Neutrinos

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Abstract

Neutrinos are one of the fundamental particles that make the universe. They are produced by the decay of radioactive elements and are elementary particles that lack the electric charge. The name neutrino was coined by Enrico Fermi as a word play on neutrone, the Italian name of the neutron. Of all high-energy particles, only weakly interacting neutrinos can directly convey astronomical information from the edge of the universe and from deep inside the most cataclysmic high energy process.

Keywords: *neutrino, simulation, radio active elements, analytical modeling.*

Introduction

Neutrinos are hard to catch particles. They travel at super high speeds and billions pass through matter including us, every second without any interaction. The traditional theoretical framework of elementary particles – the standard model of particle physics-dictates that they have no mass. But since the late 1990s, experiments have shown this isn't the case. The WiggleZ survey derive neutrino mass, using analytical modeling and simulations. "The upper value of the sum of neutrino masses was measured to be 0.29 electron volts – two million times lighter than an electron." Even then a technique sensitive enough to measure individual neutrino mass does not yet exist. They are unaffected by magnetic fields and travel with the speed of light that gives basic requirement for knowing and analyzing the universe. They are of three types, electron neutrino(ν_e), muon neutrino(ν_μ), tau neutrino(ν_τ).

A Brief History of Neutrino

The neutrino was first postulated in 1930 by Wolfgang Pauli to preserve the conservation of energy, conservation of momentum and angular momentum in the beta decay. This was done by adding an undetected particle that Pauli termed as a neutron to the proton and electron already known to be products of beta decay.

$$n^o \rightarrow p^+ + e^- + \nu_e$$

He theorized that an undetected particle was carrying away the observed difference between the energy, momentum and angular momentum of initial and final particles.

In 1942 Kan-Chang Wang proposed the use of beta-capture to experimentally detect neutrinos which was claimed to be detected by Cowan, Reines and others in 1956. In their experiment, antineutrinos created in a nuclear reactor by beta decay reacted with protons producing neutrons and positrons:

$$\nu_{e^-} + p^+ \rightarrow n^o + e^+$$

The positron quickly finds an electron and they annihilate each other. The two resulting gamma rays are detectable. The neutron can be detected by its capture on an appropriate nucleus, releasing a gamma ray. The coincidence of both events – positron annihilation and neutron capture gives a unique signature of an antineutrino interaction.

In 1962 - Experiments at Brookhaven National Laboratory and CERN make a surprising discovery: neutrinos produced in association with muons do not behave the same as those produced in association with electrons. They have, in fact, discovered a second type of neutrino (the muon neutrino).

In 1968 - The first experiment to detect (electron) neutrinos produced by the Sun's burning (using a liquid Chlorine target deep underground) reports that less than half the expected neutrinos are observed. This is the origin of the long-standing "solar neutrino problem." The possibility that the missing electron neutrinos may have transformed into another type.

In 1978 - The tau particle is discovered at SLAC, the Stanford Linear Accelerator Center. It is soon recognized to be a heavier version of the electron and muon, and its decay exhibits the same apparent imbalance of energy and momentum that led Pauli to predict the existence of the neutrino in 1931. The existence of a third neutrino associated with the tau is hence inferred, although this neutrino has yet to be directly observed.

In 1985 - A Russian team reports measurement, for the first time, of a non-zero neutrino mass.

In 1989 - Experiments at CERN's Large Electron-Positron (LEP) accelerator determine that no additional neutrinos beyond the three already known can exist

In 1994 – Kamiokande (a detector is a 50000 ton tank of water located approximately 1km underground and acts as a target for neutrino) finds a deficit of high-energy muon-neutrino interactions. Muon-neutrinos travelling the greatest distances from the point of production to the detector exhibit the greatest depletion.

In 1997 - Super-Kamiokande reports a deficit of cosmic-ray muon neutrinos and solar electron neutrinos, at rates agreeing with measurements by earlier experiments

In 1998 - The Super-Kamiokande collaboration announces evidence of non-zero neutrino mass at the Neutrino '98 conference.

In 2000 - First direct evidence for the ν_τ announced at Fermilab by DONUT collaboration.

In 2004 - K2K Experiment confirms (with limited statistics) Super -Kamiokande discovery .

In 2005 - MINOS starts data-taking to STUDY Neutrino Oscillation Phenomena

Sources of Neutrinos

The neutrinos in the universe come from weak interactions (like beta decays in atomic nuclei). There are many types of neutrinos origins, which can be quite arbitrarily classified in five sources:

Solar neutrinos

They come along with the process of thermonuclear fusion inside the stars (our sun or any other star in the universe). Their energy is quite weak (some MeV) and they can travel in a long and quite way. They come from different nuclear reactions whose main reaction (85% of the solar neutrinos come from it) is:

$p + p \rightarrow {}^2H + e^+ + \nu_e$ p is a proton, H is a deuterium nucleus, e is an anti-electron and the last one is a neutrino. Depending on the nuclear reaction concerned, the neutrino has not the same energy.

Neutrinos from mankind activity

These are high energy neutrinos produced by the particles accelerators and low energy neutrinos coming out of nuclear reactors. The first ones, whose energy can reach about 100 GeV, are produced to study the structure of the nucleons (protons and neutrons composing the atomic nuclei) and to study the weak interaction. The second ones are here although we did not ask for them. They are an abundant product made by the nuclear reactions inside the reactors cores (a standard nuclear plant radiate about 10^{20} neutrinos per second) and their energy is around 4 MeV. They have been the first to be detected and the first to be used to put some limits on the neutrino oscillation.

Neutrinos from the earth

Our great old planet has kept since its birth many radioactive atomic nuclei. This is what we call "natural radioactivity". The power coming from this natural radioactivity is estimated at about 20.000 Giga Watts (about 20.000 nuclear plants!) and the neutrinos coming from this radioactivity are numerous: about 6 millions per second and per cm^2. But those neutrinos, despite of their quantity, are often locally drowned in the oceans of neutrinos coming from the nuclear plants.

Neutrinos from cosmic rays

When a cosmic ray (proton coming from somewhere in space) penetrates the atmosphere, it interacts with an atomic nucleus and this generates a particles shower, called "atmospheric neutrinos". Some experiments like Kamiokande and Super-Kamiomande in Japan have tried to see the oscillations of the neutrinos inside those particle showers. The result in 1998 seem positive.

Neutrinos from the Big-Bang

The "standard" model of the Big-Bang predicts, like for the photons, a cosmic background of neutrinos. Those neutrinos, nobody has never seen them. They are yet very numerous: about 330 neutrinos per cm^3. But their energy is theoretically so little (about 0.0004 eV), that no experiment, even very huge, has been able to detect them.

Neutrino interaction and Detection

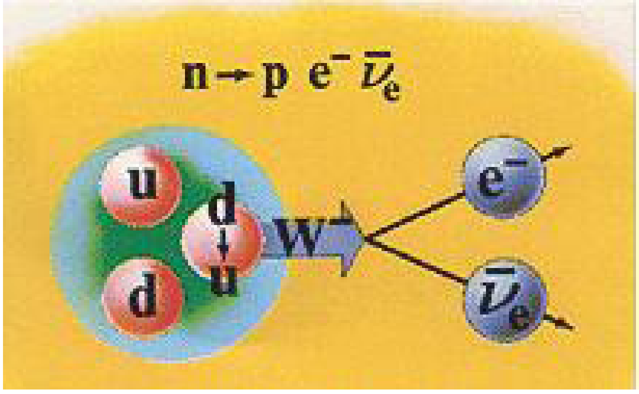

Fig. 1 Neutrino and antineutrion interaction.

The Neutron Decay

The neutrino has half-integer spin ($\frac{1}{2}\hbar$) and is therefore a fermion. Neutrinos interact primarily through the weak force. The discovery of neutrino flavor oscillations implies that neutrinos have mass. The existence of a neutrino mass strongly suggests the existence of a tiny neutrino magnetic moment of the order of 10^{-19} μ_B, allowing the possibility that neutrinos may interact electromagnetically as well. An experiment done by C. S. Wu at Columbia University showed that neutrinos always have left-handed chirality. It is very hard to uniquely identify neutrino interactions among the natural background of radioactivity. For this reason, in early experiments a special reaction channel was chosen to facilitate the identification: the interaction of an antineutrino with one of the hydrogen nuclei in the water molecules. A hydrogen nucleus is a single proton, so simultaneous nuclear interactions, which would occur within a heavier nucleus, don't need to be considered for the detection experiment. Within a cubic metre of water placed right outside a nuclear reactor, only relatively few such interactions can be recorded, but the setup is now used for measuring the reactor's plutonium production rate.

Neutrinos can interact with a nucleus changing it to another nucleus. In this case, energy levels and spin states within the target nucleus have to be taken into account to estimate the probability for an interaction. In general the interaction probability increases with the number of neutrons and protons within the nucleus.

The way neutrinos interact depends on a property called their "flavor". Electron "flavored" neutrinos participate in interactions that involve electrons, muon "flavored" neutrinos participate in interactions that involve muons, and similarly for tau neutrinos. The pion always decays to a muon and a muon-neutrino (well, almost always, 99.99% of the time). The muon neutrino interacts with a nucleus to make a muon, not an electron. This is also called conservation of lepton number. But it seems the neutrino is composed of a combination of two or three different mass states. The way a neutrino propagates from one place to another depends on the mass states. But quantum mechanics tells us that if two (or more) neutrinos are composed of the same mass states but in different combinations, then the neutrino can oscillate from one flavor to another while it travels through space.

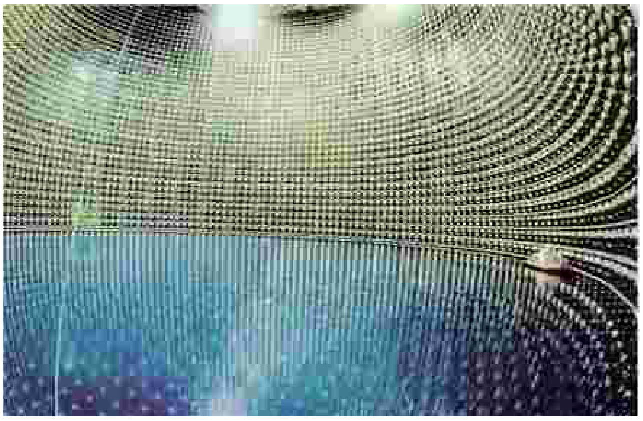

Fig. 2 The Super-Kamiokande Neutrino Telescope

A neutrino detector—one of the devices designed to confirm the activity of these infinitesimal particles—typically contains a large body of liquid, which increases the chances for particle interaction. For example, notes

Mocioiu, the Super Kamiokande detector in Japan holds 12.5 million gallons of water surrounded by more than 11,000 photomultiplier tubes, light sensors arrayed to pick up the radiation caused by interactions between neutrinos and water molecules

Neutrino oscillation

Neutrino oscillations are a peculiar quantum mechanical effect, for which it is hard to find a good macroscopic analogy, as it has to do with the particle-wave duality of fundamental matter.

The fundamental "weak" interaction not only can generate neutrinos (as is the case in nuclear reactions within the sun), but it can also make them observable when they interact in an experimental apparatus, producing various electrically charged particles that can be detected. The analysis of weak interaction has shown the existence of three different kinds, or "flavours" as physicists say, of neutrinos. It has been observed that the neutrino emitted in nuclei β decays or in reactions within the sun and other stars, is associated to an electron (e) and is called electron neutrino (ν_e). The others are the muon neutrino ν_μ and the tau neutrino ν_τ.

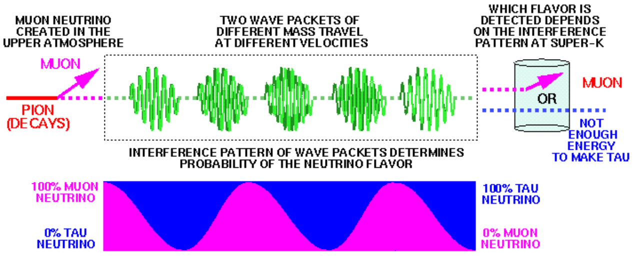

Fig. 3 Neutrino oscillation and interference pattern.

We can make a muon neutrino beam at an accelerator for example, and, after passing the beam through a kilometer of earth and iron shielding to kill off all the charged particles, we see muons ocassionally produced in a detector, in the right direction and just after the particle beam pulse strikes the production target..

The strange situation for neutrinos, different from all the other elementary particles, is that the state of the particle which we call the muon neutrino may not be the same as the particle mass state.. The muon neutrino is apparently composed of two different masses. Something like that never happens in macroscopic objects.

For example, the muon neutrino may be composed of half each of two states of slightly different mass. These massive neutrino states may be thought of as waves which have some specific periodicity for a given energy. The two mass states having different periodicities will oscillate in and out of phase with each other as they travel along (like the beats between to neighboring musical pitches). In one phase the pair may interact as a muon neutrino and when shifted by 90 degrees they may make a tau neutrino. In such a circumstance, if one could make a mono-energetic muon neutrino beam at an accelerator and had a moveable detector, then at first one would observe only muons being produced. Further one would see only taus. At twice the distance taus again, and so on. In between, one would see some fraction of each kind.

Experimentally we have not been able to do this at accelerators so far, because as it is turning out, the distance for oscillations has been too long to make a practical experiment.With one GeV neutrinos one need distances of hundreds of miles.

Another analogy which may help to understand oscillations is to compare the neutrino oscillations to the rotation of the plane of polarization of light when passing through some (so called optically active) materials. A sugar water solution has for example the property that polarized light changes the angle of the polarization as light passes through the solution. The more solution traversed, the more the rotation, and if one goes far enough, the rotation will come back to the original state. The analogy is made if we think of, say, vertially polarized light as the muon neutrino, which becomes horizontally polarized light after a while, which we call, say, the tau neutrino. The rotation of the polarization plane comes about because the light wave can be thought of as composed of right hand circular and left hand circular polarized photons, and in such media the photons of different handedness travel at slightly different speeds. In the case of the neutrinos, the neutrino waves oscillate at slightly different speeds because of their slightly different masses, and so the oscillations take place even when the neutrinos are flying through empty space.

Importance of neutrino study

Neutrinos' low mass and neutral charge means they interact exceedingly weakly with other particles and fields. This feature of weak interaction interests scientists because it means neutrinos can be used to probe environments that other radiation (such as light or radio waves) cannot penetrate.

Using neutrinos as a probe was first proposed in the mid 20th century as a way to detect conditions at the core of the Sun. The solar core cannot be imaged directly because electromagnetic radiation (such as light) is diffused by the great amount and density of matter surrounding the core. On the other hand, neutrinos pass through the Sun with few interactions. Whereas photons emitted from the solar core may require 40,000 years to diffuse to the outer layers of the Sun, neutrinos generated in stellar fusion reactions at the core cross this distance practically unimpeded at nearly the speed of light.

Neutrinos are also useful for probing astrophysical sources beyond our solar system because they are the only known particles that are not significantly attenuated by their travel through the interstellar medium. Optical photons can be obscured or diffused by dust, gas, and background radiation. High-energy cosmic rays, in the form of swift protons and atomic nuclei, are unable to travel more than about 100 megaparsecs.

The galactic core of the Milky Way is fully obscured by dense gas and numerous bright objects. Neutrinos produced in the galactic core should be measurable by Earth-based neutrino telescopes in the next decade.

Another important use of the neutrino is in the observation of supernovae, the explosions that end the lives of highly massive stars. The core collapse phase of a supernova is an extremely dense and energetic event. It is so dense that no known particles are able to escape the advancing core front except for neutrinos. Consequently, supernovae are known to release approximately 99% of their radiant energy in a short (10-second) burst of neutrinos.These neutrinos are a very useful probe for core collapse studies.

What is exciting?

- Neutrinos not only have surprised us with a small but significant mass but they are demonstrating mixing in a very different manner than quarks… why?
- Still many open questions in the neutrino sector? Very crucial but experimentally very difficult questions to answer:.
- Neutrinos, with their ability to test particular quarks can add significantly to our QCD studies if we can only determine how nuclear effects mask their quark level interactions.

Conclusion

The rest mass of the neutrino is an important test of cosmological and astrophysical theories. The neutrino's significance in probing cosmological phenomena is as great as any other method, and is thus a major focus of study in astrophysical communities.

The study of neutrinos is important in particle physics because neutrinos typically have the lowest mass, and hence are examples of the lowest energy particles theorized in extensions of the Standard Model of particle physics. For example, one would expect that if there is a fourth class of fermions beyond the electron, muon, and tau generations of particles, then the fourth generation neutrino would be the easiest to generate in a particle accelerator.

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