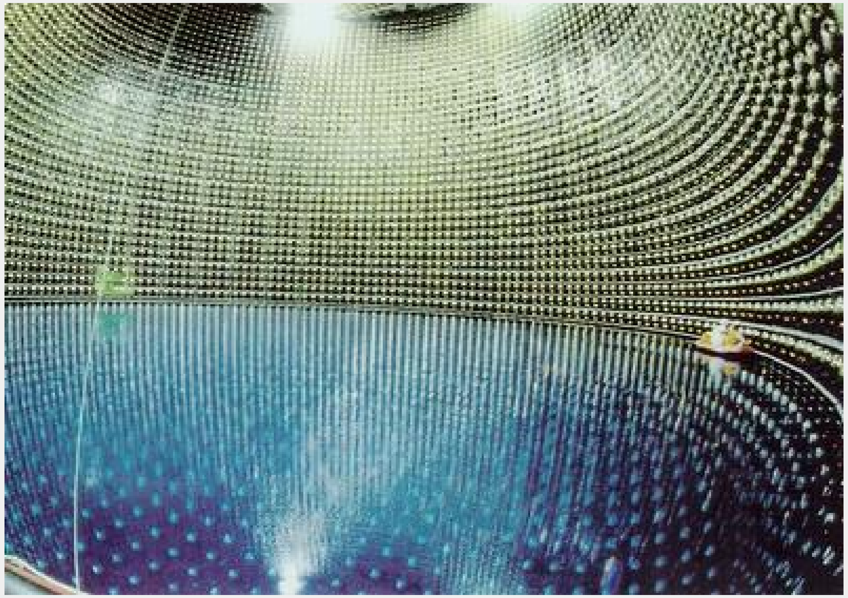
The Particle Zoo: Lend Me a Lepton



Credit: Super-Kamiokande Collaboration

Summary

In this Activity, we will begin to examine the particle zoo with the family of particles known as leptons. We will investigate:

- how observations of β-decay led to the prediction of neutrinos;
- experimental confirmation of the neutrino's existence; and
- the discovery of two additional families of leptons.

Before we can do that, however, we need to briefly discuss a form of matter that we haven't mentioned until now – *antimatter.*

Antimatter

For all the types of charged particles that exist in the Universe[1], there also exists a corresponding **antimatter particle**, or antiparticle.

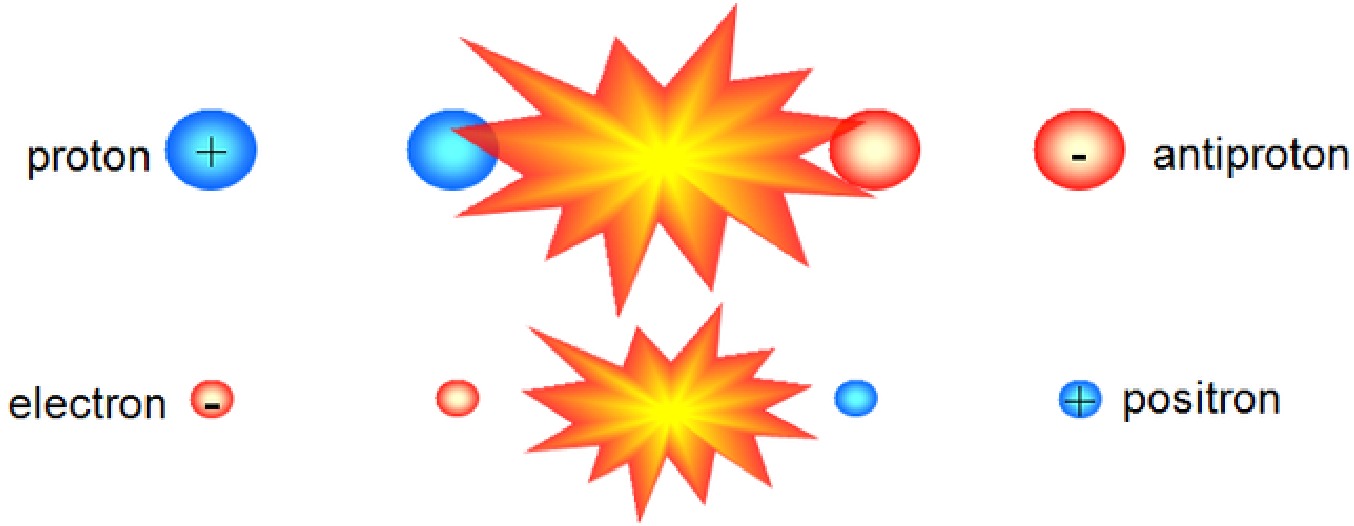
Antiparticles look and behave just like their corresponding matter particles, except they have opposite charges[2]. A particle and its antiparticle have the same mass, so, contrary to popular belief, gravity affects them in the same way.

[1] Thus far, we have only discussed protons and electrons. However, all the exotic particles that you are about to meet in the next few Modules also have corresponding antiparticles.

[2] Particles and antiparticles also have opposite quantum numbers which will be discussed more fully in the Activity *Quantum Numbers*.

Positrons and anti-protons

For instance, a proton is electrically positive whereas an **antiproton** is electrically negative. An anti-electron, on the other hand, is positively charged. It is usually referred to as a **positron**. When a matter particle and antimatter particle meet, they annihilate into pure energy.



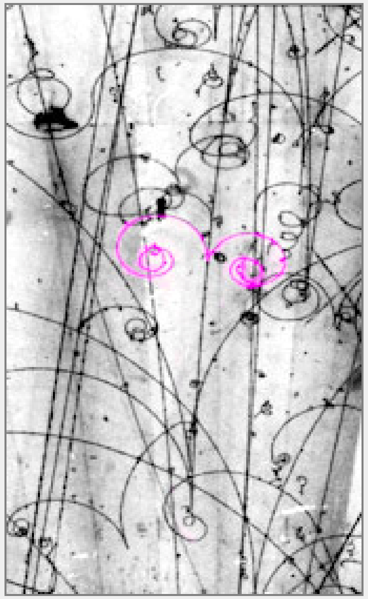
Anti-matter really exists

The idea of antimatter is strange, especially because the Universe appears to be composed entirely of matter. If there is as much antimatter as there is matter, then where has it all gone?

You can see evidence for antimatter in this early bubble chamber photo, which shows the production of electron-positron pairs. The magnetic field in this chamber makes negative particles (electrons) curl left and positive particles (positrons) curl right.

You will learn more about different types of antimatter in the next few Modules, and we'll get back to discussing the matter-antimatter imbalance in the *Particle Cosmology* Module near the end of the Unit. For now, we'll go on to investigate the "standard model" of particle physics.

Click here to visit CERN's website.

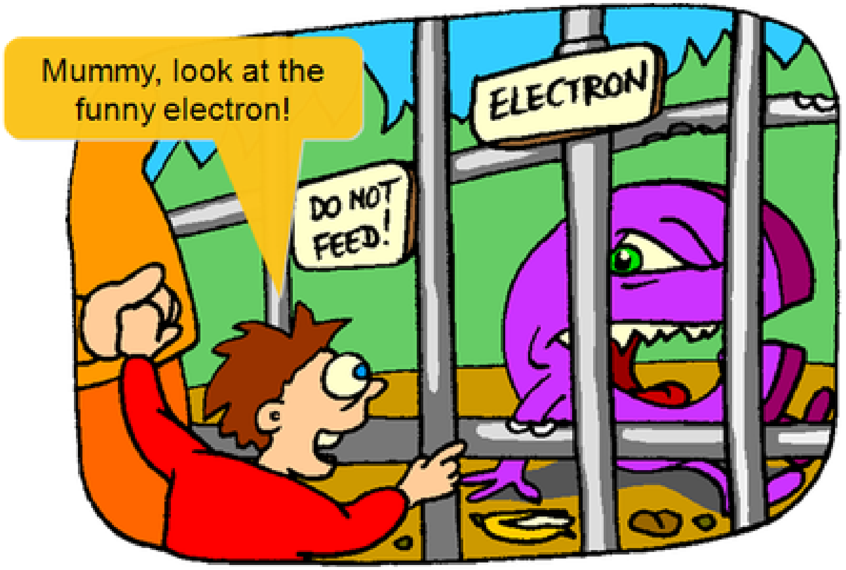


Electron-positron pairs in bubble chamber.

Credit: CERN

The Standard Model

The Standard Model of particle physics attempts to describe the fundamental particles and the interactions between them. The Standard Model is able to explain nearly all of the interactions we know about: electromagnetic, weak and strong nuclear forces. . . but not gravity.



In the next few Activities, we will investigate the "zoo" of particles which have been discovered over the last 100 years.

Fundamental differences

There is one fundamental difference between electrons as compared to protons and neutrons (collectively called nucleons).

- Nucleons “feel” the strong nuclear force.
- Electrons do not “feel” the strong nuclear force[1].

To see what we mean by a particle “feeling” a force, consider the neutron. The neutron has no charge, and so there is no electromagnetic force between neutrons and charged particles. We would say that the neutron does not feel the electromagnetic force.

[1] Neither do positrons.

Hadrons and Leptons

In turns out that all material particles can be classified into one of two groups:

- **Hadrons** are particles that “feel” the strong force.
- **Leptons** are particles that do not “feel” the strong force.

There is an additional category for some special particles which “carry” forces. These particles are called **gauge bosons**. An important gauge boson is the photon which carries the electromagnetic force between charged particles.

Classifying particles

In the following Activities, we are going to be showing you many tables of particle properties. Here is the first:

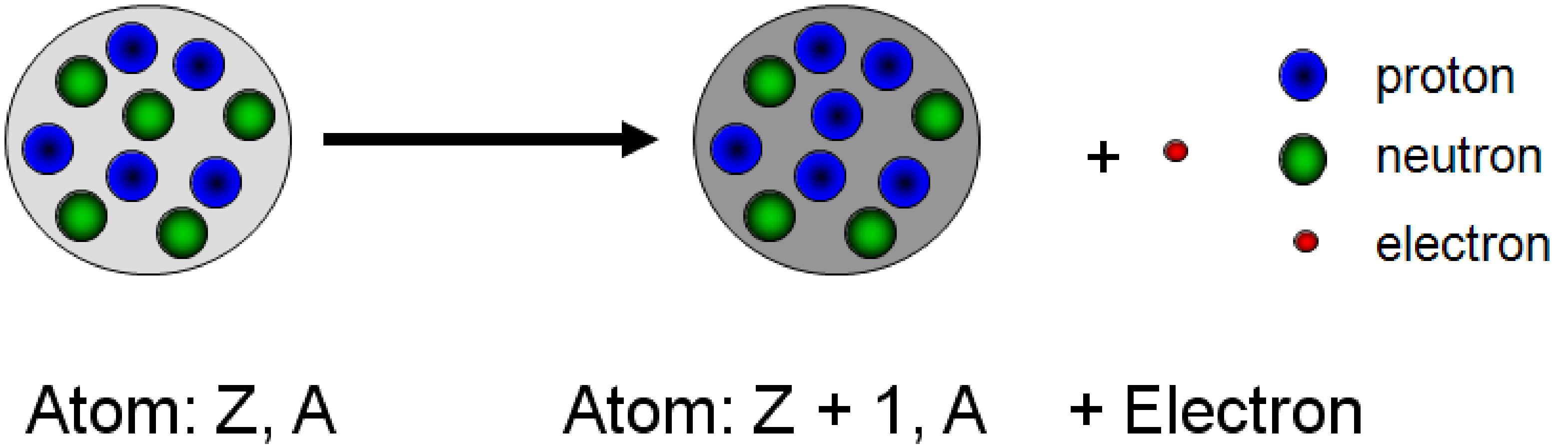
Particle	**Type**	**Charge**	**Mass**	**Symbol**
Proton	Hadron	+1	938.27	p
Neutron	Hadron	0	939.56	n
Electron	Lepton	-1	0.511	e^-
Positron	Lepton	+1	0.511	e^+
Photon	Boson	0	0	γ

(The particle masses in this table have been quoted in units of MeV/c^2, which we discussed in the previous Module.)

β-Decay and a new particle

We have already met two very important leptons: the electron and the positron. The next lepton was discovered from observations of the β-decay process.

Consider the following β-decay:

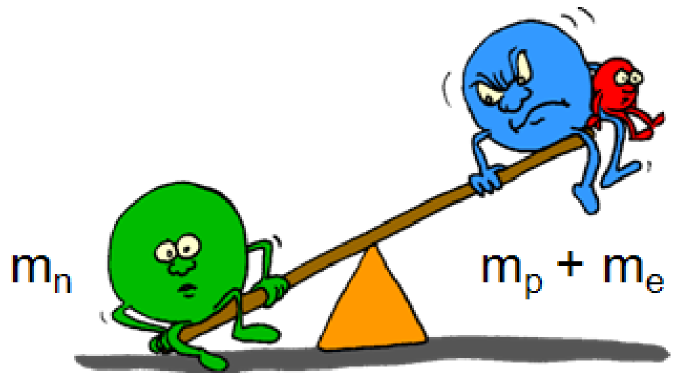


- Z is the Atomic Number = of protons.
- A is the mass number = of protons + of neutrons.

A question of mass

The β-decay process is the conversion of a neutron into a proton, where the mass of the neutron is greater than the combined mass of the proton and electron: $m_n > (m_p + m_e)$.

$$\mathbf{n \rightarrow p + e^-}$$



Because the decaying atom is much heavier than the emitted electron, we can neglect the atom's recoil.

Then by conservation of energy arguments, we have:

Mass(Atom: Z, A) = Mass(Atom: Z+1, A) + total energy of the electron

Energetic electrons

The total energy of the electron includes both the electron mass (by using $E_e = m_e c^2$) and its kinetic energy (or energy of motion), E_K.

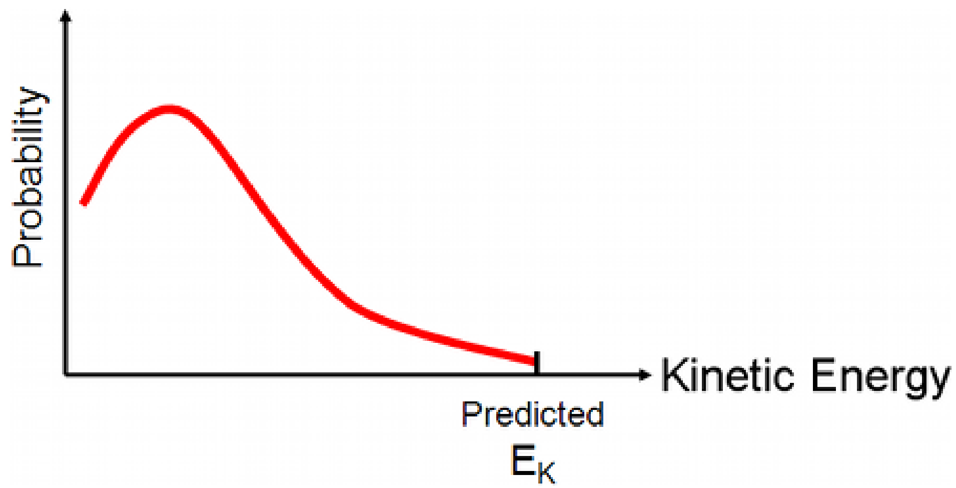
In this scenario, the electron kinetic energy has a unique value:

Mass(Atom: Z+1, A) – Mass(Atom: Z, A) = total energy(electron) = $m_e c^2 + E_K$

But the observed kinetic energy of the electron in β-decay processes was found to take on a range of values up to the predicted E_K.

The electron energy spectrum

The electron energy spectrum from β-decay looks like this:



It tells us how many electrons will occur with particular value of E_K. Note that very few electrons have the predicted energy! The continuous energy spectrum was discovered in 1914 by James Chadwick from observations of the β-decay of ^{214}Pb.

What does it all mean?

The total electron energy spectrum suggests something important: β-decay is *not* a two body process.

In other words, β-decay is not

$$\mathrm{n} \rightarrow \mathrm{p} + \mathrm{e}^-$$

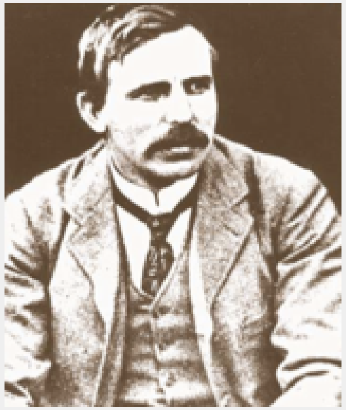
as we first wrote it, but is actually:

$$\mathrm{n} \rightarrow \mathrm{p} + \mathrm{e}^- + \textit{something else}$$

This *something else* is a particle called a **neutrino**. More precisely, it is an *electron antineutrino*, which is given the symbol: $\bar{\nu}_e$. The "bar" indicates an antiparticle.

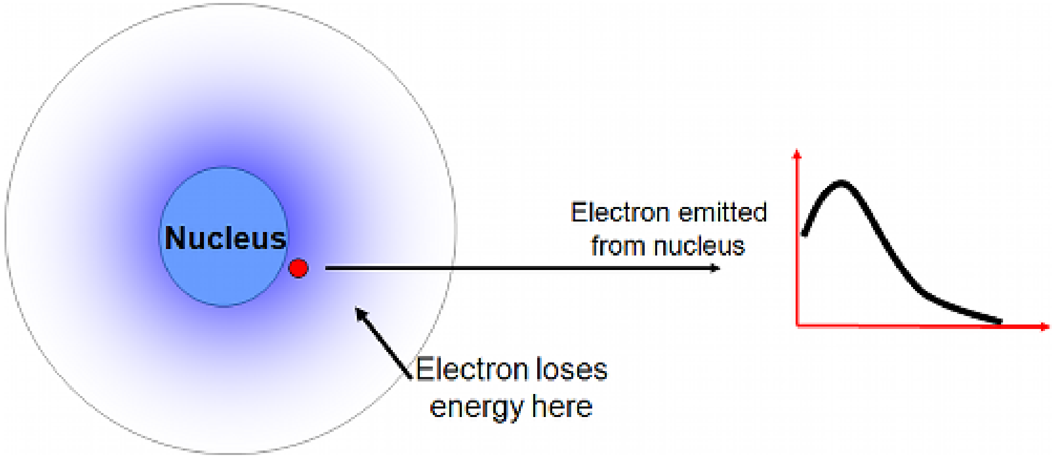
(Re)Discovering the neutrino

The neutrino was not the only explanation for the continuous β-decay spectrum. Ernest Rutherford thought that all β-decay electrons were emitted with the same energy, but lost some of this energy depending on the thickness of "atomic material" they had to pass through.



Ernest Rutherford.

Credit: AIP Emilio Segrè Visual Archives



"Neutrinos, they are very small"[1]

Lise Meitner (ca. 1928)

Credit: AIP Emilio Segre Visual Archives

Wolfgang Pauli

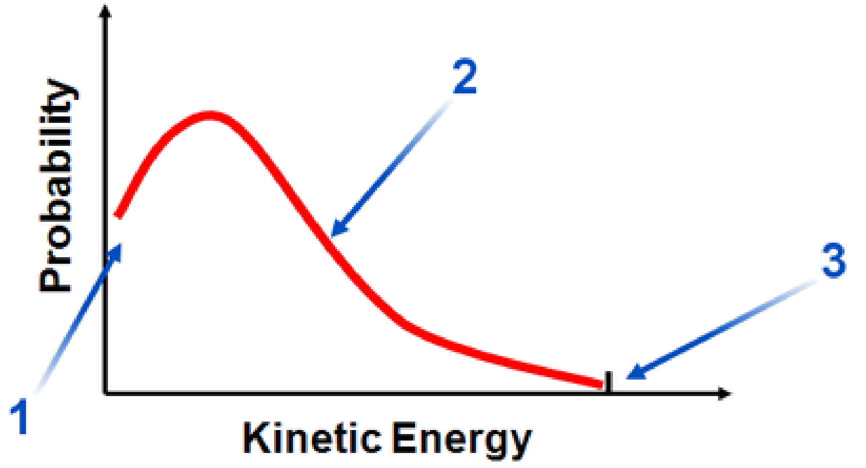
Credit: CERN

In December 1930, Wolfgang Pauli proposed the existence of the neutrino in an open letter to Hans Geiger and Lise Meitner (who had made important contributions to the understanding of β-decay herself). Pauli originally called the particle a "neutron", as this was two years before Chadwick discovered what we now call a neutron! Enrico Fermi proposed **neutrino** as an alternative in 1933. It means "*little neutral one*".

[1] J.Updike, from "*Cosmic Gall*" in *Telephone Poles and Other Poems*, André Deutsch, London (1964).

Understanding the electron energy spectrum

We can now interpret the electron energy spectrum in terms of the neutrino:



1: Electron antineutrino takes away nearly all of the energy, leaving electron “at rest”.

2: Electron and electron antineutrino both have non-zero kinetic energy.

3: Electron takes away nearly all of the energy, leaving the electron antineutrino “at rest”[1].

[1] We have to say “at rest” because it is unlikely that either particle won’t have some small amount of kinetic energy.

Antineutrinos and neutrinos

We have now seen that the β-decay process involves the decay of a neutron into a proton, an electron and an electron antineutrino. Is there also an electron neutrino, ν_e? Of course there is!

There is a second β-decay process which turns a proton into a neutron, a positron and an electron neutrino. We can denote these two decays as:

β^--decay

$$\mathrm{n} \rightarrow \mathrm{p} + \mathrm{e}^- + \bar{\nu}_e$$

β^+-decay

$$\mathrm{p} \rightarrow \mathrm{n} + \mathrm{e}^+ + \nu_e$$

No free proton decay

The β^--decay process can occur in free space. That is, a lone neutron away from any other particles can spontaneously decay into a proton, electron and electron antineutrino.

As we stated earlier, this is because

$$m_n > (m_p + m_e + m_{\bar{\nu}_e})$$

(We will justify the addition of $m_{\bar{\nu}_e}$ in a moment...)

But

$$m_p < (m_n + m_{e^+} + m_{\nu_e})$$

so the proton decay can only occur when the proton is part of an atom. In this case, the nuclear binding energy of the atom can provide the additional mass-energy required.

Experimental confirmation

Although Pauli's proposed neutrino seemed to explain the electron energy spectrum, direct experimental evidence for the neutrino did not appear until 1959, nearly 30 years later.

The reason it took so long to directly detect a neutrino, rather than infer its existence from the β-decay spectrum, is that neutrinos only interact very weakly with matter[1].

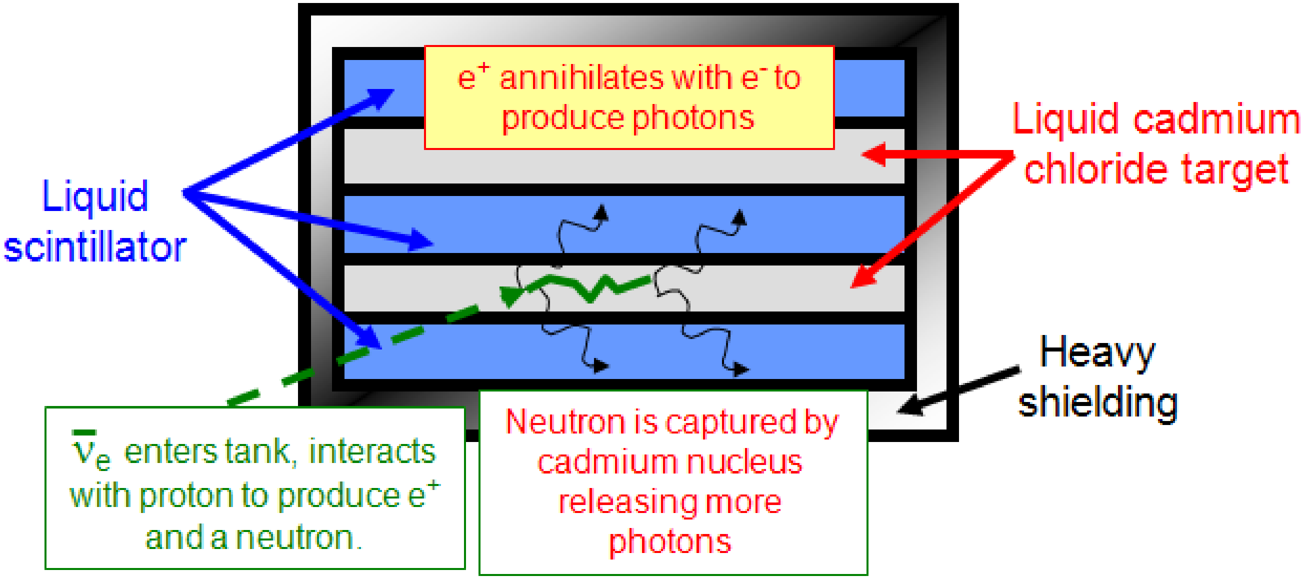
Fred Reines and Clyde Cowan's experiment with a nuclear reactor at Savannah River, North Carolina used neutron-rich fission fragments of uranium. These fragments produce copious numbers of electron antineutrinos.

[1] As we will see in the Activity *Neutrino Astronomy*, the Sun is a significant source of neutrinos, but most of them pass through the Earth (and you!) as if there was no matter in the way.

Fred Reines

Credit: AIP Emilio Segre Visual Archives

Occasionally the antineutrinos would interact with protons within the detector apparatus, producing coincidence events that were measured with layers of liquid scintillators[1].

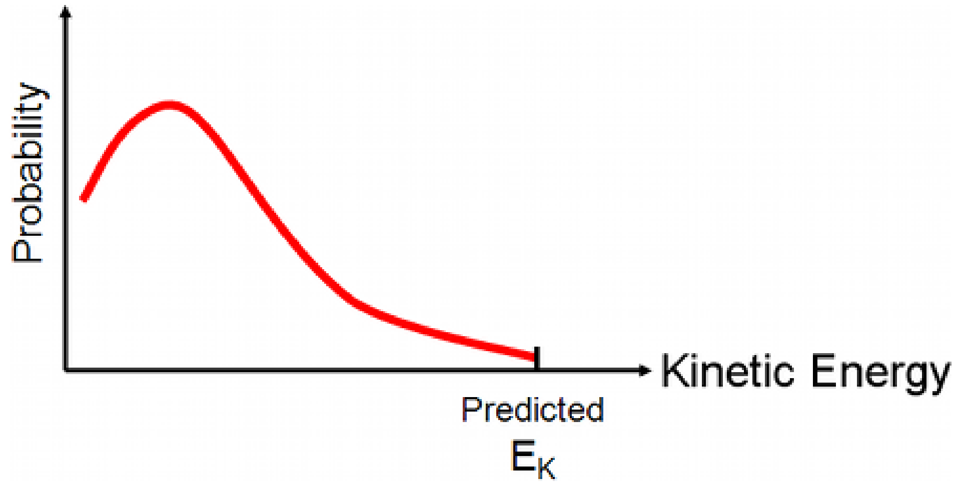


There is a time delay (a few μ sec) between the two photon production events: called a "coincidence" detection. In a 200 hour experiment, 567 coincidence signals were detected!

[1] We will describe scintillators in the Module: *Particle Physics: Detectors.*

The Mass of the neutrino

What is the mass of the electron neutrino (or antineutrino)? Let's look at the total electron energy spectrum again:

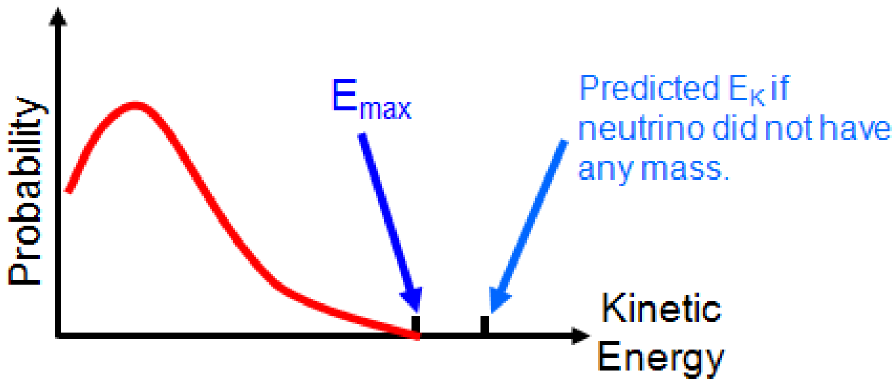


Suppose that $\bar{\nu}_e$ has a mass, $m_{\bar{\nu}_e}$, and therefore rest energy:

$$E_{\bar{\nu}_e} = m_{\bar{\nu}_e} c^2$$

To be rigorous here, the "predicted" E$_K$ determined from the simple two-body β-decay process now includes the contribution from the electron mass which we neglected before.

The maximum kinetic energy that the electron can have is when the antineutrino is emitted with "zero" kinetic energy.



Then we have the maximum electron kinetic energy:

$$E_{\max} = E_{\mathrm{K}} - m_{\bar{\nu}_e}c^2 < E_{\mathrm{K}}$$

By accurately measuring the electron energy spectrum, we can infer the mass of the neutrino. Experimentally, it was found that $E_{max} \approx E_K$, so that

$$m_{\bar{\nu}_e}c^2 \approx 0$$

Next to nothing...

In other words, the mass of the electron antineutrino is so close to zero, that in most cases we can treat its mass as zero.

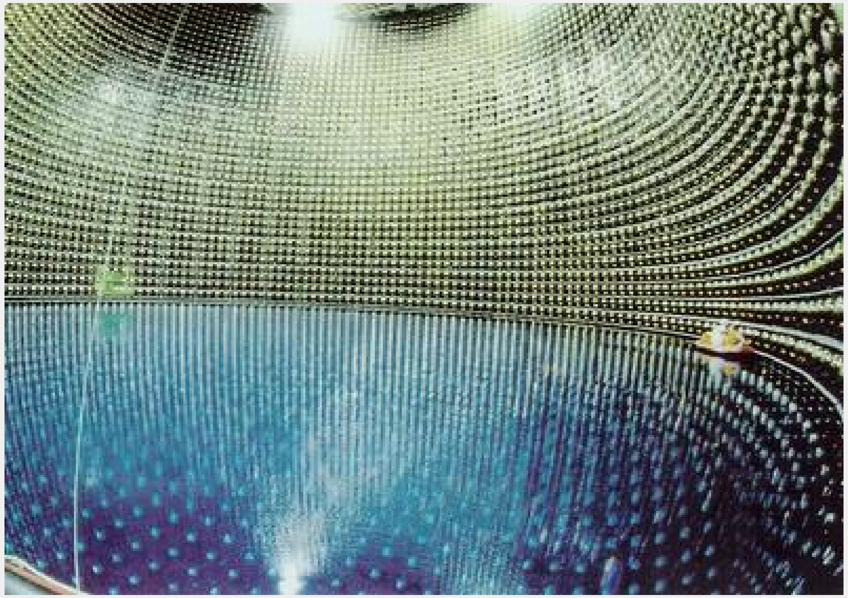
The best measurement of neutrino mass comes from the β-decay of tritium. The measurement of the maximum electron kinetic energy, E_{max} (sometimes called the "end point") sets an upper limit on the neutrino mass of 3 eV/c^2, but this still leaves open the possibility that the neutrino does in fact have zero mass.

But there is no reason *why* the neutrino should have exactly zero mass: the Standard Model of particle physics is able to explain a neutrino with mass.

Neutrino mass

In 1998, a team of nearly 100 Japanese and American physicists published evidence that the neutrinos do indeed possess mass. They used the Kamioka Underground Observatory in Japan: an enormous tank (shown above) holding 3,000 tons of water located 1000 m underground in an old zinc mine.

Neutrinos passing though the tank occasionally interact with the water, producing showers of high energy particles (often electrons) that are detected using nearly 1000 photomultiplier tubes which line the inside of the tank.



Credit: Super-Kamiokande Collaboration

Neutrino astronomy

Nearly a decade earlier, the Kamioka Underground Observatory detected a grand-total of 11 neutrinos from the supernova explosion SN1987A (first seen February 23, 1987 in the Large Magellanic Cloud).

You can learn more about the Kamioka Observatory on its website. We will investigate neutrino astronomy later in the Activity *Neutrino Astronomy*.

A half of the 2002 Nobel Prize for Physics was awarded to Raymond Davis and Masatoshi Koshiba for ”pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos”. Davis was the first scientist to detect solar neutrinos, and Koshiba led the research group at Kamiokande.

The other half of the prize was awarded to Riccardo Giacconi for his contribution to the development of X-ray astronomy.

SN1987A

Credit: Dr. Christopher Burrows, ESA/STScI and NASA

Classifying particles again

We can now add the electron neutrino and antineutrino to our table of particle properties:

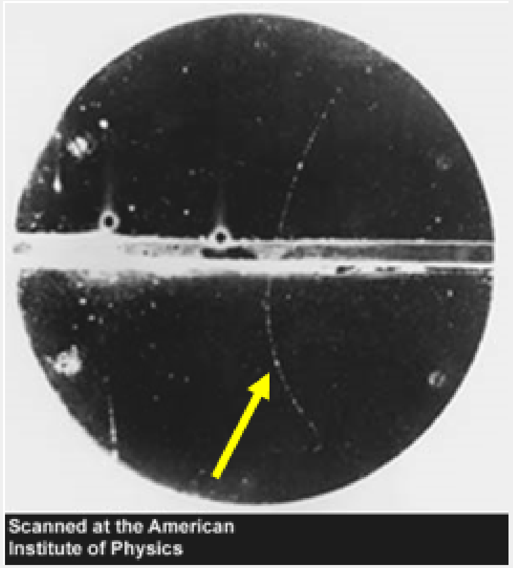
Particle	Type	Charge	Mass	Symbol
Proton	Hadron	+1	938.27	p
Neutron	Hadron	0	939.56	n
Electron	Lepton	-1	0.511	e^-
Positron	Lepton	+1	0.511	e^+
Neutrino	Lepton	0	$< 3\mathrm{eV/c}^2$	ν_e
Antineutrino	Lepton	0	$< 3\mathrm{eV/c}^2$	$\bar{\nu}_e$
Photon	Boson	0	0	γ

Mass in MeV/c^2 except where noted.

Any more leptons?

The next lepton was discovered by Carl Anderson and Seth Nedermeyer.

Anderson received the Nobel Prize for Physics in 1936, but not for identifying this new lepton. Instead, his Prize was for discovering a different lepton, the positron, four years earlier.



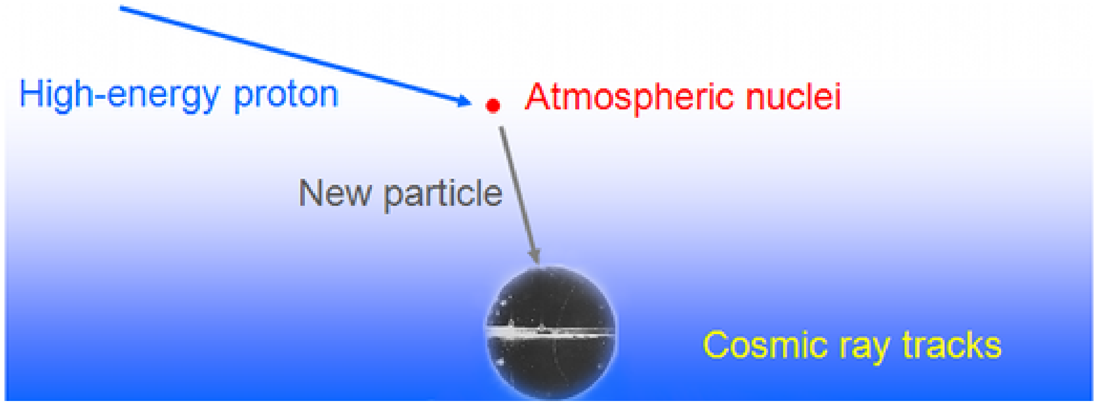
First image of positron tracks.

Credit: C.D. Anderson, AIP Emilio Segre Visual Archives

The cosmic ray connection

The atmosphere of the Earth is constantly bombarded by cosmic rays. Many of these are high-energy protons, which collide with nuclei in the atmosphere to produce new particles.

Some of these particles make it all of the way through the atmosphere, where they can be detected as cosmic ray tracks in laboratory experiments. (We will discuss this in more detail in the *Cosmic Rays* Activity.)



Muons

Anderson and Nedermeyer were examining the tracks of cosmic rays, and discovered a particle which had a negative charge, but a mass of 105.66 MeV/c^2, which is about 200 times heavier than the electron!

This new particle was called the **muon** (μ). The muon's discovery occurred between 1934, when the first cosmic ray tracks revealed a massive particle, and 1937 when conclusive results were published.

Carl Anderson

Credit: National Archives and Records Administration, AIP Emilio Segre Visual Archives

A heavy electron

Provided its higher mass is taken into account, the electromagnetic properties of the muon are identical to those of the electron! We can think of the muon as a “heavy electron”.

The muon is highly unstable, and decays with a very short lifetime of about 2.2×10^{-6} seconds.

Muons decay in the following way[1]:

$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

and

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

where μ^+ is the antiparticle of the muon: the antimuon.

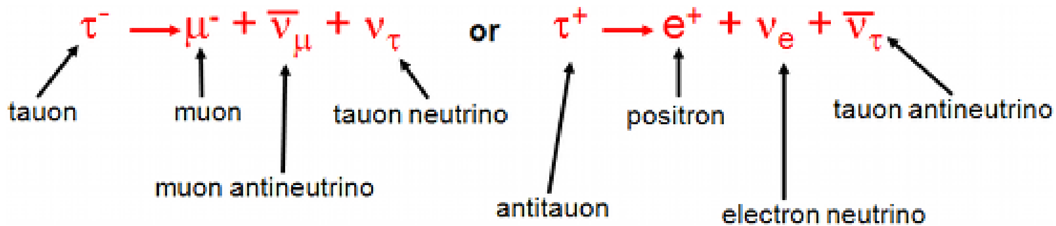
[1] In the Activity *Quantum Numbers*, we will see why the decays take this form.

Heavier electrons

An even "heavier electron", the **tauon** (τ) with mass 1777 MeV/c^2, was discovered in 1975 from experiments involving collisions of beams of electrons and positrons. Provided the energy available in the interaction was greater than 3.6 GeV, a tauon and an antitauon were produced:

$$e^- + e^+ \rightarrow \tau^- + \tau^+$$

The τ has a lifetime of only 3×10^{-13} seconds, and typical decays are :



Tauon decay is much more complex than muon decay, as there are several possible decay modes due to the extra mass of the tauon.

Antileptons

As these last few reactions show, there are not only leptons (e$^-$, μ^- and τ^-) but also antileptons (e$^+$, μ^+ and τ^+). And each of the "heavy electrons" is partnered by corresponding neutrinos[1] (and antineutrinos).

We now have quite a collection of leptons, with three different "families":

Electron family: $e^-, e^+, \nu_e, \bar{\nu}_e$

Muon family: $\mu^-, \mu^+, \nu_\mu, \bar{\nu}_\mu$

Tauon family: $\tau^-, \tau^+, \nu_\tau, \bar{\nu}_\tau$

Unfortunately we do not know why there are two heavier versions of the electron and their corresponding neutrinos. We will see another example of this "tripling" in the next Module.

[1] The existence of the tau neutrino was confirmed by a direct observation at Fermilab in 2000.

The stable electron

Although the muon and tauon can decay into lighter particles, the electron is the lightest known charged elementary particle, and so it is stable. There is nothing lighter it can decay into!

Our final summary table for this Activity includes the experimental limits on the masses of the muon and tauon neutrinos:

Particle	Type	Charge	Mass	Symbol
Electron	Lepton	-1	0.511	e^-
Neutrino	Lepton	0	< 3eV/c^2	ν_e
Muon	Lepton	-1	105.66	μ^-
Muon neutrino	Lepton	0	< 190keV/c^2	ν_μ
Tauon	Lepton	-1	1777.03	τ^-
Tauon neutrino	Lepton	0	< 18.2MeV/c^2	ν_τ

Mass in MeV/c^2 except where noted.

Coming up after the break

We have now looked at the three families of leptons. These are particles which do not feel the strong nuclear force.

In the next Activity, we turn our attention to the hadrons, and introduce some more ways to classify fundamental particles.