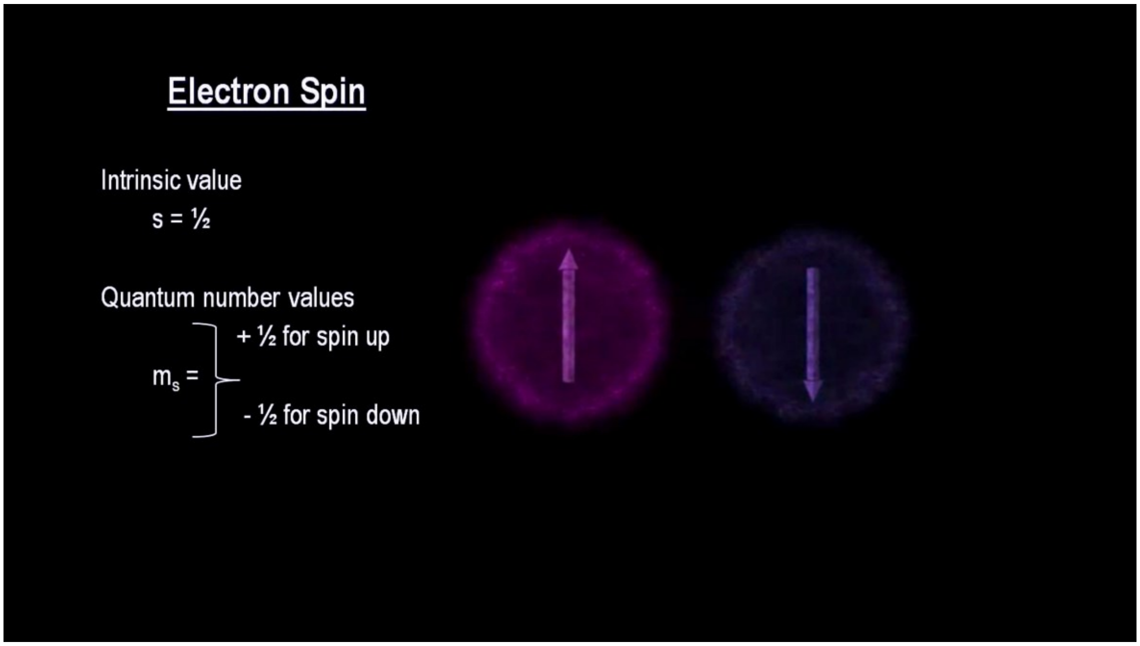


When electrons are sent through the field, they too are deflected.

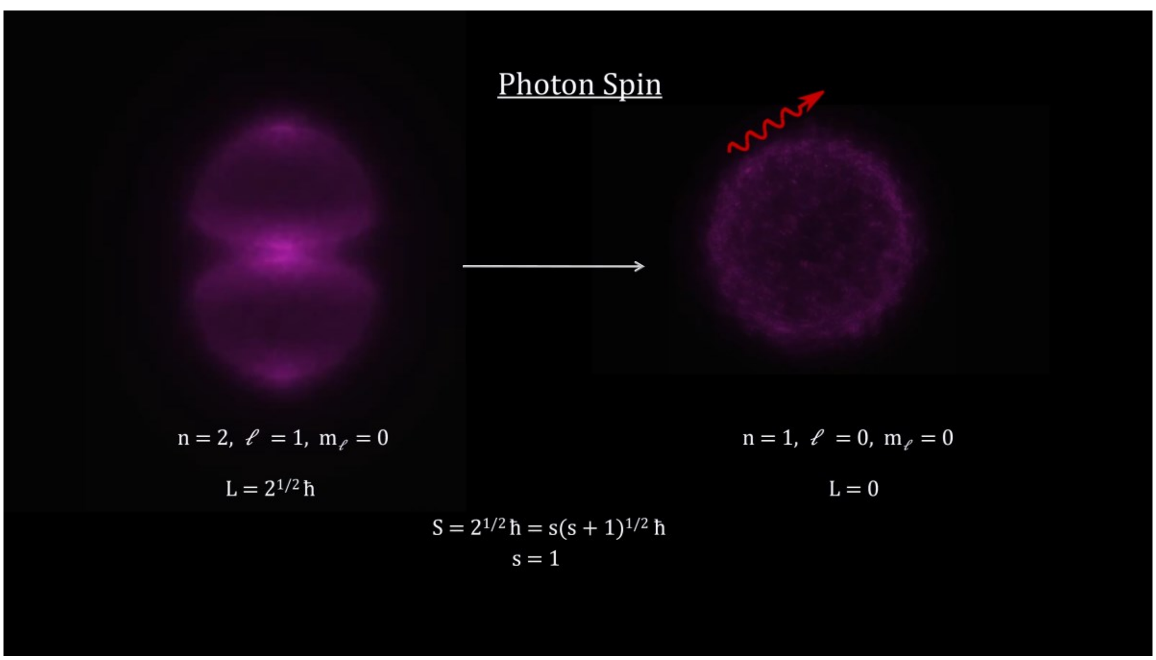
But they always arrive at the screen deflected either up or down. Never in between like the magnets.



Each electron behaves as a magnet, but with only one of two possible orientations: up or down. This intrinsic property of an electron is called 'spin'.

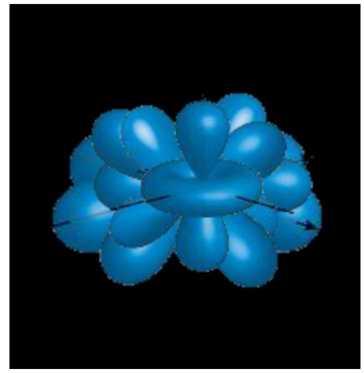


It is interesting to note that, whenever an electron in an atom changes state, the atoms angular momentum changes. For example, here an electron moves from a higher energy orbital with angular momentum to a lower orbital with no angular momentum.

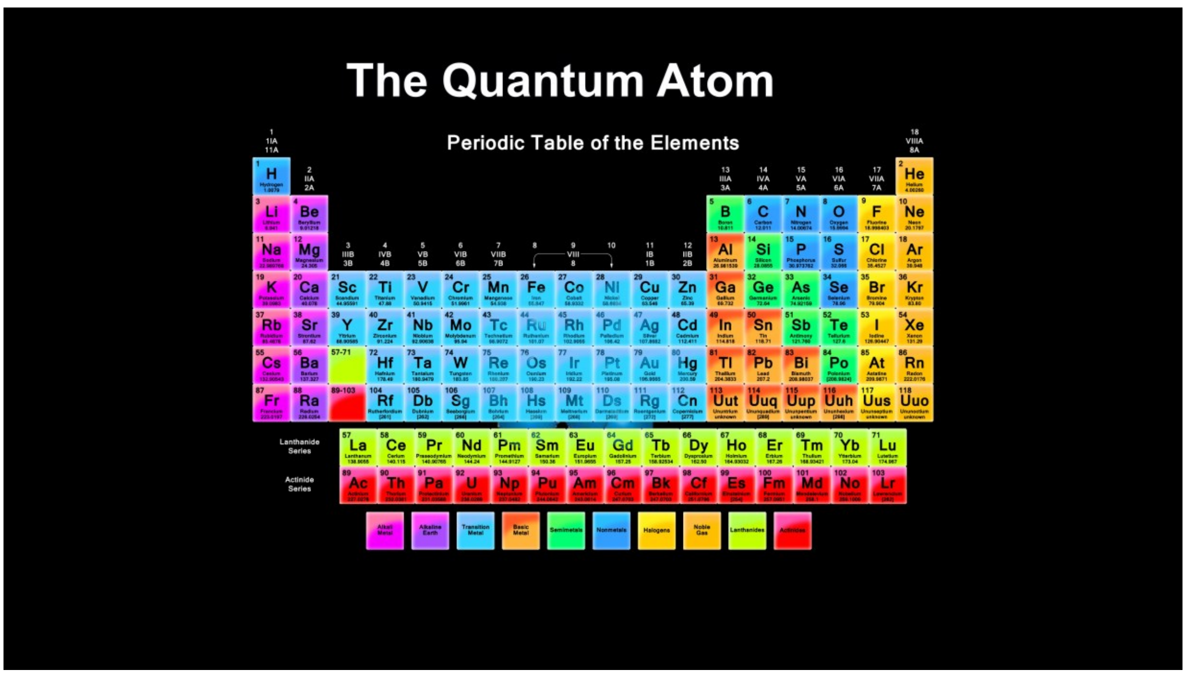


We see that the emitted photon carries away both the energy and the angular momentum, giving it a spin = 1. This has been measured to be true for all electron quantum leaps.

With the Pauli Exclusion Principle and spin as the fourth quantum number, the full set of spectral lines, orbitals, their geometries, and interactions with each other fell into place.

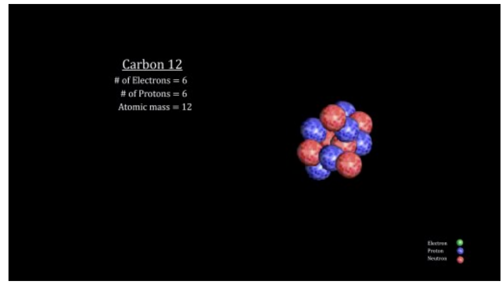


In fact, when we add this forth quantum number to Schrodinger's equations, we can generate the entire periodic table of the elements.



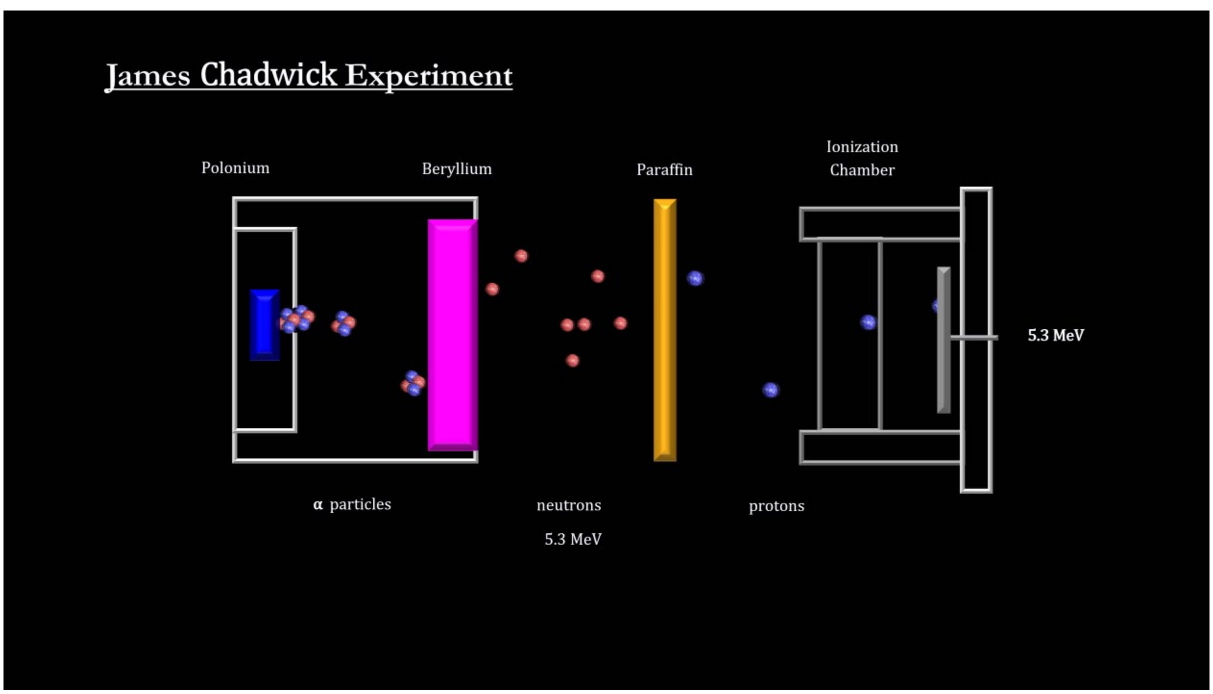
The Nucleus

Now that we have a handle on the electrons around the atom, let's take a quick look at the nucleus. For atoms to be neutral, the number of protons with a positive charge must equal the number of electrons with their negative charge.



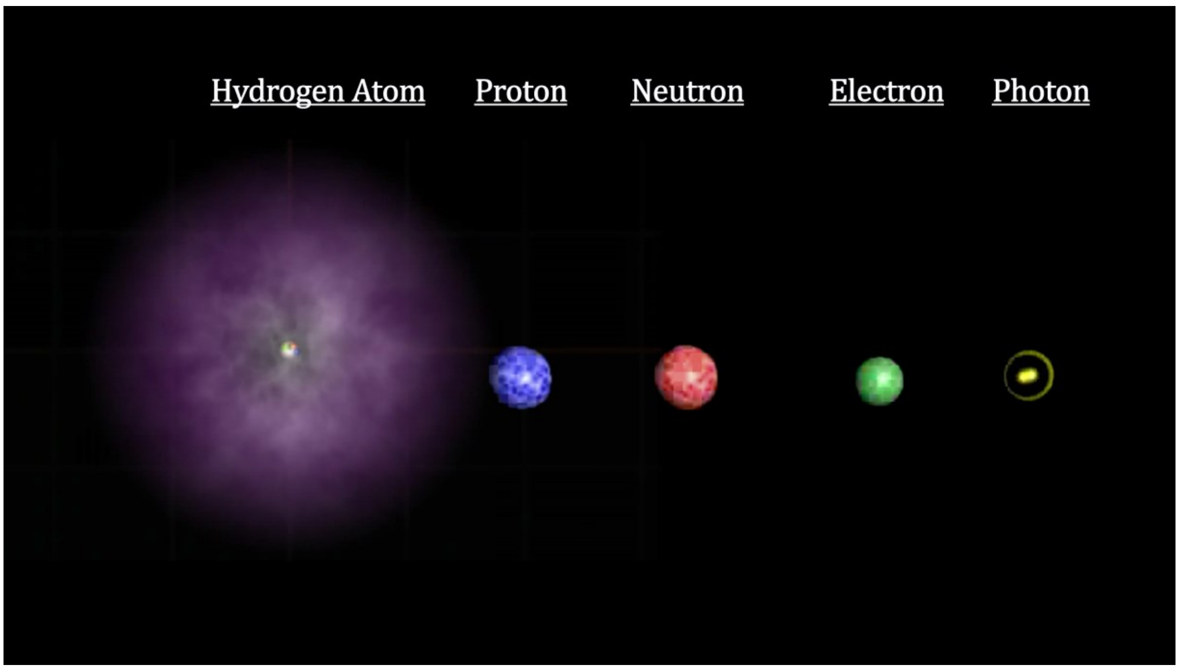
But mass spectrometers showed that atoms have more mass than the number of protons alone could account for. For example, carbon has 6 protons and 6 electrons, but its mass is just a tad more than the mass of 12 protons.

In the 1920s it was assumed that electron-proton pairs existed in the nucleus to account for the increase in mass without an increase in charge. But with the advances in quantum mechanics, it became clear that an electron couldn't exist in a volume as small as the nucleus. Ernest Rutherford and James Chadwick proposed that a new particle (the neutron) must exist in the nucleus to account for the data. In 1932, Chadwick and others performed a series of experiments verifying his suggestion. They began by beaming alpha particles into Beryllium. This produced a radiation that was not affected by applied electric fields. In other words, it was electrically neutral. At first, this was thought to be gamma rays. But when this new radiation was used to bombard a hydrogen rich substance like Paraffin, a Proton radiation was produced. The energy acquired by these protons was measured and found to be more than a gamma ray could possibly impart to a proton. In fact, the protons ejected from the paraffin on the right was equal to the energy of the radiation coming out of the Beryllium on the left. The conclusion was that the particles hitting the paraffin were of the same mass and energy as the protons but without any charge. At this point it was generally accepted that the neutron had indeed been discovered.



How Small Is It

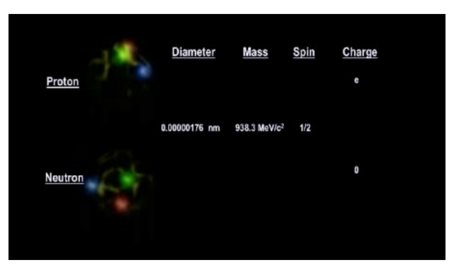
In this segment, we developed the basic quantum mechanics for electrons around the atom and measured the size of atomic components. At the end of our previous segment, we used a Scanning Electron Microscope to see carbon atoms 14 hundredths of a nanometer in diameter.



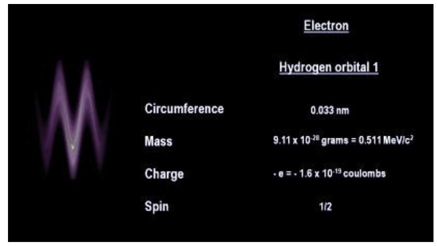
Using Rutherford scattering techniques covered in this segment, we measured the size of a proton at 1.76 millionths of a nanometer. That's 20,000 times smaller than the atom. At this scale, we find that the neutron is about the same size and mass as the proton.

Also, in this segment we added spin as an intrinsic property of particles to go along with mass and electric charge. Protons and Neutrons both display the same spin properties as electrons when they traverse the Stern-Gerlach apparatus, so their spin is ½.

The notable difference between these particles is that the Proton has a positive charge with the same magnitude as the electron's negative charge, but the Neutron is neutral with no charge at all.

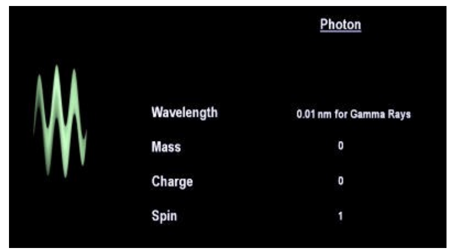


For the electron, it's hard to talk about its size because their wave packet is different for every circumstance from standing waves in thin atom shells, to scattered waves in an electron microscope. What we did in this segment was to calculate its length around the Hydrogen nucleus at .0033 nm.



For photons, we see that they have no mass at all, no charge, and a spin equal to 1.

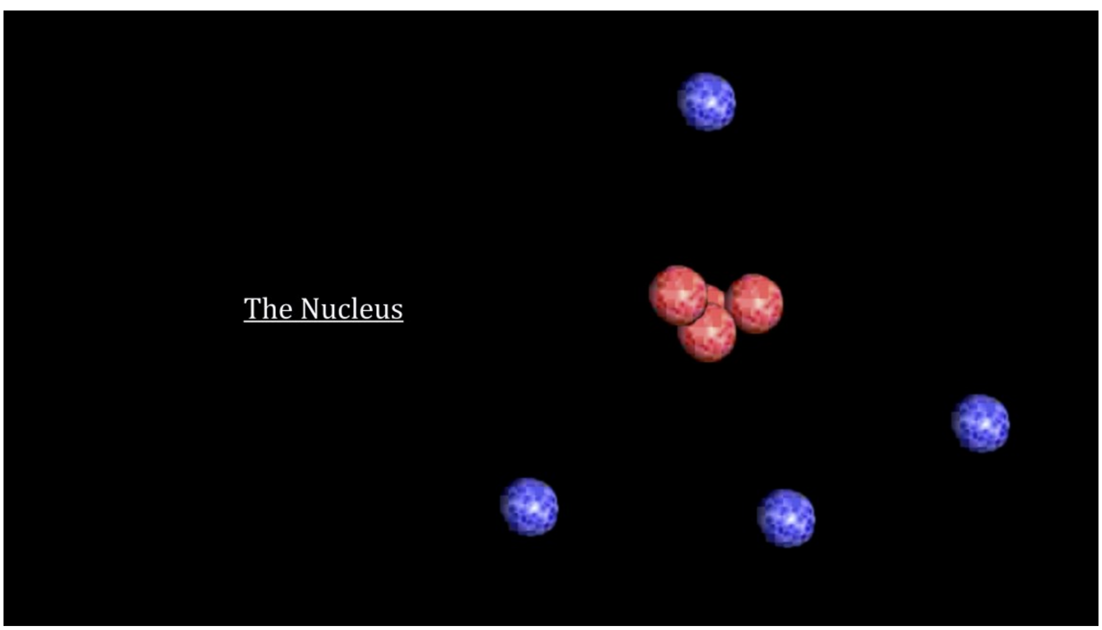
And, like the electron, it doesn't have a volume per say because it's a wave. But we can measure its wavelength. For the gamma rays used by Rutherford, the wavelength is one one hundredth of a nanometer. That's 51,000 times smaller than the wavelength of green light.



Looking at the atom's nucleus, we see one main question:

- How do positively charged protons pack together in the nucleus when their repulsive positive charges would have them flying apart?

We'll go into how we answer this question in our next segment on elementary particles.



Music

@00:00 Albinoni - Adagio in G Minor - Berlin Chamber Orchestra; from the album “50 Must-Have Adagio Masterpieces” 2013

@05:02 Haydn - Cello Concerto No 2 II Adagio - Franz Liszt Chamber Orchestra, Miklos Perenyi; from the album “50 Must-Have Adagio Masterpieces”, 2013

@09:12 Mozart - Violin Concerto No 3 - Christian Altenburger, German Bach Soloists; from the album “50 Must-Have Adagio Masterpieces” 2013

@20:01 Dave Porter - Breaking Bad Theme - Music from the Original Series Breaking Bad

@22:16 Bizet - L'Arlesienne Suite No 1, Op 23 - Budapest Philharmonic Orchestra; from the album “50 Must-Have Adagio Masterpieces” 2013

@26:57Mahler - Symphony No 5 III IV - Budapest Festival Orchestra; from the album “50 Must-Have Adagio Masterpieces” 2013

Greek letters:
- α β γ δ ε ζ η θ ι κ λ μ ν ξ ο π ρ σ τ υ φ χ ψ ω
- Α Β Γ Δ Ε Ζ Η Θ Ι Κ Λ Μ Ν Ξ Ο Π Ρ Σ Τ Υ Φ Χ Ψ Ω

$\Rightarrow \; \rightarrow \; \pm \; \odot \; \infty \; \nrightarrow \; \exists \; \nexists \; \in \; \notin \; \iint \; \int \; \cong \; \geq \; \leq \; \approx \; \neq \; \equiv \; \sqrt{} \; \sqrt[3]{} \; \sim \; \propto \; \hbar \; \div \; \partial$

Elementary Particles

*{**Abstract** – In this segment of our "How small is it" video book, we introduce elementary particles.*

We start with a description of cosmic rays and gamma rays. They collide with atoms in the atmosphere to create a wide variety of particles. We cover how cloud chambers work to 'see' these new particles. That includes taking a look at the tracks for electrons and protons. We then take a look at the new particles we found on mountain tops and up in balloons: positrons, electron-positron pair creation, muons; pions; kaons; and particle decay timing and signatures.

We then cover the hard-to-find neutrino, starting with the Ellis - Wooster experiment to measure the energy of radium decay into polonium that led to Wolfgang Pauli's 1927 prediction about the existence of the neutrino. We then take a look at the 1970 bubble chamber track that first detected it.

Next, we probe the proton using scattering experiments like the ones used by Rutherford to probe the nucleus. This time we use electrons instead of alpha particles. We cover how this was done at the Stanford Linear Accelerator Center (SLAC) in 1969. We show how particle acceleration is accomplished, and how particle detection is done with hodoscopes and calorimeters. We also examine the test results, explaining the idea of 'cross section' measurements as a way to identify scattering target sizes. We end with the results that showed that the proton has 3 parts: now called quarks.

We then cover how quarks form hadrons (baryons and mesons) with their predicted spin, charge and mass. With these predictions, the hunt for these particles went into high gear. We cover the discovery of the lambda, xi, and omega particles that show that the quark theory was correct.

We end with a review of particle sizes we've seen so far from the atom to the neutrino. We also show how this large array of new particles begins to fit into a model organized around particle masses (leptons and hadrons) and particle spins (fermions and bosons) along with their different statistical behaviors in a group.}

Introduction [***Music:*** *Stravinsky - The Firebird*]

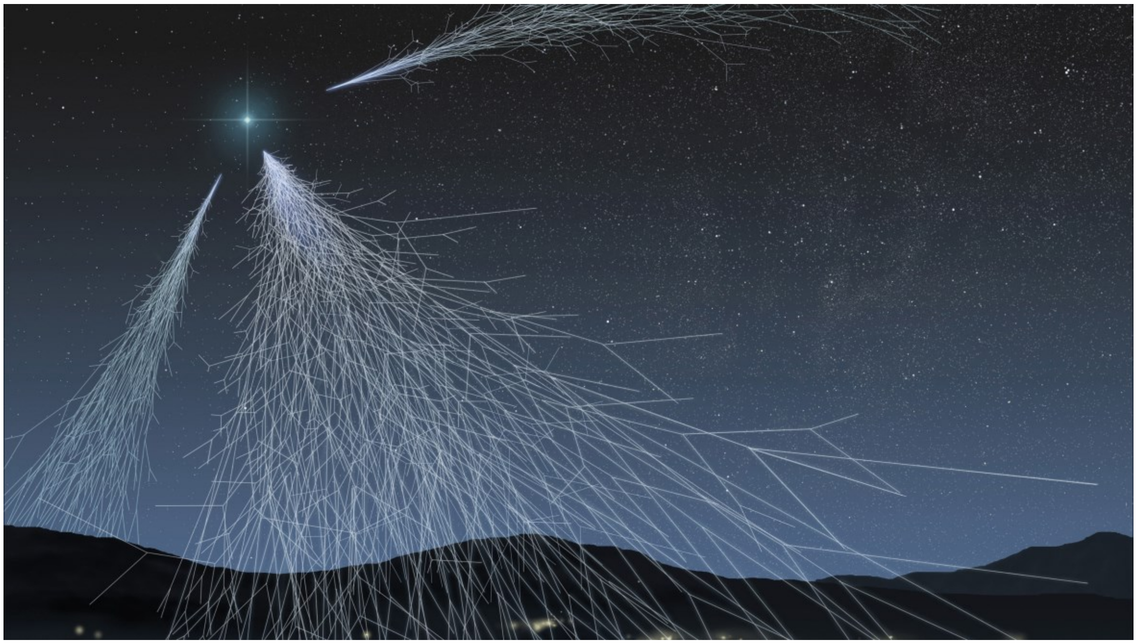
Hello and welcome to our segment on elementary particles. An elementary particle is defined as a particle that has no internal structure. In other words, it is not made up of other particles. At this point, we know that the electron and the photon are elementary. In this segment, we'll find some more.

While physicists were developing quantum mechanics that reduced the number of fundamental particles from the 92 elements down to three particles (the electron, the proton, and the neutron), other physicist were climbing mountains to gather information on a very large number of new particles that were formed by cosmic radiation bombarding the earth from outer space.

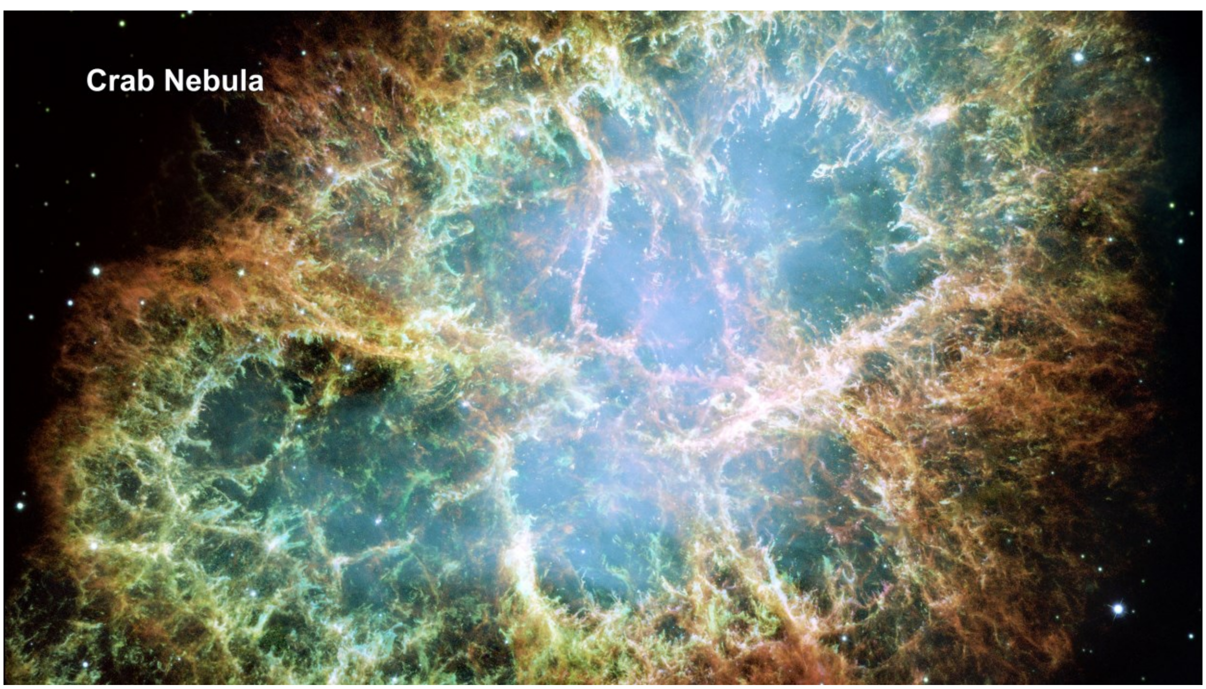
In this segment, we'll take a look at what they found. We'll also probe the nucleus and do some heavy duty scattering like Rutherford did, but this time we'll be digging into the proton to find out what it is made of. But first, we'll see what these new particles are and how we determined their characteristic properties, sizes and interactions with each other.

Cosmic Rays [*Music:* *Beethoven - Symphony No 6 (Shepherds Hymn)*]

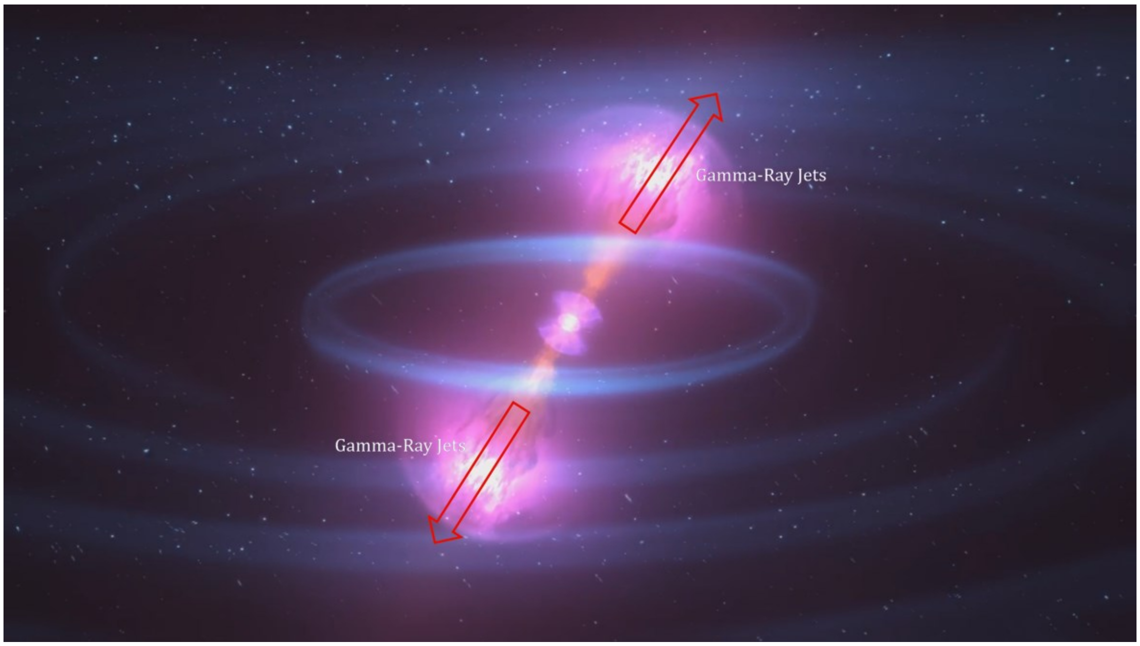
The Earth is constantly bombarded by radiation from outer space called cosmic rays made up of mostly high energy protons and high energy photons called gamma rays. These cosmic rays collide with atoms in our atmosphere, generating particle chain reactions that continue to the surface.



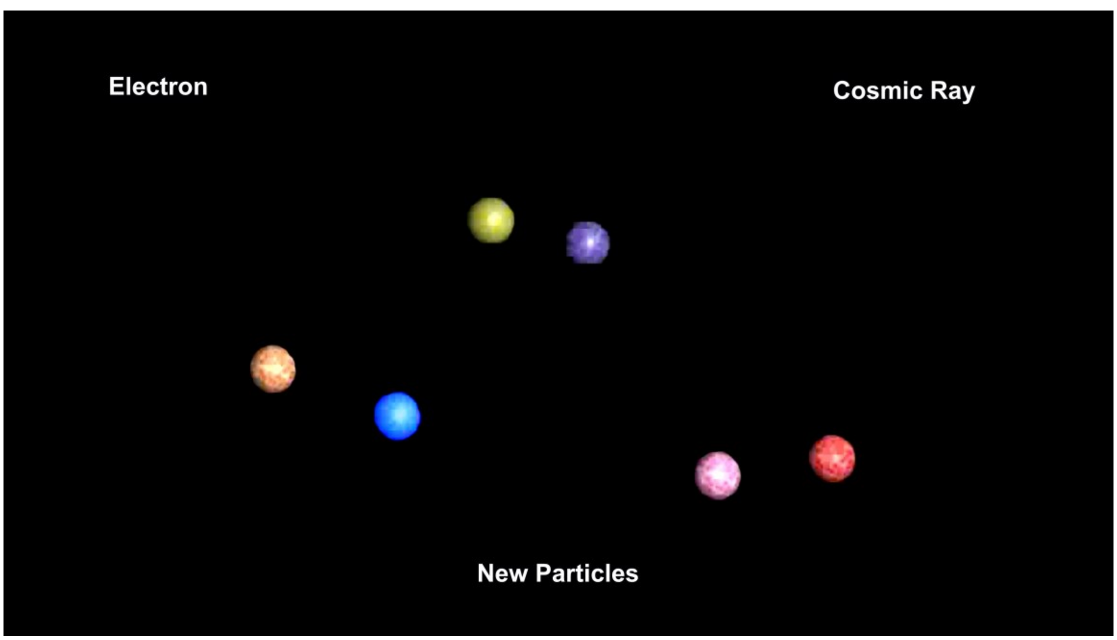
In our segment on the Milky Way in the How Far Away Is It video book, we noted cosmic rays are produced in supernova like the one that created the Crab Nebula.



Gamma-ray bursts are the most energetic and luminous electromagnetic events in the Universe. They can release more energy in 10 seconds than our Sun will emit in its entire 10-billion-year expected lifetime!

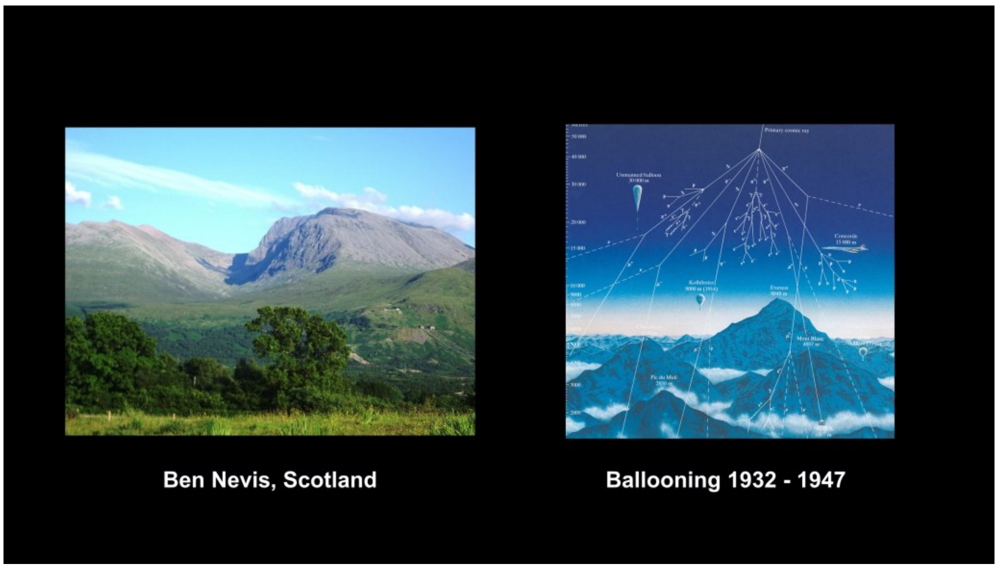


It is the very high energy of the deep space cosmic rays that have the power to smash into electrons, protons and neutrons in the atmosphere creating a wide variety of previously unknown particles.



Charles Thomson Rees Wilson invented the cloud chamber in 1911 to detect these new particles.

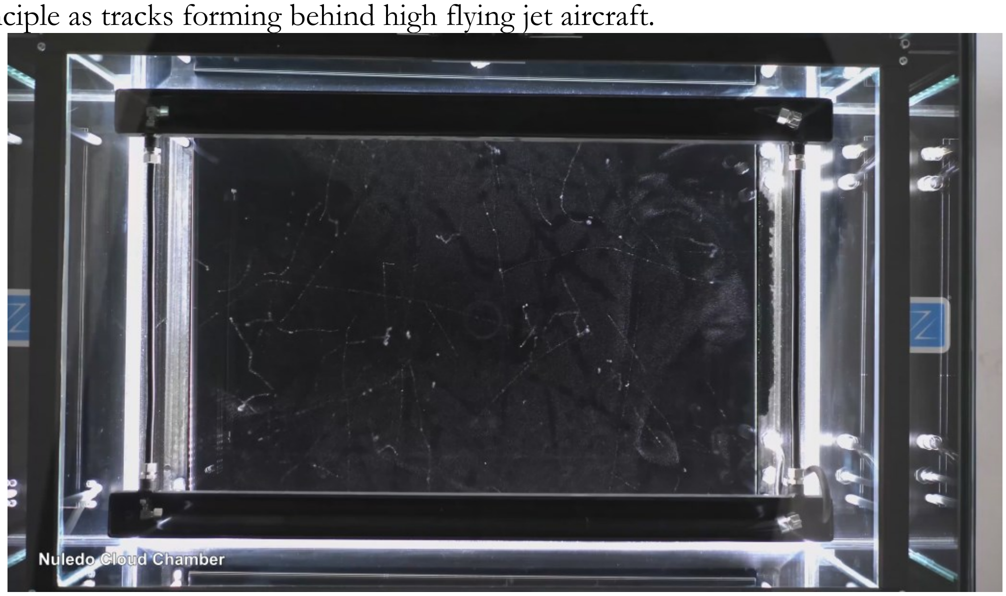
So, physicists climbed mountains like this one that Wilson used, and went up in balloons with their cloud chambers hunting for new particles.



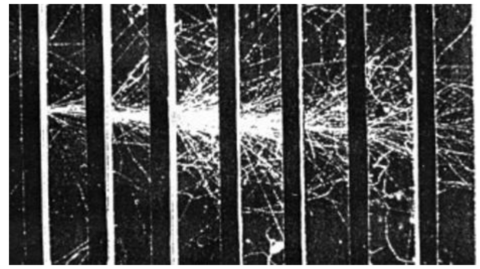
Ben Nevis, Scotland

Ballooning 1932 - 1947

Here's what it looks like when charged particles pass through a cloud chamber. The chamber contains a vapor of alcohol placed inside a magnetic field. When charged particles move through the chamber, they cause little droplets to form. These are the cloud tracks that we see. It works on the same principle as tracks forming behind high flying jet aircraft.



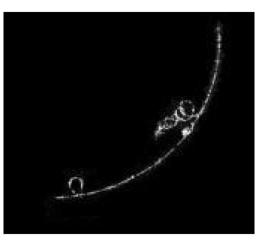
Here's what cosmic rays look like in a cloud chamber. These rays are penetrating multiple brass plates each 13 mm thick. To understand these tracks, we'll start with the two charged particles we already know: the electron and the proton.

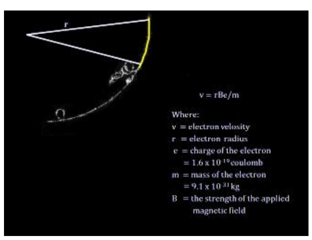


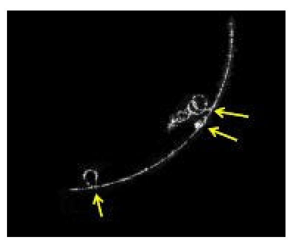
The Electron e^-

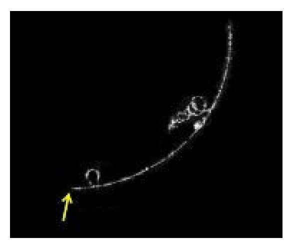
Here is a photograph of a particle track in a hydrogen bubble chamber from the Brookhaven National Lab. Given the direction of the applied magnetic field, electrons will curve clockwise. This is a medium speed electron arching through the cloud chamber. Since we know the strength of the magnetic field applied across the bubble chamber, we can calculate the particle's momentum by measuring the radius of its curvature. The straighter the path, the faster the particle is moving.

Also, remember that accelerating electrons lose energy by radiating photons. This causes the electrons to slow down and their curvature to increase. At these three points we see that stationary electrons in our path have been bumped into motion. These are called knock-on electrons. Because they are moving very slowly, they spiral rapidly to a stop. We see a lot of these in bubble chambers. The track ends when the electron is captured by a proton to form an electrically neutral hydrogen atom.



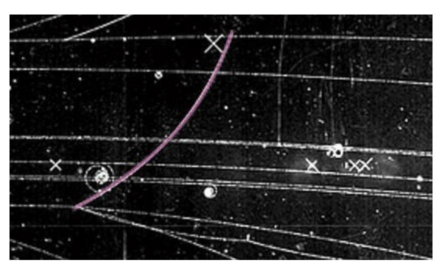






The Proton p

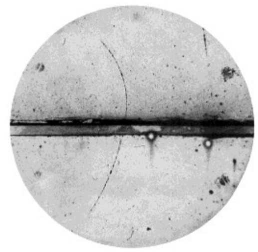
In this bubble chamber photograph from CERN, we can see a particle's track rotating counterclockwise. This indicates that it is positively charged. The particle's line is also thicker than the others. This indicates it is a large slow-moving particle. This is a characteristic of proton tracks.



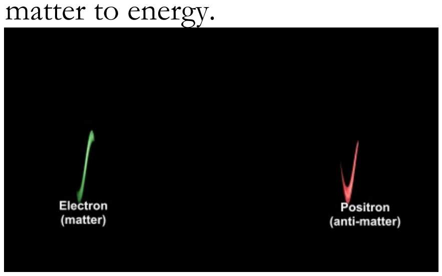
The Positron e^+ ***[Music:** Mozart - Divertimento No 10**]***

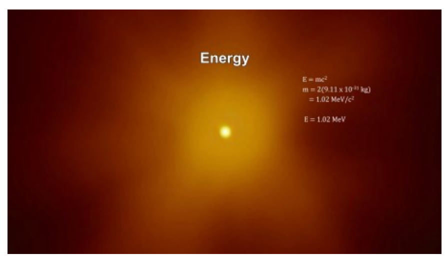
Now let's take a look at some of the new particles that sent the world of physics into never-before-seen territory. In 1932, Carl David Anderson began investigations into cosmic rays and encountered unexpected particle tracks in his cloud chamber photographs. The 6 mm thick lead plate in the chamber is designed to slow particles down.

This particle came up from the bottom and is curving counterclockwise, indicating that it has a positive charge. You'll note that its curvature increased after passing through the lead plate. This curvature indicates that its mass is the same as an electron. This was the discovery of the positron.

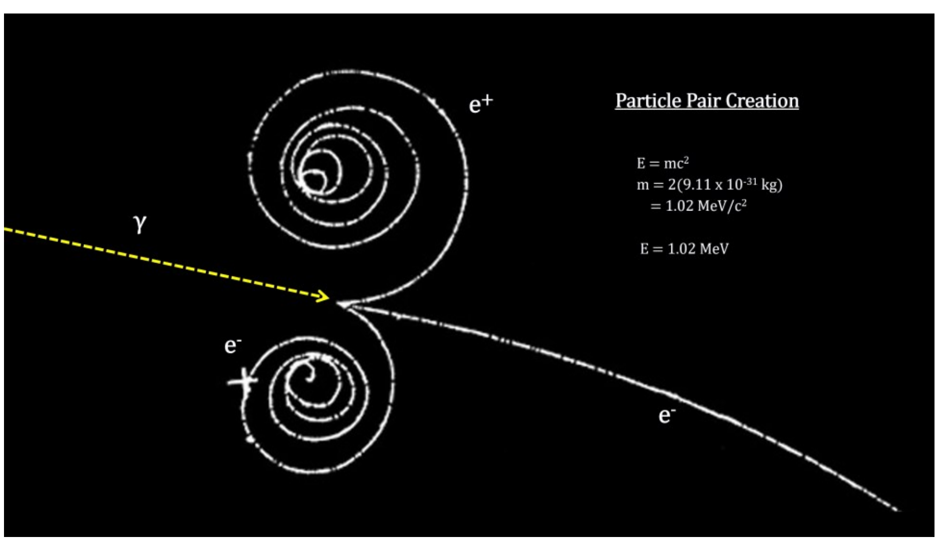


In 1928, four years before Anderson discovered the positron, Paul Dirac predicted the existence of anti-matter and proposed that all particles had an anti-particle, and that they would annihilate each other it if they came into contact. The positron is the anti-particle of the electron. This is an example of converting matter to energy.





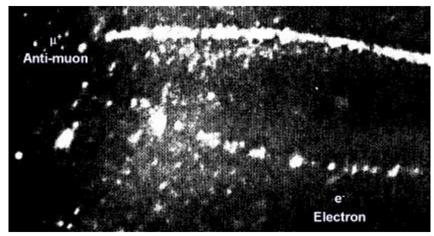
Here's an event in a cloud chamber that shows the creation of a pair of particles – one electron and one positron. The event was the conversion of a high energy gamma ray that kicked an electron out of an atom and was itself converted into the two particles. The gamma ray photon does not show up in cloud chambers because it has no charge.



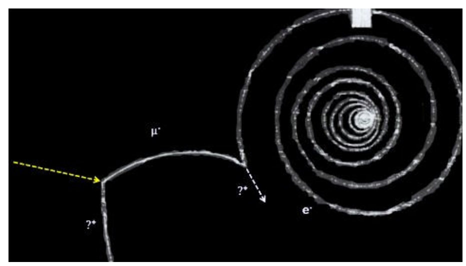
This is an example of converting energy to matter. The energy of the gamma ray photon had to be as great as the energy embodied in the two particles. For electrons and positrons that comes to around a million electron volts. Any theory that attempts to explain this behavior will need to identify a way for energy at any point in space to create matter.

The Muon μ

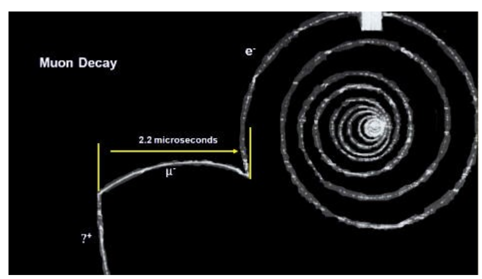
In 1932 Paul Kunze discovered the muon. Using both the direction of the curvature and the thickness of the bubble track, he calculated that it was a positively charged particle that was lighter than a proton but heavier than an electron. This one turned out to be the anti-muon.



Here's another look at a muon created by an event that created two visible particles – a muon and an unknown particle. The muon displayed a new particle property that had not been known before. It was unstable. Unlike protons, and electrons, the muon would only exist for a short period of time before it decayed into other particles. One was an electron, and the other was unknown.

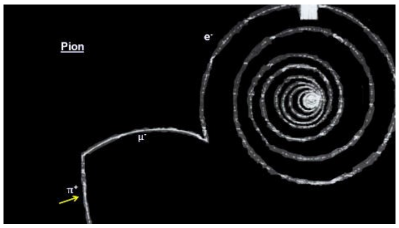


On average, it lasted only 2.2 microseconds (that's 2.2 millionths of a second). Measurements have shown that it is 207 times more massive than the electron with the same spin and charge. Muons are elementary particles like the electron and the positron. These particles are called leptons meaning light rather than heavy like a proton.



[At the point of decay, another particle must have also been created that would account for conserving energy and momentum, but that other particle didn't show up in a bubble chamber presumably because it must have been electrically neutral.]

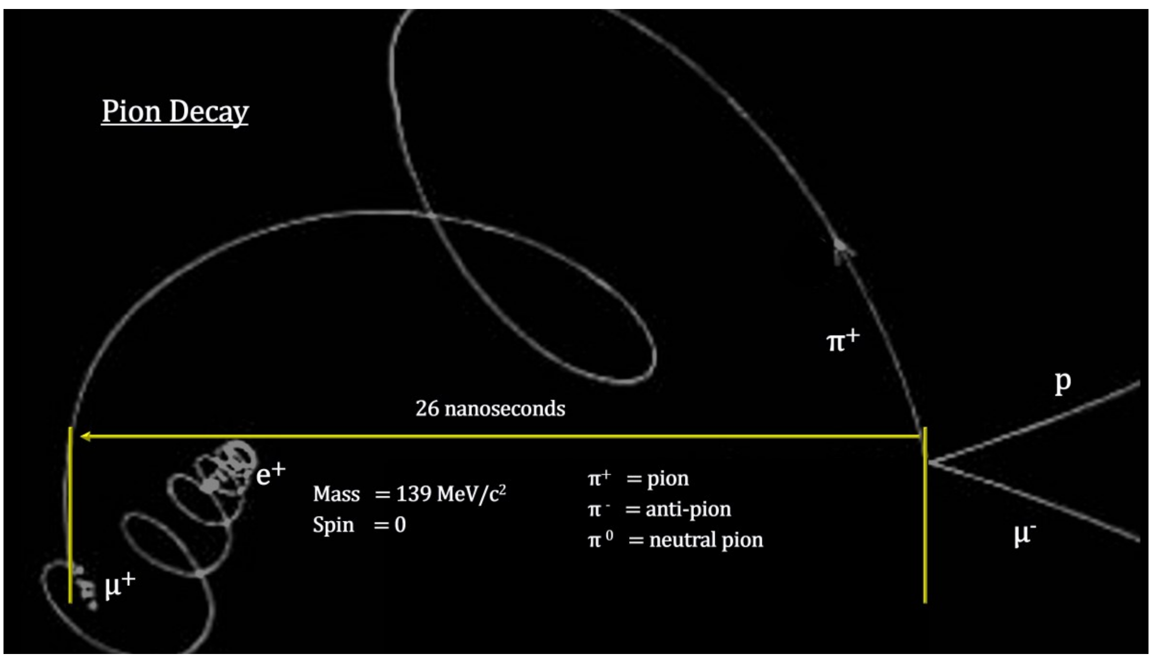
The Pion π



The particle that was created at the start along with the muon turned out to be a long sought-after particle called the pion. In 1947, using cosmic rays at high altitudes, this particle was found.

[In 1935, Yukawa Hideki proposed the existence of the pion in his theory of nuclear physics. He proposed that there was a particle exchanged between protons and neutrons in the nucleus of atoms that serve to bind them together. His computations included predictions about the mass and charge of this new particle.]

Here we see an event that kicks a proton into motion and creates a muon and a pion. Then we see the pion decay into an anti-muon that itself decays into a positron. It lasted only 26 nanoseconds. Now this is a really short lifetime. The muon lasted almost a thousand times longer than that.

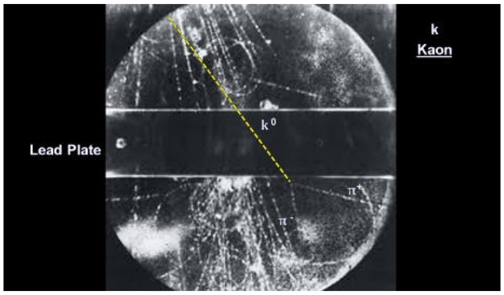


Pions are spin zero particles with around 14 hundredths of a proton's mass. Although that's small, it's a good deal more massive than the muon. Pions come in three flavors: one with a positive charge, one with a negative charge (called the anti-pion), and one with no charge.

The Kaon k

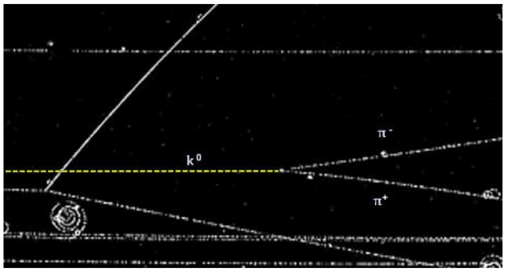
Also, in1947, another particle called the Kaon was discovered by George Rochester and Clifford Butler. They also used cosmic rays.

Here's a look at their bubble chamber picture. Just below the lead plate, in the lower right-hand quadrant, you see an inverted V that extends to the lower right. Measuring the momentum and charges they determined that they were a pion and an anti-pion. Rochester and



Butler concluded that this event had to be a photographic record of a novel phenomenon: the decay of a previously unknown neutral heavy particle – later called the kaon.

[Here's a clearer look from a CERN bubble chamber. The discovery of kaons represented the first time we deduced the existence of a particle from its decay components. Like pions, kaons also come in 3 flavors: positively charged, negatively charged, and neutral.

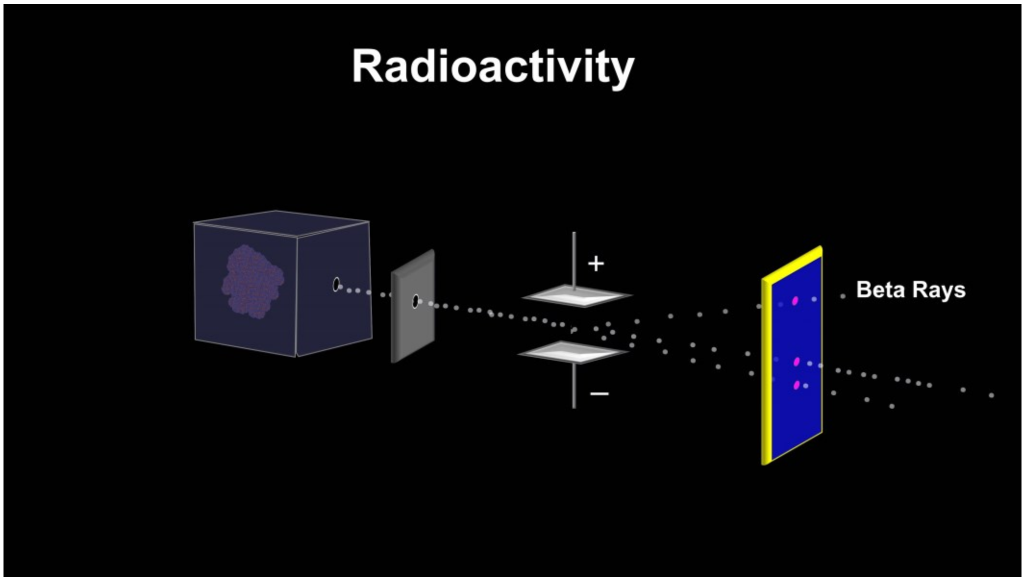


These past two bubble chamber photographs were examples of neutral kaons. Here we see a charged kaon decay. Note the kink in the path. This indicates that a charged particle decayed into another charged particle with a different mass. In this case, a positively charged kaon has decayed into an anti-muon.

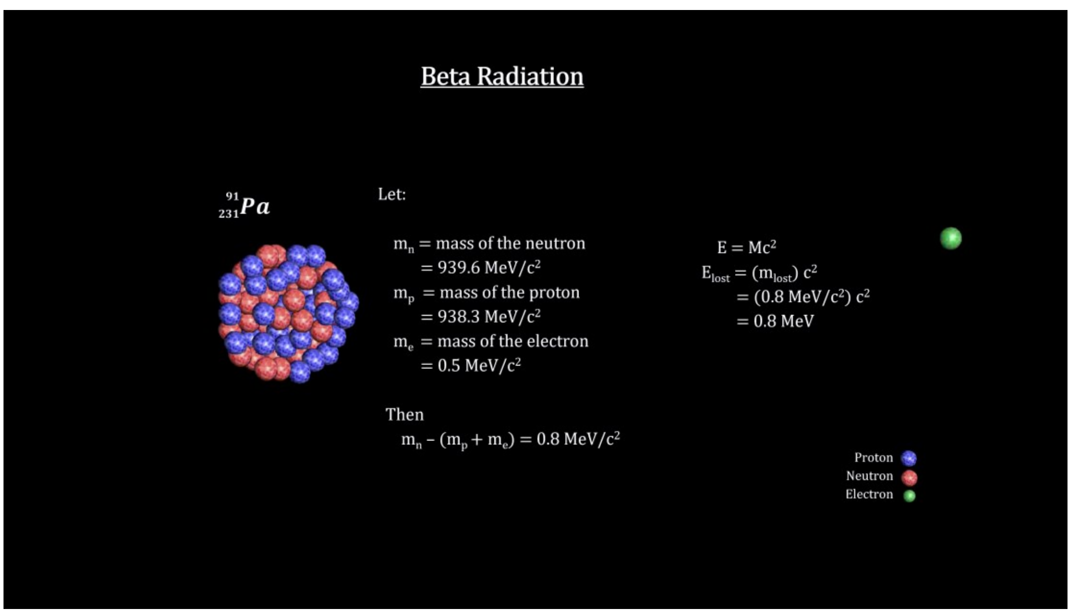
An anti-kaon would decay into a muon. Kaons have proved to be a tremendous source of information on the nature of fundamental particle interactions.]

The Neutrino ν

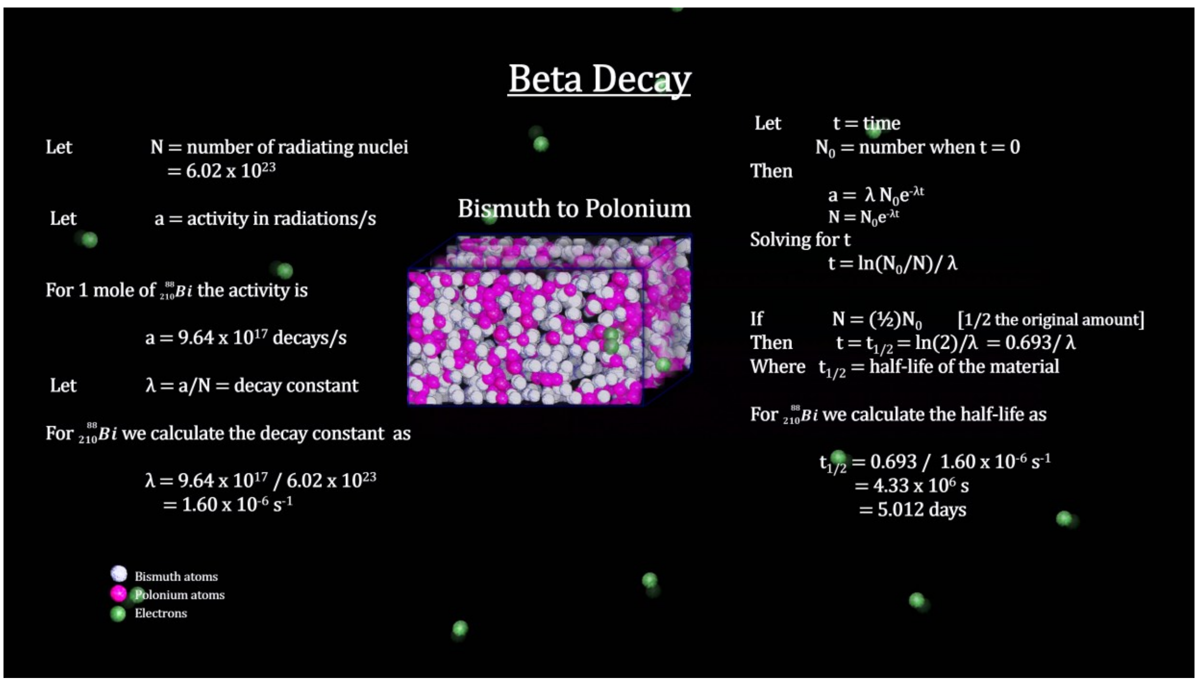
One of my favorite particles is the Neutrino. You'll recall from our segment on radiation, that the beta rays were ejected electrons.



What's happening here is that a neutron inside the nucleus of an atom is spontaneously decaying into a proton and ejecting an electron in the processes. [This is called beta decay. Here we see that beta decay changes ^{231}Th into ^{231}Pa (Protactinium).] The mass of the proton plus the mass of the electron is less than the mass of the neutron. And, because energy is conserved, some energy must be released to make up the difference. From Einstein we know that energy equals mass times the speed of light squared. So, if the lost mass is turned into energy, we can calculate the amount – a little under a million electron volts per atom. It was assumed that this energy was accounted for by the kinetic energy of the ejected electrons.

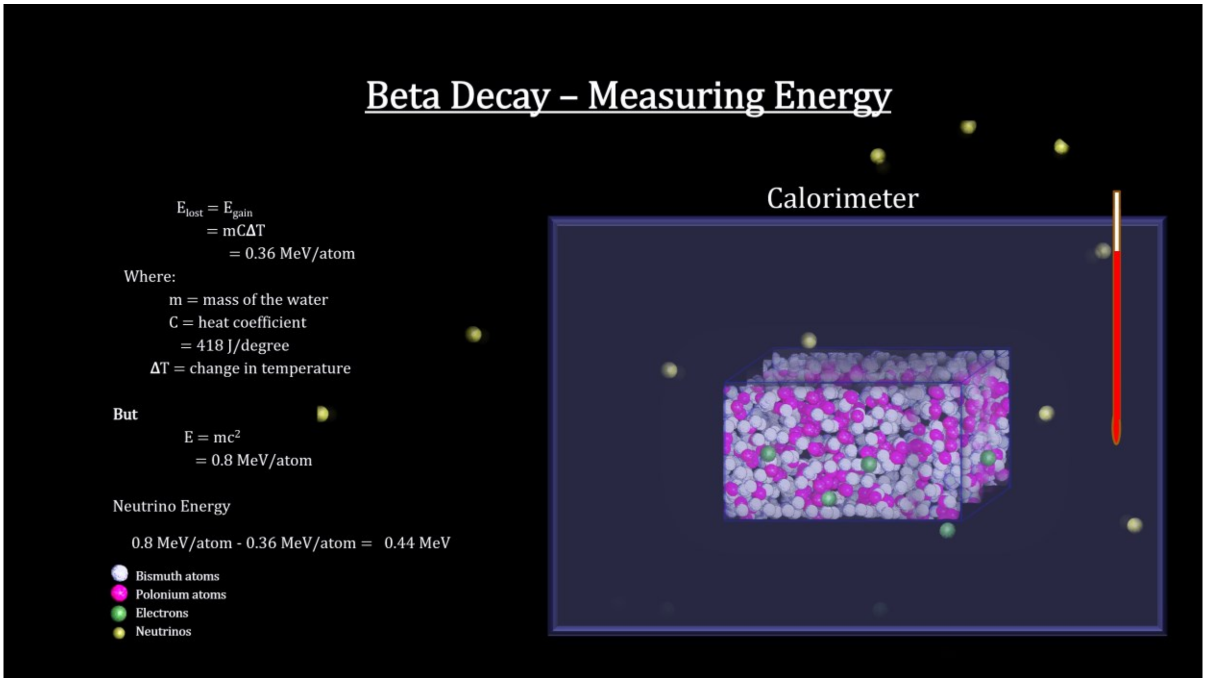


In 1927, two physicists, C. D. Ellis and W. A. Wooster, set out to measure this energy. They used Bismuth 210, a product of Radium decay that itself decays into Polonium. The rate at which unstable radioactive nuclei decay in a sample of material is called the *activity* of the sample. The greater the activity, the more nuclear decays per second. This is rather easily measured with devices like a Geiger counter. Given the number of radiating molecules in a sample, and measuring the activity, we can calculate the probability for any one molecule to decay in a second. This is called the decay constant. We find that the decay constant is always a small number, constant over time, and different for different materials. Both the activity rate and the number of radioactive nuclei vary over time. As a sample decays, the number of radioactive nuclei decreases. With fewer radioactive nuclei, the activity rate also decreases. From this we get the *exponential law of radioactive decay*. It tells us how the number of radioactive nuclei in a sample decreases with time. The *half-life* is the time that it takes for the material (and activity) to be reduced by half. Bismuth 210 has a half-life of five days, meaning, it takes 5 days for half of any amount to transform into Polonium. We cover half-life in more detail in the "How Old is the Earth-Moon System" in the "How Old Is It" video book.

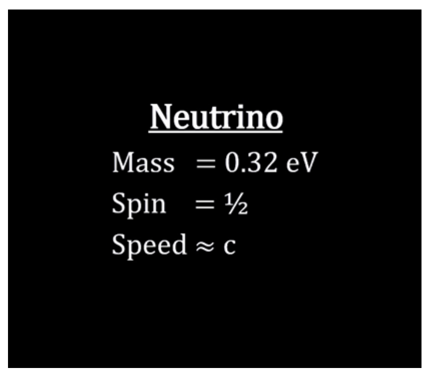


The experiment was simple: place the Bismuth into a calorimeter. A calorimeter keeps the energy of the beta radiation inside the container. Over the five days, each and every ejected electron's kinetic energy is converted to heat as they collide with the water molecules and come to rest in the calorimeter. Measuring the change in temperature allows us to calculate the amount of energy absorbed. The results showed that each Bismuth atom naturally emits 0.36 MeV.

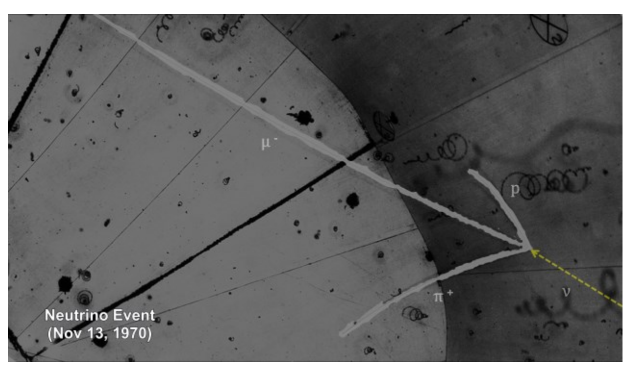
But here we had a significant discrepancy. Conservation of energy and Einstein's equations called for 0.8 MeV. That's more than twice as much as was measured. This was a real problem. Niels Bohr thought that the conservation of energy didn't hold in this case while Wolfgang Pauli thought that it did and proposed that there must be another particle that doesn't interact much with its surroundings and carried away the missing energy.



In 1931 Enrico Fermi named Pauli's particle the neutrino for a small neutral particle. Other experiments showed that conservation of angular momentum was also violated in Beta Decay, so Pauli just added spin to the mysterious particle. The neutrino's predicted mass was around a third of an electron volt. This' over a million times smaller than the electron! Its predicted spin was ½, and its predicted speed was almost the speed of light. With this, Beta Decay would look like this with the ejection of an electron and a neutron.



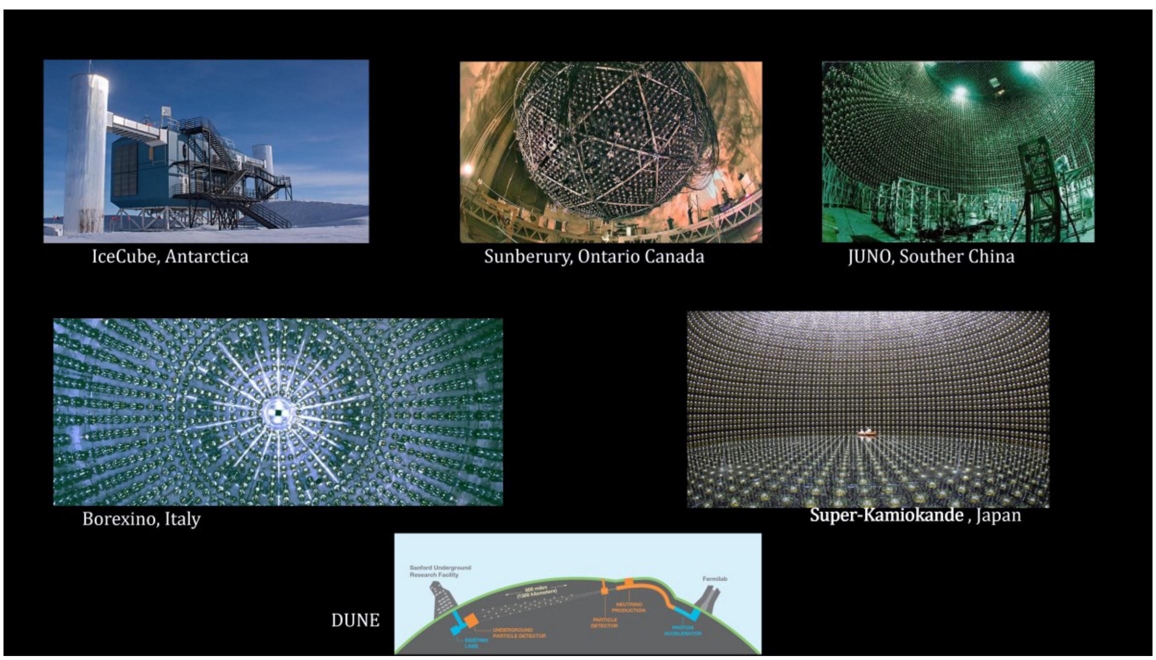
This particle was finally observed in a hydrogen bubble chamber captured in 1970. The invisible neutrino enters from the lower right and strikes a proton where the three particle tracks originate. The proton is kicked into motion, the neutrino is converted into a muon and a pion by the power of the collision.



Neutrino Astronomy

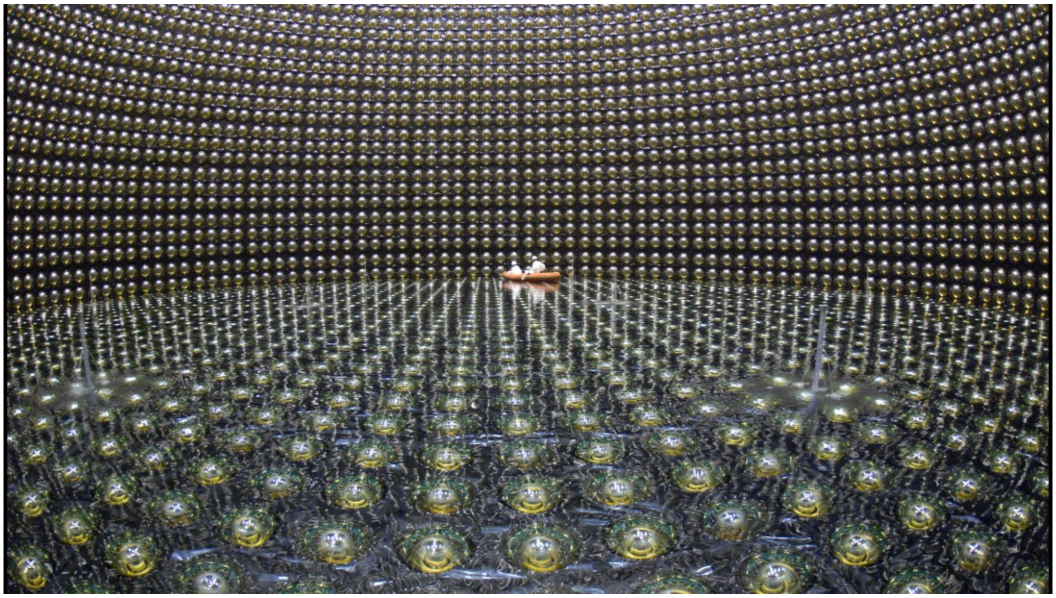
It turned out that the neutrino is a critical component in many nuclear reactions that occur in stars. The detection of solar neutrinos and of neutrinos from the SN 1987A supernova in 1987 marked the beginning of neutrino astronomy.

Today there are a number of neutrino observatories in operation around the world and one under construction to better understand these fundamental but elusive particles. We'll take a closer look at one of them, the Super-Kamiokande in Japan.



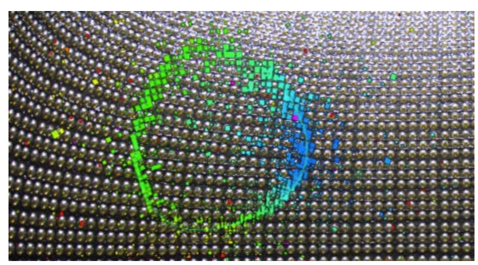
The Super-Kamiokande is located 1,000 meters underground in a Japanese mine. It contains a lake holding 50,000 tons of ultra-pure water surrounded by an inner detector with over

11,000 photomultiplier tubes that flash when struck by a photon created by a neutrino interaction with the water.



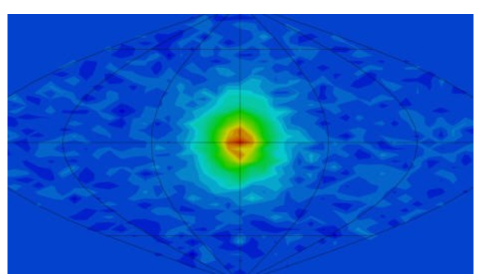
The speed of light in water is slower than the speed of light in a vacuum. A neutrino interaction with the electrons or nuclei of water can produce a charged particle that moves faster than the speed of light in water.

This creates a cone of light known as Cherenkov radiation. This is the optical equivalent of a sonic boom. The Cherenkov light is projected as a ring on the wall of the detector and recorded by the photomultipliers.



The Sun sends about 65 billion neutrinos per square centimeter our way every second. That's over 400 billion neutrinos per square inch per second. That's a lot of neutrinos. And almost all of them pass right on through the earth and out the other side. Trillions of neutrinos are passing through your body every second.

This figure shows the sun as observed by Super-Kamiokande.

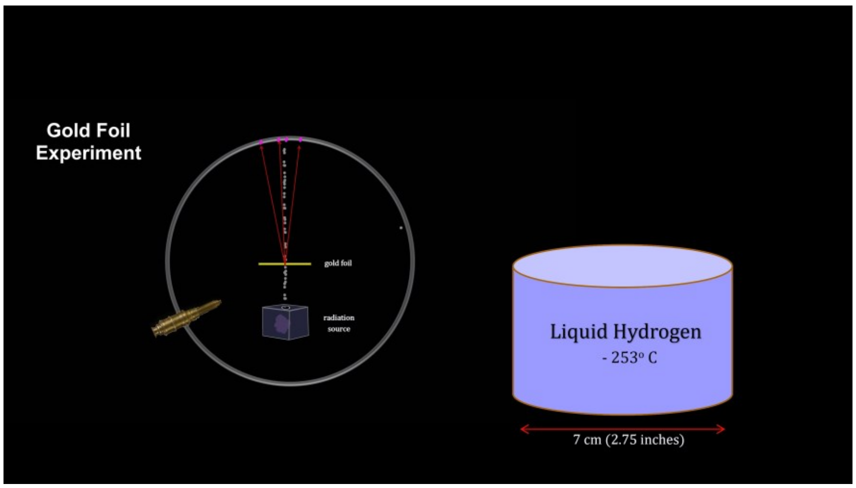


I think that neutrinos will wind up playing a significant role in understanding Dark Matter.

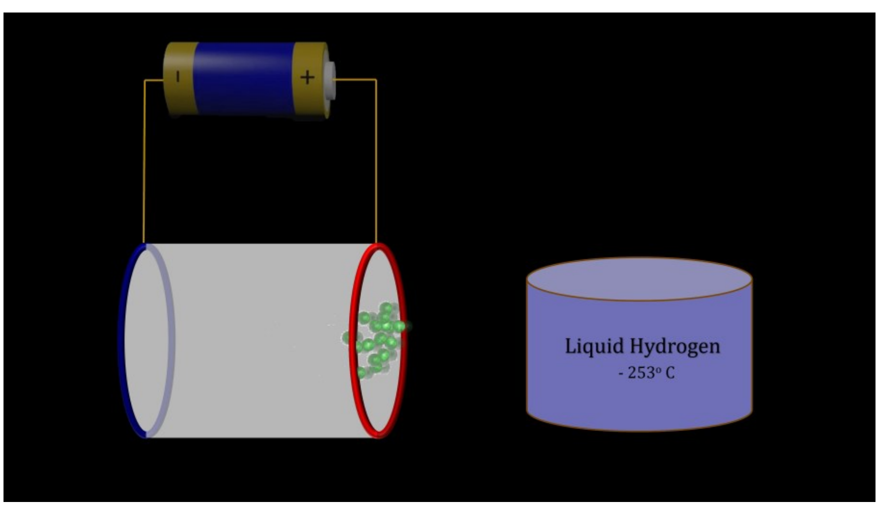
Particle Accelerators

[Music:** Rossini - William Tell Overture**]

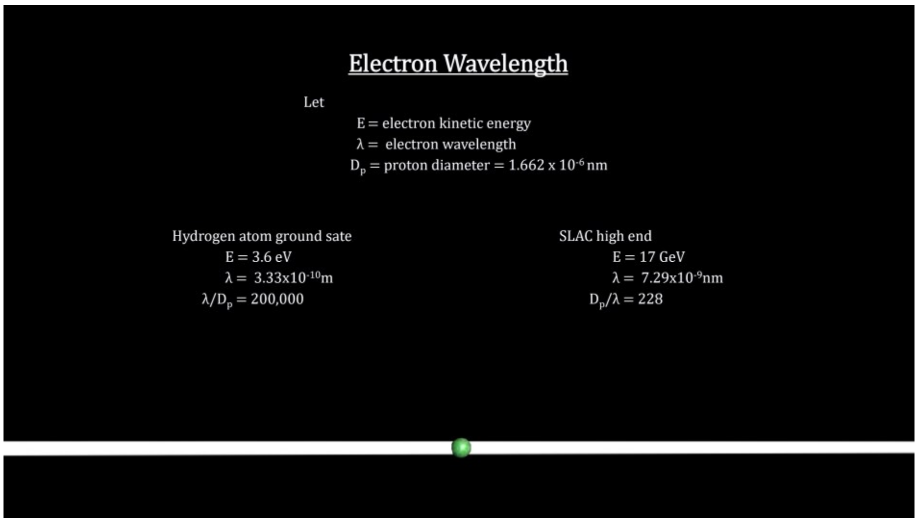
In 1969, a team of scientists at the Stanford Linear Accelerator Center or SLAC for short, in conjunction with MIT, performed scattering experiments similar in principle to what Rutherford did to probe the atom 58 years earlier. Rutherford's target was a gold foil. In the SLAC experiment the target was liquid hydrogen at a very cold temperature to keep the protons as close together as possible. As a source, Rutherford used a small piece of radium. The energy of the naturally occurring alpha particles was 7.7 million electron volts.



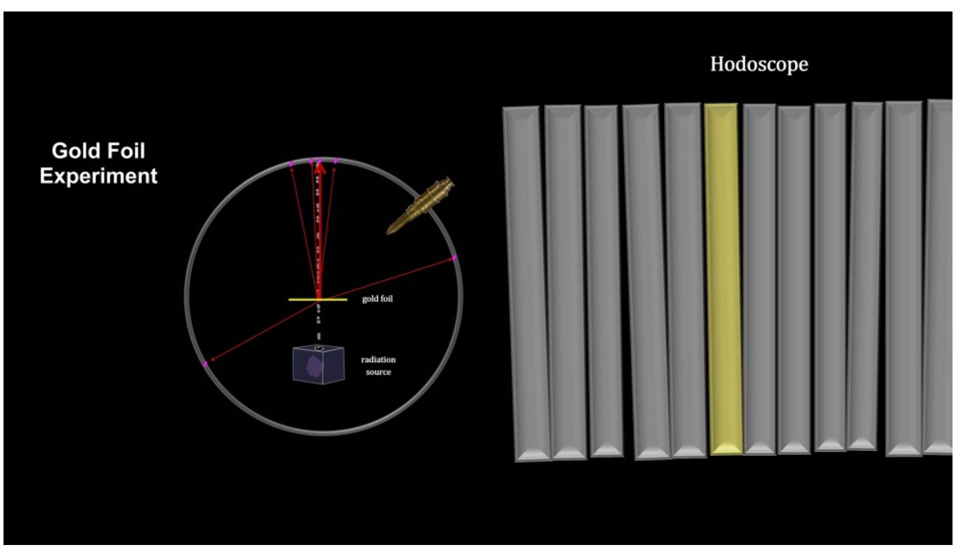
Here we use electrons and accelerate them to nearly the speed of light. To do that, we construct a glass tube. Then we connect a negative charge to the entrance and a positive charge to the exit. When the battery is turned off, electrons flow in any direction. But with the battery turned on, the electrons accelerate down the tube along the electrical field.



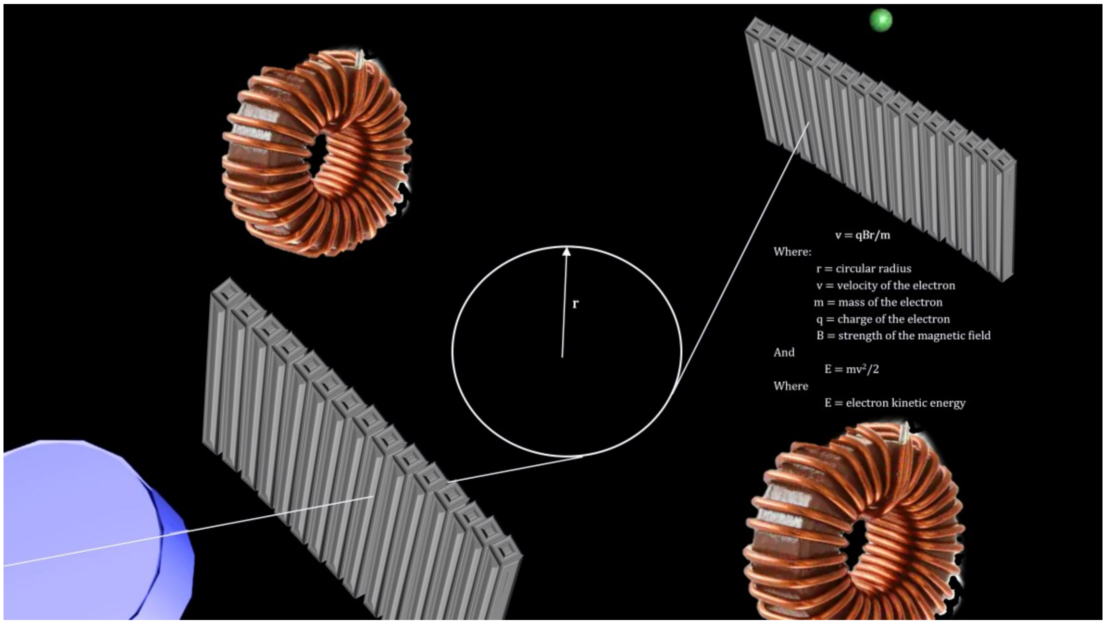
To get a really high velocity, we connect more and more of these tubes together. At SLAC, the length of the tube is 3 km (That's 1.86 miles). This creates electrons with 40,000 times the energy than the alpha particles used by Rutherford. This high energy is essential. You cannot probe inside a proton with a large wavelength electron. Remember that the wavelength of an electron in its ground state around a hydrogen nucleus is 200,000 times larger than the diameter of a proton. But, if an electron's velocity is large enough, making its de Broglie wavelength small enough, it can. SLAC accelerates electrons to greater than 99.9999 % of the speed of light, creating a wavelength for the electron that ranges from 2 to 200 time smaller than the proton.



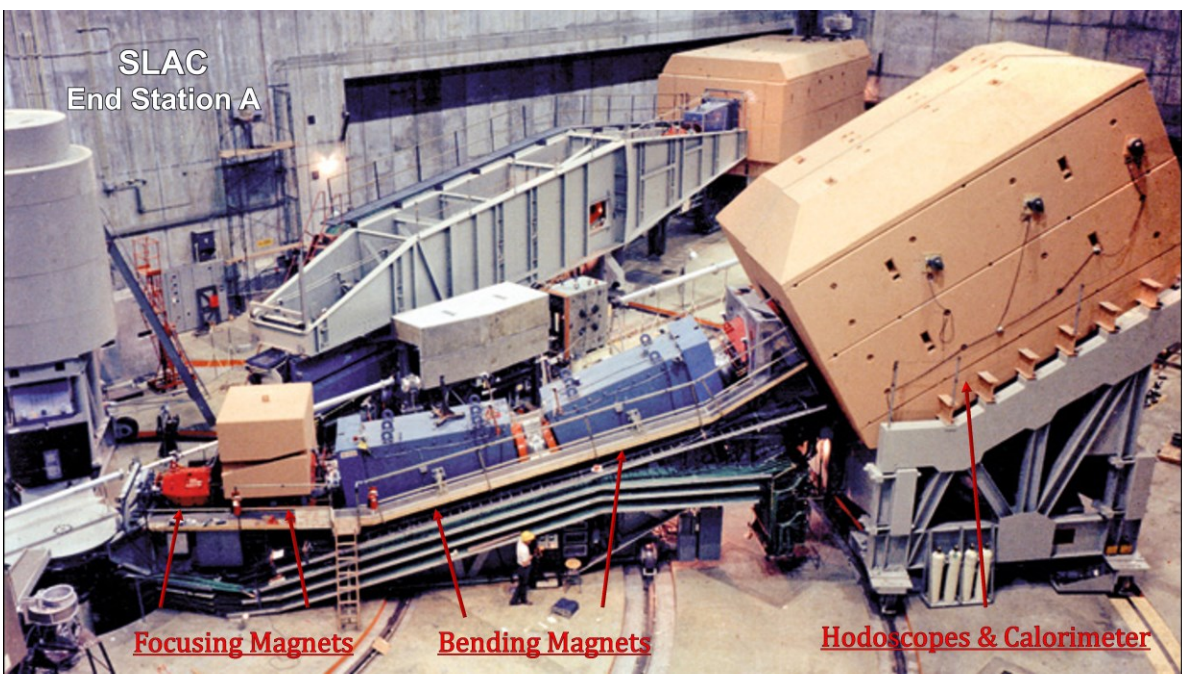
The scintillator screen used by Rutherford covered the inside of the apparatus. He had to manually note the flash locations as he viewed them through the swiveling microscope. At SLAC, we partitioned the scintillator screen into small strips. Each strip has an attached photo element that converts the flash into an electrical signal. This enables the sending of electronic location coordinates to a computer. This is called a hodoscope. With this, we can precisely measure the scattering angles as the high energy electrons penetrate the hydrogen atom and approach the proton at the center.



SLAC also introduces a strong magnetic field that will cause the scattered electrons to curve as they pass through. As you'll recall from mass spectrometers and bubble chamber analysis techniques, the measured curvature will give us the momentum and velocity of the electrons. To measure this, a second hodoscope is installed at an angle.

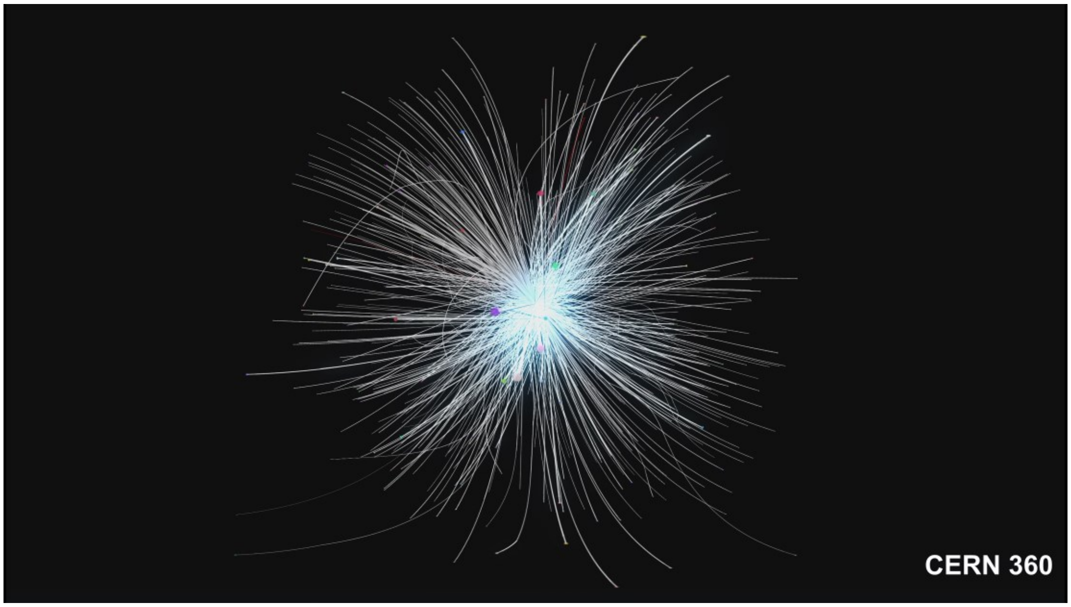


At the end of the process the electrons enter a calorimeter that will measure its energy much like we just did to discover the neutrino. Putting all these pieces together gives us the complete linear accelerator detector. It weighs 750 tons.

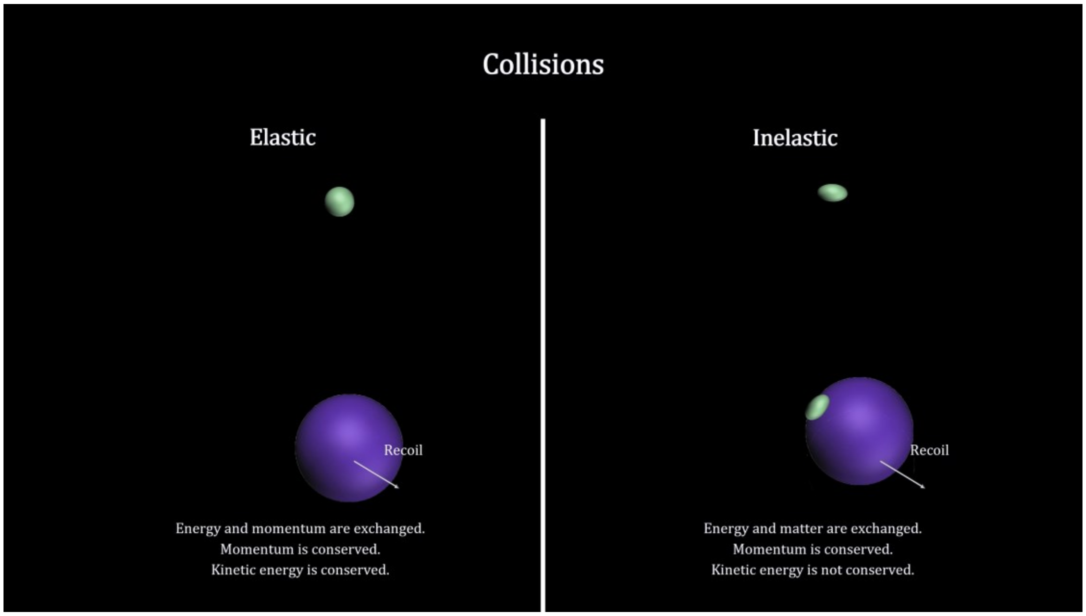


Probing the Proton **[Music:** Beethoven - Symphony No 6 (Shepherds Hymn)**]**

The Stanford Linear Accelerator was built to probe the proton with electrons like Rutherford probed the atom with alpha particles. They both used scattering techniques. These techniques are key to understanding how the Higgs particle was found at CERN in 2012, so we'll take a little time to understand what they found and the principals involved.

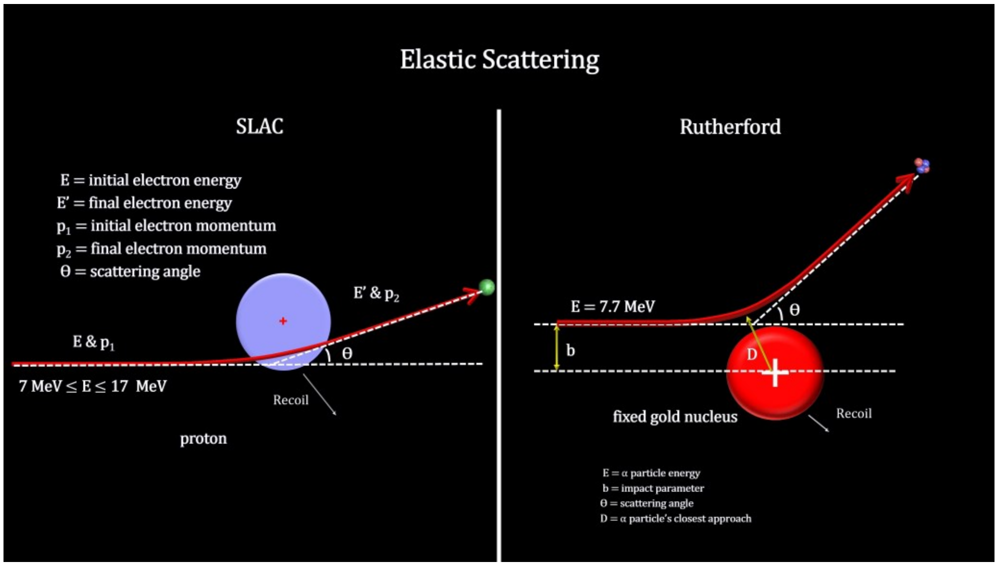


There are two basic types of scattering. One is called inelastic scattering where both of the colliding objects change. For example, here we have some of one object's mass transferred to the other at the point of collision. The transfer absorbs energy, so conservation of energy doesn't hold. The other is called elastic scattering, where no parts of the participating objects are changed. Total kinetic energies are preserved or nearly preserved. In both elastic and inelastic collisions, the conservation of momentum always holds true.

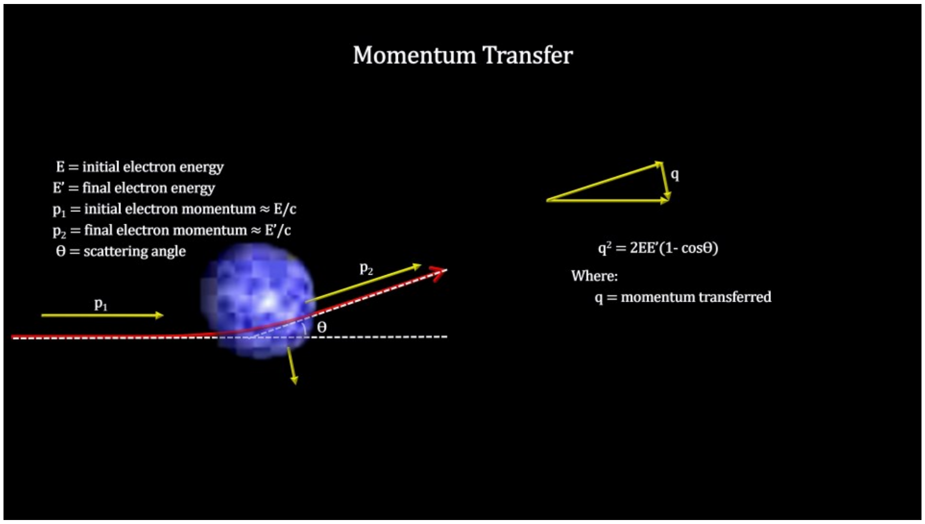


Rutherford was examining alpha particle scattering angles off a gold atom target to determine the size of the nucleus. He had to use an alpha particle probe with fixed energy at 7.7 MeV. The coulomb force was repulsive and his target nucleus was fixed in the solid gold foil, so the target recoil velocity was tiny because the entire foil had to move.

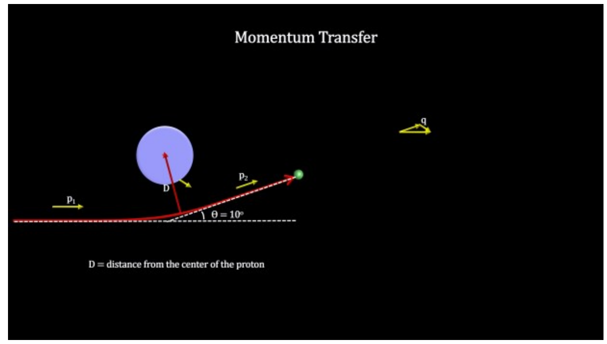
The SLAC experiment could vary the incoming electron energy up to 17 GeV. The coulomb force was attractive with significant target recoil when a high velocity electron collided with a target proton. The SLAC experiment was designed to examine this transfer of momentum from the electron to the proton at various electron energies and scattering angles to find out if the proton's positive charge was distributed evenly throughout its volume.



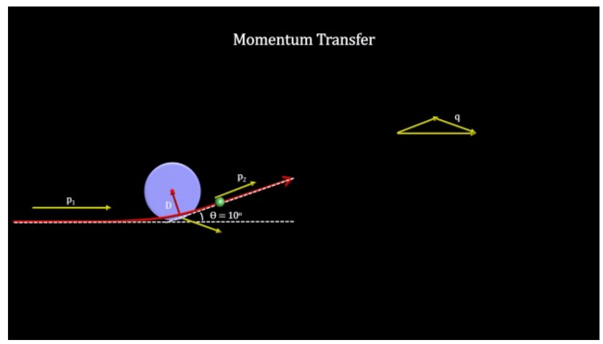
The physicists controlled the incoming electron's energy and momentum and carefully measured the outgoing energy and momentum for a particular scattering angle. With that, they calculated the amount of momentum lost by the electron. Given the conservation of momentum, the electron's loss would be equal to the proton's gain.



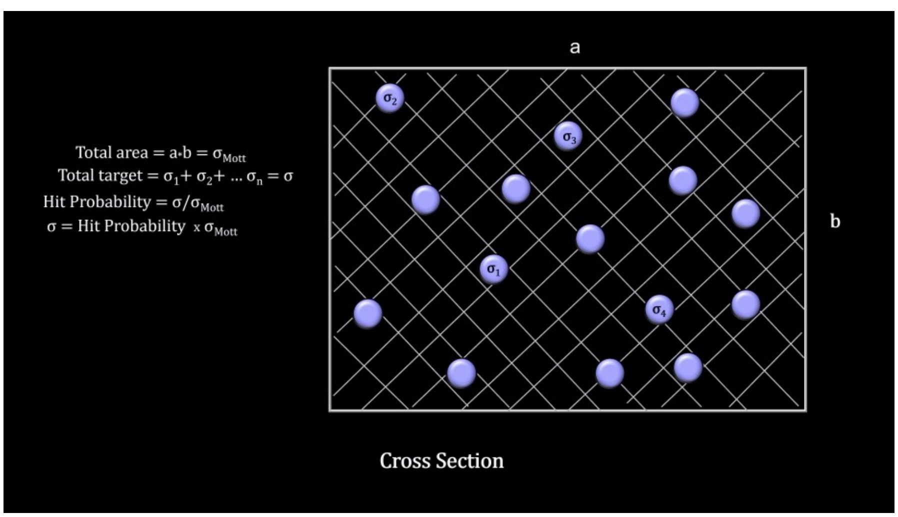
Suppose we're counting 10º deflections as a hit. A relatively slow-moving low energy electron can get a 10º deflection far from the center of the proton. This would make the size of the proton look large. In addition, the interaction between the electron and the proton would be weak. We'd find that only a small amount of momentum would be transferred.



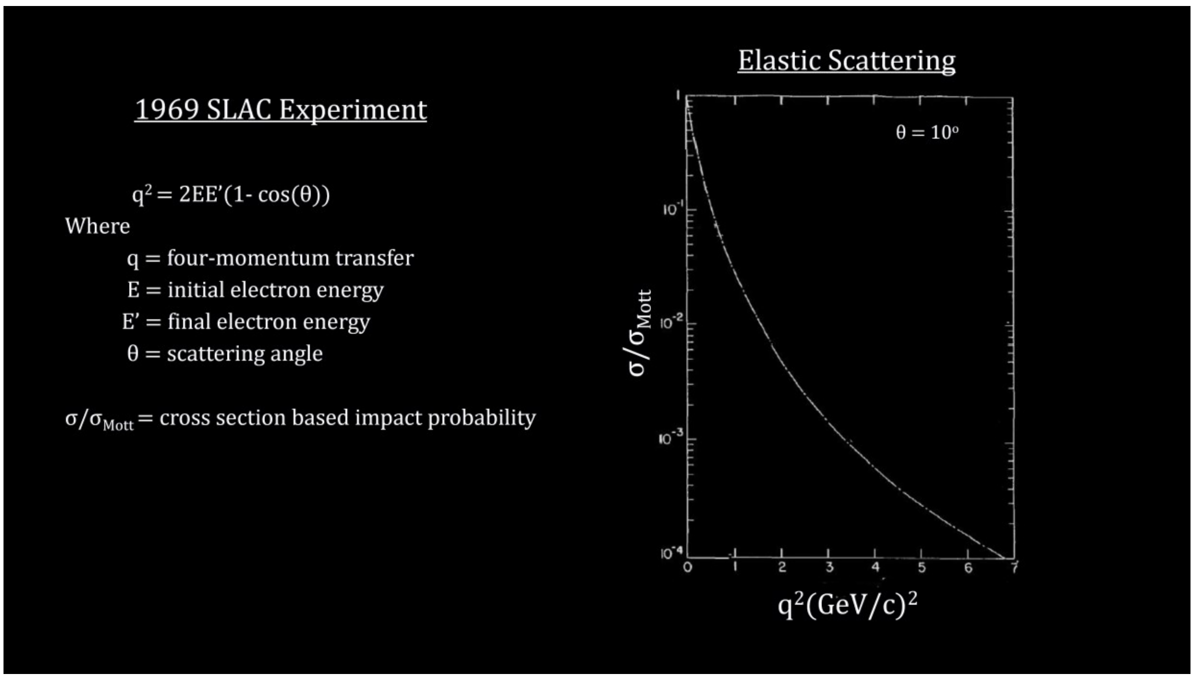
If we increased the velocity of the electron and kept its distance from the proton the same, it would not be deflected 10º, and the interaction would be considered a miss. An electron with this increased energy would have to approach closer to the proton to get deflected 10º. This would have the effect of making the proton look smaller and in addition, the momentum transfer would be greater.



This gives the gives rise to the concept of 'cross section'. If we take a look at the total area we are shooting into and the smaller area that represents the target, we see that the probability of a hit is equal to the target size divided by the total area. You can see that as the target cross section shrinks, the probability of a hit goes down. Of course, we have a large number of targets in the area (the liquid hydrogen protons), so we add them together to get the total cross section.



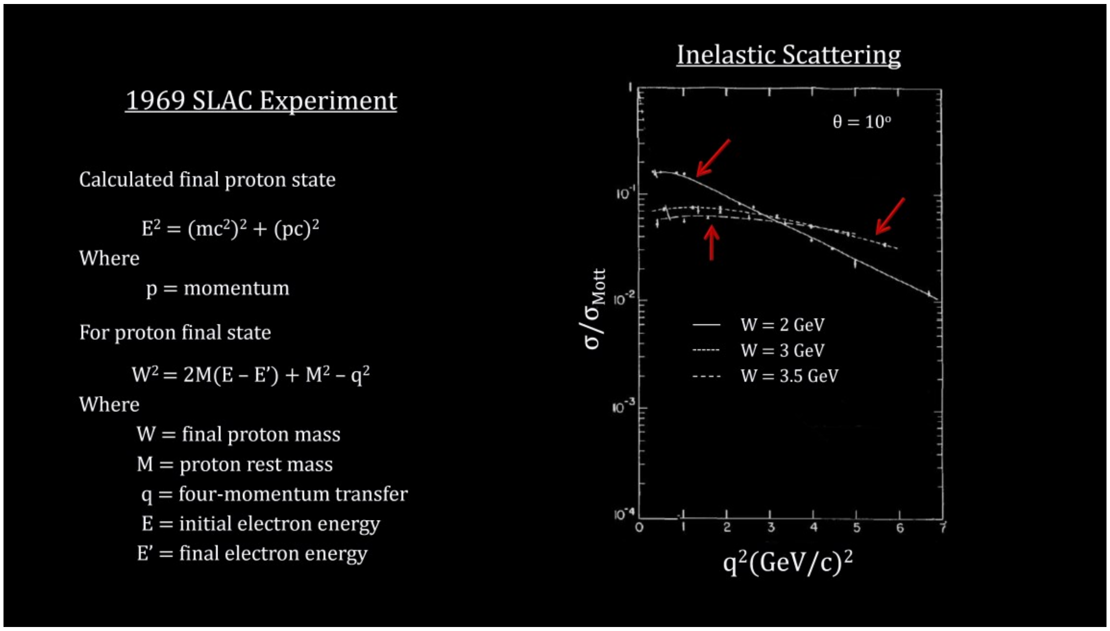
SLAC calculated the cross section by controlling the number of incident electrons and counting the hits. Here's a graph of the interaction probabilities against the momentum transfer found by the SLAC experiment for electrons with energies below 7 GeV that scattered by 10 degrees. The closer to the target we get, the smaller the cross section - decreasing the probability of a hit. While at the same time, the momentum transfer increases with each hit that we do get. The velocity of the electrons remained the same indicating that no energy was being transferred to the proton. This is exactly what we would expect from elastic scattering.



But at incoming electron energies between 7 and 17 GeV, this dependency changed significantly. In particular, for three final proton state energies, the momentum transfer dependance on cross section was significantly weaker than for elastic scattering. And what's more, the protons absorbed significant amounts of energy from the impacting electrons. Physicists refer to this phenomenon as resonance.

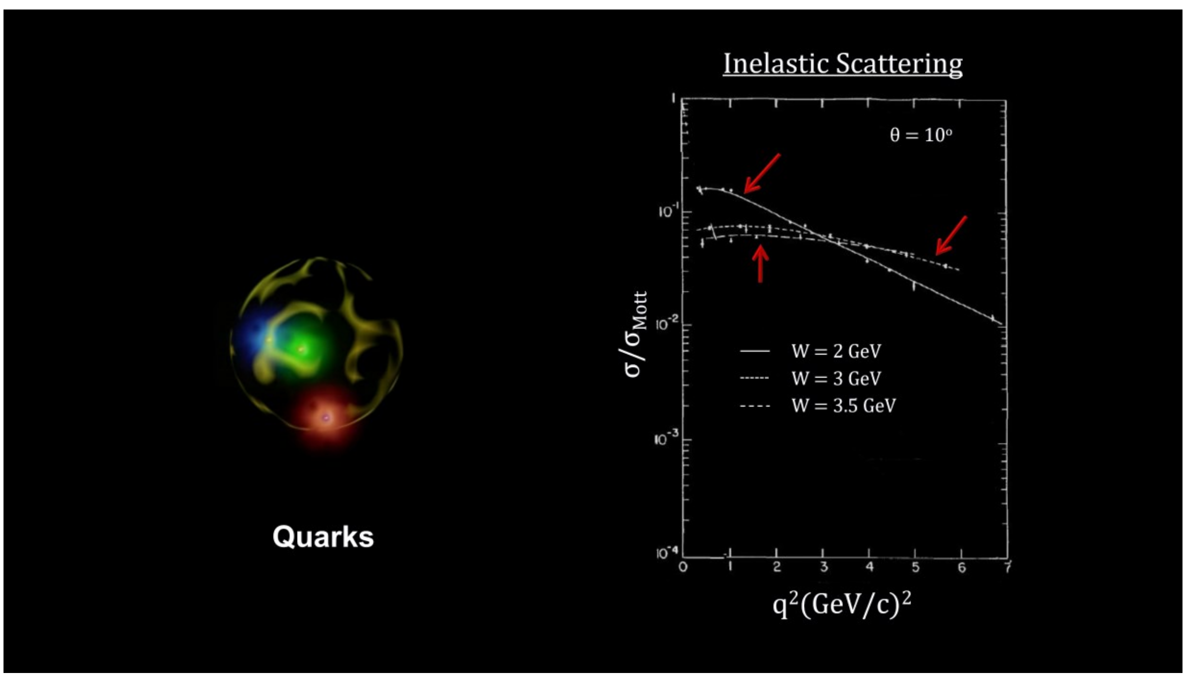
To understand what might be going on, we'll take a closer look at the final proton state. You may recall that Einstein's formula for mass and energy is $E = mc^2$. But this only applies to a mass at rest. For a moving particle, the energy-mass conversion includes the particle's momentum. In our case, we see that the final mass of the proton goes up with an increase in energy and goes down with an increase in momentum.

If you think of mass as confined energy, what is happening here is that the incoming electron's energy is being converted into increasing the mass of the proton. This is inelastic scattering and the three 'resonances' indicate that the proton has three internal components.

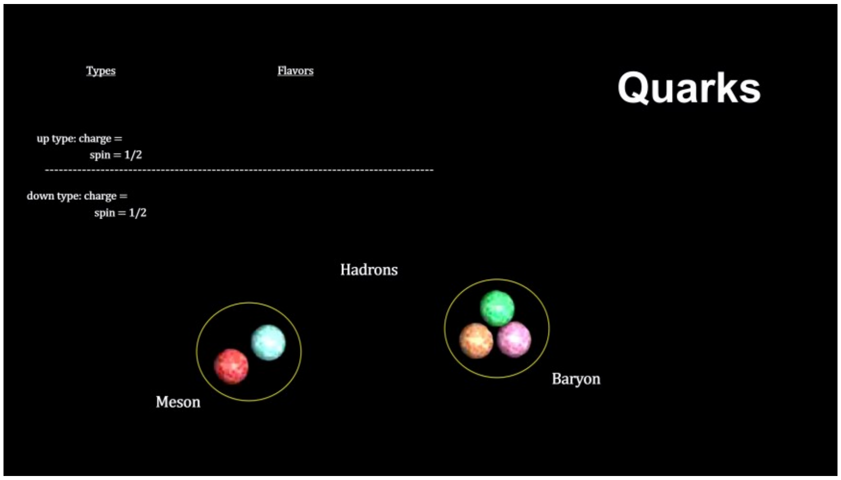


Quarks & Hadrons

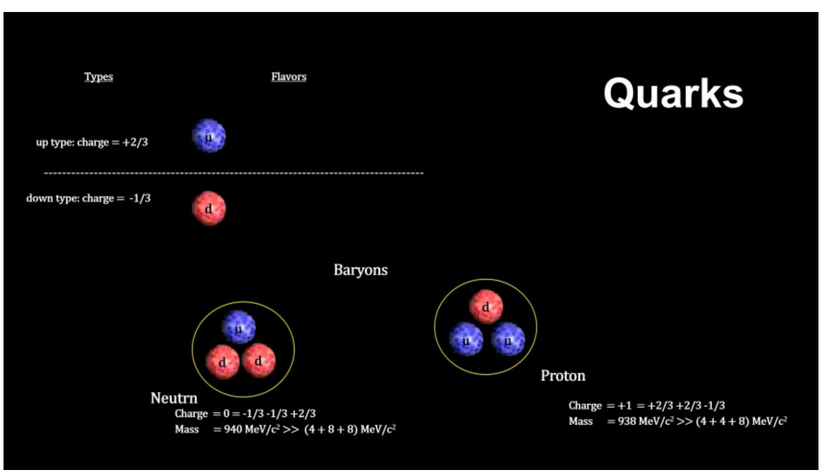
Back in 1964, a quark model was proposed by Murray Gell-Mann and George Zweig to help explain protons, neutrons and the wide variety of newly discovered heavy particles like Pions, Kaons and others. The discovery at SLAC in 1969 that the proton has three parts constituted evidence that quarks were real.



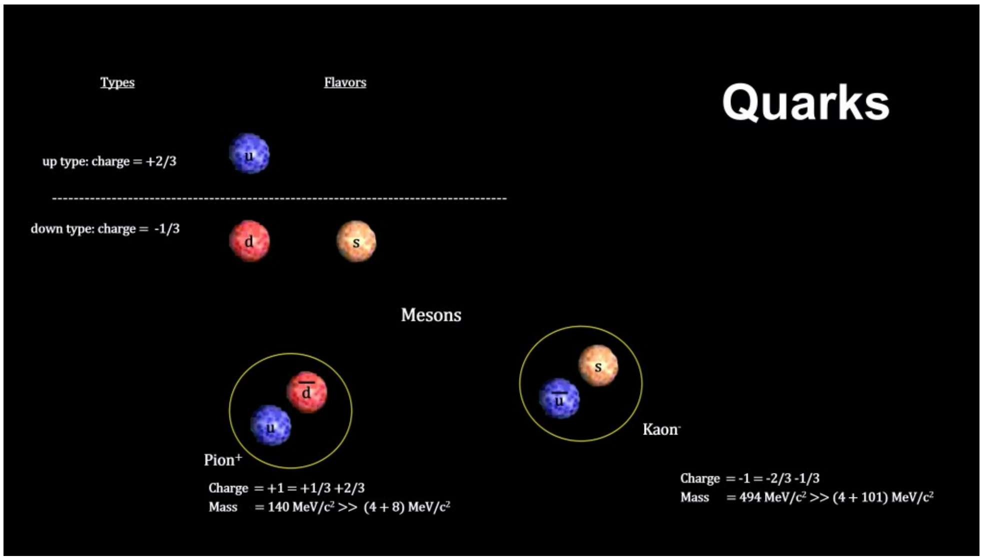
One of the key things to remember about the theory is that quarks are so strongly bound together that it is impossible to study one on its own in order to determine its properties. This means that all we know about quarks is derived from the properties of the particles that bound quarks create. [Aso, as we have seen, every elementary particle has an anti-particle - quarks included. We'll cover just how strong the quark binding is in our next chapter on the Higgs Boson.] We call particles made of quarks 'hadrons' meaning heavy. In studying hadrons, we find two kinds: those with two quarks are called mesons; and those with three quarks are called baryons. All quarks have a spin of ½ and the sum of quark charges needs to give us the charge of the hadron.



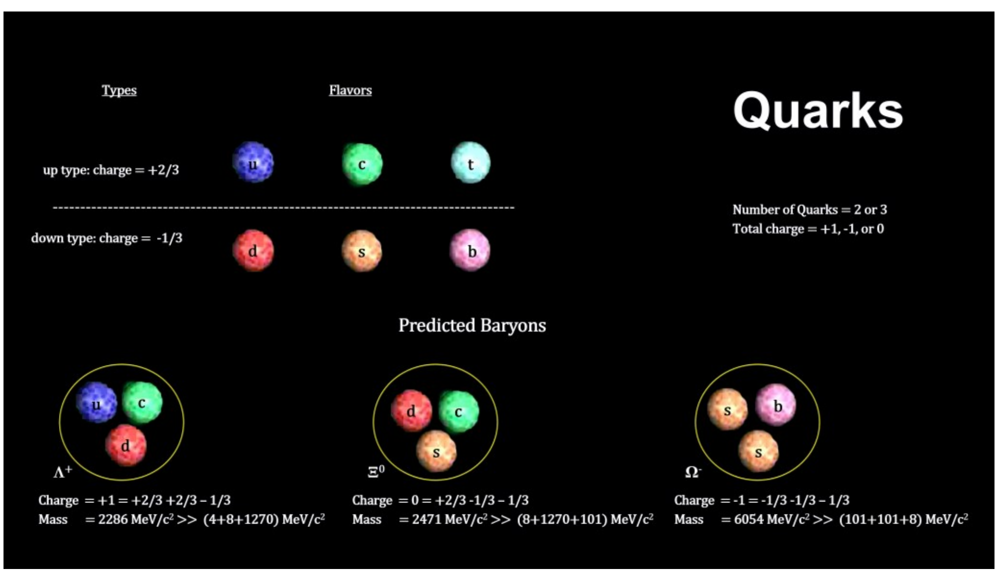
The baryons we've seen so far are the proton and the neutron. Quark theory has it that there are two flavors of quarks that make up these baryons called the up quark and down quark. Protons have 2 up quarks with one down quark, and the neutron has one up quark and two down quarks. In order to get the correct charge of the proton and the neutron, the up quark must have a positive charge that is 2/3's the charge of an electron. The down quark must have a negative charge that is 1/3 the charge of an electron. The down quark must also have a little more mass than the up quark for the neutron to have a little more mass than the proton. Note that the sum of the quark masses falls far short of the mass of the hadron. This indicates that there is a lot more going on inside the proton than we've seen so far. The up and down quarks are the lightest and most stable quarks. All other quarks will decay into these two over time.



The two mesons we've seen so far are the Pion and the Kaon. The positively charged pion has an up quark and an anti-down quark. The negatively charged Kaon contains an anti-up quark and a third kind of quark called the 'strange' quark needed to explain the length of time it took the kaon to decay. These two mesons, are sometimes called the pi-meson and the k-meson.[These two mesons, are sometimes called the pi-meson and the k-meson.]



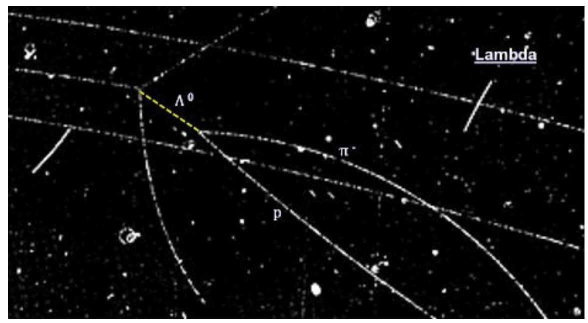
In addition to the up, down and strange quarks, we have discovered the charm, top and bottom quarks for a total of 6. One of the key rules seems to be that they can only combine in combinations of two or three as long as the sum total of charge always equals the charge of an electron or proton or zero. So armed with quarks, physicists intensified their search for some of the three quark particles predicted by Gell-Mann's and Zweig's theory: lambda, xi, and omega baryons.



Lambda Λ

In 1947 the Lambda particle was discovered during a study of cosmic ray interactions. The technique use in the discovery was to study the decay patterns and using known conservation of things like mass, energy, momentum and charge, deduce the characteristics of the decaying particle.

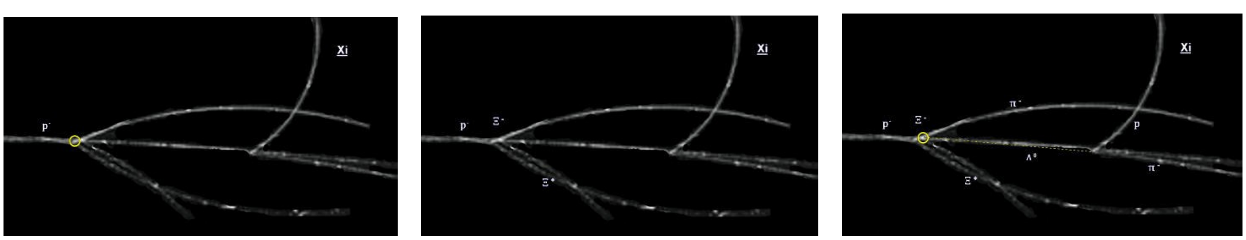
Here we see a V shape with the creation of a pion and a proton. It was the proton that told us the decaying neutral particle Lambda must have had three quarks. The particle was expected to live for ~10^{-23} s, but it actually survived for ~10^{-10} s. The property that caused it to live so long was dubbed *strangeness* and led to the discovery of the strange quark.



Xi Ξ

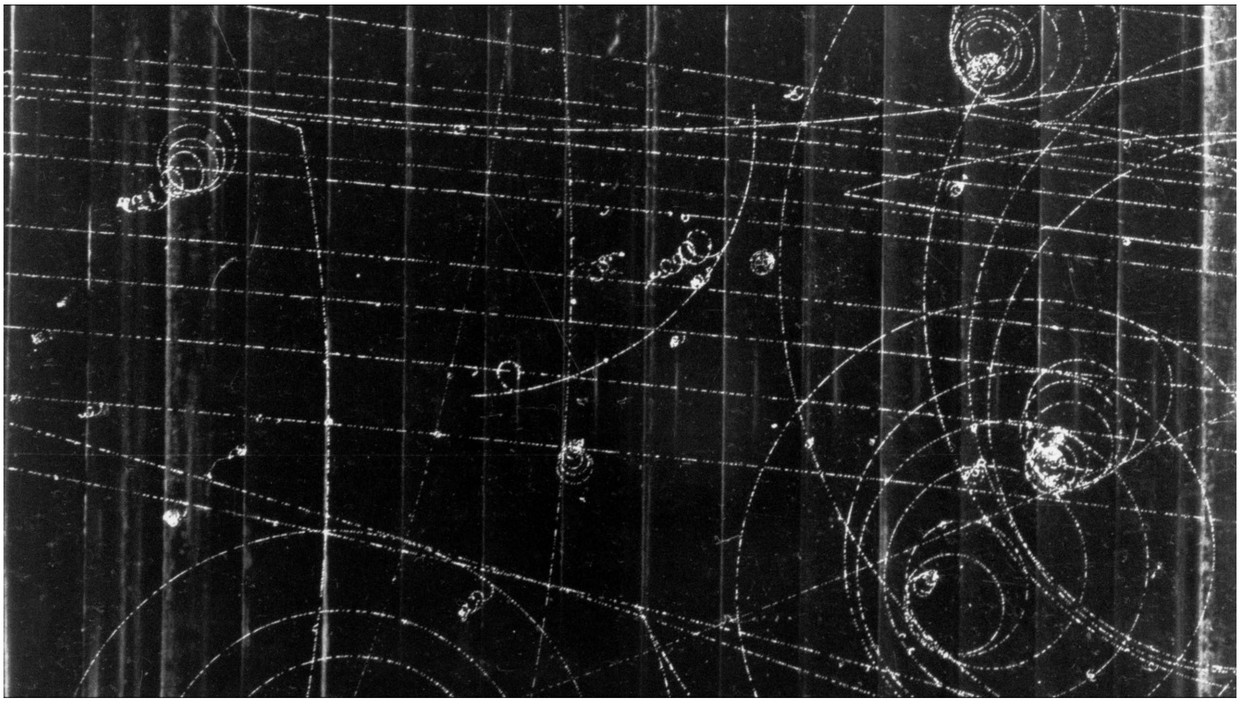
In 1964, the Xi baryon was discovery at the Brookhaven National Laboratory.

Antiprotons arrive from the left. One of these antiprotons collides with a hydrogen nucleus (a proton), resulting in mutual annihilation. The mass of the proton and the mass and kinetic energy of the antiproton give birth to two heavy particles: a negative xi and its antiparticle, which is a positively charged anti-xi. [The xi and anti-xi are visible as the first faint fork to be seen in the tracks, left of centre; the decay of the anti-xi then gives rise to the more visible spray of tracks.]

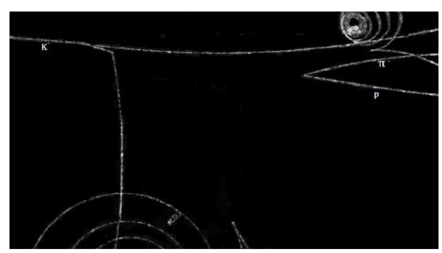


Omega Ω

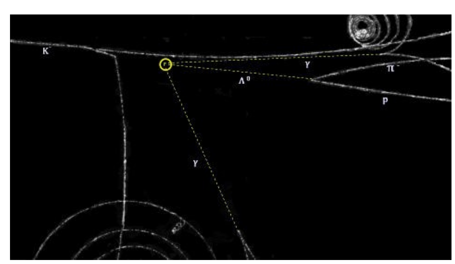
Also, in 1964 at the Brookhaven National Laboratory, the Omega particle was discovered. This is one of the most famous bubble chamber pictures of all. It shows the discovery of this long-predicted particle. In this photograph, we have manufactured Kaons entering the chamber on the left.



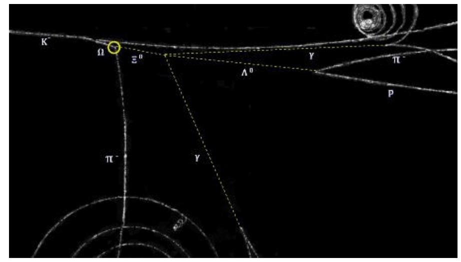
To help see the omega particle, I'll remove all but the tracks associated with the omega event, and work backwards from the V on the right that creates a pion and a proton. This is the trademark decay signature for the Lambda particle.



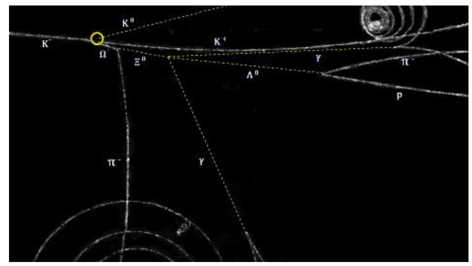
We also see Vs in the upper right and in the lower middle where a positron and an electron are created. This is the signature for high energy gamma rays. If we draw lines back to where the Lambda particle and the two gamma rays cross, we see that a neutral particle decayed into the neutral Lambda and two gamma rays. This is the decay signature for the neutral Xi particle.



We can now draw the path of the Xi particle back to the kink where another particle has decayed into the neutral Xi and a Pion. Given all the masses, energies, strangeness, and charges involved, this fit the expected properties of the Omega particle made up of three strange quarks.



Tracing the path of the Omega particle back to the kink in the path of the Kaon, we can see the decay that created the Omega particle and measure the length of time the Omega particle existed. It has a very short life of 82 trillionths of a second.

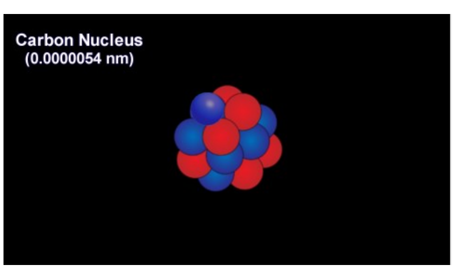


The physicist working on analyzing this photograph was so excited about his find that he woke up the director of the Brookhaven Laboratory in the middle of the night to give him the new! As with other predictions of previously unobserved particles, this discovery gave a tremendous boost to quark theory.

Particle Sizes so far *[Music:* *Haydn - Piano Concerto No 4*]

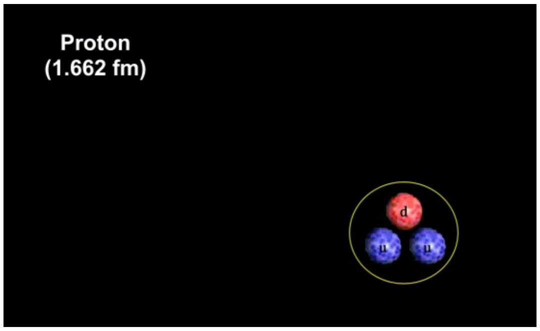
Now's a good time to review the particle sizes we've seen so far.

In our first segment, we used an electron microscope to see a carbon atom with a diameter of 0.14 nanometers. That's a million times smaller than the width of a human hair.

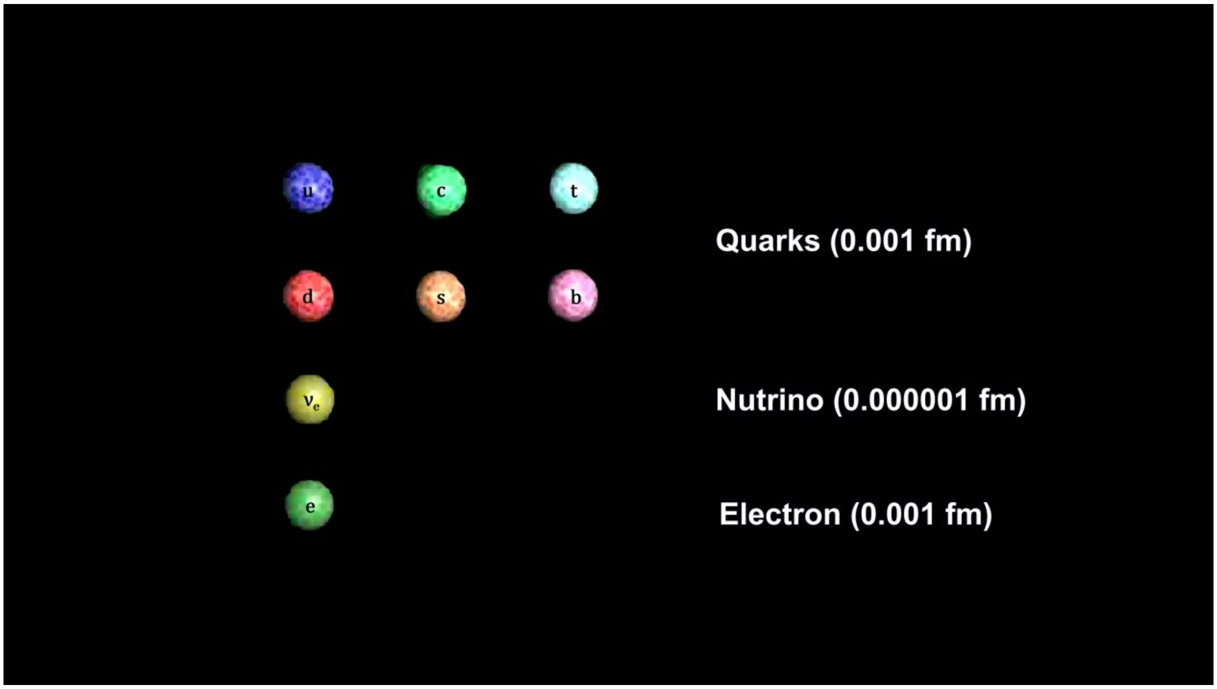


In our second segment, we probed the atom with alpha particles and found that the nucleus was very small compared to the atom. Here we have the carbon nucleus at around 26 thousand times smaller than the carbon atom.

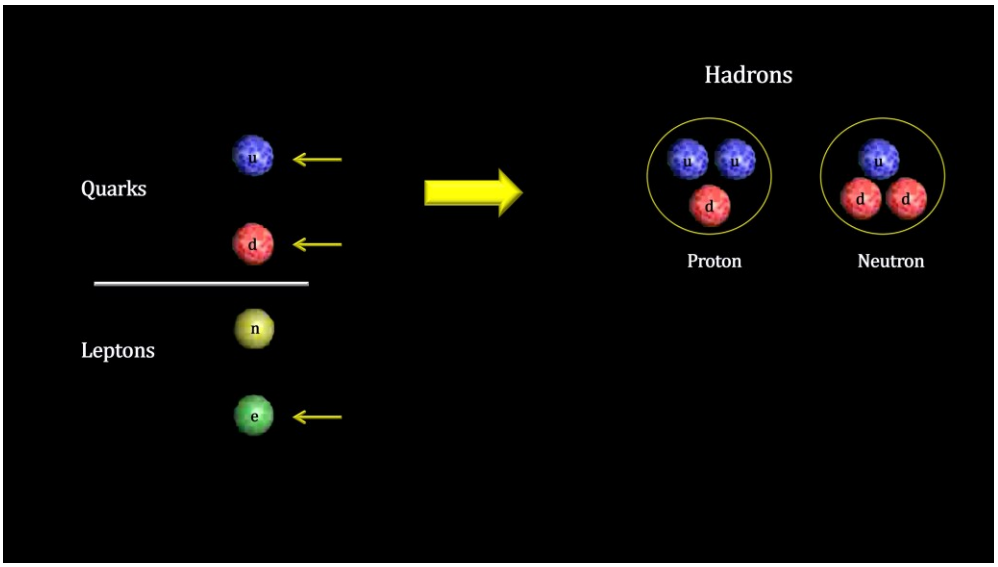
The simplest nucleus is hydrogens. It has just one proton. At this level, the nanometer is way too large. So, we'll move to femtometers instead. There are a million femtometers in a nanometer. Modern experiments have produced excellent results and show that the diameter of a proton is 1.662 femtometers.



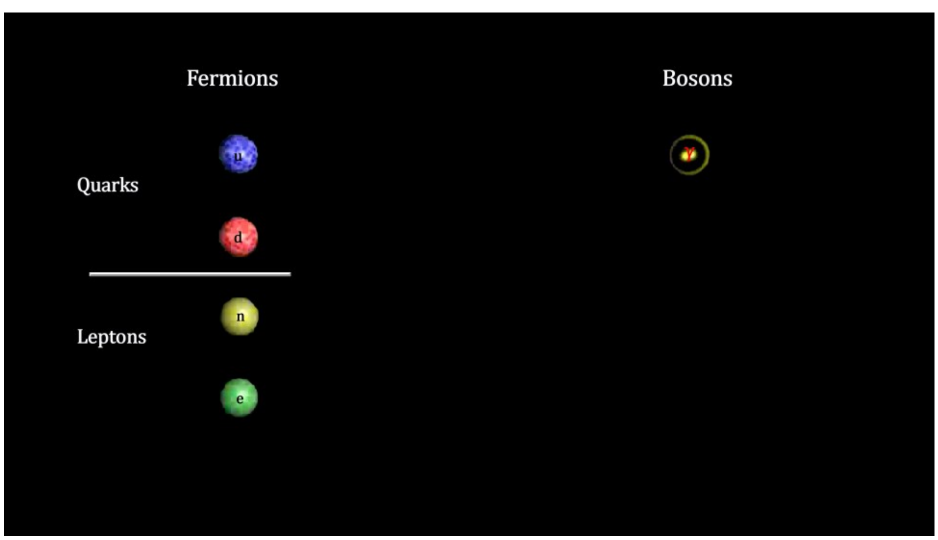
In this segment, we probed the proton with high velocity electrons and found that it contained three quarks. Powerful accelerators and hadron colliders have put the upper limit on the diameter of the cross section of a quark at 0.001 fm. That's 1,760 times smaller than a proton, and a 140 million times smaller than a carbon atom. This is also the upper limit for the cross section of an electron. The neutrino is the smallest elementary particle with a cross section that is a thousand times smaller than an electron or a quark. That makes it a 140 thousand trillion times smaller than the diameter of a human hair!



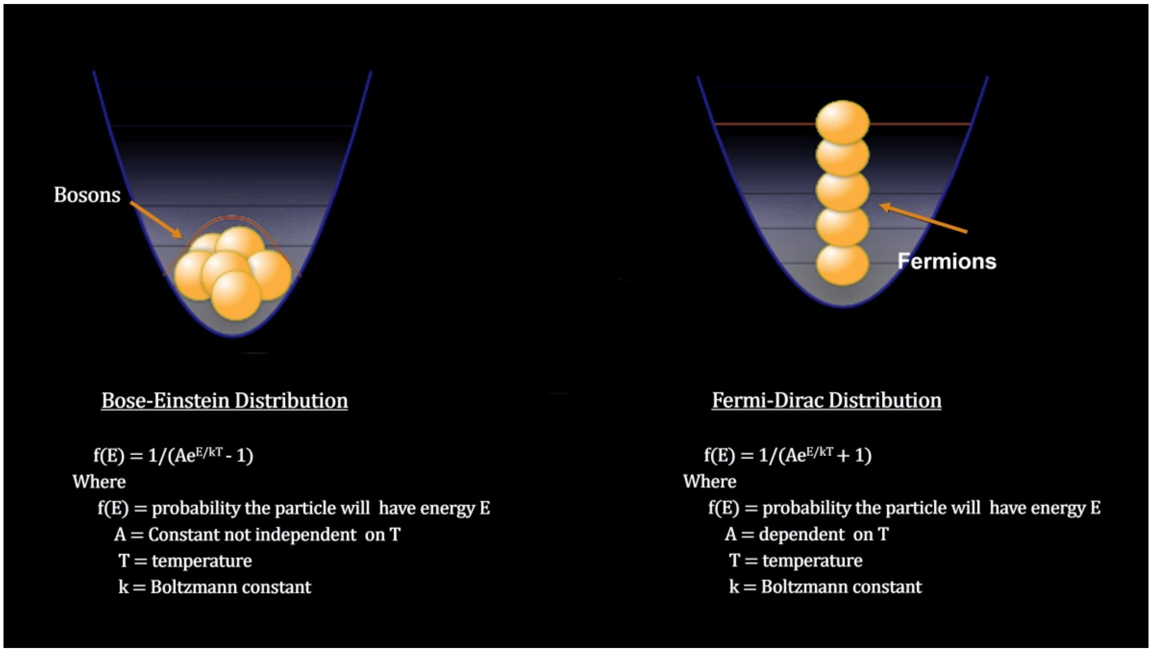
Fermions and Bosons
When confronted with a vast number of observations, a first step to understanding, is categorization. We try find the similarities and differences between things. When it comes to elementary particles, we have already made some distinctions. We have the small light particles like the electron and the neutrino called leptons (meaning light). And we have the Quarks that make up the big heavy particles like protons and neutrons called hadrons (meaning heavy). Everything we see around us is made of these three stable elementary particles – the electron, the up quark and the down quark.



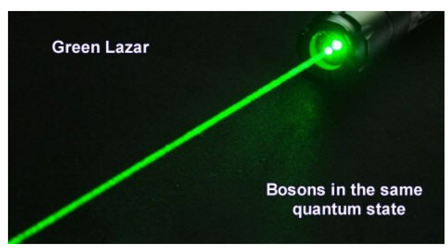
A particle's spin is another key distinction that helps us categorize all these particles. You'll recall that electrons and quarks have spin ½ and therefor follow Pauli's Exclusion principle. Photons have spin 1 and do not follow the exclusion principle. The statistics that describe spin 1/2 particle behavior in large groups was developed by Enrico Fermi and Paul Dirac. They are called fermions after Dr. Fermi. The statistics that describe spin 1 particle behavior in large groups was developed by Satyendra Nath Bose and Albert Einstein. They are called bosons after Dr. Bose.



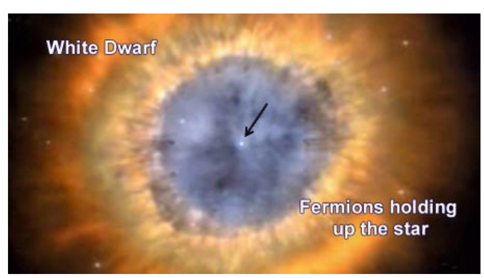
You can image that large groups of particles that can't fit into the same quantum state will behave differently than particles that can. In an energy well, the bosons all sit in a condensate at the bottom. The fermions arrange themselves in a hierarchy like electrons in an atom.



For example, a beam of photons can be made to have the same quantum state. This is how a lazar works.



On the other hand, the inability of electrons to fit into the same quantum state creates an outward pressure that halts a star's collapse and creates white dwarfs.



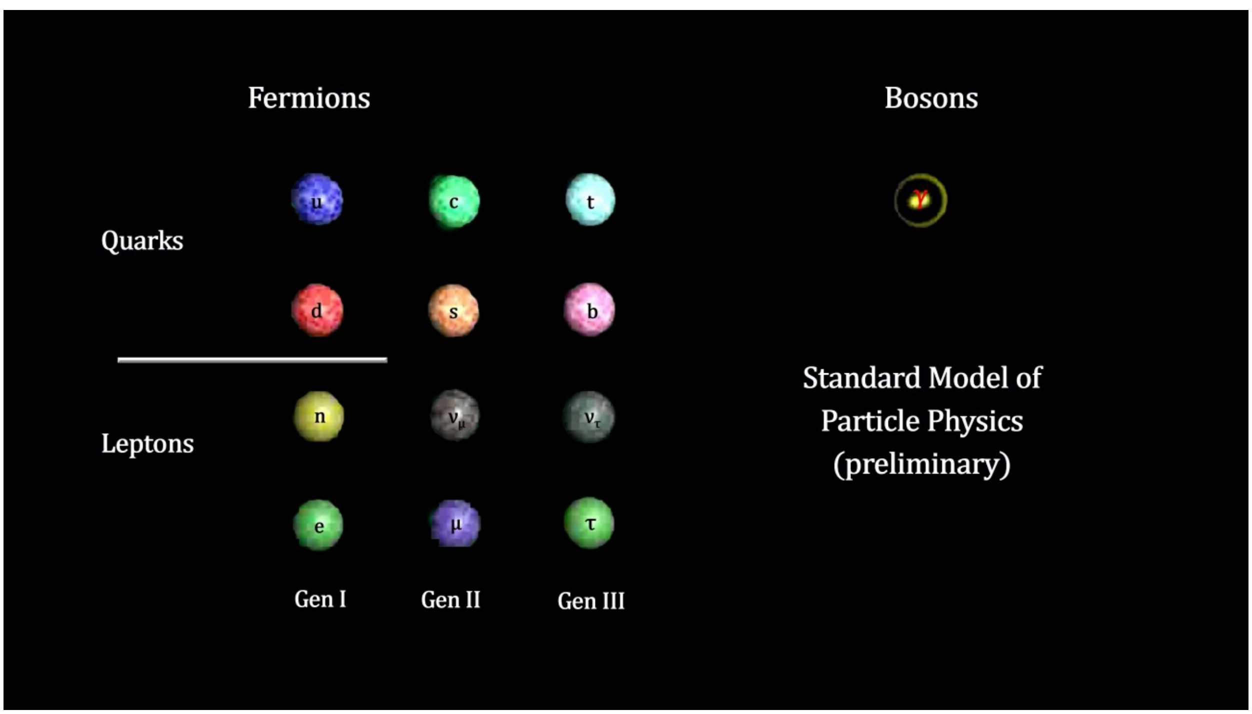
Standard Model of Particle Physics

In this segment we also covered the muon – a higher energy version of the electron. At even higher energies, another electron like particle called the Tau was discovered in 1975. [Its mass is 3,484 times an electron. But we still call it a lepton!]

When these leptons decayed, their neutrinos were slightly different, so we have two additional neutrinos to go along with the ubiquitous electron neutrino. The muon neutrino and the tau neutrino. The tau neutrino was found in the year 2000.

Experimental evidence indicates that decay rates for these particles are different. We have the Gen 1 particles that are stable. They do not decay. In addition, we find that Gen 2 particles decay slower than Gen 3 particles. This gives us one more organizational category to go along with heavy vs light and integer vs non-integer spin.

So here we see the beginnings of the Standard Model of Particle Physics. We'll finish developing this model in our final segment on the Higgs Boson.



Music

@00:00 Stravinsky - The Firebird - from the album “The Firebird Suite” 2010

@01:13 Beethoven - Symphony No 6 (Shepherds Hymn) - Philadelphia Orchestra; Riccardo Muti; from the album “Essential Adagios” 2010

@05:5 Mozart - Divertimento No 10 - Franz Liszt Chamber Orchestra – from the album “50 Must-Have Adagio Masterpieces” 2013

@19:18 Rossini - William Tell Overture - London Philharmonia Orchestra and Alfred Scholz; from the album “The London Philharmonic Collection: Light Classics” 2009

@36:18 Haydn - Piano Concerto No 4 - Nicolai Evrov, Sofia Philharmonic Orchestra; from the album “50 Must-Have Adagio Masterpieces” 2013

Greek letters:
- α β γ δ ε ζ η θ ι κ λ μ ν ξ ο π ρ σ τ υ φ χ ψ ω
- Α Β Γ Δ Ε Ζ Η Θ Ι Κ Λ Μ Ν Ξ Ο Π Ρ Σ Τ Υ Φ Χ Ψ Ω

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The Higgs Boson

Abstract

{*In our final segment, we cover the Higgs Boson starting with force fields and their particles.*

First, we cover Quantum Electrodynamics - QED. We note that a disturbance in the electric field can create a particle – the photon. We show how the virtual photon mediates the electromagnetic force with virtual photons that are actually not particles. We also introduce coupling constants and Feynman Diagrams. We then extend this 'force particle from a force field' concept to include a matter particle from a matter field. In electromagnetic quantum field theory, this is the electron.

Next, we cover Quantum Chromo Dynamics – QCD. We show how the electromagnetic force is used as the model for the strong nuclear force that holds quarks together in protons and neutrons and holds protons and neutrons together in the atomic nucleus. We introduce color charge, gluons, virtual gluons, quark containment, and pion exchange between nucleons (the residual strong force). We also highlight the origin of mass for the proton. We then fill out the Standard Model of particle physics with the weak nuclear force and its force particles - the W and Z bosons. Using Beta Decay, we show how this force can change the actual particle in an interaction, not just accelerate it.

Next, we discuss spin oscillation as the origin of mass for elementary particles that lead to the Higgs Field and the Higgs Mechanism, and, as with all other fields, a disturbance in the Higgs Filed should create a particle – the Higgs boson. We show how the Large Hadron Collider (LHC) at CERN works and how the Higgs particle was discovered.

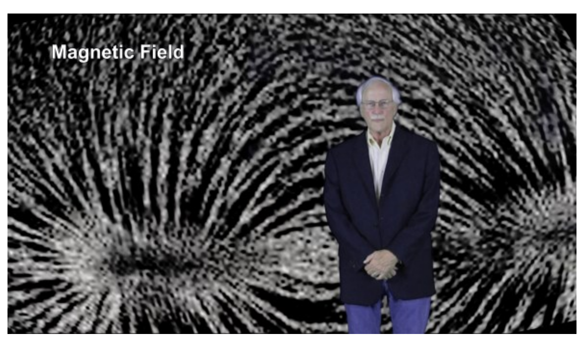
We'll conclude with a brief look at what the standard model doesn't cover (like gravity) and some of the theories in development that may very well take physics to the next level (like Super Symmetry). We end with a description of Planck's Length (the shortest distance that can exist) and its implications for the next generation of physicists.}

Introduction

[**Music**: Albinoni - Concerto for Oboe and Strings No 2 II]

Hello. And welcome to our segment on the Higgs Boson. I remember back in high school, a long time ago, when we were learning about magnetism. I was particularly impressed by what could be going on at a point here - far from the actual magnet that could move an object like an iron filing. It was back in 1894 that Michael Faraday first studied magnetic fields. He coined the phrase force field. And it was Maxwell a few years later who developed the first physics of fields - electric fields magnetic fields.

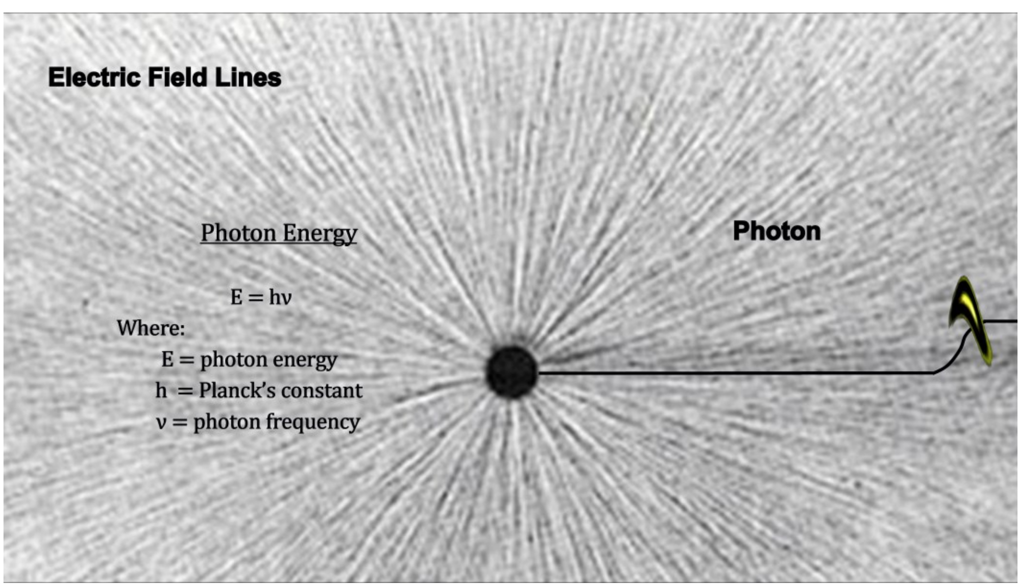
I think it was my curiosity back then that led me to the math institute at oxford where I studied the mathematical foundations for quantum field theory. Which is the theory of what's going on in this so-called empty space. If we can get a deeper understanding of the nature of force in space distant from a particle. We'll have what we need to know in order to get an understanding of the Higgs boson.



Quantized Electromagnetic Field

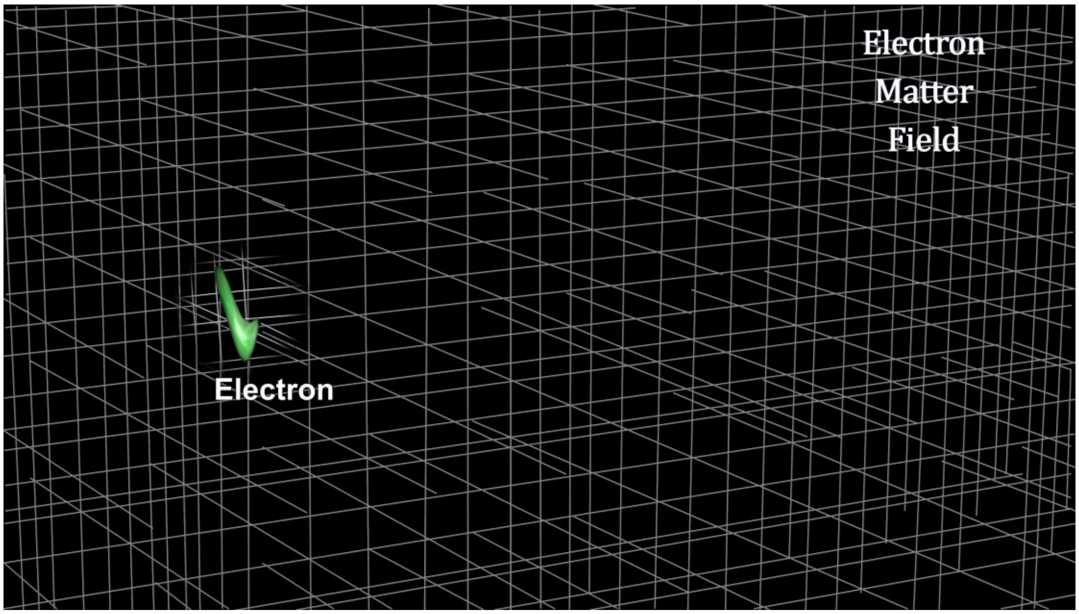
We saw in our first segment that particles with electric charge create an electromagnetic field around themselves that stretches out in all directions. This field is attached to the particle. It will go where the particle goes. In quantum field theory, fields like this are quantized. That is, they contain tiny massless energyless bits of the field.

We have seen that the photon is a certain type of disturbance (an excitation or vibration) in the electromagnetic field. We'll call these a localized vibrating ripple. It moves with a life of its own. It is not attached to the particle that created and sustains the field. The photon has no mass, no charge, a spin of 1 (a boson) and travels at the speed of light in a vacuum. In our segment on the atom, we saw that energy was quantized, and equal to Planck's constant times the photon's frequency.

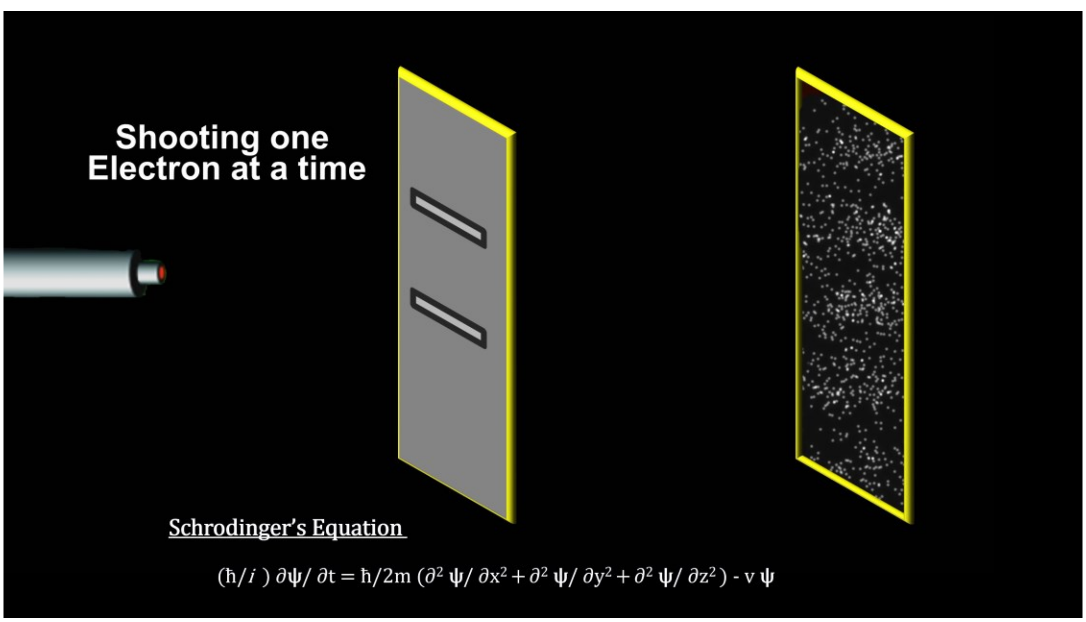


Matter Fields

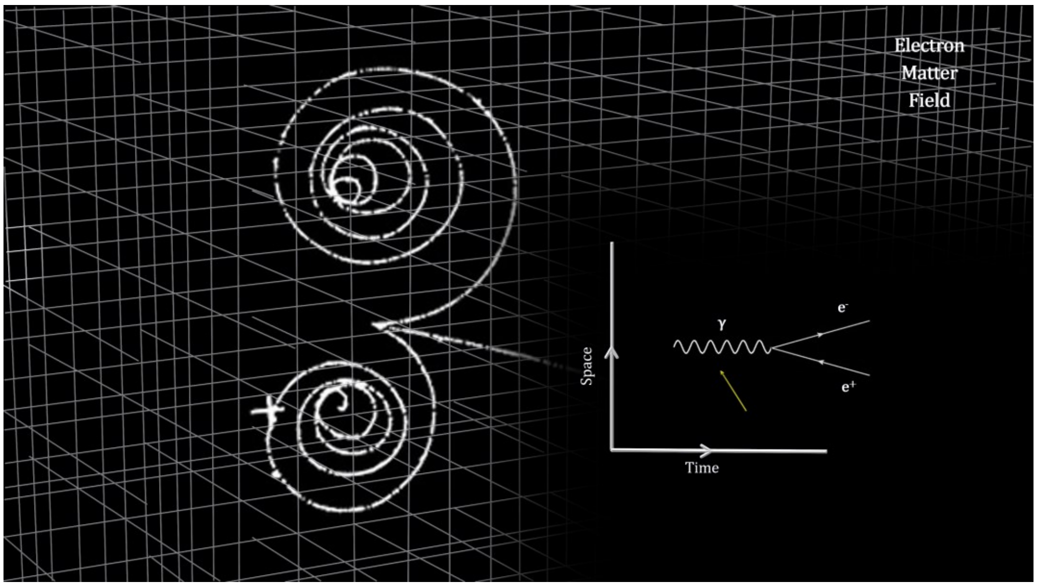
Now we take a leap. If a photon is actually a localized vibrating ripple in the quantized EM field, why not consider the electron to be a localized vibrating ripple in a quantized matter field – a field that permeates all the space in the universe.



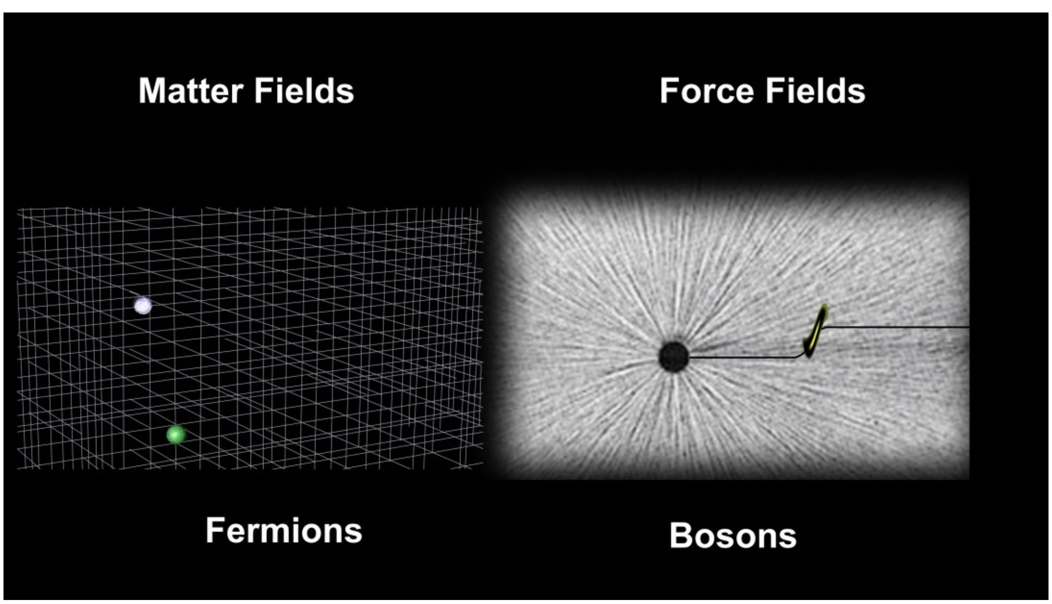
This is not as odd as it might look. In our first segment on the microscopic, we saw the wave properties of the electron. And in our second segment on the atom, we saw that its behavior is described by the Schrodinger Wave Equation.



And in our third segment on elementary particles, we saw how electrons and positrons can materialize at any point in space. What's happening is that the photon has disturbed the electron field to the point that it generates the kinds of waves that constitute electrons. A convenient way to illustrate elementary particle interactions is to use Feynman Diagrams invented by Richard Feynman in 1948. Straight lines are for fermions, squiggly lines are for force particle bosons, and the back arrow on a fermion indicate an anti-particle.

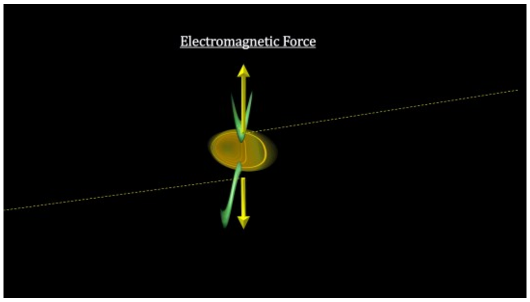


This is what Quantum Field Theory is all about. These fields generate particles. You can't have a particle without a field. And every filed will have its particle. Elementary bosons (force particles) require force fields. Elementary Fermions (matter particles) require matter fields. In modern physics, there is no such thing as empty space. Fields pervade space; they are a condition or property of space; you can't have space without fields.

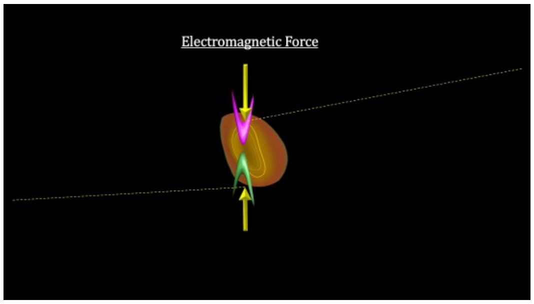


Quantum Electrodynamics QED

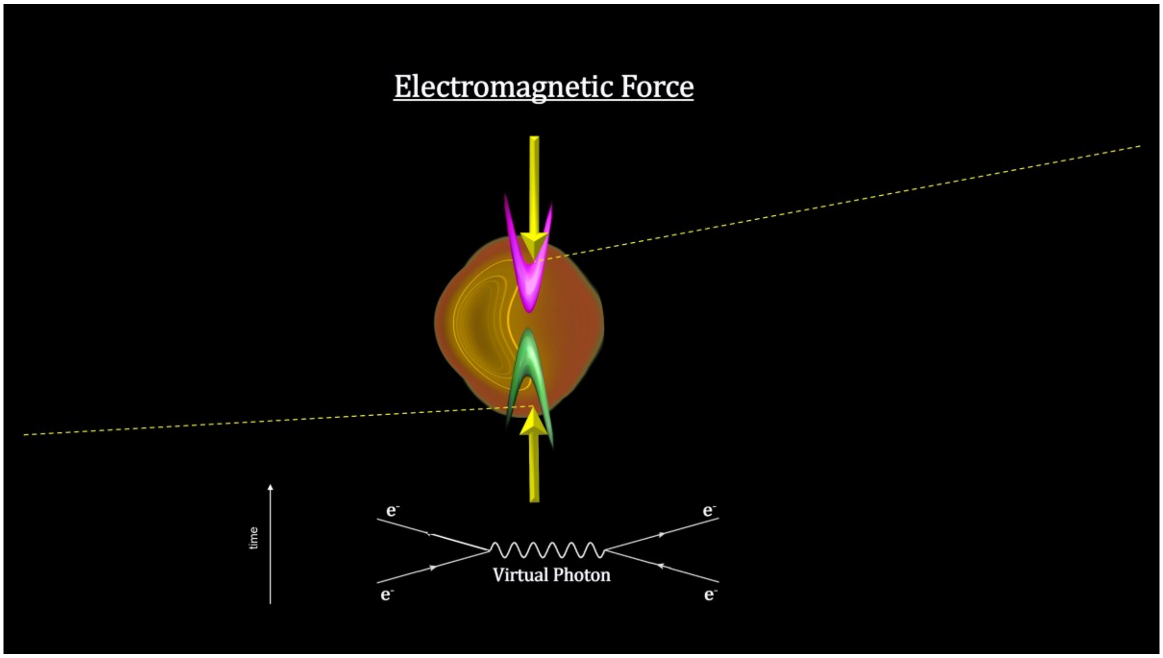
Here's a couple of examples of how this electromagnetic force works. When two electrons approach each other, their charge generates a disturbance in the electromagnetic field; this disturbance pushes them apart, and their paths are bent outward.



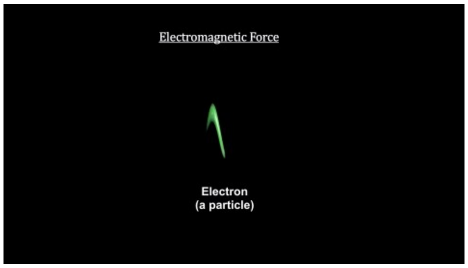
The same is true if an electron and a positron pass near each other. The disturbance in this case is similar in type but different in its details, with the result that the oppositely charged electron and positron are attracted to each other. Their paths are bent inward.



Here's the Feynman Diagram of an electron-electron interaction where the photon field 'mediates' the force that changes the momentum of the two electrons.

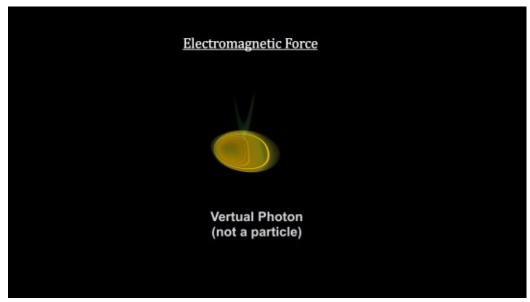


One says they "exchange virtual photons", but this is just jargon. The diagram is used for convenience. A virtual particle is not a particle at all.

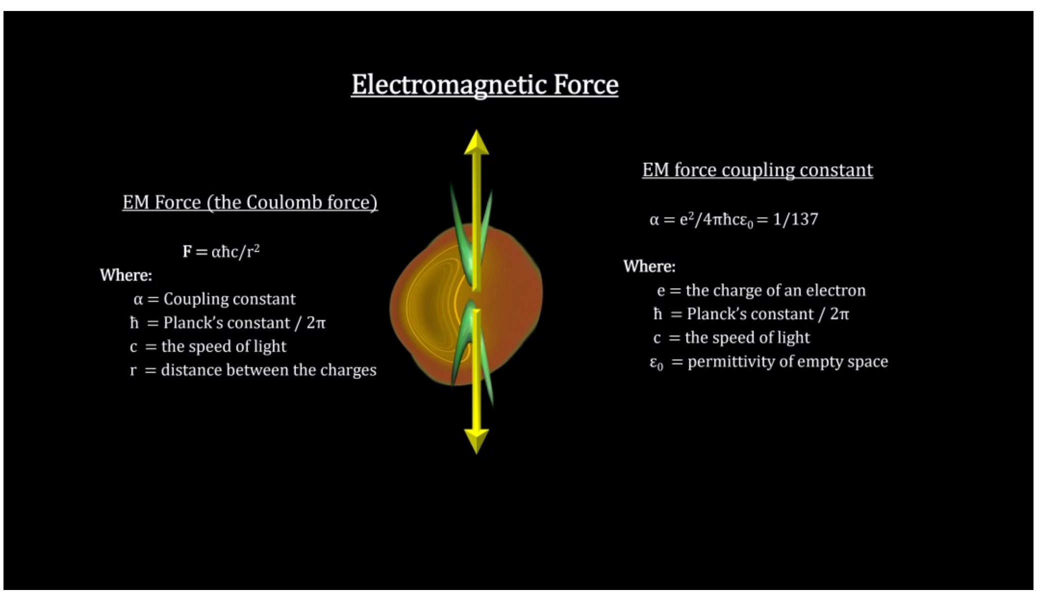


A particle is a nice, regular ripple in a field, one that can travel smoothly and effortlessly through space.

This disturbance is not a photon. It doesn't have the energy to become a well-formed ripple moving through space. This "virtual particle" is a disturbance in a field that will never be found on its own, but instead is something that is caused by the presence of other particles, often of other fields. This kind of disturbance will decay, or break apart, once its cause is gone.



This kind of interaction between the electromagnetic field and the electron field is important because the force that the two charged particles exert on each other (the coulomb force) is generated by this interaction. This force is the first of four fundamental forces in nature. They are characterized by a 'coupling constant'. The coupling constant for the electromagnetic force is 1/137. We will use the electromagnetic force as a model for the strong and weak nuclear forces. The complete picture of what is going on is still an area of active research called Quantum Electrodynamics or QED for short.

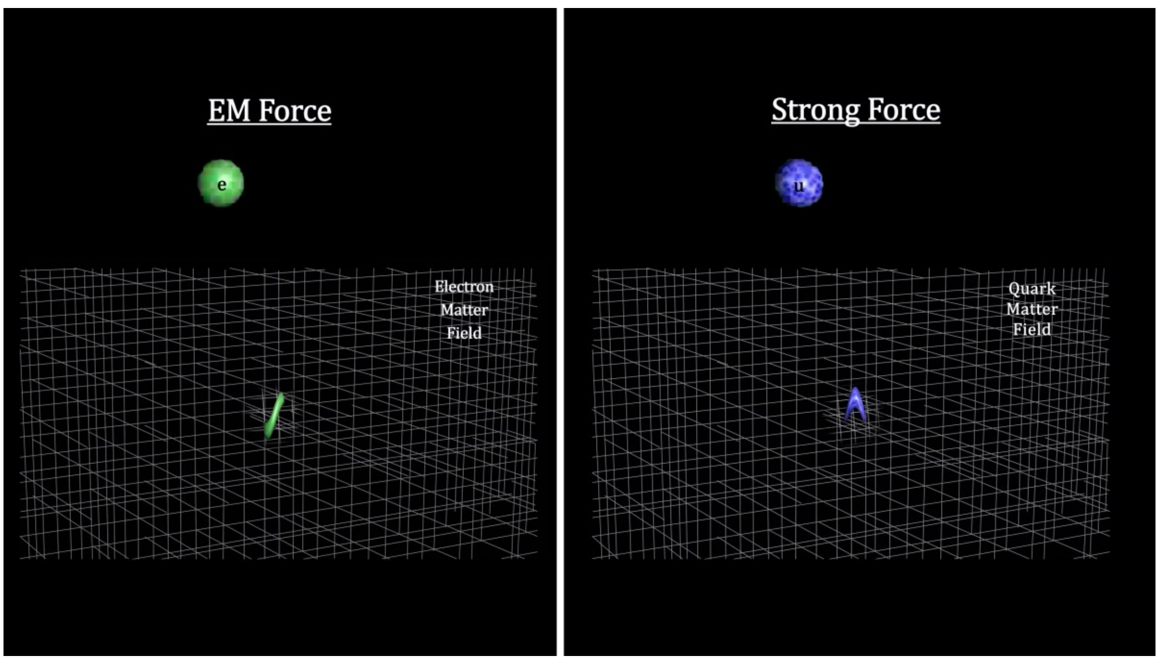


[Steven Weinberg, a theoretical physicist, summed up what we learned from QED very nicely:

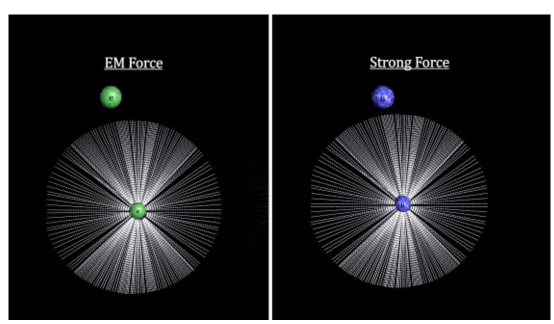
> "Just as there is an electromagnetic field, whose energy and momentum come in tiny bundles called photons, so there is also an electron field, whose energy and momentum and electric charge are found in the bundles we call electrons, and likewise for every species of elementary particle. The basic ingredients of nature are fields; particles are derivative phenomena."]

The Strong Nuclear Force – Quarks [**Music**: Rachmaninoff - Symphony No. 2 Adagio]

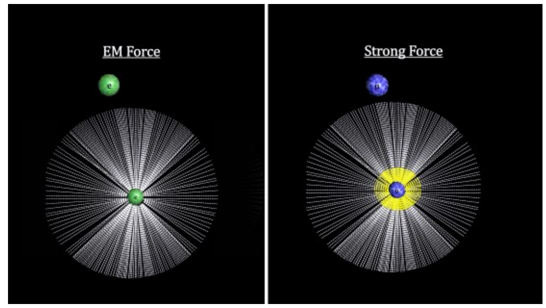
In Quantum Electro Dynamics, electrons are the central matter particle for the electromagnetic force. Using this as the model, and data from thousands of high energy scattering and collision experiments over the past twenty-five years, we have come to understand that quarks are the central matter particle for the strong nuclear force. -We have seen that an electron is a vibrating ripple in the electron matter field. Similarly, a quark is a vibrating ripple in the quark matter field.



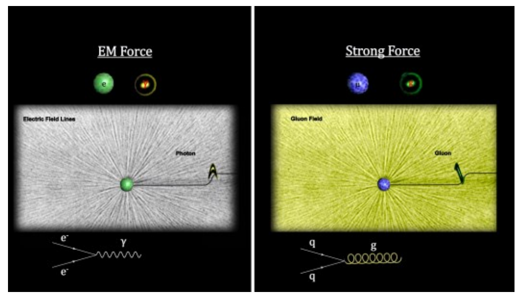
Electrons carry the electric charge that generates an electromagnetic force field. Quarks also carry electric charge so they too generate an electromagnetic force field, although, with only 1/3 or 2/3s of a charge, their electromagnetic force field is weaker than the electron's.

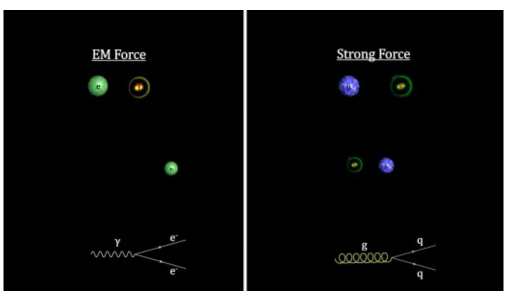


It turns out that they also carry a different kind of charge we call 'color charge'. This charge generates a gluon force field. This is a significant difference and we'll cover it in more detail shortly.



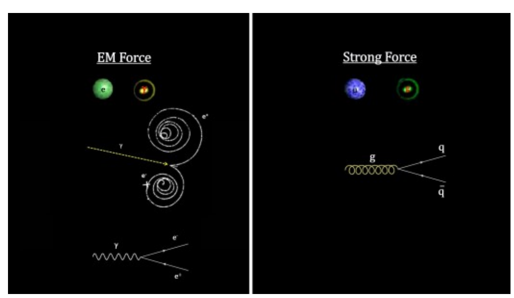
We have seen that an accelerating electron creates a vibrating ripple in its electromagnetic field called a photon. Similarly, an accelerating quark creates a vibrating ripple in its gluon field called a gluon. And like photons, gluons are massless spin 1 particles making them bosons.



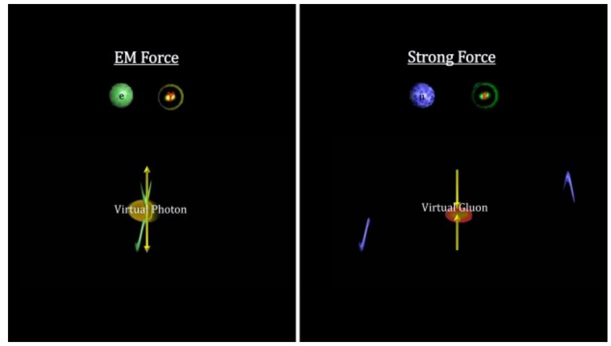


And where photons can accelerate electrons, gluons can accelerate quarks.

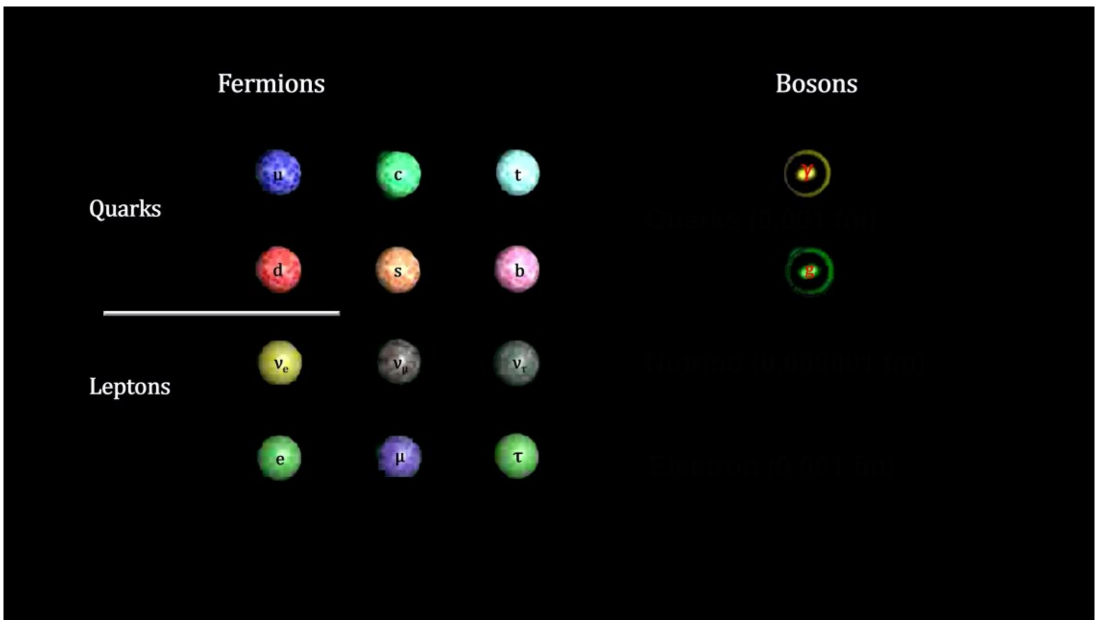
And where an energetic photon can create electron anti-electron (positron) pairs, an energetic gluon can create a quark antiquark pair.



And where interacting electrons disturb the electric field in a way that creates virtual photons that exert the force of the Electromagnetic field – the EM force, interacting quarks disturb the gluon field in a way that creates virtual gluons that exert the force of the gluon field – the strong nuclear force. Note that the EM force can be attractive or repulsive depending on the charge. But the strong force is always attractive.

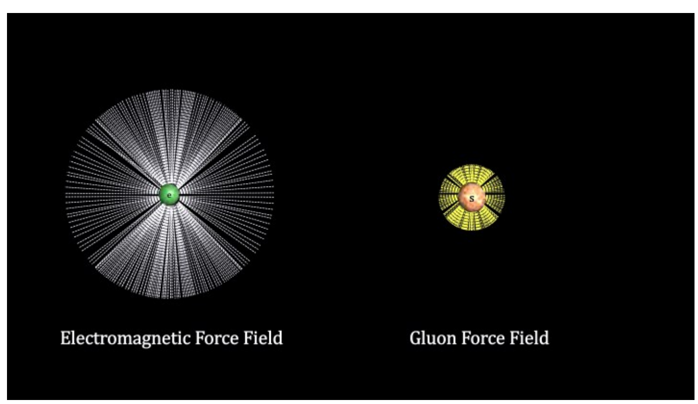


So, we can now add gluons to our standard model of particle physics.

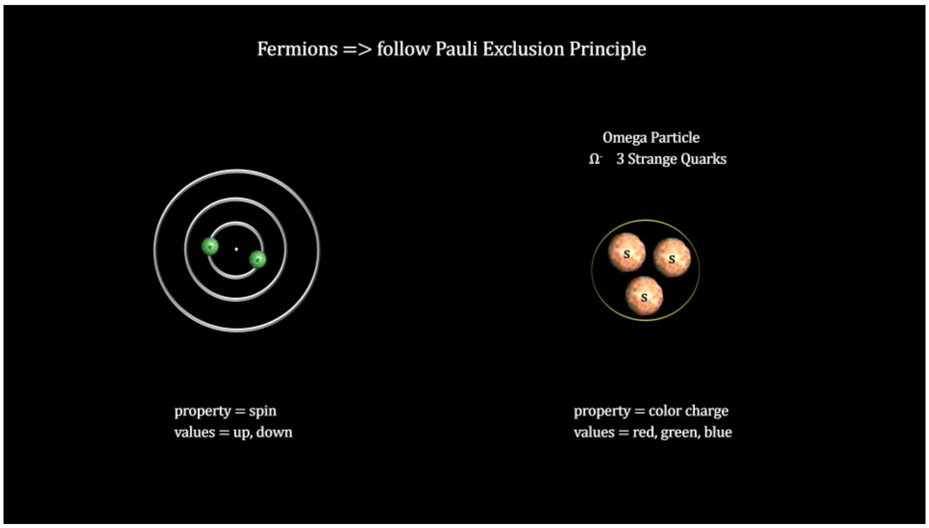


Color Charge

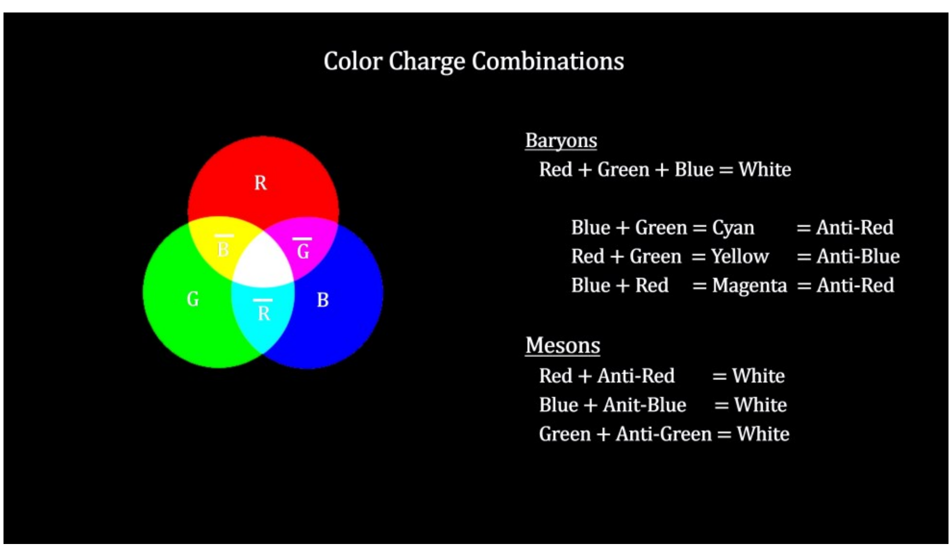
One of the key differences between the EM force and the Strong force is that the EM force involves an electromagnetic force field, whereas the Strong force involves a gluon force field.



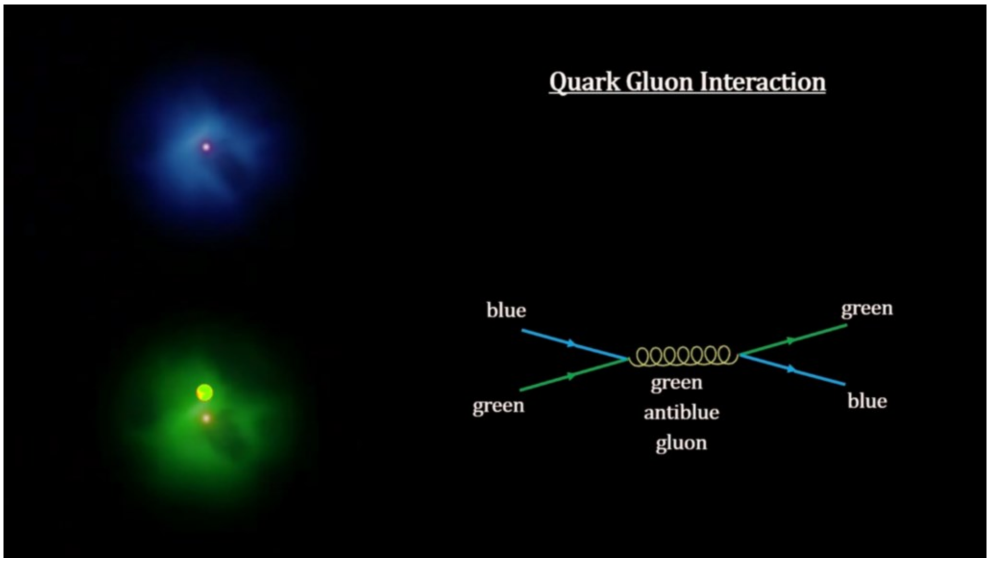
You'll recall from our previous chapter on elementary particles, that quark theory predicted the existence of the Omega particle - which was eventually discovered. One of the particle configurations turn out to have 3 strange quarks. Like 2 electrons in the ground state orbital for atoms, this presented a problem. These are fermions and follow the Pauli Exclusion principle. So, an extra quantum number was needed to explain the combinations. For electrons, it was spin with two values – up or down. For quarks it was color charge with 3 values – red, blue or green.



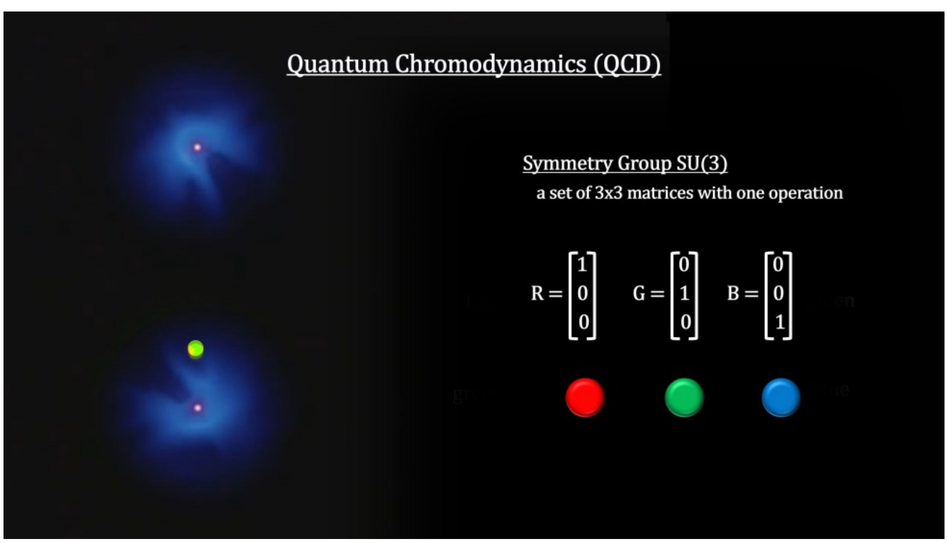
The fact that no such charge has ever been seen in the mesons and hadrons made from quarks indicates that the three charge colors neutralize each other in these configurations. This led to the idea to use red green and blue because they neutralize each other when combined. Our rule for allowed quark combinations was that they had to add up to a whole unit of electric charge. We can now add the rule that they also have to add up to no color charge at all.



Another even more dramatic difference is that gluons carry color charge as well as quarks, whereas photons do not carry the electric charge. Where quarks carry a red, green, or blue charge, gluons carry two charges one is a color and the other is an anti-color. Here's an example of how this works. We have two quarks. One with a green charge and another with a blue charge. When the green quark disturbs the gluon field, it creates a gluon. This gluon carries away a green charge and an anti-blue charge. This turns the green quark blue. When the gluon encounters a blue quark, it is absorbed and the gluon's anti-blue and green charge turns the quark green.

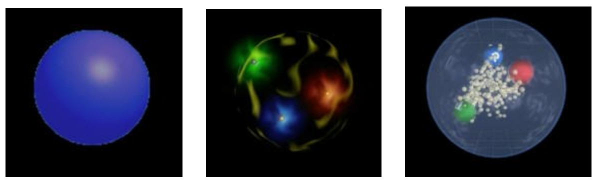


The actual functioning of the quark-gluon relationship follows the mathematical model called SU(3). The math was invented in the late1800s and was the foundation for today's abstract algebra. A hundred years later, it turned out to be very useful for particle physics. But using color is quite helpful. In fact, the study of quarks, gluons, and their color charges is called Quantum Chromodynamics or QCD for short. It is a very active area of research and changes in our understanding are expected as we learn more.



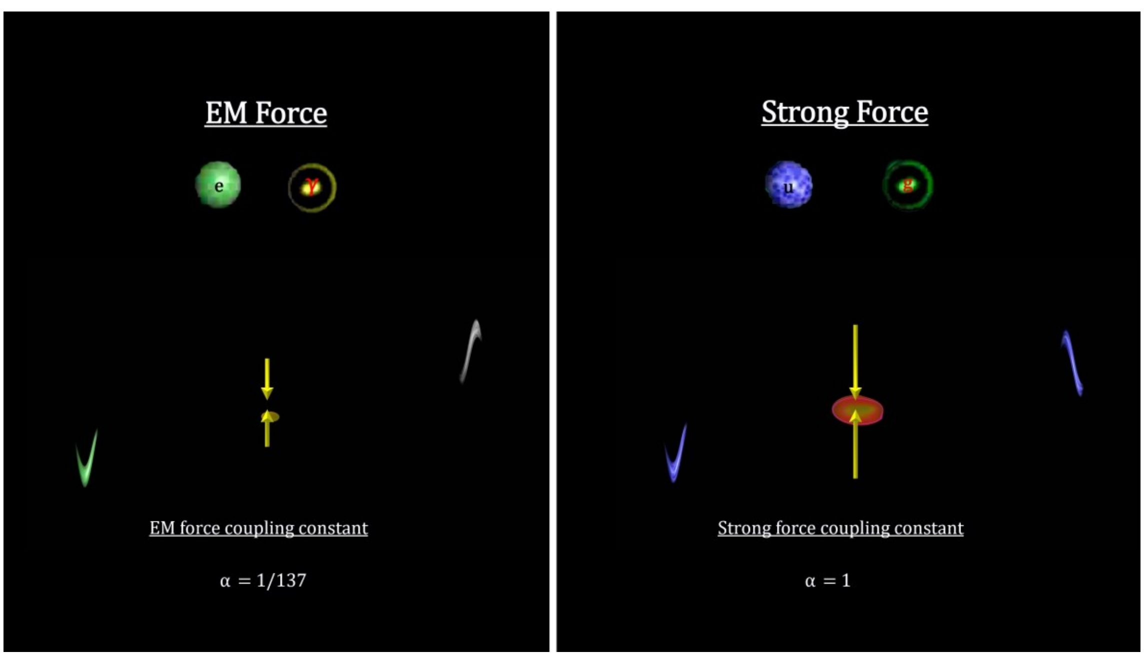
[It turns out that the nucleons (protons and neutrons) contain a sea of gluons, virtual gluons, photons, quarks, and quark-antiquark pairs being created and annihilated in the space of millionths of a second with standing waves and particles moving around near the speed of light in a ball of energy squeezed into the tinny volume of a proton.]

Our very idea of what a proton looks like has now shifted from a point particle to a three-part particle to a whirlwind of elementary particle activity. In fact, it is very difficult to distinguish between the disturbances that represent virtual particles and disturbances that represent actual particles in a plasma like this. But for our purposes, we can view a proton as a cloud of gluons holding three quarks together.

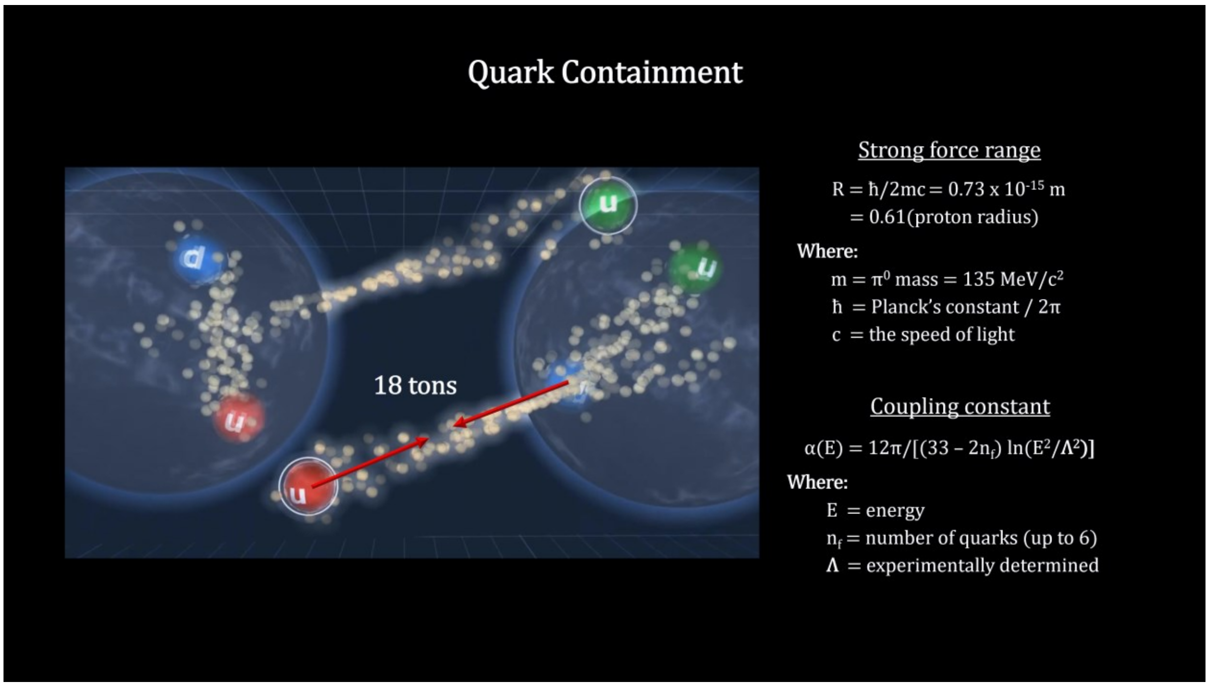


Quark Containment

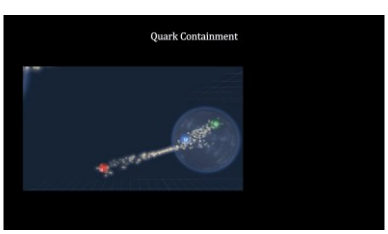
Another significant difference between the EM force and the Strong force is that the coupling constant for the strong force is 137 times stronger. And most importantly, were the EM force decreases with distance, the strong force increases with distance.

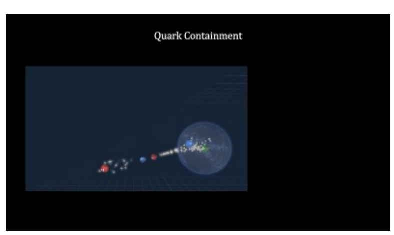


As the distance between quarks grows to the diameter of a proton, the strength of the force approaches 18 tons! Imagine 18 tons focused on such a tiny spot. This makes it virtually impossible to separate quarks.

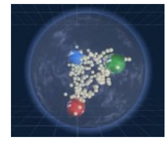


In fact, with a force that strong, the energy it takes to separate two quarks in a hadron is greater than the energy it takes to create two new quarks! So, before we reach separation energies, new quarks are created instead. These new quarks immediately combine to create new hadrons. This is called Quark Confinement or Color confinement and it explains why we can never see a quark or a gluon or a color charge on its own.

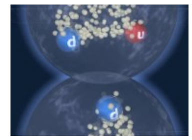




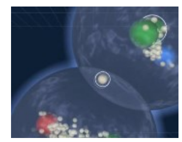
[Let's take a look at a proton-proton collision to see how this happens. Here we see a proton with its three quarks and a bevy of gluons interacting with the quarks and holding them together.



When the colliding protons get very close, they overlap.

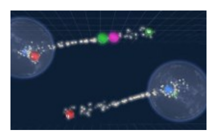


An energetic gluon finds its way to a quark in the other proton.



Now, as the protons separate, the two quarks that exchanged the high energy gluon are pulled out of their respective protons.

The gluon train is also called a gluon flux tube. As the energy of the tube reaches the amount needed to create quarks, the gluon field breaks and a quark-antiquark pair is created instead of the quarks getting further apart.



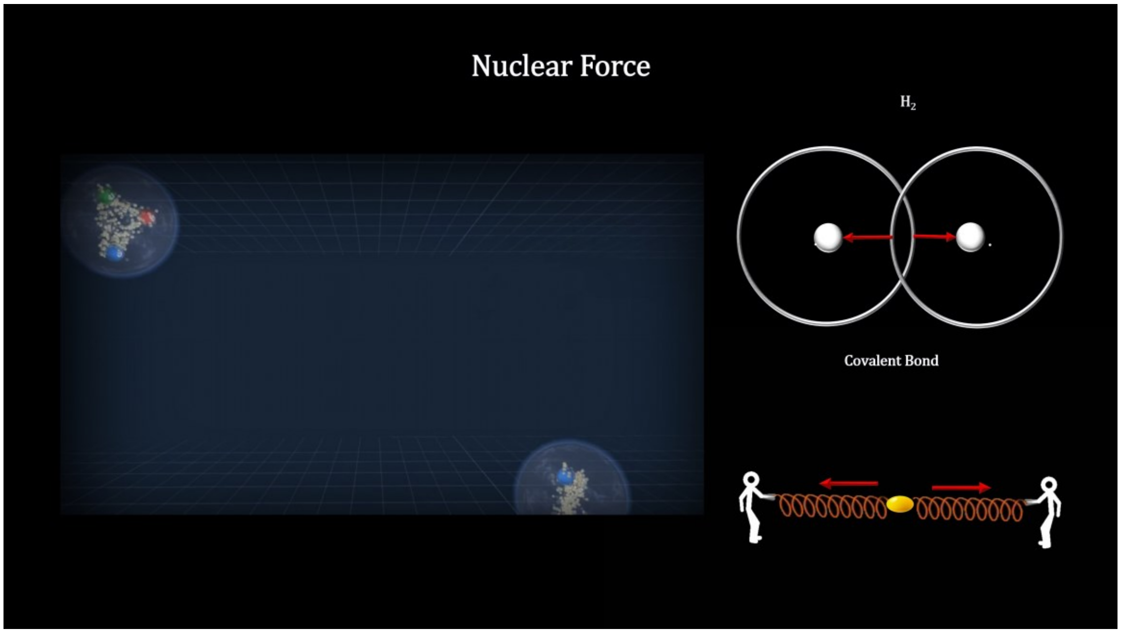
This stretching-breaking-pair production process continues until the gluon field energy is used up and separation stops. Meanwhile, the created quark-antiquark pairs are combining to form their own hadrons.

The end result is four or more jets of hadrons flying out with the remains of the colliding protons which may or may not recapture a quark. No quark is released to travel on its own and be detected.]

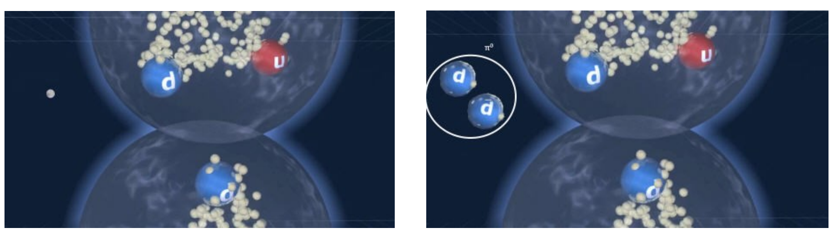
Residual Strong Force (aka Nuclear Force)

One last item on the strong force answers the question I raised at the end of our segment on the atom: 'what holds the protons together in the nucleus?'

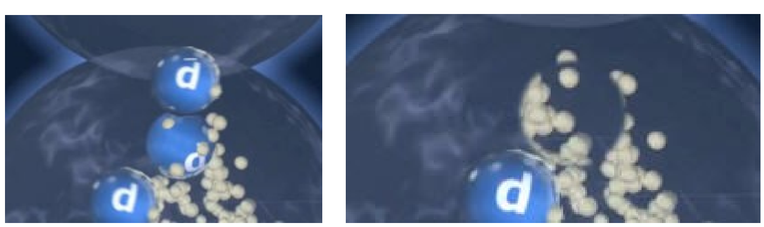
In 1934, a Japanese physicist Hideki Yukawa made the earliest attempt to explain the nature of the nuclear force. According to his theory, a particle was being shared between nucleons like molecules share electrons between atoms to bind them together. He even calculated the mass of this particle we now know as a pion. The shared particle is attracted to both protons. The situation is similar to two people pulling on a ball. Each person exerts a force on the ball, and the effect is as if each exerted a force on the other.



Here's a two-proton example of how we think it works. First, in one of the protons, an energetic gluon spontaneously creates a down quark – antidown quark pair. This is a neutral pion. [You'll remember the discovery of the pion in 1947 that we covered in the Elementary Particles segment.]

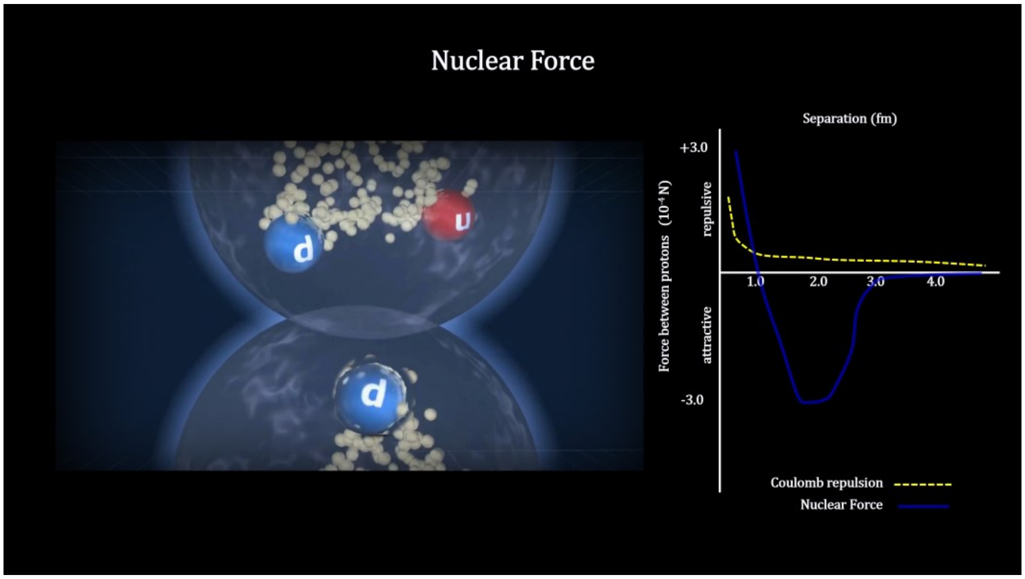


Next, the pion drifts into the other proton, and the antidown quark annihilates a down quark, leaving the other down quark to take its place.



The diameter of the proton is 1.662 fm. At a separation of less than a half a fm the nuclear force is repulsive. This prevents nucleon collapse. It then becomes attractive over a short range, peaking at

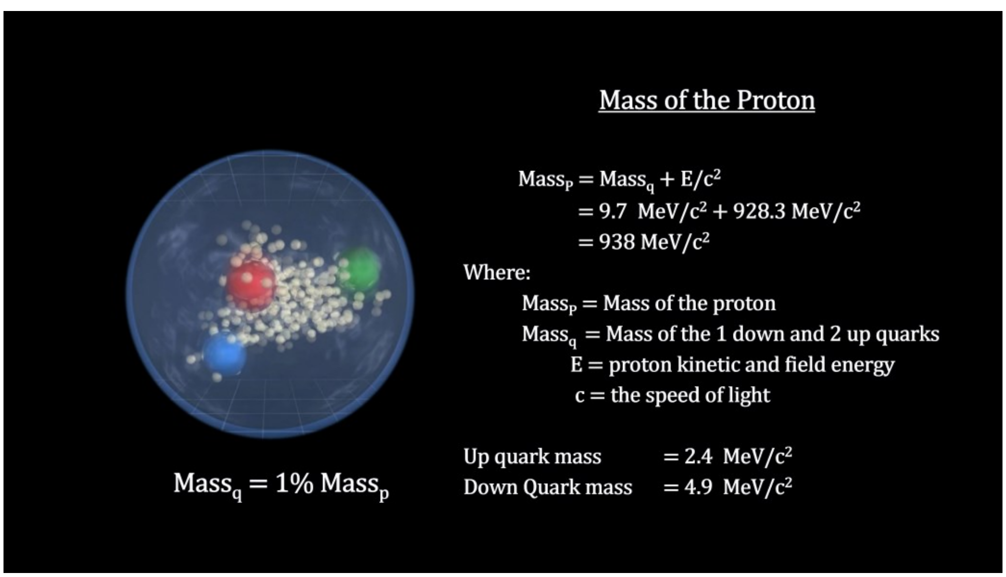
1.3 fm with a force much stronger than the electromagnetic repulsion. And it becomes negligible by around 3 fm separation where the electromagnetic repulsion takes over.



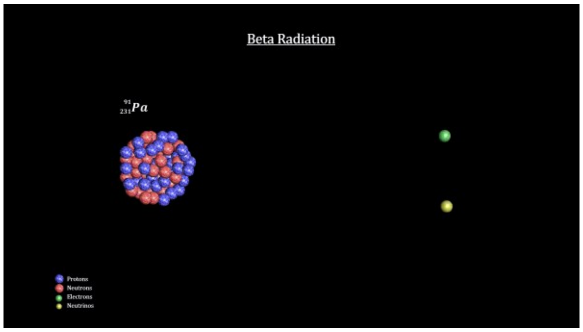
[This range for the nuclear force, given the mass of the pion, is around the diameter of an iron nucleus. This is the dividing line between the energy needed for fusion (joining nucleons) and the energy achieved through fission (the separation of nucleons).]

Proton Mass

The proton is a key to helping us understand "the origin of mass". The only stable elementary particles in the proton with mass are the two up quarks and one down quark. Their tiny masses constitute only 1% of the mass of the proton. 99% comes from the energy of the fields and motion the moving parts following the famous $E = mc^2$ formula. So, it is quite accurate to say that "confined Energy is the origin of mass." We'll bring this point home when we get to the Higgs boson.

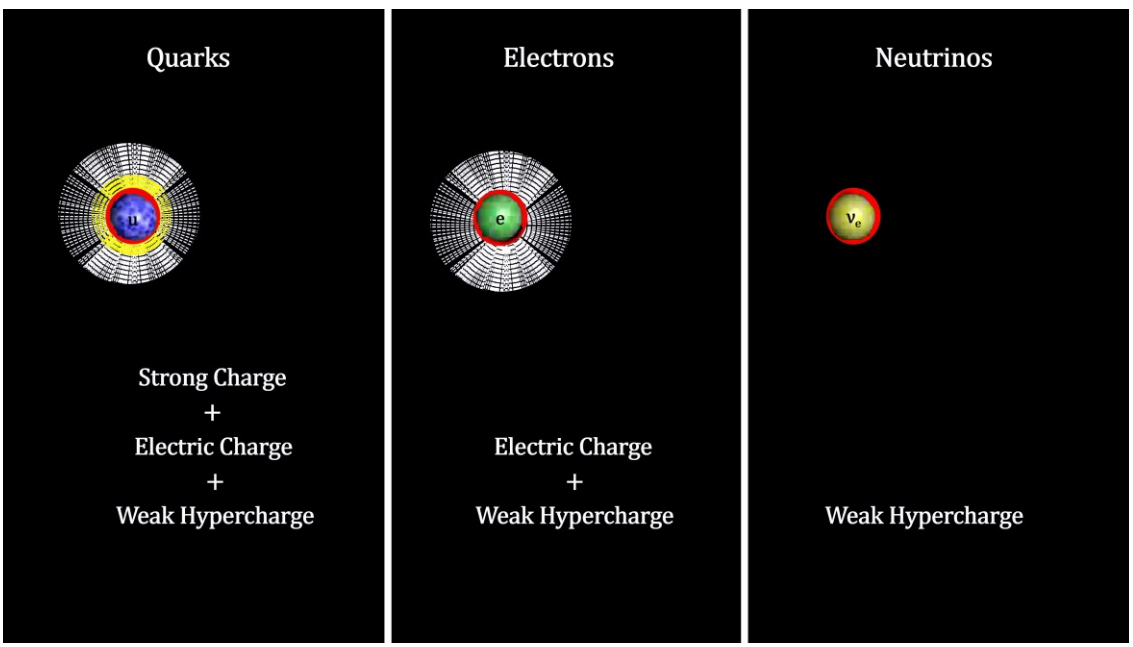


Weak Nuclear Force



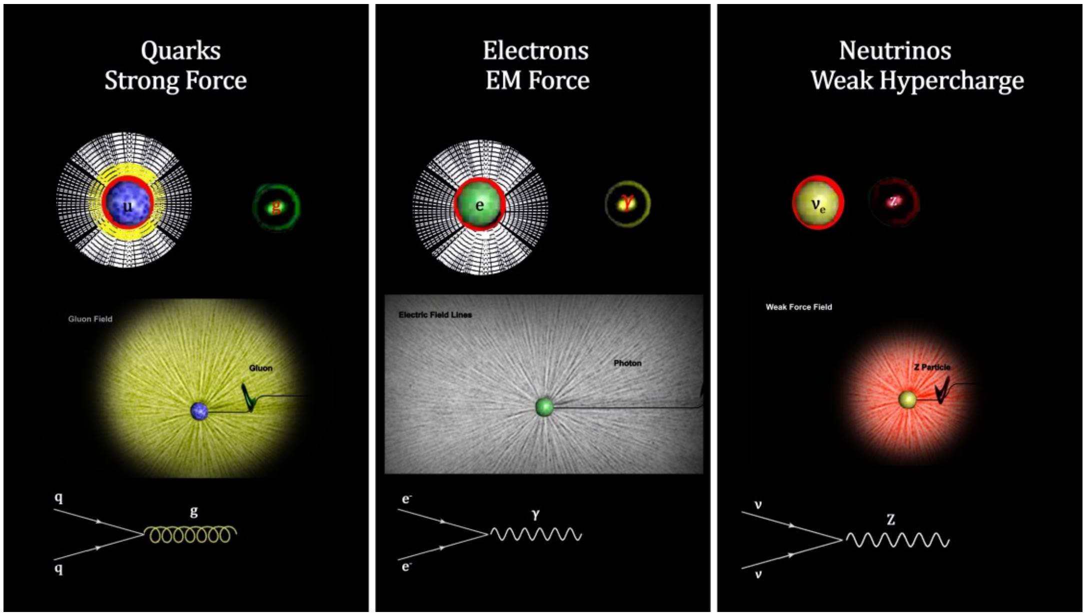
The Weak nuclear force or weak interaction is responsible for radioactivity (for example Beta radiation ejecting electrons and neutrinos). It's the force that turns a neutron into a proton.

Unlike QED and QCD, there is no separate matter field that creates a particle with a Weak Force Charge – sometimes called weak isospin or weak hypercharge. Instead, all fermions already have this charge including electrons, quarks, and neutrinos.

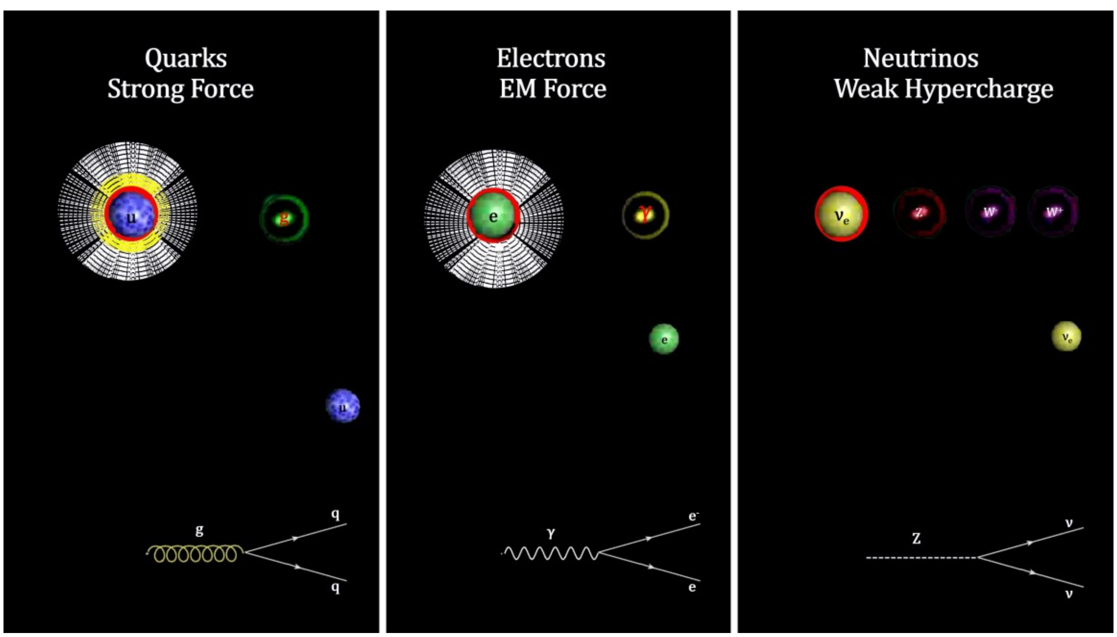


[For this reason, it is most often included in theories that combine it with the electromagnetic force into a theory called the electroweak interaction developed by Steven Weinberg along with Abdus Salam and Sheldon Glashow.]

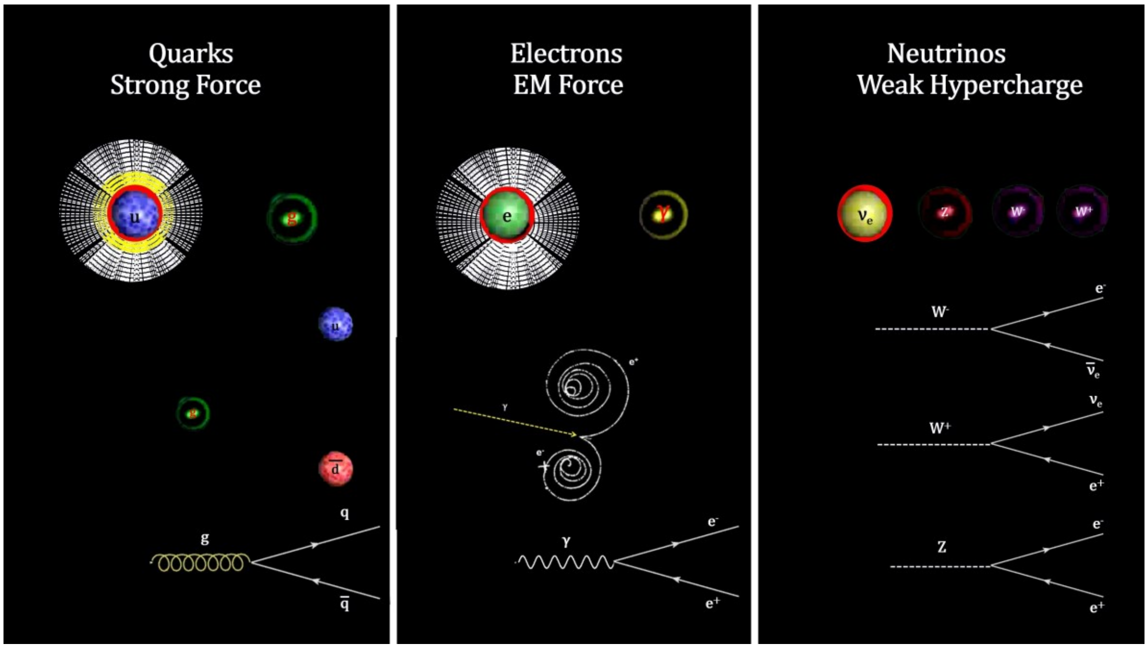
Like accelerating electrons and quarks create vibrating ripples in their respective force fields called photon and gluons, accelerating electrons, quarks, and neutrinos can create vibrating ripples in the weak hypercharge field called Z particles.



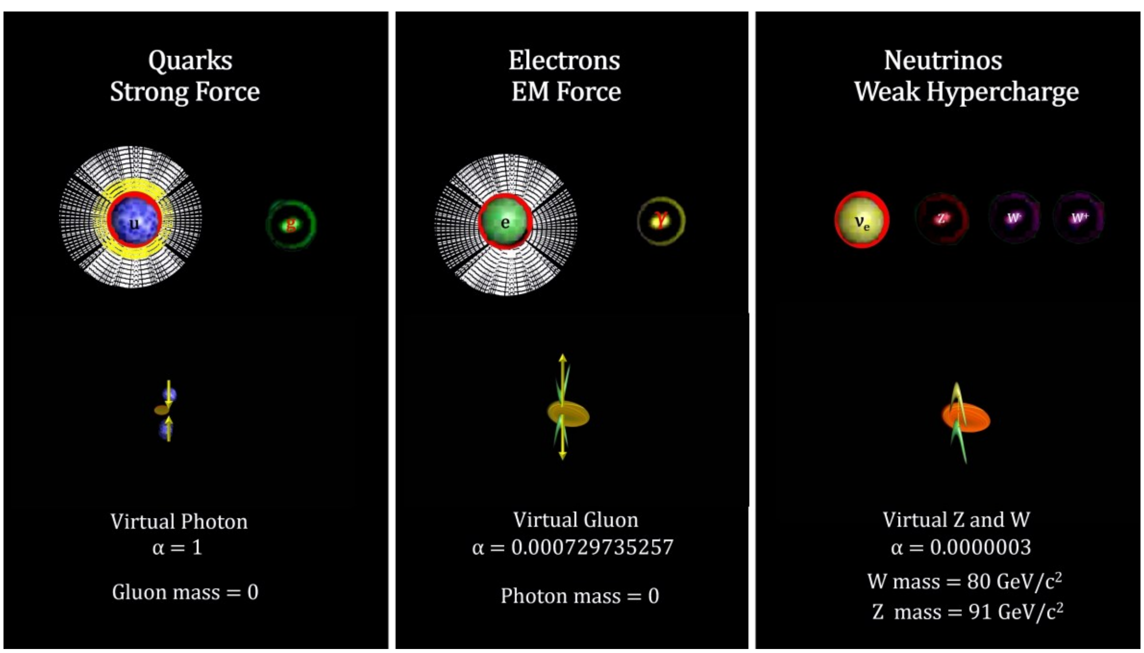
And where photons can accelerate electrons, and gluons can accelerate quarks, Z particles can accelerate neutrinos and electrons and quarks, because they all carry the weak charge. But for the weak hypercharge, there are 2 additional particles called W^- and W^+. Like the gluon caries color charge, W^- caries a negative electric charge equal to the charge of an electron, and W^+ carries a positive electric charge equal to the charge of a positron. The Z particle has no charge at all. They are all spin 1 particles, making them bosons. They are the force particles for the weak interaction.



Like photons and gluons can create matter anti-matter particle pairs, the W and Z bosons can create matter anti-matter particle pairs.

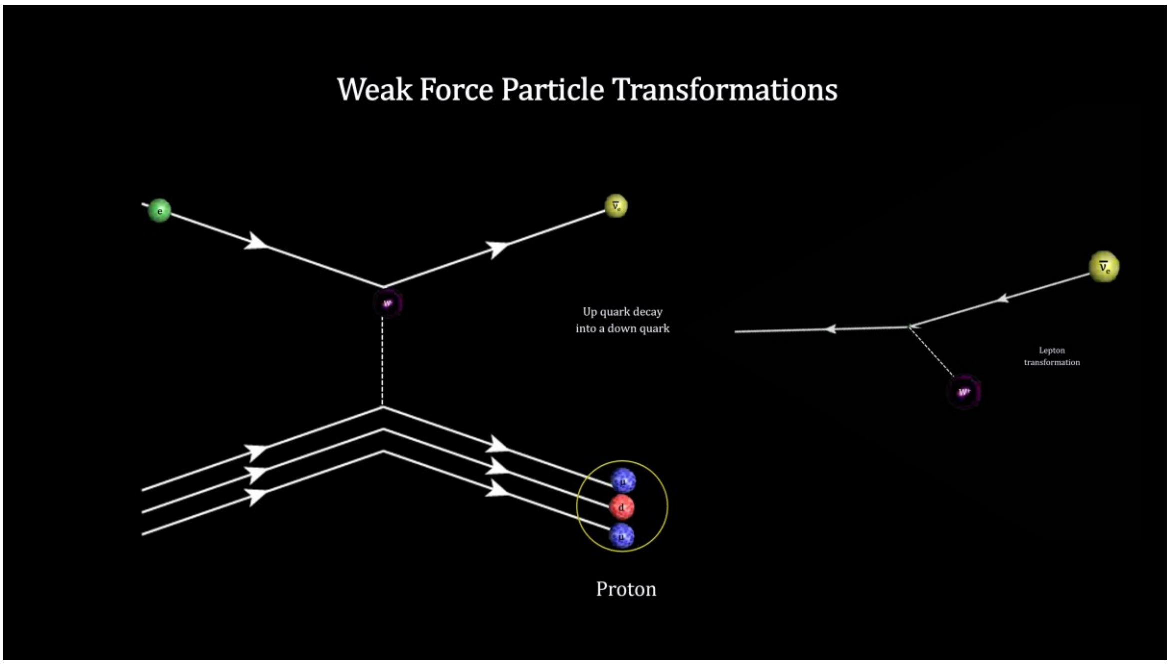


And like interacting electrons and quarks disturb their respective force fields creating virtual photons and gluons that exert the force of the field, interacting particles carrying the weak hypercharge disturb the weak hypercharge field creating virtual W and Z bosons that exert the force of the field. The force can be attractive or repulsive depending on a variety of circumstances.

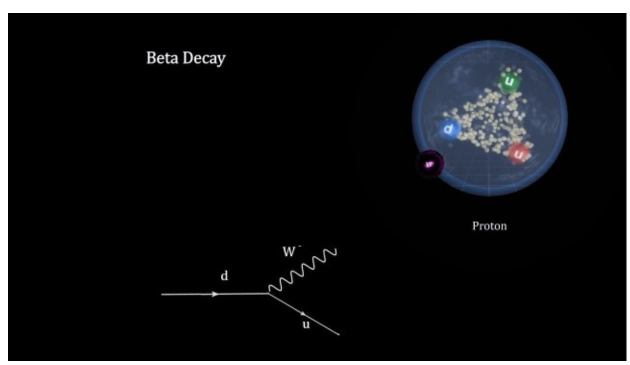


We call it the weak force because its coupling constant is 3.3 million times smaller than the strong force coupling constant. And, unlike massless photons and gluons, these particles are massive – around 53 times more massive than an up quark, and 160 thousand times more massive than an electron. This makes its range incredibly short – around 0.1% of the diameter of a proton.

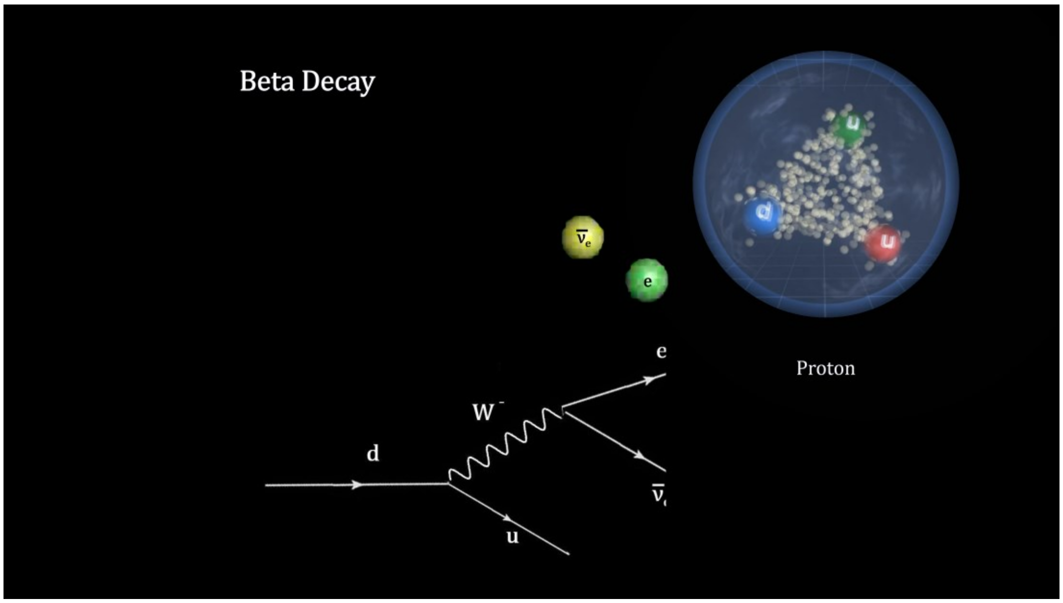
All the force particles actually exert a force on their respective matter particles. But the weak force has a unique additional capability: it can change one flavor of quark into another, or one type of lepton into another. The idea that a force field particle can cause a matter field particle to decay, i.e., transform into another particle was a new one.



We'll use beta decay from our Radium to Polonium energy experiment to help illustrate how this works. The process consists of two phases. The first phase is similar to the way an electron emits a photon when it drops to a lower energy state in an atom. Here a down quark drops to the lower energy up quark and emits a W boson that carries away the energy and a full unit of electric charge. The remaining quark's charge has gone from -1/3s to +2/3 making it an up quark.



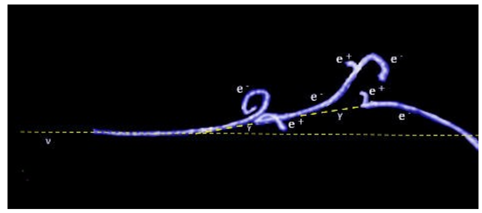
However, the mass of the weak field quantum is so large that there is not enough energy in a down quark quantum leap to an up quark to create a fully independent W boson. Instead, what is created is a virtual W Boson. However, in the second phase, because there **is** enough energy in the virtual boson to create an electron and a neutrino, it decays into these particles. This is possible because both the electron and neutrino carry the weak hypercharge. This is how our Radium turned into Polonium in our segment on the atom.



Because of the significant amount of energy needed to produce these massive Z and W weak force bosons, it wasn't until 1972 that the first evidence for Erico Firme's Weak Interaction theory was found. This event shows a neutrino–electron interaction that would require a Z boson. It was recorded by the Gargamelle bubble chamber at CERN. Final proof came for Z and W bosons when the proton anti-proton collider was built at CERN in 1983.

[The neutrino, which leaves no track because it has no electric charge, entered the bubble chamber from the left of this image and hit an electron. Unlike all other neutrino events seen before, this collision did not transform the incoming neutrino into another type of particle. Instead, the neutrino remained a neutrino and continued on its way.

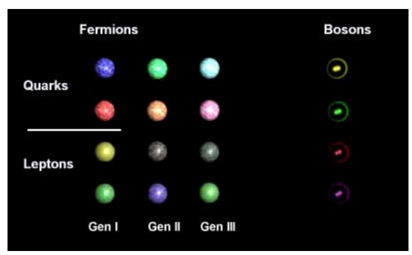
The impacted electron on the other hand was propelled forward at a high speed. Moving through the liquid, the electron slowed down and emitted a powerful photon. This photon, in turn, created an electron-positron pair visible in the photo, making the initial electron identifiable. This was followed by additional particle pair creations.



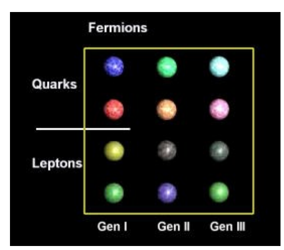
The interaction between the neutrino and the electron did not involve the charged W boson, so it must have been done by a weak force boson without a charge. This boson was named the Z boson. These results firmly established the mathematical framework that predicted the weak neutral current and this Z boson. The framework became known as the Standard Model of particle physics.]

Standard Model of Particle Physics Summary [**Music**: Ravel – Boléro]

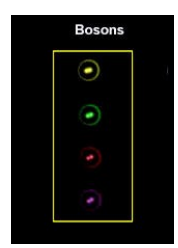
Here's the Standard Model with all the stable fermions. If we add the excited state versions of these fermions, we get the full view.



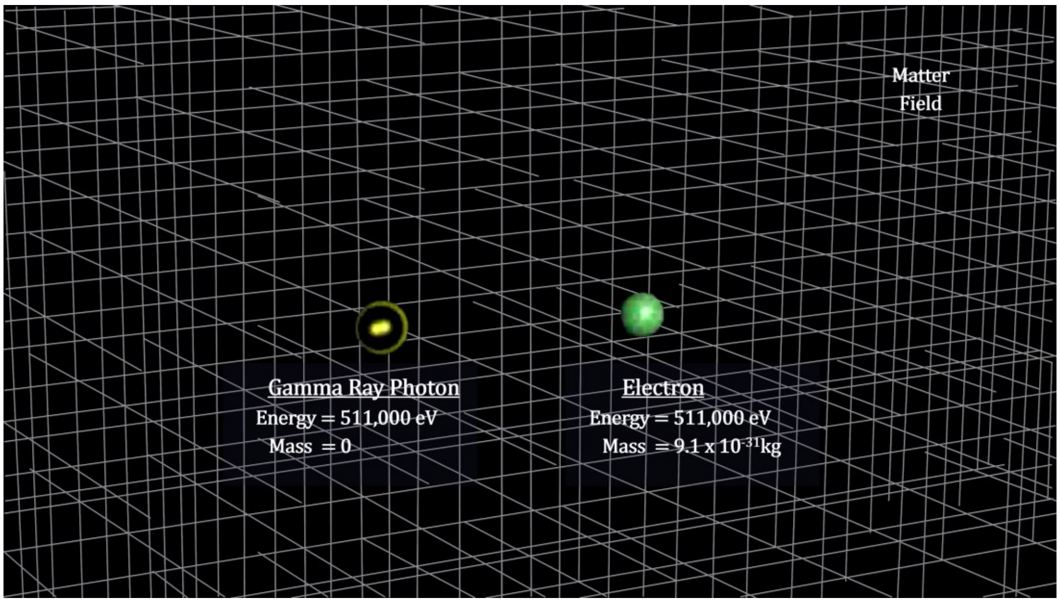
In summary, all of space is filled with matter fields that can spawn fermion particles as waves in the elements of their respective fields. This includes all the Leptons and the Quarks.



These particles carry one or more charges: Color charge, Electromagnetic charge, and weak hypercharge. Particles with a charge fill the space around them with a force field that can spawn force particles when excited by particles that carry their charge. These are the bosons. The bosons are the force carriers or mediators for all fermion particle interactions.

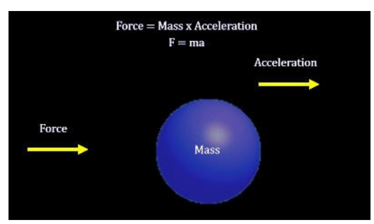


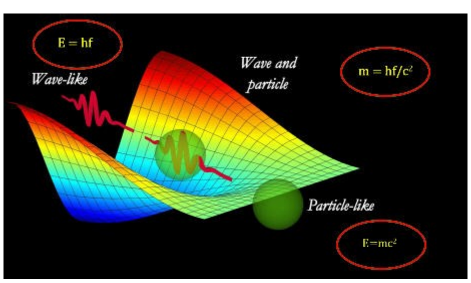
This model has had great success in explaining observed natural behavior at the quantum level. But there was one serious problem that had to do with the mass of the particles. One way to look at it is that it didn't explain how elementary particles acquire mass. Or, given that we know that confined energy generates mass, another way to look at the problem is that the standard model did not explain how photons, no matter how much energy they have confined, do **not** have mass.



The Origin of Elementary Particle Mass

In classical physics, mass is a measure of the inertia of a body. The mass of an object causes it to resist a change in its speed or direction. The greater the mass, the greater the resistance. This is codified as Force = Mass times Acceleration.





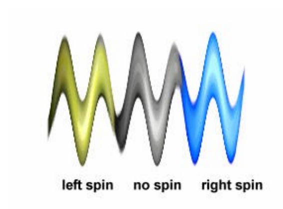
In QFT, on the other hand, the energy of a quantum is represented by oscillations in its field. Since both mass and energy are associated with oscillations in the particle field, we can simply combine Einstein's equation for mass energy and Planck's equation for wave energy to calculate the mass of a wave.

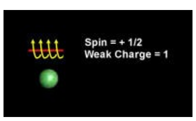
The faster a particle is oscillating, the harder it is to change its direction or speed. So, this fits our common understanding of mass.

Paul Dirac identified the oscillation of a particle between its right-handed incarnations and its left-handed incarnations as the mechanism for fermion mass.

The faster the oscillation, the more energetic the particle, the more massive it is. [With these oscillations as the key to a particle's mass, we need to take a closer look at the nature of left-handed and right-handed spins.]

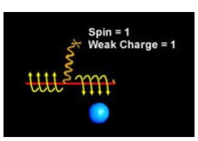
It might seem strange – a particle changing its spin on the fly. But if you recall that particles travel as waves, and spin can be viewed as a phase shift in the wave, it's not too hard to visualize.





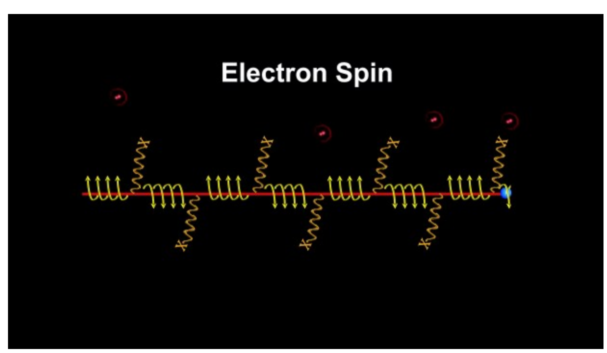
We'll use electrons for an example. A left-handed spinning electron has a spin of ½ and carries a weak hypercharge.

A right-handed spinning electron has a spin of – ½ and carries 0 weak hypercharge.



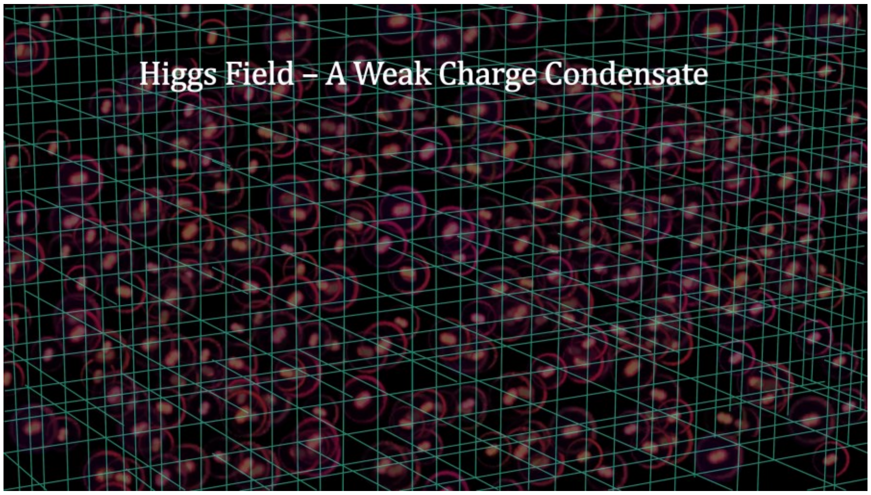
So, for an electron to switch from left to right, it must emit a quantum of weak charge and lose a full unit of spin. And for it to switch back, it must absorb a quantum of weak charge and gain a full unit of spin.

Now here we had a very large problem for particle physics. It was understood that a derivative of the Z boson was a candidate for the electron's spin and charge transition, but there was no standard model mechanism for ejecting and absorbing weak hypercharge out of the blue. Where did the charge go? And where did it come from?



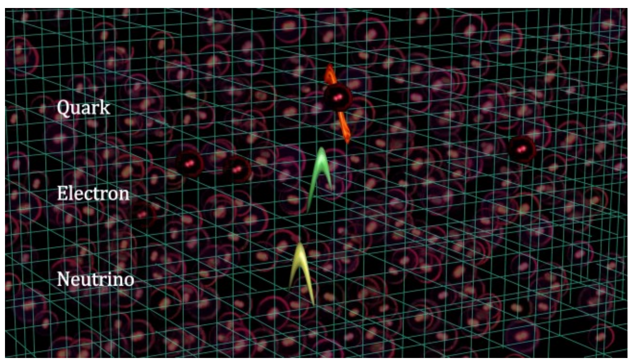
The Higgs Field

In 1964, in order to resolve this problem, François Englert, Robert Brout, Peter Higgs and others proposed a new field that permeated all of space – now called the Higgs field. They proposed that this field contained a condensate of weak charge. A condensate has the property that adding to it or subtracting from it leaves it the same.



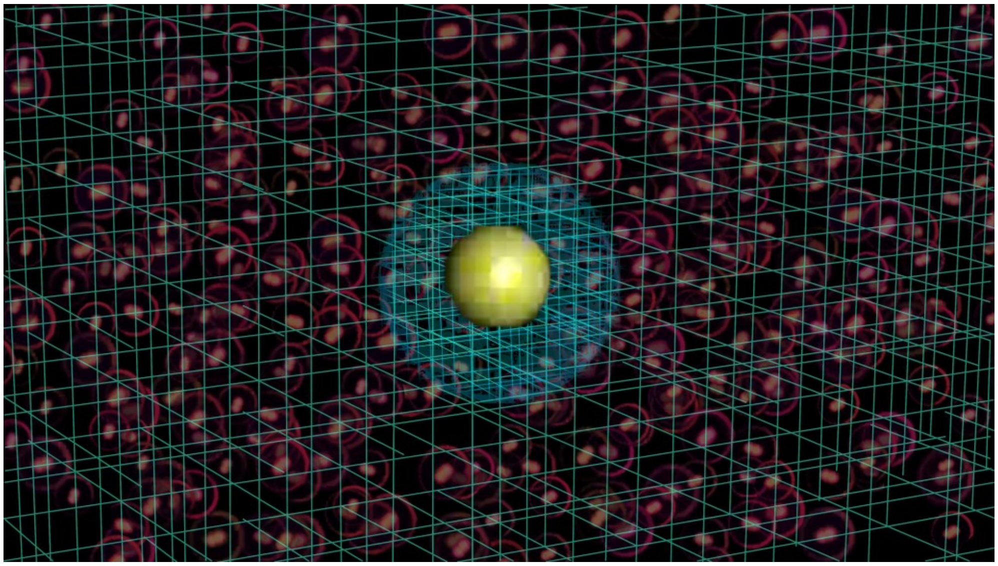
A particle carrying weak charge could use a weak charged virtual Z Boson to move the charge to this condensate without noticeably changing the field, and it could use the same Z Boson mechanism to absorb a weak charge from the condensate without noticeably changing the field. This was called the Higgs mechanism. With the Higgs mechanism, an elementary particle that carries the weak hypercharge can oscillate and therefore has mass. Electrons, Neutrinos and Quarks all carry this charge and interact with the Higgs field. So, they can oscillate and therefor they have mass.

Photons don't carry weak hypercharge and therefore, they cannot interact with the Higgs field, and therefor they cannot oscillate and therefore, no matter how much energy they have, they have no mass. The process is a little different from particle to particle, and physicists use subtler concepts of chirality, gauge symmetry and symmetry breaking, but this is the basic idea.

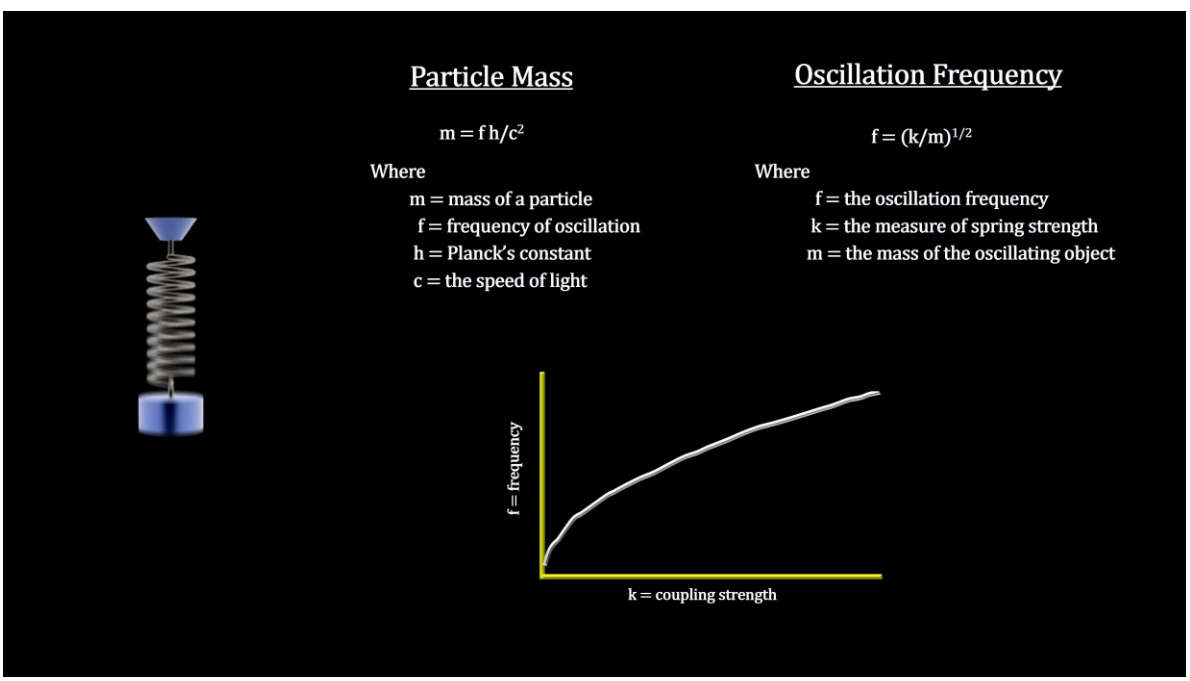


[Earlier we determined that "confined Energy is the origin of mass." So, from one point of view, we can see that the Higgs mechanism provides a Standard Model vehicle for elementary particles to acquire the mass their energy content predicts they should have. But from another point of view, we see that Higgs explains the more mysterious question about why photons, no matter how energetic they may be, do not have mass.]

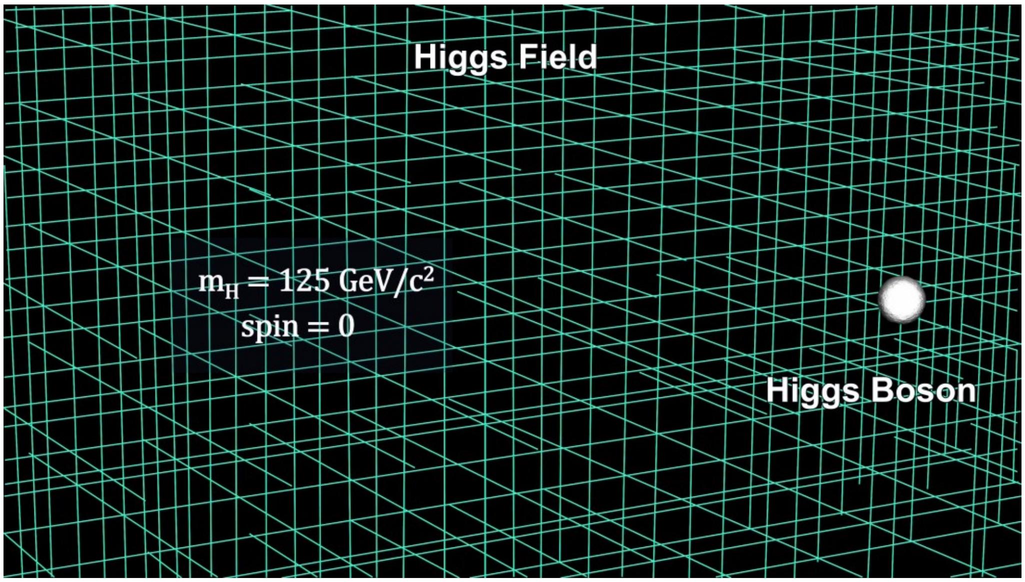
You'll note that the particles that interact with the Higgs field are not slowed down. The Higgs field is not like molasses. If the Higgs field slowed particles down in any way, objects in motion would no longer remain in motion. This is not what we see in the real world.



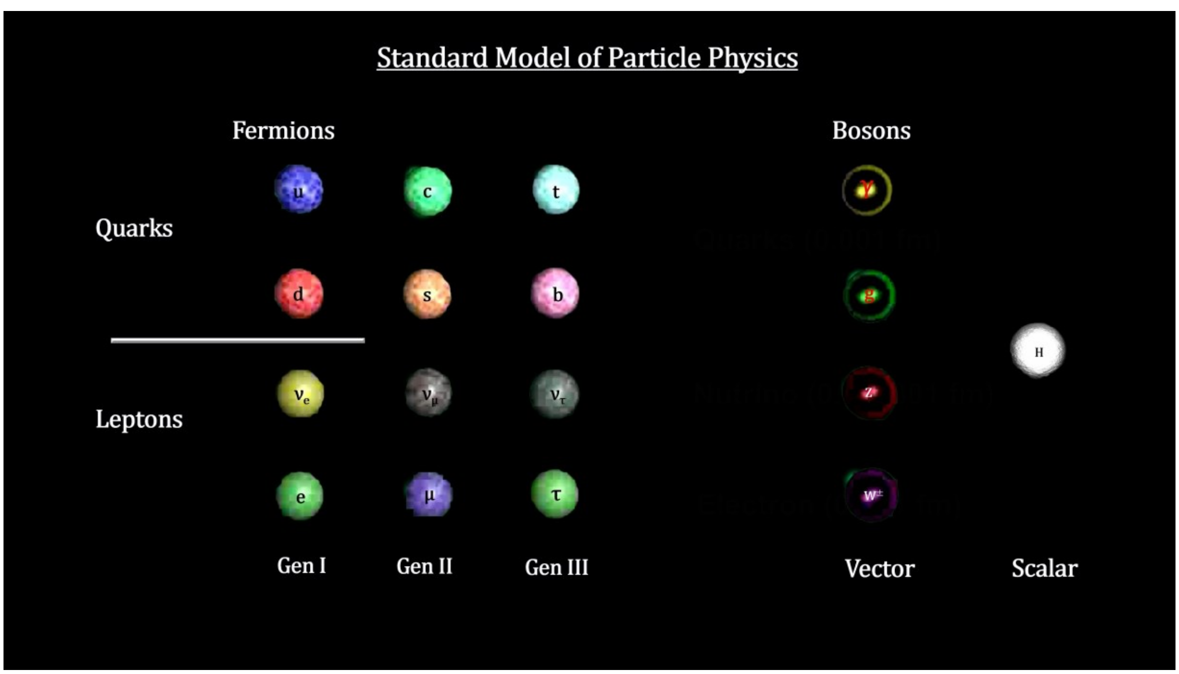
Here's one more important idea about mass. The reason the masses are different for different particles, is that the coupling strength of the interaction with the Higgs field is stronger for some particles than others. Increasing the coupling strength is like increasing the stiffness of the spring in a harmonic oscillator. It has the effect of increasing the oscillator's frequency. And we have already determined, that if we increase a particle's oscillation frequency, we increase its mass.



Now we can ask: "What is a Higgs boson?" We have learned that, under the right circumstances, excited fields generate particles. This also applies to the Higgs field. If it exists, it has an associated particle – that particle is called the Higgs boson. So, working in reverse, if we can find the Higgs boson, we'll have strong evidence that the Higgs field exists and the Higgs mechanism is real, and the Standard Model of Particle Physics, is correct. Quantum filed theory predicts that this particle's mass should be around 125 GeV/c^2 with zero spin called a scalar boson.



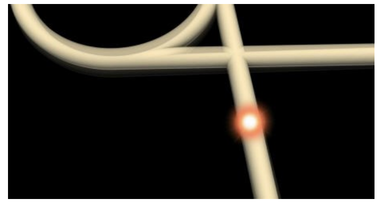
Note that all the other force particle bosons (photon, gluon, W and Z) had a spin of 1 and are called vector bosons.



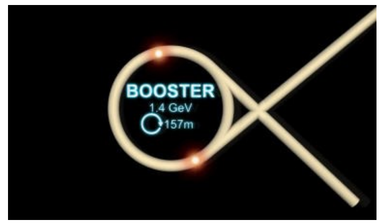
This large mass - around 133 times more massive than a proton - makes it difficult to form one. It takes a great deal of energy. At the time the Higgs boson was proposed, no existing accelerator could do the job. This is why the Large Hadron Collider at CERN was built.

Large Hadron Collider
This Large Hadron Collider or LHC for short is the world's largest and most powerful particle accelerator. [Inside the accelerator, two high-energy particle beams travel at close to the speed of light before they are made to collide. The beams travel in opposite directions in separate beam pipes – two tubes kept at an ultrahigh vacuum (a vacuum as empty as interplanetary space). They are guided around the accelerator ring by a strong magnetic field maintained by superconducting electromagnets. This requires chilling the magnets to -271°C – a temperature colder than outer space. It uses a system of liquid helium to cool the magnets.]

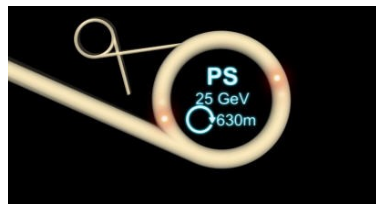
Here's how it works. Using hydrogen with the electrons removed, proton packets containing billions of protons are accelerated down a linear accelerator like we saw at SLAC. By the time the protons reach the first cyclotron, they are traveling at 1/3 the speed of light.



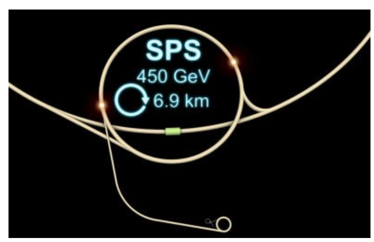
The first booster is 157 meters in circumference and accelerates the protons to 91.6% of the speed of light.



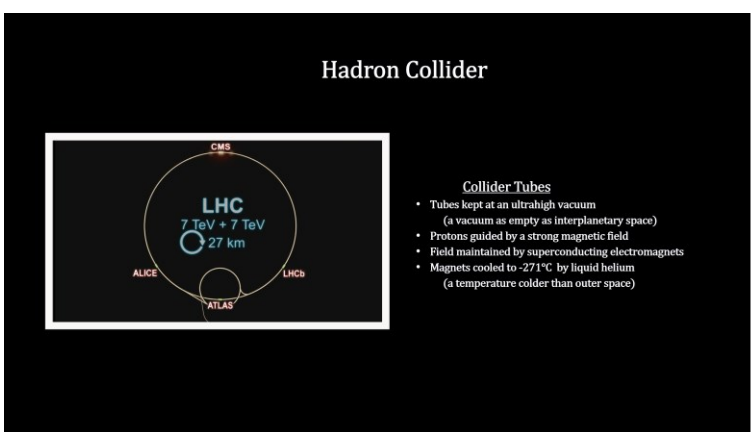
The protons are then flung into the proton synchrotron. They circulate here for 1.2 seconds reaching 99.9 % of the speed of light.



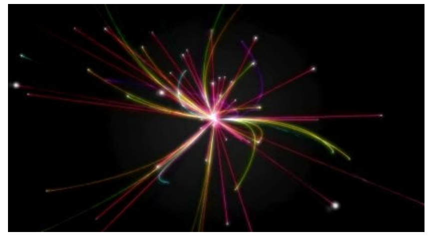
The protons are then channeled into the Super Proton Synchrotron. This is a huge ring, almost 7 kilometers in circumference. Here they are accelerated to the point where they can enter the LHC.



Here there are two pipes that carry the proton beams in opposite directions. Each stream is accelerated to 7 TeV – that's 7 trillion electron volts. And because they are traveling at each other, the total energy of a collision is 14 trillion electron volts. This ought to be enough to kick the Higgs field into producing a Higgs boson. As the protons approach each other, they are traveling at 99.999999% of the speed of light.



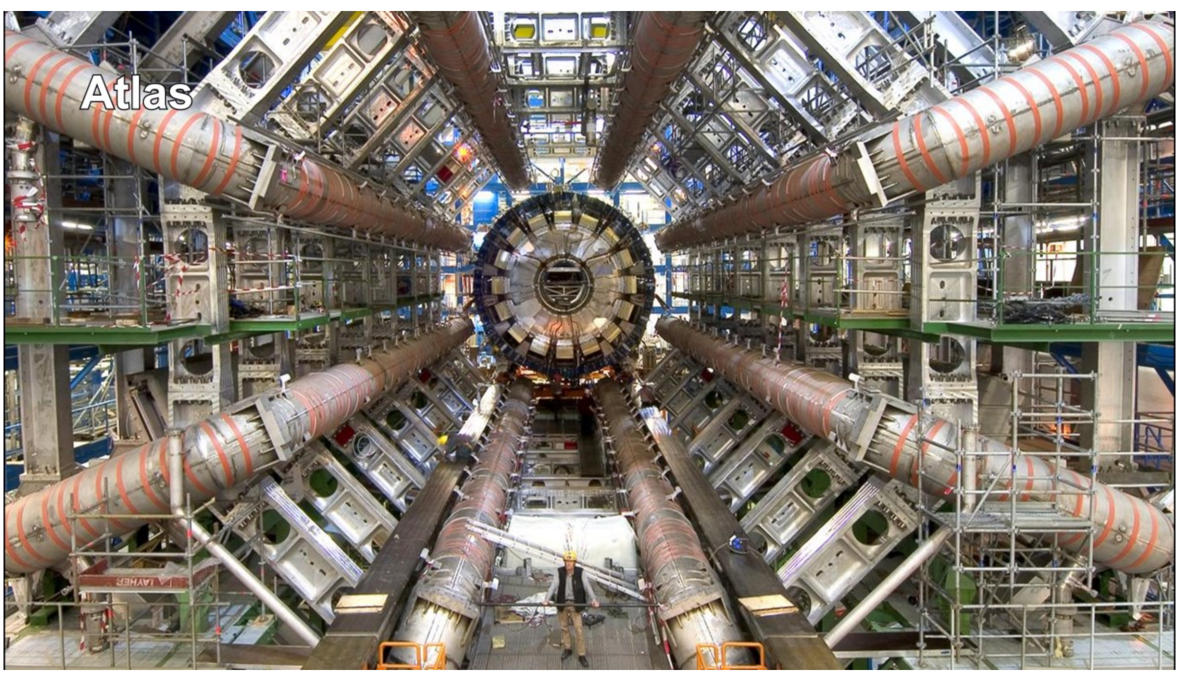
The actual collision creates hundreds of particles that scatter out in all directions. Detecting, and measuring the trajectories, momentum, and energy of each of these particles is the next big step.



CERN Particle Detectors – CMS and ATLAS [**Music**: Vaughan Williams - The Lark Ascending]

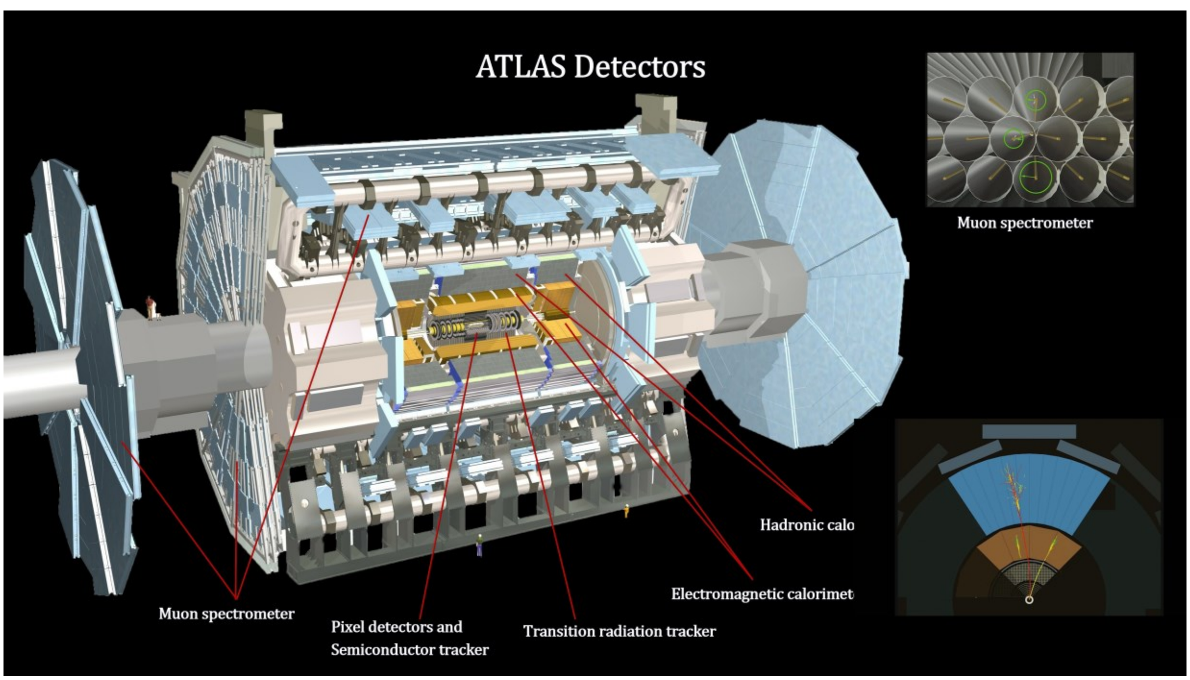
For crosschecking purposes, CERN uses two main detectors. One of them is the Compact Muon Solenoid or CMS for short. It was designed to search for the Higgs boson, and dark matter, [CMS is 21.6 meters long, 15 meters wide, and weighs around 14,000 tons.]

The second detector called ATLAS uses different technical solutions and a different magnet-system design than CMS. It is 7 stories high. We'll take a closer look at this one.



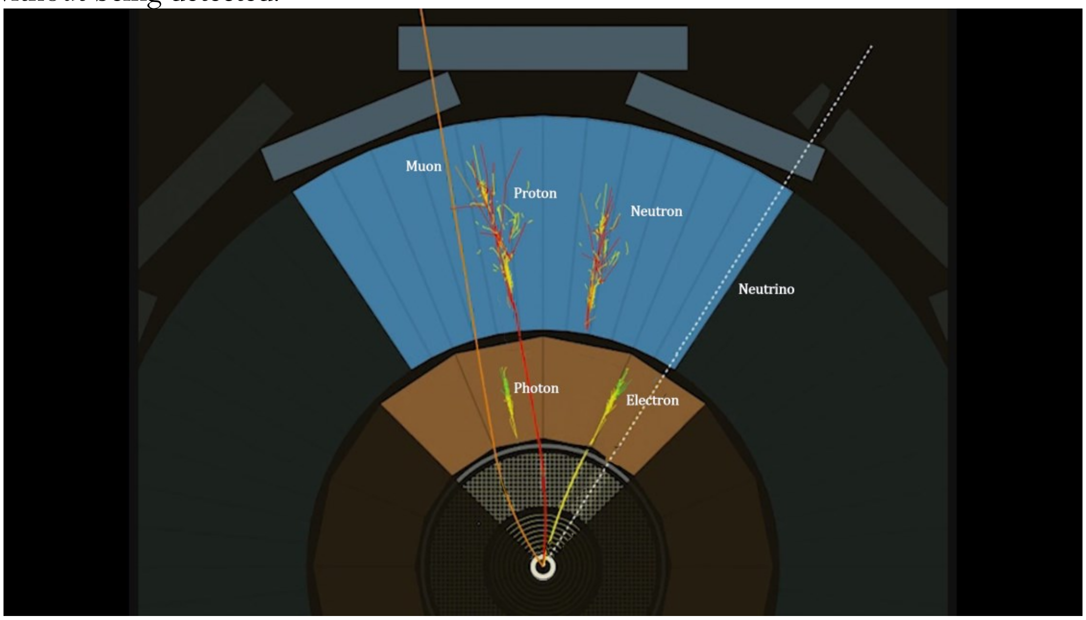
The detecting components in ATLAS are each designed to detect different kinds of particles. The pixel detector and semiconductor tracker contain layer of silicon. Charged particles passing through the silicon release electrons that flow to millions of microscopic metallic spheres under the silicon layer. These are all electronically connected to the computer that keeps track of their path. The Transition Radiation Tracker can distinguish between different types of charged particles. It contains a large number of tubes filled with gas. Passing charged particles produce electrons that flow down a wire in each tube. Different particles produce different currents. A strong magnetic field is created around these inner trackers. The generated curves in particle paths enable us to calculate the particles momentum, like we did at SLAC.

ATLAS has two calorimeters. Like the calorimeter used in the Beta Decay experiment, they are used to measure the energy of transiting particles. But these two don't use heating water. That would take forever. The Electromagnetic Calorimeter measures the energy of photons and leptons like electrons and positrons. It contains many layers of lead and stainless steel that absorb the particles. Between the layers is liquid argon at -180 degrees C. Immersed in the liquid argon is a copper grid. Passing particles drive electrons to the copper and measuring their number gives us the energy of the particle. The Hadronic Calorimeter measures the same for hadrons like protons, neutrons and mesons. It is a large array of steel and scintillator sheets that create photons when struck by a charged particle. Light fibers carry the light to intensity measuring devices. The light intensity gives us a measure of the energy of the hadrons entering the calorimeter. At the outer layer there is a Muon Spectrometer with a surface area the size of several football fields. In the attached chambers there are tubes also filled with gas. The electrons that are generated by the passing muon drift to the center. This enables the system to determine its track.



Here are a few examples.

Photons will act the same way in the calorimeter, but they do not leave any track through the inner detector since they have no charge. Protons leave a track, but will most likely pass through the electromagnetic calorimeter into the hadronic calorimeter. Neutrons behave in a similar way, but leave no track through the inner detector. Muons passe all the way through Atlas leaving tracks behind in every layer. And as was the case with beta radiation, neutrinos passe all the way through Atlas without being detected.

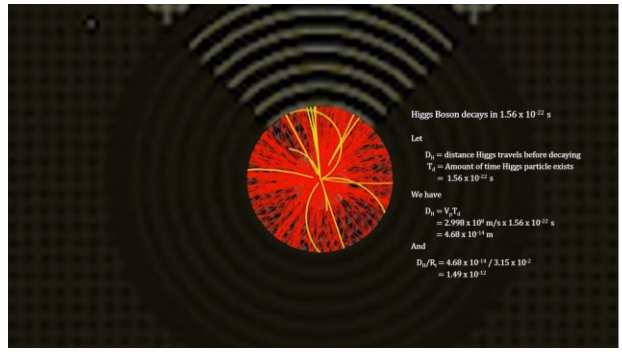


The Higgs Boson Discovery [Music: Brahms - Violin Concerto, Op 77 II Adagio]

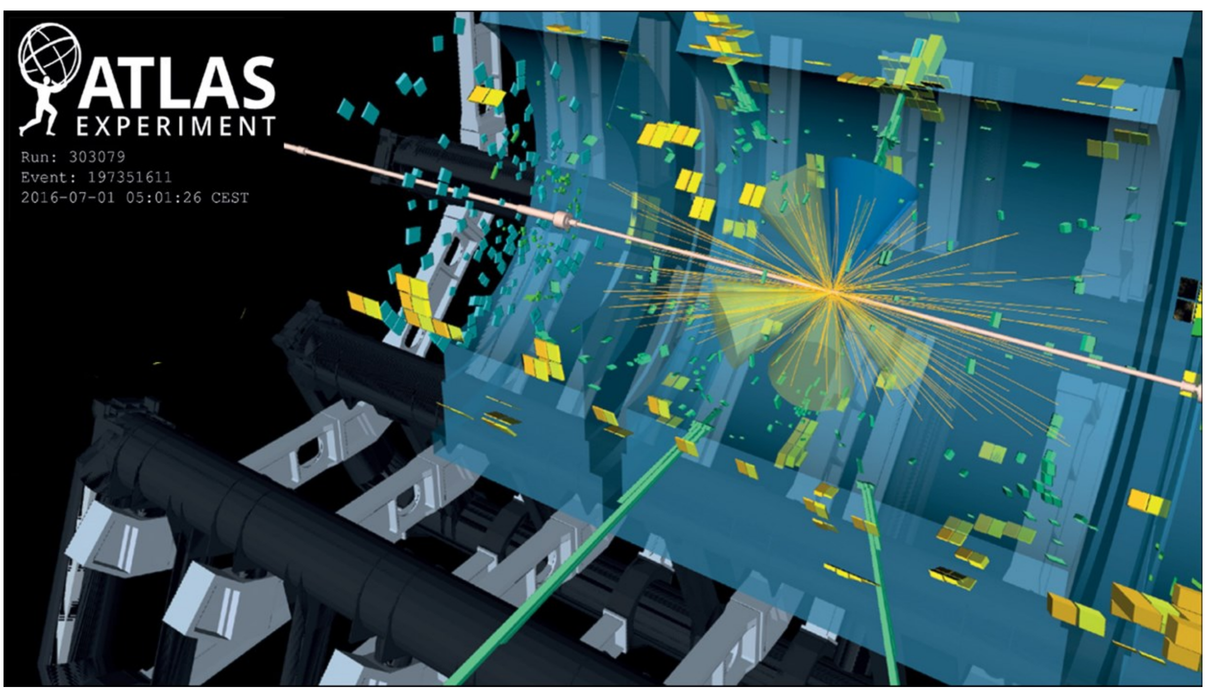
The LHC produces a billion collisions per second. That gives the particles produced by any one collision less than a billionth of a second to clear the tunnel and pass into the detectors. But with particles traveling near the speed of light and the radius of the tube being just over 3 cm, they are all clear in 10^{-10} seconds.

Out of hundreds of billions of particles created by a few seconds worth of collisions, only a few are massive enough to be interesting.

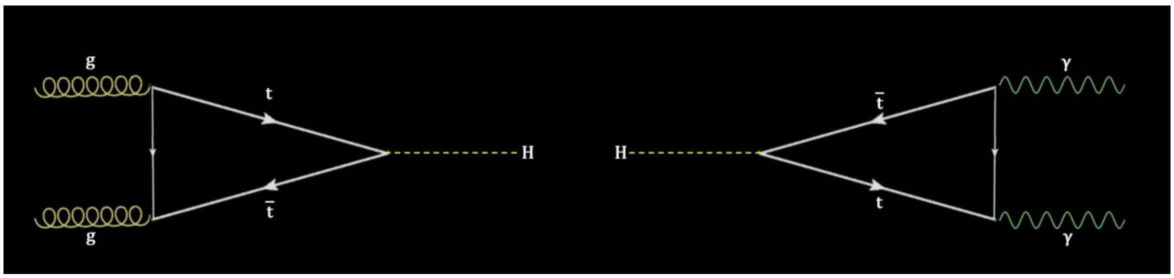
Massive particles like the Higgs Boson itself will decay into lighter particles so rapidly that they never reach the detectors. It's gone before it reaches 2 trillionths of the way out. We cannot see them directly. But we can detect the lighter particles created by their decay. We can then deduce the originating particles by their decay signatures just like we did with the kaon in a cloud chamber.



On July 4, 2012, 45 years after Peter Higgs proposed its existence, CERN announced that one of these interesting particles created in a 2011 collision turned out to fit the decay signature for the Higgs Boson. Here's a Higgs Boson decay into two photons event recorded by ATLAS in 2016 that illustrates the decay mode for Higgs found in the 2011 event. Orange lines show the trajectories of charged particles as they passed through the inner tracking systems. The green and blue cones show jets of particles produced in the collision. The green boxes show the energy deposits in the electromagnetic calorimeter. The yellow boxes show the energy deposits in the hadronic calorimeter. The longer the box, the greater the energy deposited. The extremely long green boxes out the bottom represent the energy deposited by the 2 photons created by the Higgs boson decay.

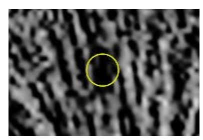


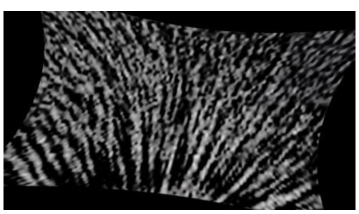
According to the Standard Model of particle physics, there are several ways for a Higgs particle to form and to decay through W, Z and quark particles. Here is a 2 photon one. It's rare, but easily identified when it happens. As two colliding protons approach each other, they overlap. Then two highly energetic gluons collide, creating a virtual top quark and anti-top quark pair. This is called gluon-gluon fusion. These unstable quarks quickly decay into a Higgs boson. The Higgs boson in turn decays into a virtual top quark and an anti-top quark that quickly decay into two high energy photons. It is the photons that were detected by Atlas.



Conclusion

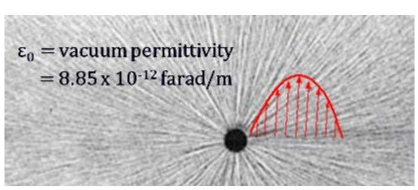
In our search to find out what is actually happening at that point in 'empty' space outside the magnet, we have learned a lot.

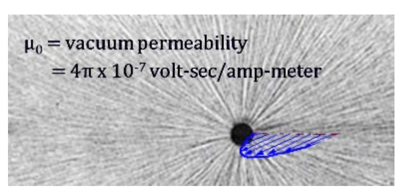




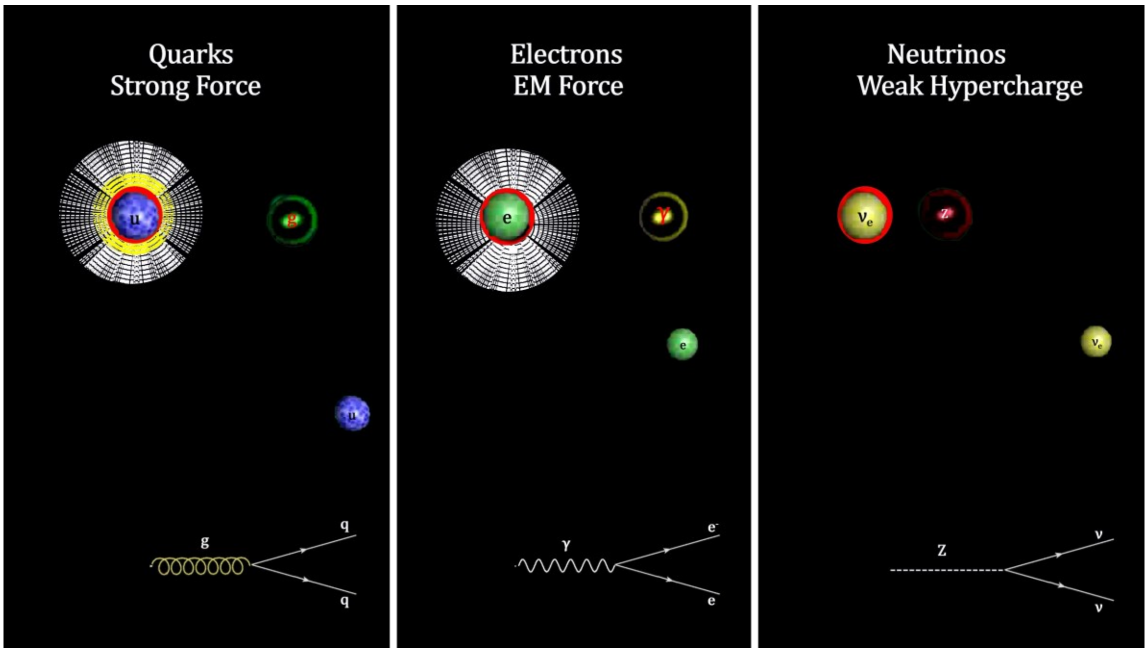
What we have discovered is that "empty space" is a complex entity. It can be stretched (as seen in the expanding universe). It can be bent (as understood by general relativity).

It's filled with various types of matter fields, force fields and the Higgs field (according to the Standard Model). The elements of these fields are quantized, massless, and almost energyless. And we know that empty space offers resistance to changes in these fields (e.g., permittivity and permeability).

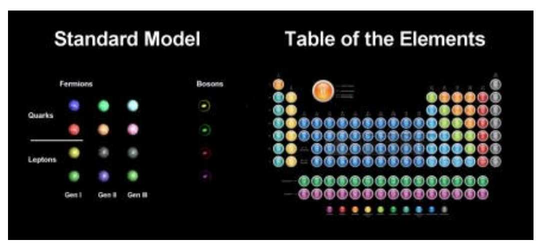


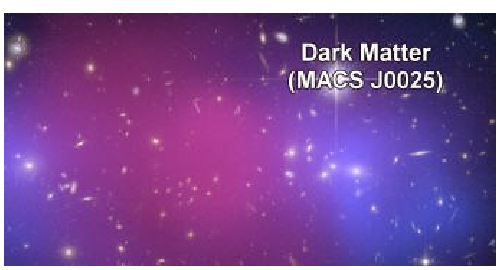


We know that, with enough energy, the elements of a field can bunch up into localized particles with properties like mass, spin, and various types of charges that spew out their own field elements into the empty space around them.



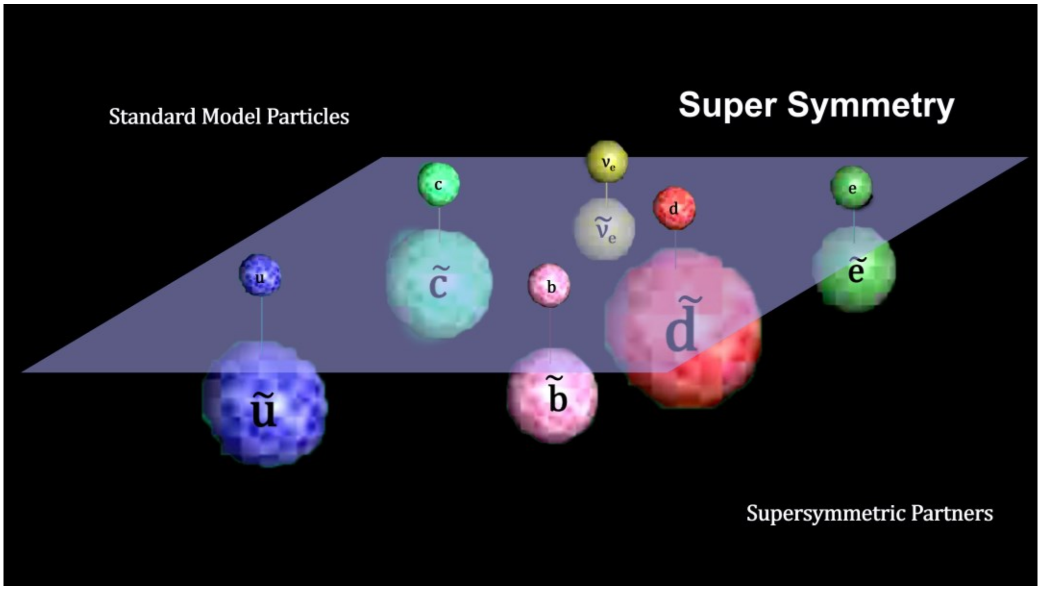
But as much as we've discovered, it feels like we're still just scratching the surface. The order in the Standard Model, like the order in the Periodic Table of the Elements, lends itself to the theory that there is an underlying structure yet to be discovered.



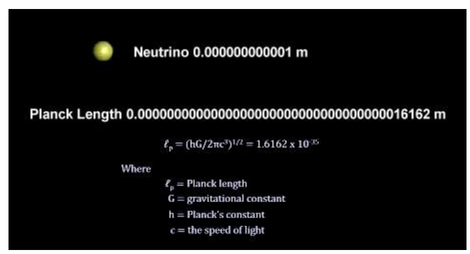


This, along with the mysteries of dark matter and dark energy plus the fundamental incompatibilities with general relativity also speak to a deeper reality.

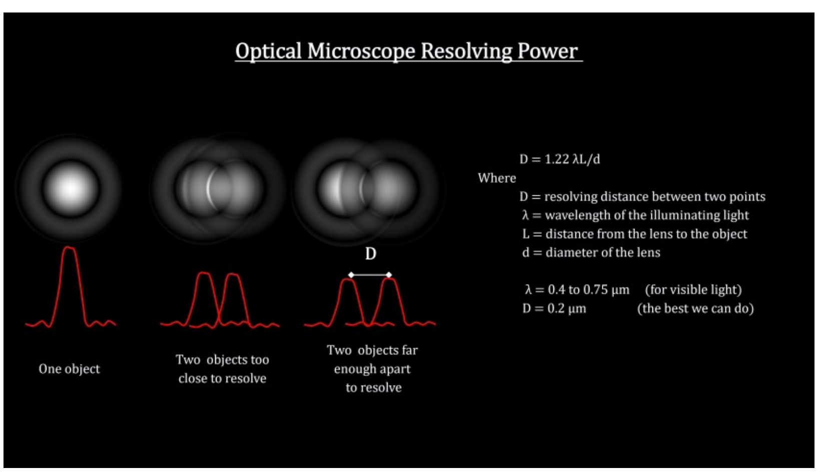
String theory, super symmetry, and loop quantum gravity are just a few of the candidate theories currently being explored.



In that vein, as we approach the end of our "How Small Is It" video book, we'll take a look at the smallest that small can get. In quantum mechanics, there is a minimum length called the Planck length. It is over 62 trillion times smaller than a neutrino – our smallest elementary particle!



This Planck length is as many times smaller than this dot ".", as this dot is smaller than the visible universe! Theoretically, it is impossible to determine the difference between two locations less than one Planck length apart. This idea takes us back to our first segment on the microscopic where we saw how light diffraction created the same problem for optical microscopes.



As we pointed out at the start of our story, you can't probe a grain of sand with your finger. How are we going to find out what's happening at this level – the level where the quantized field elements operate? This is just one of the many challenges for the physicists of tomorrow. It should be interesting.

Please take a look at the credits segment. It will point you to resources for additional research.

Thank you for watching.

Music:

@00:00 Albinoni - Concerto for Oboe and Strings No 2 II: Frank Berger, Hans-Dieter Weber; from the album "50 Must-Have Adagio Masterpieces" 2013

@06:59 Rachmaninoff - Symphony No. 2 Adagio: Sofia Philharmonic Orchestra; Emil Tabakov; from the album "Sergei Rachmaninoff: Symphony No. 2 in E Minor, Op. 27" 2011

@23:02 Ravel – Boléro: The London Symphony Orchestra; from the album "Classical Masterminds - Ravel" 2007

@33:22 Vaughan Williams - The Lark Ascending: Hugh Bean; New Philharmonia Orchestra; Sir Adrian Boult; from the album "Essential Adagios" 2010

@37:43 Brahms - Violin Concerto, Op 77 II Adagio: Sofia Philharmonic Orchestra, Vesselin Eshkenasi; from the album "50 Must-Have Adagio Masterpiece" 2013

Greek letters:
- α β γ δ ε ζ η θ ι κ λ μ ν ξ ο π ρ σ τ υ φ χ ψ ω
- Α Β Γ Δ Ε Ζ Η Θ Ι Κ Λ Μ Ν Ξ Ο Π Ρ Σ Τ Υ Φ Χ Ψ Ω

$\Rightarrow \rightarrow \pm \odot \infty \nrightarrow \exists \nexists \in \notin \iint \int \cong \geq \leq \approx \neq \equiv \surd \sqrt[3]{} \sim \propto \hbar \div \partial$

Superpositions and Entanglement

{Preface - *In this, the last chapter in the 'How Small Is It' video book, we'll cover quantum superposition and quantum entanglement. We'll also finish the work on the double slit experiment we covered in our first chapter on 'The Microscopic'. We'll be using electron spin and polarized light in most of our examples. Beginning with light, we'll cover exactly how polarization works. Then we'll use it to illustrate how we know which slit light went through in the double slit experiment. This illustration will highlight the nature of quantum linear superposition. As part of this we'll take a look at Schrodinger's Cat.*

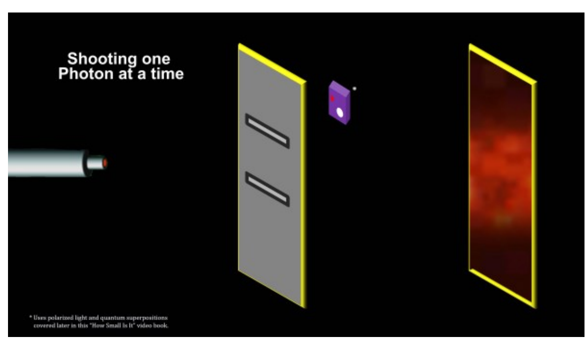
With superposition in hand, we'll cover how these superposition states can become entangled across multiple particles. We'll start with some classical behavior associated with water waves and spinning coins. Then, using electron spin, we'll illustrate entanglement. We'll follow that with Einstein's problem with 'spooky action at a distance'. We'll cover several experiments both thought (from John Bell) and real as quantum physics progressed in its ability to manage the quantum world. We'll see what a 'ghost image' is and how it was used to show Einstein was wrong. As part of this segment, we'll cover the 'Quantum Eraser' experiment.

*We'll end with a look at Quantum Computers. Here we cover how electrons are controlled in such a way that they can be put into and taken out of a superposition state at will. And in addition, they can be managed into and out of entangled states. This ability enables quantum computing.***}**

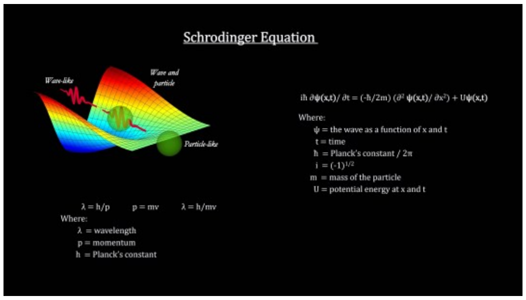
Introduction **[Music:** Bach - Flute Concerto in B Flat, Adagio**]**

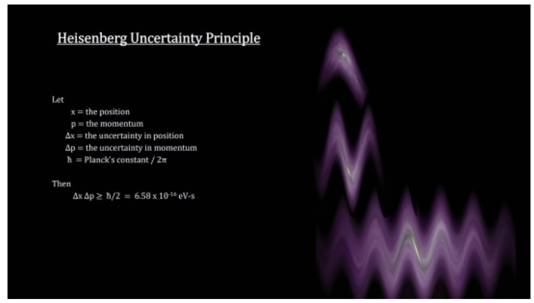
Quantum state superpositions and entanglement are two of the most fundamental concepts in quantum mechanics, and also two of its most misunderstood. And they are turning out to be the key to the next generation of quantum computing.

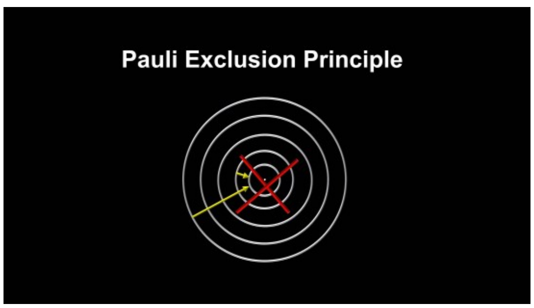
In our first chapter, The Microscopic, we covered the double slit experiment that showed how photons and electrons display both wave and particle properties. It's called wave-particle duality or complementarity. The key to the experiment was to observe what happens when we detect the slit a particle went through. For photons, we never explained how we could detect a photon without disturbing its path. This final chapter brings us full circle where we will cover in detail how this was done.

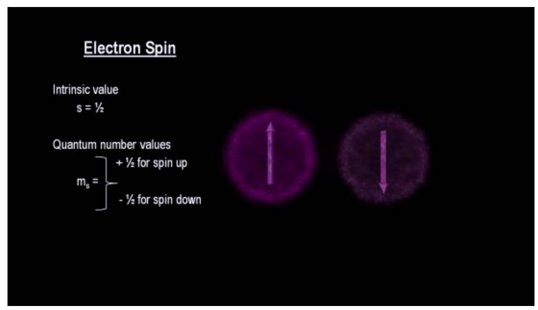


In our second chapter on The Atom, we covered Schrodinger's equation with its probability wave; Heisenberg's Uncertainty Principle; and Pauli's Exclusion Principle with electron spin; These constitute the base physics for understanding superpositions and entanglement.

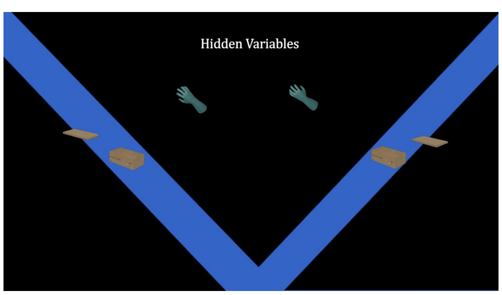


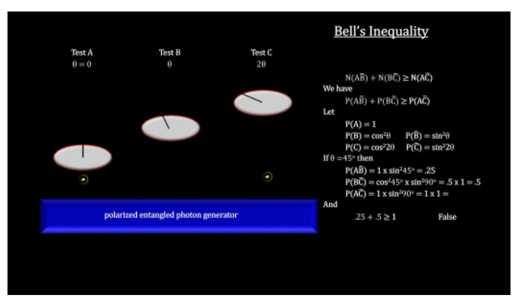


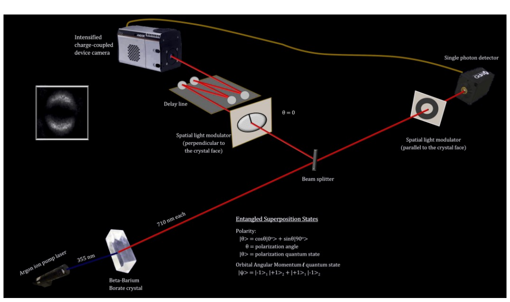


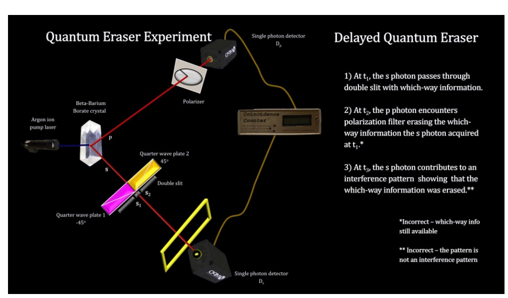


We'll cover exactly what quantum superposition and entanglement are. We'll cover Einstein's problem with quantum mechanics and his prediction that we will someday find "hidden variables" to explain entanglement. We'll cover a thought experiment designed to show that "hidden variables" cannot exist. It's called Bell's Theorem or Bell's Inequality. We'll cover a real experiment that uses entangled photons to create "Ghost Images" that produce a Bell Inequality. Along the way, we'll clear up a few misconceptions about Schrodinger's Cat and the Quantum Eraser.

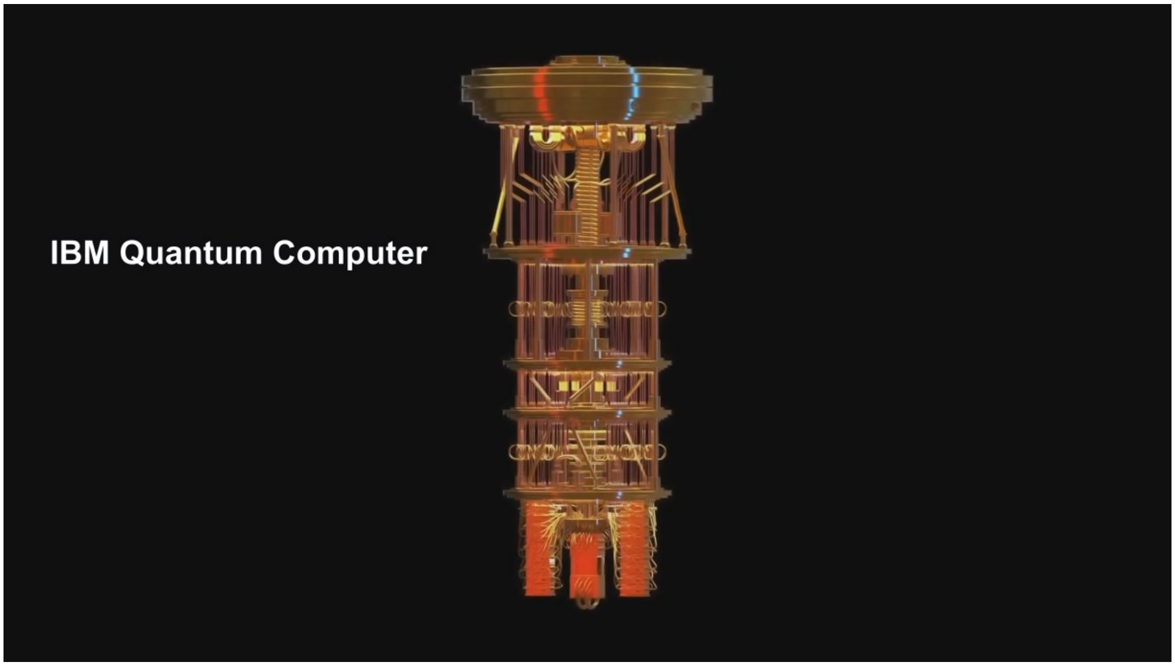






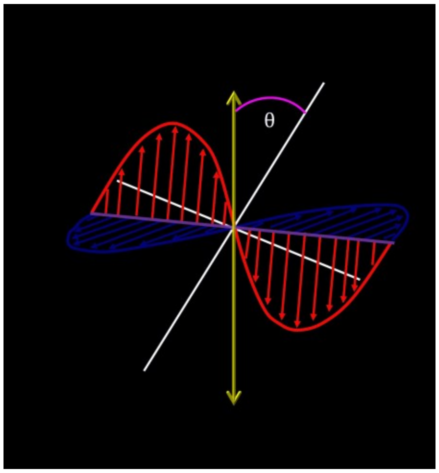


We'll end with a look at Quantum Computing and how it directly manifests and leverages these quantum properties. Our first encounter with quantum superpositions will be the double slit experiment. So, in preparation, we'll cover some key characteristics of light polarization.



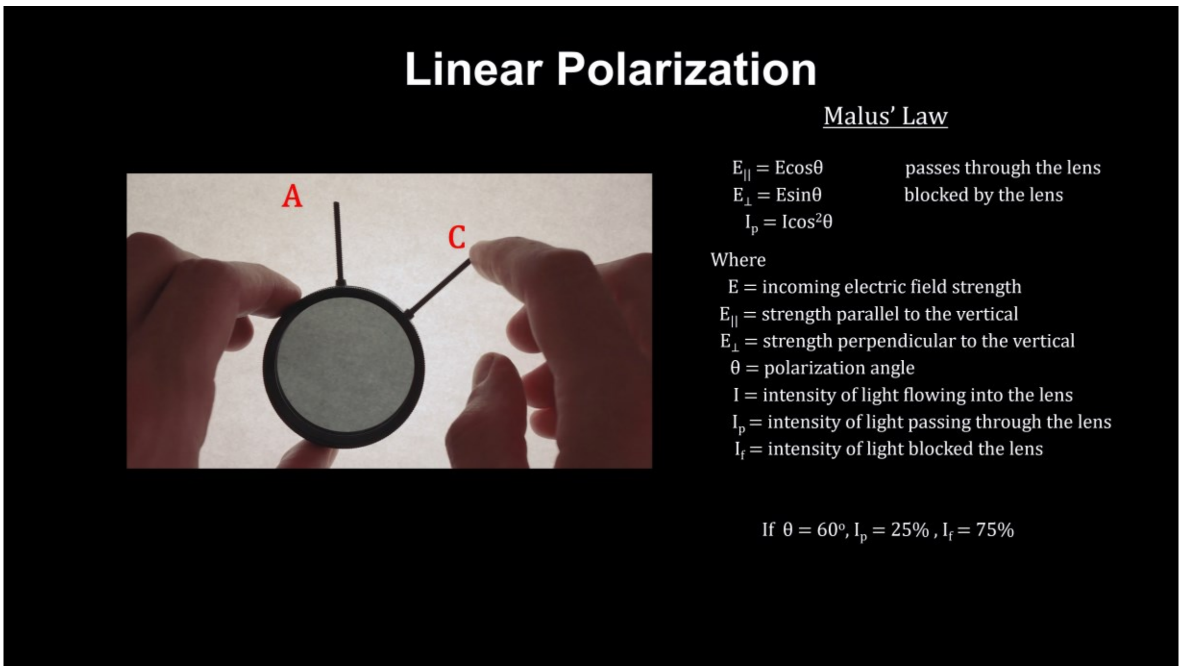
Light Polarization

We understand light as an electromagnetic wave.

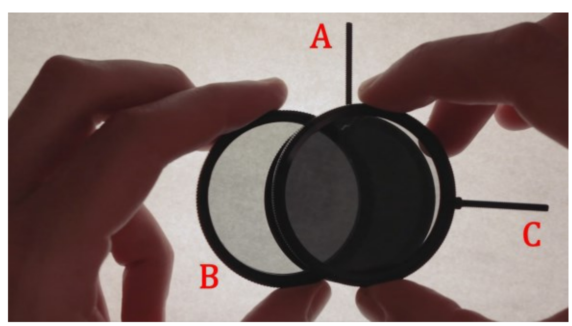


The direction of the electric field is called the wave's linear polarity. Here we see the polarity at different angles from a fixed reference. It is also possible for the polarity to be rotating clockwise or counter-clockwise around the line of motion. These properties hold for the basic unit of light – the photon.

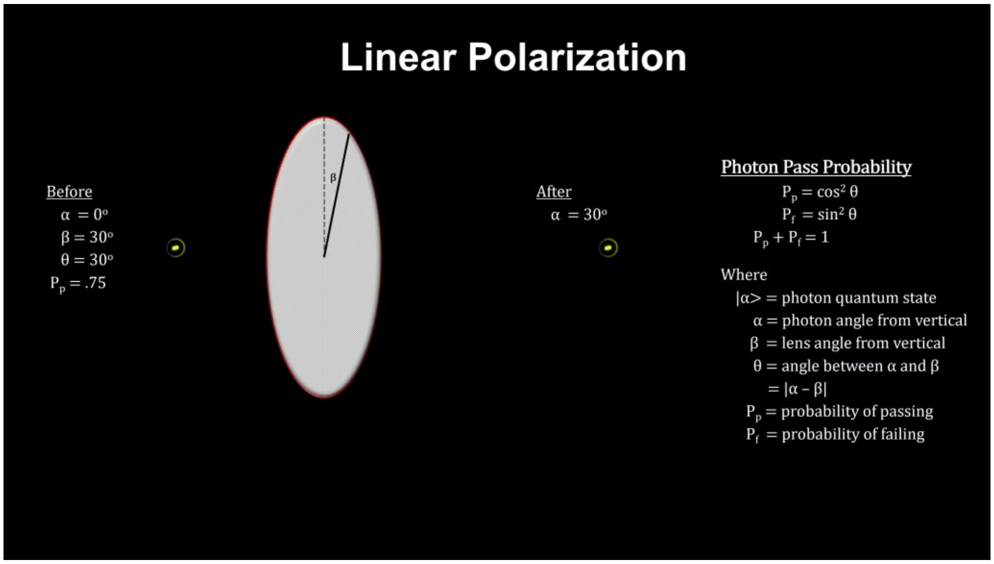
When light passes through a polarized lens, the amount of light that makes it through depends entirely on the angle between the incoming light's polarization and the polarization direction of the lens. To see this, here are a couple of experiments you can do at home if you have three pairs of polarized glasses. Photons leaving the background table have a wide variety of polarizations. We start with a lens that only allows light polarized in the vertical direction to pass through. All the other light is blocked. We'll call this lens A. If we bring in a second lens (lens C) and orient it the same as the first, all the light that passed through A, passes through C. But as we rotate lens C, we see the amount of light passing through is going down. By the time we reach 90 degrees, C is blocking all the light that passed through A.



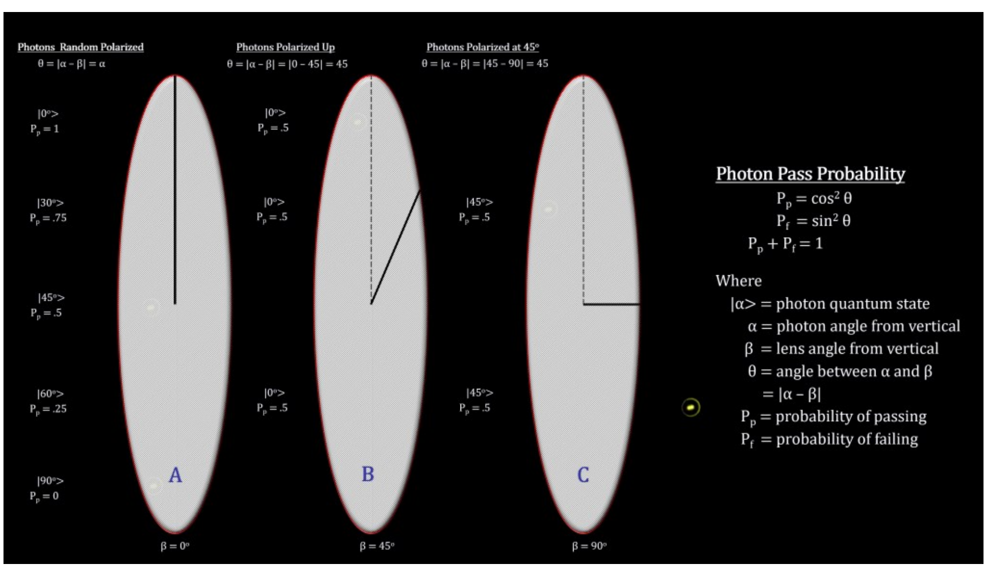
Now, if we bring in a third lens (lens B) and place it between the first two, and angle it at 45 degrees, we see that light that could not make it through C before is now coming through. In other words, lens B designed to reduce the amount of light that reaches C, actually enables more light to get through C.



To see what is happening here, we need to go down to the photon level. Classically, we calculated the percentage of light that goes through a lens. But a photon will go through or not go through. It cannot be divided. In quantum mechanics, it's the angle between the orientation of the photon's quantum state and the orientation of the lens' polarization that provides the probability for passing through the lens. In addition, the interaction between the lens and the photon will change the orientation of the ponton's state to equal the orientation of the lens it passed through.



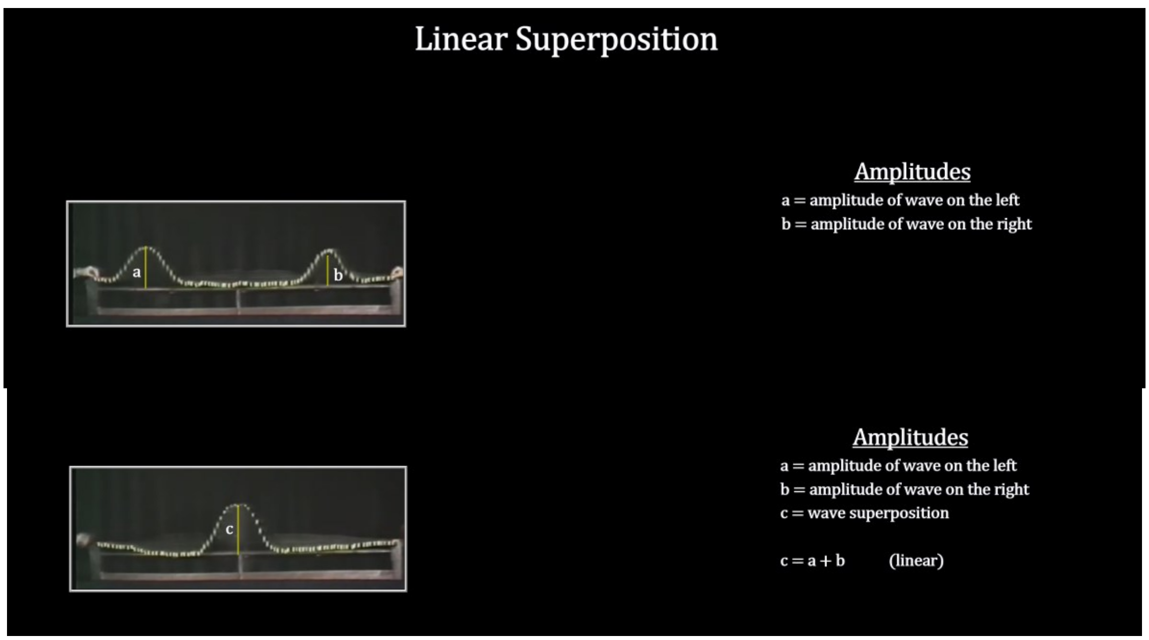
With this understanding, we can examine how light made it through Lens C once we added lens B. Here we have a number of photons with random polarizations trying to pass through the vertically polarized lens A. Some make it and some don't. All the photons that passed through A have now been changed to have the quantum state "vertical" to match the lens. With this polarization, the probability of passing through lens C, which is rotated 90 degrees from the vertical, is zero. No light gets through C. Now we introduce lens B, which is rotated 45 degrees from vertical. We see that some of the vertically polarized photons coming through lens A will pass through lens B. In addition, the interaction between the photons and lens B changed the photons' quantum state to "oriented at 45 degrees" to match the lens. This enables some of the photons that passed through lens B to now pass through lens C.



The key takeaway here it that objects like lenses, crystals, electric fields etc. can and do modify the quantum states of particles that encounter them.

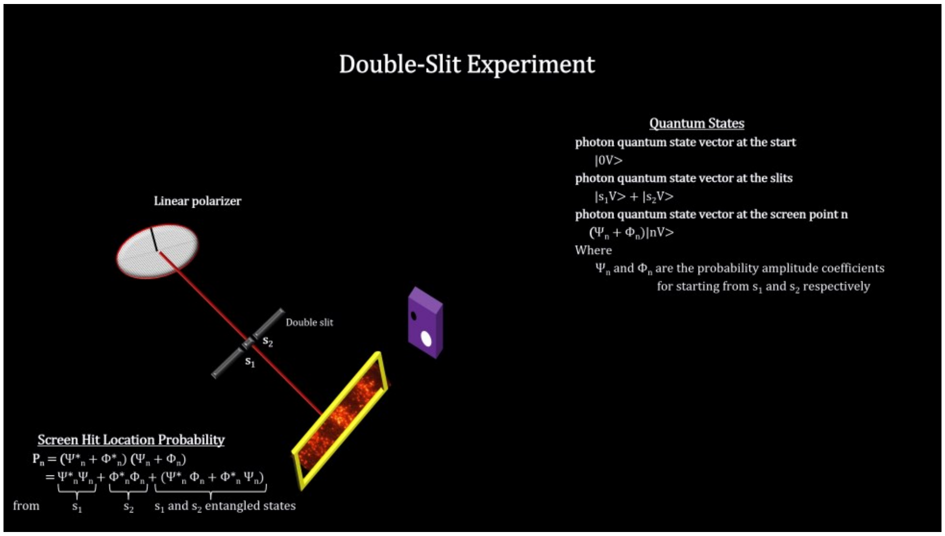
Linear Superposition

Based on the wave nature of particles, superposition is the combining of multiple waves. For example, here we see two waves with amplitudes a and b. When they combine, the superposition state has an amplitude of a + b. The relationship is linear. In this next example, where one has an amplitude a and the other has an amplitude -a, the superposition is zero. They cancel each other out. Remembering that a physical system can be described by a wave function and Schrodinger's wave equation, their quantum states can be linearly combined like these waves. This is the principle of quantum linear superposition.

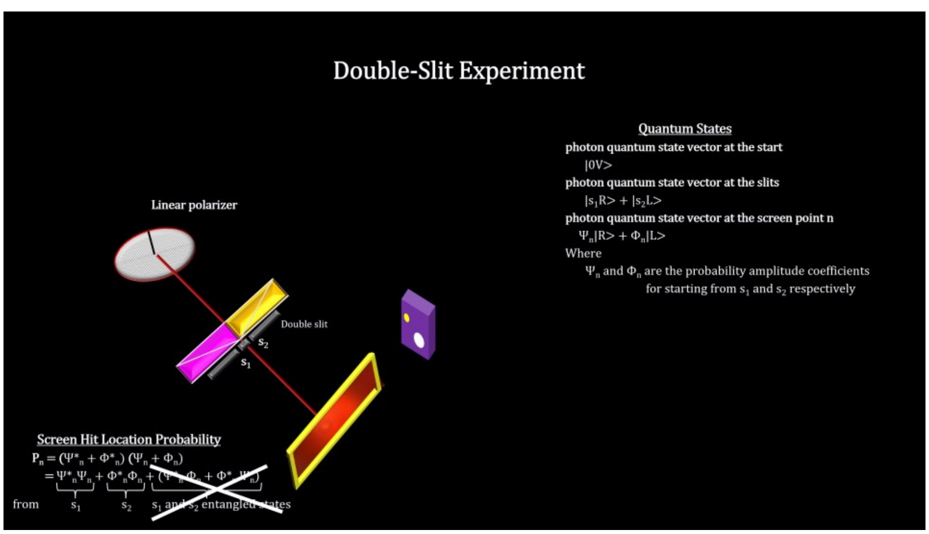


The double slit experiment with photons helps illustrate how this linear superposition works. As light flows through the process, we'll keep track of the quantum state of the photons. We start out with light being passed through a linear polarizer. On exiting the polarizer, we mark the first quantum state as zero for location and V for vertically polarized. As it travels to the double slit, it evolves into a linear superposition state for s_1 and s_2. It represents the state where it could be at either s_1 or s_2. [We're not interested in photons that don't make it through either slit.] For photons reaching the screen from s_1, the state evolves into one that includes coefficient amplitudes that vary for different screen locations. The same is true for photons reaching the screen from s_2. Only the amplitudes will be different. And, unique to quantum mechanics, photons reaching the screen from the $s_1 + s_2$ state, evolve to a linear superposition of the two (like a wave passing through both).

We square the wave functions to get the probabilities. We see that the probability for hitting any particular point on the screen has 4 components. One is for photons going through s_1. One is for photons going through s_2. And 2 are for the photons going through both. It is the interaction between these two that came from the superposition states on the far side of the double slit that creates the interference pattern.

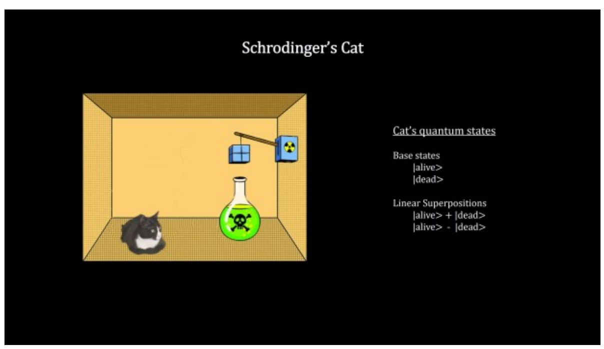


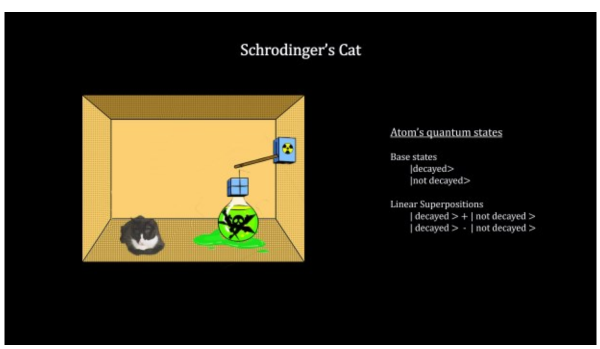
To find out "which-way" a photon went, two quarter wave plates are placed in front of the slits. A quarter wave plate is a special crystal that can change linearly polarized light into circularly polarized light. Plate 1, in front of slit 1, will change the photon's polarization to be clockwise while plate 2, in front of slit 2, will change it to be counter clockwise. These are reflected in the photon's new quantum state where R is for clockwise and L is for counter clockwise. Once the photon reaches the screen, we can measure its polarization and know which slit it went through. But, because the left and right polarized terms are orthogonal, they cancel out when we calculate the probability distribution. We are left with a probability distribution that only contains terms for the two slits giving us the blob instead of the interference pattern. Now if we remove the quarter wave plates, we get back the superposition states and the interference pattern.



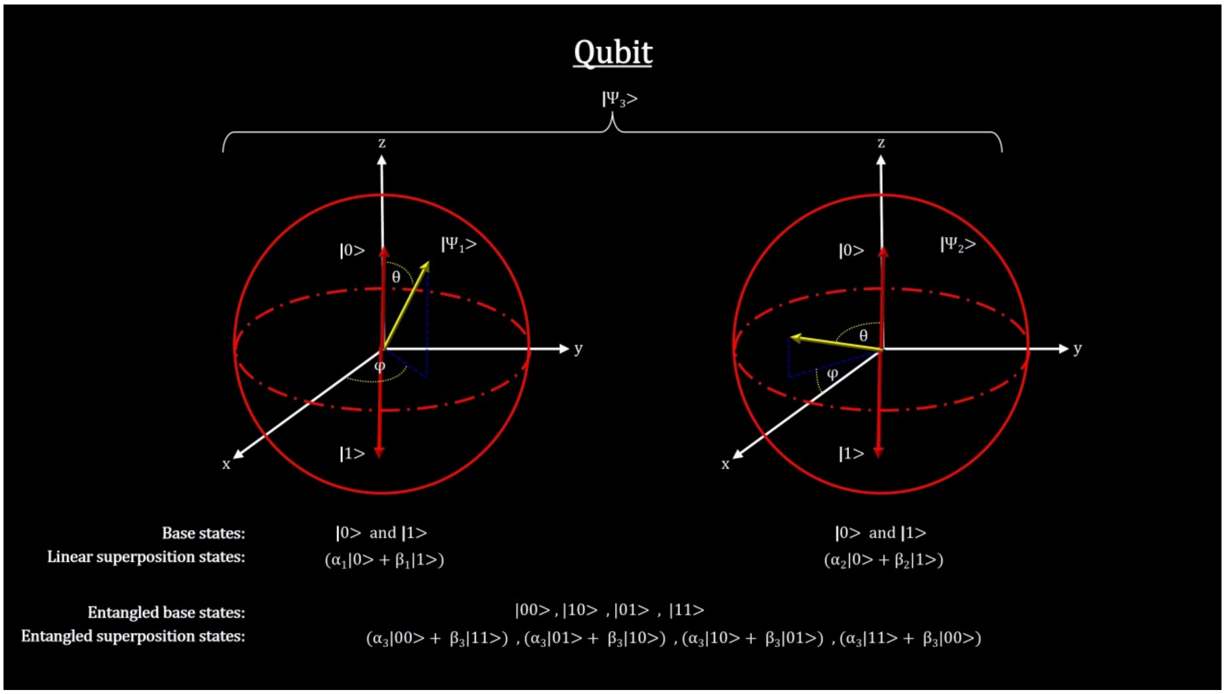
In the early days of Quantum Mechanics development, some physicists proposed that linear superposition was appropriate for macroscopic objects and that superposition states only degenerated into base states when the system was 'observed' or 'measured' implying the need for a human. To counter these misconceptions, Schrodinger, with a bit of humor, proposed a thought experiment now called Schrodinger's Cat. It went like this: Suppose we had a cat penned up in a box with a tiny bit of a radioactive substance, so small, that in the course of an hour one of the atoms might decay, but with an equal probability that it does not decay. He added a Geiger counter to detect the decay should it happen. The Geiger counter is hooked up to a lever that drops a weight on a glass bottle of hydrocyanic acid should it detect a decay. The released poison gas would kill the cat.

If we were to consider the quantum state of the cat during this hour, we'd say it is in a superposition of alive and dead (|alive> + |dead>) and this state would persist until we opened the box and the subjective observer-induced collapse of the wave function revealed the state of the cat: alive or dead. Firstly, the idea that life and death could be considered quantum states isn't right. And secondly, the idea that the cat, if found dead, died when the box was opened is ridiculous. An autopsy could prove that it was dead earlier than that. The real situation has the decaying atom in a linear superposition state of (|decayed> + |not-decayed>). It's wave function collapses at decay time when the Geiger counter encounters it. The subsequent observation by a human, records only what has already occurred.



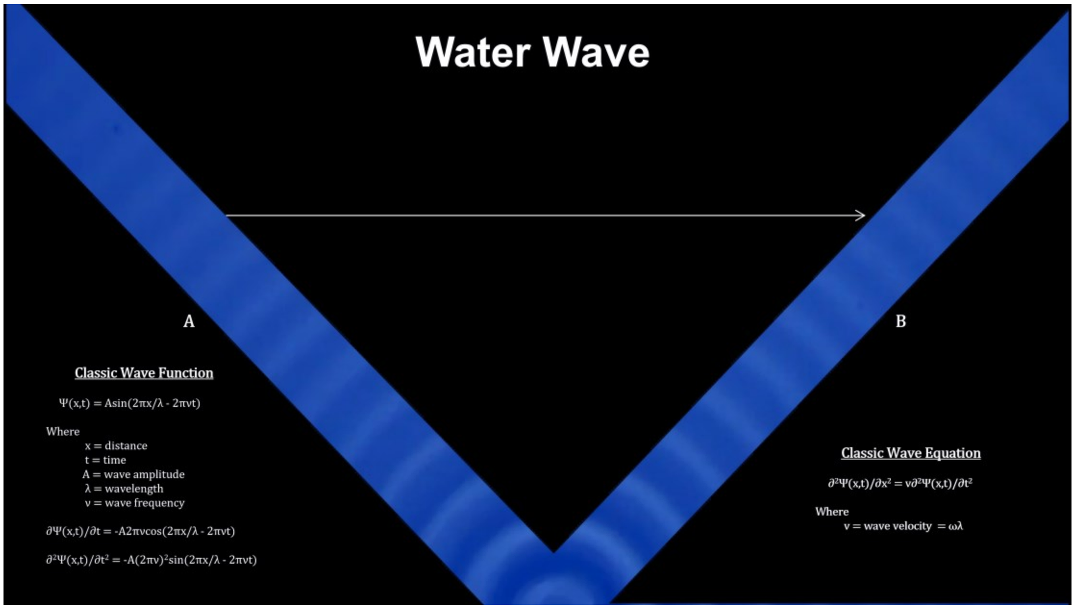


With the understanding that particle base quantum states can and do combine into linear combinations called superposition states, we can examine how these states combine when particles become entangled with each other.

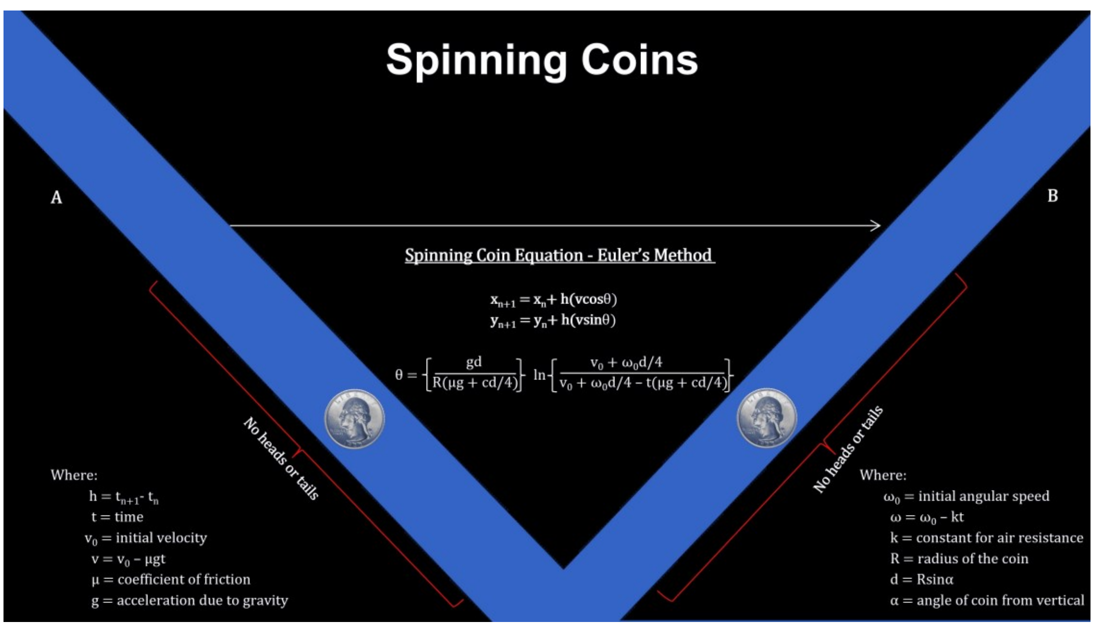


Quantum Entanglement **[Music: Puccini - La Bohéme - Musette Waltz]**

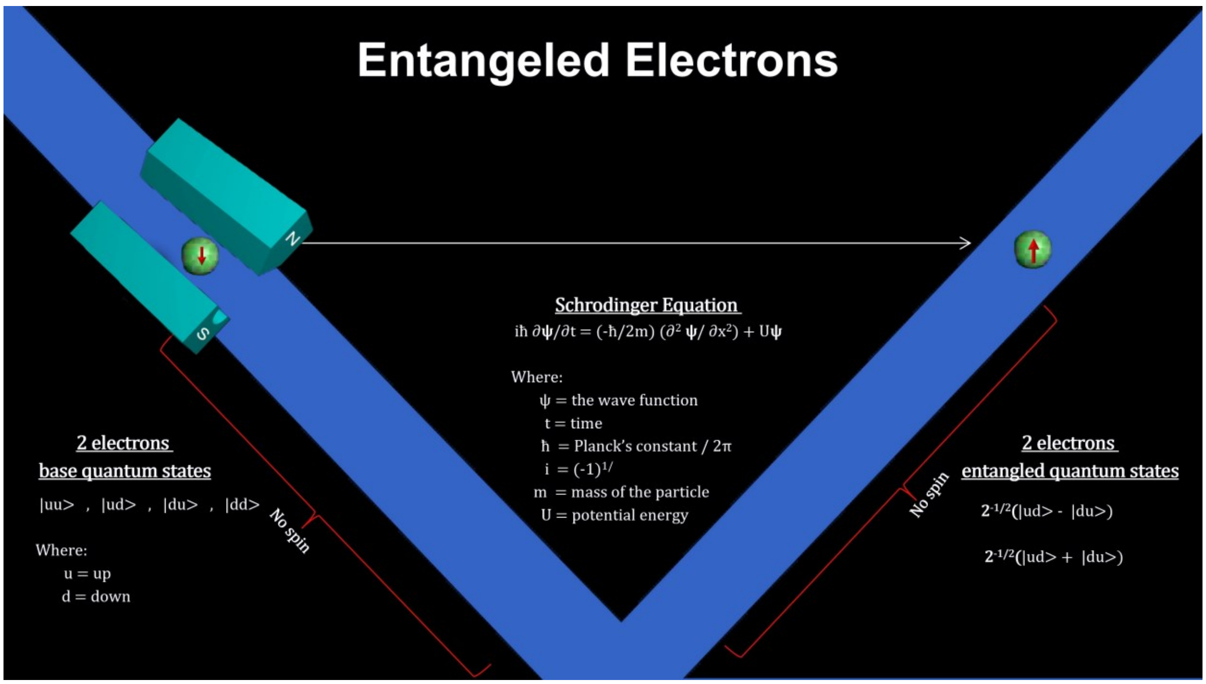
Here's a water wave. It's described by a wave function that determines its operation and a wave equation that determines the change in the function over time. We can channel this wave into two directions say A and B. With enough time, we can a create a great distance between the two branches. If we examine branch A at some time t and find that the wave is at a peak, we will know immediately that at that exact time, the branch B wave will also be at a peak. We don't ask "how did the A branch inform the B branch that it needed to be at a peak". We did not analyze weather information was flowing from A to B faster than the speed of light. We simply note that both branches are a part of a single wave equation that determines its state at any time t. Of course, if we drop channel A's water over a cliff, the wave in channel B will continue on its marry way.



To help isolate the key difference between classical mechanics and quantum mechanics, let's look at one more classical example. Here we start with two coins, each with a heads one side and a tails on the other. If we put them both into a spin and send them up the two channels, we note that during the journey, they exhibit neither heads nor tails. But they carry a probability that, once stopped, they will either come out heads or tails. The probability is 50/50. But unlike the water wave, the results for one of them does not tell us anything about the results for the other. They are independent. But like water waves, the outcomes can be predicted if the starting conditions and channel environment are known. [Items like time and the coin's mass, diameter, rotation rate, starting conditions, air resistance, surface friction etc., enable Newtonian mechanics to predict the outcomes for each of the coins in advance.]



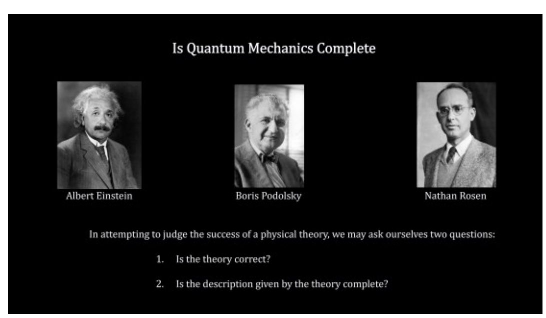
For the quantum mechanics view, we'll start out with 2 electrons that have been put together in a magnetic field to 'entangle them'. Entangled particles are particles that have their quantum states described by a single wave function. The quantum state in question here is the electrons' spin. In their lowest energy state, when one is up, the other will be down. Now we send one of the electrons down channel A and the other down channel B. As they travel, they will not exhibit any spin much like the coins did not exhibit heads or tails. In this example, the moment the electron in channel A interacts with a strong magnetic field such as in a Stern-Gerlach apparatus, it will bring either up spin or down spin to the interaction with (like the coins) a 50/50 probability. At the same instant, the other electron's spin is determined – (like the water wave). If A was up, B will be down. If A was down, B will be up. This is as expected because both particles are following the one wave function.



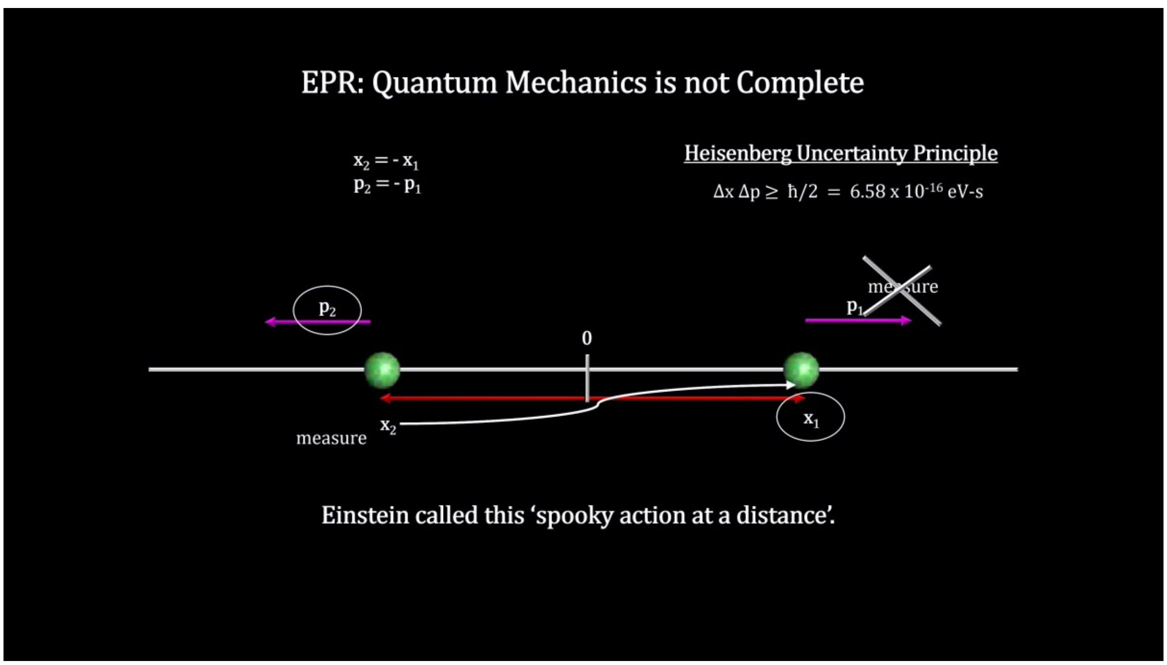
Einstein's Problem with Quantum Mechanics

In 1935, Einstein along with Boris Podolsky and Nathan Rosen argued that quantum mechanics was not 'complete' as a theory. They wrote that:

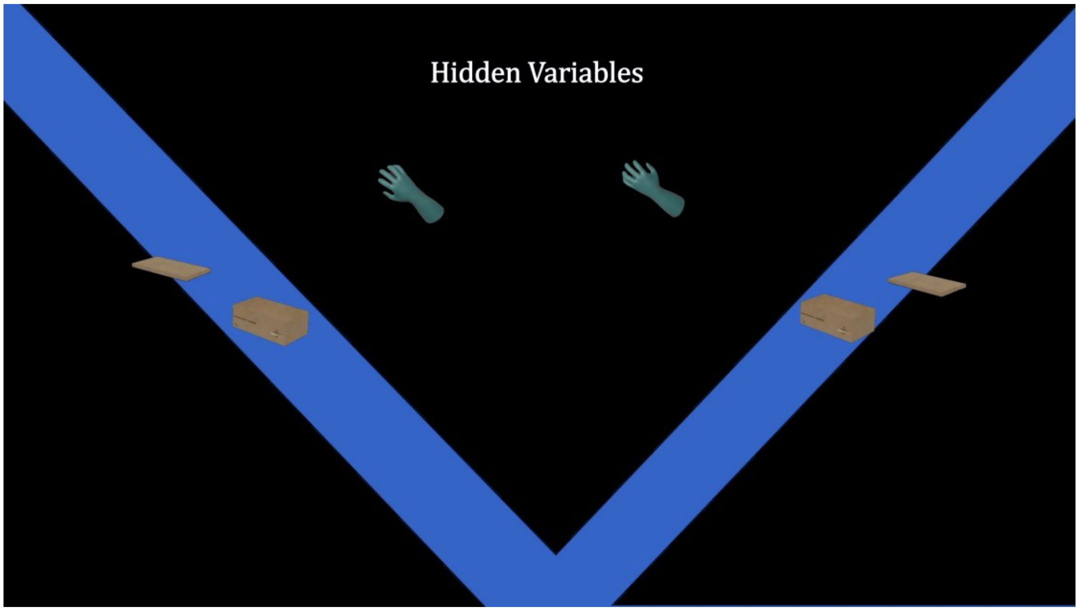
> To be correct, the theory must match what we observe through experiment and measurement. To be complete, every element of physical reality must have a corresponding element in the theory.



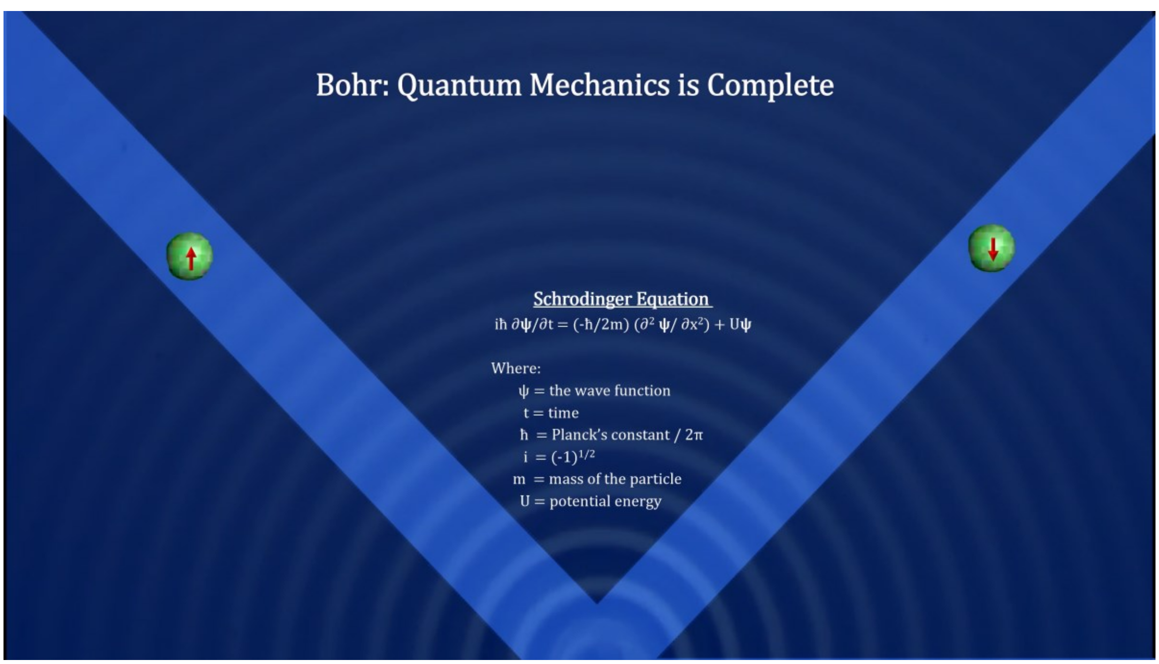
Einstein used the following thought experiment to illustrate this point. Consider two identical entangled particles starting from the same place and moving at the same speed in opposite directions from a common starting point. Letting x represent the distance traveled, x_2 would have the opposite sign as x_1. Letting p represent particle momentum, and given that the initial momentum was zero, p_2 would have the opposite momentum of p_1, so their sum would be zero. That each particle has a location and a momentum means that these quantities are elements of a physical reality. Heisenberg's Uncertainty principle rules out the ability to measure these two quantities at the same time for any one particle because interacting with one impacts the ability to measure the other. But, according to Einstein, measuring x_2 allows us to predict x_1. And measuring p_1 allows us to predict p_2. With this, we can know both the position and momentum of both particles at the same time. According to Einstein, this is how a 'complete theory' would work. But in quantum mechanics, given that these two particles are under a single wave function, measuring x_2 impacts x_1 in such a way as to make it impossible to measure p_1. From Einstein's point of view, this was 'spooky action at a distance' and made Quantum mechanics 'incomplete'.



Einstein proposed that there are 'hidden variables' at play that determine the state of particles like these, in advance. One of his examples went like this. Suppose we have a pair of gloves; one is right-handed and one is left-handed. We place them in two identical boxes and mix up the boxes to the point where we do not know which glove is in which box. Now send these two boxes down the channels A and B. As soon as you open one and find out which handedness it has, you immediately know the other. He thought that someday, a new physics theory will uncover these currently hidden variables.

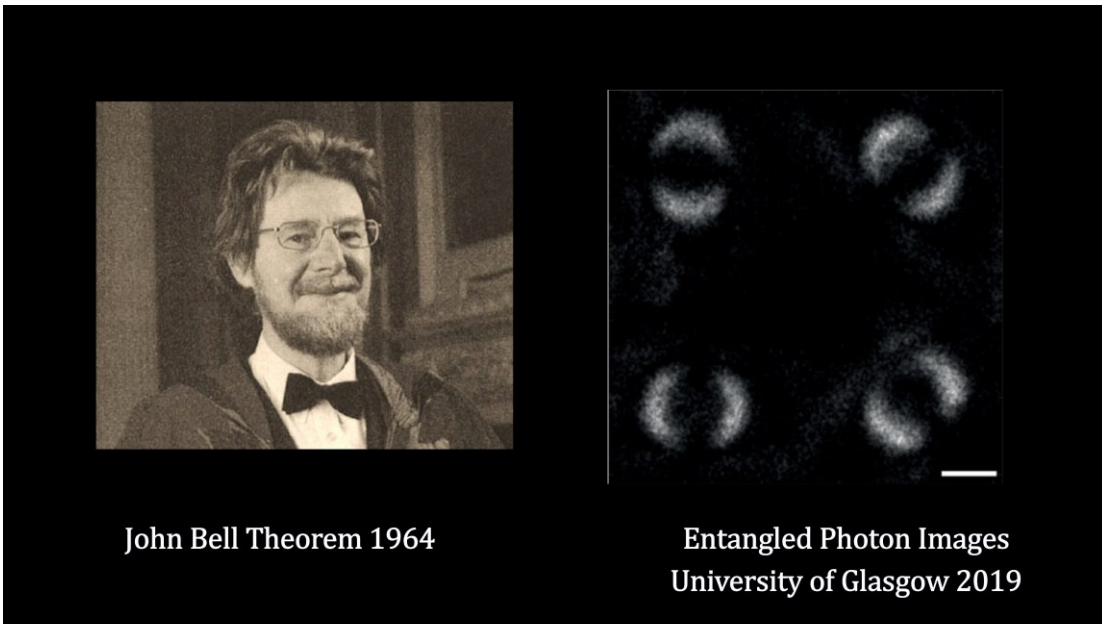


Niels Bohr responded with support for quantum mechanics. In his view, reality follows the wave nature of matter without any need for ‘hidden variables’. At the time, there was no way to prove whether ‘hidden variables’ did or could not exist. In fact, how can you even go about ‘proving’ that a ‘hidden’ variable doesn’t exist.

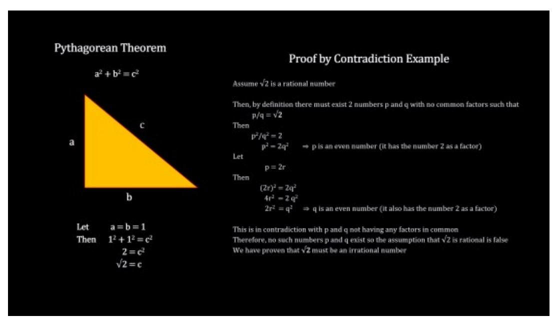


Bell's Inequality

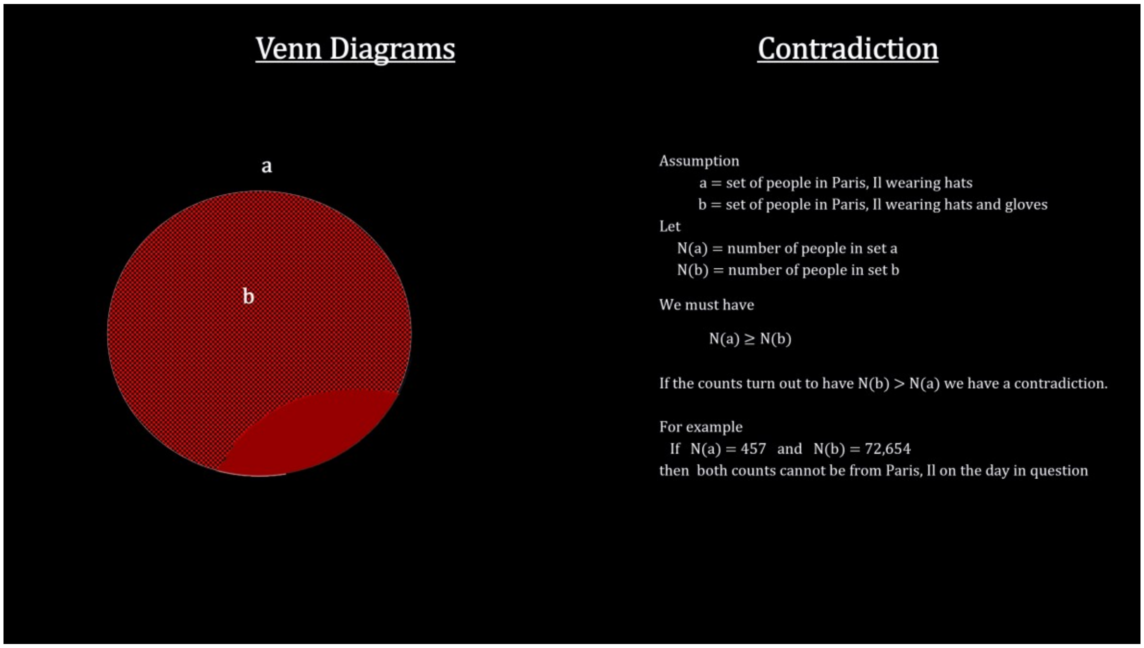
In 1964, an Irish physicist, John Bell, published a mathematical paper proposing a way to test for hidden variables. His work is called "Bell's Theorem" or "Bell's Inequalities." It was based on entangled electrons and Stern-Gerlach apparatus spin detectors. But we'll use the more easily managed particle – photons and polarized lenses.



Bell's idea was to assume Einstein's 'hidden variables' hypothesis is true, and then show how it leads to a contradiction. This would prove that the 'hidden variables' hypothesis is false.



The best way to understand Bell's Theorem is to use Venn diagrams from basic set theory. Here's a simple Venn diagram example. Consider the set of all people in a town, say Paris, Illinois who go out on a particular rainy day wearing a hat. Some of these people are also wearing gloves. This would be a subset of the whole. Now we count the number of people with hats and we count the number of people with hats and gloves. If the number of people with hats and gloves is greater than the number of people with hats, you have a contradiction – a violation of the basic assumption. The assumption that you are counting people in the same town on the same day must be false. For example, this violation could happen if the count for hats was indeed taken in Paris, Il, but the count of hats and gloves was taken in Paris, France.



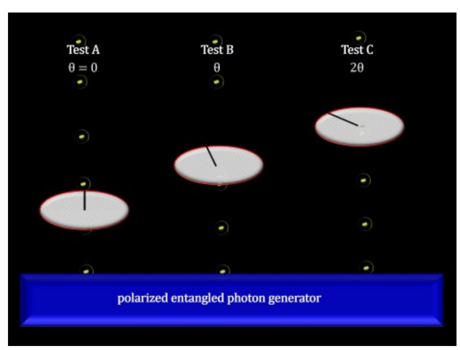
Bell's thought experiment involved sending photons through polarized filters. If a photon passes through a filter, it is referred to as 'passed'. If it's blocked, it's referred to as 'failed'. The probability that a photon will pass or fail depends entirely on the angle between its polarization state and the filter's.

Photon Pass/Fail Probability

$P_p = \cos^2\theta$
$P_f = \sin^2\theta$
$P_p + P_f = 1$
$\cos^2\theta + \sin^2\theta = 1$

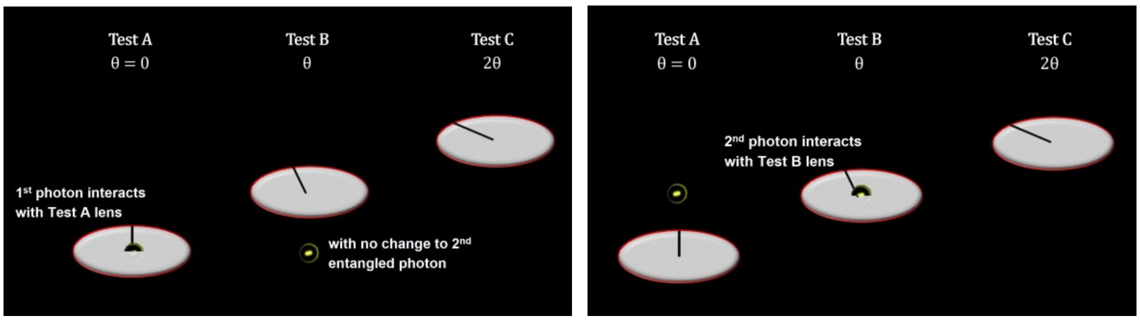
Where
P_p = probability of passing
P_f = probability of failing
θ = polarization angle
$|\theta>$ = quantum state
$|0^o>$ = unit vector – vertical
$|90^o>$ = unit vector – perpendicular

Here we have three tests: A, B and C. Test A sends vertically polarized photons into a vertically polarized filter. Test B sends vertically polarized photons into a filter polarized at an angle θ. And test C sends vertically polarized photons into a filter polarized at an angle 2θ.

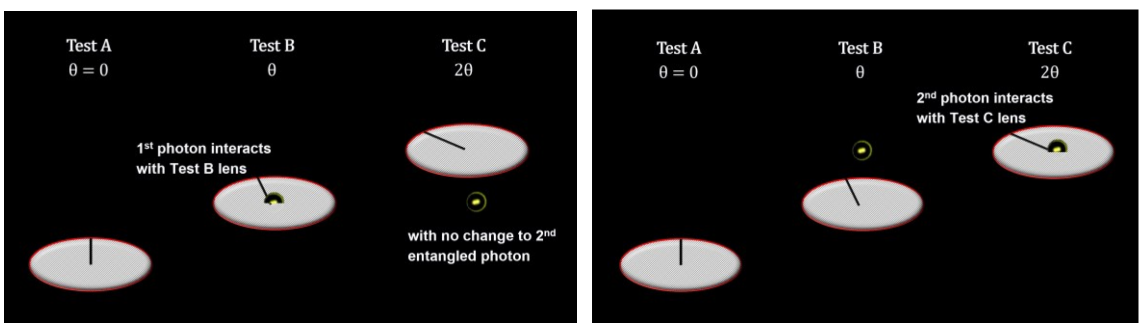


Now the object of the exercise is to examine the role of Einstein's entangled particle 'hidden variables' hypothesis, so we'll use quantum entangled photons along with the assumption that interacting with one of them does not change the state of the other. So, all tests start out with vertically polarized entangled photons.

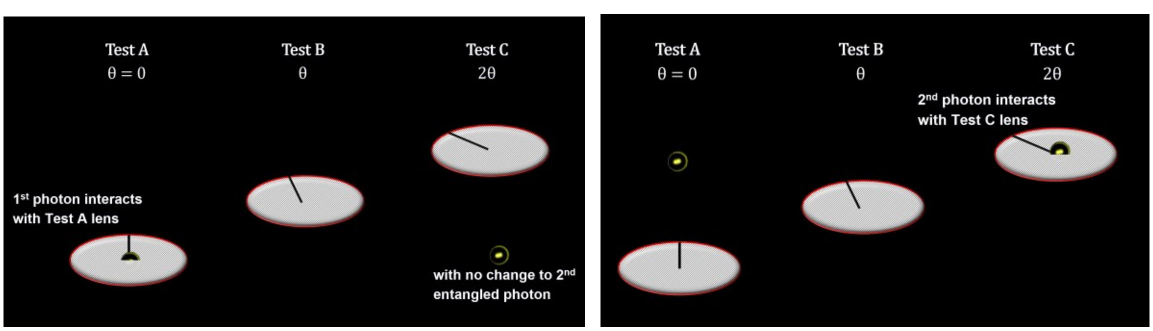
The thought experiment used tests in 3 particular combinations. One was to run a photon through test A followed by running it's entangled photon through test B.



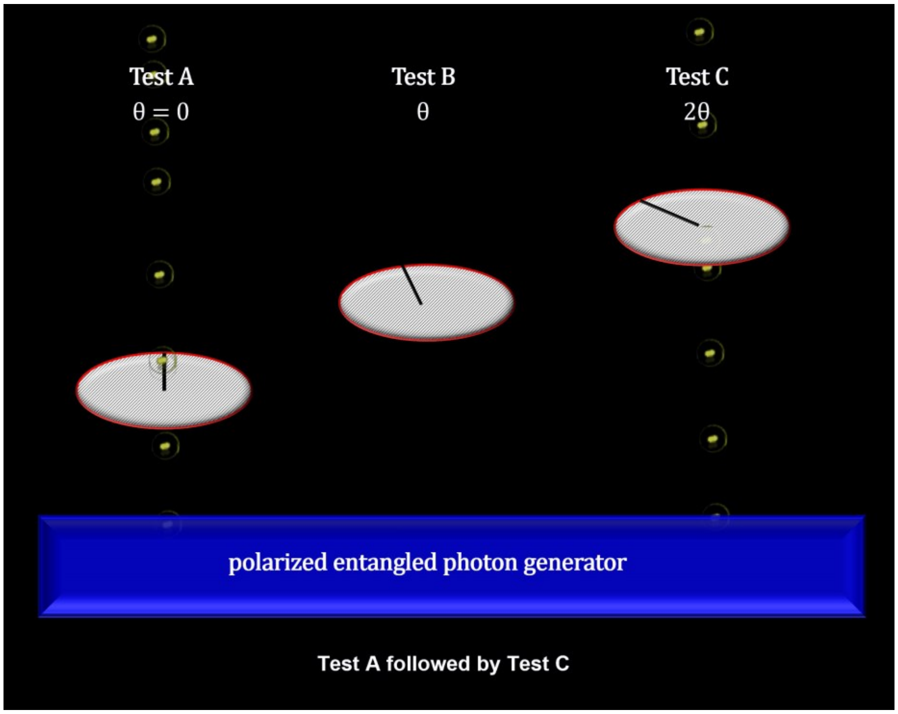
The second was to run a photon through test B followed by running it's entangled photon through test C.



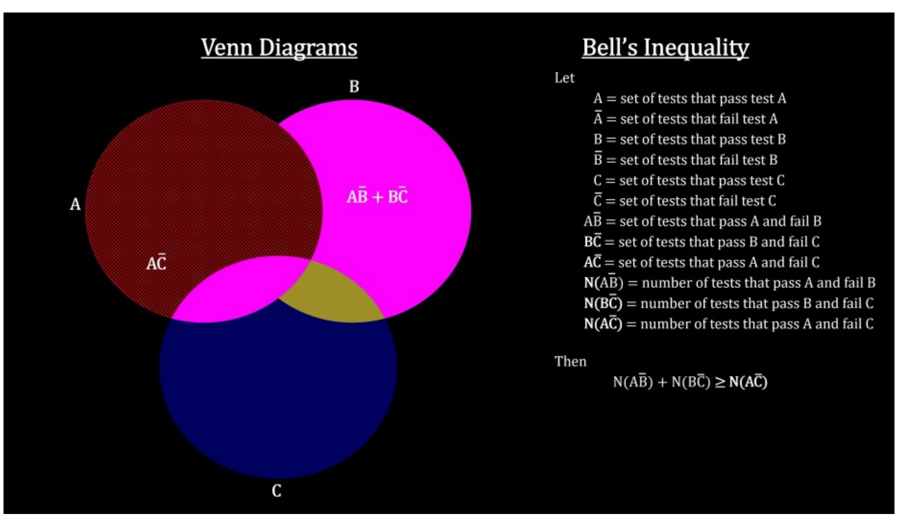
And the third was to run a photon through test A followed by running it's entangled photon through test C.



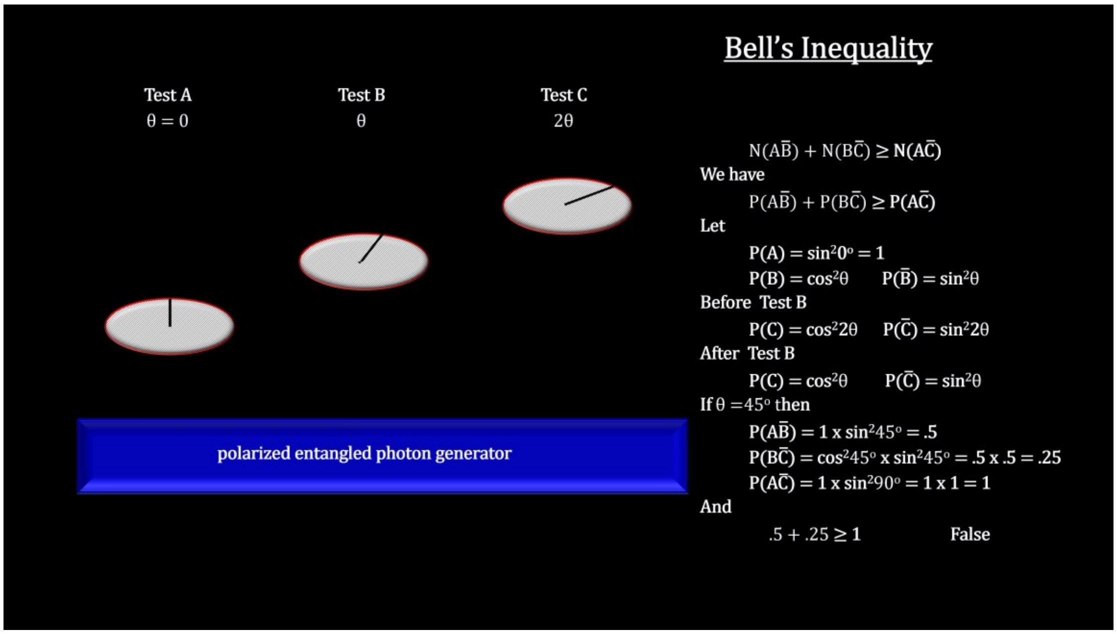
What Bell was looking for are the number passing test A followed by failing test B called (AnotB); the number passing test B followed by failing test C called (BnotC); and the number passing test A followed by failing test C called (AnotC).



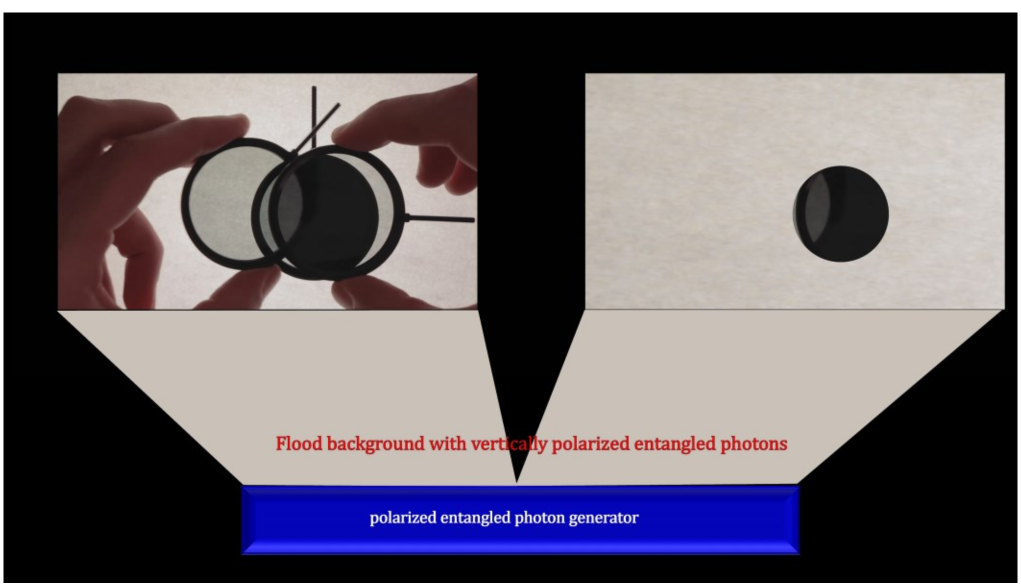
Now consider the 3 sets: set A of all the tests that passed test A, set B of all the tests that passed test B, and set C of all the tests that passed test C. Notice where they overlap and where they don't. Here's the subset (A not B) and (B not C). When we combine them, you can see that 'A not C' is a subset. From set theory we know that the number in (A not B) + the number in (B not C') must be greater or equal to the number in (A not C). This is the famous Bell Inequality.



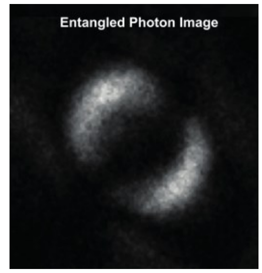
Remember that our assumption is that the states of the entangled particles depend only on their original 'hidden variables' and cannot change just because there was a measurement taken on the other particle. Being a thought experiment, we cannot actually run the tests and count the results. But we can use the quantum state probabilities to compute the results for these 3 numbers. For an angle of 45° we get .75 ≥ 1. Clearly not true. This is called a "Bell Violation". It tells us that the assumption that states are determined by 'hidden variables' must be false.



The problem is that complex thought experiments like this are filled with assumptions and loopholes. And, in the 1960s, there was no known way to build an entangled photon generator. If we could create and manage such photons in large enough numbers, we could flood volumes and see the entanglement behavior directly. As of now this is not possible.

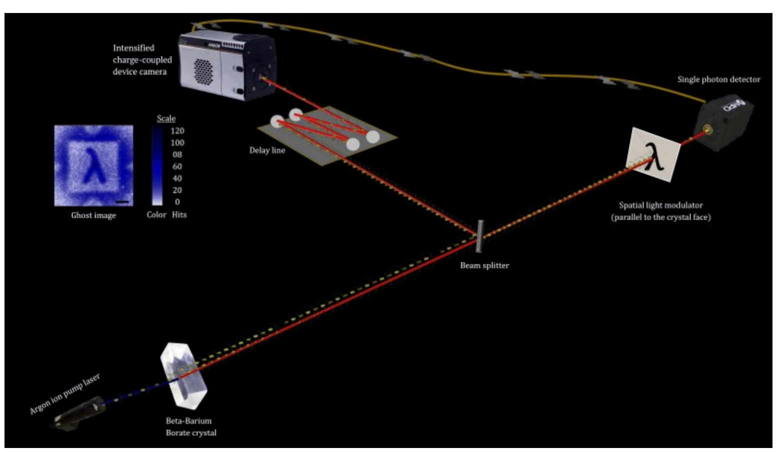


But today we can produce entangled photons at will and see the states of entangles particles change.

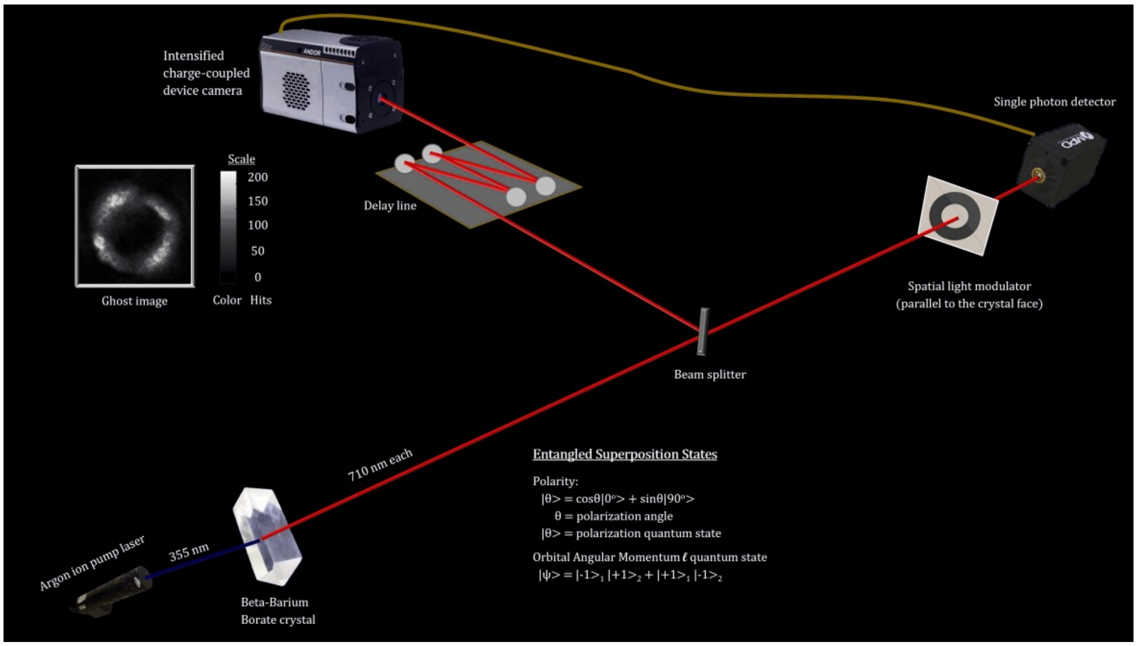


Quantum Ghost Images **[Music:** Svendsen - Romance in G**]**

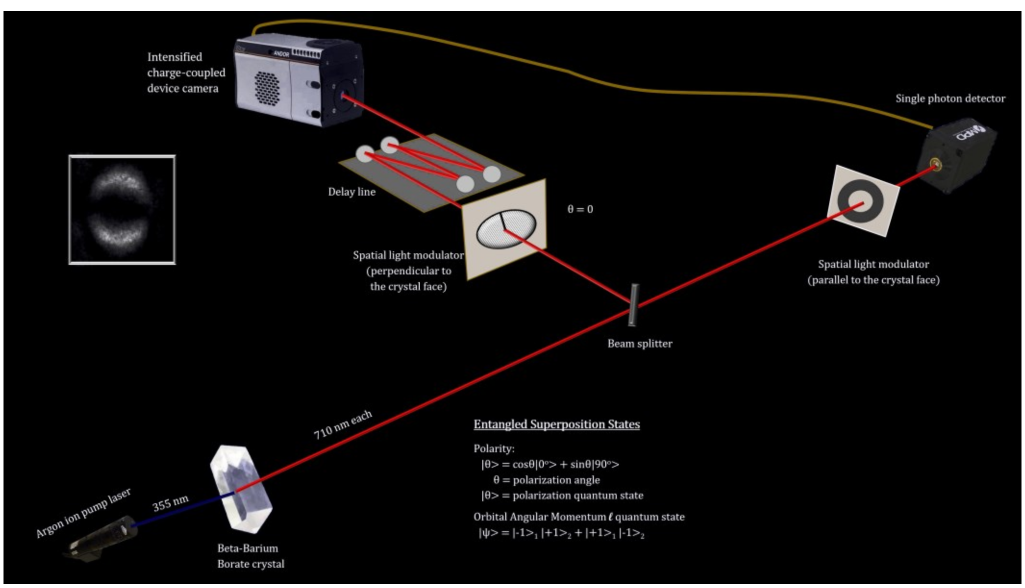
In 2019, a team of physicist at the University of Glasgow devised an actual experiment that used ‘ghost images’ to prove quantum entanglement. First, we’ll cover what a ghost image is and how one is created. Then we’ll cover how they proved quantum entanglement via a Bell Inequality. Here we have an argon laser sending its output into a beta-barium borate crystal. These are unique crystals in that they can turn a photon into two entangled photons. The process is called ‘spontaneous parametric down-conversion’. A beam splitter separates the photons. One, called the ‘idler’ proceeds through a liquid crystal spatial light modulator. There are many types of such modulators. This one has a thin gold image of the Greek letter ‘lambda’ imbedded in silicon. Given the idler photons’ wavelength, they will pass through gold and be blocked by silicon. The photons that do pass through enter a single photon detector. This detector then sends a signal to the camera.-For each photon that travels to the spatial modulator, its entangled counterpart, called the ‘signal photon’ is guided to an intensified charge-coupled device camera. This is the kind of camera technology we see in modern telescopes. We cover how they work in the ‘How far away is it’ video book chapter on ‘Planetary Nebula Exploding Star’. There is a delay loop in the photon’s path to ensure that it enters the camera at exactly the same time that its entangled counterpart’s signal reaches the camera, if indeed it passed through the modulator. The match of one photon with one signal is called a coincidence count.-When the camera senses a photon and a signal simultaneously, it lights the corresponding image pixel. If the camera gets a photon without a signal, it ignores it. As you can see, over time, the ‘lambda’ image is constructed. This is called a ‘ghost image’. The light that creates it never encountered the object itself.



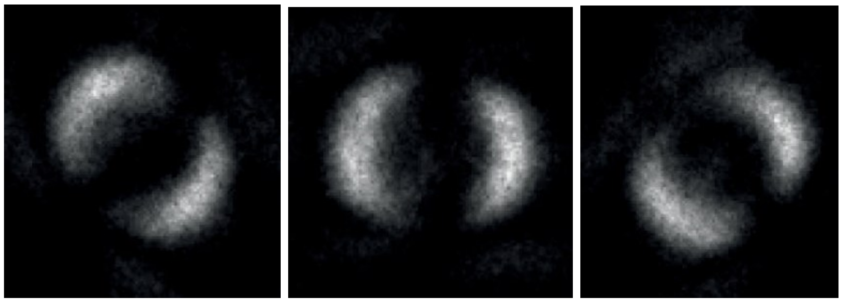
To ghost image a photon's polarization, the Glasgow team made some adjustment to this configuration to take advantage of the entangled polarization and the entangled orbital angular momentum created by the Beta-Barium Borate crystal. First, the image in the special modulator is replaced with what they call a 'phase object' that covers the outer edge of photon phase plane. This highlights the region of interest. If we ran with just this change, we'd see this ghost image.



The next step is to introduce a second spatial modulator on the 'signal' path of the photon heading to the camera. If the first angle is 0, we get this base image.

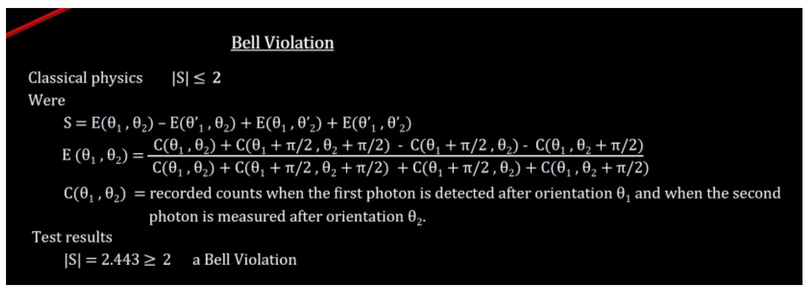


If we change the angle with a new special modulator, say one with a 45° angle the orientation of the image changes accordingly. This was done for 90° and 135°.

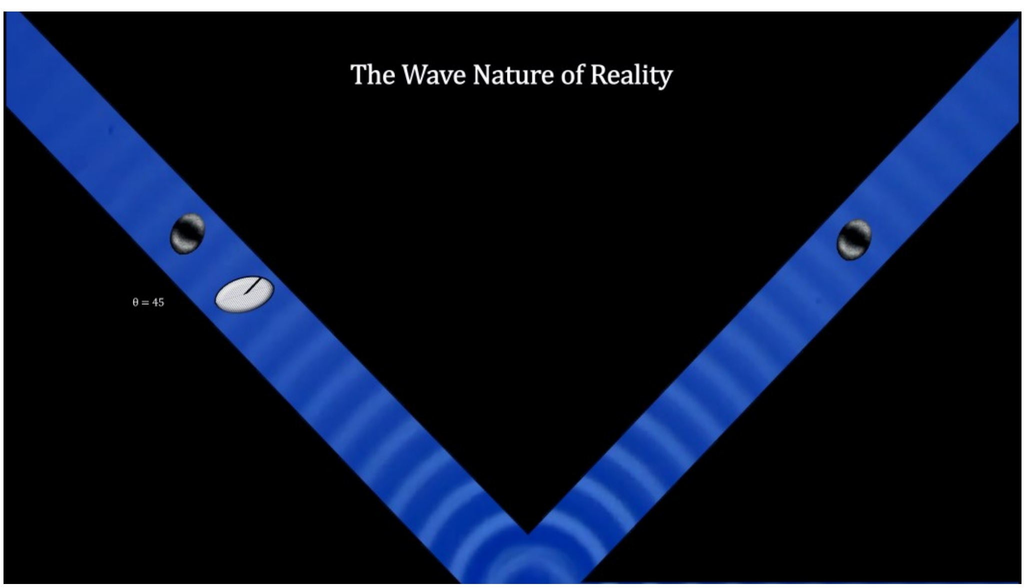


$\theta = 45^{o}$ $\theta = 90^{o}$ $\theta = 135^{o}$

Now the key to the experiment is that there is a relationship between the angular momentum of the photon and its orientation that shows itself in the light intensity profile – measured as the number of coincidence counts. In other words, the intensity features of the ghost image reveal entanglement. The counts show a Bell violation – proof that there are no hidden variables.

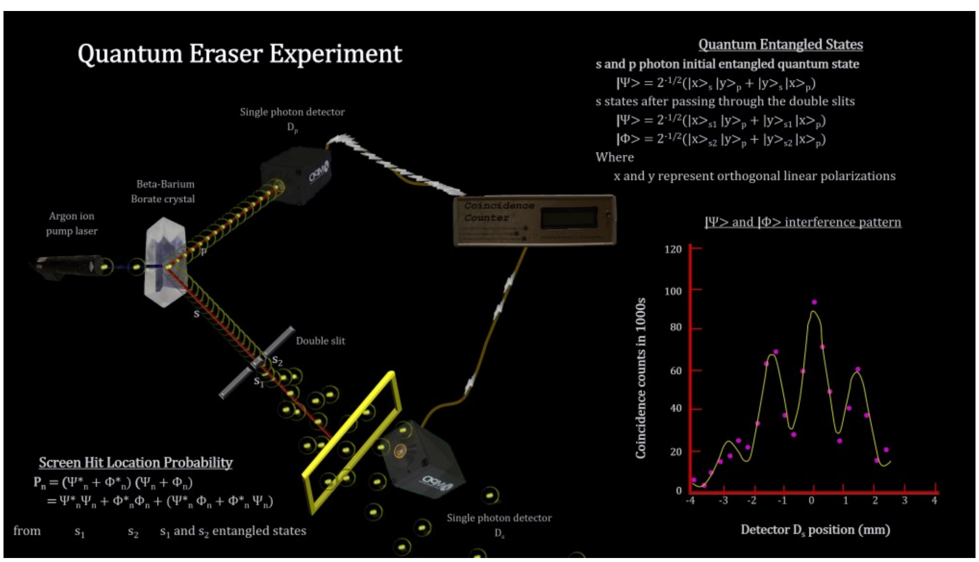


Therefore, we see that the entanglement is real, but it is not 'spooky action at a distance' as Einstein proposed. It is just the wave nature of reality as Bohr and proposed.

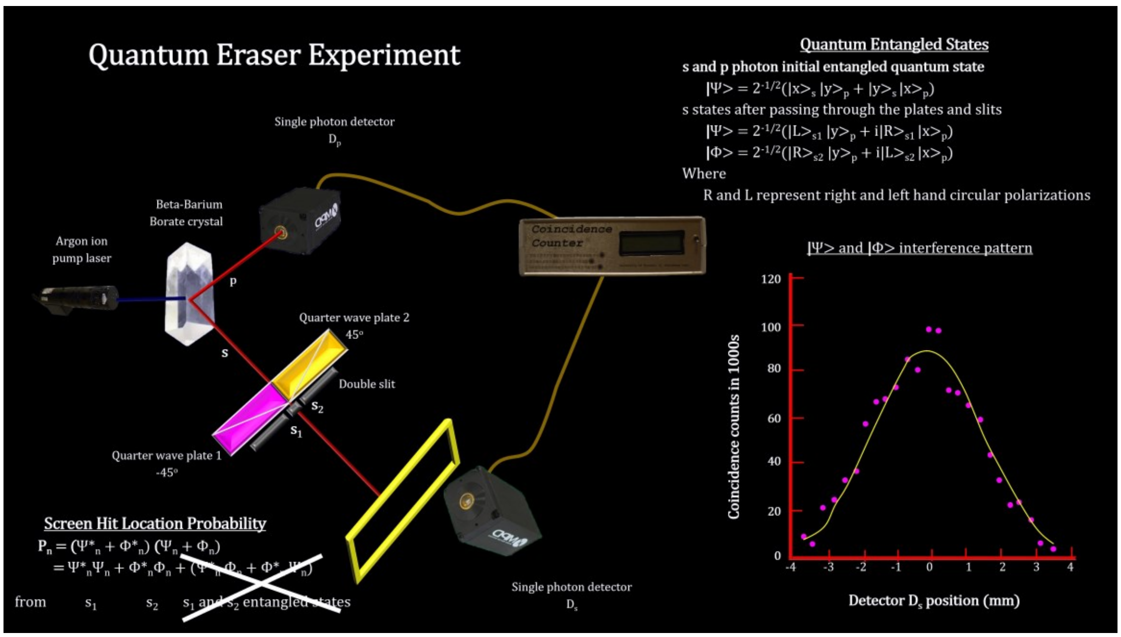


Quantum Eraser Experiment

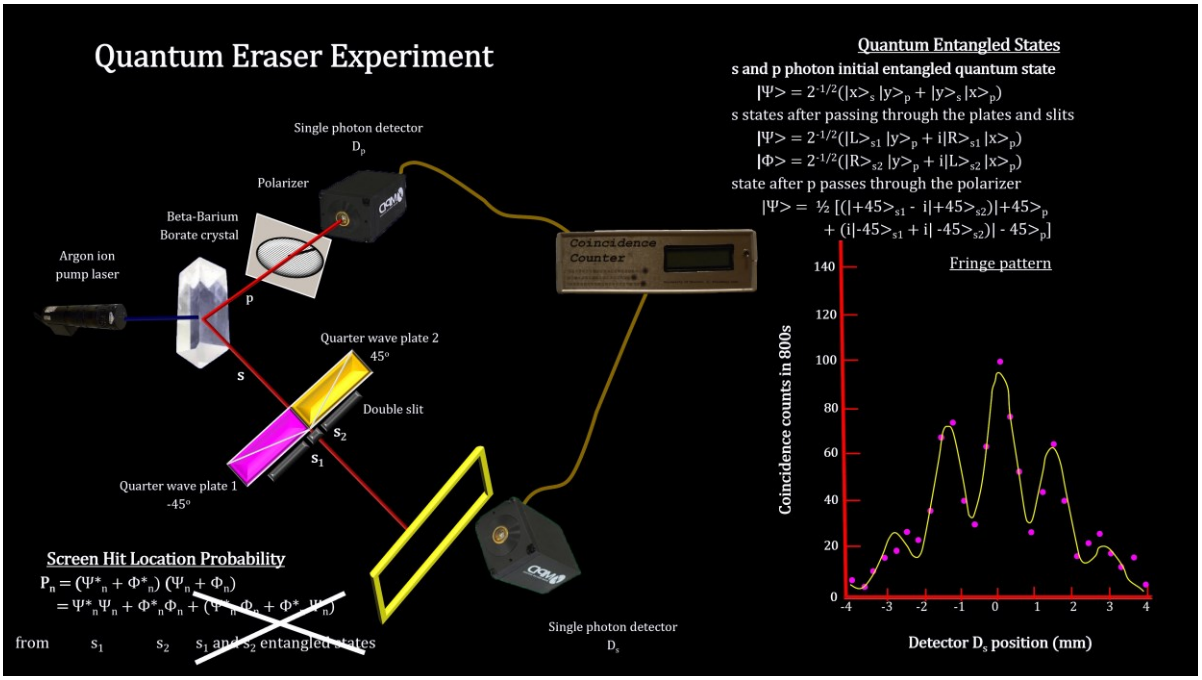
The following quantum eraser experiment was conducted by a team of physicist [S. P. Walborn, M. O. Terra Cunha, S. Padua, and C. H. Monken] at the Brazilian federal Universidad in Minas Gerais (mee·naas zhr·ise). It starts with the normal 'double slit' experiment like we saw earlier, but uses counters instead of a florescent screen to develop the interference patterns. Here we have a laser that feeds a Beta-Barium Borate crystal to create two entangled linearly polarized photons sent off in two directions. In this experiment, we call one direction *p* and the other *s*. The photons that go down path *p* are called *p* photons and those that go down *s* are called *s* photons. We'll label their linearly polarized quantum states x and y. Because they are entangled, they will travel with probabilities for these states without actually exhibiting them – much like the spinning coin's heads and tails. But we know that if the p photon is found to be in state x, then we know the s photon is in state y and vice versa. The p photons go directly to a single photon detector D_p. The detector registers the photon and sends a signal to a coincidence counter. The s photons go through a double slit. But instead of hitting a florescent screen, some enter a moveable single photon detector D_s. When it detects a photon, it too sends a signal to the coincidence counter. Once the Coincidence counter receives this second signal, a 'count' is recorded. The counts are tallied for 400 seconds. Then the detector is moved a millimeter and the number of counts in a 400 second interval is recorded for the new detector position. This is repeated until the detector has scanned across a region equivalent to the screen in a normal double slit experiment. The results are displayed by plotting the number of counts as a function of the detector's position. The interference pattern is clearly observed. As we did with the double-slit experiment, we keep in mind the quantum state of the particles, both initial and after the s photon passes through the double slit. Remember that it is the interaction between the two superposition states on the far side of the double slit that creates the interference pattern.



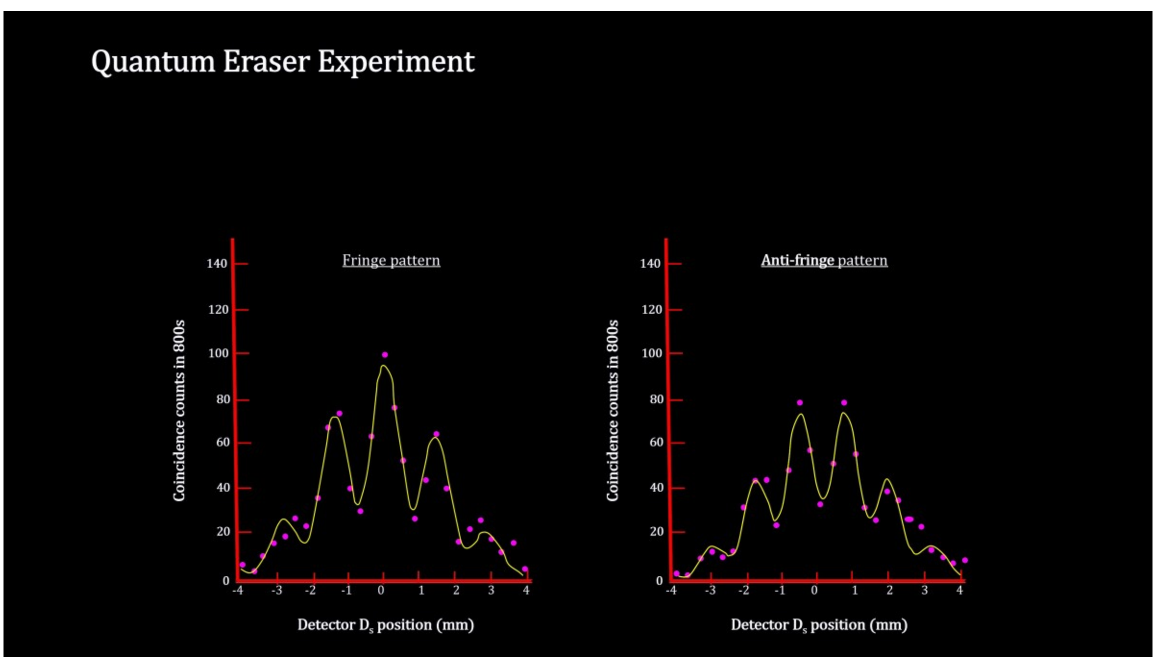
Like we did to provide 'which-way' information in the double slit experiment, we put quarter wave plates in front of each slit. Measuring the polarization at the detector tells us which slit the photon went through. Given the + or - 45° shifts created by the quarter wave plates, the two superposition states cancel each other out. We are left with just the two particle like probabilities. When the coincidence counts were tallied at each detector location, it was found that indeed the interference pattern was gone.



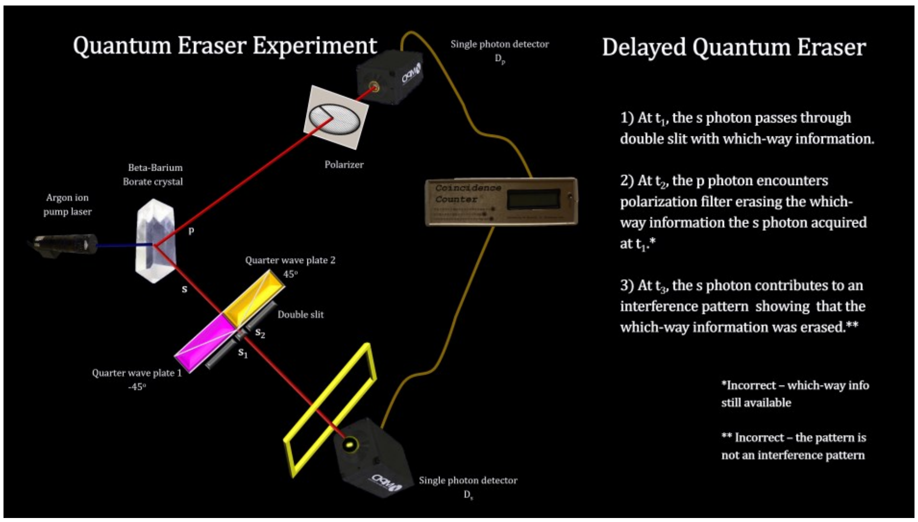
In order to regain an interference pattern, we place a polarizer in the *p* beam closer to the source crystal than the quarter wave plates oriented-at +45° (the same as plate 1) or -45° (the same as plate 2). This changes the p photon's state. The entangled s photon is modified as well, but maintains its linear polarity. Therefor it will still be turned into left or right circular polarity by the wave plates, and therefor still eliminate the interference pattern generating quantum state terms, and therefor still create the 'blob' rather than an interference pattern. But now we will no longer 'count' all the detected s photons. We count only the ones that corresponded to p photons that make it through the polarization filter. This will produce an interference like pattern that reflects what is going on with the p photons This is called a 'fringe' pattern.



When we do a run with the filter at -45°, we get the 'anti-fringe' pattern. Superficially, it looks like the situation that prevented interference has been erased. That is why this is called the 'quantum eraser'. But in fact, we see that nothing has been erased. When we add these two together, we get exactly the blob image we've created ever since we added the which-way information.

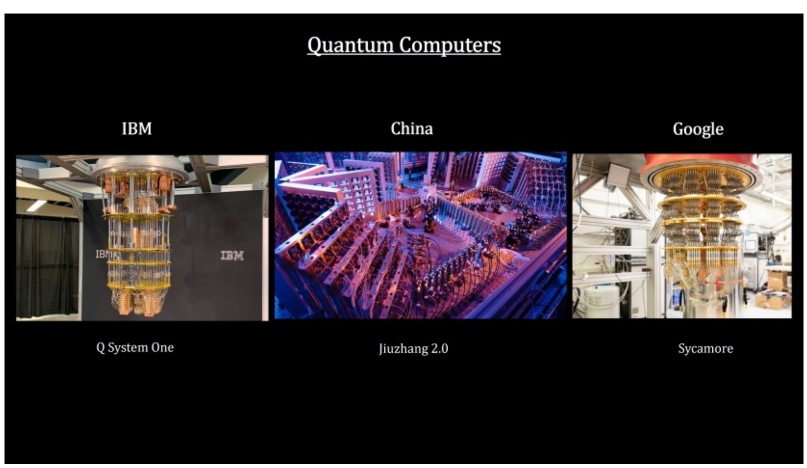


You may have already noted that having the p photon reach the polarizer before the s photon reaches the double slit is irrelevant. The exact same behavior happens if the s photon passes through the double slit before the p photon hits the filter or after. Again, fringe and anti-fringe patterns are produced. This setup is made to look like interacting with the p photon changed what happens to the entangled s photon in the past! This has been given its own name 'delayed quantum eraser' even though nothing has been erased. Many eraser experiments use beam splitters and adjusted path lengths to turn the blob into fringe and ant-fringe patterns. Either way, I find it very sad that some physicists characterize this experiment as an example of the cause coming after the effect.

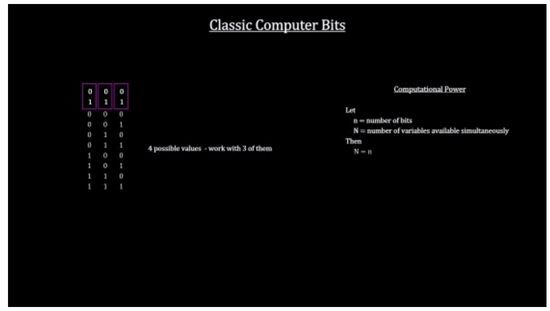


Quantum Computing

Developing experiments without loopholes to prove that the entanglement phenomenon is real has always been difficult. But there's nothing like actually using a phenomenon to remove all doubt. Quantum computing is doing just that for quantum linear superposition and entanglement. There is an amazing amount of work around the world going into the development of quantum computers and their subsystems. Here's just 3 of them. The superposition states and quantum entanglement covered in the preceding segments represent the foundational physics for quantum computing. In order to illustrate how this is the case, we'll actually construct a two-electron quantum computer.

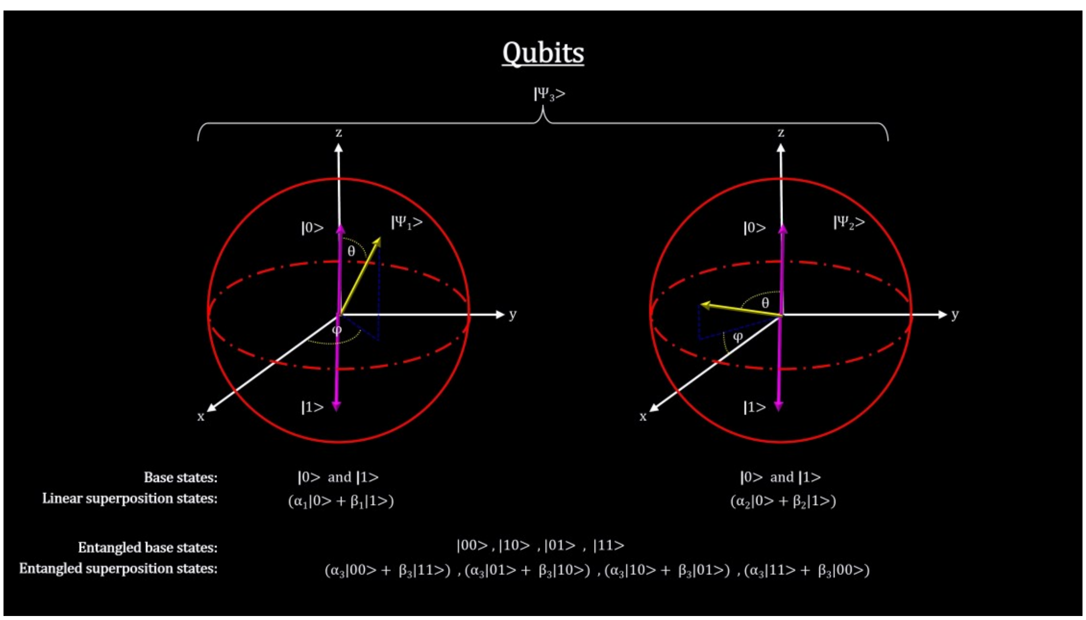


The key difference between classical computers and quantum computers starts with their basic unit of information. For classical computers it is the bit with 2 values per bit 0 or 1.

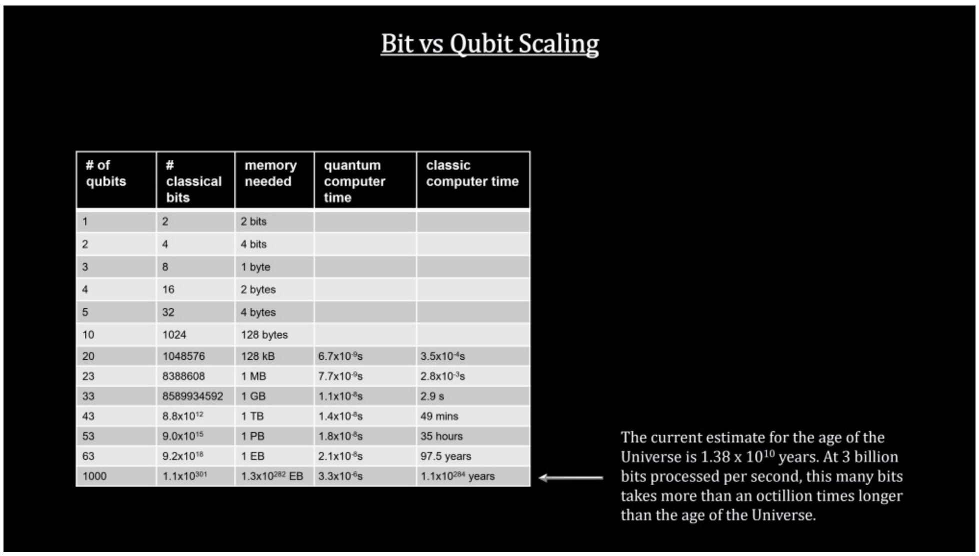


Quantum computers use quantum bits or qubits for short. And because of quantum linear superposition, a qubit has 4 values. For example, here's a state vector for the spin of an electron. It's position is determined by two angles that define its state. This state can be divided into 2 base states and 2 superposition states for a total of 4 – twice the number of possible values for classical bits. What's more, because of quantum entanglement, every time we add a qubit, we double the number of classical bits the entangled whole can represent.

[Going just a little deeper, we can start with Schrodinger's wave equation for the system. In quantum mechanics, a particle is represented by a wave function, Ψ. For electron spin, a quantum state for this function can be represented as a vector. When we put in coordinates, we get an angle from the vertical θ, and an angle on the x-y plane φ. We can construct two base vectors |0> and |1> where |0> is up and |1> is down along the vertical axis. The quantum state |Ψ> can be expressed as a combination of these two base states with appropriate coefficients that represent 'amplitudes'. These amplitudes give us probabilities when the states are squared. These are the superposition states.**]**



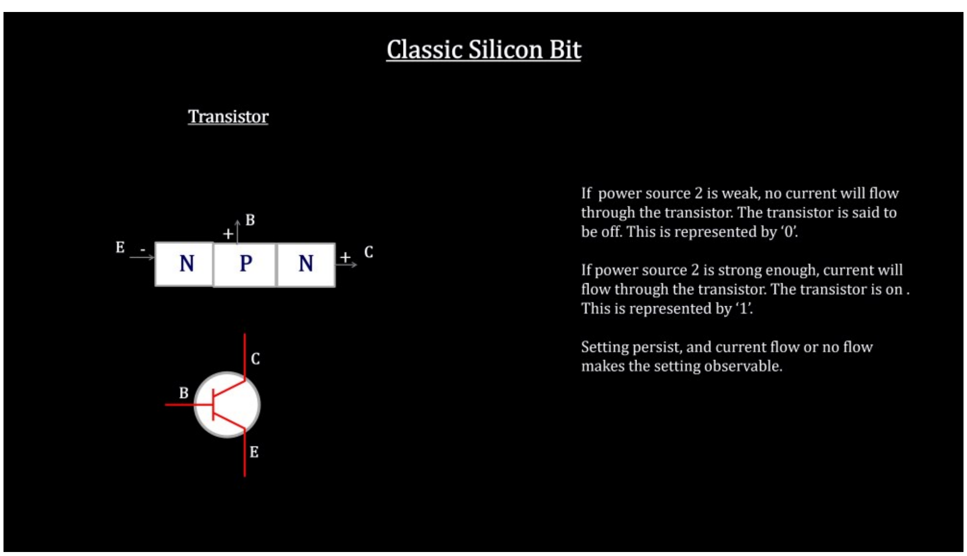
Here's a table that compare classical computer bits to qubits. 3 qubits are equivalent to 8 bits - a full byte. This scaling grows into significant numbers as the number of qubits are increased. The real impact comes when we start talking about hundred or even a thousand qubits. This exceptional scaling for the qubits has a significant impact on the time computer operations will take. For example, let's assume we have a computer with a clock speed of 3 GHz. It could perform 3 billion operations per second. Let's also assume one operation on one bit or qubit can be done in one clock cycle. These numbers are a little optimistic but they provide an order of magnitude estimate. This scaling potential is what's motivating the development of quantum computers.


Bit vs Qubit Scaling

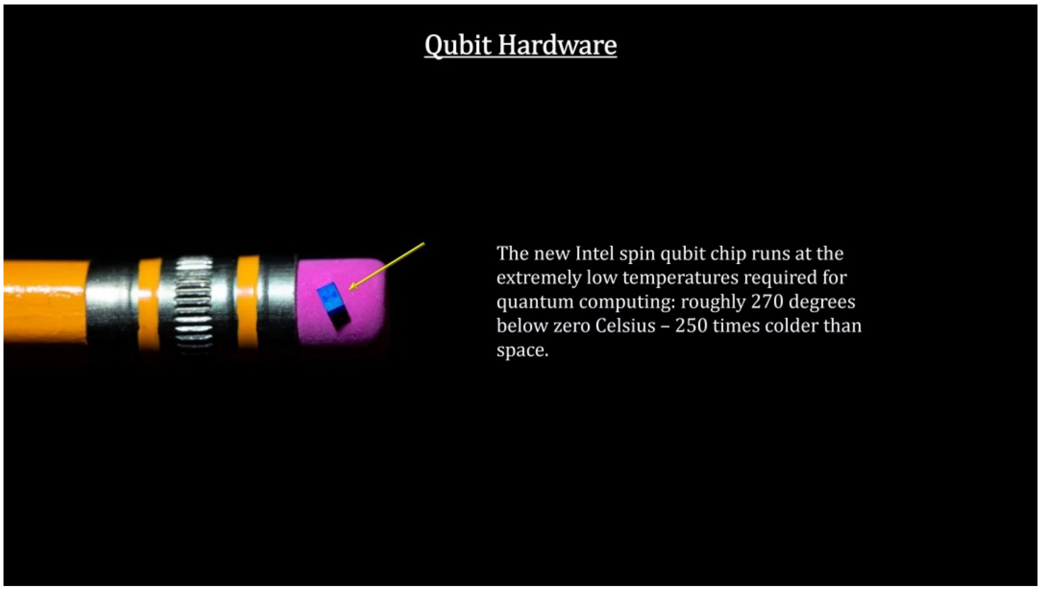
# of qubits	# classical bits	memory needed	quantum computer time	classic computer time
1	2	2 bits		
2	4	4 bits		
3	8	1 byte		
4	16	2 bytes		
5	32	4 bytes		
10	1024	128 bytes		
20	1048576	128 kB	6.7×10^{-9}s	3.5×10^{-4}s
23	8388608	1 MB	7.7×10^{-9}s	2.8×10^{-3}s
33	8589934592	1 GB	1.1×10^{-8}s	2.9 s
43	8.8×10^{12}	1 TB	1.4×10^{-8}s	49 mins
53	9.0×10^{15}	1 PB	1.8×10^{-8}s	35 hours
63	9.2×10^{18}	1 EB	2.1×10^{-8}s	97.5 years
1000	1.1×10^{301}	1.3×10^{282} EB	3.3×10^{-6}s	1.1×10^{284} years

The current estimate for the age of the Universe is 1.38×10^{10} years. At 3 billion bits processed per second, this many bits takes more than an octillion times longer than the age of the Universe.

A bit has to be able to have its settings of 0 or 1 set or changed and have these settings persist over time. It's setting must also be detectable. In classical computers, bits are made of transistors. For a transistor, the absence of a voltage on its control line stops current from passing through - making it 'off' or = 0. An applied voltage will trigger a current making it 'on' or = 1. These values are easily set, changed, and read and once set they persist for as long as needed.



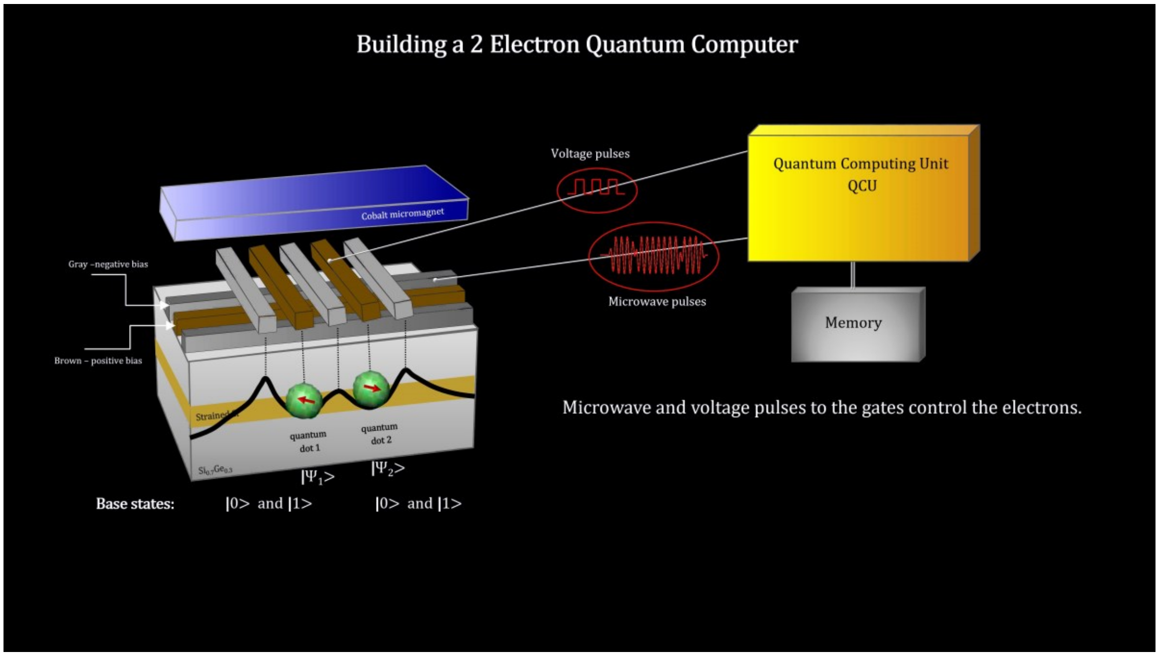
There are a number of ways to create quantum bits: atoms, photons, superconductors etc. Silicon spin qubits are also promising. A number of companies are working on them. As of early 2022, Intel appears to have the lead with a 26-qubit product. The long-term goal is to reach a million.



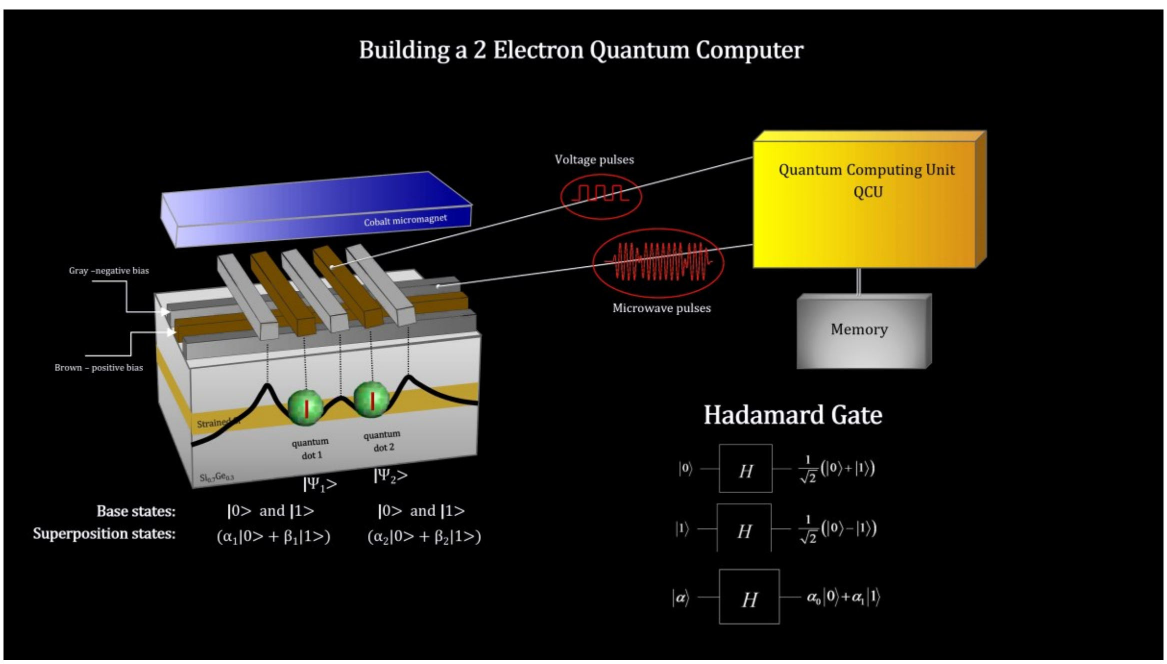
To understand how quantum superposition and entanglement are used, we'll construct a quantum computer out of two electron spin qubits. We start with three layers of silicon. The yellow layer in the middle is made of 'stretched' silicon. It is actually stretched. The distance between the atoms is increased making it easier for electrons to move around. Electrons in this layer will not move up or down into the more compressed silicon without a push.

On top of the silicon, we construct an electronically controlled lattice of gates. Negatively biased electrostatic gates (in gray) and positively biased gates (in brown) are organized to create two energy wells capable of holding two electrons in place. These two wells are called quantum dots. On top of these two components, we add a micromagnet to create a tapered magnetic field. This field couples electron spins to the electric field set up by the gates. With this configuration, we can introduce two electrons.

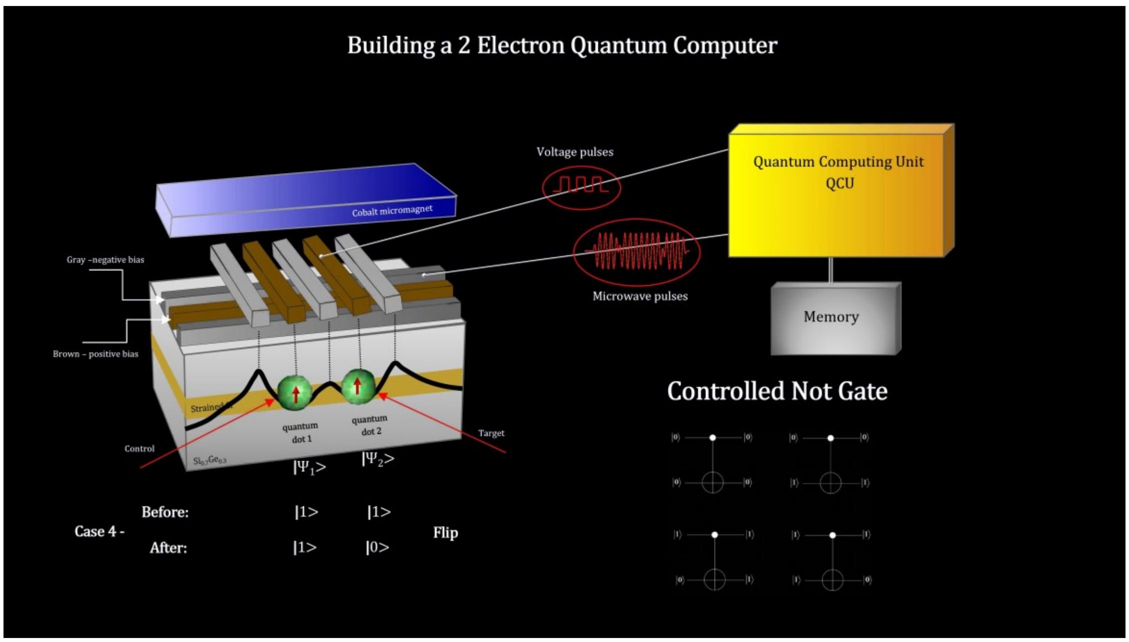
The states of these electrons are controlled by microwave and voltage pulses applied to the gates by the Quantum Computing Unit. For example, electron spin can be aligned with the magnetic field in the up or down direction. And the two electrons can also be put into an entangled state by managed exchange interactions across the Coulomb barrier between them.



An important operation is called the Hadamard Gate. It takes in a single qubit in a base state as input and outputs a Qubit in a superposition state with equal coefficients. [That would be a state where, if measured, it has a 50–50 chance of either being a 1 or a 0.] This qubit can then be used in further calculations.

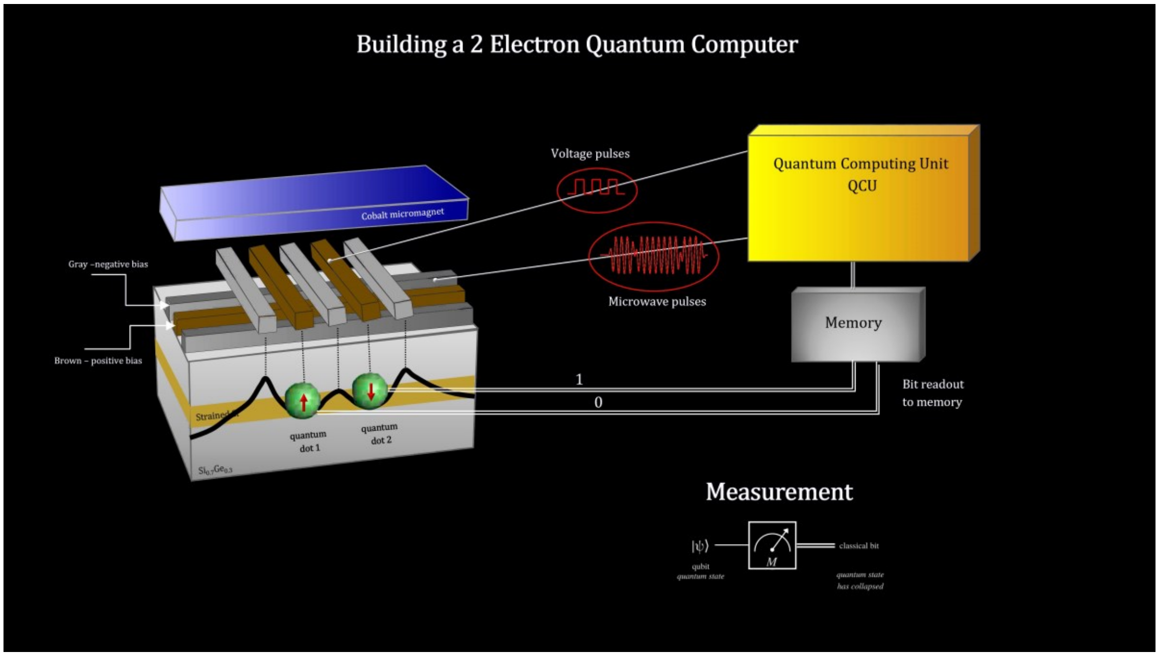


The Controlled NOT gate or CNOT Gate is heavily used. It takes in 2 Qubits and only flips the second Qubit called the target from $|0\rangle$ to $|1\rangle$ or $|1\rangle$ to $|0\rangle$ if the first Qubit called the control is $|1\rangle$. Otherwise, it leaves the target unchanged. Taking advantage of the fact that up = 0 has a slightly lower energy than down = 1, a series of microwave pulses will flip the target qubit only when the control qubit had enough energy to have measured as a 1. This is the function of CNOT and it is done without reading the control qubit. Like changing a photon's polarity, this can be done for any number of entangled qubits without disturbing the entanglement state. This is the case for all quantum gates.

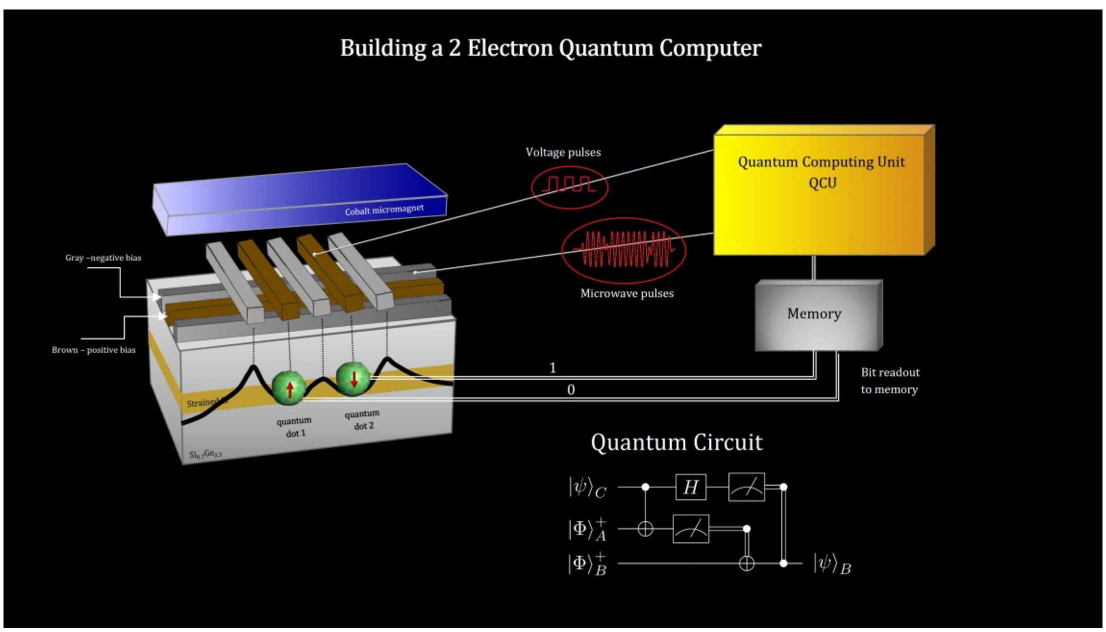


Measurement is a special type of operation done on qubits at the end of a series of gate operations to get the final values. In a magnetic field, electrons have two discrete energy levels based on their spin. [Spin up has a lower energy level than spin down.] Detecting these energy levels tells us what the spin was. Compared to the gates, Measurement is irreversible and hence, is not actually a Quantum Gate. It's execution removes the qubit from its entangled superposition state into a 0 or a 1. The results of a measurement are always stored in classical computer bits for analysis.

[A magnetic field is applied to split the spin-up and spin-down states by the Zeeman energy. The dot potential is then tuned such that if the electron has spin-down arrow, it will leave, whereas it will stay on the dot if it has spin-up. The spin state has now been correlated with the charge state, and measurement of the charge on the dot will reveal the original spin state.]

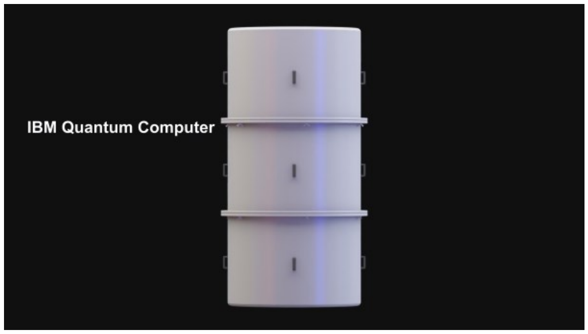


Combinations of quantum gates are called quantum circuits that combine to execute computer instructions. This is a 2 electron-spin qubit quantum computer.

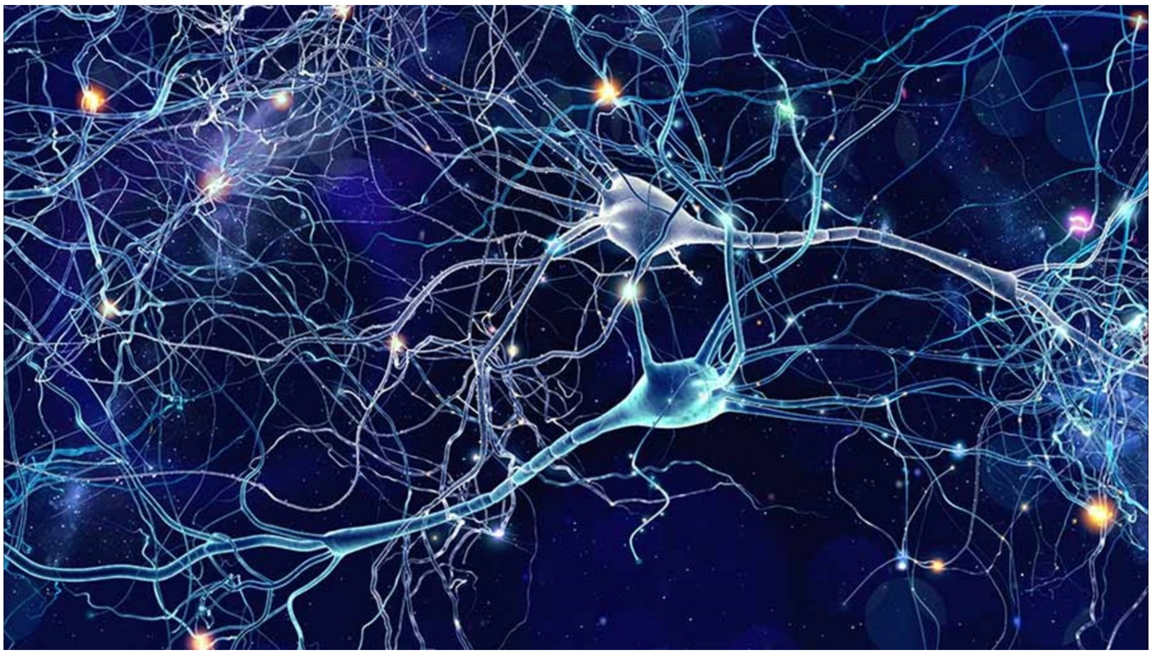


Quantum dot states are extremely fragile. The slightest vibration or change in temperature can cause them to tumble out of superposition causing errors – lots of errors.

That's why in order to best protect qubits from the outside world they are housed in supercooled fridges and vacuum chambers. This makes them very expensive compared to classic computers. Because of this, it is expected that quantum computers will only work on those problems that need a gigantic number of bits: jobs like factoring extremely large numbers.



Schrodinger pointed out that superposition and entanglement are the two primary characteristics of the quantum world. And whenever particles find themselves close together, they will become entangled - creating unobservable quantum states.



Music:

@00:00 Bach - Flute Concerto in B Flat, Adagio; conducted by Eckart Haupt; from the album Meditation: Classical Relaxation, 2010

@13:21 Puccini - La Bohéme Act II- Musette Waltz; Sofia Philharmonic Orchestra; from the album 100 Must-Have Italian Opera Highlights, 2014

@26:50 Svendsen - Romance in G; Miklos Szenthelyi; from the album Meditation: Classical Relaxation, 2010

2^{100} is 1,267,650,600,228,229,401,496,703,205,376.
In the US number naming system, it is one nonillion, 267 octillion, 650 septillion, 600 sextillion, 228 quintillion, 229 quadrillion, 401 trillion, 496 billion, 703 million, 205 thousand, 376.

Greek letters:
- α β γ δ ε ζ η θ ι κ λ μ ν ξ ο π ρ σ τ υ φ χ ψ ω
- Α Β Γ Δ Ε Ζ Η Θ Ι Κ Λ Μ Ν Ξ Ο Π Ρ Σ Τ Υ Φ Χ Ψ Ω

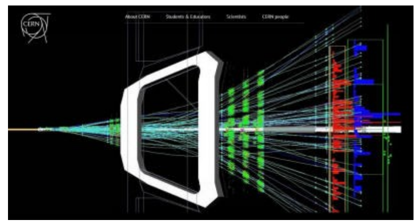
⇒ → ± ⊙ ∞ ↛ ∃ ∄ ∈ ∉ ∬ ∫ ≅ ≥ ≤ ≈ ≠ ≡ √ ∛ ~ ∝ ħ ÷ ∂ ⊥

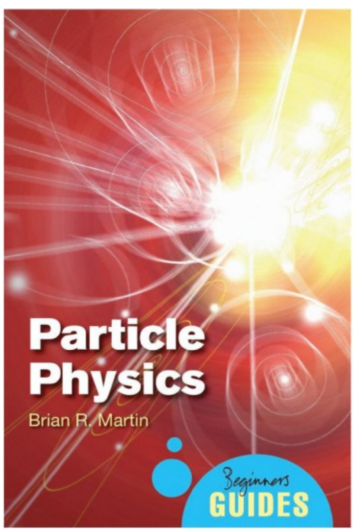
Credits and Research

Here's the list of sources I used to put together the "How small is it" video book. These books, videos, and websites also represent resources you can use to do additional research into areas touched on in this video book.

> **[Music:** *Igor Stravinsky – "The Firebird" – Written in 1910, the ballet is based on Russian folk tales of the magical glowing bird that can be both a blessing and a curse to its owner.***]**

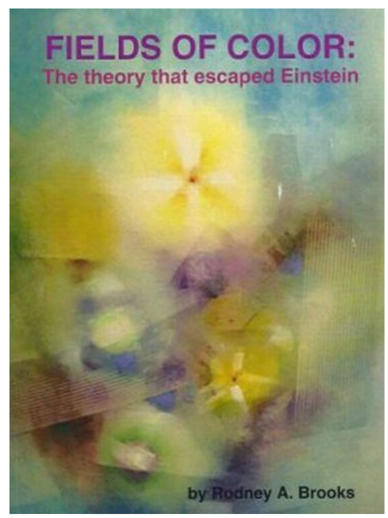
First is the CERN website itself. It has a wealth of information on Higgs and other areas of research I think you'll find very interesting. It also has great content for students and teachers.





There are two books I used extensively. One is "FIELDS OF COLOR: The theory that escaped Einstein" by Rodney Brooks. It's a really good book on Quantum Field Theory explained without any math.

The other is Particle Physics by Brian Martin. It is jam packed with info on particles and particle accelerators.



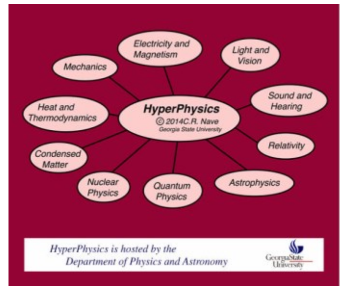
There is a great video series on YouTube from Stanford University presented by Leonard Susskind. I used it extensively and I think you'd find it fascinating –especially the finally on Demystifying the Higgs Boson.

STANFORD UNIVERSITY

http://www.youtube.com/watch?v=JqNg819PiZY

HyperPhysics

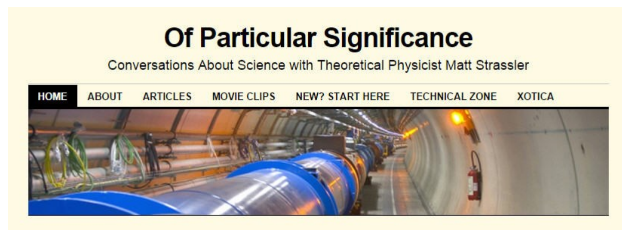
HyperPhysics is the physics department website for Georgia State University. It is a very good site with clear explanations for quarks, gluons, color charge, Feynman diagrams and more.



http://hyperphysics.phy-astr.gsu.edu

Of Particular Significance

This is Professor Matt Strassler's website. I's an excellent site with a wealth of information on particle physics from a particle physicist. I used it extensively in the Higgs Boson segment.



http://profmattstrassler.com/

The following identifies all my sources.

Thanks for watching.

Websites

Optical microscope http://www.popsci.com/technology/article/2011-03/worlds-most-powerful-optical-microscope-can-let-researchers-see-inside-viruses-and-human-cells-no-ele

Head Louse http://education.nationalgeographic.com/education/media/human-body/?ar_a=1

Larva of Asian Tiger Mosquito http://www.fei.com/_template/Images/ImagePage.aspx?id=2147483677

Secrets Of Human Body http://humanbodysecrets.blogspot.com/2012/07/microscopic-images.html

Visual http://wonderopolis.org/wonder/what-is-the-smallest-thing-you-can-see/

Microsphere nanoscope http://www.nanowerk.com/spotlight/spotid=33865.php

Electron microscope
http://uic.igc.gulbenkian.pt/micro-em.htm
http://en.wikipedia.org/wiki/Scanning_electron_microscope

Texture of the skin of a spider. María Carbajo
http://iliketowastemytime.com/2013/03/16/very-best-of-macro-photography-pt6-10-pics

Basic Science Partnership, Harvard medical School http://bsp.med.harvard.edu/node/221

The Daya Bay Neutrino Experiment http://www.interactions.org/cms/?pid=2100&image_no=LB0056

A bubble chamber track. (Courtesy of Fermilab Visual Media Services)
http://www.interactions.org/cms/?pid=2100&image_no=FN0141

Welcome to the Higgs site at the University of Edinburgh http://www.ph.ed.ac.uk/higgs/

Young double slit experiment http://physics.about.com/od/lightoptics/a/doubleslit.htm

Gamma Ray Burst

http://www.theregister.co.uk/2013/11/21/scientists_spot_bigger_ever_gamma_ray_burst_from_birth_of_black_hole/

University of California, Lawrence Berkeley National Laboratory Antiproton – proton collision

http://photos.lbl.gov/viewphoto.php?&albumId=341513&imageId=9067377&page=1&imagepos=12&sort=&sortorder=

Discovery of W at CERN
http://www.interactions.org/cms/?pid=2100&image_no=CE0015

W and Z discoveries http://www.interactions.org/

Understanding Bubble Chambers (very good) https://teachers.web.cern.ch/teachers/archiv/HST2005/bubble_chambers/BCwebsite/

CERN documents http://cds.cern.ch/record/1373706

Brian Koberlein's blog: A Puff of Logic http://briankoberlein.com/2014/06/25/puff-logic/#more-3391

Drum Vibrations - Oleg Alexandrov - self-made with MATLAB, http://en.wikipedia.org/wiki/Atomic_orbital

Ultraviolet Coverage of the Hubble Ultra Deep Field (UVUDF) project. -
http://www.spacetelescope.org/images/heic1411a/

Transverse Zeeman effect.jpg - http://commons.wikimedia.org/wiki/File:Transverse_Zeeman_effect.jpg

Microscopes - http://wonderopolis.org/wonder/what-is-the-smallest-thing-you-can-see/

Comet resolution - http://hubblesite.org/newscenter/archive/releases/2014/19/image/a/

Wave pattern for particles
http://www.livescience.com/19261-quantum-weirdness-big-molecules-act-waves-video.html

International Master Class – Hands on Particle Physics
http://cms.physicsmasterclasses.org/pages/cmswz.html

Quantum Diaries – great place for QED and Feynman diagrams
http://www.quantumdiaries.org/tag/qed/

Excellent particle physics site with pages for teachers
http://www.particleadventure.org/index.html

The CERN website with pages for teachers in multiple languages
http://home.web.cern.ch/

The Standard Model of Electroweak Physics, Christopher T. Hill, Head of Theoretical Physics Fermilab
http://users.phys.psu.edu/~cteq/schools/summer07/hill/HillCTEQ1.pdf

The Rutherford Atom
http://www.personal.soton.ac.uk/ab1u06/teaching/phys3002/course/02_rutherford.pdf

The Bohr Atom
https://opentextbc.ca/chemistry/chapter/6-2-the-bohr-model/

Schrodinger's equation
https://scholar.harvard.edu/files/david-morin/files/waves_transverse.pdf
https://courses.lumenlearning.com/boundless-physics/chapter/introduction-9/#:~:text=Sine%20Wave,-Plot%20of%20Sine&text=A%20general%20form%20of%20a,sine%20wave%20given%20in%20radians

Scanning Tunneling Electron Microscope (STM)
http://hoffman.physics.harvard.edu/research/STMintro.php

Schrodinger's Atom
https://chem.libretexts.org/Courses/University_of_California_Davis/UCD_Chem_107B%3A_Physical_Chemistry_for_Life_Scientists/Chapters/4%3A_Quantum_Theory/4.10%3A_The_Schr%C3%B6dinger_Wave_Equation_for_the_Hydrogen_Atom#:~:text=The%20hydrogen%20atom%2C%20consisting%20of,particle%20with%20a%20reduced%20mass.

[Sudbury Neutrino Observatory in Ontario Canada http://web.mit.edu/josephf/www/nudm/SNO.html

IceCube Neutrino Observatory at the South Pole https://www.pri.org/stories/2018-03-18/new-book-recounts-amazing-history-icecube-neutrino-observatory

Jiangmen Underground Neutrino Observatory (JUNO) in southern China, about 150 kilometers west of Hong Kong

https://www.scientificamerican.com/article/powerful-new-observatory-will-taste-neutrinos-flavors/

Borexino, one of the most sensitive neutrino detectors on the planet, located deep beneath Italy's Apennine Mountains. https://www.cns.umass.edu/news-events/news/complete-spectrum-suns-neutrinos-captured-first-time

DUNE under construction. https://www.dunescience.org/]

Probing the Proton

http://www.hep.manchester.ac.uk/u/ukyang/fpp2/dis/dis_lec1.pdf

https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.23.930

https://cds.cern.ch/record/2714080

https://videos.cern.ch/record/2715476

http://hyperphysics.phy-astr.gsu.edu/hbase/Particles/quark.html

https://physicsworld.com/a/the-spin-of-a-proton/

Color Charge
https://webhome.phy.duke.edu/~kolena/modern/kim.html

https://www.researchgate.net/publication/277931428_ATLAS_physics_prospects_for_the_upgraded_LHC/download

YouTube credits:

Euglena veridis – x1000 http://www.youtube.com/watch?v=sYupCQT46cI

Bees Under Electron Microscope http://www.youtube.com/watch?v=ETbeYUcfYU0

Deep Inelastic Scattering https://www.youtube.com/watch?v=ETbmjDeLo5k

Photons, Gravitons & Weak Bosons | Standard Model Of Particle Physics
https://www.youtube.com/watch?v=JHVC6F8SOFc

Quarks | Standard Model Of Particle Physics
https://www.youtube.com/watch?v=PxQwkdu9WbE&index=4&list=PL4A8C50311C9F7369

Gluons | Standard Model Of Particle Physics
https://www.youtube.com/watch?v=ZYPem05vpS4&index=5&list=PL4A8C50311C9F7369

Electrons, Protons And Neutrons | Standard Model Of Particle Physics
https://www.youtube.com/watch?v=Vi91qyjuknM&list=PL4A8C50311C9F7369&index=6

Neutrinos | Standard Model Of Particle Physics
https://www.youtube.com/watch?v=m7QAaH0oFNg&index=8&list=PL4A8C50311C9F7369

'The God Particle': The Higgs Boson
https://www.youtube.com/watch?v=1_HrQVhgbeo&index=9&list=PL4A8C50311C9F7369

Quantum Mechanics 8b - Spin II https://www.youtube.com/watch?v=1cUUSq3jARE

The Zeeman Effect https://www.youtube.com/watch?v=TJrej02BmQA#t=43

Scanning Tunneling Electron Microscope (STM)
https://www.youtube.com/watch?v=VP22wD_PHvs

https://www.youtube.com/watch?v=i15ef618DP0 Nuledo Cloud Chamber

Probing the Proton

https://www.youtube.com/watch?v=GZzrMyY01tE

https://www.youtube.com/watch?v=328pw5Taeg0

CERN

https://www.youtube.com/watch?v=1nNq1tS9QNE

BestOfScience series

Quantum Mechanics: The Structure of Atoms
http://youtu.be/-YYBCNQnYNM

Quantum Mechanics: The Uncertainty Principle
http://youtu.be/Fw6dI7cguCg

Quantum Mechanics Part 3 of 4: Shells
https://www.youtube.com/watch?v=Q9Sl1PYSyOw

Quantum Mechanics Part 4 of 4 - Electron Spin
https://www.youtube.com/watch?v=28Xe4FCCjt4

Waves on a string Dr James Dann, Nicole Yee, and Brad Ecert
https://www.youtube.com/watch?v=-gr7KmTOrx0

Newton's corpuscular theory of light
https://www.youtube.com/watch?v=uO2uyvf-E3k

Rise of the atomic orbitals
https://www.youtube.com/watch?v=OkDYbIhisZE

Types of radiation and radioactive decay
https://www.youtube.com/watch?v=vuGvQjCOdr0

Slow motion water drop
https://www.youtube.com/watch?v=QQ37RLXNAgc

Double Slit Experiment explained by Jim Al-Khalili
http://www.youtube.com/watch?v=A9tKncAdlHQ

SPIN VA
http://www.youtube.com/watch?v=uqDlIgUDEIA#t=3

New Revolutions in Particle Physics: Basic Concepts (Leonard Susskind Stanford University lectures)
http://www.youtube.com/watch?v=2eFvVzNF24g&list=PL4E35E60B6EF36216

Demystifying the Higgs Boson with Leonard Susskind
http://www.youtube.com/watch?v=JqNg819PiZY

Origin of Mass - Search for the Higgs
http://www.youtube.com/watch?v=JBhAjTpx_Os&list=TLwgSidC27rok_afyjxPUmBi6ecfbx8zl8

Jets of Particles http://www.youtube.com/watch?v=8H8HdaMAVhY

Higgs decay into 2 photons http://www.youtube.com/watch?v=51XK4YeNEn8

Event with 2 protons http://www.youtube.com/watch?v=bTdMUJZr4Fs

Event with 4 muons http://www.youtube.com/watch?v=G4O3ciWHVdg

Event with Two Electrons and Two Muons http://www.youtube.com/watch?v=HCFqVpLz8j8

Higgs Boson http://www.youtube.com/watch?v=JBhAjTpx_Os

Creating a black hole http://www.youtube.com/watch?v=AHT9RTlCqjQ

Quantum Physics | The Fabric of the Cosmos http://www.youtube.com/watch?v=tgH8_GjFXT4

Spooky Actions At A Distance: Oppenheimer Lecture http://www.youtube.com/watch?v=ta09WXiUqcQ

Cosmic Voyage http://www.youtube.com/watch?v=qxXf7AJZ73A

A Microscopic Tour of My Back Yard – Craig Smith http://www.youtube.com/watch?v=M8NYDU4t8Aw

The World's Most Powerful Microscope - KQED QUEST http://www.youtube.com/watch?v=sCYX_XQgnSA

Visualizing Mechanics: Natural Frequency of a Spring-Mass System
https://www.youtube.com/watch?v=lZPtFDXYQRU

Simple harmonic motion https://www.youtube.com/watch?v=SZ541Luq4nE

Quark Gluon plasma https://www.youtube.com/watch?v=7kChj3Wu4G0

Books

Rodney A. Brooks, "Fields of Color: The theory that escaped Einstein" Epic Publications 2010

Brian Cox and Jeff Forshaw, "The Quantum Universe" DaCapo Press 2011

Brian Green, "The Elegant Universe Superstrings - Hidden Dimensions and the Quest for the Ultimate Theory" W. W. Norton & Company 2003

Stephen Hawking, "The Universe in a Nutshell" Bantam 2001

Albert Einstein, "The Meaning of Relativity "Princeton University Press 1956

Gerard G. Emech, "Algebraic Methods in Statistical Mechanics and Quantum Field Theory" Wiley-Intersicence 1972

Arthur Beiser, "Perspectives of Modern Physics" McGraw-Hill 1969

Jerry B. Marion, "Classical Dynamics of Particles and Systems" Academic Press 1970

Richard T. Weidner & Robert L. Sells, "Elementary Modern Physics" Allyn and Bacon, Inc. 1969

C. Moller, "The Theory of Relativity" Clarendon Press 1972

Papers

"Sub Microscopic Description of the Diffraction Phenomenon" Volodymyr Krasnoholovets, Nonlinear Optics and Quantum Optics, Vol. 41, pp. 273–286, ©2010 Old City Publishing, Inc.

"On the Wave Function of the Photon" Bialynicki Birula, Proceedings of the International Conference "Quantum Optics", Szczyrk, Poland, 1993

"High Energy Inelastic e-p Scattering at 6^{o} and 10^{o}", E.D. Bloom, D.H. Coward, H. DeStaebler, J. Green, G. Miller, L.W. Mo, an R.E. Taylor, Stanford Linear Accelerator Center, SLAC-PUB 642, August 1969

"Deep inelastic scattering: Experiments on the proton and the observation of scaling", Henry W. Kendell, reviews of Modern Physics, Vol. 63, No 3, July 1991

Maxwell's Equations and Electromagnetic Waves, MIT OpenCourseWare

Superpositions and Entanglement

Schrodinger's Cat
https://www.zmescience.com/science/news-science/physicist-schrodinger-cat-04323/
https://www.youtube.com/watch?v=R8cnrLKLDY0

https://ieeexplore.ieee.org/abstract/document/8158663
TEACHING MATHEMATICS AND ITS APPLICATIONS Volume 20, No. 1, 2001

https://www.mathsisfun.com/physics/bra-ket-notation.html
https://www.youtube.com/watch?v=8UxYKN1q5sI
https://www.youtube.com/watch?v=unb_yoj1Usk
https://www.youtube.com/watch?v=sAXxSKifgtU&t=273s Good Bell's Inequality videos
https://www.youtube.com/watch?v=zcqZHYo7ONs has some interesting results
https://arxiv.org/ftp/quant-ph/papers/0208/0208161.pdf good paper on the assumptions
https://www.coursera.org/lecture/quantum-optics-two-photons/4-2-pairs-of-photons-entangled-in-polarization-ZjJu9

Quantum Ghost Images
https://www.bbc.com/news/uk-scotland-glasgow-west-48971538
https://www.science.org/doi/10.1126/sciadv.aaw2563
https://www.science.org/doi/epdf/10.1126/sciadv.aaw2563
https://www.informationphilosopher.com/solutions/experiments/dirac_3-polarizers/
https://www.diva-portal.org/smash/get/diva2:913824/FULLTEXT02.pdf

Quantum Eraser Experiment

https://laser.physics.sunysb.edu/_amarch/eraser/index.html
The pdf version of the publication can be found here.
https://www.youtube.com/watch?v=RQv5CVELG3U
https://www.preposterousuniverse.com/blog/2019/09/21/the-notorious-delayed-choice-quantum-eraser/

Quantum Computing

https://www.cbinsights.com/research/quantum-computing-classical-computing-comparison-infographic/
https://dl.acm.org/doi/pdf/10.1145/3373376.3378500 good whitepaper
https://www.ijser.org/paper/Design-of-High-Speed-32-bit-Microarchitecture-for-Emulation-of-Quantum-Computing-Algorithms.html
https://web.stanford.edu/class/cs101/hardware-1.html
https://www.science.org/doi/pdf/10.1126/science.aar6209
https://medium.com/coderscorner/what-exactly-is-in-a-1-bit-of-digital-memory-d5395f9001a6
https://www.cs.bu.edu/~best/courses/modules/Transistors2Gates/https://optima-systems.co.uk/how-does-a-computer-add-two-numbers-together/
https://towardsdatascience.com/quantum-computing-with-colorful-diagrams-8f7861cfb6da
https://towardsdatascience.com/the-quantum-oracle-demystified-65e8ffebd5d5
https://qiskit.org/textbook/ch-gates/introduction.html
https://arxiv.org/ftp/arxiv/papers/1708/1708.03530.pdf
https://medium.com/@sashwat.anagolum/arithmetic-on-quantum-computers-addition-7e0d700f53ae
https://vincentlauzon.com/2018/03/21/quantum-computing-how-does-it-scale/
https://www.ncbi.nlm.nih.gov/books/NBK538701/#:~:text=Quantum%20computers%20have%20the%20potential,great%20progress%20is%20under%20way.
https://medium.com/@kareldumon/the-computational-power-of-quantum-computers-an-intuitive-guide-9f788d1492b6
https://semiengineering.com/the-great-quantum-computing-race/
https://semiengineering.com/the-great-quantum-computing-race/
https://www.youtube.com/watch?v=jHoEjvuPoB8&t=31s
https://magazine.caltech.edu/post/untangling-entanglement
https://www.quantamagazine.org/entanglement-made-simple-20160428/
http://www.quantumphysicslady.org/glossary/quantum-entanglement/
https://www.sciencealert.com/quantum-computers
https://www.youtube.com/watch?v=jHoEjvuPoB8&t=31s

Single-neuron theory of consciousness

http://consc.net/slides/collapse.pdf]
https://www.extremetech.com/extreme/295013-scientists-capture-photographic-proof-of-quantum-entanglement
https://physics.aps.org/articles/v8/123
https://www.forbes.com/sites/bernardmarr/2017/07/04/what-is-quantum-computing-a-super-easy-explanation-for-anyone/?sh=2cc2b2a11d3b
https://www.sciencedirect.com/science/article/abs/pii/S0022519305002766?via%3Dihub
https://dana.org/article/how-does-the-brain-work/

Music

The Microscopic

@02:38: Tchaikovsky – "Swan Lake": New Symphony Orchestra from the album "Tchaikovsky's Greatest Ballets", 2009

@25:57 Dvorak – "Symphony No 9 The New World": Oslo Philharmonic Orchestra; Mariss Jansons; from the album "Essential Adagios", 2010

@30:09 Chopin – "Piano Concerto No II Romance" : Martha Argerich; Orchestre Symphonique de Montréal; Charles Dutoit; from the album "Essential Adagios", 2010

The Atom

@00:00 Albinoni - Adagio in G Minor - Berlin Chamber Orchestra; from the album "50 Must-Have Adagio Masterpieces" 2013

@05:02 Haydn - Cello Concerto No 2 II Adagio - Franz Liszt Chamber Orchestra, Miklos Perenyi; from the album "50 Must-Have Adagio Masterpieces", 2013

@09:12 Mozart - Violin Concerto No 3 - Christian Altenburger, German Bach Soloists; from the album "50 Must-Have Adagio Masterpieces" 2013

@20:01 Dave Porter - Breaking Bad Theme - Music from the Original Series Breaking Bad

@22:16 Bizet - L'Arlesienne Suite No 1, Op 23 - Budapest Philharmonic Orchestra; from the album "50 Must-Have Adagio Masterpieces" 2013

@26:57Mahler - Symphony No 5 III IV - Budapest Festival Orchestra; from the album "50 Must-Have Adagio Masterpieces" 2013

Elementary Particles

@00:00 Stravinsky - The Firebird - from the album "The Firebird Suite" 2010

@01:13 Beethoven - Symphony No 6 (Shepherds Hymn) - Philadelphia Orchestra; Riccardo Muti; from the album "Essential Adagios" 2010

@05:5 Mozart - Divertimento No 10 - Franz Liszt Chamber Orchestra – from the album "50 Must-Have Adagio Masterpieces" 2013

@19:18 Rossini - William Tell Overture - London Philharmonia Orchestra and Alfred Scholz; from the album "The London Philharmonic Collection: Light Classics" 2009

@36:18 Haydn - Piano Concerto No 4 - Nicolai Evrov, Sofia Philharmonic Orchestra; from the album "50 Must-Have Adagio Masterpieces" 2013

The Higgs Boson

@00:00 Albinoni - Concerto for Oboe and Strings No 2 II: Frank Berger, Hans-Dieter Weber; from the album "50 Must-Have Adagio Masterpieces" 2013

@06:59 Rachmaninoff - Symphony No. 2 Adagio: Sofia Philharmonic Orchestra; Emil Tabakov; from the album "Sergei Rachmaninoff: Symphony No. 2 in E Minor, Op. 27" 2011

@23:02 Ravel – Boléro: The London Symphony Orchestra; from the album "Classical Masterminds - Ravel" 2007

@33:22 Vaughan Williams - The Lark Ascending: Hugh Bean; New Philharmonia Orchestra; Sir Adrian Boult; from the album "Essential Adagios" 2010

@37:43 Brahms - Violin Concerto, Op 77 II Adagio: Sofia Philharmonic Orchestra, Vesselin Eshkenasi; from the album "50 Must-Have Adagio Masterpiece" 2013

Superposition and Entanglement

@00:00 Bach - Flute Concerto in B Flat, Adagio; conducted by Eckart Haupt; from the album Meditation: Classical Relaxation, 2010

@13:21 Puccini - La Bohéme Act II- Musette Waltz; Sofia Philharmonic Orchestra; from the album 100 Must-Have Italian Opera Highlights, 2014

@26:50 Svendsen - Romance in G; Miklos Szenthelyi; from the album Meditation: Classical Relaxation, 2010

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