

General information on Neutrino Oscillation

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In 1931 the existence of a neutrino was proposed by Wolfgang Pauli to account for the apparent violation of the conservation of energy and momentum witnessed during Beta decay, e.g. when carbon-14 decays to become nitrogen-14 and an electron (e^-).

In order to conserve energy, momentum, and charge the particle Pauli proposed needed to have zero mass and no electric charge. Enrico Fermi later named Pauli's new particle a neutrino, Italian for "little neutral one." We now know that neutrinos are formed during "weak" interactions, such interactions occur in β decay, and nuclear reactions such as those that occur in the sun and nuclear reactors.

The characteristics of the neutrino (zero mass and no electric charge) made neutrinos difficult to detect even though they are extremely numerous. There are literally trillions of neutrinos passing through your body every second; the elusive neutrino was finally detected in 1956 (it was actually an anti-electron neutrino and was detected at the Savannah nuclear power plant).

Neutrinos are now believed to have some mass, however they are so non-interactive that they can pass through the Earth with very little probability of hitting a single nucleus, they will only interact with an atom if they hit a nucleus.

A neutrino is a member of the lepton family of particles. Leptons are elementary particles meaning they exist separately, and do not join together to make more complex particles. Quarks,

are also elementary; however, they will join together to make more complex particles such as mesons (two quarks) and baryons (three quarks). An example of a meson is the pion⁺ and an example of a baryon is the proton.

Altogether there are three charged leptons, each has a neutrino associated with it, making a total of six leptons; there is also an antiparticle for each lepton.

symbol	Name (flavor)	Mass	Charge
e^-	electron	0.511 MeV	-1
ν_e	Electron neutrino	< 3eV	0
μ^-	muon	0.106 GeV	-1
ν_μ	Muon neutrino	< 170 KeV	0
τ^-	tau	1.777 GeV	-1
ν_τ	Tau neutrino	18.2 MeV	0

Of the three charged leptons only the electron is a stable particle, the remaining two leptons quickly decay into other particles. The decay rates are 2.2×10^{-6} seconds for the muon and 2.96×10^{-13} seconds for the tau.

Every instant Earth's atmosphere is bombarded by cosmic rays. Approximately 90% of these are hydrogen nuclei (protons), with alpha particles making up most of the rest. When a high-energy proton strikes an atom in the upper atmosphere a cascade of other particles are formed-the particles that interest us are pions. A pion is a member of a family of particles called mesons. A meson contains only two quarks one of which is an anti-quark, an example is the positive pion

(π^+). This pion is composed of an up quark and an anti-down quark, it is very unstable, and after 2.6×10^{-8} seconds it decays into a muon (μ^-) and a muon neutrino (ν_μ). A muon is a particle that has the same charge as an electron, but is 207 times more massive. It is unstable and after 2.2 microseconds it decays into, among other things, a muon neutrino.

More than half of the cosmic radiation that actually reaches the Earth's surface are muons. If you are standing on the surface of the Earth there are two muons passing through your hand every second. If you were in the MINOS cavern, 2400 feet underground, only one muon would pass through your hand every 24 hours, clearly the rock filters out most cosmic rays. Because of its size the MINOS Far Detector still records one cosmic ray interaction every second.

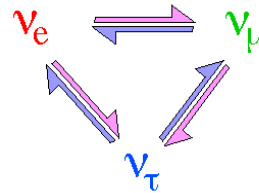
Muon neutrinos (in fact all neutrinos) are also unstable, they are believed to oscillate from one flavor (type) to another. This theory is relatively new, in fact it has only been within the past few years that it has gained wide acceptance. The oscillation theory owes its creation to the ground-breaking research conducted by Ray Davis at the Homestake gold mine in South Dakota. In research that spanned from 1967-1985, he consistently found only one-third of the solar neutrinos that standard theories predicted. His results left many physicists scratching their heads and many questioned his methodology; however peer review verified his results. For nearly three decades physicists tried to resolve the so-called "solar neutrino puzzle." The solar neutrino puzzle was, simply put, what happen to the missing solar (electron) neutrinos?

It is now believed that the missing electron neutrinos became muon

neutrinos while traveling from the sun to Earth.

Research at the SuperKamiokande neutrino detector in Japan confirmed Ray Davis' results and made another discovery. They found that the number of atmospheric neutrinos detected (those formed by cosmic ray interactions) changed depending of the location of the sun. The number of detected muon neutrinos was less when these neutrinos had to pass through the Earth. These results gave further credibility to the oscillation theory.

Simply put, the oscillation theory states that neutrinos will oscillate between types, or flavors.



Owing to mass differences there is a greater likelihood (probability) that the oscillation will follow a certain path. Electron neutrinos are more likely to become muon neutrinos and muon neutrinos are more likely to become tau neutrinos.

In quantum physics particle behavior is described by probability functions (equations). The equation that describes the probability of a muon neutrino (ν_μ) becoming a tau neutrino (ν_τ) is,

$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2(2\theta) \sin^2(1.27 \Delta m^2 L/E)$$

$P(\nu_\mu \rightarrow \nu_\tau)$ means the probability of a muon neutrino becoming a tau neutrino

$\sin^2(2\theta)$ is a value currently accepted to be greater than 0.90, it is essentially the amplitude of the sine wave, so at a quarter of a wavelength there is more than a

- 90% probability of the event happening.
- Δm^2 This term means the square of the difference in masses, of the two types of neutrinos.
- L Is the distance from the origin
- E Is the energy of the neutrinos

The Soudan Underground Laboratory in concert with Fermilab is involved in the MINOS project: Main Injector Neutrino Oscillation Search.

Fermilab will use its existing booster and main injector to send high-energy protons crashing into a graphite target; simulating high-energy protons (cosmic rays) hitting the atmosphere. During the proton-graphite interaction positive pions will be formed, and these will quickly decay into muon neutrinos.

These neutrinos will then be sent through the Earth, ending up at the far detector located a half-mile underground in Soudan Underground Laboratory in Northern Minnesota.

Physicists will then compare the composition of the Fermilab neutrino beam to the composition of the beam received at Soudan. The expected result is that $> 90\%$ of the muon neutrinos will have oscillated into tau neutrinos. The outcome of this experiment will be that we obtain a more accurate understanding of the masses of the various neutrinos as well as their oscillation rate

The cause of the neutrino oscillation is beyond the scope of this document; however, I will attempt to briefly explain its genesis.

Weak interactions are responsible for the fact that all the more massive quarks and leptons decay to produce lighter quarks and leptons. When a particle decays, it disappears and in its place two or more

particles appear. The sum of the masses of the produced particles is always less than the mass of the original particle. This is why stable matter around us contains only electrons and the lightest two quarks (the up and down.)

When a quark or lepton changes type (i.e. a muon changing to an electron) it is said to change flavor. All flavor changes are due to the weak interaction. The carrier particles of the weak interactions are the W^+ , W^- , and the Z bosons. The W's are electrically charged and the Z is neutral. (1)

The actual flavor of a particle, in our case the neutrino, is defined by certain eigenstates, which we could liken to waves. There are mass eigenstates and flavor eigenstates.

All particles can be described as wave packets formed by the superposition of a number of waves. By wave packets I am referring to the location where the peaks of the various constituent waves sum or reinforce each other. An example of a wave packet is the "beat" musicians use to tune their instruments.

The different constituent eigenstate waves all have different wavelengths; the summations of certain waves cause an electron neutrino to be formed. At some later distance other waves sum to form a different neutrino, this oscillation will continue indefinitely.

References:

1. <http://pdg.web.cern.ch/pdg/cpep/weak.html>
2. <http://www.bnl.gov/bnlweb/pubaf/pr/2002/bnlpr100802.htm>
3. <http://hyperphysics.phy-astr.gsu.edu/hbase/hframe.html>

Oscillation graphic

<http://www.lapp.in2p3.fr/neutrinos/ankes.html>