# Neutrinos and our Sun – Part 1

*S N Ganguli*

**S N Ganguli, an experimental high energy physicist, retired last year from the Tata Institute of Fundamental Research, Mumbai. He participated in the LHC experiment at CERN, Geneva. He studied properties of Z and W bosons produced in electron-positron collisions at the Large Electron Positron Collider, also at CERN. He now lives in Pondicherry.**

The elusive neutrinos have periodically yielded their secrets to man and at each such juncture major advances have been achieved in our understanding of the sub-atomic phenomena. These particles also carry invaluable information about the centre of the Sun where energy is generated through nuclear fusion. In Part I of this article, history of the discovery of neutrinos is traced, their properties and types are described. Also, the Standard Model which forms the basis of the structure of matter and of which massless neutrinos are an integral part, is described.

The role of neutrinos in solar energy generation and the great 'solar neutrino puzzle' and its solution will be described later in the series.

## 1. Introduction

The neutrino is one of the elusive tiny particles created by nature. The hint of its existence came from radioactive beta-decay of nuclei. Although radioactivity was discovered at the very end of the nineteenth century (1896), it was only in 1931 that the neutrino was postulated by Pauli to save the principle of energy conservation in radioactive beta-decay. It took another twenty five years to detect neutrino interactions in the laboratory (1956).

Our sun, a dominant source of neutrinos, is powered by proton-proton fusion reactions in which 600 million tons of hydrogen are burned every second in the core. This nuclear fusion reaction, a process in which two light atomic nuclei merge to form a single heavier nucleus, produces not only heat and light but also a vast number

Keywords
Radioactive beta decay, neutrino-detection, types of neutrinos.

of neutrinos. Nearly seventy billion neutrinos from the sun pass through every square centimetre of our body (like our thumb nail) every second without any interaction. Photons or light produced in the deep interior of the sun undergo multiple interactions and take nearly ten million years to reach the surface of the sun and in this process of radiation transfer through the interior of the sun, the information of the core is lost. On the other hand, the neutrinos, because of their extremely weak interactions with matter, escape straightaway from the core without interacting and can thus be used to study the core of the sun, the seat of its energy generation. Neutrinos take only a few seconds to escape from the sun and they take another eight minutes to arrive on the earth.

A new role of neutrinos was realised on February 24, 1987, when astronomers observed a dazzling supernova in the Large Magellanic Cloud, which is a satellite galaxy to our own Milky Way, and is generally visible from the southern hemisphere. This supernova is named SN 1987A. It was bright enough to be seen by the naked eye. The parent star was about twenty times heavier than the sun. The most interesting part of SN 1987A is that two underground neutrino detectors, Kamiokande in Japan and IMB in USA, detected eight to twelve neutrinos from the supernova over a ten second interval. The detected neutrino signal strongly brought out the important role of neurtinos in the explosion of a massive star and its transformation into a tiny and incredibly dense object called a neutron star. Neutron stars are about twenty kilometres in diameter and extremely dense objects. They are as massive as or slightly more massive than the sun.

Only recently there is some evidence that neutrinos may possess a small mass (about a millionth the mass of an electron). What happens if neutrinos do possess some mass? As far as our day-to-day life is concerned, there will be no difference as we will continue to get our light and heat from the sun, which is essential for the sustenance of life on earth. On the other hand, neutrinos are the second most abundant species after the photons that permeate the universe. Neutrinos with mass may have some impact on cosmology, a science which deals with the evolution and structure of the universe. Astronomers and cosmologists, after several decades of observations, are now coming to the conclusion that luminous matter in the universe (like stars, galaxies, etc.) is not enough to explain the total mass of the universe. They find that the bulk of the mass in the universe is unseen and this has been given the name – dark matter[1]. Neutrinos with mass may be one of the candidates for dark matter.

[1] Bikram Phookun and Biman Nath
Dark Matter
Part 1. *Resonance*, Vol.4, No.9, 1999.
Part 2. *Resonance*, Vol.4, No.10, 1999.

[2] S N Ganguli
The Story of Large Electron Positron Collider
Part 1. *Resonance*, Vol.7, No.10, 2002.
Part 2. *Resonance*, Vol.7, No.11, 2002.

We begin our story by giving a very brief account of radioactivity that first led to the postulate of the existence of neutrinos and then the first detection of the beta-decay neutrinos in the laboratory. Then we discuss the discovery of the second type of neutrinos in 1960. We describe the experimental results from the Large Electron Positron collider (LEP)[2] commissioned in 1989 at CERN, Geneva, which indicated that the number of neutrino species in nature is three. Then we describe the Standard Model with the postulate of only three generations of quarks and leptons with three massless neutrinos.

In the second part of this article we shall switch our attention to the sun and describe the energy generation process via hydrogen burning reactions, in which weak interaction plays an important role. This process leads to a huge flux of nearly seventy billion solar neutrinos incident per square centimetre of the surface of the earth per second. It is not an easy task to detect these neutrinos and physicists have managed to detect them using very large detectors in the last three and a half decades. The experimental measurements indicated that one is seeing on the earth only about a third to a half of these neutrinos compared to the theoretical prediction. This came to be known as 'the solar neutrino puzzle'. Only very recently a solution to this puzzle seems to have been found with the new results from the SNO detector (the Sudbury Neutrino Observatory). We shall conclude the article with the results from the KamLAND experiment and the future outlook on neutrino physics.

The experimental measurements indicated that one is seeing on the earth only about a third to a half of these neutrinos compared to the theoretical prediction. This came to be known as 'the solar neutrino puzzle'.

## 2. Radioactivity

Curiosity and perseverance are the two important requirements of a good researcher, and Becquerel had both in plenty. The discovery of X-rays by Röntgen in the first week of January 1896 triggered him. Henri Becquerel of France was all of 44 years then, busy investigating the phenomena of fluorescence and phosphorescence – why some metals and minerals glow in the dark. When he learnt about Röntgen's discovery, he immediately started wondering whether X-rays and phosphorescence are related.

For his phosphorescence work, Becquerel used to expose uranium crystals to sunlight for several hours with the idea that sunlight will energise the crystals. On a particular cloudy day in Paris, he could not use the sun to expose his crystals, so he wrapped them up in black paper and placed the package on the top of a photographic plate and by accident some metal pieces were left in between. After a few days Becquerel decided to develop the unexposed plates, and to his great surprise he found shadow images of the metal pieces in the photograph. This meant that the uranium salt emitted radiation without an external source of energy, in this case, the sun. He reported his discovery to the French Academy of Sciences in March 1896. Within another week he was able to establish beyond doubt that energetic and penetrating radiations were being emitted by the uranium in the salt and thus Becquerel discovered radioactivity.

The name radioactivity was given by Marie Curie. The Curies developed a new method, called radiochemistry, to extract radioactive elements from natural ores.

Marie Sklodowska of Poland came to Paris in 1891 and met Pierre Curie who was with the Ecole de Physique et de Chemie Industrielle. They got married in 1895. They started investigating the findings of Becquerel. Marie Curie found that the intensity of radiation was proportional to the amount of uranium in the compound, thus indicating that the radiation was an atomic property of the element uranium. Marie Curie soon found that thorium, a white metal found in minerals, also emits this mystery radiation. The name radioactivity was given by Marie Curie. The Curies developed a new method, called radiochemistry, to extract radioactive elements from natural ores. Soon they identified and isolated new elements which are radioactive: polonium and radium. In 1903, Marie and Pierre Curie shared the Physics Nobel Prize with Becquerel, and in 1911, Marie Curie received the Nobel Prize in Chemistry for her work on radium. We will see later that our elusive neutrino is deeply entangled with the radioactivity of nuclei.

## 3. Beta Decay and the Neutrino Hypothesis

Three types of radiation are associated with radioactivity: alpha, beta and gamma. Alpha particle is the nucleus of the helium atom, beta particle is an electron and gamma is a high energy photon. Radioactive decays occur spontaneously and are a consequence of the breakdown of one type of atomic nucleus into another. Natural radioactivity arises in very heavy nuclei such as uranium and radium, containing a large number of protons and neutrons, and the tendency is to disintegrate into more stable structures. Each radioactive product has a characteristic half-life which is defined as the amount of time in which half of the atoms disintegrate into atoms of a new element. The nature of this disintegration law indicates that we are dealing with a statistical law for the first time.

With detailed measurements of the radioactive decay products, it was realised in 1914 that there is a serious problem in understanding beta decay. The first measurements by Lise Meitner and Otto Hahn suggested that the beta particles are emitted with discrete energies. However, the measurements of Chadwick revealed that the energy spectrum of beta particles is continuous, that is, the beta particles emitted in the decays have a wide spread in kinetic energy ranging from zero up to a maximum possible value. It was generally believed that, like in alpha decay, in beta decay too the final products are the electron and the daughter nucleus. If so, the beta decay of a nucleus can be written as: (A,Z) $\rightarrow$ (A,Z+1) + $e^-$, where A and Z are respectively the mass and atomic numbers of the parent nucleus (A,Z), which decays into an electron and the daughter nucleus (A,Z+1); we have assumed here that the initial and final states have the same total values for the mass number and the electric charge. In all these reactions the total energy and momentum of the final state will be the same as those of the initial state; these are known as conservation laws of energy and momentum. For a two-body final state, as in the present case, one expects from the above conservation laws the electron to emerge with a fixed value of energy, which is nearly equal to the difference of masses of the parent and daughter nuclei, known as the Q-value or the energy release in the reaction:

$$\mathrm{Q} \simeq \mathrm{M(A,Z)} - \mathrm{M(A,Z+1)}. \text{ (See } Box \text{ 1)}$$

With detailed measurements of the radioactive decay products, it was realised in 1914 that there is a serious problem in understanding beta decay.

On the other hand, the measurements of Chadwick showed a continuous energy spectrum of a beta particle which was a great surprise and a puzzle, (*Figure* 1).

Niels Bohr, who was awarded the Nobel Prize in 1922 for his theory of the hydrogen atom, attempted to understand the continuous energy spectrum of the nuclear beta decay with a hypothesis of the restricted validity of the principle of energy conservation. This was unacceptable because the principle of the conservation of energy

**Box 1. Two Body Decay**

Let a hypothetical beta decay occur from rest into a two-body final state, A → B + C, where A and B are the parent and daughter nuclei and C is the electron. The aim is to get the energy of the electron in this so-called two-body decay. From the momentum conservation in the reaction, we get: $\vec{p}_A = \vec{p}_B + \vec{p}_C$. Since the nucleus A decays at rest, that is $\vec{p}_A = 0$, and hence $\vec{p}_B = -\vec{p}_C$. Now we use the energy conservation in the reaction, that is the total energy of the initial state should be the same as that of the final state: $E_A = E_B + E_C$. For the sake of simplicity let us set c = 1, where c is the speed of light. Let us rewrite the energy relation and using $|\vec{p}_B| = |\vec{p}_C|$ we get:

$$E_A = \sqrt{p_B^2 + M_B^2} + E_C = \sqrt{p_C^2 + M_B^2} + E_C.$$

We will use $M_A$, $M_B$ and $M_C$ as the rest masses for A, B and C respectively. With a little bit of simplification of the above equation, we get:

$$E_C = \frac{E_A^2 + M_C^2 - M_B^2}{2E_A} = \frac{M_A^2 + M_C^2 - M_B^2}{2M_A}$$

where we have used $E_A = M_A$ since $p_A = 0$. We make a further simplification by noting that the parent and daughter nuclei A and B are nearly of the same mass, and the outgoing electron C has negligible mass compared to A:

$$E_C = \frac{M_A + M_B}{2M_A} \cdot (M_A - M_B) + \frac{M_C^2}{2M_A} \simeq M_A - M_B$$

which is same as the Q value of the reaction.

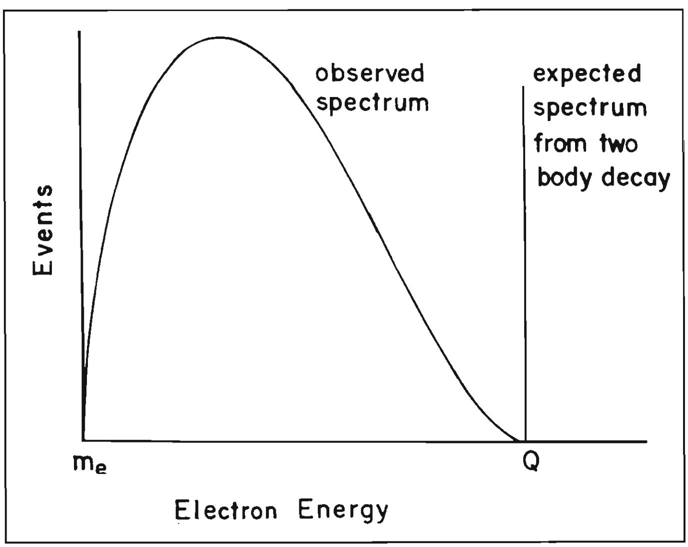


***Figure 1. Schematic plot of continuous spectrum from beta decay, labelled as observed spectrum, and an expected line spectrum from two-body decay.***

had been proved beyond doubt in all fields of physics.

On December 4, 1930, Wolfgang Pauli, famous for his exclusion principle postulated in 1925, suggested a desperate solution to the beta decay puzzle through his now famous letter addressed to the 'Dear Radioactive Ladies and Gentlemen', who had gathered in Tübingen for a conference which Pauli could not attend. In this letter Pauli outlined his idea that a nucleus undergoing a beta decay did not emit the electron alone, rather the decay was accompanied by another sub-atomic particle with no electric charge and with negligible interaction. The neutral third particle, according to him, was responsible for the continuous energy spectrum of the electron in beta decay: (A,Z) $\rightarrow$ (A,Z+1) + $e^-$ + $\nu$.

In 1934, the Italian physicist Enrico Fermi, developed a theory of beta decay using Pauli's idea and named the new particle *neutrino* or the 'little neutral one' in Italian.

In 1934, the Italian physicist Enrico Fermi, developed a theory of beta decay using Pauli's idea and named the new particle *neutrino* or the 'little neutral one' in Italian. A beta decay is then visualised as a neutron breaking up into a proton, an electron and a neutrino ($\nu$): $n \rightarrow p + e^- + \bar{\nu}$ (for technical reasons it is the antiparticle of the neutrino, namely the antineutrino that is involved in the decay of the neutron). Pauli realised that it would be difficult to detect neutrinos. A detailed calculation was made by Hans Bethe and Rudolf Peierls in 1934 regarding the interaction of neutrinos with matter and they estimated the cross-section (see *Box* 2) as $\sigma_\nu \approx 10^{-44}\,\text{cm}^2$. To gauge the smallness of this cross-section, it is enough to note that on an average only one neutrino out of $10^{10}$, that is ten billion, will interact during its passage through the earth and the rest will pass through like in empty space. So it was thought that it is hopeless to make an attempt to detect these neutrinos in the laboratory.

### 3.1 *Neutrinos from Reactor*

Anything that is created should in principle be detected otherwise its creation is a colossal waste on the part

**Box 2. Cross-section**

The cross-section of a process is a measure of the probability of its occurrence. Thus in an interaction or a collision between two particles, the cross-section, (measured in units of area, $cm^2$), may be taken as an effective area of the target nucleus as seen by an incident projectile. Let us consider a beam of particles, say protons, which is incident on a thin target of hydrogen of thickness $x$ cm. A detector placed behind the target detects all outgoing particles from collisions. Let the flux of the beam of protons be denoted by $F$ in units $cm^{-2}$ $sec^{-1}$ and let it be incident on an area $A$ $cm^2$ of the target. If the number density of the target nuclei is $n$, the total number of them as seen by the beam is $nAx$. Let $R$ denote the number of collisions taking place in unit time. It is also called the event rate and is measured in units of $sec^{-1}$. The cross-section, denoted by $\sigma$ is then given by $\sigma = \frac{R}{F\,n\,a\,x}$. We note that the dimension of $\sigma$ is $cm^2$. In nuclear physics, one uses the unit *barn* for cross-section, where 1 barn = $10^{-24}$ $cm^2$.

Another useful quantity describing such an interaction is the *mean free path*, denoted by $\lambda$, which is the distance a particle traverses on an average before colliding with a target nucleus. The mean free path is given by $\lambda = (n\,\sigma)^{-1}$ and its unit is the unit of length.

Now let us compare two different types of collision cross-sections, one due to a beam of protons and the other due to a beam of neutrinos, but both with energy of 10 GeV, incident on a liquid hydrogen target of density $n = 4 \times 10^{22}$ $cm^{-3}$. One GeV is a unit of energy commonly used in high energy interactions and equals $10^9$ eV, where an eV or an electron-volt is defined as the kinetic energy gained by an electron when it is accelerated in an electric field produced by a potential difference of one volt. The value of the proton-proton cross-section for 10 GeV protons is $\sigma_{pp} = 5 \times 10^{-26}$ $cm^2$, while the neutrino-proton cross-section is $\sigma_{\nu p} = 7 \times 10^{-38}$ $cm^2$. Thus $\lambda_p = 500$ cm while $\lambda_\nu = 3 \times 10^{14}$ cm. This indicates that neutrinos hardly collide.

of nature. To be sure of detecting neutrinos one needs intense beams of neutrinos (that is a large flux of neutrinos) and a very large amount of target material. Besides detecting neutrinos, one also needs to understand the background events which may mimic the signal one expects for the neutrino.

A nuclear reactor provided the first possibility of detecting neutrinos. The uranium fission fragments from a reactor are neutron-rich and they undergo beta decay; as a result the reactor acts as a copious source of antineutrinos of about $10^{12}$ to $10^{13}$ per second per $cm^2$. In 1953, Clyde Cowan and Fred Reines proposed an experiment to detect neutrinos utilizing this very great supply. The reaction expected between an antineutrino and a

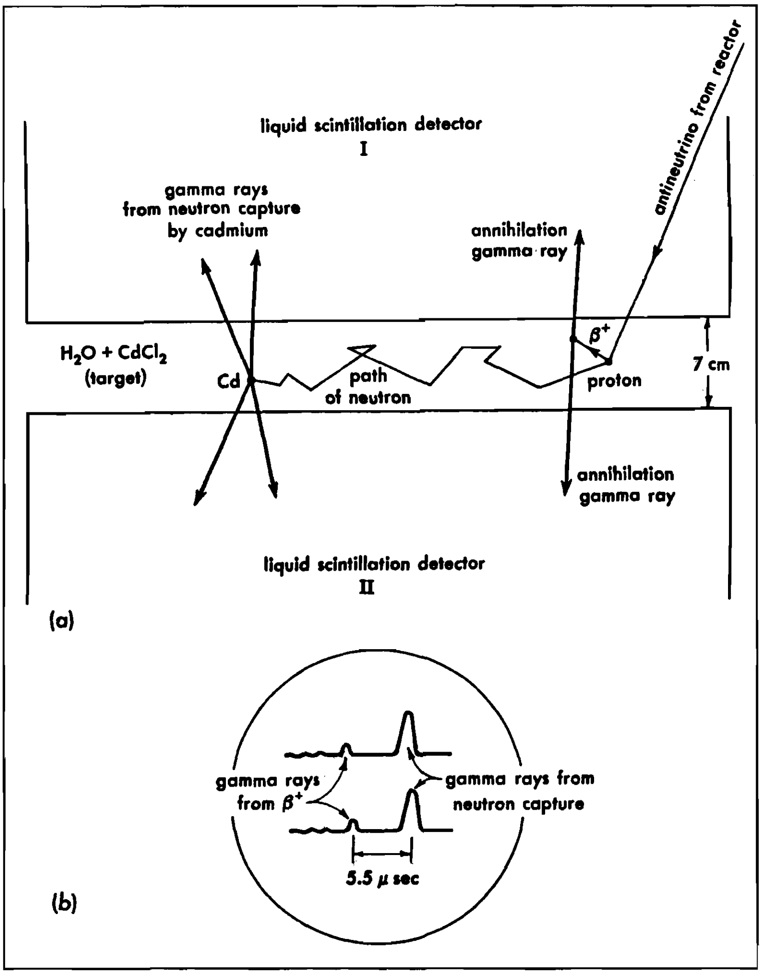


*Figure 2. Schematic diagram of the reactor experiment by Reines and Cowan.*

proton is the formation of a neutron and the emission of a positron, the reaction being: $\bar{\nu} + \mathrm{p} \rightarrow \mathrm{e}^+ + \mathrm{n}$. To detect this reaction, the antineutrinos were allowed to enter a large tank of water which provided the target protons. Some cadmium chloride was dissolved in the water. This target of about 400 litres of water containing cadmium chloride was placed between two tanks containing liquid scintillation detectors, (*Figure* 2).

The light from the scintillations was detected by photomultiplier tubes at the ends of the tanks and fed to an oscilloscope. The estimated cross section of the above reaction is of the order $6 \times 10^{-20}$ barn. In order to be certain that the above reaction was taking place, both the neutron and the positron had to be detected. The positron, in its passage through the tank, was captured by an electron in the water giving rise to annihilation radiation producing two gamma rays, of energy 0.5 MeV each, ($e^+ + e^- \rightarrow \gamma\gamma$), and these, in turn, were detected by the two liquid scintillation detectors and a small pulse was recorded on the oscilloscope trace for that detector. The neutron released in the reaction diffused through the water losing speed by collision with protons and was finally captured by a cadmium nucleus, resulting in the emission of several gamma rays with their total energy equal to 9 MeV. These gamma rays were then detected by the scintillation detectors and produced higher pulses on the oscilloscope. The time interval between the pulses from the annihilation gamma rays and the gamma rays from neutron capture was $5.5\mu$ sec (see *Figure* 2(b)). The first results of Cowan and Reines yielded a rate for the neutrino signal that was marginally higher when the reactor was 'on' compared to when it was 'off'. Their studies convinced them that the background was due to neutrons produced by the cosmic rays. Their next attempt was to use a more powerful reactor to get a higher yield of neutrinos. They also built an improved detector better shielded (the detector was kept 12 metres underground) to reduce the background events due to cosmic ray hits. This time they were successful and detected neutrino interactions without any doubt; their experimental value for the event rate was in good agreement with the theoretical calculations. Thus the neutrino was finally detected in a physics laboratory.

In 1937 a charged particle called muon (m), about 200 times heavier than an electron, was discovered in cosmic rays.

In 1956 Pauli made the important announcement:

*I received on June 15 the following telegram from F Reines and C Cowan (Los Alamos): "We are happy to inform you that we have definitely detected neutrinos from fission fragments by observing inverse beta decay of protons. The observed cross-section agrees well with ex-*

*pected six times ten to the power minus forty four square centimeter" Fred Reines was awarded the Nobel Prize for this discovery in 1995.*

### 3.2 *Second Neutrino* ($\nu_\mu$)

In 1937 a charged particle called muon ($\mu$), about 200 times heavier than an electron, was discovered in cosmic rays. The strange thing about this particle was that it behaved exactly like an electron and this led I Rabi, a well-known physicist of that period, to exclaim "who ordered the muon?" The muon is known to decay in $\sim 10^{-6}$ sec into three particles: an electron, a neutrino ($\nu$) and an antineutrino ($\bar{\nu}$) as follows: $\mu^- \rightarrow e^- + \nu + \bar{\nu}$. Particles which are detected in this reaction are only muons and electrons, since neutrinos are neutral and escape detection. During the early 1950s high energy accelerators came into operation which made it possible to study the production of particles in collisions between high energy beams of charged particles and various targets like hydrogen, helium, copper, etc. Muons are not directly produced in high energy collisions of protons with target nuclei, rather they are the decay products of other particles like pions: $\pi^\pm \rightarrow \mu^\pm + \nu$. Muons thus produced in laboratories were studied and the energy spectrum of electrons from their decays were found to be well understood in terms of the Fermi theory of beta decay mentioned earlier.

It was suggested that there are two types of neutrinos: one associated with the electron, and the second one associated with the muon.

An interesting suggestion was made towards the end of the 1950s regarding the neutrino and antineutrino pair seen in the decay of muons. Since it was assumed in the decay of the muon that the antineutrino was an antiparticle of neutrino, it was argued that the muon could also decay by the emission of a gamma ray: $\mu^- \rightarrow e^- + \gamma$ and the theoretical calculation predicted that one out of 10,000 muons should decay by this mode. All experimental searches failed to see this decay mode, and one could not detect even a single muon decaying via the gamma mode out of a total of ten billion decays.

The only way one could reconcile the above negative result was to conclude that the antineutrino emitted in the decay of the muon is not an antiparticle of the neutrino. So it was suggested that there are two types of neutrinos: one associated with the electron, let us call it $\nu_e$, as in beta decay ($n \rightarrow p + e^- + \bar{\nu}_e$), and the second one associated with the muon, let us call it $\nu_\mu$, like in the decay of a pion: $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$. It means that the neutrino detected by Reines and Cowan in the reactor referred to the first neutrino associated with the electron. The next obvious question is how does one distinguish between $\nu_e$ and $\nu_\mu$? The answer is that a $\nu_e$ on interaction with matter will produce an electron and not a muon, while a $\nu_\mu$ will produce a muon and not an electron. In other words these two types of reactions are allowed: $\nu_e + n \rightarrow e^- + p$ and $\nu_\mu + n \rightarrow \mu^- + p$; while the following types are not allowed: $\nu_e + n \not\rightarrow \mu^- + p$ and $\nu_\mu + n \not\rightarrow e^- + p$.

In 1960 Lederman, Schwartz, Steinberger and collaborators carried out an experiment to detect the neutrino species associated with the muon. They used the high intensity pion beam from the accelerator of the Brookhaven National Laboratory. They extracted the neutrinos associated with the muons from pion decay: $\pi^+ \rightarrow \mu^+ + \nu$. The neutrinos were allowed to interact in a 13.5 metres thick steel wall which was followed by a special detector called a *spark chamber* to detect electrons and muons. These neutrinos were found to produce only muons and not electrons, and thus a second neutrino species, the $\nu_\mu$, was discovered. For this discovery, Lederman, Schwartz and Steinberger shared the Nobel Prize for Physics in 1988. Since the Nobel Prize was awarded nearly thirty years after the work, Steinberger, while giving a seminar at CERN, made a remark that one must have a long life to receive the Nobel Prize.

In modern physics, interactions between particles are often described in terms of the exchange of field particles or quanta.

### 3.3 *Three Light Neutrinos*

In modern physics, interactions between particles are often described in terms of the exchange of field particles or quanta. In the case of the familiar electromagnetic interaction, the field particles are photons. Likewise, the weak force that is responsible for beta decays, is mediated by field particles called the $W$ and $Z$ bosons. To see the signatures of these particles, physicists study interactions at very high energies.

In 1989, the LEP collider was commissioned at CERN, Geneva with an electron beam of energy of about 45 GeV colliding head-on with a positron beam of the same energy from the opposite direction. Remember 1 GeV equals $10^9$ eV of energy. This energy was chosen to study the production and decay of Z bosons, responsible for the weak 'neutral current' interactions. The beams were made to collide at four intersection regions surrounded by four giant detectors called: ALEPH, DELPHI, L3 and OPAL [3]. These detectors collected over seventeen million Z decays.

[3] Physicists of experimental high energy physics gorup of Tata Institute of Fundamental Research are members of this collaboration.

If the lifetime of an unstable particle is very short, as is the case with the Z particle, there is a measurable spread in the mass of the particle called the decay width, denoted by $\Gamma$ The decay width, whose units are those of energy, and the lifetime of the particle, denoted by $T$ are related through the uncertainty principle $\Gamma \times T = h/2\pi$, where h is the Planck's constant with the value $4.13 \times 10^{-21}$ MeV sec. The total decay width is equal to the sum of the partial widths; each partial width corresponds to a decay mode of the particle. For the Z particle, the total width $\Gamma_Z$, which includes contributions from all possible decay channels, is measured independent of the partial widths. The experiments at CERN made precision measurements of Z production cross-sections as a function of collision energy – same as the mass distribution of Z – for the following four fi-

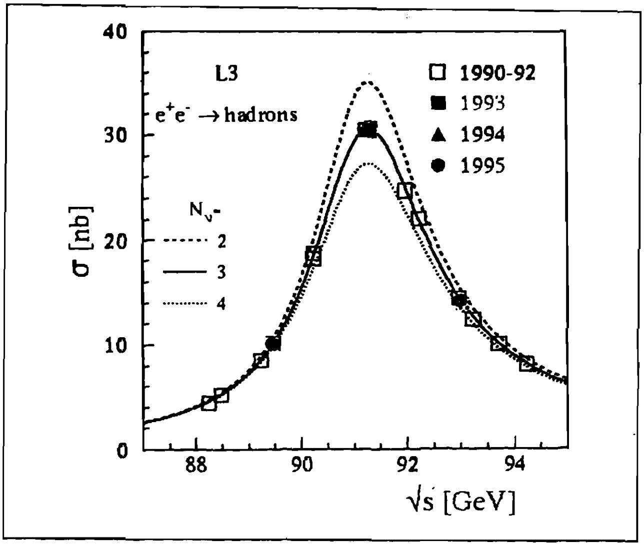


*Figure 3. Cross-section of $e^+e^- \rightarrow$ hadrons vs centre of mass energy.*

nal states corresponding to Z decays: $e^+e^- \rightarrow$ hadrons, $e^+e^- \rightarrow e^+e^-$ (also called Bhabha scattering), $e^+e^- \rightarrow \mu^+\mu^-$ and $e^+e^- \rightarrow \tau^+\tau^-$ Experimental results from the L3 experiment for the final state $e^+e^- \rightarrow$ hadrons are shown in *Figure* 3. The width of the mass distribution increases with the number of modes of decay of the Z particle. This brings out the sensitivity of the mass distribution of Z to the number of neutrino species (Z can decay to neutrino pairs of all existing species: $Z \rightarrow \nu_e\bar{\nu}_e, \nu_\mu\bar{\nu}_\mu, ...$) as can be seen from the curves with the number of neutrino species as: $N_\nu = 2, 3$ and 4. The partial widths are due to Z decaying into hadrons, $\Gamma_{had}$, to three charged lepton pairs: $e^+e^-(\Gamma_{ee})$, $\mu^+\mu^-(\Gamma_{\mu\mu})$, and $\tau^+\tau^-(\Gamma_{\tau\tau})$ and to pairs of neutrinos like $\nu_e\bar{\nu}_e$, $\nu_\mu\bar{\nu}_\mu$, $\nu_\tau\bar{\nu}_\tau$, etc. The ratio of a partial width to the total width gives the fraction of the time Z decays into a given final state, e.g., the ratio $\Gamma_{had}/\Gamma_Z$ gives the Z decay via the hadronic mode. Since the neutrinos are neutral, one cannot experimentally detect them. Let us call the sum of the partial widths due to the neutrinos $\Gamma_{inv}$. From theory, one knows that the partial width of Z decay to one neutrino pair $\Gamma_{\nu\nu}$ is 166.9 MeV and therefore, the number of neutrino pairs can be written as: $N_\nu = \frac{\Gamma_{inv}}{\Gamma_{\nu\nu}}$

or $\Gamma_{inv} = N_\nu \times \Gamma_{\nu\nu}$. We can then write $\Gamma_Z = \Gamma_{had} + \Gamma_{ee} + \Gamma_{\mu\mu} + \Gamma_{\tau\tau} + N_\nu \times \Gamma_{\nu\nu}$. From a fit to the data one obtains the value of $N_\nu$, the number of light neutrino species and this value is determined to be $N_\nu = 2.99 \pm 0.01$. Thus, there are only three light neutrinos in nature. Two of them, $\nu_e$ and $\nu_\mu$, were already known, and the direct observation of the third neutrino, called tau-neutrino ($\nu_\tau$) was made several years later in 2000 at Fermilab by the DONUT experiment.

There are only three light neutrinos in nature. Two of them, $\nu_e$ and $\nu_\mu$, were already known, and the direct observation of the third neutrino, called tau-neutrino ($\nu_\tau$) was made several years later in 2000 at Fermilab by the DONUT experiment.

## 4. Building Blocks of Matter

By the 1960s there were many particles discovered, e.g., the proton, the neutron, the pion, and then the electron, the muon, the neutrino, etc. It became necessary to take a closer look and update the classification of particles in terms of a smaller number of building blocks. Fortunately, evidence was accumulating from the experiments with high energy electrons, muons and neutrinos that particles like the proton and the neutron have structure. A Standard Model of particle physics was put forth putting these ideas together. According to the Standard Model, particles were classified into two groups – matter particles and force particles. Matter particles, as we understand today are of two types – quarks and leptons; these are the fundamental constituents of matter. There are three generations of these and each generation comes in a doublet. In the quark sector the generations are: (up, down), (charm, strange) and (top, bottom), while in the lepton sector these are:($e^-$ $\nu_e$), ($\mu^-$ $\nu_\mu$) and ($\tau^-$ $\nu_\tau$). In the scheme of the Standard Model, neutrinos are assumed to have zero mass and zero charge. Hadrons are particles that are formed out of quarks. Hadrons are further subdivided into two types: baryons (like p, n, $\Lambda$, etc.) and mesons (like $\pi$, K, etc.). Baryons consist of three quarks and mesons consist of a quark and an antiquark. The visible matter that we see around us is formed out of two kinds of quarks (up and down) and one lepton (electron). High energy particles from accel-

Matter particles are acted on by four basic forces of nature and they are – the gravitational force, the electromagnetic force, the weak force and the strong force.

erators (or from cosmic rays) in collisions with target nuclei produce additional quarks and leptons.

Matter particles are acted on by four basic forces of nature and they are – the gravitational force, the electromagnetic force, the weak force and the strong force. These forces are mediated by the exchange of particles, which are different from the matter particles through an internal property called spin. All matter particles have half-integral spin and they obey the exclusion principle of Pauli which states that two particles cannot occupy the same state; they are called fermions (after Enrico Fermi, the Italian physicist). The force particles have integral spin and they do not obey the exclusion principle; they are called bosons (after Satyendranath Bose, the Indian physicist). The gravitational force is universal, meaning every object experiences it. It is also the weakest of the four forces and the force carrier is called a graviton. Gravitational force plays a vital role in the formation and sustenance of stars, galaxies and other objects in the universe. The electromagnetic force is experienced by all electrically charged particles (quarks and charged leptons), and the force is due to exchange of massless particles called photons, which form the electromagnetic radiation, including visible light. It is responsible for the stability of atoms and molecules. The strong force, mediated by a particle called gluon, is responsible for the compactness of atomic nuclei and for holding the quarks together in protons and neutrons; leptons are not sensitive to the strong force. Finally, the weak force, weaker than the electromagnetic force but stronger than gravitation, is responsible for the phenomena of radioactivity and decays of unstable particles like muons $(\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu)$; quarks and leptons both experience the weak force.

The weak force, weaker than the electromagnetic force but stronger than gravitation, is responsible for the phenomena of radioactivity and decays of unstable particles like muons.

The weak force has two components. The one in which the interaction is mediated by the exchange of a charged vector boson ($W^+$ or $W^-$) is known as 'charged-current' interaction (examples: $\nu_e + n \rightarrow e^- + p$. and neutron decay via the quark transition $d \rightarrow u + e^- + \bar{\nu}_e$, where d and u are down and up quarks respectively), and the other in which the exchange vector boson has no charge ($Z^0$), called 'neutral-current' interaction (examples: $\nu_e + p \rightarrow \nu_e + p$ and $e^+ + e^- \rightarrow Z^0 \rightarrow \mu^+ + \mu^-$). Weak interaction has very interesting properties – it violates the spatial symmetry called parity, that is, the mirror image of a physical process does not exist in nature (P violation), it violates the symmetry between particles and antiparticles (C violation) and it also violates the combination of CP symmetry. At this stage it is important to note that neutrinos are involved in only weak interactions

## Suggested Reading


[1] John N Bahcall, *Neutrino Astrophysics*, Cambridge University Press, 1989.
J N Bahcall's homepage: http://www.sns.ias.edu/~jnb/

[2] Erika Böhm-Vitense, *Introduction to stellar astrophysics*, Vol .3, Cambridge University Press, 1992.

[3] A C Phillips, *The Physics of Stars*, John Wiley & Sons, 1994.

[4] B Pontecorvo, *Sov. Phys. JETP*, Vol. 7, p.172, 1958.

[5] Z Maki, M Nakagawa and S Sakata, *Prog. Theor. Phys.*, Vol. 28, p.870, 1962.

[6] Frederick Reines, 40 years of Neutrino Physics, *Progress in Particle and Nuclear Physics*, Vol. 32, p. 1-12, 1994. ( for electron-neutrino)

[7] Leon M Lederman, The Two-Neutrino experiment, *Scientific American*, March 1963. (for muon-neutrino)



*Address for Correspondence*
S N Ganguli
Aspiration Apts
32, Francois Martin Street
Kuruchikuppam
Pondicherry 605 012, India
Email: sngnaguli@vsnl.net


Human beings, who are almost unique in having the ability to learn from the experience of others, are also remarkable for their apparent disinclination to do so.

*Douglas Noel Adams*
From: *Hitchhiker's Guide to the Galaxy*