Neutrinos and our Sun – Part 3

S N Ganguli

In the concluding part of the article on Neutrinos and our Sun we discuss the detection of atmospheric neutrinos, their fluxes and zenith angle distributions. Here too one finds discrepancies with theoretical predictions. We discuss how the idea of neutrino oscillations helps resolve both the solar neutrino puzzle (discussed in Part 2) and the discrepancy observed in atmospheric neutrino fluxes. This is followed by a discussion of neutrino masses and the recent confirmation of the neutrino oscillations in the KamLAND experiment.

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1. Atmospheric Neutrinos

Atmospheric neutrinos are produced by interactions of high energy cosmic ray particles (protons, alpha particles, etc.) with air nuclei leading to the production of charged mesons (pions, kaons, etc.) which subsequently decay yielding two types of neutrinos: the electron-neutrino (ν_e) and the muon-neutrino (ν_μ) (see *Figure* 1). The chain of reactions may be summarised as follows:

$$\begin{aligned} \text{proton} + \text{air} - \text{nucleus} &\rightarrow \pi^{\pm}(\mathrm{K}^{\pm}) + X \\ \pi^{\pm}(\mathrm{K}^{\pm}) &\rightarrow \mu^{\pm} + \nu_\mu(\bar{\nu}_\mu) \\ \mu^{\pm} &\rightarrow \mathrm{e}^{\pm} + \nu_\mathrm{e}(\bar{\nu}_\mathrm{e}) + \bar{\nu}_\mu(\nu_\mu), \end{aligned}$$

where X represents anything else. By simply counting the two types one expects that the muon-type neutrinos should be twice as many as the electron-type neutrinos, i.e., $(\nu_\mu + \bar{\nu}_\mu)/(\nu_\mathrm{e} + \bar{\nu}_\mathrm{e}) = 2$. In reality, one should take into account the lifetime differences of pions, kaons and muons, as well as their energy spectra. Several experiments are being carried out to study these atmospheric neutrinos. Atmospheric neutrinos are much less abun-

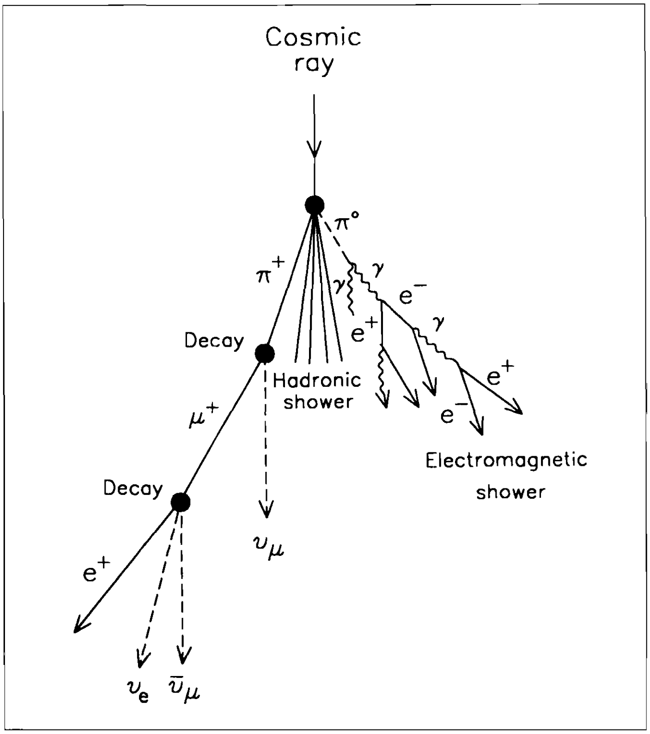

Figure 1. Schematic diagram of cosmic ray interaction with an air-nucleus. Primary cosmic ray particles consist of ~80% protons, ~9% alphas, ~8% neutrons, a few percent of electrons and heavy nuclei. Most of the particles at the sea level are muons and neutrinos.

dant than the solar neutrinos, but these are high energy neutrinos in the range ~ 100 MeV to ~ 100 GeV (in comparison, the solar neutrinos are < 20 MeV), and are easily detected via the charged-current reactions:

$$\begin{aligned} \nu_{\rm e}(\bar{\nu}_{\rm e}) + {\rm A} &\rightarrow e^-(e^+) + X, \\ \nu_\mu(\bar{\nu}_\mu) + {\rm A} &\rightarrow \mu^-(\mu^+) + X, \end{aligned}$$

where A represents a target nucleus. Besides detecting electrons and muons as the final products of neutrino interactions, detectors also measure the angular distributions of these particles, called zenith angular distribution, which tell us the original direction of the neutrinos. Two important experimental results from the Super-Kamiokande (SK) detector are summarised below.

Measurement of $R = \frac{(\nu_\mu/\nu_{\rm e})_{\rm Data}}{(\nu_\mu/\nu_{\rm e})_{\rm MC}}$: The overall uncertainty of the calculated atmospheric neutrino fluxes of ν_μ and $\nu_{\rm e}$ are as large as 20 30%. In order to minimise the uncertainties, one measures the double ratio R which is the ratio of $(\nu_\mu/\nu_e)_{\text{Data}}$ and $(\nu_\mu/\nu_e)_{\text{MC}}$ where MC stands for Monte Carlo simulation, and Data refers to the experimental ratio. The expected value of R is unity. The measurements of R based on 1489 days of the running of the SK experiment for fully contained events in the detector are:

$$\text{R} = 0.64 \pm 0.02 \text{ (stat)} \pm 0.05 \text{ (syst) (sub-GeV)},$$

$$\text{R} = 0.66 \pm 0.03 \text{ (stat)} \pm 0.08 \text{ (syst) (multi-GeV)},$$

where sub-GeV refers to those events where the visible energy in the detector was < 1.33 GeV, and multi-GeV for those events with visible energy > 1.33 GeV; stat stands for statistical error and syst for systematic error. The value of R is significantly different from unity, thereby bringing out the discrepancy between the observed and the predicted atmospheric neutrino fluxes. The existence of this anomaly was also confirmed by other experiments: IMB, Soudan and MACRO.

Zenith Angle Distributions: Distances travelled by neutrinos before they reach the detector vary significantly with the zenith angle, (see *Figure* 2). For example, the neutrinos coming vertically down travel only ~ 15 km (zenith angle $\theta = 0°$), the neutrinos coming from the horizontal direction travel ~ 500 km (zenith angle $\theta = 90°$), and the neutrinos reaching the detector from below the earth travel $\sim 13,000$ km (zenith angle $\theta = 180°$). The zenith angle distributions of events initiated by ν_e are called electron-like events, and those by ν_μ are called muon-like events. Experimental results are displayed as a function of cos θ in *Figure* 3. They have been further subdivided into two categories: sub-GeV and multi-GeV as explained above. The solid lines refer to Monte Carlo predictions. One sees from the figure that the electron-like events agree very well with the MC predictions for both the sub-GeV and multi-GeV samples, while the muon-like events show strong

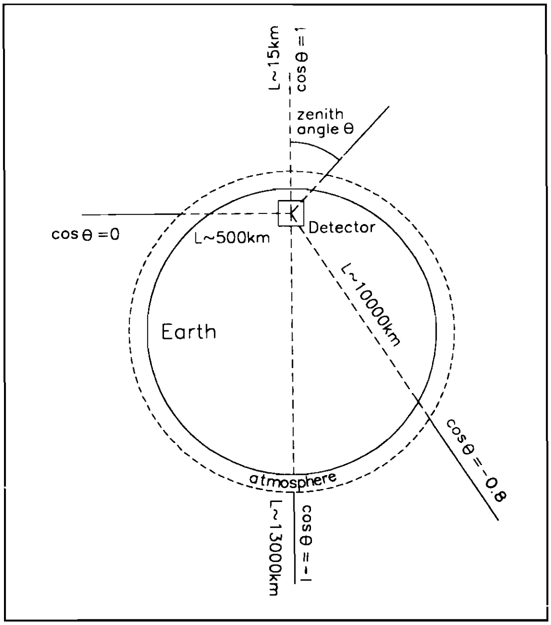

Figure 2. Schematic diagram of neutrinos hitting Super-Kamiokande detector at different zenith angles; for example: at cos θ=1 neutrinos will cross about 15 km of the atmosphere and at cos θ=−1 neutrinos will enter the detector from below by crossing about 13000 km of earth.

deficiency of events with respect to the MC predictions which are zenith angle dependent. For the multi-GeV muon events, the discrepancy is stronger for zenith angles between 90 and 180 degrees ($-1 < \cos\theta < 0$, that

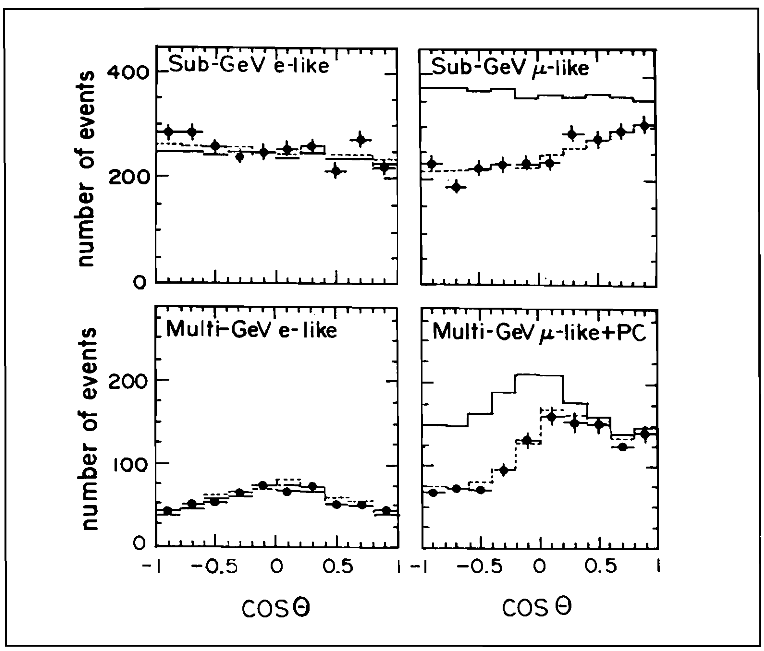

Figure 3. Zenith angle distributions of e – like and μ–like events for sub-GeV (visible energy <1.3 GeV) and multi-GeV (visible energy >1.3 GeV) data sets. The solid histograms show the Monte Carlo expectation for no oscillation, while the dashed histograms refer to the best fit with oscillation ($\Delta m^2 = 3\times10^{-3}$ eV^2). Adapted from H Sobel, Nucl. Phys. B (Proc. Suppl.) Vol.92, p.127, 2001.

is for neutrinos with larger pathlengths between 500 and 13,000 km), while for the sub-GeV muons one sees a deficit of muons for all zenith angles. Thus the SK data demonstrate a strong evidence for zenith angle dependent deficiency of muon neutrinos.

2. Neutrino Oscillation Hypothesis

Vacuum oscillation: Earlier we had described the solar neutrino experiments which indicated that the electron-neutrinos from the sun are measured to be fewer than are predicted by the standard solar model, and experiments with the atmospheric neutrinos demonstrate that there is a depletion of atmospheric muon-neutrinos while there is no depletion of electron-neutrinos. One possible explanation for the observed solar neutrino deficit is that the ν_e (electron-neutrino) produced in the centre of the sun could convert itself to another type, i.e., $\nu_e \rightarrow \nu_x$, with $x = \mu$ or τ, during its passage to the earth via a process called neutrino oscillation. Similarly, the atmospheric muon-neutrino deficit could be due to the conversion of ν_μ to ν_τ. The possibility of neutrino oscillation, a purely quantum mechanical effect, was conjectured in 1958 by B Pontecorvo and in 1962 by Z Maki, M Nakagawa and S Sakata. However, neutrinos must have some mass for oscillations to occur[1].

[1] Neutrino masses: So far there is no direct evidence of non-zero neutrino mass from laboratory experiments. Upper limits on neutrino masses have been obtained from kinematic considerations and are as follows: $m(\nu_e) < 2$ eV, $m(\nu_\mu) < 0.17$ MeV, $m(\nu_\tau) < 15.5$ MeV. These upper limits have been obtained from kinematical studies of the particles produced in the following reactions: $H^3 \rightarrow He^3 + e^- + \overline{\nu}_e$, $\pi^+ \rightarrow \mu^+ + \nu_\mu$ and $\tau \rightarrow 4\pi + \nu_\tau$.

A simple way to understand neutrino oscillation is in terms of two-flavour mixing: for example, between ν_e and ν_μ. (We leave out a discussion of the more complicated three-flavour mixing hypothesis.) Let $\theta_{e\mu}$ be the $\nu_e - \nu_\mu$ mixing angle. If a neutrino were produced as a ν_e at the source and travelled a distance L, the probability that it oscillated into a ν_μ is given by:

$$\begin{aligned} P(\nu_e \rightarrow \nu_\mu) &= \sin^2 2\theta_{e\mu} \ \sin^2\left(\frac{1.27 \ \Delta m^2 \ L}{E_\nu}\right) \\ &= A \ \sin^2\left(\frac{\pi L}{\lambda}\right) \end{aligned}$$

Neutrino source	Neutrino energy E	L	Δm^2 (eV^2)
Solar	1-10 MeV	10^8 km	10^{-10}-10^{-11}
Atmospheric	1-10 GeV	10-10^4 km	1-10^{-4}
Reactor	~4 MeV	1 km	~10^{-3}
	~4 MeV	100 km	~ 10^{-5}

Table 1. Expected Δm^2 under vacuum oscillation hypothesis.

where $\lambda = \frac{\pi E_\nu}{1.27 \cdot \Delta m^2}$ acts as an oscillation length and $A = \sin^2 2\theta_{e\mu}$ as the amplitude of oscillation; $\Delta m^2 = |m_2^2 - m_1^2|$ in eV^2 measures the square of the mass-difference between the neutrinos, E_ν is the neutrino energy in GeV, and L in km is the distance of the detector from the neutrino source. Basically there are two variables: Δm^2 and θ.

The following points may be noted: (i) The ideal distance of the detector from the source for observing the oscillations is $L = \lambda/2$, so that $\sin^2\left(\frac{\pi L}{\lambda}\right) = 1$. (ii) Δm^2 is dependent on (E/L); for small values of Δm^2 one needs small values for (E/L) to see the oscillations. The expected values of Δm^2 from different neutrino sources are summarised in *Table* 1.

MSW effect: There is another kind of oscillation called the Mikheyev-Smirnov-Wolfenstein (MSW) effect which is a matter-enhanced neutrino oscillation; in this, the conversion $\nu_e \rightarrow \nu_x$ results from interaction between ν_e and solar electrons as the neutrinos travel from the centre of the sun.

3. Confirmation of Solar Neutrino Oscillation

Sudbury Neutrino Observatory (SNO): The aim of the Sudbury Neutrino Observatory is to measure the total neutrino flux of all three flavours $(\nu_e, \nu_\mu, \nu_\tau)$ from the sun, unlike the previous detectors where one measured only electron-neutrinos. To accomplish this the SNO employs ultra-pure heavy water (D_2O), and neutrino interactions with deuterium nuclei are studied. It detects both the charged-current reaction (CC) which is sensitive to electron-neutrino, and the neutral-current reaction (NC) which is sensitive to all the three neutrino flavours (ν_e, ν_μ, ν_τ). The threshold energy for the neutrino flux is 2.2 MeV (the binding energy of a deuterium nucleus) and it means that SNO measures the B^8 solar neutrinos (E_ν < 14.6 MeV). The reactions studied are:

$$\begin{aligned} \nu_e + d &\rightarrow p + p + e^- \text{ (CC)} \\ \nu_x + d &\rightarrow p + n + \nu_x \text{ (NC)} \\ \nu_x + e^- &\rightarrow \nu_x + e^- \text{ (ES)} \end{aligned}$$

where the index x refers to e, μ and τ. The neutral current (NC) is sensitive to all the three flavours. The elastic scattering (ES) is sensitive fully to ν_e, but partially to ν_μ and ν_τ.

The aim of the Sudbury Neutrino Observatory is to measure the total neutrino flux of all three flavours (ν_e, ν_μ, ν_τ) from the sun, unlike the previous detectors where one measured only electron-neutrinos.

The main part of the SNO detector consists of a 12-metre diameter acrylic sphere filled with 1000 tons of heavy water and surrounded by about 9500 photomultiplier tubes to detect Cerenkov photons generated in the heavy water. This 10-storey-tall detector is located in a mine at a depth of about 2 km near Sudbury, Canada. SNO started operation in November 1999. Results based on the data collected up to May 2001, consisting of 306 active data taking days, have been published. *Figure* 4 shows the angular distribution of events, where the angle is defined as the Cerenkov event direction from the direction of the sun ($\cos\theta_\odot$). A total of 2928 events were obtained after various cuts. Their results are presented below in units of 10^6 $cm^{-2}sec^{-1}$:

$$\begin{aligned} \Phi(\nu_e) &= 1.76 \pm 0.10 \\ \Phi(\nu_\mu + \nu_\tau) &= 3.41 \pm 0.66 \\ \Phi(\nu_e + \nu_\mu + \nu_\tau) &= 5.09 \pm 0.64. \end{aligned}$$

For the first time a non-ν_e flux from the sun has been observed in the SNO neutral-current data. The measurement of the total flux of B^8 neutrinos is thus

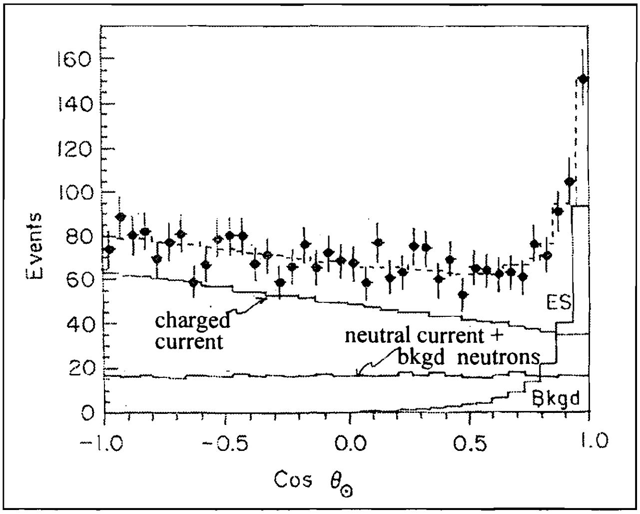

Figure 4. Distribution of the cosine of the angle of the neutrino event direction (measured from Cerenkov light) with respect to the direction of the sun. Monte Carlo predictions for CC (charged-current), ES (electron scattering) and NC (neutral current) events are also shown; the dashed line shows the total sum of expected spectrum. Adapted from the SNO collaboration [7].

$(5.09 \pm 0.64) \times 10^6$ $\mathrm{cm^{-2}sec^{-1}}$ and this is in good agreement with the prediction of the standard solar model flux of $(5.05^{+1.01}_{-0.81}) \times 10^6$ $\mathrm{cm^{-2}sec^{-1}}$.

So for the first time we have a direct confirmation that the solar electron-neutrinos are getting converted into muon/tau neutrinos. This also implies that the standard solar model is correct and our understanding of the energy generation process in the sun is complete.

4. Neutrino Masses

We discussed two types of neutrino experiments – one to detect the solar neutrinos and the other to detect the atmospheric neutrinos. In the case of solar neutrinos, we now have the confirmation from the SNO data that the oscillation of electron-neutrinos to muon- or tau-neutrinos is indeed taking place. This essentially means that neutrinos are not massless. Using the neutrino oscillation hypothesis several attempts have been made to fit the solar neutrino as well as the atmospheric neutrino data. Making a global analysis of the solar neutrino data, there are several solutions, and the two best solutions yield the values for square of the mass-difference Δm^2_{sol} as $\sim 6 \times 10^{-5}$ eV^2 or $\sim 4 \times 10^{-10}$ eV^2 for the MSW or vacuum solution re-

Solar electron-neutrinos are getting converted into muon/tau neutrinos.

Neutrino source	Δm^2	Mixing angle	Remark
Solar	$\sim 6 \times 10^{-5}$ eV^2	$\tan^2\theta \approx 0.4$	MSW solution
Solar	$\sim 4 \times 10^{-10}$ eV^2	$\tan^2\theta \approx 2.0$	Vacuum solution
Atmospheric	$\sim 3 \times 10^{-3}$ eV^2	$\sin^2 2\theta > 0.9$	–

Table 2. Neutrino oscillation results.

spectively. Analysing the atmospheric neutrinos[2] one gets Δm^2_{atm} as $\sim 3 \times 10^{-3}$ eV^2. These values are summarised in *Table* 2. It is believed that the solar neutrinos lead to the oscillation of $\nu_e \rightarrow \nu_\mu$, while the atmospheric neutrinos result in the oscillation of $\nu_\mu \rightarrow \nu_\tau$. This indicates that two of the neutrinos (let us label them as 1 and 2) are very close to each other in mass with Δm^2 in the range $\sim 10^{-5}$ to 10^{-10} eV^2, and the third one (let us label it as 3) is much different from the two with Δm^2 of $\sim 10^{-3}$ eV^2. In other words the following two scenarios are emerging: either $m_1^2 \approx m_2^2 \ll m_3^2$, or $m_1^2 \approx m_2^2 \gg m_3^2$.

[2] Results from K2K: K2K stands for KEK to Kamioka long-baseline neutrino oscillation experiment. The aim of this experiment is to study muon-neutrino (ν_μ) oscillation from neutrinos produced in the laboratory with the explicit goal of probing the same Δm^2 region as that explored with atmospheric neutrinos. For this experiment muon-neutrinos are produced with a mean energy of 1.3 GeV by the 12 GeV proton accelerator at KEK, Japan. These muon-neutrinos are directed through the earth towards the Super-Kamiokande underground neutrino detector, located about 250 km from KEK. Data collected from June 1999 to July 2001 yielded 56 neutrino events in the Super-Kamiokande; the expected number of neutrino events was 80. The observation of a clear deficit of ν_μ events is consistent with the expectation from the atmospheric neutrino oscillation results. The best fit results are: Δm^2 as 2.8×10^{-3} eV^2, and $\sin^2 2\theta$ as 1.0, and confirms the results of atmospheric neutrinos.

5. First Evidence for Reactor Antineutrino Oscillation

Kamioka Liquid Scintillator Anti-Neutrino Detector (KamLAND): The aim of the KamLAND detector is to detect the flux and energy spectrum of low energy antineutrinos (E_ν < 7.5 MeV) produced by a cluster of Japanese commercial nuclear reactors, which are situated typically at an average distance of about 180 km. If they measure fewer $\bar{\nu}_e$ than expected from the standard propagation of $\bar{\nu}_e$ from the reactors to KamLAND, then the oscillation of anti-neutrinos is seen. KamLAND is expected to see oscillations if Δm^2 is $\sim 10^{-5}$ eV^2 (see also *Table* 1). The KamLAND detector, placed in a 1 km deep Kamioka mine, consists of one kton of very high purity liquid scintillator, which is kept in a transparent thin film balloon of 13 m diameter. The balloon is housed in a 18 m diameter stainless steel container with a special 2.5 m thick layer of mineral oil in between, to shield the liquid scintillator from external neutron and gamma radiation. The detector uses 1879 photomultiplier tubes of 17 and 20 inch-diameter mounted on the stainless steel container.

The inverse β decay reaction is used to detect $\bar{\nu}_e$ in liquid scintillator: $\bar{\nu}_e + p \rightarrow e^+ + n$. One detects both the positron and the delayed 2.2 MeV gamma-ray photon from neutron capture on a proton (same methodology as was used by Reines and Cowan in 1953 to detect neutrinos). Antineutrinos from uranium and thorium beta decays inside the earth are rejected by selecting antineutrinos with energies larger than 3.4 MeV. The KamLAND collaboration has reported results based on the data collected between March and October 2002. They have observed a total of 54 events. They estimate a background of 1 event. The total number of events expected was 87. Thus the ratio of observed $\bar{\nu}_e$ events from the reactor, after subtracting the background, to that expected is: $N_{obs}/N_{exp} = 0.611 \pm 0.094$. A clear evidence for antineutrino disappearance is thus seen by KamLAND.

The best fit to the KamLAND data yields: $\Delta m^2 = 6.9 \times 10^{-5}\, eV^2$ and $\sin^2 2\theta = 1.0$. This result should be compared with the ν_e oscillation as seen in solar neutrinos, and it agrees with the MSW solution. Thus one may conclude the following two values for Δm^2 from results known so far from reactor, solar and atmospheric neutrinos:

$$\Delta m^2 \sim 6 \times 10^{-5}\, eV^2 \quad \text{(reactor + solar neutrinos)}$$

$$\Delta m^2 \sim 3 \times 10^{-3}\, eV^2 \quad \text{(atmospheric neutrinos).}$$

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6. Summary and Future Outlook

The building blocks of matter as we understand today consist of six quarks and six leptons. Among the leptons there are three charged species and three neutral ones called neutrinos: ν_e, ν_μ and ν_τ. We know very little about neutrinos, although the first hint of the existence of neutrinos appeared more than a hundred years ago, in the beta-activity of nuclei. Neutrinos interact with matter via the weak interaction. The understanding of charge-current and neutral-current weak-interactions came from the studies based on neutrinos produced in high energy particle accelerators. Till about a decade back neutrinos were thought to be massless, and the standard model of particle physics assumed them to be so. Neutrinos are also produced in large numbers in our sun during energy generation through fusion; about seventy billion neutrinos pass every cm^2 of the earth every second. The sun generates only electron neutrinos (ν_e). R Davis set up a detector at the Homestake mine in 1968, to detect solar neutrinos and the data collected over several decades showed that the neutrino flux from the sun fell short by a factor of three with respect to the best theoretical predictions. This gave rise to the **Solar Neutrino Puzzle**. During the 1980's and 1990's several new experiments were commissioned, and in all cases the observed neutrino flux was significantly lower than the prediction. One of the new experiments, the Super-Kamiokande, came out with another anomaly in the atmospheric neutrino data. The precise measurements unambiguously demonstrated that the muon-neutrinos produced in the earth's atmosphere get depleted in passage through large distances of about 500 to 13,000 km in the earth.

Neutrino oscillation is a quantum mechanical effect stating that a neutrino produced as one kind (say, ν_e) has a finite probability of getting converted into another kind (say, ν_μ) after travelling a certain distance.

These two experimental observations led to the revival of the idea of neutrino oscillations. Neutrino oscillations, requiring finite masses of neutrinos, were proposed in the early 1960s by Pontecorvo and Maki et al [2,3]. Neutrino oscillation is a quantum mechanical effect stating that a neutrino produced as one kind (say, ν_e) has a finite probability of getting converted into another kind (say, ν_μ) after travelling a certain distance. This idea is very recently confirmed by the observations made at the Sudbury Neutrino Observatory.

For the pioneering neutrino experiments carried out at Homestake and at Kamiokande/Superkamiokande, the Nobel Prize in Physics for 2002 was awarded to Raymond Davis Jr (USA) and Masatoshi Koshiba (Japan).

There are still many things about neutrinos that we need to know. A few of them are: individual neutrino masses, whether neutrinos are Majorana particles ($\bar{\nu}_i = \nu_i$) or Dirac particles ($\bar{\nu}_i \neq \nu_i$), what the mixing angles are, if neutrinos decay, etc. There are several new neutrino experiments under construction and some of them are ready to take data. Some of the new experiments are: (i) $\nu_\mu \rightarrow \nu_\tau$ **oscillation**: Several long-baseline experiments are planned where neutrinos of one type will be produced in high energy accelerators (namely at KEK, CERN and Fermilab) and they will be focussed to distant detectors: at Kamioka which is 250 km from KEK (K2K), at Gran Sasso which is 730 km from CERN (CNGS), and at Soudan which is 730 km from Fermilab (MINOS). The KEK to Kamioka experiment has already reported its first results of neutrino oscillation and they are seeing less number of muon-neutrinos than expected. (ii) $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$: MiniBooNE experiment at Fermilab has started taking data to look for oscillations reported by LSND. (iii) Many experiments are planned to search for neutrinoless double-beta-decay with an aim to reach sensitivity in neutrino mass to: $< m_\nu > \sim 10^{-2}$ eV in 5 years running period. Some of these very large detectors are: GENIUS with 1 ton of Ge^{76}, MAJORANA with 0.5 ton of Ge^{76}, CUORE with 760 kg of Te^{130}, EXO with 1 ton of Xe^{136} and GEM with 1 ton of Ge^{76}. (iv) Several underwater/underice high energy ($\sim$ 1 TeV) neutrino observatories (AMANDA, NESTOR, ANTARES, IceCube, Baikal, etc.) are under construction/consideration, and their aim is to observe neutrinos from astrophysical sources.

Neutrino physics continues is to be a very exciting field and may also bring us new surprises.

Suggested Reading

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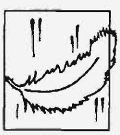

... taking the present flora of the earth as an individual organism, botanists can scarcely afford to study it simply as it exists today for they would thus obtain at best a sectional view. To the noble science of geology, then, we owe a veritable 'Time Machine' with which, although we cannot follow Dr H G Wells into the realm of the Future, we can at least obtain a glimpse into a romantic past.

– *Birbal Sahni*