Neutrino Oscillations

New Windows to the Particle World

Suman Beri

The 2015 Nobel Prize in Physics was awarded to two physicists-Takaaki Kajita and Arthur B McDonald, whose teams discovered that neutrinos, which come in three flavours, change from one flavour to another. This discovery is a major milestone in particle physics as it gives a clear evidence of physics beyond the Standard Model. Neutrino oscillation is a quantum mechanical phenomenon whereby a neutrino created with a specific lepton flavour (electron, muon, or tau) can later be measured to have a different flavour. Historical development of the field in chronological order of experiments is briefly described in this article.

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The problem of neutrino flavour change or neutrino oscillation, is one that has intrigued researchers since 1956 when Clyde Cowan, Frederick Reines, F B Harrison, H W Kruse, and A D McGuire published the confirmation reports of detection of the neutrino [1] in *Science*. The path-breaking discovery that led to a Nobel Prize, almost forty years later in 1995 was perhaps just the beginning.

After years of research, two physicists – Takaaki Kajita and Arthur B McDonald (*Figure* 1) came up with concrete evidence to prove that neutrinos, which exist in three flavours, can change from one flavour to another. The Royal Swedish Academy of Sciences, bestowing the 2015 Nobel Prize in Physics to Kajita and McDonald cited – "*for the discovery of neutrino oscillations, which shows that neutrinos have mass.*"

This discovery is hailed as a major milestone in particle physics as it expands the horizons of physics beyond the widely accepted Standard Model (SM). Neutrino oscillations and related issues such as nature of the neutrino, neutrino masses and possibility of Charge-Parity (CP) violation among leptons[1] are today widely pursued research areas in particle physics.

Keywords
Neutrino oscillations, standard model, super-kamiokande, sudbury neutrino observatory, solar-neutrinos, muons, tau-neutrinos.

Takaaki Kajita
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Arthur B McDonald
Sudbury Neutrino Observatory, Queen's University, Canada.

Figure 1. The 2015 Nobel Prize in Physics was awarded jointly to Takaaki Kajita and Arthur B McDonald "*for the discovery of neutrino oscillations, which shows that neutrinos have mass*".

Changing Identities

The possibility of neutrino oscillations has been a long standing problem and was first raised in 1957. But the Nobel Prize winning work of Takaaki Kajita and Arthur B McDonald clearly demonstrated the occurrence of neutrino oscillations.

In 1998, Takaaki Kajita of the Super-Kamiokande (SK) Collaboration, Japan, speaking at the Neutrino'98[2] presented a discovery that strengthened the suspicion that neutrinos from the atmosphere shift between two identities. The data presented by Kajita clearly demonstrated that the neutrinos produced when cosmic rays interact with the Earth's atmosphere, disappear as they travel from their point of origin to the SK detector.

The experiments solved the mystery behind the missing two-thirds of the solar-neutrinos during the theoretical calculations on Earth. The answer was – neutrinos changed identities. The metamorphosis which requires that neutrinos have mass led to a game-changing conclusion – neutrinos, however small, must have some mass.

Supporting this, during 2001–2002, the Sudbury Neutrino Observatory (SNO) Collaboration, Canada, led by Arthur B McDonald, reported evidence for the conversion of electron-neutrinos (ν_e) from the Sun into muon- or tau-neutrinos (ν_μ or ν_τ). Furthering the observations of SK detector, SNO demonstrated that the neutrinos from the Sun were not actually disappearing during their transit to Earth, instead they were captured with a different identity when arriving at SNO.

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[1] See *Resonance*, V V Raman, Darshana Jolts-The World of Elementary Particles, Vol.17, No.10, pp.1000–1012, 2012.

[2] The largest international neutrino conference series.

This discovery was stunningly contrary to the SM and the long-time belief that neutrinos are massless particles. The discovery clearly meant that the SM was no longer acceptable as the complete theory of the fundamental constituents of the universe. The results transformed the understanding of the innermost workings of matter, thus opening up novel avenues of understanding universe.

Neutrinos – Introduction and History

Apart from photons (particles of light), neutrinos are the most abundant particles in the entire universe and the Earth is being constantly bombarded by them. Neutrinos are produced during the nuclear reactions inside the Sun and also as a result of interactions of cosmic radiations with the Earth's atmosphere. Each second, many billions of harmless neutrinos are passing through our bodies which are transparent to these neutrinos. Hardly anything can stop them from passing through. It has been experimentally established that the neutrinos and the antineutrinos which take part in weak interactions are of three types or flavours, namely: electron (ν_e), muon(ν_μ), and tau (ν_τ).

The history and first hint of the neutrinos goes back to 1911 and then subsequently to 1914, when J Chadwick first showed that the $\beta-$spectrum from the decay of a radioactive element was continuous, as opposed to the α- or γ-spectrum [2]. This implied that there should be a missing particle which carries the extra energy.

In 1930, W Pauli proposed a solution to this puzzle in terms of a new component of the atomic nucleus. The new constituent was an electrically neutral, weakly interacting, spin $-\frac{1}{2}$ fermion with mass similar to the electron. In resemblance with the proton, Pauli suggested that this particle be named the neutron [3]. But in 1932, when Chadwick discovered a much more massive, neutral and strongly interacting particle similar to the proton, which could sensibly bear that name [4], E Fermi proposed the term neutrino instead of neutron for Pauli's mysterious particle, also concluding that it might be massless [5]. Fermi incorporated the idea of neutrino into his ground-breaking theory on β-decay, published in 1934 [6]. Though, Fermi's successful theory established the existence of the neutrinos, the particle itself remained elusive

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at large, to the extent that Pauli himself was concerned that he might have postulated a particle which could never be detected. However, the nuclear fission experiments during 1930s–40s provided an unprecedentedly intense source of antineutrinos, which offered hope towards the experimental detection of neutrinos.

Though, Fermi's successful theory established the existence of the neutrinos, the particle itself remained elusive at large, to the extent that Pauli himself was concerned that he might have postulated a particle which could never be detected.

In the early 1950s, encouraged by B Pontecorvo, F Reines and C L Cowan Jr., set up a crucial experiment at the Savannah River nuclear reactor in South Carolina. The team could successfully demonstrate that the antineutrinos produced during certain processes in the reactor sometimes interacted with protons in the detector medium. Each reaction resulted in a neutron and a positron which could be registered (so-called inverse β-decay). This was the much awaited, definite evidence for the existence of neutrinos. In June 1956, just two years prior to Pauli's death, Reines and Cowan could send a telegram informing Pauli about their discovery. The discovery quoting the verification of the neutrino hypothesis suggested by Pauli was published in *Science* in July 1956 [7]. Reines shared the 1995 Nobel Prize in Physics with M L Perl.

The idea of neutrino oscillations and masses was first proposed in 1957–58 by B Pontecorvo [8, 9]. This was the time when the Gell-Mann and Pais [10] theory of $K^0 \leftrightarrow K^{-0}$ mixing and oscillations was experimentally confirmed. Pontecorvo was captivated by the idea of particle-mixing and oscillations and proposed the possibility of oscillations among leptons. His idea of neutrino masses and oscillations was very bold, proposed at a time when it was widely accepted that neutrinos are two-component, massless particles.

The discovery of the second flavour of neutrino namely the muon, once again revolutionized particle physics. The discovery proved that in addition to the first family of leptons (ν_e, e) comprising electron-neutrinos (ν_e), a second family (ν_μ, μ) existed with muon-neutrinos (ν_μ) and each family corresponded to two different (in mass) leptons e and μ.

The assumption that neutrinos are massless and characterised by distinct, individual lepton numbers was incorporated into the theory of electroweak interactions and subsequently into the Glashow-Weinberg-Salam Standard Model[3]. The model also incorporated the fact that weak interactions violate parity by only

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[3] The Nobel Prize in Physics 1979 was awarded jointly to S L Glashow, A Salam and S Weinberg.

allowing left-handed neutrinos and right-handed antineutrinos to participate in weak interactions. Right-handed neutrinos and left-handed antineutrinos have not been observed so far and if they do exist, do not interact through the known interactions. Hence, right-handed neutrinos and left-handed antineutrinos are known as 'sterile'. The chirality or handedness of the neutrino is consistent with the measured neutrino helicity[4], h = -1, within the experimental uncertainties, just as expected for a massless particle [11].

The Brookhaven neutrino experiment of 1957 was the first experiment in this context with high energy neutrinos originating from decays of pions, kaons and muons produced at accelerators. However, the first direct proof for the existence of muon neutrinos was obtained in 1962 by L M Lederman, M Schwartz, J Steinberger *et al.*, during their experiment with accelerator neutrinos. Despite the fact that some reasonable arguments for small non-zero masses were proposed and a general phenomenological theory of neutrino mixing and oscillations was developed during the 70s, the interest in neutrino masses and oscillations remained low and the idea of two-component, massless neutrinos was still leading, until the Nobel Prize in Physics 1988 was awarded to L Lederman, M Schwartz and J Steinberger "*for the neutrino beam method and the demonstration of the doublet structure of the leptons through the discovery of the muon neutrino.*"

The first direct proof for the existence of muon neutrinos was obtained in 1962 by L M Lederman, M Schwartz, J Steinberger *et al.*, during their experiment with accelerator neutrinos.

I would like to add a personal note here. It was my pleasure to listen to the work of L Lederman and interact with him during my visit to Fermilab.

During the 1980s and 1990s, novel solar neutrino experiments and the increase in the number of detected atmospheric neutrino events provided stronger evidence in favour of neutrino masses and oscillations.

In 1998, during the SK atmospheric neutrino experiment [12] in Japan, significant up-down asymmetry of the high-energy muon events were observed. SK is a second generation, 50,000 t water Cherenkov detector. It is ten times larger than its predecessor Kamiokande in the Mozumi zinc mine. SK started its operations in April 1996 and in less than two years of data collection reported the first prominent results. The detector reported a deficit in the number of up-going high energy muon-neutrinos,

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[4] See Amit Roy, Helicity of the Neutrino, *Resonance*, Vol.20, No.8, pp.699–710, 2015.

strongly varying with the zenith angle[5]. The $\nu_\mu \leftrightarrow \nu_\tau$ oscillation interpretation of SK's zenith angle results were further strengthened by the observation of the expected sinusoidal behaviour of the ν_μ flux as a function of L/E – the ratio of the distance from the point of production reconstructed from the neutrino direction, and the neutrino energy – which displays a minimum at 500 km/GeV [13], (*Figure* 2). The Earth is constantly exposed to a large flux of cosmic radiations. While they mostly consist of protons, but they also contain a small admixture of heavy nuclei which interacts with atomic nuclei in the atmosphere, creating many secondary particles including all kinds of hadrons. During this process, many pions and kaons are produced which decay into muons and muon-neutrinos. The muons, in turn decay into electrons, muon-neutrinos and electron-neutrinos.

$$\pi^\pm \rightarrow \mu^\pm + \nu_\mu\,(\bar{\nu}_\mu), \quad \mu^\pm \rightarrow e^\pm + \nu_e(\bar{\nu}_e) + \bar{\nu}_\mu\,(\nu_\mu)\,. \tag{1}$$

Neutrinos which are produced in the Earth's atmosphere and those coming from the outer space, travel distances ranging 20–500 km. Similarly, neutrinos coming to the detector from below pass the earth and travel distances of 500–12,000 km. During the SK experiment, it was discovered that the number of up-going

The result of the SK atmospheric neutrino experiment proved to be the first, model-independent evidence of neutrino oscillations. The study marked a new era in the exploration of neutrino oscillations – an era of experiments in which neutrinos from various sources were studied, in order to generate model-independent evidence of neutrino oscillations.

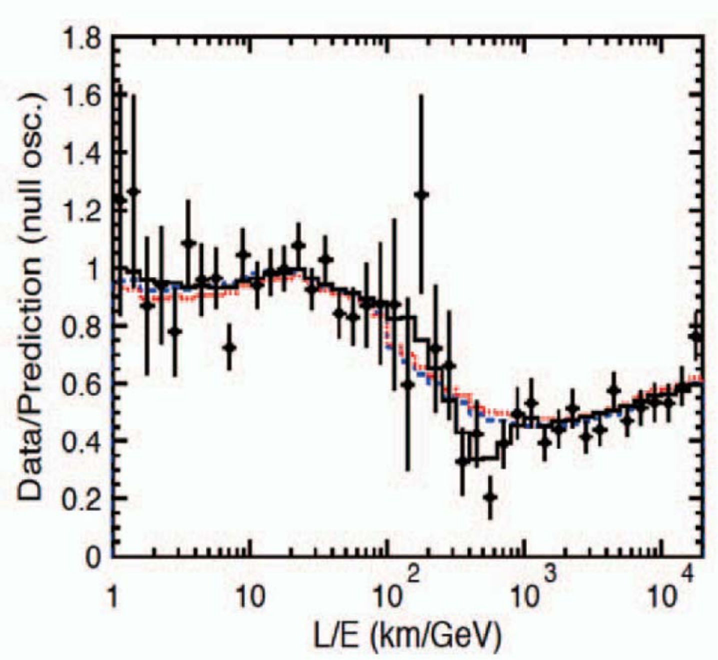

Figure 2. Ratio of data from Super-Kamiokande to Monte Carlo expectation assuming no oscillation, as a function of reconstructed L/E [13]. The black histogram is a fit to a two flavour oscillation hypothesis.

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[5] The angle between the neutrino direction and vertical.

high-energy muon-neutrinos was about two times smaller than the number of the down-going high-energy muon-neutrinos. The experiment thus proved that the number of observed muon-neutrinos depends on the distance travelled by the neutrinos from its origin to the detector. The result of the SK atmospheric neutrino experiment proved to be the first, model-independent evidence of neutrino oscillations. The study marked a new era in the exploration of neutrino oscillations – an era of experiments in which neutrinos from various sources were studied in order to generate model-independent evidence of neutrino oscillations.

The third flavour of neutrino called the tau-neutrino (ν_τ), the partner of the τ-lepton, was discovered through an experiment performed by the DONUT Collaboration at Fermilab in 2000 [14].

In short, the SK observations supported the conclusion that atmospheric muon-neutrinos are converted into tau-neutrinos and exclude alternative hypotheses like neutrino decay and neutrino decoherence at more than 3σ (blue and red dashed lines in *Figure* 2). Recently, a statistical search was performed with SK data demonstrating not only muon-neutrino disappearance but also tau-neutrino appearance at almost 4σ level [15].

In 2002, during the SNO solar neutrino experiment [16], Canada, model-independent evidence for the disappearance of solar electron-neutrino was obtained. Thermonuclear fusion reactions occurring in the solar core produce energy along with neutrinos. During the theoretical predictions, the flux of neutrinos from the Sun when measured on the Earth appears anomalously low. This anomaly was referred to as the ‘solar-neutrino problem’. The solar-neutrino problem was pondered upon by researchers for more than 30 years before it was finally resolved by measurements with the SNO heavy water detector. When the idea of SNO was put forth, the Davis experiment to measure the expected number of solar-neutrinos had already been running for 20 years. The results consistently showed a deficit in the flux of ^{8}B solar neutrinos, inviting two possible interpretations. It was possible that the Standard Solar Model (SSM) as proposed by Davis experiment was wrong – for instance, if the temperature in the Sun’s interior was lower than anticipated, it would result in a decreased production of ^{8}B-neutrinos and hence a lower than expected flux of electron-neutrinos. Alternatively, the ^{8}B-neutrinos, predicted by

In October 1987, the SNO collaboration proposed the construction of a neutrino observatory deep underground in the Creighton mine near Sudbury, Canada. The vital feature of the proposed observatory was the use of heavy water (D_2O), which could be loaned in large quantities from Canada’s reserves.

the SSM, could be changing into other neutrino flavours during their transit.

Under these debates, in 1984, the SNO Collaboration to undertake neutrino studies was first established. The collaboration initiated with G Ewan from Queen's University, Canada, and H Chen from University of California, USA, as co-spokespersons. In 1985, D Sinclair from Oxford University, UK, joined the team as co-spokesperson. In October 1987, the collaboration proposed the construction of a neutrino observatory deep underground in the Creighton mine (town of Walden) near Sudbury, Canada. The vital feature of the proposed observatory was the use of heavy water (D_2O), which could be loaned in large quantities from Canada's reserves. Use of D_2O would allow simultaneous measurement of the relative rate of neutrino-deuteron reactions forming two protons (possible only for electron-neutrinos), and neutrino-deuteron reactions resulting in a proton and a neutron (possible for all neutrino flavours). The ratio would indicate any neutrino transformations taking place.

The SNO heavy water Cherenkov detector, consisted of 1,000 t ultra-pure D_2O in an acrylic sphere, 12 m in diameter. The volume of the detector was monitored by photomultiplier tubes mou nted on a geodesic support structure 17 m in diameter. The tubes were surrounded by ultra-pure H_2O which acted as a shield against radioactive decays in the support structure and the surrounding rock (*Figure* 3). The overburden of rock shielded the instrument from cosmic rays. Meanwhile, Mikheev and Smirnov [17] in 1986 proposed a mechanism, which would enhance neutrino conversion in solar matter based on a theory initially developed by Wolfenstein [18]. If this process was to work, the Sun would not only produce electron-neutrinos but also convert a large fraction of its electron-neutrinos into muon-neutrinos and tau-neutrinos. Since 1990, A B McDonald from Princeton University, is leading the SNO collaboration as the first Director. During the SNO experiment, high-energy solar neutrinos from ^{8}B-decay were detected through the observation of Charged Current (CC) and Neutral Current (NC) reactions. CC reactions are mediated by charged weak bosons (W) and are sensitive only to ν_e. CC reactions provide the electron-neutrino flux – ϕ (ν_e). In case of CC reactions, the electron carries off most of the energy and a measurement of the electron energy spectrum provides information on possible

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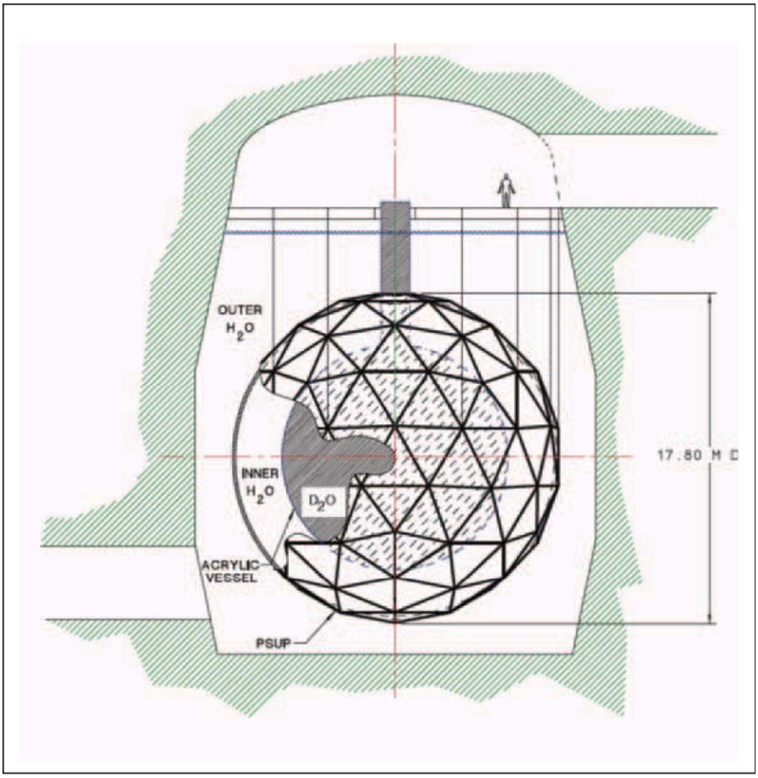

Figure 3. Layout of SNO detector with PMT support structure (PSUP) shown inside the SNO cavity, surrounding the acrylic vessel, with light water and heavy water volumes located as indicated [19].

distortions of the ν_e spectrum due to oscillations. On the other hand, NC reactions are mediated by neutral weak bosons (Z^0) and are sensitive to all neutrino flavours. Finally, elastic scattering (ES) reactions, although common for all the three flavours of neutrinos, are primarily sensitive to v_e, as the interaction cross-sections for v_μ and ν_τ are about six times smaller. ^{8}B solar-neutrinos reactions which were detected are

$$\begin{aligned} &\nu_e +^2 H \rightarrow e^- + p + p \quad && (\mathrm{CC})\,, \\ &\nu_x +^2 H \rightarrow \nu_x + p + n \quad && (\mathrm{NC})\,, \\ &\nu_x + e^- \rightarrow \nu_x + e^- && (\mathrm{ES})\,. \end{aligned} \qquad (2)$$

The direction of the neutrino, was deciphered from the direction of the final electron produced in an ES reaction. This results were used to confirm that the neutrinos actually originated from the Sun. The NC reaction was identified by observing the rays from the capture of the final neutron in deuterium, although with a fairly low detection efficiency. Hence, a second phase of the ex-

The first results from the SNO experiment were published during 2001–2002, and provided the first evidence for neutrino flavour conversion. The data demonstrated clearly that the total flux of ^{8}B-neutrinos was in agreement with the Solar Model prediction. Continued data collection refined these results.

periment was run using two tons of sodium chloride (NaCl) along with thousand tons of D_2O. This improved the neutron capture efficiency due to the larger neutron capture cross-section of chlorine relative to deuterium. In the final step, the reliability of NC measurements were checked and improved by purging the NaCl and installing ^{3}He neutron counters.

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$$\phi = \phi(\nu_e)+\phi(\nu_\mu)+\phi(\nu_\tau) = 5.25\pm0.16(stat)^{+0.11}_{-0.13}(sys)\times10^6\text{cm}^{-2}\text{s}^{-1}\,, \tag{3}$$

which is in very good agreement with the theoretically expected 5.94(1 ± 0.11) [SSM BPS08] or 5.58(1 ± 0.14) [SSM SHP11] (see [22] and references therein). The flux of muon- and tau-neutrinos deduced from the results are shown in *Figure* 4 and is deviating significantly from zero:

$$\phi(\nu_\mu) + \phi(\nu_\tau) = (3.26 \pm 0.25^{+0.40}_{-0.35}) \times 10^6\text{cm}^{-2}\text{s}^{-1}\,. \tag{4}$$

A comparison with the total ^{8}B-flux clearly indicated that about

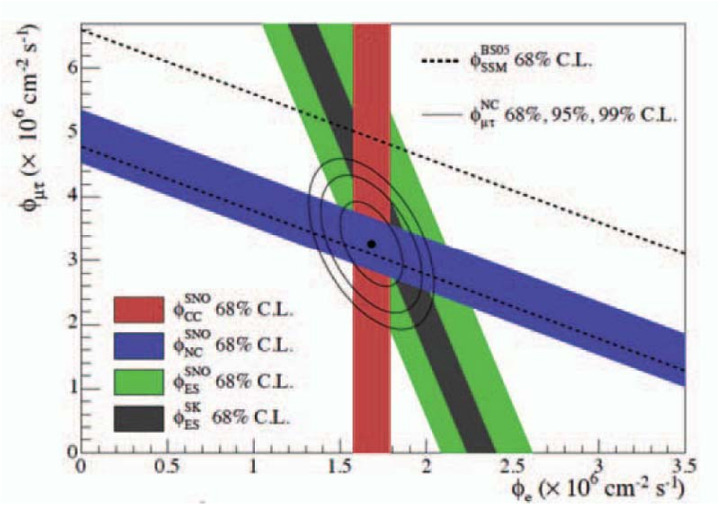

Figure 4. Fluxes of ^{8}B solar-neutrinos from SNO and SK. The SSM BS05 [23] prediction is shown as a range between the dashed lines. C.L. stands for confidence level (from [22] and references therein).

two-thirds of the solar electron-neutrinos change flavour, converting to muon-neutrinos or tau-neutrinos during their transit to Earth. SNO's ES results are in agreement with the results from the SK detector and with the SNO results stated above. However, standing alone by themselves, the results may be deemed insufficient as evidence for flavour change.

Further during 2002–2004, model-independent evidence of oscillations of reactor ν_{e} was obtained by the KamLAND reactor experiment [24] of Japan. In this experiment ν_e's from 55 reactors at an average distance of about 170 km from the large KamLAND detector were recorded. It was observed that the total number of anti-ν_e events was only about 0.6% of the number of the expected events. Also, a significant distortion of the anti-ν_e spectrum with respect to the expected spectrum was observed in the experiment. Neutrino oscillations were also observed during the long-baseline accelerator K2K experiment [25] (the distance L between the source and the detector was about 250 km) and in the MINOS accelerator neutrino experiment [26] (with a distance L of about 730 km). These experiments fully supported the results obtained by the SK and SNO experiments and confirmed the existence of neutrino oscillations. Further studies proved that neutrinos had small masses and that the flavour neutrinos ν_e, ν_μ, ν_τ were 'mixed particles'.

In a scenario where only two neutrinos participate in the oscillation, the probability of oscillation follows a simple pattern as shown in *Figure* 5. The blue curve shows the probability of the original neutrino retaining its identity. The red curve shows the probability of neutrino flavour conversion. While maximum probability of conversion is equal to $\sin^2 2\theta$, the frequency of the oscillation is controlled by Δm^2. The experimental results are used to obtain the mass differences Δm^2 and the mixing angles θ. This is achieved using global fits including all available experimental data, observations of solar and atmospheric neutrinos, and neutrinos studied in reactor and accelerator experiments. Recent values of the parameters of the PMNS matrix based on a global analysis of all available oscillation data assuming a three-neutrino mixing scheme is available for reference [22].

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Nonetheless, the Standard Model, including the quantum field theory of strong interactions and the unified theory of electro-

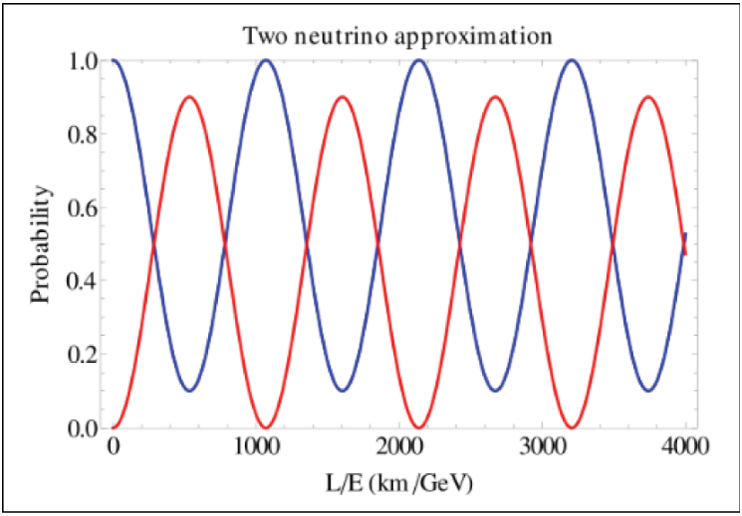

Figure 5. Two neutrino probabilities in vacuum.

magnetic and weak interactions, has proved to be extremely successful in describing matter at the fundamental level.

A breakthrough in this context was the discovery of the theoretically predicted Higgs Boson[6] which is necessary for the mass generating mechanism [27]. The discovery was made by the ATLAS and CMS Collaborations at CERN (2013 Nobel Prize in Physics to F Englert and P W Higgs for their theoretical contributions). The predictions of SM have been verified through precision experiments, conspicuously at the Large Electron Positron Collider LEP at CERN. In the SM, lepton numbers are conserved, neutrinos are massless and neutrino flavours do not oscillate. However, based on the measurement of the so-called invisible Z^0 width, these experiments established that there are three types of light neutrinos consistent with the effective number of relativistic degrees of freedom determined in cosmology.

The history and development of weak and electroweak theory has been very well discussed in a previous issue of *Resonance* [28] and references therein. Neutrino oscillation experiments have revealed that neutrinos change flavour after propagating a finite distance. The simplest and only satisfactory explanation of all experimental data discussed before is that neutrinos have distinct masses, and mix. An elementary review of discoveries in neutrino physics, culminating in the solution of the solar neutrino problem and the discovery of neutrino mass as well as atmospheric neutri-

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[6] See Prafulla Kumar Behera, Discovery of SM Higgs Boson in ATLAS Experiment, *Resonance*, Vol.18, No.3, pp.248–263, 2013.

nos, reactor neutrinos and other important developments are also briefly described in a previous issue of *Resonance* [29].

Experiments continue in this area and intense research activity is ongoing worldwide in order to capture neutrinos and further the understanding of their properties. New discoveries in this area are expected to provide more insights into the history, structure and future of the cosmos.

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Note from the Chief Editor

Readers will notice one significant change on the inside front cover of this issue – the names of Sujatha Mohankumar and M Raj Lakshmi no longer appear. Between them, they have served the journal since its inception, keeping a close eye on each article for style, content, and improvements to readability. Additionally, they have been a veritable mine of information regarding the journal – the history, authors, referees, special issues, and much more. Members of successive editorial boards have tapped this resource which provided valuable continuity. They can certainly feel satisfied with a long job well done. We wish Sujatha and Raj Lakshmi all the best in the many activities they must have planned now that they have passed the baton of *Resonance* to younger colleagues.