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*]

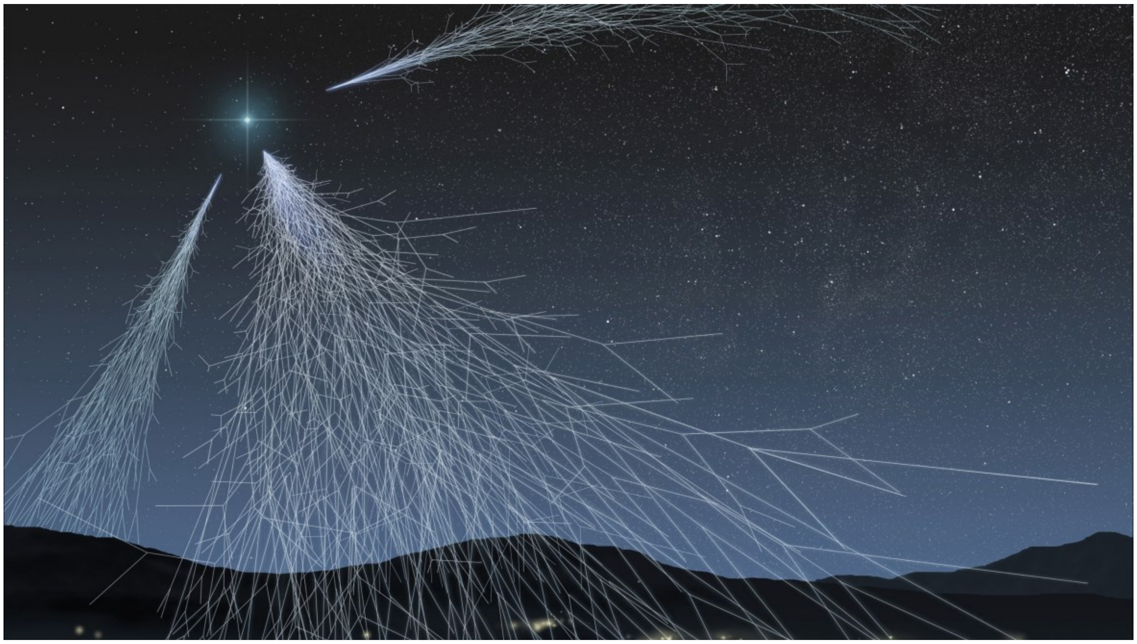
Hello and welcome to our segment on elementary particles. An elementary particle is defined as a particle that has no internal structure. In other words, it is not made up of other particles. At this point, we know that the electron and the photon are elementary. In this segment, we'll find some more.

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.

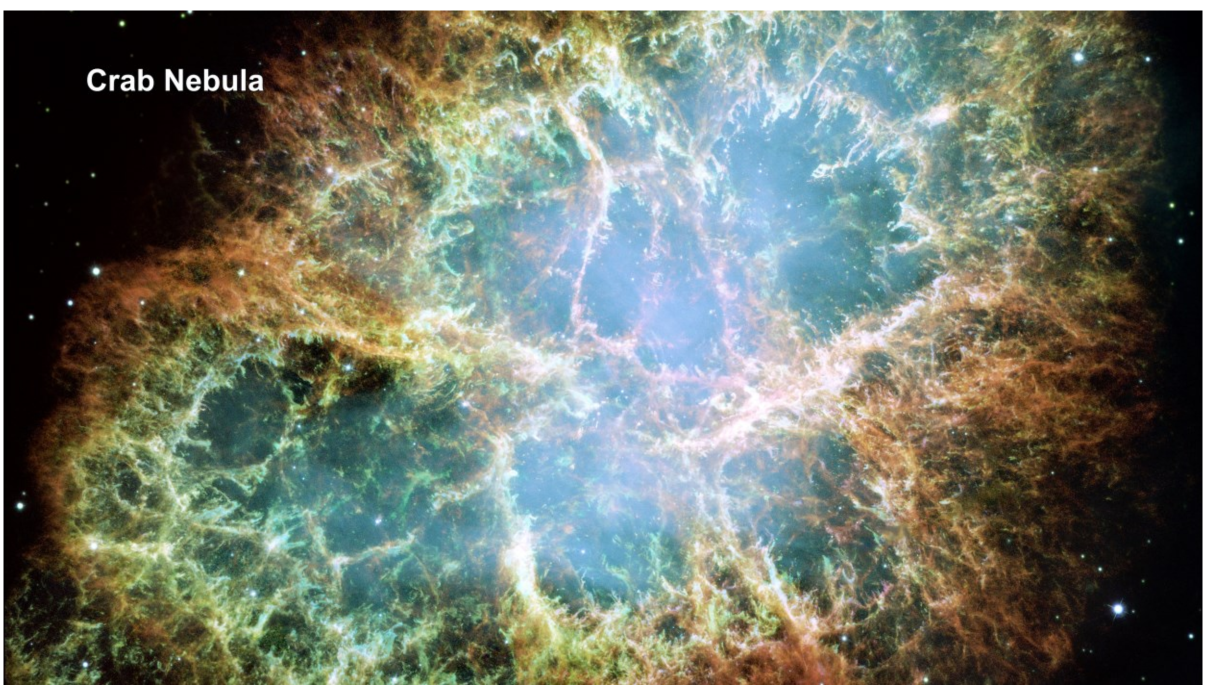
In this segment, we'll take a look at what they found. We'll also probe the nucleus and do some heavy duty scattering like Rutherford did, but this time we'll be digging into the proton to find out what it is made of. But first, we'll see what these new particles are and how we determined their characteristic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

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

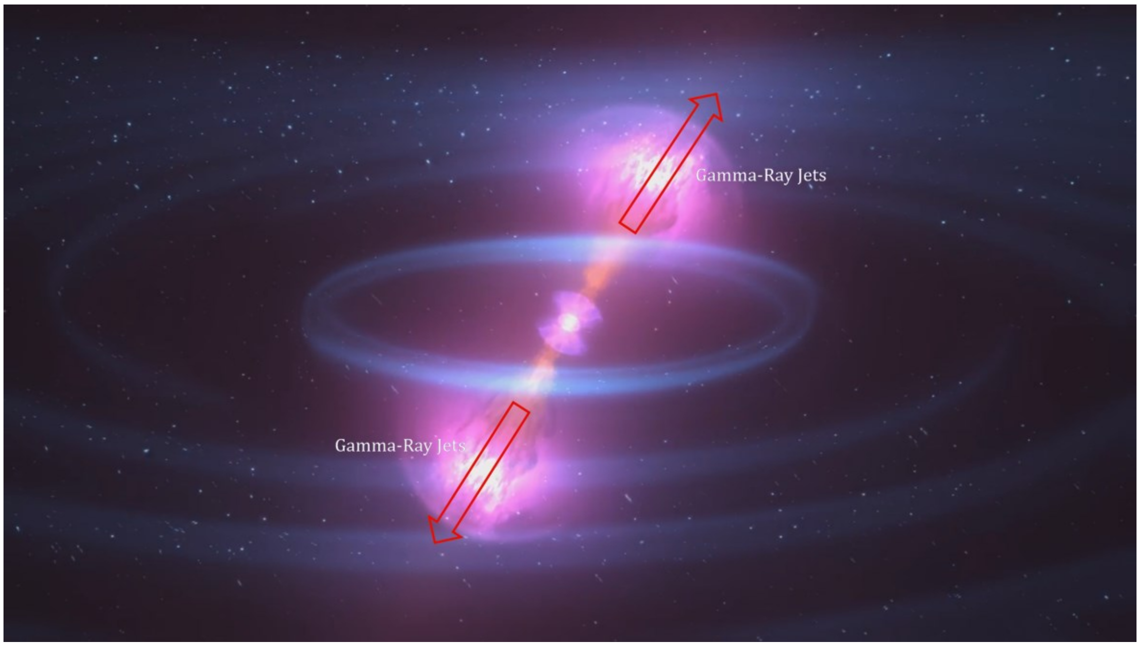
The Earth is constantly bombarded by radiation from outer space called cosmic rays made up of mostly high energy protons and high energy photons called gamma rays. These cosmic rays collide with atoms in our atmosphere, generating particle chain reactions that continue to the surface.



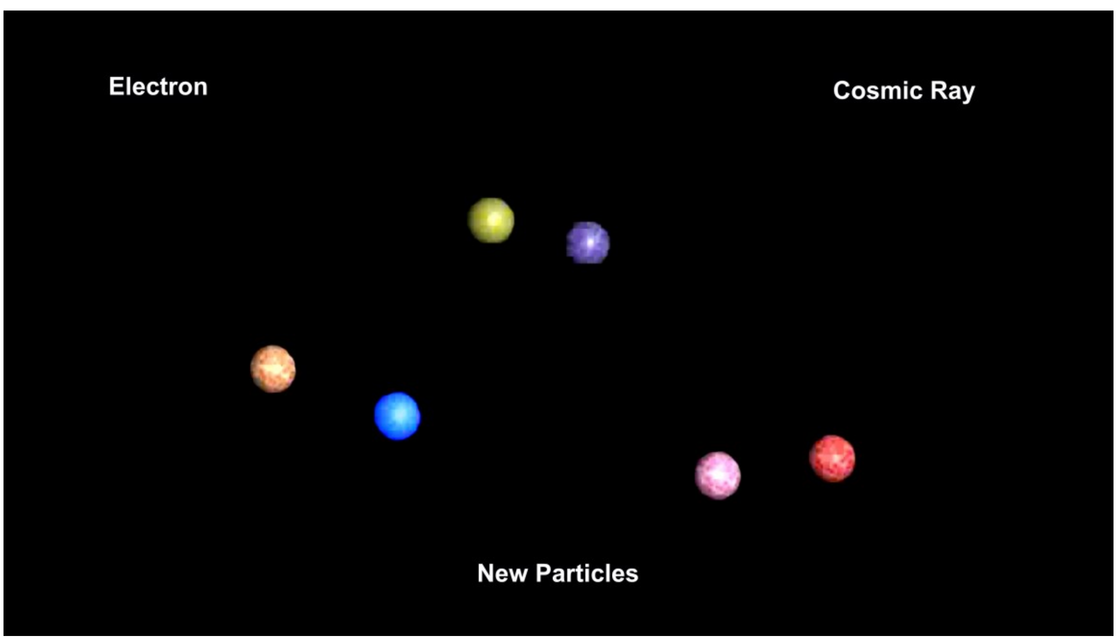
In our segment on the Milky Way in the How Far Away Is It video book, we noted cosmic rays are produced in supernova like the one that created the Crab Nebula.



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!

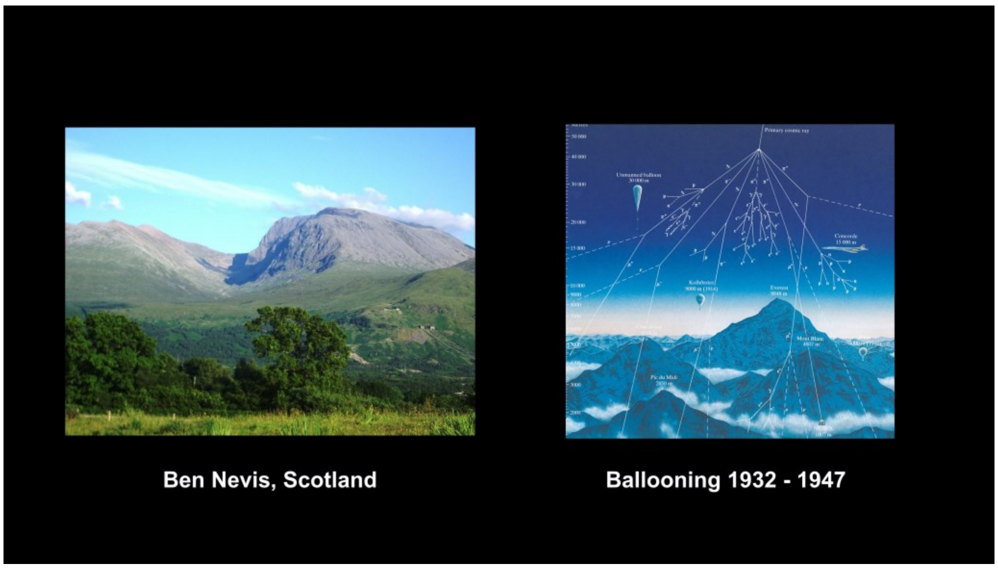


It is the very high energy of the deep space cosmic rays that have the power to smash into electrons, protons and neutrons in the atmosphere creating a wide variety of previously unknown particles.

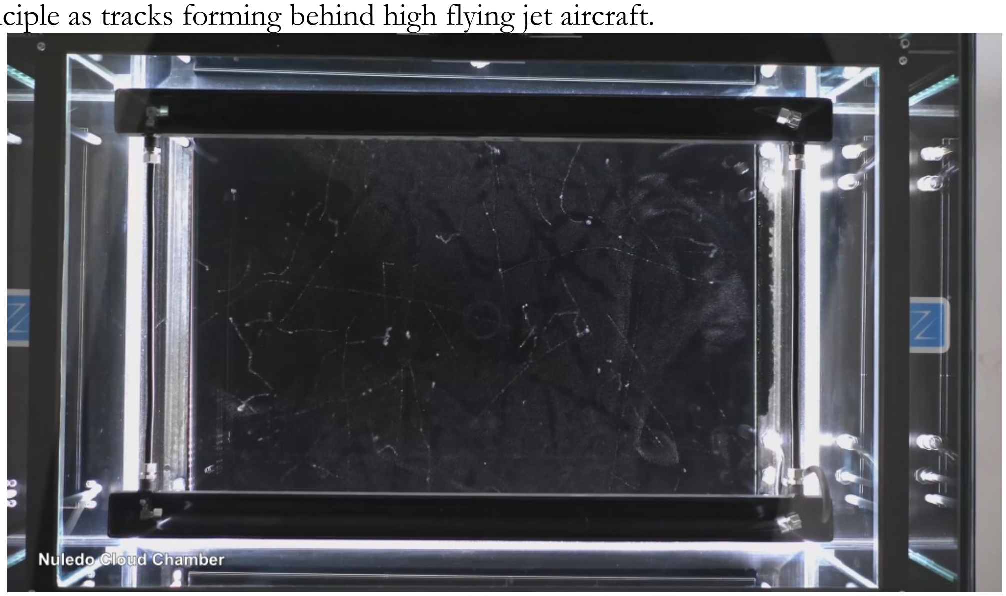


Charles Thomson Rees Wilson invented the cloud chamber in 1911 to detect these new particles.

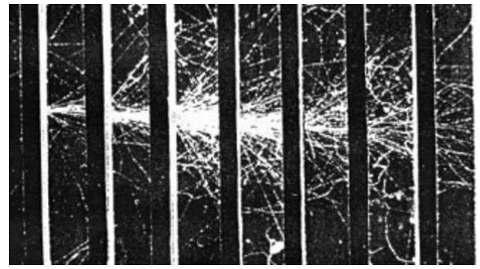
So, physicists climbed mountains like this one that Wilson used, and went up in balloons with their cloud chambers hunting for new particles.



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.



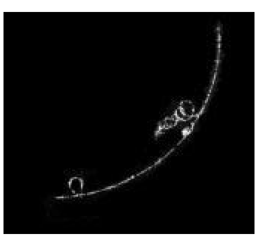
Here's what cosmic rays look like in a cloud chamber. These rays are penetrating multiple brass plates each 13 mm thick. To understand these tracks, we'll start with the two charged particles we already know: the electron and the proton.

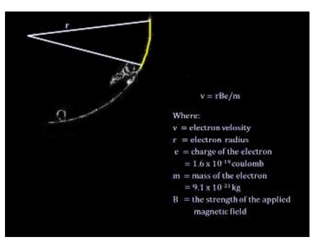


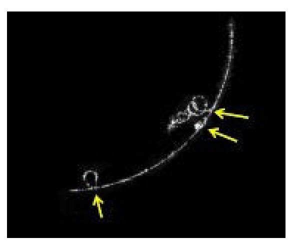
The Electron e^-

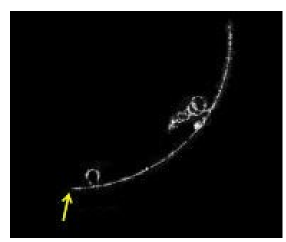
Here is a photograph of a particle track in a hydrogen bubble chamber from the Brookhaven National Lab. Given the direction of the applied magnetic field, electrons will curve clockwise. This is a medium speed electron arching through the cloud chamber. Since we know the strength of the magnetic field 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.



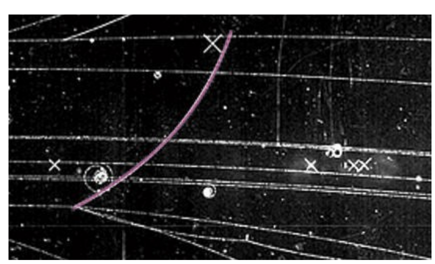






The Proton p

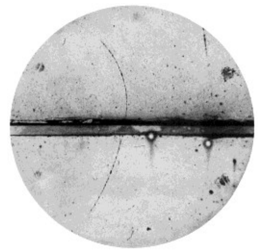
In this bubble chamber photograph from CERN, we can see a particle's track rotating counterclockwise. This indicates that it is positively charged. The particle's line is also thicker than the others. This indicates it is a large slow-moving particle. This is a characteristic of proton tracks.



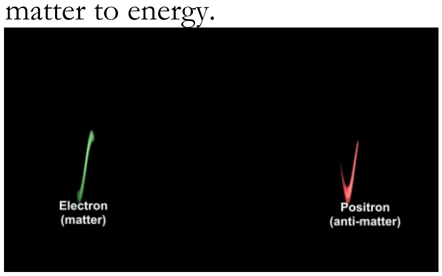
The Positron e^+ ***[Music:** Mozart - Divertimento No 10**]***

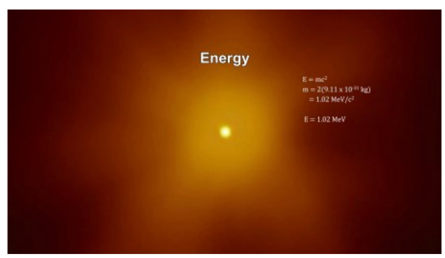
Now let's take a look at some of the new particles that sent the world of physics into never-before-seen territory. In 1932, Carl David Anderson began investigations into cosmic rays and encountered unexpected particle tracks in his cloud chamber photographs. The 6 mm thick lead plate in the chamber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

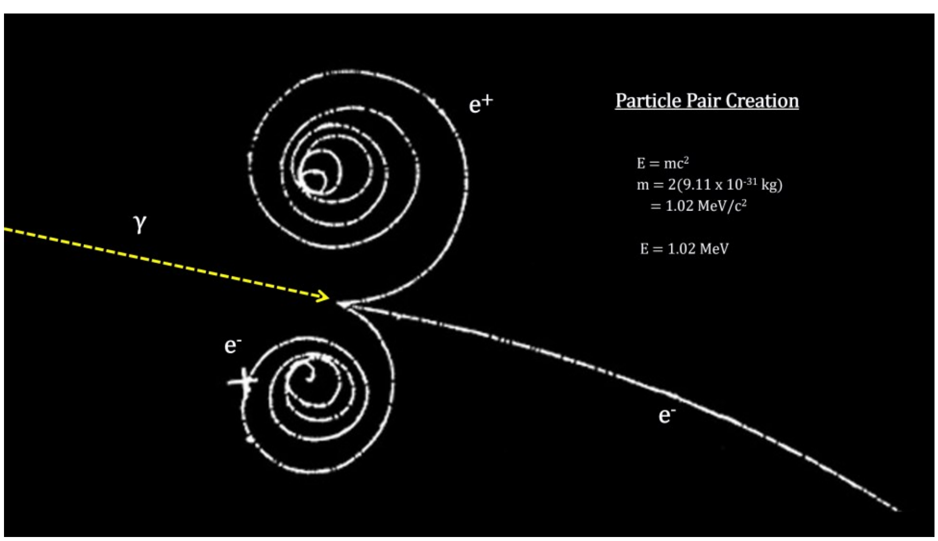


In 1928, four years before Anderson discovered the positron, Paul Dirac predicted the existence of anti-matter and proposed that all particles had an anti-particle, and that they would annihilate each other it if they came into contact. The positron is the anti-particle of the electron. This is an example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





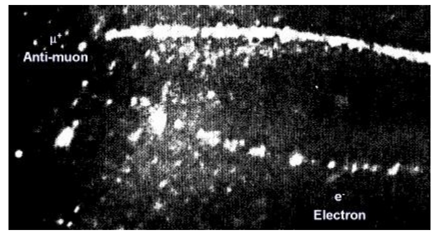
Here's an event in a cloud chamber that shows the creation of a pair of particles – one electron and one positron. The event was the conversion of a high energy gamma ray that kicked an electron out of an atom and was itself converted into the two particles. The gamma ray photon does not show up in cloud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



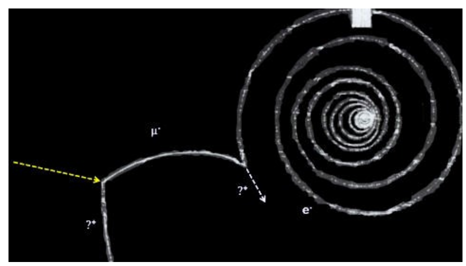
This is an example of converting energy to matter. The energy of the gamma ray photon had to be as great as the energy embodied in the two particles. For electrons and positrons that comes to around a million electron volts. Any theory that attempts to explain this behavior will need to identify a way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

The Muon μ

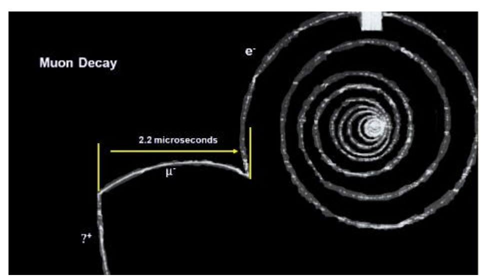
In 1932 Paul Kunze discovered the muon. Using both the direction of the curvature and the thickness of the bubble track, he calculated that it was a positively charged particle that was lighter than a proton but heavier than an electron. This one turned out to be the anti-muon.



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.

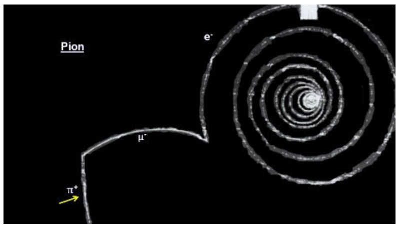


On average, it lasted only 2.2 microseconds (that's 2.2 millionths of a second). Measurements have shown that it is 207 times more massive than the electron with the same spin and charge. Muons are elementary particles like the electron and the positron. These particles are called leptons meaning light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

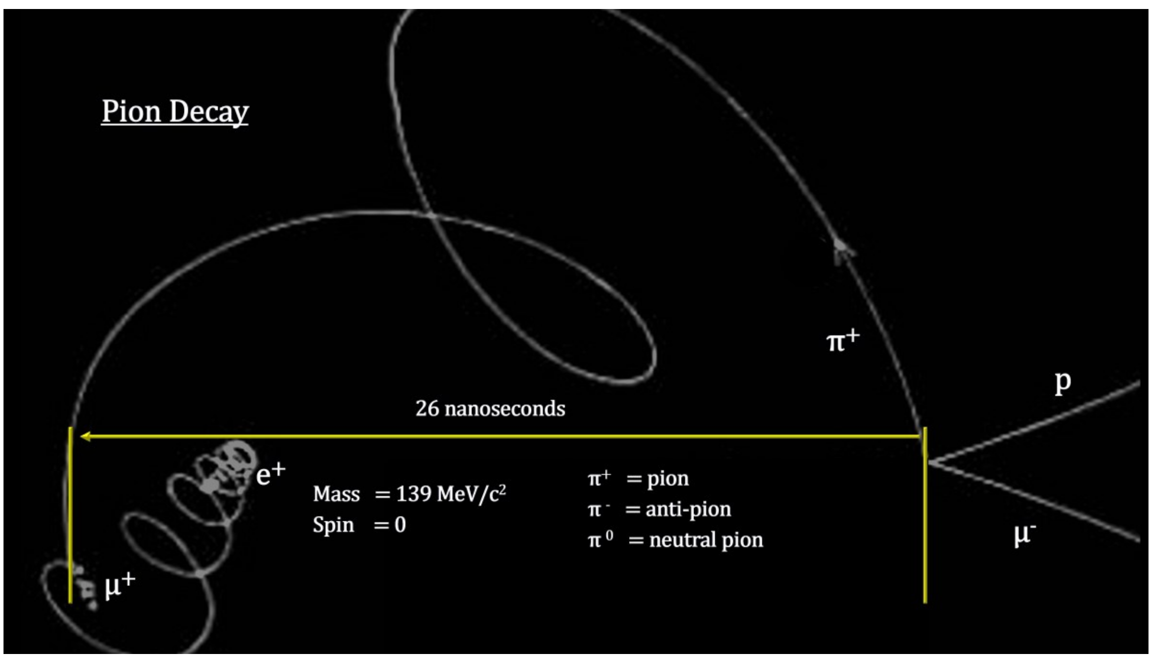
The Pion π



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.

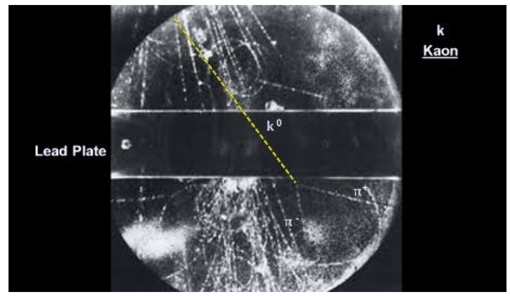


Pions are spin zero particles with around 14 hundredths of a proton's mass. Although that's small, it's a good deal more massive than the muon. Pions come in three flavors: one with a positive charge, one with a negative charge (called the anti-pion), and one with no charge.

The Kaon k

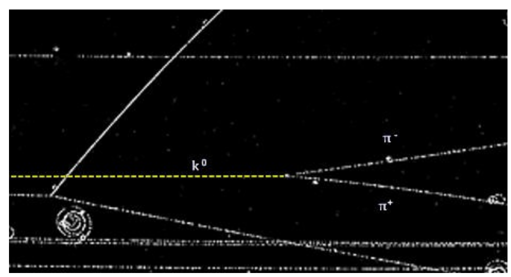
Also, in1947, another particle called the Kaon was discovered by George Rochester and Clifford Butler. They also used cosmic rays.

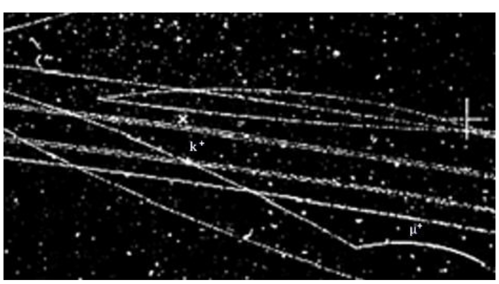
Here's a look at their bubble chamber picture. Just below the lead plate, in the lower right-hand quadrant, you see an inverted V that extends to the lower right. Measuring the momentum and charges they determined that they were a pion and an anti-pion. Rochester and



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.



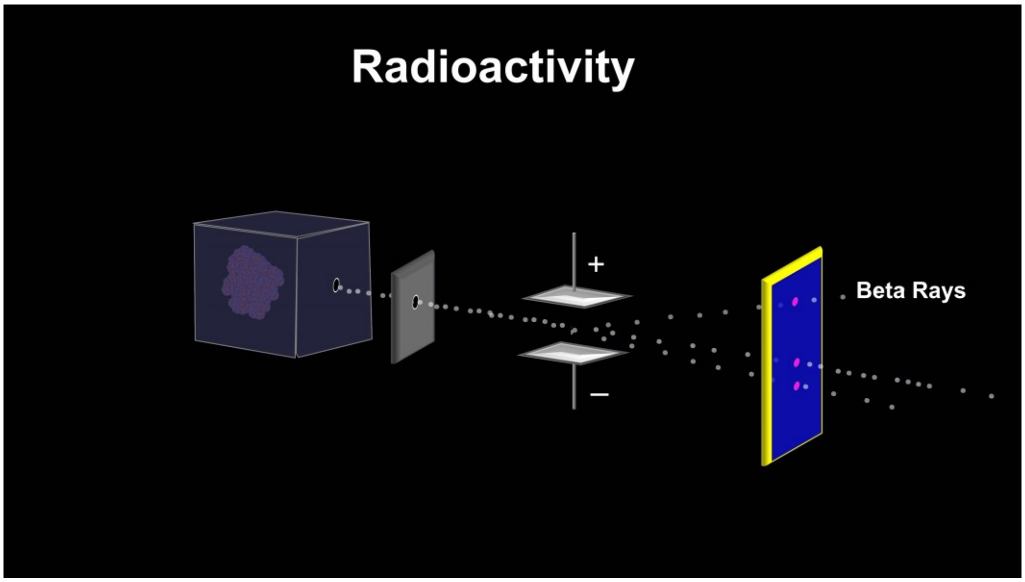


These past two bubble chamber photographs were examples of neutral kaons. Here we see a charged kaon decay. Note the kink in the path. This indicates that a charged particle decayed into another charged particle with a different mass. In this case, a positively charged kaon has decayed into an anti-muon.

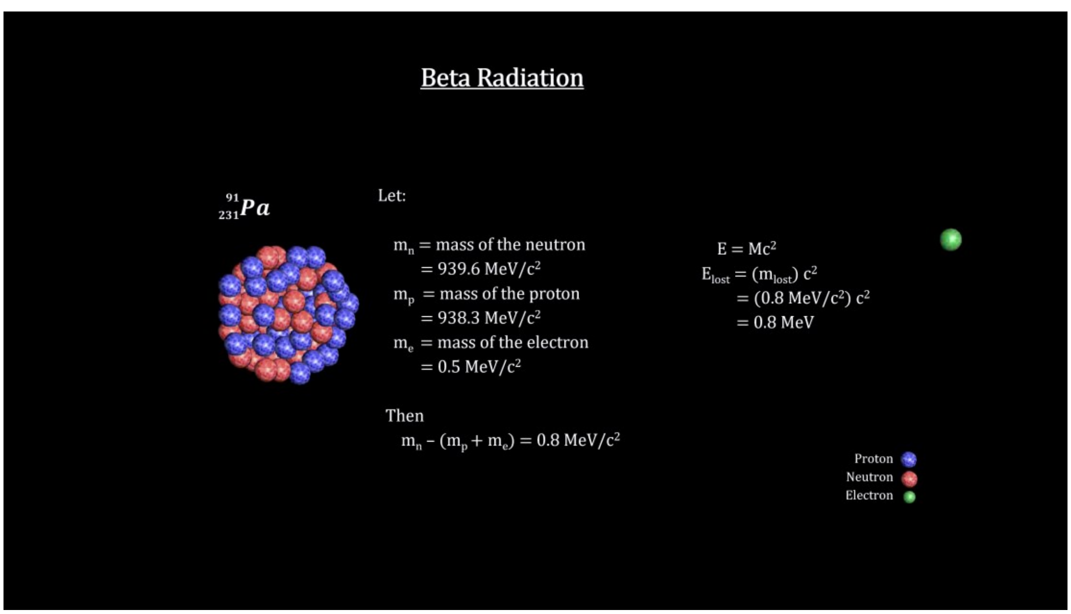
An anti-kaon would decay into a muon. Kaons have proved to be a tremendous source of information on the nature of fundamental particle interactions. **]**

The Neutrino ν

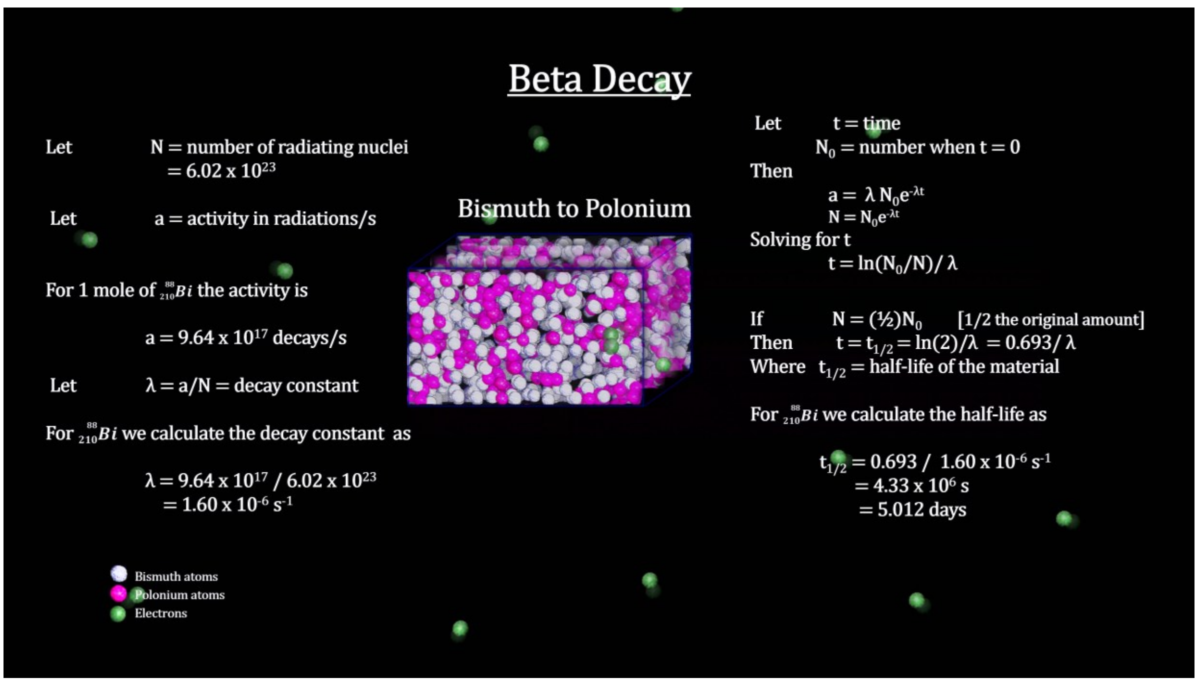
One of my favorite particles is the Neutrino. You'll recall from our segment on radiation, that the beta rays were ejected electrons.



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.

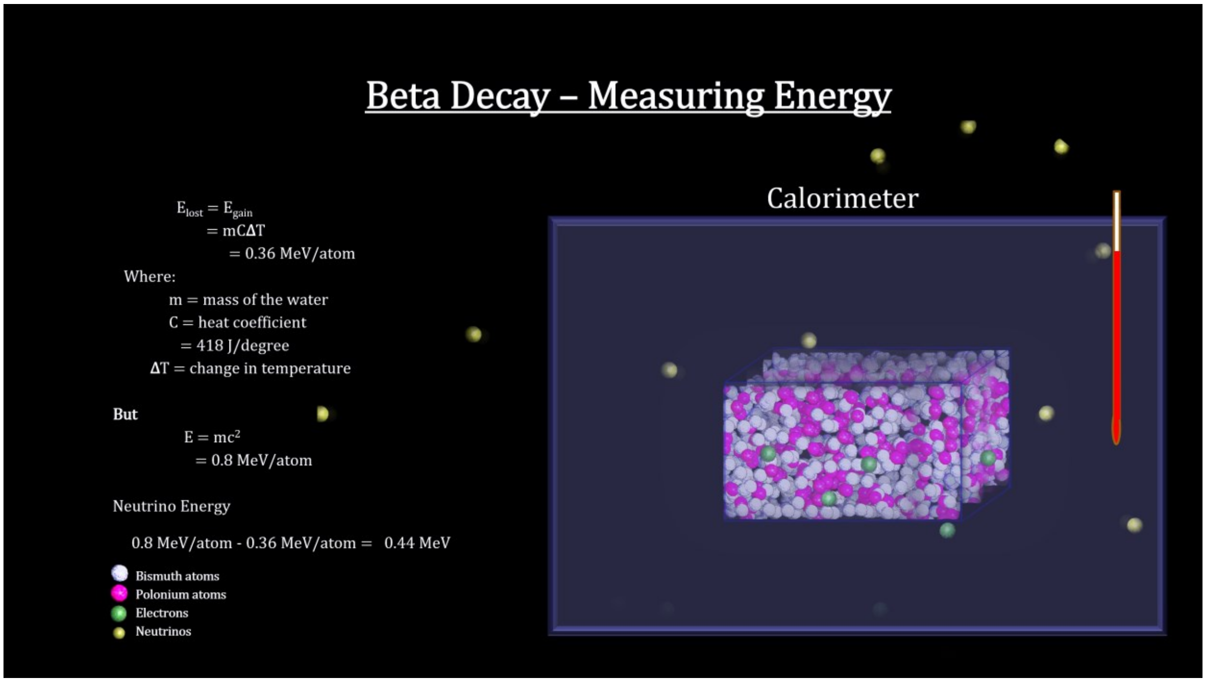


In 1927, two physicists, C. D. Ellis and W. A. Wooster, set out to measure this energy. They used Bismuth 210, a product of Radium decay that itself decays into Polonium. The rate at which unstable radioactive nuclei decay in a sample of material is called the *activity* of the sample. The greater the 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.

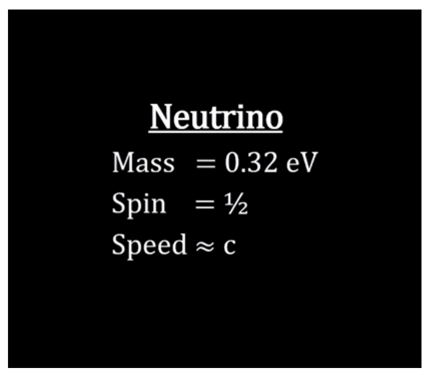


The experiment was simple: place the Bismuth into a calorimeter. A calorimeter keeps the energy of the beta radiation inside the container. Over the five days, each and every ejected electron's kinetic energy is converted to heat as they collide with the water molecules and come to rest in the calorimeter. 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.

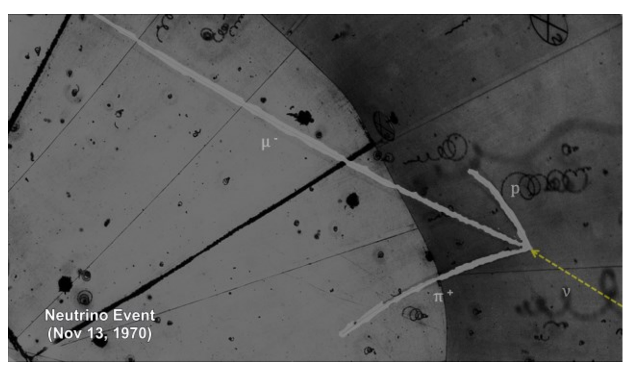
But here we had a significant discrepancy. Conservation of energy and Einstein's equations called for 0.8 MeV. That's more than twice as much as was measured. This was a real problem. Niels Bohr thought that the conservation of energy didn't hold in this case while Wolfgang Pauli thought that it did 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.



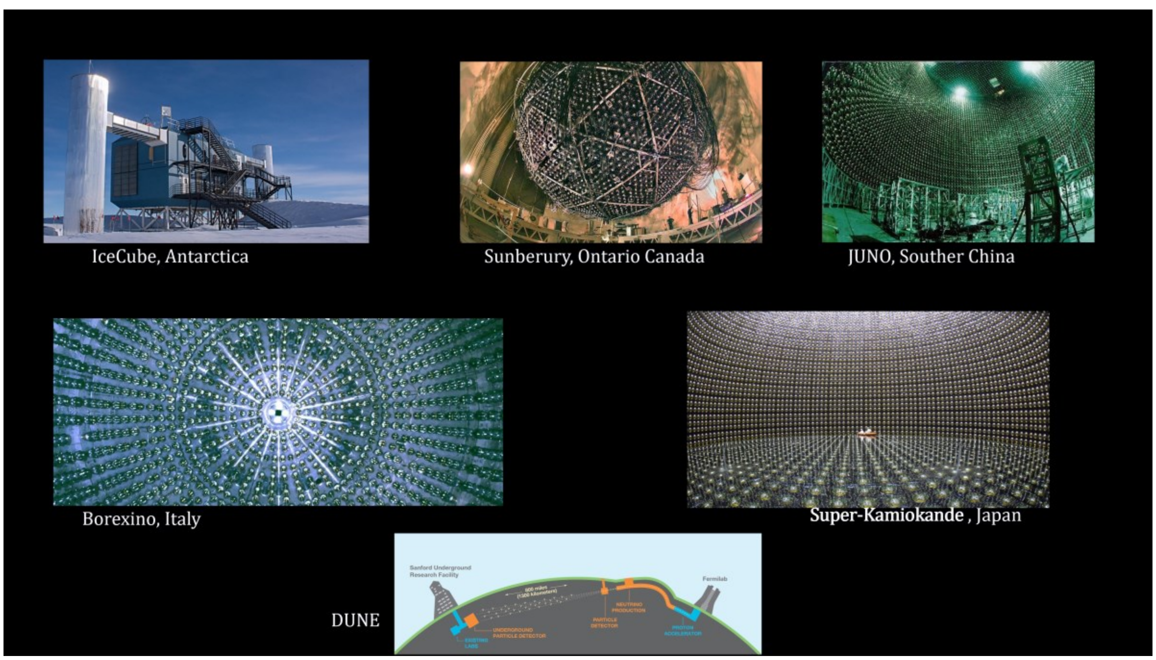
This particle was finally observed in a hydrogen bubble chamber captured in 1970. The invisible neutrino enters from the lower right and strikes a proton where the three particle tracks originate. The proton is kicked into motion, the neutrino is converted into a muon and a pion by the power of the collision.



Neutrino Astronomy

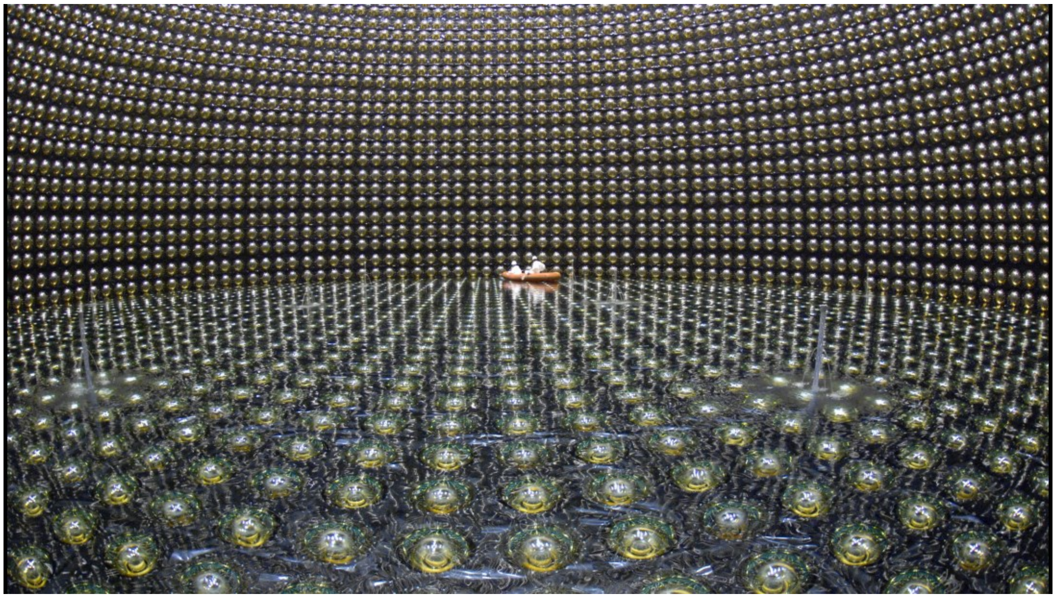
It turned out that the neutrino is a critical component in many nuclear reactions that occur in stars. The detection of solar neutrinos and of neutrinos from the SN 1987A supernova in 1987 marked the beginning of neutrino astronomy.

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.



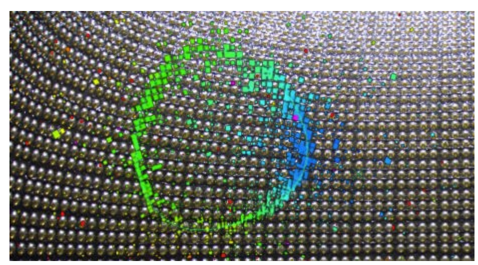
The Super-Kamiokande is located 1,000 meters underground in a Japanese mine. It contains a lake holding 50,000 tons of ultra-pure water surrounded by an inner detector with over

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



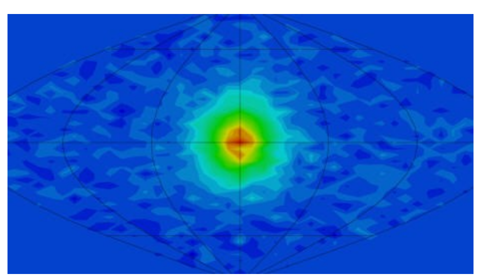
The speed of light in water is slower than the speed of light in a vacuum. A neutrino interaction with the electrons or nuclei of water can produce a charged particle that moves faster than the speed of light in water.

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.

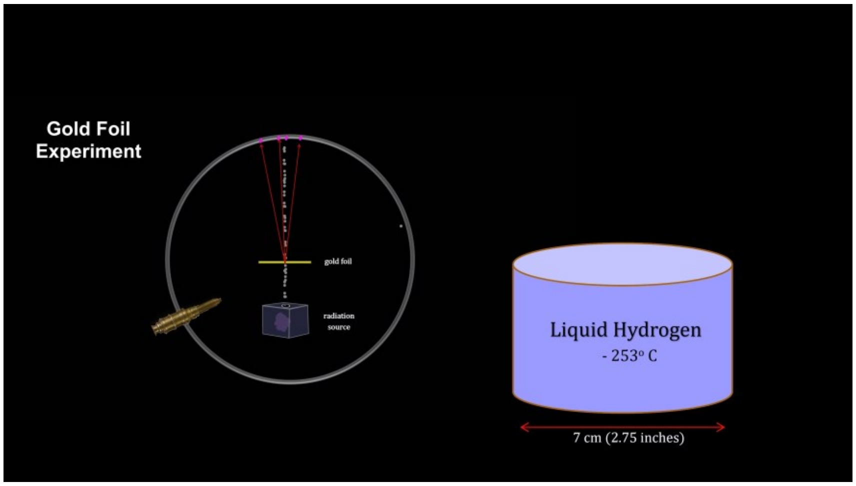


I think that neutrinos will wind up playing a significant role in understanding Dark Matter.

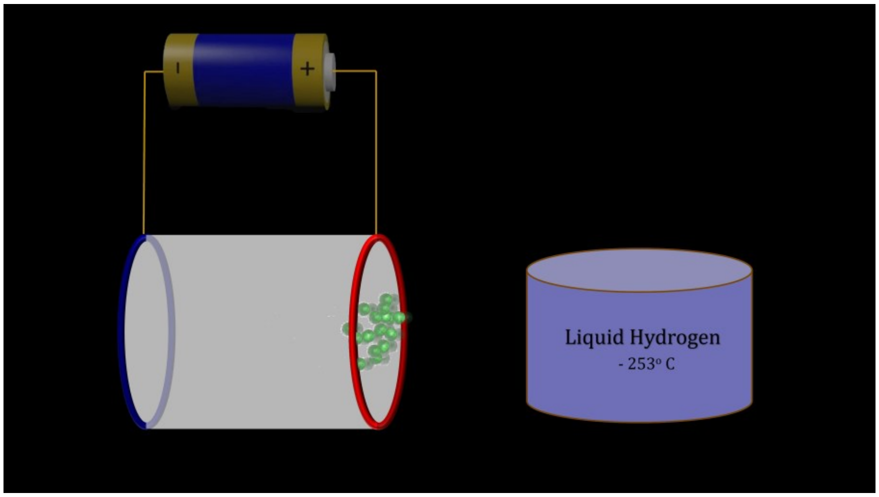
Particle Accelerators

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

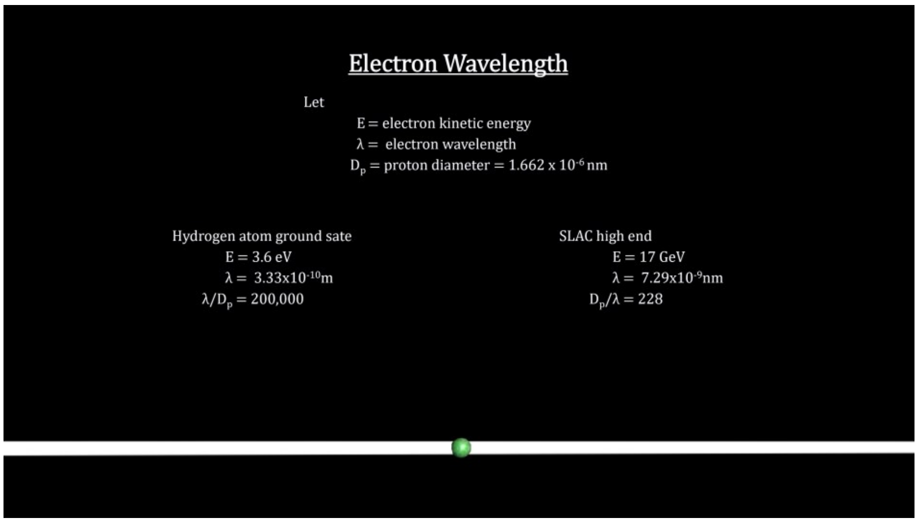
In 1969, a team of scientists at the Stanford Linear Accelerator Center or SLAC for short, in conjunction with MIT, performed scattering experiments similar in principle to what Rutherford did to probe the atom 58 years earlier. Rutherford's target was a gold foil. In the SLAC experiment the target was 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.



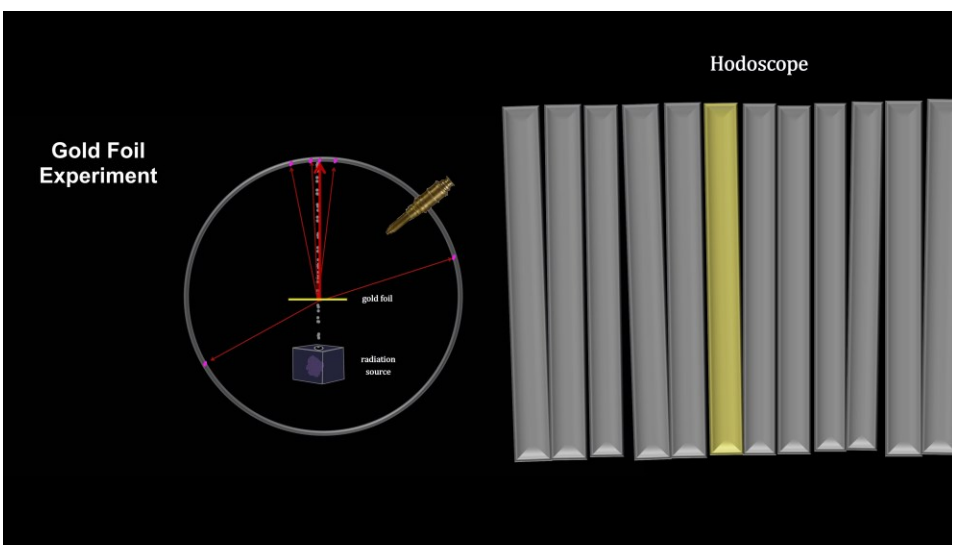
Here we use electrons and accelerate them to nearly the speed of light. To do that, we construct a glass tube. Then we connect a negative charge to the entrance and a positive charge to the exit. When the battery is turned off, electrons flow in any direction. But with the battery turned on, the electrons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



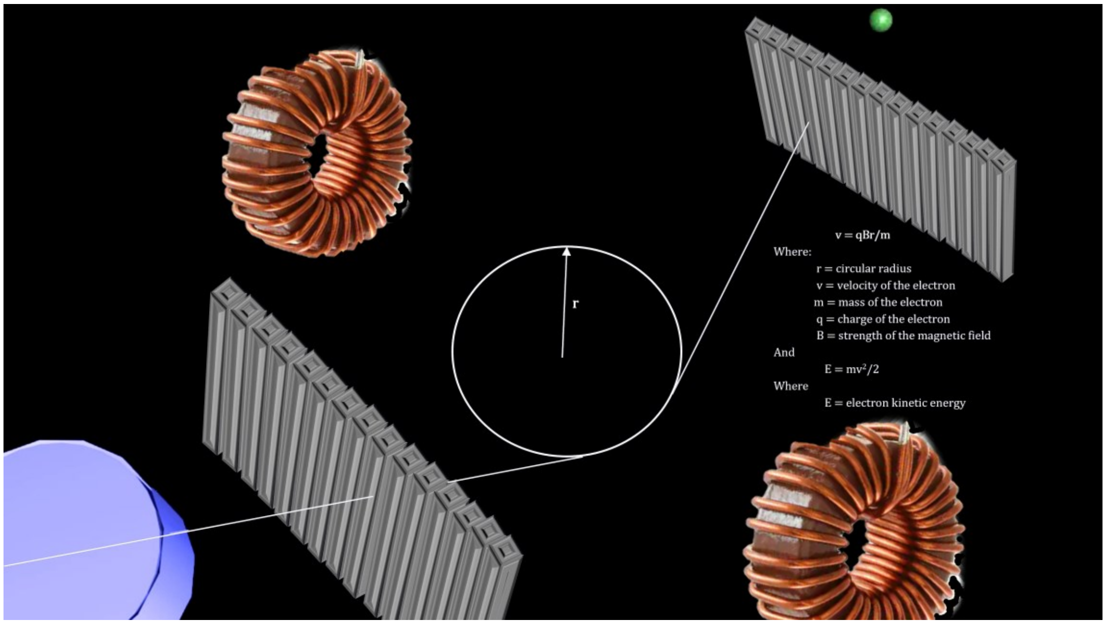
To get a really high velocity, we connect more and more of these tubes together. At SLAC, the length of the tube is 3 km (That's 1.86 miles). This creates electrons with 40,000 times the energy than the alpha particles used by Rutherford. This high energy is essential. You cannot probe inside a proton 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.



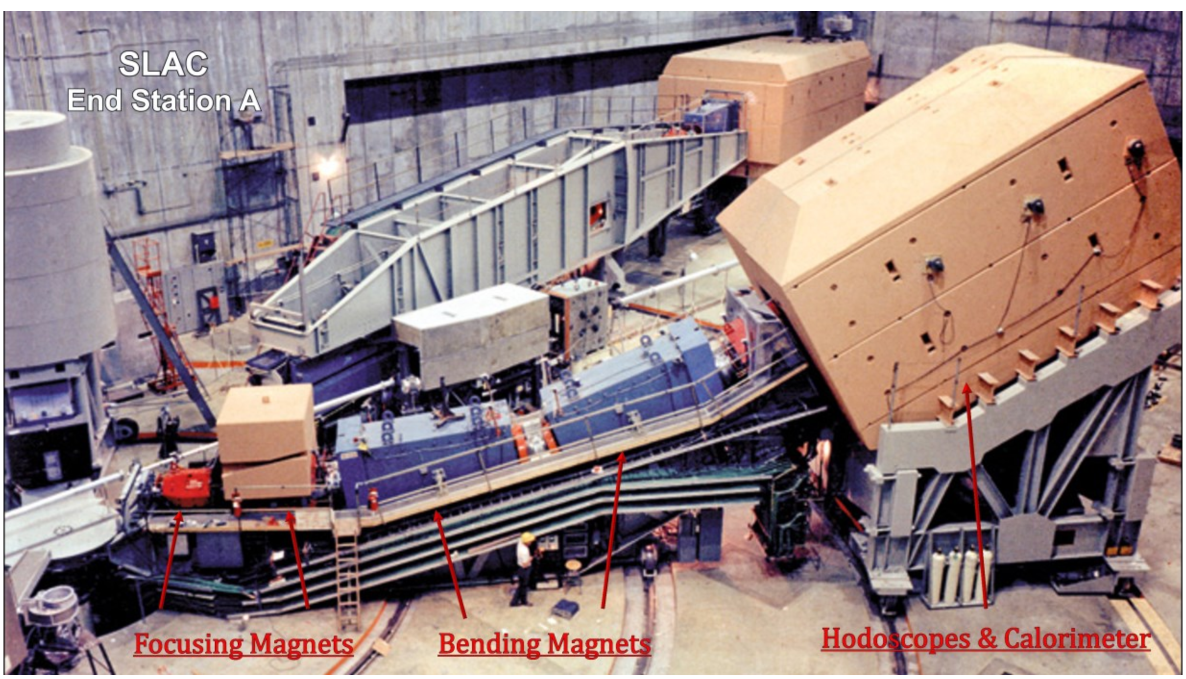
The scintillator screen used by Rutherford covered the inside of the apparatus. He had to manually note the flash locations as he viewed them through the swiveling microscope. At SLAC, we partitioned the scintillator screen into small strips. Each strip has an attached photo element that converts the 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.

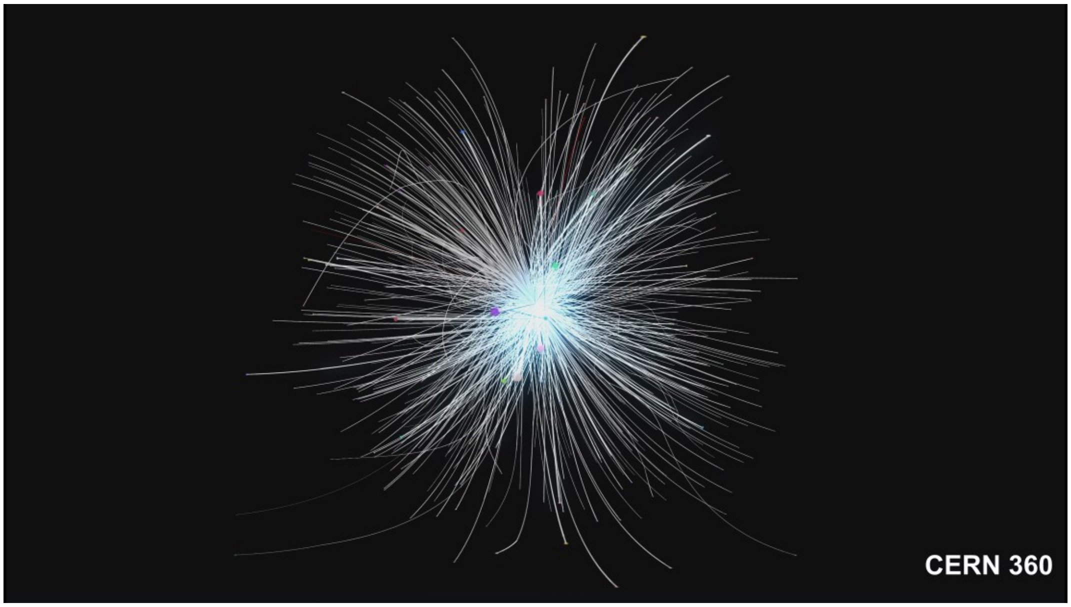


At the end of the process the electrons enter a calorimeter that will measure its energy much like we just did to discover the neutrino. Putting all these pieces together gives us the complete linear accelerator detector. It weighs 750 tons.

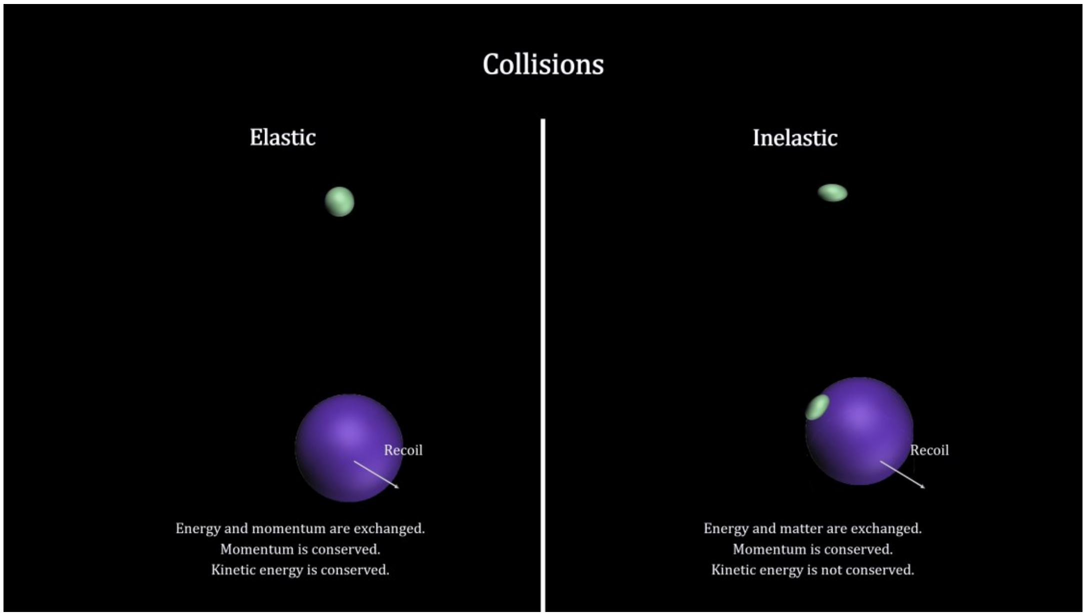


Probing the Proton **[Music:** Beethoven - Symphony No 6 (Shepherds Hymn)**]**

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.

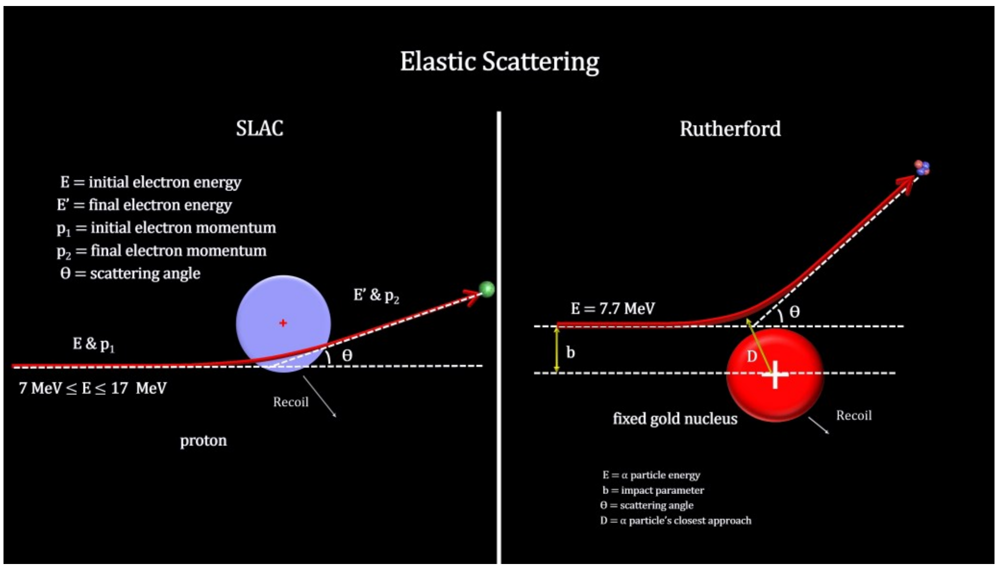


There are two basic types of scattering. One is called inelastic scattering where both of the colliding objects change. For example, here we have some of one object's mass transferred to the other at the point of collision. The transfer absorbs energy, so conservation of energy doesn't hold. The other 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.

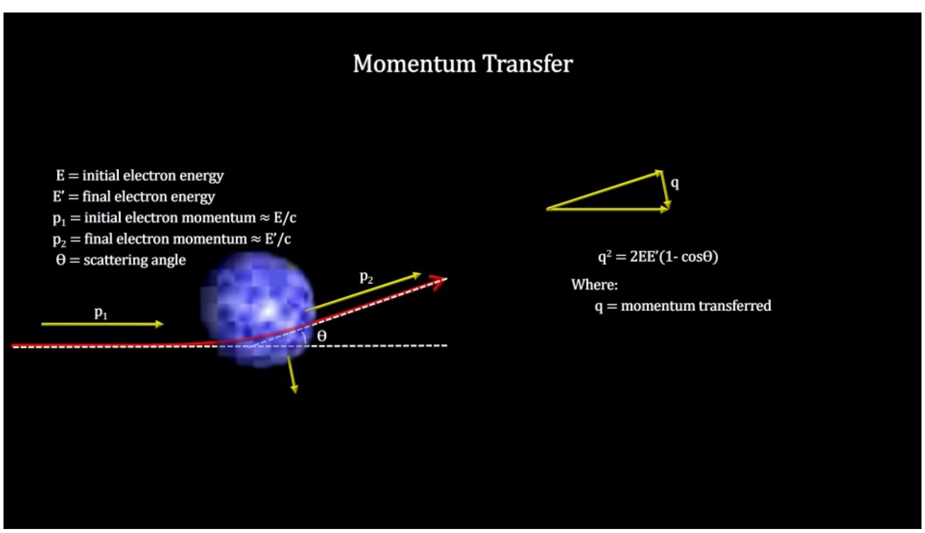


Rutherford was examining alpha particle scattering angles off a gold atom target to determine the size of the nucleus. He had to use an alpha particle probe with fixed energy at 7.7 MeV. The coulomb force was repulsive and his target nucleus was fixed in the solid gold foil, so the target recoil velocity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

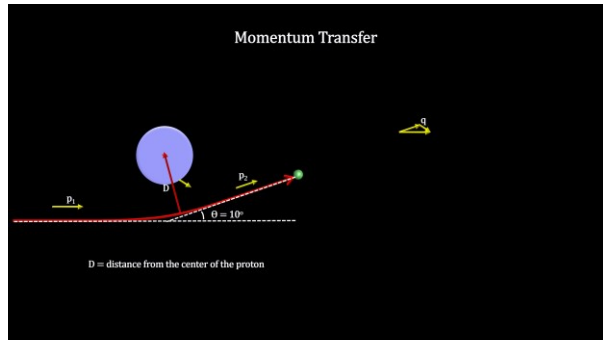
The SLAC experiment could vary the incoming electron energy up to 17 GeV. The coulomb force was attractive with significant target recoil when a high velocity electron collided with a target proton. The SLAC experiment was designed to examine this transfer of momentum from the electron to the proton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



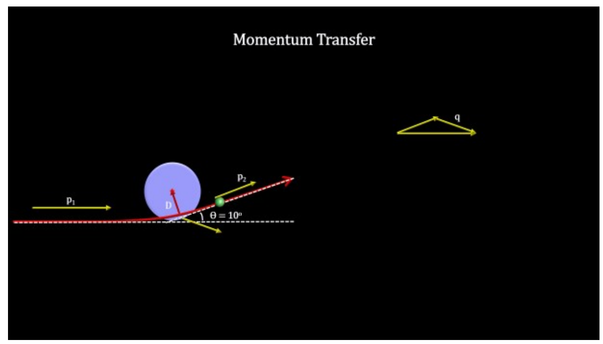
The physicists controlled the incoming electron's energy and momentum and carefully measured the outgoing energy and momentum for a particular scattering angle. With that, they calculated the amount of momentum lost by the electron. Given the conservation of momentum, the electron's loss would be equal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



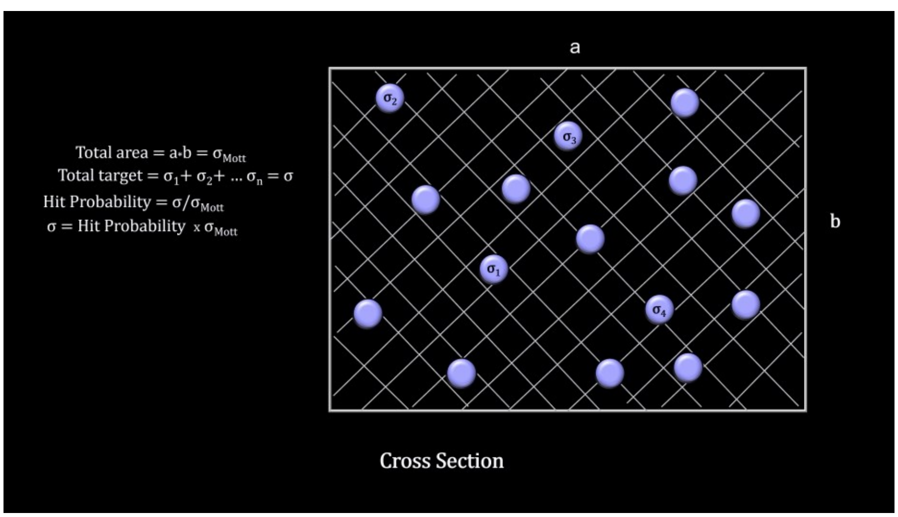
Suppose we're counting 10º deflections as a hit. A relatively slow-moving low energy electron can get a 10º deflection far from the center of the proton. This would make the size of the proton look large. In addition, the interaction between the electron and the proton would be weak. We'd find that only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



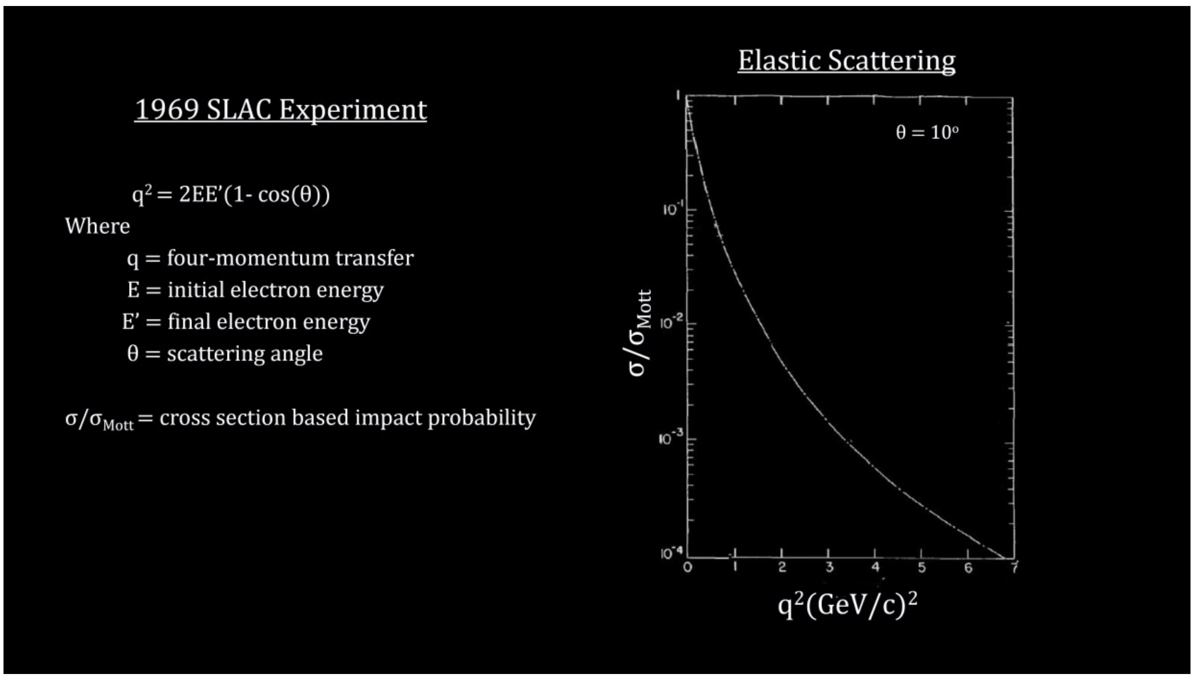
If we increased the velocity of the electron and kept its distance from the proton the same, it would not be deflected 10º, and the interaction would be considered a miss. An electron with this increased energy would have to approach closer to the proton to get deflected 10º. This would have the effect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



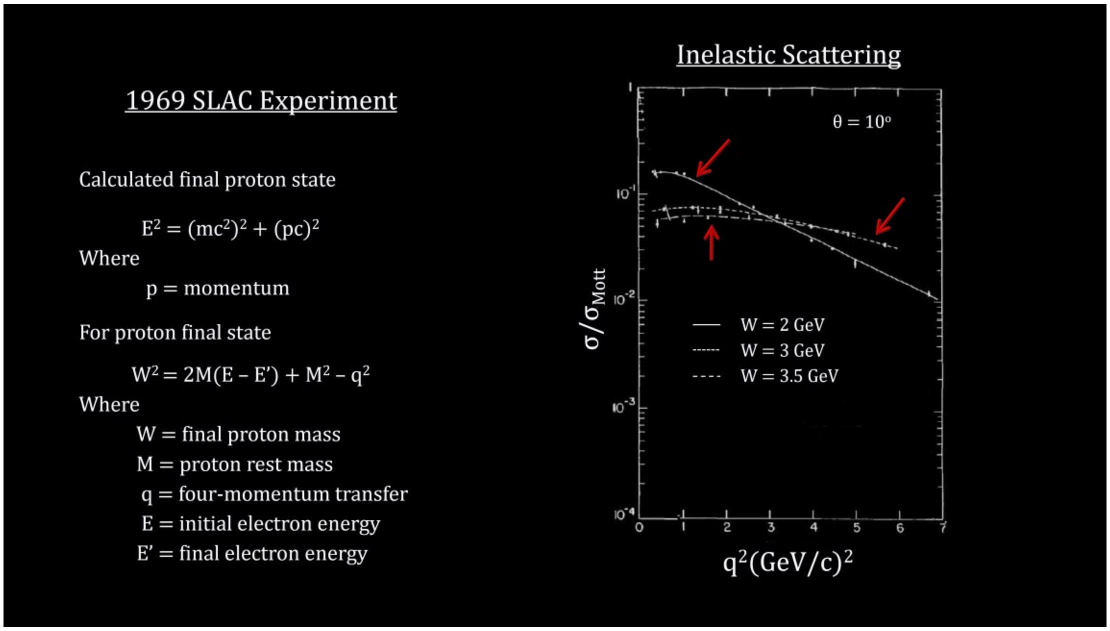
SLAC calculated the cross section by controlling the number of incident electrons and counting the hits. Here's a graph of the interaction probabilities against the momentum transfer found by the SLAC experiment for electrons with energies below 7 GeV that scattered by 10 degrees. The closer to the target 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.

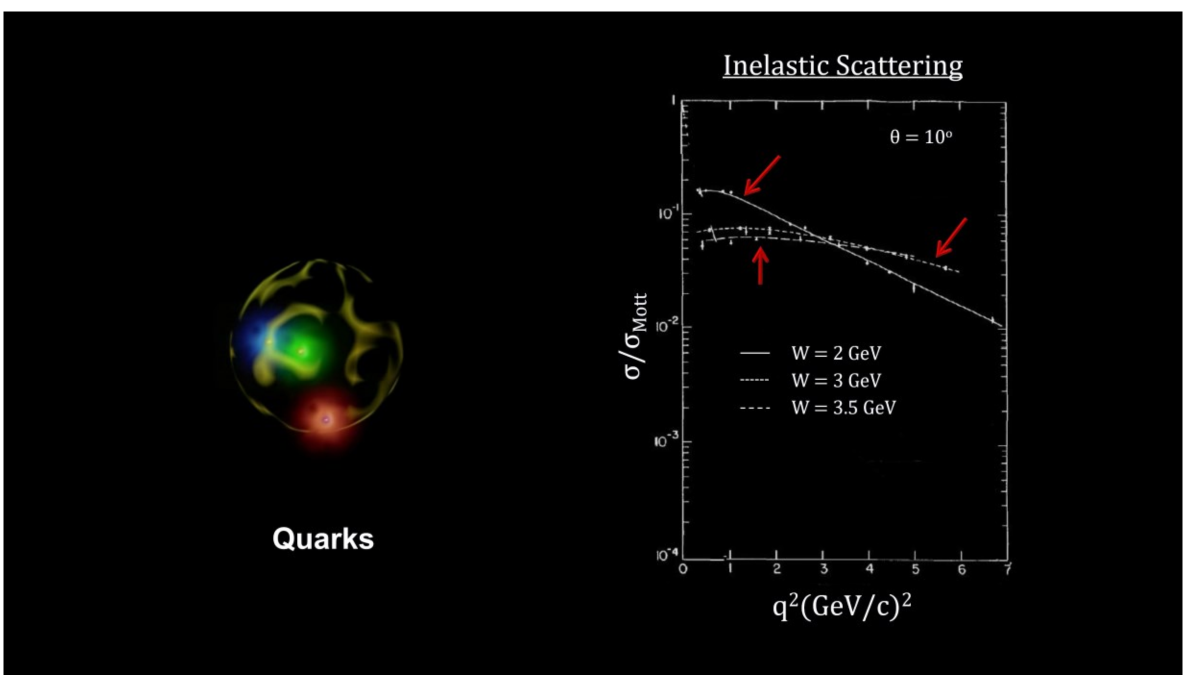
To understand what might be going on, we'll take a closer look at the final proton state. You may recall that Einstein's formula for mass and energy is $E = mc^2$. But this only applies to a mass at rest. For a moving particle, the energy-mass conversion includes the particle's momentum. In our case,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

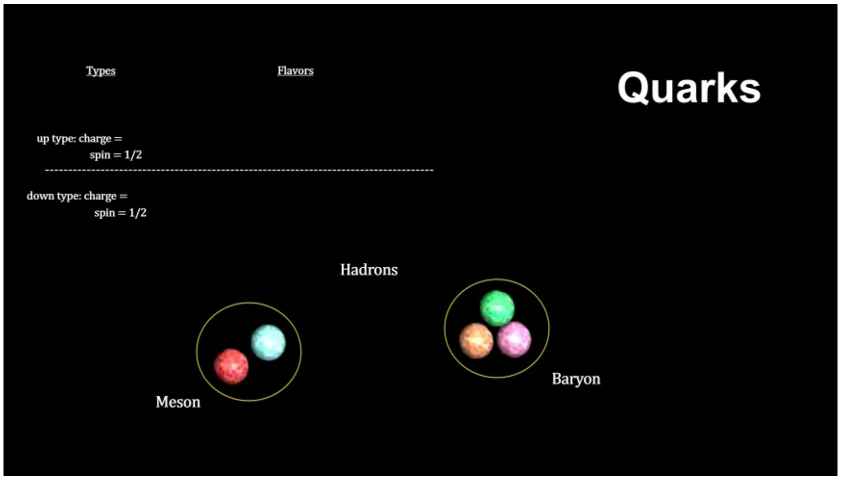


Quarks & Hadrons

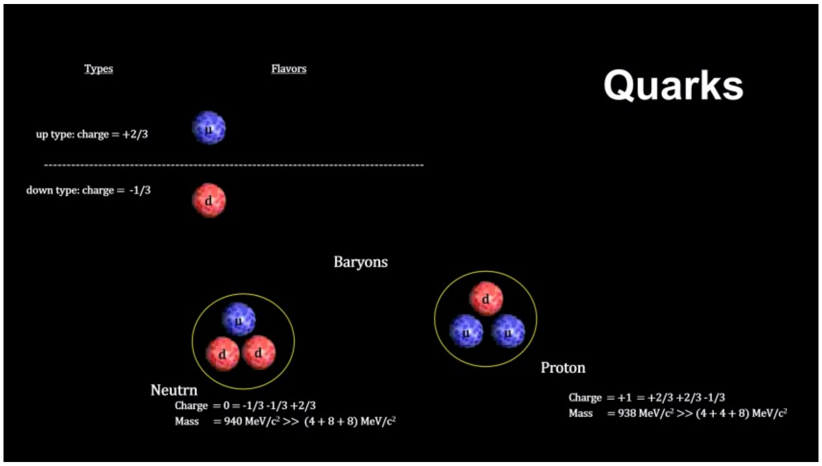
Back in 1964, a quark model was proposed by Murray Gell-Mann and George Zweig to help explain protons, neutrons and the wide variety of newly discovered heavy particles like Pions, Kaons and others. The discovery at SLAC in 1969 that the proton has three parts constituted evidence that quarks were real.



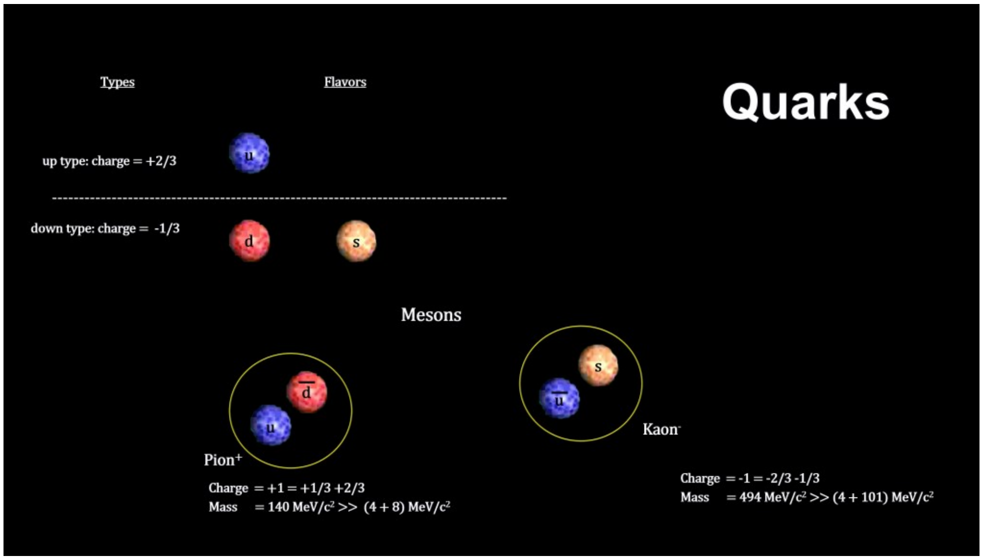
One of the key things to remember about the theory is that quarks are so strongly bound together that it is impossible to study one on its own in order to determine its properties. This means that all we know about quarks is derived from the properties of the particles that bound quarks create. [Aso, 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.



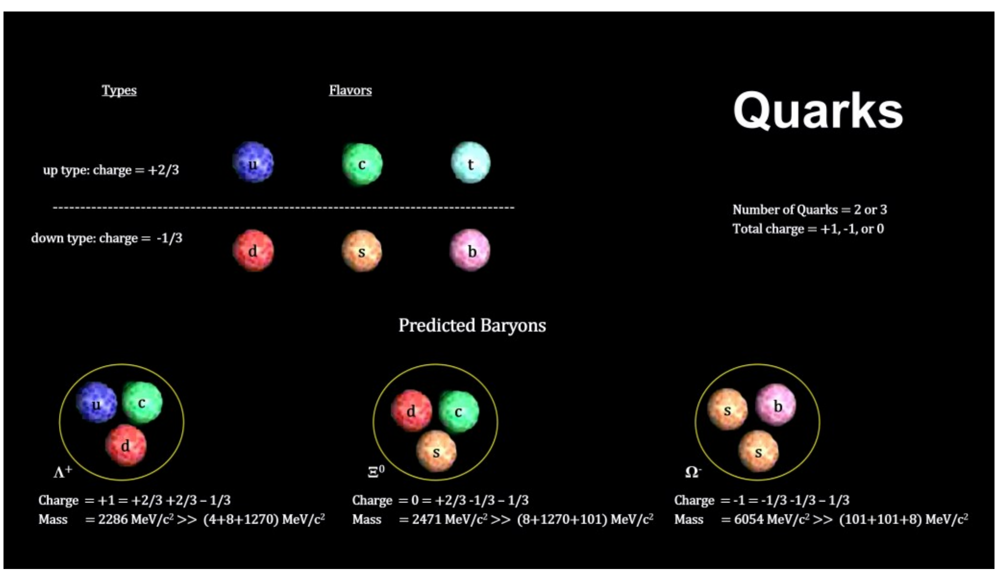
The baryons we've seen so far are the proton and the neutron. Quark theory has it that there are two flavors of quarks that make up these baryons called the up quark and down quark. Protons have 2 up quarks with one down quark, and the neutron has one up quark and two down quarks. In order to get the 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.]



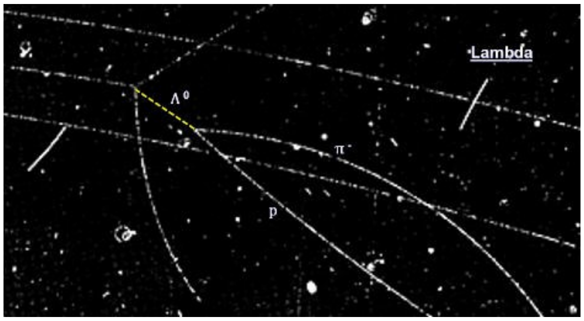
In addition to the up, down and strange quarks, we have discovered the charm, top and bottom quarks for a total of 6. One of the key rules seems to be that they can only combine in combinations of two or three as long as the sum total of charge always equals the charge of an electron or proton or zero. 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.

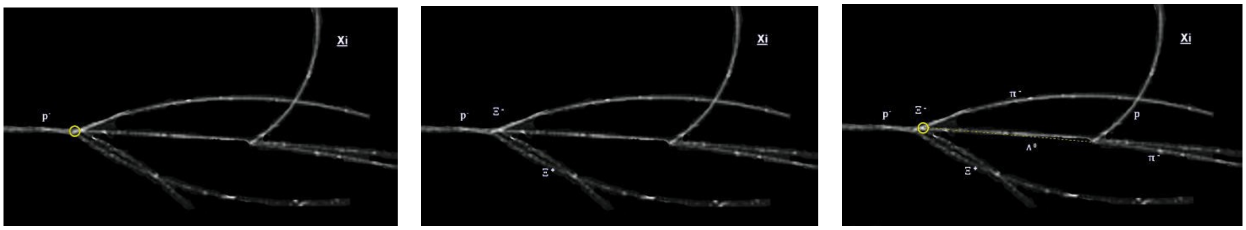
Here we see a V shape with the creation of a pion and a proton. It was the proton that told us the decaying neutral particle Lambda must have had three quarks. The particle was expected to live for $\sim 10^{-23}$ s, but it actually survived for $\sim 10^{-10}$ s. The property that caused it to live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



Xi Ξ

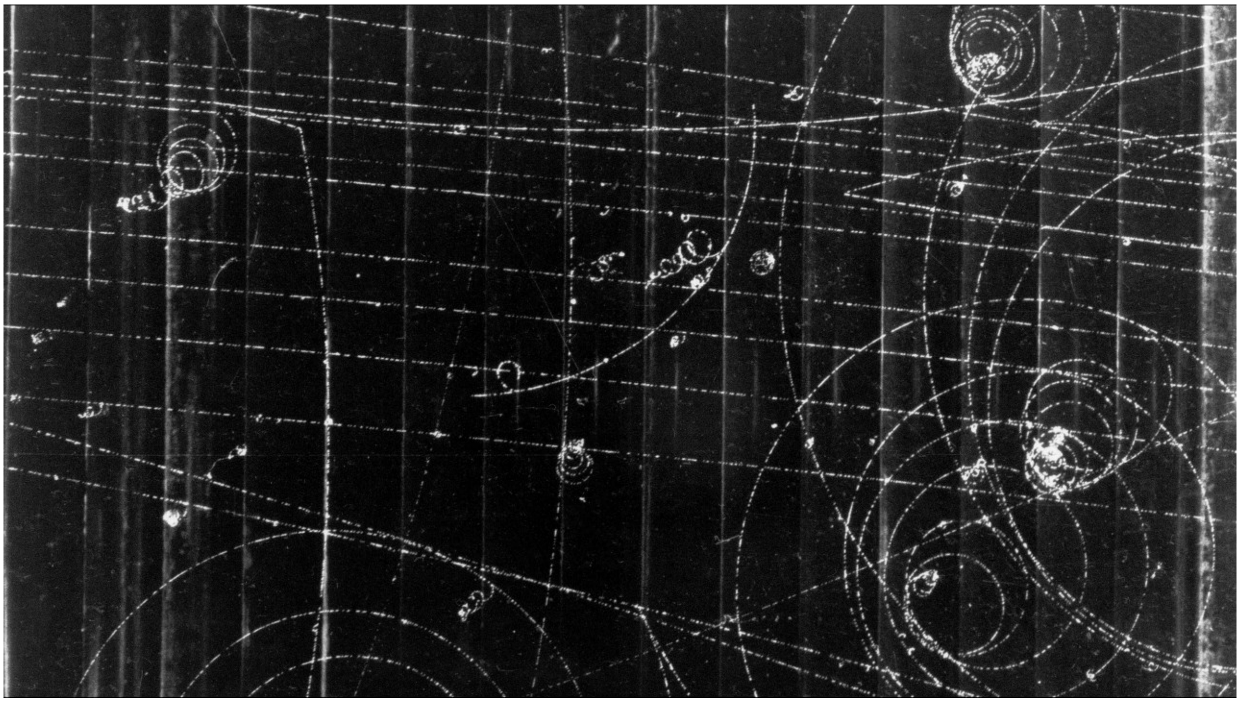
In 1964, the Xi baryon was discovery at the Brookhaven National Laboratory.

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.]

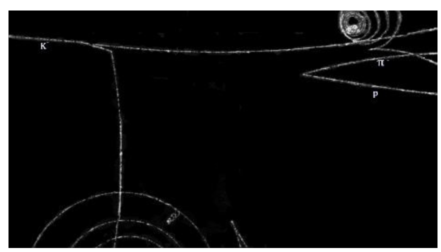


Omega Ω

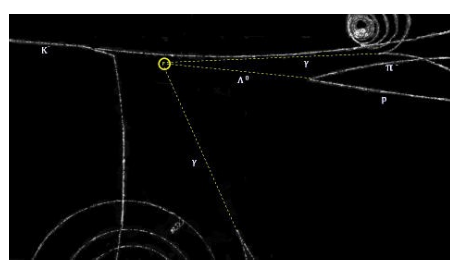
Also, in 1964 at the Brookhaven National Laboratory, the Omega particle was discovered. This is one of the most famous bubble chamber pictures of all. It shows the discovery of this long-predicted particle. In this photograph, we have manufactured Kaons entering the chamber on the left.



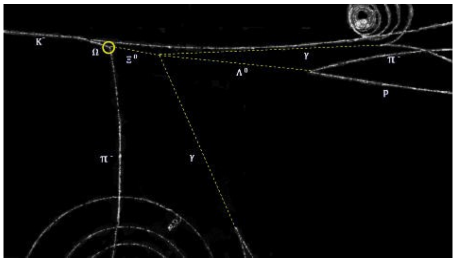
To help see the omega particle, I'll remove all but the tracks associated with the omega event, and work backwards from the V on the right that creates a pion and a proton. This is the trademark decay signature for the Lambda particle.



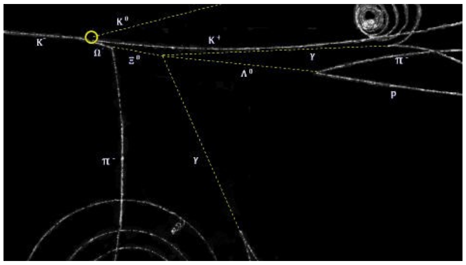
We also see Vs in the upper right and in the lower middle where a positron and an electron are created. This is the signature for high energy gamma rays. If we draw lines back to where the Lambda particle and the two gamma rays cross, we see that a neutral particle decayed into the neutral Lambda and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

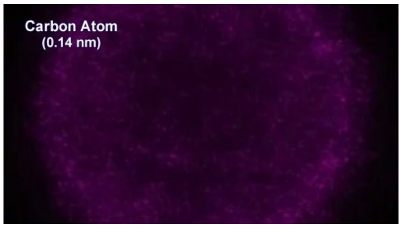


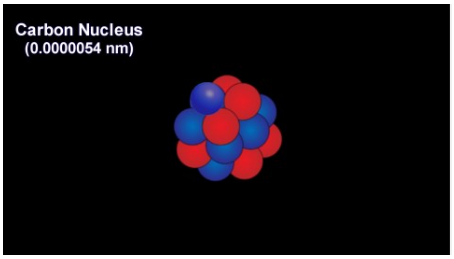
The physicist working on analyzing this photograph was so excited about his find that he woke up the director of the Brookhaven Laboratory in the middle of the night to give him the new! As with other predictions of previously unobserved particles, this discovery gave a tremendous boost to quark theory.

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.

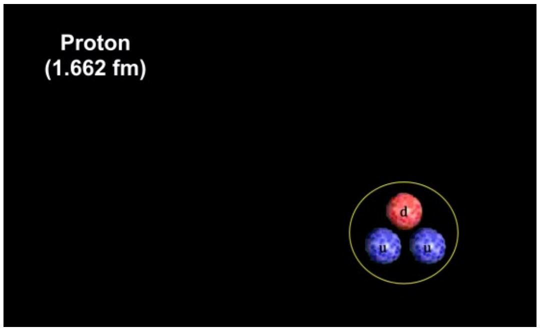
In our first segment, we used an electron microscope to see a carbon atom with a diameter of 0.14 nanometers. That's a million times smaller than the width of a human hair.



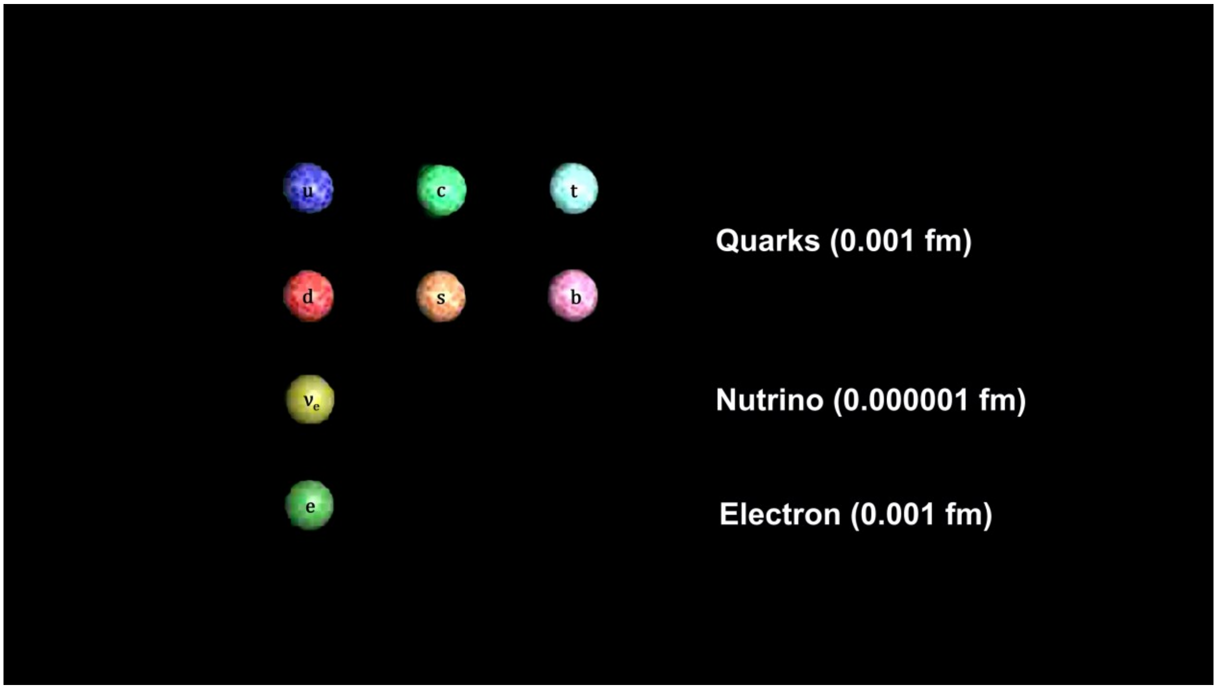


In our second segment, we probed the atom with alpha particles and found that the nucleus was very small compared to the atom. Here we have the carbon nucleus at around 26 thousand times smaller than the carbon atom.

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.

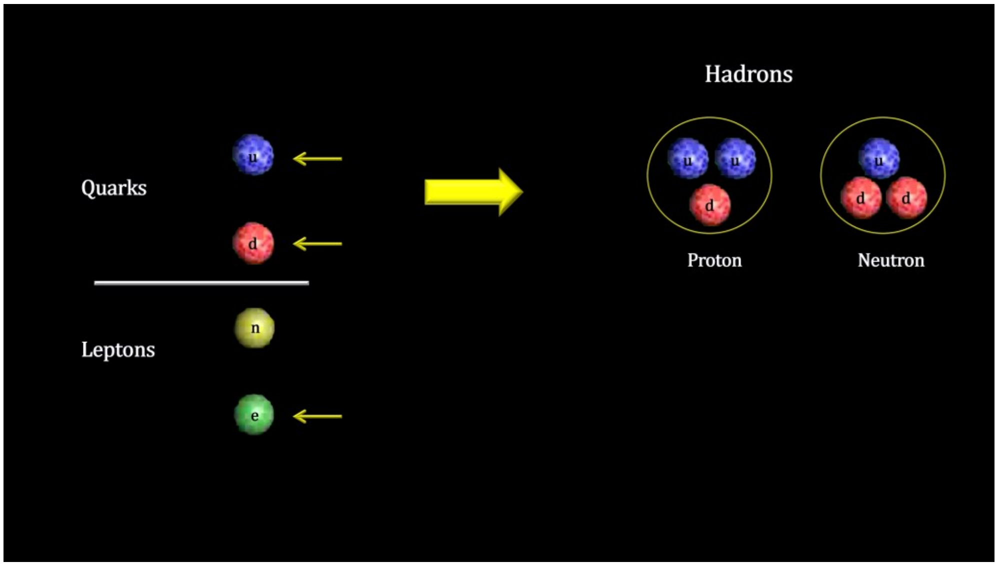


In this segment, we probed the proton with high velocity electrons and found that it contained three quarks. Powerful accelerators and hadron colliders have put the upper limit on the diameter of the cross section of a quark at 0.001 fm. That's 1,760 times smaller than a proton, and a 140 million times 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!

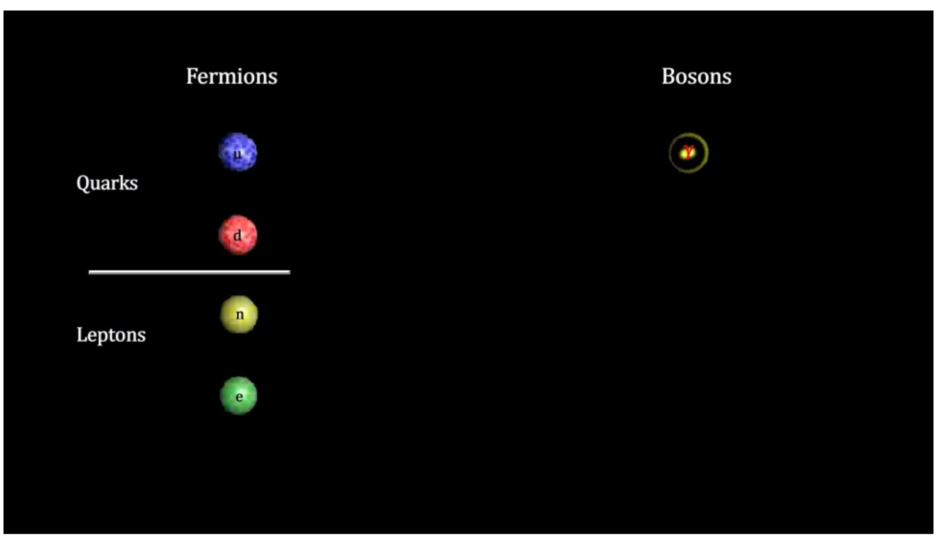


Fermions and Bosons

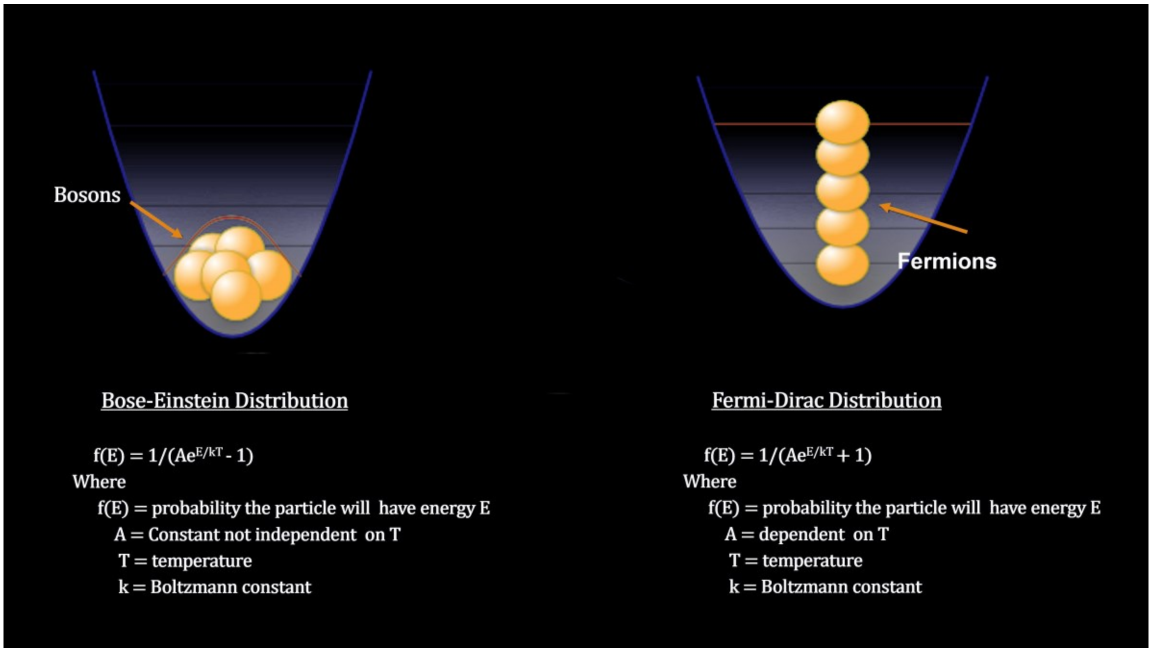
When confronted with a vast number of observations, a first step to understanding, is categorization. We try find the similarities and differences between things. When it comes to elementary particles, we have already made some distinctions. We have the small light particles like the electron and the 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.



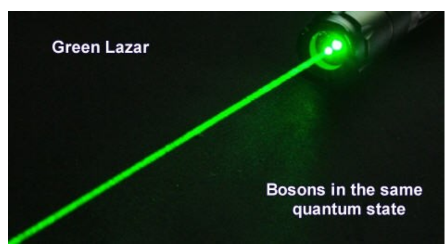
A particle's spin is another key distinction that helps us categorize all these particles. You'll recall that electrons and quarks have spin ½ and therefor follow Pauli's Exclusion principle. Photons have spin 1 and do not follow the exclusion principle. The statistics that describe spin 1/2 particle 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.



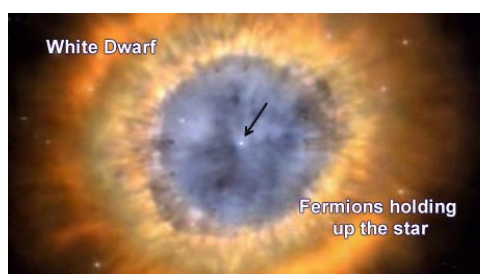
You can image that large groups of particles that can't fit into the same quantum state will behave differently than particles that can. In an energy well, the bosons all sit in a condensate at the bottom. The fermions arrange themselves in a hierarchy like electrons in an atom.



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.



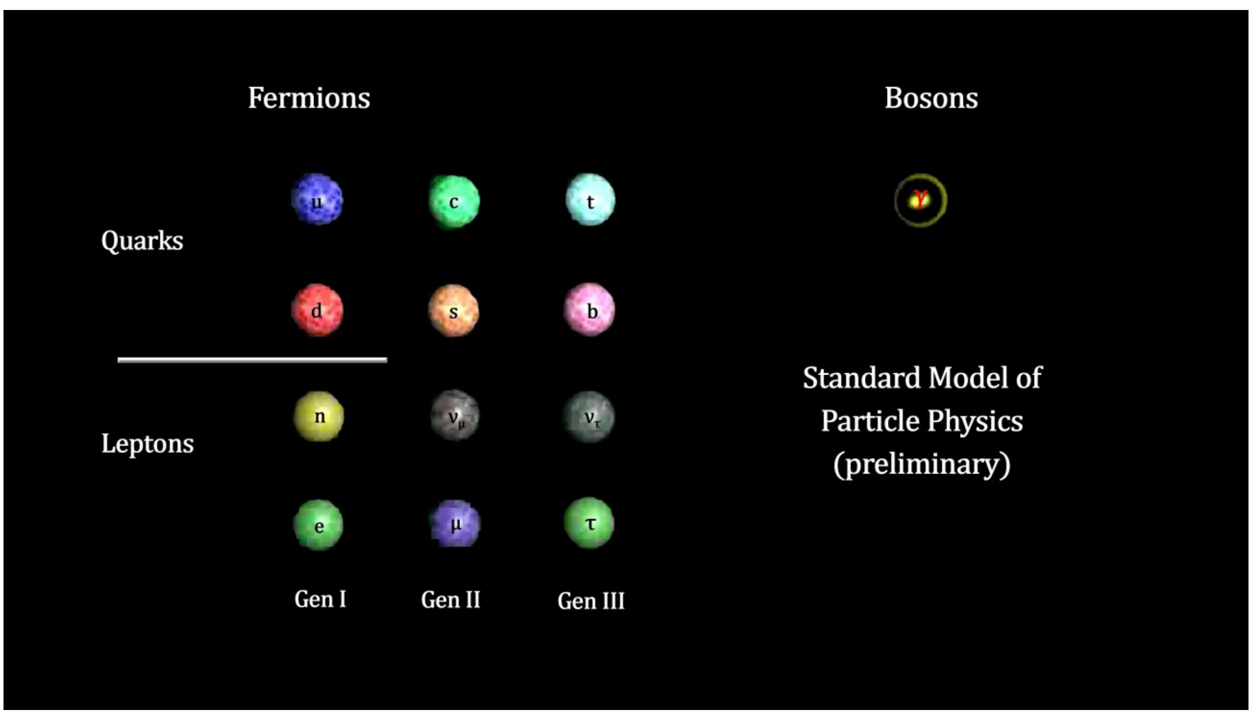
Standard Model of Particle Physics

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

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